THE OLD RED SANDSTONE OUTLIERS OF GAMRIE AND RHYNIE, ABERDEENSHIRE.

VOLUME 1

R.Archer BSc (Newcastle-upon-Tyne)

THESIS SUBMITTED FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

UNIVERSITY OF NEWCASTLE UPON TYNE

SEPTEMBER 1978

LIST OF CONTENTS

VOLUME ONE

CHAPTER FOUR SOURCE AND DISPERSAL OF SEDIMENTS OF THE GAMRIE AND RHYNIE OUTLIERS

PAGE

ABSTRACT

The Gamrie and Rhynie Outliers are the major outcrops of Old Red Sandstone in north-east Scotland. The stratigraphy of these deposits is reviewed and the Crovie and Findon Groups recognised at Gamrie, whilst the Rhynie Group is proposed at Rhynie. The existing stratigraphical subdivision has been modified, expanded, and the sediments described in detail. The resulting stratigraphy allows speculation as to the relationships between the numerous isolate coastal outcrops, but does not as yet allow correlations between the Gamrie and Rhynie Outliers.

A study of the sedimentary facies forms a basis of the stratigraphy, and it is concluded that the Gamrie Outlier existed as an almost enclosed intermontain basin surrounded by relatively low mountains from which a variety of alluvial fan environments debouched onto an extensive Piedmont floodplain/Playa surface. Ephemeral stream processes dominate the sedimentary record, with sheets of sediment eventually splaying out onto the floodplain surface which at times supported temporary lakes. The climate at this time was probably arid/semi-arid allowing the extensive accumulation of pedogenic carbonate in thick calcrete profiles.

Sedimentation trends indicate that following the development of the basin a period of fan recession and floodplain aggradation occurred, but renewed tectonism is evident (ultimately causing the Middle Old Red Sandstone unconformity) and eventually caused re-advance of alluvial fans at a time when the 'Orcadian Lake' to the north was rapidly expanding. In the highest deposits of the Gamrie sequence, the Orcadian Lake temporarily extends into the Gamrie Outlier.

Paleocurrent and source rock studies allow detailed source area reconstruction and help to confirm the above mentioned trends and indicate that an early south east/south supply of granite-rich detritus was eventually dominated by a south west/west supply of slate material.

At Rhynie, the picture is clouded by poor exposure, but the sedimentation trends are analogous to the early period of fan recession at Gamrie, evident from early sheetflood conglomerates being replaced by braided stream and finally floodplain sediments. The floodplain sediments at Rhynie allowed the development of an extensive, primitive land flora, now preserved in excellent detail in fossil 'peats' of the Rhynie Cherts.

Paleocurrents and source area evidence strengthen the hypothesis that the Rhynie Outlier drained northwards to the Orcadian Basin, and not south to the Midland Valley as has been suggested. A probable link between the Rhynie and Gamrie Outliers is considered.

The Lower Old Red Sandstone of both Outliers (originally considered 'Barren') offers a surprising collection of trace fossils including possible lungfish or annelid burrows, insect tracks and worm burrows, and helps to build up a more complete picture of the Lower Old Red Sandstone fauna and environment.

The clastic sediments have been studied by a variety of techniques including reflected and transmitted light microscopy, scanning electron microscopy and x-ray diffraction; their chemistry by a combination of atomic absorption, x-ray fluorescence and electron microprobe techniques, whilst thermal/magnetic techniques have allowed an insight into the location and genesis of iron oxides.

Overall, it is concluded that the climatic conditions were conducive to the formation of primary red-beds, but the normally accepted mechanism of formation are regarded as incomplete. In the present case, instead of biotite liberating iron by the accepted mechanism of in-situ chemical degradation, this study concludes that biotite has in fact concentrated iron and liberated clay sized haematite principally by the mechanical degradation of biotite in floodplain sites during transport. In-situ degradation and remobilisation of iron is considered to be minimal.

ACKNOWLEDGEMENTS.

Many people have contributed in a variety of ways during the course of this study, and I would like to take this opportunity to offer my sincere thanks to all of them.

In particular, special thanks are extended to :

Prof. T.S.Westoll, for suggesting the topic, providing supervision and assisting in the production of the final draft.

Dr.P.Turner, for a wealth of discussion, and in particular, constructive criticism both in the field and in the laboratory.

Dr.R.N.Donovan, for guidance during the early stages of the project.

Dr.M.Tucker and Dr.P.Shannon, for assistance in reading the manuscript.

Mr.P.Oakley, for advice and assistance with chemical analysis.

Dr.Lyons, for unrestricted access to the 'Rhynie Chert site' , and to Dr. J.M.Jones for his futile attempt to drill the deposit.

Miss.L.McGuinness for patiently typing the manuscript, and Miss. Y.Rogerson for assistance with the production of tables.

The Natural Environment Research Council for financial support.

Finally, I would like to thank my wife Marilyn for the help and support that she has provided during the production of this thesis.

GENERAL INTRODUCTION

This thesis is primarily concerned with providing a detailed reappraisal of the stratigraphy of the sediments of the Gamrie and Rhynie Outliers, and providing a comprehensive description of the sequences therein. The absence of any substantial fauna or flora necessitates the application of purely lithostratigraphical techniques, and therefore a detailed summary of the sediments (Chapters 1 and 2) is complimented by a detailed interpretation of the sedimentology and sedimentary history of the deposits (Chapter 3).

A consideration of the source and dispersal of the sediments in north east Scotland (principally paleocurrents, conglomerate composition and sandstone composition) is made in Chapter 4, where an attempt is made to compliment the sedimentology with a regional reconstruction of the Old Red Sandstone paleogeography.

A study of the fauna and flora of a sequence may provide valuable evidence as to the nature of the environment. As the sediments concerned are effectively barren a study of trace fossils from both Outliers has been made in Chapter 5 as an alternative approach to this problem.

Finally, the sediments themselves may provide further climatic and paleogeographic evidence in the form of pedogenic carbonate accumulations (described in Chapter 7); and in red-beds (described in Chapter 6). Paleomagnetism has existed for many years, but its wider applications have only been realised in recent years. The use of paleomagnetic techniques in conjunction with Dr. P. Turner has allowed a detailed study of red-bed genesis to be made during the course of this study. Although not directly applicable to the main theme of the thesis, this work has been included in Chapter 6 as the conclusions reached are critical of accepted models of haematite genesis in red-beds.

Although each chapter is intended to contribute to a single aim, each chapter remains largely independent, and therefore all discussion and conclusions have been restricted to within the chapter concerned rather than being isolated within a separate section.

CHAPTER 1

STRATIGRAPHY OF THE OLD RED SANDSTONE SEDIMENTS OF THE GAMRIE OUTLIER

1.1 (i) Introduction

In recent years several successful studies have been directed towards the Old Red Sandstone of the Orcadian Basin, the more recent work being carried out on predominantly lacustrine and related facies in Caithness and Orkney. In these instances a working stratigraphy evolved, leaning heavily upon lithological criteria, and often being substantiated by biostratigraphical evidence. The Gamrie Outlier differs quite significantly from previous studies in that the sediments comprising the Outlier are of inferred marginal position to the Orcadian Basin and as discussed at a later stage (Chapter 3) are interpreted in terms of a variety of alluvial deposits; such are noted for rapid spatial and temporal facies variation. The absence of an abundant fauna or flora preclude any biostratigraphical confirmation of stratigraphic interpretation.

The following section offers a resumé of past interest in the geology of the Gamrie Outlier, in none of this past work was a detailed study of the rocks attempted, although some stratigraphic relationships were considered and established without formal discussion or description. Any attempt to define a stratigraphy for the Gamrie Outlier is fraught with problems:

(i) lithological variation in many sequences prevents an accurate characterisation of such sequences.

(ii) limited exposure prevents the study of 'equivalent sections' and leaves many rock units fault-bounded and isolated from the remainder of the sequence.

(iii) lithological variations on a large scale may be expected in sequences of alluvial deposits in a tectonically active area, and cast doubts on any conclusions drawn.

(iv) biostratigraphical confirmation (or even assistance) is conspicuously rare.

In many ways it is understandable that a formal stratigraphy has not been attempted, a final blow probably being that outside the realms of the Gamrie Outlier such a stratigraphy would have a limited practical value. Facies variation may be extreme and correlation within the outlier may be the limit to which the stratigraphy may be stretched. Nevertheless a sedimentological study of the Gamrie Outlier is desirable in order to reconstruct the local Old Red Sandstone paleogeography and for such a study to be temporally and spatially coherent a stratigraphy must be formulated, and must in this case rely totally upon lithostratigraphical criteria.

It is tempting to become involved in circular arguments as to order of merit, stratigraphy and sedimentology must work hand in hand, but as far as possible restraints have been applied in order to prevent assumptions from promoting interpretations. The erection of a stratigraphy has required the incorporation of many fields of work, from the sedimentological study to a study of the structure of the area, and including conglomerate composition, sandstone composition, and paleocurrent studies. All of these aspects have been combined to aid the interpretation and correlation of the short sequence of sediments exposed at Gamrie and it therefore seems unjust that the end product, a stratigraphy, be considered the basis of the remainder of the study.

Accepting that any stratigraphy must be erected on lithostratigraphic grounds the rocks of the Gamrie Outlier have been studied and considered in terms of their constituent lithofacies, a term proposed by Krumbein and Sloss (1963) "... the physical and mineralogic and petrographic characteristics of sedimentary rocks are expressed in terms of lithologic aspects which result in the delineation of lithofacies." Any consistency of lithofacies composition has been considered a characteristic lithofacies association or more simply, facies association. Such facies associations are presumably a record of distinct sedimentary environments, and with adequate exposure would form mappable rock units. On these grounds, wherever practical, this has formed the basis for the subdivision of the sequence into formations. Distinct lithological assemblages suffering significant restrictions in abundance or character have been assigned the Member subdivision in an attempt to utilise the resulting stratigraphy to characterise the sequence more fully.

1.1 (ii) Previous Research

Very little attention has been directed towards a detailed study of the rocks of the Gamrie Outlier in the past. The earliest recorded interest is the discovery of fossil fish at Gamrie in 1826 by Messrs. Christie and Docker (1826). Murchison (1829) was the first to draw attention to the outlier announcing the discovery of fossil fish in the Den of Findon. Sedgwick and Murc'ison (1835) were the first to direct attention to the geology of the outlier, but it was Prestwich in 1838 who first considered its stratigraphy. He examined the (Gardenstown) coastal section where he felt he could trace red sandstone passing down into schistose rocks. He assumed that the red sandstones were equivalent in age to the Old Red Sandstone of England, and claimed that the conglomerates and fish bearing horizon rested unconformably upon this sequence of Sandstones, thus concluding that the fish bearing deposits "belonged to the Carboniferous Series, and most probably to be the representative of the Millstone Grit or Mountain Limestone". Malcolmson (1839) was quick to challenge these conclusions noting that no passage existed (at Gardenstown) between red sandstones and conglomerate sequences. He recognised the Gamrie strata as lithological and paleontological equivalents of the Old Red Sandstone exposed to the west, and had no hesitation in referring the Gamrie rocks to the Old Red Sandstone series. His observations unfortunately only referred to the rocks of the western part of the Outlier, and he was indeed correct to point out a lack of "passage into schistose rocks". Although an unconformity exists he was also correct in pointing out that none is apparent at Gardenstown, yet his comments do imply that he thought that no unconformity existed anywhere in the Outlier. In 1843 Prestwich's work was attacked yet again by Hay Cunningham who rather unsuccessfully argued that the Gamrie Outlier was not fault bounded but instead that it had been deposited against large steep cliffs. In 1860 Gregory briefly described fossil-ferous Old Red Sandstone localities of the region and noted the character of the Gamrie fish bearing nodules. Geikie in 1879 was the first to offer details of the whole Outlier, his information eventually forming the basis of the Geological Survey Memoir. Geikie offered details of the sequences, noting the basal unconformity, and the fault-repeated sequences west of Dundarg Castle. He commented upon the similarity between sequences at New Aberdour Beach and Counter Head, and that "... they may possibly be regarded as the same". He also suggested an equivalence between the lower deposits at Gardenstown with those farther east. Geikie proposed a seven-fold subdivision of the Gardenstown sequence (later adopted by the Geological Survey) and estimated a total thickness of 1000 feet for the sequence. He suggested that the Gardenstown slate-rich conglomerate was equivalent to the conglomerate east of Pennan, an opinion not supported by the present work.

Traquair (1896) illustrated and offered details of fossil fish from Gamrie, from which direct correlation can be made with Middle Old Red Sandstone horizons of Caithness.

In 1890 the Geological Survey published explanatory Memoirs to sheets 86 and 97 but as noted the editions were largely based upon work by Dr.

J. Horne which was carried out prior to 1890. Much of the information provided by the Memoir echoes the thoughts of Geikie, "... his succession is adopted with but slight modifications in this Memoir" (Geological Survey sheet 86 p. 167). The survey memoir did not extend the stratigraphy proposed by Geikie, but it did add valuable field observations as to fault relationships etc. Inland exposures were noted, but little detail offered. The Geological Survey Memoir was the last work to consider the stratigraphy of the Outlier, the only other consideration being on the source of the sediments, an admirable approach carried out by Mackie in 1925. Mackie carried out extensive work on local igneous rocks enabling him to track down several of the rock types common in the Gamrie Conglomerates (see Chapter 4).

1.1. (iii) Outcrop Distribution

The map shown in fig. 1.1. shows the location of the Gamrie Outlier and demonstrates the distribution of Lower and Middle Old Red Sandstone strata. Inland exposure is very poor but extends southwards to Fyvie near Turriff (see Fig. 1.1). Along the 10 km. of coast between Gamrie Bay and Quarryhead the Old Red Sandstone sediments are exposed in natural fault bounded blocks, and for the purpose of the stratigraphic study these four naturally occurring blocks of sediment will be discussed separately (their extent is shown in Fig. 1.2).

i.e. (i) The Western Coastal Section extending between the Afforsk Fault and the western end of the Troup Head Fault.

(ii) The Central Coastal Section between the eastern continuation of the Troup Head Fault and the Langlitterty Fault.

(iii) The Eastern Section between the New Aberdour Fault and the basal unconformity at Fleckies Meadow.

(iv) The Quarryhead Section, a small embayment containing a short fault bounded sequence of Lower Old Red Sandstone resting unconformably on Dalradian.

Lower Old Red Sandstone of the Gamrie Outlier

1.2 Western Coastal Section

1.2 (i) Introduction

In their description of the Gamrie Outlier the early workers of the Geological Survey recognised a need for a two fold subdivision of the Old Red Sandstone sequence. Without reference to an unconformity, upper and lower divisions were termed Findon and Crovie Groups respectively.

The Findon Group was so named because of its occurrence in the Den of Findon, the Crovie Group for its outcrop along the Crovie foreshore to Gardenstown. Wholly on the basis of this Western Coastal section the Geological Survey erected the following sequence (Table 1.1).

Geological Survey Bed Number	
7.	Conglomerate and breccia.
6.	Grey and red clay with limestone nodules, containing fish remains, and lenticular grey micaceous shales, yielding plant remains and some scales of fishes.
5.	Coarse red conglomerate with some intercalations of red sandstones with fish scales.
...	
4.	Friable, bright red and mottled sandstone with scattered pebbles and occassional lenticular bands of conglomerates
3.	Red and grey sandy flags, shales and marls with ribs of limestone and calcareous nodules which have not proved fossiliferous.
2.	Dull red sandstone with calcareous concretions.
1.	Conglomerate, faulted against the Macduff Group.

Table 1.1 Stratigraphic Subdivision of the Gamrie Outlier outlined by Geological Survey

During the course of the present survey a total of ten lithofacies have been recognised along the western coastal section, and they have been employed to subdivide and characterise the sequence. These lithofacies will be detailed at a later stage, but a brief consideration of their distribution will outline the nature of the sequence and allow an insight into the basis for the various proposed subdivisions. As noted earlier, the basic unit recognised is the lithofacies, and characteristic groups of the lithofacies (facies association) have been recognised and assigned various stratigraphic status. Figure 1.3 is a summary of the lithofacies distribution in the western section illustrating the presence or absence of lithofacies in relation to relative stratigraphic height. The diagram performs several useful functions:

(i) it illustrates the basis from which the stratigraphy has been formulated.

(ii) the unique facies content of each stratigraphic unit is summarised

(iii) the lithofacies have been arranged in a fining order, and therefore the initial fining trend is apparent and can be seen to be superseded by a coarsening trend.

Therefore in terms of facies associations, the following sequence is recognised along the Western Section, its spatial distribution being illustrated in Figure 1.4. In the following table (Table 1.2) numbers refer to the original Geological Survey numerical subdivision noted in Table 1.1

Geological Survey, Bed Number	Present Study Facies Association	Proposed Formation
5	coarse conglomerate facies	Findon Conglomerate
----- fault -----		
4	sandstone facies	Castle Hill Sandstone
----- fault -----		
3	Heterolithic facies	West Harbour
3		East Harbour
----- fault -----		
3	Siltstone facies	Crovie Siltstone
2	Sandstone facies	Crovie Sandstone
----- fault -----		
1	conglomerate facies	Crovie Conglomerate
----- fault -----		

Table 1.2 Comparison of Geological Survey Stratigraphy with subdivisions proposed during present study

In noting this sequence the Geological Survey offered few details, a direct equivalence can confidently be made between their 1, 4, and 5 Beds and the facies associations listed above. Geological Survey Beds 2 and 3, being gradational sequences are difficult to locate from their brief descriptions, but bed 2 is apparently equivalent to the sandstone facies and part of the siltstone facies.

i.e. "... red and grey sandy flags, shales and marls with ribs of limestone and nodules which have not proven fossiliferous."

SANDY FACIES	SILTSTONE FACIES

During the course of this study, based upon the distribution of lithofacies, it has been found necessary to further subdivide the Geological Survey's bed 3. Details of this will be left until a relevant stage.

The Western Coastal Section exposes essentially two almost complete sequences of Crovie Group sediments:

(i) between the Troup Head Fault and the Snook, the Crovie sub section

(ii) between the Snook and the Afforsk Fault, the Gardenstown sub section

For convenience these two sections will be dealt with separately, as the faulting exposed at the Snook mars the continuity of the sequence and introduces problems as to the continuity of the sequence, and particularly the problem of strata removed due to faulting.

1.2 (ii) The Crovie Coastal Subsection

The lowest exposed strata of the Crovie coastal section belong to the Crovie Group and are faulted against the Dalradian strata in the middle of Crovie Village by the 055N trending Troup Head Fault (see Figs. 1.4 and 1.5). The basic subdivision of the Crovie section and thus of the lowest Crovie Group sediments is quite clear.

i.e. faulted against the Dalradian is a Conglomerate facies superseded by a sandstone facies which passes ultimately into the siltstone facies.

1.2 (ii)a Crovie Conglomerate Formation (Conglomerate Facies)

Faulted against the Dalradian by the Troup Head fault its position in the sequence remains conjectural. The restricted clast assemblage (>95% local Dalradian material) suggests a local supply of detritus and hints that the Crovie Conglomerate may genuinely be a representative of the earliest sediment deposited in this area. The faulting at the base of the sequence prevents an accurate estimation of its thickness or true position relative to an unconformable base.

Characteristics	A monotonous sequence of internally massive conglomerates consisting of essentially local detritus interbedded with thin, rare, medium to coarse grained sandstones.
Type Section	The type section is that exposed between the Troup Head fault and the North Crovie fault in the middle of Crovie.
Equivalent section	None
Lowest Stratum	Fault-bounded by the Troup Head fault bringing conglomerate and Dalradian rocks into juxtaposition.
Uppermost Stratum	The 055 N trending North Crovie fault bringing the conglomerates into contact with the sandstone facies.
Thickness	Impossible to determine. 30 m are exposed, but the section passes from the sea wall out to sea. Considerations of the structure of Gamrie Bay have lead to important conclusions relative to the thickness and nature of the Crovie sequence (see later discussion, page 23).
Nature of Outcrop	A narrow stretch of rocky shore exposing a broken sequence of conglomerate. The orientation of the unit is such that only a short strike section can be studied (Figs 1.4 & 1.5)

General Stratigraphy

The formation is comprised alternations of the following three lithofacies.

1. conglomerate
2. massive sandstone
3. flat bedded sandstone

Conglomerate dominates the sequence (90.5%), being very poorly sorted and ranging in grade from gravel to cobble sized clasts (plate 1.1a). Bedding is poorly defined also but has been established on the basis of variations of grain size, sorting and packing, visible from a distance as a crude planar layering (plate 1.1b).

Interbedded with the conglomerate are:

a) coarse to medium grained reddish brown sandstones (3.5%) with flat bedding. The base of such units is frequently sharp but may also be gradational from sandy conglomerate.

b) Massive units of sandstone with the above characters (6%) which may be equivalent to (a) but lack apparent bedding.

Exposure is neither adequate nor extensive enough to obtain sufficient data to summarise the formation in a tabular form. Conglomerate bed thickness cannot be accurately ascertained but variations in character (i.e. grain size, packing and sorting) suggest that conglomerate bed thickness may be in the order of 15 to 60 cms. From these textural variations it is apparent that multistorey conglomerate units are common, sandstones only rarely occurring and often related to graded conglomerate units.

1.2 (ii)b Crovie Sandstone Formation (Sandstone Facies)

The Crovie Sandstone Formation is regarded as being directly equivalent to the lower portion of the Geological Survey's Group 2 beds "... red and grey sandy flags, shales and marls with ribs of limestone and nodules which have not proved fossiliferous...", although the upper part of their division now belongs to the Crovie Siltstone Formation

(i.e. "... marls with ribs of limestone...")

The Sandstone Formation is faulted against the Crovie Conglomerate to the north but is overlain conformably to the south by the Crovie Siltstone Formation; the majority is exposed to the north of Crovie Pier.

Characteristics	A sequence representing gradual but rapid change from the Crovie Conglomerate Formation through to the Crovie Siltstone Formation. Alternations of sandstone and siltstone with associated minor conglomerates predominate. At higher levels siltstones contain nodular carbonate.
Type Section	Crovie foreshore between the 'North Crovie Fault' and 60 m south of Crovie Pier (see Figs. 1.4 and 1.5).
Equivalent Section	None, but similar sediments are exposed at the Snook and at Craigendargity (see discussion page 23).
Lower Exposed Stratum	Adjacent to the 55 N trending North Crovie Fault north of Crovie Pier.
Upper Boundary	To the south of Crovie Pier, the highest development of trough cross stratified sandstones.
Thickness	At least 45 m. The faulted base complicates an accurate estimation of the total development.
Fossils	Poorly preserved spores extracted from silty bands in upper part.
Nature of Outcrop	Easily accessible but narrow foreshore, no cliff section but very poor exposure in the hillside and in the lower part of Braco Den. Small faults are abundant.

General Stratigraphy

The Crovie Sandstone Formation consists of cyclic alternations of the following lithofacies:

1. Conglomerate
2. Massive sandstone
3. Flat bedded sandstone
4. Trough cross stratified sandstones
5. Ripple cross laminated sandstones
6. Siltstone (modified by concretionary carbonate - lithofacies 9)

Lithofacies 1 - Conglomerate ranging from gravel to cobble grade, moderately well sorted but poorly stratified thick units, to thin sheets of well sorted gravel occurring at the base of lithofacies 4 units (Plate 1.2a)

Lithofacies 2 - Coarse to medium grained reddish brown sandstones with no detectable internal structure (Plate 1.2b). The true nature of lithofacies 2 is debatable - as they frequently occur related to lithofacies 2 or in similar sites it may be that lithofacies 2 = lithofacies 3 with no obvious bedding (i.e. they may have been produced by the same physical process - bedding is merely not apparent).

Lithofacies 3 - Coarse to fine grained reddish brown sandstones with well developed internal flat bedding. The base of such units is usually sharp and may be slightly erosive - otherwise the base is sharply transitional (Plate 1.2c).

Lithofacies 4 - Medium to fine grained reddish brown sandstones showing large scale trough cross-stratification (Plate 1.3a). The base of such units is usually erosive, but may follow lithofacies 3 by sharp passage. Erosive lithofacies 4 usually rests on lithofacies 6 and has a thin layer of lithofacies 1 at the base. Units of lithofacies 4 are usually multi-storey in that:

a) trough sets overlie one another to produce cosets of trough cross stratification.

b) trough sandstone sets may have individual mud drapes.

Individual sets range from 15 cm to 25cm the total development never exceeding four sets thickness.

Lithofacies 5 - Medium to fine grained red brown sandstone with internal ripple cross lamination (see plate 1.2b). Lithofacies 5 is usually graditional from lithofacies 2, 3 or 4 and may commonly be interbedded with lithofacies 6. Upper and lower surfaces are usually sharp but not erosional.

Lithofacies 6 - Brown siltstone, generally fine grade tending to mudstone, generally structureless, but may contain thin sheets of lithofacies 5 and/or scattered lithofacies 7 (Plate 1.3b and 1.3c). Finest grade horizons may show poorly developed flat or wavy bedding. Higher deposits of lithofacies 6 show well developed symmetrical ripples and abundant desiccation cracks (1.3c).

Lithofacies 7 - Nodular carbonate, the occurrence of which is restricted to lithofacies 6, more commonly to the upper portion (plate 1.3b). Two forms exist:

1. Large individuals arranged in sheets, red brown, internally comparable with nodules of same size, shape and appearance described from New Aberdour Shore.
2. Small irregular shaped nodules generally pale grey in colour. This variation shows no layered arrangements - i.e. randomly distributed and frequently coalescing. Their size is smaller than (1) size,shape and form is comparable with nodules found in the silts of the Quarryhead Section.

Fig. 1.6 shows selected field logs from lower, middle and upper portions of the Crovie Sandstone sequence. Fig. 1.7 shows a detailed summary of the form of the sequence.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Conglomerate	5.8	29	0.2	0.66	0.02	13	9.5
Flat bedded Sst.	8.0	40	0.2	0.68	0.02	18	13.3
Massive Sst.	3.8	20	0.19	0.65	0.03	9	6.3
Trough cross-stratified Sst.	15.91 15.91	43 43	0.37 0.37	1.10 1.10	0.1 0.1	19.3	26.1
Ripple cross-laminated Sst.	5.04	42	0.12	0.40	0.03	18.9	8.3
Siltstone	24.48	48	0.51	1.80	0.06	21.6	36.5
TOTAL	63.03						

Table 1.3 Thickness Parameters of the Lithofacies in the Crovie Sandstone Formation

In conjunction with the bed thickness frequency distributions shown in Fig. 1.8, table 1.3 allows a summary of the Formation to be made, but care must be exercised in any attempt to interpret the pooled data in such a table as the sequence is non-stationary, i.e. the nature of the sequence, the proportions of the individual lithofacies etc. are variable with stratigraphic height although the lithofacies present are invariable.

General Stratigraphy

From Table 1.3 it is clear that overall the Sandstone Formation consists of sandstones and siltstones in sub-equal abundance (sandstone being slightly more common overall i.e. sandstone 63%). The bulk of the sandstone part of the sequence consists of cross bedded sandstones, although numerically flat bedded sandstone and cross laminated sandstone are almost as common, reflecting the small units commonly developed in the latter two lithofacies compared to the thick developments of cross bedded sandstone.

The following section defines the Formation more specifically and takes into account the gradational nature of the sequence.

The thickness frequency histograms (Fig. 1.8) help to summarise the character of the sequence, i.e. Conglomerate occurs in units up to 66 cm thick, but thin units are most common, the average being 20 cm. Flat bedded sandstone may form units as thick as the Conglomerate, but these are rare, most likely units will be thin, i.e. average 20 cm. Massive sandstone averages 19 cm and has a similar range of thicknesses, and therefore much of this lithofacies may actually be flat bedded, but bedding is difficult to detect. Cross stratified sandstone has the largest unit thickness of all sandstone facies average 37 cm and ranging from 110 cm to 10 cm skewed towards smaller units, which is a reflection of the set size, and the common occurrence of multistorey units of trough cross bedding, i.e. set size is in the order of 10 cm and cosets often show only four sets or less. The average bed thickness is consistent with this. Ripple cross laminated sandstone shows a strong tendency to only occur in thin units 12 cm average. Cross laminated sandstones are up to 40 cm thick, thicker examples occurring in relationship with cross stratified beds, the bulk of the cross laminated sandstone occurrences i.e. the thin beds are those occurring interbedded with the siltstone lithofacies. Siltstone comprises the thickest individual lithofacies (51 cm average with a maximum development of 180 cm) again the deposits are skewed towards smaller units.

Basis for Formation Subdivision

The Sandstone Formation as defined contrasts strongly with the underlying Conglomerate Formation, the former having 64% sandstone compared to a mere 9.5% in the latter. New lithofacies are developed in the Sandstone Formation; to lithofacies 1, 2 and 3, the Sandstone Formation adds cross stratified sandstone (lithofacies 4), cross laminated sandstone (lithofacies 5) and siltstone (lithofacies 6). Initially, cross stratified sandstone dominates the sandstone portion of the sequence with only minor amounts of lithofacies 6 siltstone. With increase in stratigraphic height various changes occur in the abundance of the lithofacies which serve to to demonstrate the gradational nature of the sandstone sequence and illustrate its mid way position between conglomerate and siltstone Formations.

i.e.

1. Lithofacies 1 conglomerate is initially very abundant in thick units. At higher levels the abundance decreases leaving only thin sheets of gravel and pebbles as lags at the base of cross stratified sandstone units. A temporary return of conglomerate occurs towards the top of the sequence adjacent to the pier at Crovie (Fig. 1.9a).

2. The decline of conglomerate is accompanied by a decline of lithofacies 3 flat bedded sandstone (Fig. 1.9c).

3. With decreasing lithofacies 1 and 2, an increase in the abundance of lithofacies 3, 4, 5 and 6 are noted. Towards the middle of the Formation cross bedded sandstone and siltstone are approximately equal in abundance (Fig. 1.9c).

4. Towards higher levels cross laminated sandstone and flat bedded sandstone remain quite consistent in their abundance, but lithofacies 6 siltstone increases dramatically at the expense of lithofacies 4 cross stratified sandstone. The proportion of massive sandstone also accompanies this increase. The proportion of cross laminated sandstone remains constant but numerically the abundance increases due to the presence of numerous sandstone sheets in the siltstone portion of each cycle at higher levels (Fig. 1.9d).

5. Eventually the decrease of cross stratified sandstone heralds the incoming of the Mudstone Formation. The highest development of cross stratified sandstone being used to define the upper limit of the Sandstone Formation (compare Fig. 1.9d and 1.9e).

The above details are illustrated schematically in Fig.1.9, a series of facies profiles demonstrating the intermediate position of the Sandstone Formation. Fig. 1.9 also illustrates the problem mentioned earlier of accurately characterising a sequence by listing the abundance of the various lithofacies.

1.2 (ii)c The Crovie Siltstone Formation

The Crovie Siltstone Formation is a natural continuation of the upwards fining sequence initiated by the Crovie Conglomerate and continued by the Crovie Sandstone Formation. The Geological Survey were vague in defining their subdivisions but it is apparent that the Siltstone Formation is equivalent to a large portion of the Geological Surveys Bed 3. i.e. "... Red and grey sandy flags, Shales, and Marls with ribs of limestone and calcareous nodules which have not proved fossiliferous."

Characteristics	A sequence dominated by siltstones but with associated regularly spaced subordinate amounts of sandstone occurring as thin sheets. Lower parts of the succession have wavybedded and laminated mud lithofacies.
Section	South of Crovie Pier to the south end of Crovie Village.
Equivalent Section	None directly comparable but a relationship is suggested between this formation, the East Harbour Formation and the New Aberdour Siltstone Formation.
Lower Boundary	The base of the siltstone unit overlying the highest development of cross stratified sandstone used to define the top of the Sandstone Formation.
Upper Boundary	Faulted against sediments equated with the West Harbour Formation by the South Crovie Fault.
Thickness	94 m exposed but the proportion removed by the South Crovie Fault cannot be estimated.
Fauna	Poorly preserved spores such as *Dibolisporites* and

various smooth walled azonate varieties.

Nature of Outcrop A low wave cut platform covered at most tides. Transected by many joints and small faults. Easily accessible.

General Stratigraphy

The Crovie Siltstone Formation consists of alternations of the following four lithofacies.

Lithofacies 6 - Red Brown Mud/Siltstone

Lithofacies 5 - Sandstone, ripple cross laminated.

Lithofacies 8 - "Wavybedded" fine Sandstone with Siltstone partings (Heterolithic Lithofacies)

Lithofacies 7 - Laminated Mudstone/Siltstone

Lithofacies 5 and 6 are recorded continuously since the Crovie Sandstone Formation, lithofacies 7 laminated mudstone/siltstone and lithofacies 8 are newly introduced.

Crovie Siltstone Lithofacies

Red Brown Mud/Siltstone - Thick units (generally) of siltstone, frequently coarse, but often as fine as mud grade, red brown in colour (Plate 1.4). Generally structureless internally except for rare developments of mud as laminae preserving an irregular "wavy" bedding. Bedding is also demonstrated by interbedded thin sandstones (c/cm). Mudcracks are abundant throughout finest horizons, and thin muddy lamellae show the development of symmetrical (oscillation) ripples. Thin sandstones show linguoid ripple development. This lithology is considered equivalent to lithology 6 of Crovie Sandstone Formation.

Sandstone - Thinly bedded drab sandstones of medium to fine grain size. Always sharp based and also commonly sharp topped, although gradational tops are recognised (Plate 1.4). Internally bedding is often obscured by extensive carbonate cement but numerous examples have been found showing the development of micro trough-cross-lamination or ripple drift - often with mudstone veneers. This lithology is represented by lithofacies 5 in higher parts of the Crovie Sandstone Formation but is more analogous to interbedded sandstones in the lower East Harbour Formation and New Aberdour Shore Siltstone Formation.

Laminated Mudstone - A new lithology not recognised in lower parts of the sequence also remains quite rare (<1%) within the Mudstone Formation. Thinly developed units of not great lateral persistence composed of thinly laminated grey mudstones. Frequently desiccated and ripple marked.

The abundance of these four lithologies throughout the Formation is shown in Table 1.4 but as with sequences at higher levels it has been deemed necessary to subdivide the sequence further to allow a more accurate portrayal of the succession.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	185.3	87	2.13	5.7	0.03	53	95
Sandstone	4	67	0.06	0.25	0.01	41	2
Laminite	0.25	5	0.05	0.11	0.01	2	1
Wavy-bedded sand and siltstone	4.5	7	0.64	1.04	0.23	4	2
TOTAL	194						

Table 1.4 Thickness Parameters of Lithofacies in the Crovie Siltstone Formation

Basis for Formation

As with previous Stratigraphic Units the designation of strata to the Mudstone Formation has been carried out with the distribution of lithofacies as a basis. The top of the Sandstone Formation was defined as the highest occurrence of Trough bedded sandstone - this must also serve as the base of the Mudstone Formation. The choice of this level as a stratigraphic boundary is supported by further lithological evidence.

Above the designated base of the Mudstone Formation.

(a) as stated - trough bedded sandstones no longer occur,

(b) flat bedded sandstone, and conglomerate no longer occur,

(c) new lithologies are introduced,

(i) Wavy bedded fine sandstone

(ii) Laminated mudstone/siltstone, (laminite),

(d) siltstone continues but in greater abundance, but suffers a marked decrease in average unit thickness, i.e. from 51 cm. average in the Sandstone Formation to 30 cm. average in the Lower part of the Mudstone Formation.

Basis for Member Division

Further consideration of the distribution and nature of the mentioned lithologies also leads to the necessity for further lithostratigraphic subdivision.

i.e. (a) The newly introduced laminated mudstone and wavy bedded fine sandstone lithologies cease to occur after approx. 20 metres and during this 20 m. the siltstone thickness remains consistently quite low (Fig. 1.10).

(b) Above the level where the laminite and wavy bedded lithofacies disappear a rapid increase in siltstone unit thickness occurs and this continues to a stratigraphic height of approx 55 m. (Fig. 1.10).

(c) Above 55 m. the siltstone unit thickness decreases again.

These features are illustrated in Fig. 1.10, a smoothed time trend analysis of siltstone bed thickness data showing a clear three fold subdivision of the Mudstone Formation. Throughout these three members Fig. 1.11 illustrates that the percentage distribution of lithologies remains fairly constant and for this reason they have been grouped into the Siltstone Formation, divisions being allocated 'Member' status.

Summary of Stratigraphy

Thus the Lower Siltstone Member consists predominantly of Siltstone, but in quite thin units (average 30 cm.) interspaced with wavy bedded lithofacies in thick units (approx. 64 cm.) but with only minor amounts of laminated mudstone and sandstone. (Fig. 1.12a, Fig. 1.13) Frequently an arrangement of facies exists such that fining upward cycles develop:

(a) based by sandstone,

(b) succeeded by wavy bedded lithofacies,

(c) capped by siltstone,

(d) occasionally laterally impersistent laminated mudstones may follow.

A further phenomenon separating the lower member is the common occurrence of calcareous nodules in such cycles. They occur either as densely packed small nodules, as in the Sandstone Formation, or as individual sheets of isolate large nodules (c.f. New Aberdour Shore).
Table 1.5 lists the lithofacies abundance data for the lower mudstone Member.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	15.7	51	0.3	1.74	0.03	53	84
Sandstone	1.6	34	0.05	0.15	0.01	35	9
Laminite	0.2	5	0.05	0.11	0.01	5	1
Wavy-bedded sand and siltstone	1.1	7	0.64	1.04	0.23	7	6
TOTAL	18.6						

Table 1.5 Thickness Parameters of the Lithofacies in the Crovie Siltstone Fomration, Lower Member

The Middle Siltstone Member composition is displayed in Table 1.6 demonstrating clearly that only two lithologies alternate, sandstone and siltstone. Siltstone thickness is high, average 2.2 m., and is consistently so, ranging from 0.9 m. to 5.7 m. Sandstone thickness on the other hand is always persistent laterally. Laminite and wavy bedded lithofacies do not occur, and in contrast to the Lower Member no calcareous nodules are present. (Fig. 1.12b, Fig. 1.13)

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	37.6	17	2.2	5.7	0.9	48	98
Sandstone	0.8	18	0.04	0.11	0.01	52	2
Laminite	-	-	-	-	-	-	-
Wavy-bedded sand siltstone	-	-	-	-	-	-	-
TOTAL	38.4						

Table 1.6 Thickness Parameters of Lithofacies in the Crovie Siltstone Formation, Middle Member

The Upper Siltstone Member consists of the same lithofacies as the Middle Member but has been distinguished on bed thickness data.

(1) Siltstone has decreased in mean thickness to 1.2 m. and similarly the total range has decreased to 3.4 m. to 3 cm.

(2) Sandstone on the other hand has marginally increased, both in abundance and in average thickness (9 cm.) having a maximum thickness of 25 cm. compared to 6 cm. in the Middle Member.

Table 1.7 lists the composition of the Upper Member.(see Figs. 1.12c, 1.13)

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	22.8	19	1.2	3.4	0.03	56	93.4
Sandstone	1.4	15	0.09	0.25	0.03	44	5.7
Laminite	-	-	-	-	-	-	-
Wavy-bedded sand and siltstone	-	-	-	-	-	-	-
TOTAL	24.2						

Table 1.7 Thickness Parameters of Lithofacies in the Crovie Siltstone Formation, Upper Member

1.2 (ii)e Summary and Discussion

The upward fining trend, and the gradational nature of the sequence at Crovie leaves little doubt as to the nature of the sequence, and order of stratigraphic units. Problems do exist, and are concerned mainly with the thickness of each Stratigraphic Unit, and the nature of the sediment removed by faulting.

The Crovie Conglomerate Formation has an exposed thickness of 30 m but passes out to sea. 45 m. of Crovie Sandstone Formation strata outcrop but the unit has a faulted base. Equivalent sections of strata analogous to the Sandstone Facies and tentatively assigned to the Sandstone Formation are exposed at Craigendargity, and at the Snook. Fig.1.14illustrates the main structural elements of Gamrie Bay, and shows the disposition of the Stratigraphic Units.

Due to the immature assemblage of detritus it may be true that the Crovie Conglomerate Formation represents the earliest sediment deposited in the Western Section. Nevertheless no evidence exists to allow the nature or the thickness of sediment removed by faulting at the base of the sequence to be estimated.

The Crovie Sandstone contains conglomerate horizons at the base, and near the top, and in both of these restricted developments the composition of the detritus is identical to that of the Conglomerate Formation, and more significantly the composition of the conglomerate exposed at the Snook and at Craigendargity.compares with that of the Conglomerate Formation also. There is little doubt therefore that the Conglomerate Formation and Sandstone Formation are related, and it is tempting to assume that the sandy developments at the top of the exposed Conglomerate Formation Sequence are related to the conglomerate developments at the bottom of the Sandstone sequence and, therefore, to suggest that only a small amount of strata has been removed by the faulting that connects the two sequences.

At first sight this appears reasonable, and the writer is confident that the two sequences are related, but the gap between Conglomerate and Sandstone Formations may be large.

The Conglomerate Formation is comprised 90% Conglomerate, the Sandstone Formation 19%. Siltstone is immediately present in the Sandstone Formation Sequence, but absent from the Conglomerate Formation. The short sections exposed at the Snook and at Craigendargity are sandstone dominated, and about 90% of this is coarse and conglomeratic, quite dissimilar to either Conglomerate or Sandstone Formations.

The problems are:-

(i) What is the true thickness of the Conglomerate Formation?

(ii) What is the true thickness of the Sandstone Formation?

(iii) Do the Craigendargity and Snook exposures belong to a sequence of rocks originally between the Conglomerate and Sandstone Formations?

A consideration of the structure of Gamrie Bay allows some light to be cast upon these problems. Fig. 1.14 shows that the faulting between Craigendargity and the harbour at the Snook follows a trend comparable with that of the Troup Head and North Crovie faults, and the possibility that these faults may be related is not unreasonable. If such faults are connected, then the exposure of Dalradian rocks in the bay at Crovie "Black Stones" implies that the unconformable base to the Devonian sequence may exist beneath Gamrie Bay and if this assumption is correct then a normal sequence may exist up to the conglomeratic sandstones at either the Snook or at Craigendargity.

This consideration does not assist in an estimation of Conglomerate and Sandstone Formation thickness but it does serve to suggest that the thicknesses may be well in excess of those measured, and also, the conglomerate sandstones at the Snook and at Craigendargity may belong to a sequence not represented along the Crovie Section but originally deposited between the Conglomerate and Sandstone Formations. The Crovie Siltstone Formation may continue into the East Harbour Formation, this would be acceptable, but remains unproven. Whatever the relationship - no estimation can be made of the nature or thickness of sediment removed.

In summary therefore the Crovie section displays the following:-

——— Faulted ———	Unknown thickness of sediment removed
Crovie Siltstone Formation	94 m. exposed
- - - - - - -Transition- - - - - - -	
Crovie Sandstone Formation	45 m. exposed, but thickness may be well in excess of this
——— Faulted ———	
Snook and Craigendargity Sections	It is suggested that a further facies, poorly representated at present, may exist at this horizon.
——— Faulted ———	
Crovie Conglomerate	30 m +, thickness may well exceed this value
——— Faulted ———	
Dalradian	

1.2 (iii) The Gardenstown Coastal Subsection

1.2 (iii)a Introduction

The section of coastal exposure between the Snook and the Findon Fault completes the exposure of the Basement Group in the Western Section, and provides a reasonably continuous exposure of the higher deposits of the Crovie Group sediments. Unfortunately, as elsewhere, continuity of exposure is marred by the incomplete nature of the sequence caused by faulting. As was shown in Fig. 1.14 the section is bounded to the east by the Findon Fault and to the west by the Afforsk Fault. It will be apparent from this map that minor faulting complicates the section, frequently forming boundaries between proposed rock stratigraphic units.

Along the section the following sequence is exposed, as defined earlier on page

5	Conglomerate facies	Afforsk Fault.
4	Coarse sandy facies	
3	Sandy facies	
3	Silty facies	Findon Fault

Direct comparison can be made between the conglomerate and coarse sandy facies with the Geological Survey's beds 5 and 4 respectively. Again, the boundaries of the Geological Survey's bed 3 horizon are obscure and during the present survey it has been found necessary to subdivide the sediments lying between the definite bed 2 and bed 4 (presumably bed 3!!) into two lithological dissimilar units. The above broad groupings can be made without recourse to "lithological-statistical" means as the four divisions are lithologically quite dissimilar, whilst at the same time appear to be gradational from one unit to the next.

As mentioned previously the Geological Surveys numerical notation is obsolete and contravenes the proposed code of stratigraphic practice (Krumbein & Sloss 1963) and it is proposed to redefine the sequence on a Formation/Member basis. On these grounds the above sequence becomes:

5	Findon Conglomeration Formation		Middle Old Red Sandstone
		Afforsk Fault	
4	Castle Hill Sandstone Formation		Lower Old Red Sandstone
3	West Harbour Formation		
3	East Harbour Formation		
		Findon Fault	

1.2 (iii)b <u>East Harbour Formation</u> (or silty facies)

The East Harbour Formation constitutes the lowest exposed sediments of the Gardenstown section and is equivalent to the lower portion of the Geological Survey's bed 3 sediments. The naming of the unit is derived from its total exposure to the east of Gardenstown harbour, the basis for further subdivision will be discussed later (page 33)

<u>Characteristics</u>

A sequence of repetitive units of four distinct litho-facies:

1. Sandstone
2. Wavy bedded sandstone and siltstone
3. Siltstone
4. Laminated mudstone

The sequence is dominated by facies 2 and 3, the proportions being variable throughout the sequence and necessitating a further subdivision of the sequence.

<u>Type Section</u>

The type section is the wave cut platform exposed between the Snook and the east pier of Gardenstown Harbour. This remains the only section available of sediments of this character.

<u>Lowest Exposed Stratum</u>

Siltstones outcropping to the west side of the Findon Fault in the vicinity of the Snook (see Fig. 115)

Topmost Exposed Stratum The incoming of persistent sheets of cross laminated fine sandstone occurring adjacent to the seaward extension of the eastern pier of Gardenstown Harbour (see Fig. 1.15)

Thickness A measured thickness of 94 m is exposed between the defined boundaries, but the total extent of this unit is unknown because of the faulted base, and faulting in mid sequence.

Nature of Outcrop A broad wave cut platform with easy access but requiring low water. The section is backed by a sea wall and only poor exposure is available behind this in parts of the heavily overgrown cliff.

Faulting complicates the otherwise simple structure by causing minor folding at the base of the section, and by removing an unknown thickness of sediment from the middle of the sequence.

General Stratigraphy

The sequence is composed of sequences involving the following four lithofacies, selected field logs are shown in Figs. 1.16 and 1.17, (see also 1.18)

Lithofacies 1 - Sandstone

(Plate 1.5) Thin laterally persistent, drab, fine sandstone sheets, showing sharp, often slightly erosive bases. Ripple cross lamination may be present but most commonly the sandstones are massive with occasional flat bedded units showing parting lineations. The tops of sandstone units are always sharp, i.e. they occur as discrete sandstone units rather than grading into higher sediments, and although laterally persistent, sandstones may show variation of 50% or more in thickness over distances of the order of 20 m. Sandstone frequently occurs interbedded within other lithofacies, or recording a change from one association to the next.

Lithofacies 2 - Wavy Bedded Sandstone and Siltstone

(Plate 1.5) Alternations of thinly bedded impersistent sheets of sandstone and siltstone forming thick laterally persistent units. Lithofacies 2 always follows the previous facies by sharp passage, but may be gradational into succeeeding facies in a simple fining sequence. The base of lithofacies 2 units is never erosive, but lithofacies 1 commonly forms the base (55.3% of lithofacies 2 units are based by lithofacies 1). Laterally the units are persistent both in thickness and internal form. Compared with this the interal bedding is frequently obscure and impersistent, consisting of sharp, often slightly erosive based thin sandstones which rarely continue for more than 2 m, these grade rapidly into siltstones and very fine sandstones which are usually of the same order of thickness, i.e. 1 to 3 cms. Internally the sands and silts are frequently massive, but occasionally the sandstones show a poorly developed ripple cross lamination which is further reflected by the overall wavy nature of the interbedding. The colour ranges from buff (mainly sandstone) to brown (mainly siltstone). The siltstones may grade into mudstone in some instances and in these cases symmetrical rippled surfaces may be preserved. Flasered lenses of sandstone may also be found in the thicker units of siltstone. Lithofacies 2 is commonly desiccated, and often at numerous levels within each unit. Lithofacies 2 is commonly overlain by siltstone, but in several cases thin lenticular units of laminated mudstone have been observed, but always on the tops of the units and never within the units. Less commonly the following structures are observed:

Well developed sheets of ripple cross lamination,

Well developed sheets of climbing ripple cross lamination,

Graded units,

Ball and pillow structures,

Convolute bedding.

Lithofacies 3 - Siltstone

(Plate 1.5) Thick units of siltstone or muddy siltstone occurring in massive or finely laminated units with a very low percentage of impersistent thin fine sandstone sheets. Units of siltstone are persistent and consistent laterally and usually develop by rapid gradation from the previous unit, which is commonly lithofacies 1 or 2, i.e. 32% and 40% respectively. The rapidly gradational base often incorporates thin flaser type sandstones more typical of lithofacies 2. On the whole bedding is obscure and denoted by thin slightly coarser siltstone sheets or more rarely lenticles of very fine sandstone. Mud veneers are commonly present in thin persistent sheets but generally only occur towards the top of a unit. The ultimate sediment is usually either laminated mudstone or reddish brown mudstone. The laminated mudstone is similar to those developed at higher levels, i.e. in the West Harbour Formation, and although uncommon, does occur in fairly persistent levels. The mudstone is less common and occurs only as infillings of lenticular hollows in the top surface of the siltstone or laminated mudstone. The upper surface is always sharp, and may be desiccated although desiccation cracks are rarely recorded within siltstone units. The soft nature of such units usually prevents the formation of bedding plane surfaces - rare examples found often show symmetrical ripple marks or trains of linguoid ripples formed in thin sandstone sheets. The colour of siltstone units ranges from dark grey to reddish brown. Grey sediments dominating the base of the formation whilst brown and reddish brown siltstones increase in abundance towards higher levels. In lower and mid portions of the sequence levels of isolated calcareous nodules are common in thicker siltstone beds.

Lithofacies 4 - Laminated Mudstone

Thinly interbedded laminae of mudstone and siltstone, usually grey in colour and commonly of very restricted lateral persistence. Laminated mudstone is uncommon in the sequence, but when present always occurs at the top of units of lithofacies 3 (never interbedded). Internal bedding is developed on a mm scale and of no great persistence but often having a micro-ripple appearance.

Mudstone - occurs very infrequently and has not been included as a characteristic lithofacies. Essentially very thin units of reddish mudstone, internally massive and always in laterally impersistent lenticular units. Desiccation is abundant in these red mudstones. Small tubular infillings occur and may represent either rootlets or burrows, comparable to structures more abundant in the West Harbour Formation.

Table 1.8 is a summary of the lithofacies content for the East Harbour Formation, mudstone has been omitted as it comprises much less than 1% of the measured thickness.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	39.9	53	0.75	2.1	0.02	25.9	42.4
Sandstone	4.6	57	0.08	0.24	0.03	27.9	4.9
Laminated Mudstone	6.9	26	0.26	0.7	0.02	12.7	7.3
Wavy-bedded sand-siltstone	42.6	68	0.63	2.1	0.1	33.3	45.3
TOTAL	94.0						

Table 1.8 Thickness Parameters of Lithofacies in the East Harbour Formation

Lithofacies 2 and 3 (wavy bedded sandstone-siltstone and siltstone) clearly dominate the overall sequence having infrequent interbedded thin units of lithofacies 4 - laminated mudstone, and also thin units of lithofacies 1 - sandstone. (i.e. compare thickness percentages and numerical abundance)

Basis For the Recognition of the East Harbour Formation

The East Harbour Formation is the lowest group of deposits recognised in the Gardenstown section and comprises a sequence of sediments similar in many respects to the Crovie Siltstone Formation, but differing significantly from overlying deposits in the Gardenstown sequence. In contrast to the Crovie sequence new lithofacies have been introduced (i.e. lithofacies 1 and 4) and are the basis for the erection of a new formation rather than assigning the sequence to the Crovie Siltstone Formation.

In terms of lithofacies abundance, the East Harbour Formation is a gradational sequence necessitating a two fold division of the sequence. As no new lithofacies are introduced or previous ones lost within either of the subdivisions proposed, it is felt more appropriate to retain the whole section as the East Harbour Formation but add an internal upper and lower subdivision on a member basis as the latter characterises the gradational sequence more accurately than the one major grouping.

Fig. 1.19 illustrates the vertical profile constructed for total data and compares it with profiles erected using partial data from the proposed upper and lower subdivisions. The East Harbour Fault (Fig.1.15) forms a convenient mid point division to the sequence, dividing it into an incomplete lower siltstone rich sequence and an incomplete upper sequence rich in the wavy bedded lithofacies. Table 1.9 summarises the appropriate lithofacies composition data for the proposed upper and lower members.

	Lower Member	Upper Member
Laminated mudstone	6.1	7.2
Siltstone	59.4	24.6
Wavy bedded Sst. Silts.	32.8	48.3
Sandstone	1.7	19.8

Table 1.9 Summary of Lithofacies content of Upper and Lower East Harbour Members

It is clear from Table 1.9 that the Lower East Harbour Member is siltstone dominated (59%) whilst in comparison the Upper Member shows a considerable reduction in siltstone to 25%, see Figs. 1.19 and 1.21 This upward reduction in fine lithologies being accompanied by a concomitant increase in wavy bedded and sandstone lithofacies (i.e. an increase in coarse sediment).

A time trend analysis of lithofacies thickness data (Fig. 1.20) shows a slight change in form of the sequence with increase in stratigraphic height, a feature more clearly illustrated by the thickness frequency histograms (Fig. 1.21). Lithofacies 2, 3 and 4 show a clear distinction in the thickness distributions in upper and lower members, the upper member in each case having a tendency towards thinner units. Also in general, the standard deviation is lower for the bed thickness data of the upper member.

A one way analysis of variance carried out on bed thickness data indicates that to within the 95% level of confidence no significant correlation exists between the lithologies of upper and lower members

Stratigraphic Summary

Lower East Harbour Member - Table 1.10 summarises the lithofacies composition of the lower member, clearly demonstrating the predominance of siltstone over wavy-bedded deposits, both of which make up the bulk of the sequence.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	26.9	24	1.12	2.1	0.3	42	59.4
Sandstone	0.53	11	0.05	0.12	0.03	19	1.7
Laminated Mudstone	2.75	8	0.34	0.7	0.15	14	6.05
Wavy-bedded sand-siltstone	15.3	14	1.1	2.1	0.2	24	32.8
TOTAL	45.48						

Table 1.10 Thickness Parameters of Lithofacies in the Lower East Harbour Member

The frequencey distribution of bed thickness data (Fig. 1.21) shows the predominance of thick units of siltstone and wavy bedded lithofacies, interspaced with thin infrequent laminite and sandstone.

Upper East Harbour Member - Table 1.11 lists the lithofacies composition of the upper member.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	12.96	29	0.45	2.02	0.02	19.7	24.6
Sandstone	4.13	46	0.09	0.22	0.05	31.3	19.8
Laminated Mudstone	4.17	18	0.23	0.4	0.02	12.2	7.2
Wavy-bedded sand-silkstone	25.36	54	0.47	1.25	0.08	36.7	48.3
TOTAL	46.62						

Table 1.11 Thickness Parameters of Lithofacies in the Upper East Harbour Member

Clearly the upper member consists of the same lithofacies, but it is characterised by:

(i) a decrease in the importance of siltstone, wavy bedded deposits are most abundant, and sandstone increases markedly;

(ii) laminite thickness is marginally lower;

(iii) siltstone range of thickness has varied very little but as shown in the thickness frequency histograms the distribution is skewed towards smaller beds in the upper member;

(iv) the same is true in the case of the wavy bedded lithofacies;

(v) sandstone thickness has increased, but most important the numerical abundance of sandstone beds has almost doubled.

Fig. 1.19 illustrates the lithofacies composition of the East Harbour Formation, and compares the form of upper and lower members.

1.2 (iii)c West Harbour Formation (sandy facies)

Characteristics A rhythmic sequence of coarse and fine beds with bedforms arranged in simple fining-upwards asymmetric cycles. A gradational sequence divisible into "upper" and "lower" members on the basis of the abundance of individual lithofacies, and dominated throughout by ripple laminated fine sandstone and siltstone.

Lower Boundary — The incoming of the first ripple cross laminated fine micaceous sandstone adjacent to the end of the east pier of Gardenstown Harbour. (Fig. 1.15)

Upper Boundary — N.W.-S.E. trending fault located 25 m. from West Pier, illustrated in Fig. 1.22

Thickness — At least 45 m (logged thickness). A determination of thickness is complicated by faulting within the sequence.

Nature of Outcrop — An easily accessible section formed by a low wave cut platform only exposed fully at low water. The section is backed by sea wall and offers no cliff exposure. The general strike is 300 N, dip 35° NW although this is complicated by the Gardenstown Basin - a small low angle basin occurring on the seaward side of the foreshore. The strike of the beds parallels that of the East Harbour Formation sediments initially, but rapidly bends to the west to form the 'basin'. Sediments rest horizontally in the centre of this structure, but are transected by the West Harbour Fault - a fracture which causes little disturbance on the east side, but produces steep dips and steeply plunging minor folds on the west. A small island of West Harbour Formation sediment outcrops to the north and dips at 40° to the North West. The sediments of this outcrop are closely comparable with the Lower West Harbour Member. The line of rocks known as Craigendairgity is separated from the foreshore by a further fault apparently parallel to the offshore fault just described. The Upper Member outcrops to the west of the West Harbour Fault and is formed into a relatively steeply plunging syncline with several small faults located on the fold axis.

Equivalent Section

A short section of sediments, similar in many respects to the West Harbour Formation, outcrops to the south of Crovie Village, fault bounded on all sides (see page 43)

General Stratigraphy (Plates 1.6, 3.9 – 10 – 11).

The West Harbour Formation consists of cyclic alternations of the following six lithofacies:

1. Cross-laminated sandstone;
2. Flat-bedded sandstone;
3. Siltstone;
4. Laminated mudstone;
5. Mudstone;
6. Cross-stratified sandstone.

1. Cross-laminated Sandstone

Thin, almost parallel units of fine to medium grained buff to red micaceous sandstone, generally slightly erosively based. Ripple cross lamination dominates the units, being a mixture of ripple drift (predominates) and climbing ripple cross lamination.

2. Flat-bedded Sandstone

Either medium grained sandstone with flat bedding and parting lineation occurring at the base of cross laminated sandstone units, or, fine grained sandstone with flat bedding at the top of similar units.

3. Siltstone

Massive red brown siltstone occurring in alternation with sandstone units, always passing gradationally from underlying sandstone. Immediately above the sandstone the siltstone may contain thin sandstone lenses. Siltstones are very rarely desiccated.

4. Laminated Mudstone

A thin interbedding of siltstone and red mudstone in small 0.5 cm graded couplets. Desiccation is quite common in these levels.

5. Mudstone

Thin developments of internally massive red mudstone, with abundant desiccation and sand filled burrows or rootlets. Mudstone units being thin tend to be impersistent and form in small channel shaped shallow depressions.

6. Cross-stratified Sandstone

Thick developments of fine to medium grained buff to red micaceous sandstone. Generally units have an overall lenticular or channel shape and have an internal cross stratification.

Lithofaces 1 to 4 are common in the lower member, whereas lithofacies 6 dominates the upper member as will be discussed later.

Basis for Proposal of West Harbour Formation

A significantly different assemblage of lithofacies marks the rapid transition into the West Harbour Formation. The previously common sandstone sheets and heterolithic facies are no longer recorded, whilst siltstone, laminite, and red mudstone remain allowing some sense of continuity to be envisaged. New lithofacies replace those removed - primarily fine grained micaceous sandstone with an abundance of ripple cross lamination. The form of the sequence alters with the above changes, and instead of the simple alternations recorded previously, graded bedding becomes common and characterises many lithological relationships. Associated with the sandstone there is abundant evidence of scouring and other minor erosional features uncommon at lower levels.

Overall the % distribution of lithofacies, particularly those retained differs markedly from that previously recorded, except in the case of siltstone. For example:

	Upper East Harbour Member	Lower West Harbour Member	
	T%	T%	T%
Laminated Mudstone	7	19	27
Siltstone	26	23	22
Heterolithic Facies	48	0	0
ripple laminated Sst.	0	58	50

Table 1.12 Comparison of Lithofacies content of Upper East Harbour Member and the Lower West Harbour Member

Basis for Member Subdivisions

Of the six lithofacies comprising the Formation only four occur in the lower division whilst all six develop at higher levels. Of the lithofacies common to all levels only lithology 3 remains relatively unchanged; the remainder suffer marked increases or decreases in abundance. Coarse member lithologies are drastically reduced but replaced by a considerable thickness of cross bedded sandstone whereas fine members suffer an overall reduction in abundance.

The dependence of individual cycles upon coarse or fine member thickness is considered in Fig. 1.23 where sandstone thickness is plotted against cycle thickness and siltstone thickness. These graphs show that in the lowest member sandstone thickness is related to cycle thickness, but the trend is not close to the 1 : 1 line as in the upper member. This implies a far greater importance of siltstone in the lower member. The second plot (Fig.1.23b) of sand v silt illustrates a clear separation of the two members either side of the 1 : 1 line of equal abundance. Thus it is clear that the lower member is heavily dependent upon siltstone whereas the upper member is dominated by sandstone units.

This trend of increasing abundance of coarse sediment is continued into the Castle Hill Sandstone Formation; indeed a coarsening trend has existed since the East Harbour Formation. In the Lower East Harbour Formation siltstone occupied 59% of the succession reducing to 26% by the Upper East Harbour Member. The Lower East Harbour Member consisted of 23% whilst the Upper Member contained 7% and looking ahead temporarily the Castle Hill Sandstone contains <<1%. Thus a coarsening upward trend exists and is a gradational one but the rate of such gradation cannot be estimated due to the incomplete nature of the sections involved.

The coarsening trend is also reflected in the bed thickness relationships with height which serve to separate the upper and lower members further. Fig. 1.24 represents a 'smoothed' time trend analysis of the thickness of sandstone beds for the West Harbour Formation, it is clear that by the highest level in the lower member deposits just east of the West Harbour Fault an irregularity exists in the otherwise regular distribution of sand bed thicknesses. Beyond the West Harbour Fault this irregularity continues but is enhanced in a slow upward trend towards thicker deposits.

Thus, overall, several lines of evidence coincide to support the erection of the Formation and its further two fold subdivision.

A further feature (but of less value) is the change in dominant sandstone colour with increasing stratigraphic height. Essentially drab beds are replaced by red at higher levels, red only being dominant in the Castle Hill Sandstone Formation (see Fig. 1.25).

Lower West Harbour Member (Fig. 1.26 and 1.27)

Table 1.13 summarises the lithofacies abundance data for the Lower West Harbour Member.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	2.1	16	0.13	0.3	0.08	22.2	22.9
Flat-bedded Sst	0.61	7	0.08	0.16	0.04	9.7	6.6
Ripple laminated Sst	4.66	29	0.16	0.38	0.04	40.3	50.8
Laminated Mudstone	1.79	20	0.89	0.18	0.04	27.8	19.5
Mudstone	-	-	-	-	-	-	-
TOTAL	9.16						

Table 1.13 Thickness Parameters of Lithofacies in the Lower West Harbour Member

Four lithologies alternate in simple fining upward cycles, an alternation which is rigidly adhered to, i.e. although sandstone dominates each cycle (57.4%), numerically, sandstone occurs in exactly 50% of the recorded transitions.

Ripple cross-laminated sandstone is the most abundant lithofacies, and forms the base of every cycle. Units are laterally persistent over the whole foreshore, except in two instances where ripple lamination changes to planar cross stratification. Vertically and laterally ripple cross-lamination may change into flat bedding or more commonly climbing ripple cross-lamination.

Ripple-laminated sandstone may be preceded by coarse grained flat-bedded sandstone in thin units, or superceded by very fine, flat-bedded sandstone in thin units. The fine portion of each cycle always rests gradationally upon the sandstone, gradation often being very rapid. Siltstone is most abundant (23%) and may be rippled in the lower coarser portion, or flat-bedded, but at highest levels massive siltstone is most common.

With reduction in grain size the siltstone bed invariably shows the development of thin reddened mud laminae which soon alternate with silt laminae producing the very characteristic 'red striped' laminite lithofacies.

Thickness frequency histograms for the lower member are shown in Fig. 1.28 and clearly demonstrate that:

1. Ripple drifted (cross-laminated) sandstone has an average thickness of 16 cm.
2. Siltstone ~ 13 cm.

While:

3. Flat bedded sandstone and laminite are much thinner ~ 8 cm and ~ 9 cm respectively.

Upper West Harbour Member (see Figs. 1.26 and 1.29)

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Siltstone	1.53	6	0.25	1.1	0.04	10.1	7.0
Flat bedded Sst	0.63	5	0.13	0.2	0.07	8.4	2.9
Ripple laminated Sst.	2.07	10	0.21	0.48	0.03	16.9	9.5
Laminated Mudstone	2.04	18	0.11	0.22	0.03	30.5	9.4
Mudstone	2.01	4	0.5	1.2	0.15	6.7	9.2
Cross Stratified Sst.	13.25	15	0.88	1.6	0.2	25.4	60.8
TOTAL	21.78						

Table 1.14 Thickness Parameters of Lithofacies in the Upper West Harbour Member

Table 1.14 contrasts the upper member in that:

1. New lithofacies are included, but none of those previously occurring have been lost.
2. Sandstone dominates the cycles 73%

3. Mudstone is present.
4. The previous simple alternation of coarse and fine is no longer typical.

Alternation of sandstone and siltstone is still the characteristic feature of the upper member, but facies relationships have altered. Graded units, although still present, are not typical of the sequence. Instead of being dominated by simple cross laminated sandstone sheets (the abundance of which has decreased to 9.5%) cross stratified sandstone dominates the cycles (61%) with fine lithologies being reduced to 26%.

Unit thickness increases markedly as mentioned previously - cross stratified sandstones average 1.6 m. in thickness. Ripple cross laminated sandstones show a remarkable consistency in average thickness, being 16 cm in the lower member and 16.9 cm in the upper. Flat bedded sandstone still occurs in thin sheets, whereas siltstone has doubled its average thickness to 25 cm. More significantly its maximum thickness has increased from 30 cm to 1.1 m laminite has only increased from 9 cm average to 11, the maximum values also remaining similar (i.e. 18 cm of 22 cm). Mudstone only occurs infrequently in the upper member, but tend to form thick units (average 50 cm maximum 1.2 m).

As mentioned, facies associations differ between the two members:
1. Graded cycles were typical in the lower member.
2. Graded cycles occur in the upper member but are overshadowed in importance by the newly introduced cross stratified sandstone lithofacies.
3. Sharp changes in lithofacies became more typical, and cycles became indistinct as erosive surfaces became more apparent with increasing stratigraphy height, erosion removing the final deposits of the preceding cycle.
4. Cross stratified sandstones may be internally graded, i.e.

cross stratification is often a form of channel infilling and the grain size and sequence of bedforms often grades upwards in a similar manner to the deposits of the lower member - the main difference being that the deposits of the upper member are not laterally persistent, i.e. they are restricted to channels.

Crovie Equivalent Section

Sediments directly comparable to those assigned to the West Harbour Formation occur in a small fault bounded block at the south end of Crovie Village. The short sequence is directly comparable to the Lower West Harbour Formation in terms of grain size, lithofacies, and sequences of bedforms. The proportions of the various lithofacies are listed in the following table (Table 1.15), and illustrated in Fig. 1.30 A close comparison exists, but consideration of bed thickness distributions (Fig. 1.31) demonstrates that the lithofacies of the Crovie sequence occur in much thicker units. The limited exposure available prevents anything but speculation as to the equivalent position of these sections, although the nature of the Crovie section with the notable absence of large scale cross bedding suggests its probable equivalence with the Lower West Harbour Formation. Being a fault-contained section this possible correlation is of little value, other than to suggest that the South Crovie Fault has a large downthrow, possibly in an order of 100 m as no representatives of the East Harbour Formation are present. The fault brings the strata into juxtoposition with the Crovie mudstone.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Mudstone	3.08	8	0.38	0.51	0.02	10	13.5
Laminated mudstone	5.94	25	0.23	0.53	0.03	27	26
Siltstone	3.19	5	0.63	1.50	0.18	5	14
Ripple-laminated sandstone	7.64	39	0.19	1.30	0.03	42	33.5
Flat-bedded sandstone	2.96	15	0.19	0.64	0.05	16	13
TOTAL	22.81						

Table 1.15 Thickness Parameters of Lithofacies in the West Harbour Formation - Crovie "equivalent" Section.

1.2 (iii)d Castle Hill Sandstone Formation

Introduction

In the western section the coarsening upward trend initiated at the base of the Gardenstown section culminates with the Castle Hill Sandstone. Unfortunately the Castle Hill Sandstone Formation is difficult to characterise primarily due to the inconsistent nature of the sediments but also complicated by their soft nature, which has resulted in much of the sea cliff decaying and becoming vegetated whilst the wave platform shows dense sediment-trapping algae covering most of the rock and flourishing in the increasing volumes of untreated sewage dispersed along this section in recent years. Although much of this 'damage' is of recent origin, the Rev. John Pratts' thoughts when he recalled Gamrie Bay as a "... deeply inlaid detached strip of mouldering Old Red Sandstone" are probably more applicable today than in 1870 when written (Pratt 1870).

Castle Hill Sandstone Formation

The Formation consists essentially the Geological Surveys Bed 4 "... friable, bright red and mottled sandstone with scattered pebbles and occasional lenticular bands of conglomerate."

Characteristics	A sandstone dominated sequence consisting of fine to coarse grained bright red sandstone with abundant channelling and cross stratification. Higher levels show the introduction of conglomerate in small proportions and quite fine grades.
Type Section	Shore section west of Gardenstown Harbour up to the Den of Findon.
Equivalent Section	Bright red sandstones attributed to the Castle Hill Sandstone Formation are exposed in a fault bounded block south of Crovie Village and also fault

bounded between the Snook and Crovie (see Figs. 1.4, 1.5, 1.22).

Lower Boundary — Red medium grained sandstone following fine micaceous sandstone of West Harbour Formation.

Upper Boundary — Faulted against Middle Old Red Sandstone Conglomerate in the Den of Findon by the Afforsk Fault, and against Dalradian by the Findon Fault.

Thickness — Impossible to estimate due to faulting, but at least 300 m are present.

Fossils — None

Nature of Outcrop — Continuous exposure exists along the Gardenstown foreshore but its continuity is marred by repeated faulting and the dense growth of sediment-binding algae. Majority of the wave platform is obscured by such weed leaving only narrow sections visible adjacent to the beach. An irregular cliff forms the back of the beach but the soft nature of the red sandstone has produced an almost 'badland' topography much of the cliff having collapsed, the remainder becoming rapidly vegetated.

General Stratigraphy — In the initial summary of the Gardenstown Section the Castle Hill Sandstone Formation was described as a coarse sandy facies. This serves to distinguish distinct lithological assemblages, but lithostratigraphically an internal two fold subdivision is apparent.

Upper Member	Conglomeratic Subfacies	Castle Hill Sandstone Formation
Lower Member	Sandy Subfacies	

Basis for Formation Subdivision

The Upper West Harbour Formation with its trough-shaped units of ripple cross-laminated sandstone is replaced rapidly by units of coarser grained sandstone lacking the abundant mica of the West Harbour Formation and totally lacking the extensive developments of ripple cross lamination so common in the previous group. The abundance of laminite decreased upwards from the Lower West Harbour Formation and is not recorded above the base of the Castle Hill Sandstone.

Basis for Internal Subdivision

The Gardenstown section is noteable for its coarsening upward trend in sedimentation and as illustrated in the initial distribution of lithofacies this trend is continuous throughout the Castle Hill Sandstone Formation sediments. Of the nine lithologies making up the Basement Group sediments 2, 3, 4, 6 and 7 comprise the lower portion of the Castle Hill Sandstone while 1, 2 and 3 characterise the upper. The coarsening trend is truly gradational and a mixed assemblage of these lithologies is preserved between the sandy facies and the conglomeratic facies.

Lower Castle Hill Sandstone Member (Plate 1.7)

The fine micaceous ripple laminated sandstones previously recorded in the West Harbour Formation gradually decrease in abundance and are replaced by large, broad trough shaped units of coarser sandstone showing very little micaceous material. It is this change that demarcates the base of the lower Member of the Castle Hill Sandstone Formation, i.e. the change from ripple cross laminated fine micaceous sandstones to cross bedded medium sandstone devoid of ripple lamination except in finest portions.

The lower member is characterised by a predominance of cross stratified sandstones arranged in small fining upward units. Cycles are erosively based and begin with coarse sandstone, gravel or lags of small pebbles. Flat bedded sandstone may replace conglomerate, but rarely overlies it. Cross bedding is initially of trough cross bedding form replaced at higher level by planar cross stratified sets. Cross bedding is overlain by finer sandstones with poorly developed small scale cross lamination. The finest deposits recorded are red mudstones and brown laminated siltstones but unlike the previous formation their chances of preservation appear to be minimal, particularly with increasing stratigraphic height (see Fig. 1.32). As mentioned the condition of the exposed section is not conducive to the production of detailed logged sections and therefore the abundance of the various lithologies cannot be calculated with accuracy. Perhaps the most significant observation to arise is that with increasing stratigraphic level planar cross-stratification is replaced by trough cross-stratification and marks the change into the upper member.

Upper Castle Hill Sandstone Member (Plate 1.7)

The coarsening upward sequence ends with the introduction of conglomeratic sediments, only a short sequence is exposed beginning at the Den of Findon. In contrast to the abundant cross stratified sandstone and mudstone beds in the lower member, the upper member consists of laterally persistent thin sheets of gravel and pebbles, frequently showing scoured surfaces to the otherwise parallel units. Cross stratification is minimal, although some cross bedding may be developed in higher parts of rate channel sequences. Overall sandstone grades are coarser, flat and irregular bedding surfaces are common. Small channel shaped conglomerates occur but infrequently. Examples of field logs are shown in Fig. 1.32 and demonstrate clearly the above mentioned features. Fig. 1.32 demonstrates the large scale cross stratified units common at the base of the sequence, noting also the depletion of fine grained sediment.

Fig. 1.32a and Fig. 1.32b show that the lower member is rich in sandstone with large scale cross stratification whereas Fig.1.32c and Fig. 1.32d show a predominance of planar erosion surfaces, and abundant conglomerate in the upper member, with a complete lack of large scale cross stratification.

1.2(iii)e Summary and Discussion

Similar problems exist in the Gardenstown Section to those mentioned at Crovie. Basically faulting has broken up the sequence and:

(i) The total thickness of strata removed from the base of the East Harbour Formation cannot be estimated.

(ii) No clues are available as to the strata removed by faulting in mid sequence of the same Formation.

(iii) The West Harbour Formation follows the East Harbour Formation conformably but its upper and lower members are fault separated. No evidence is available as to the magnitude of this fault. Dissimilar sequences are exposed either side of such faulting.

(iv) Faulting separates the West Harbour and Castle Hill Sandstone Formations, and faulting within the Sandstone Formation prevents an accurate estimation of its total thickness.

The relationship between the fining-upward Crovie sequence and the coarsening-upward Gardenstown sequence is an important problem, to which there is no conclusive answer. Many similarities exist between the highest sediment at Crovie, and the lowest sediment at Gardenstown, so that a relationship between the two sequences is not unlikely. It can only be concluded that these two sequences are related, and possibly continuous, but no evidence is available as to the nature or thickness of sediment occurring between the exposed Crovie Siltstone Formation and the exposed East Harbour Formation. Faulting (the Afforsk Fault) terminates the Castle Hill Sandstone sequence, bringing the conglomeratic upper member into contact with the Middle Old Red Sandstone Conglomerate. The amount of strata removed by this fault is unknown, the unconformity only being observed to the east near Pennan where conglomeratic sandstones of a different provenance to the Castle Hill sequence are eroded. A knowledge of the amount and nature of the strata removed by faulting would be desirable, as it would allow speculation as to the tectonic events during the Lower-Middle Old Red Sandstone period.

Overall in the Western Coastal Section, the following conclusions have been reached:

1. The term Crovie Group has been retained for the sediments exposed between Crovie and Gardenstown.

2. The sequence of sediments described by Geikie and adopted by the Geological Survey has been verified although further subdivisions are necessary on lithostratigraphical grounds.

3. The lowest deposits exposed belong to the Crovie Conglomerate Formation and are believed to be not far above the oldest sediments of the area. The sequence is incomplete due to faulting.

4. The Crovie Sandstone Formation is believed to follow the Conglomerate Formation unconformably. Faulting shortens this unit, there is no indication of the amount of sediment lost.

5. Conglomerates and sandstones exposed at Snook and Craigengargity are believed to rest between Conglomerate and Sandstone Formations. The Crovie Siltstone Formation completes the Crovie section, resting conformably on the Sandstone Formation.

6. The Crovie Section is terminated by faulting.

7. The Gardenstown Section is initiated with the East Harbour Formation originally part of the Geological Surveys Group 3 and is believed to belong to a similar environment to that responsible for the deposition of the Crovie Siltstone Formation. No estimation can be made of the amount of sequence lost by faulting either at the base or within the sequence, but the East Harbour Formation is believed to be a continuation of the Crovie Siltstone Formation.

8. The West Harbour Formation conformably overlies the East Harbour Formation but is also shortened by faulting. Sediments equivalent to the lowest West Harbour member are exposed in a faulted block at Crovie and given an idea of the magnitude of the South Crovie Fault.

9. The Castle Hill Sandstone Formation completes the Gardenstown Section, resting comformably upon the West Harbour Formation. Considerable faulting complicates any estimation of its total thickness. Red Sandstones analogous to lower and middle members of the Castle Hill Sandstone are exposed between Crovie and the Snook but are extremely broken by faulting. They nevertheless allow an estimation of the extent of faulting in that vicinity, i.e. most of the West Harbour Formation has been removed.

10. The sequence described represents a fining upwards trend to the Siltstone Formation followed by a coarsening upwards sequence towards the Castle Hill Sandstone Formation.

11. The top of the sequence is not exposed, only faulted relationships exist between known middle and lower Old Red Sandstone deposits.

12. Crovie Group sediments have yielded spores suggesting but not proving a Lower Old Red Sandstone age.

1.3 Central Coastal Section

1.3 (i) Introduction

The Central section extends almost from Downie Shore at a point south of Cowper's Craig to Langlitterty in the east. The Troup Head Fault bounds the section in the west, the Langlitterty Fault in the east. Old Red Sandstone is faulted against Dalradian Metasediments in both cases. Fig. 1.33/1.34 illustrates the distribution of Old Red Sandstone sediment along this section.

Middle Old Red Sandstone conglomerate occupies much of the section particularly between Cowper's Craig and Pennan Village, and although difficult to confirm inland, most of the sea cliff is capped by Middle Old Red Sandstone slate-rich conglomerate as illustrated in Fig. 1.33, 1.34. Lower Old Red Sandstone is unconformably overlain by Middle Old Red Sandstone in Sidegate and Meal Girnel, but is not continually exposed until further west. On the east side of Sandy Haven Lower Old Red Sandstone is faulted against Middle Old Red Sandstone conglomerate, the Middle Old Red Sandstone unconformity being present but obscure high in the cliff. Lower Old Red Sandstone is continually exposed between Sandy Haven and Pennan but the Sandy Haven to 'Quarry'* section remains inaccessible. Between the Quarry and Pennan Village Middle Old Red Sandstone is in an inaccessible position at the top of the sea cliff, its base approximating to the 100 m. contour. Although accessible, the Lower Old Red Sandstone of most of the Quarry to Pennan section is difficult to observe. Access is by means of a narrow 'boulder' base to the cliff and only negotiable at low tides, low swell and preferably offshore winds. The cliffs are very friable preventing access from above or below, their

*The embayment here referred to as the 'Quarry' is not recorded on published maps, but is locally known from its former days as a quarry for millstones.

vertical or even overhanging nature often preventing observation from the narrow vantage point close to the cliff base.

Because of these restrictions only a minor portion of the section has been studied, the remainder being observed from the sea. Numerous gaps are present with regards to details of sedimentology, logged sections cover only a minority of the outcrop and are by no means representative sections.

Due to these inadequacies the writer considers that an attempt to formalise a stratigraphy as carried out elsewhere would be somewhat contemptible. Instead, five facies associations have been recognised on lithological and sedimentological grounds and will be described as such. These are:

5. Pennan Sandstone Facies Association
4. Pennan Conglomeratic Sandstone Facies Association
3. Need Haven Conglomerate Facies Association
2. Pennan Head Conglomeratic Sandstone Facies Association
1. Sandy Haven Conglomeratic Sandstone Facies Association

Of these five facies association, four could tentatively be regarded as having Formation status having an apparent internal litholigic homogeneity, the fifth, the Sandy Haven Conglomeratic Sandstone Facies Association has not been observed directly and little information can be provided.

Of the Facies Associations listed above only 2, 3, and 4 are observed in sequence. The Pennan Sandstone Facies Association is fault bounded on all sides, whilst the Sandy Haven Sandstone Facies is faulted on two sides, one against Middle Old Red Sandstone, the other against the Pennan Head Conglomeratic Sandstone Facies Association. Fault relationships such as folding adjacent to faulting suggests that the east Sandy Haven Fault is a normal fault dropping Middle Old Red Sandstone against Lower Old Red Sandstone, similarly the east Quarry Fault has a normal downthrow to the west implying that the Sandy Haven sequence is older than the Pennan Head sequence.

On these perhaps shaky grounds the apparent sequence is as listed above, although the position of the Pennan Sandstone Formation at the top of the sequence is without justification other than considerations of its composition which will be discussed later.

1.3 (ii)a Sandy Haven "Conglomeratic" Sandstone Facies Association

Apparently the oldest identifiable Lower Old Red Sandstone of the Central Section but unfortunately occurring along an inaccessible section of coast. Viewed from the sea, but not at close range, the sequence appears to be conglomeratic, but of a fine nature. In many respects the sediments look similar to the Dundarg Castle sequence i.e. lateral impersistence of bedding and apparent abundance of gravel. The presence of feldspar gravel would, in the lack of pebble data, suggest that a granitic source area was present.

1.3 (ii) b Pennan Head Conglomeratic Sandstone Facies Association (Plate 1.8, 1.9)

Fault bounded to the east, in juxtoposition with the Sandy Haven sequence, the conglomerates and conglomeratic sandstones forming Pennan Head bear several distinct similarities with both the Sandy Haven sequence and the Dundarg Castle sequence. Approximately 150 m to 200 m of sediment are exposed between 'The Quarry' and a point west of Pennan Head where the Need Haven Conglomerate reaches the shore. Faulting complicates the sequence leaving a small amount of uncertainty as to the total thickness.

The sequence is comprised alternations of conglomerate, conglomeratic sandstone and sandstone. The conglomerate occurs as laterally persistent sheets of moderately well sorted pebble and cobble grade detritus, mainly of granite and felsite, but with large amounts of Lower Dalradian Metasediments. Feldspar gravel is an important constituent of both conglomerate matrix and conglomeratic sandstone horizons. The conglomerates occur in thin parallel fairly persistent non-erosive sheets, they are often well packed and frequently show well developed clast imbrication. Conglomerate occurs interbedded with conglomeratic sandstones. Feldspar gravel is abundant in such units, but perhaps not as rich as in the Dundarg Castle sequence. A crude flat parallel horizontal bedding is discernable but again no marked erosion has been recorded. Sandstone is a minor constituent in the observed sequence and generally occurs in relationship with the conglomeratic sandstone rather than conglomerate. At higher levels in the succession it appears that conglomerate and conglomeratic sandstone occur in thick parallel units up to 10 m in thickness in alternation with conglomeratic sandstones and sandstones in similar units but up to 1.5 m thick. The sequence passes rapidly into the Need Haven Conglomerate, but not without suffering significant changes.

The upper portion of the sequence is readily accessible below Pennan Head and demonstrates that although the overall nature of the sediments and their interrelationships remain generally as described, the following trends are apparent with increasing stratigraphic height:-

1. conglomerate bed thickness increases (Fig. 1.35);
2. sandstone bed thickness decreases (Fig. 1.35);
3. maximum clast size increases (Fig. 1.35);
4. feldspar gravel decreases;
5. the proportions of certain clast compositions alter,
    (i) granite becomes scarce
    (ii) felsite temporarily becomes abundant
    (iii) vitreous quartzite becomes very common;

6. an increase in clast roundness and sphericity accompanies these changes;
7. with the increase in bed thickness, packing becomes closer, sandstone becomes scarce and erosion becomes readily apparent with accompanying cross stratified gravels and multistorey cross bedded conglomerate units.

This coarsening upward trend culminates in a quartzite-rich conglomerate sequence virtually devoid of sandstone, i.e. the Need Haven Conglomerate.

1.3(ii)c The Need Haven Conglomerate Facies Association (Plate 1.9).

A thick, uniform development of quartzite-dominated conglomerate. The sequence is characterised by a marked lack of sandstone, either as matrix or individual sandstone beds. The conglomerates display a high packing density, being framework-supported throughout, minor proportions of sand and gravel occur as infilling to this framework. Being dominated by quartzite the values of roundness and sphericity appear much higher; while clast size is variable, the quartzite also provides large clasts. Bedding is indistinct but when apparent it is usually thicker than adjacent conglomerate sequences.

The Need Haven Conglomerate is observed to rest directly upon the Pennan Head Conglomeratic Sandstone - a rapid transition being recorded. The sediments of the Quarry section contain similar conglomerate but in thin units only, faulting prevents an accurate location of these deposits in the sequence. The Need Haven Conglomerate is present from a position west of Pennan Head dipping moderately to the south west until finally descending into Need Haven and the small ridge to the east.

Just as the Need Haven Conglomerate occurs by reduction of sand detritus from the Pennan Head Conglomerate so it passes into the Pennan Conglomeratic Sandstone by a reverse of this process. Towards the top of the unit sand becomes more abundant and bedding planes become more persistent until discrete conglomerate/sandstone units are present. Accompanying this development we find:- (see Fig. 1.36)

1. conglomerate bed thickness decreases;
2. sandstone bed thickness increases;
3. clast size decreases;
4. feldspar gravel returns;
5. quartzite decreases markedly;
6. slate detritus is introduced.

1.3(ii)d The Pennan Conglomeratic Sandstone Facies Association (Plate 1.10)

A thick, but largely inaccessible sequence of pebble to cobble grade conglomerates and interbedded sandstones.

The previous paragraph detailed the changes occuring with increasing (Fig. 1.36) stratigraphic height, and in doing so summarised the important characters of this facies. The sequence is distinct in its abundant sandstone, thin laterally persistent fine conglomerates and abundance of slate detritus (see chapter 4). Feldspar gravel is present, but not in large quantities.

High in the cliffs to the east of Pennan the sequence can be seen to vary with height becoming sandier, or more conglomeratic, in thick sequences. Unfortunately none of this material is accessible and thus conglomerate composition etc. cannot be studied.

The Pennan Conglomeratic Sandstone Facies is faulted against the Pennan Sandstone Facies, but there is no indication of fining to confirm that the sandstone facies actually sits on top of the conglomeratic sequence.

1.3(ii)e The Pennan Sandstone Facies Association (Plate 1.16)

Immediately east of Pennan Village the final deposits of the Central Section are exposed, faulted against Middle Old Red Sandstone Conglomerate in the Harbour, and 600 m east also faulted against the Pennan Head Conglomerate Sandstone Facies. The relationship of this facies to preceding deposits is uncertain due to this faulting. The Pennan Sandstone is the highest deposit in the sequence being unconformably overlain by Middle Old Red Sandstone Conglomerate high in the cliff to the east of Pennan.

The Pennan Sandstone rests almost horizontal, dipping to the S.S.E. at 5°. Approximately 30 m are exposed, and overall the sandstone remains quite uniform, only one conglomerate horizon is recorded high in the cliff. Internal bedding is poorly developed, jointing implies small cross stratified sets in the order of 30 cms. in thickness, although larger trough cross-stratification is locally developed near the foreshore. Within the cross bedded sets bedding is rarely shown.

Thin dull red brown silt and mud veneers are occasionally developed between cross sets and may show extensive small scale polygonal desiccation cracks. Discoidal mudclasts are common, but not as well developed horizons, instead merely scattered throughout. Occasionally bedding may be discerned by thin gravel strings.

It has been implied (Geikie 1879) that the sediments to the east of Pennan are equivalent to those at Gardenstown. The unconformity exposed to the east of Pennan refutes any correlation between these sediments and the Middle Old Red Sandstone at Gardenstown, whilst grain size, colour, and composition contradict any attempt to correlate the red sandstones of Pennan with those of Gardenstown.

With the abundance of conglomerate in the Old Red Sandstone sequence mineralogical studies of the sediments have not been made in bulk. Preliminary studies do, however, show that a distinct difference exists between the non conglomeratic Pennan Sandstone and the eastern and western sediments of a similar grade (see Fig. 1.37).

1.3 (iii) Discussion

Because of the problems mentioned the Central Coastal Section poses some of the greatest difficulties in evaluation of the local and regional stratigraphy. An attempt has been made to formulate a sequence, and at present no improvement can be made on this proposal. It is of great interest to determine:-

(i) the relative age of the sediments in comparison to the eastern and western sections;

(ii) the nature and relationships of the Sandy Haven Conglomeratic Sandstone Facies to the rest of the sequence;

(iii) the relationship of the Pennan Sandstone Facies to the lower deposits.

From the study of sediment dispersion (Chapter 4) it has been concluded that the Central Section sediments are probably related to the coarsening portion of the Lower Old Red Sandstone sequence exposed at Gardenstown, but a more specific correlation is beyond the realms of the present information. The position of the Pennan Sandstone is conjectural, it is assumed to follow the Pennan Head Conglomerate although the amount of strata removed by faulting is unknown. Approximately 30 m of Pennan Sandstone are visible against the conglomerates, and as both are overlain by Middle Old Red Sandstone conglomerate the situation does confirm the pre Middle Old Red Sandstone tectonic event producing folding and faulting of the Lower Old Red Sandstone sediments.

1.4. Quarryhead

1.4 (i) Introduction

Approximately 1 km east of Dundarg Castle (see Fig. 1.1) a small outlier of Old Red Sandstone occurs in Quarryhead Bay and although of very restricted development this small section serves to illustrate the nature of the Old Red Sandstone Dalradian unconformity. The outlier is fault-bounded to the west, and rests unconformably on Dalradian grits to the east. No inland exposure is available. The restricted development and lateral impersistence of the sediments (i.e. great lateral variation) makes a formal stratigraphic subdivision impractical. Three facies associations are distinguished:-

1. Conglomeratic facies association,
2. Sandstone facies association,
3. Siltstone facies association.

These three facies associations probably correspond to distinct sedimentary environments to be discussed later (Chapter 3). Six litho-facies make up the three facies:-

A. Nodular Carbonate............)
)
B. Fine sandstone/siltstone.....) Facies 3

C. Sandstone....................)
)
D. Gravels.....................) Facies 2

E. Cobble conglomerate..........)
)
F. Very coarse conglomerate.....) Facies 1

It is important to note that in the Quarryhead section the facies divisions are at any horizon laterally interchangeable and thus facies boundaries are purely lithostratigraphic, no chronostratigraphic implications aré intended

Nature of Outcrop — A sheltered Bay (albeit in the flight path of an R.A.F. offshore bombing range!) with easy access and almost complete exposure at all but high tides. (Fig. 1. 38).

Base of Formation — An irregular plane of unconformity between very coarse conglomerate and Dalradian metasediments.

Top of Formation — Faulted junction between sandstones and andalusite schist towards the western edge of the Bay.

Thickness — 28 m are exposed.

Fauna — None found (but possible trace fossils have been recorded and are discussed in Chapter 5).

General Stratigraphy (Plates 1.11, 1.12)

As noted previously six lithofacies occur in the Quarryhead section.

A. Nodular Carbonate Grey green to red brown coalescing nodular carbonate in thick units, always 'modifying' lithofacies B.

B. Fine Sandstone/Siltstone Deep red brown and generally massive to poorly horizontally bedded; isolated gravel, granule or coarse sand strings may clarify bedding.

C. Sandstone Reddish brown occuring either as thick massive sheets adjacent to lithofacies D and E, or as poorly sorted thin beds in higher parts of the succession. Internal bedding is rare, flat bedding being commonest and showing well developed parting lineations. At a few levels a shallow trough cross bedding is evident, but its occurrence in solitary sets may assign this bedding to scour and fill rather than true trough cross-bedding. Pebble and gravel strings are present but uncommon.

D. Gravel Generally medium to coarse grained sandstone with a very high percentage of coarser grained material of granule to gravel grade. Bedding is irregular, flat and impersistent. No cross bedding has been recorded although minor scour structures are present. Bedding occurs in approximately 1 cm units (3 cm maximum).

E. Cobble Conglomerate Conglomeratic sandstone with clasts up to small cobble grade commonly arranged in sheets but often as isolated 'floating' fragments.

F. Very Coarse Conglomerate Coarser than cobble grade and usually well into the boulder class. The maximum clast size recorded is 4 m in length. This lithofacies is characterised by poor sorting, lack of well defined bedding and lateral impersistence.

Within the 28 m exposed at Quarryhead the sequence fines upward from predominantly very coarse-grained conglomerate at the base to siltstones and sandstones at the top. The basal unconformity is well exposed and demonstrates a considerable basement relief, frequently steep sided and downcutting in the order of 15 m over very short distances. The lower 15 m of sediment may be traced along the strike and demonstrates the great lateral variation present. Fig. 1.38 shows the distribution of Old Red Sandstone sediment at Quarryhead while Fig. 1.39 and Table 1.16 allow the distribution of lithofacies to be studied.

Section \ Lithofacies	A	B	C	D	E	F
	%					
1	32	36.5	8.5	34.5	20.5	0
2	0	0	11.4	0	21.3	67.2
3	0	0	0	0	28.5	71.5
4	0	0	0	0	0	100

Table 1.16 Distribution of lithofacies at Quarryhead (lines of section refer to fig 1.39).

The northernmost extent of the exposure is comprised the conglomerate facies and is entirely lithofacies F. Progressive sections towards the south (illustrated in Figs. 1.38 and 1.39) demonstrate:

a) much of lithofacies F is rapidly replaced by lithofacies E,

b) lithofacies F continues to decrease, accompanied by a decrease in lithofacies E but introduction of lithofacies C.

At the south of the Bay lateral exposure is not available, but the sequence is completed by:

c) the absence of lithofacies F,

d) only small amounts of lithofacies E are present,

e) large amounts of lithofacies D and B, with the introduction of lithofacies A,

f) lithofacies C remains very low.

Thus in vertical terms the conglomerate facies fines through the sandstone facies to the siltstone facies. If this were simply the case the erection of stratigraphic units would be relatively simple. As it is, the sequence also fines laterally; the irregular basement depressions being infilled by coarsest detritus, whilst sandstone occupies a lateral position, resting on high-spots of the Dalradian basement. The lowest members of the siltstone sequence are laterally equivalent to both sandstone facies and conglomerate facies sediments. Fig. 1.40 is an attempt to summarise the Quarryhead facies relationships and serves to demonstrate the diachronous nature of the units, particularly the sandstone facies. Fig. 1.40 also holds the suggestion that upper and lower sandstone developments may be regarded as one facies.

The reconstruction is very generalised and lack of adequate exposure prevents certain details being proven,

1. The continuity of the conglomerate facies cannot be proven. Laterally to the south sandy conglomerate rests upon the Dalradian Basement.
2. The sandstone facies may not connect as implied in Fig.1.40, i.e. they may in fact be two separate sedimentary environments. Paleocurrent directions suggest that the upper and lower sections of the sandstone facies may have slightly different source directions, and clast composition does support this.
3. The siltstone facies is continuous but cannot be accurately related to similar grade carbonate bearing sediments further west, (Counter Head, New Aberdour Shore and Crovie).

Relationships to Adjacent Sequences

No fauna has been extracted from the sediments at Quarryhead and therefore the age of the sediments cannot be confirmed. They rest directly upon the Dalradian Basement and compare favourably with the sequence recorded a few kilometres to the west at Fleckies Meadow which is confidently regarded as Lower Old Red Sandstone age.

Correlation between the main outlier and Quarryhead is not difficult, but may be open to criticism. Clearly the basal conglomerates at Quarryhead and at Fleckies Meadow occupy analogous situations and lithostratigraphically must be regarded as equivalent. At Quarryhead the fining sequence is very short compared to the Dundarg Castle-New Aberdour Shore section. Correlation within this fining sequence is difficult and direct equivalence cannot be stated between the finer conglomerates at Quarryhead and the conglomerates of Dundarg Castle; in fact the composition of conglomerate fragments contradicts such an idea.

As discussed later (Chapter 7) the nodular carbonate developed in the siltstones at Quarryhead has been identified as a pedogenic development and such calcretes are commonly considered to have wide lateral extents and are related to drastems, periods of slow aggradation in an alluvial environment. In the main sequence at Dundarg Castle and Gardenstown only one such development of calcrete is recognised and it seems reasonable to assume that the Quarryhead calcrete is comparable with this horizon. If this assumption is correct the 15 m of sediment below the Quarryhead calcrete are equivalent to approx. 200 m of sediment in the west. Three possible implications of this are:

1. the correlation is invalid,
2. Quarryhead Bay contains a condensed sequence,
3. sedimentation at Quarryhead began at a later stage.

Assuming correlation is valid, and from paleocurrent studies discussed later (Chapter 4) it is evident that the regional paleoslope was towards the east and south-east; combining this with the sedimentological interpretation of the Quarryhead sequence (Chapter 3) as colluvium or similar, the suggestion that the Quarryhead sequence accumulated at a later stage than lithologically similar sediments in the west is reasonable. Furthermore if the environmental interpretation is valid then the basin margin at Quarryhead would receive little detritus compared to more easterly regions; a 'condensed' deposit would therefore also be likely.

1.5 Eastern Coastal Section

1.5 (i) Introduction

The Eastern Coastal Section extends between Fleckies Meadows in the east to a point below Little Kipp at the west end of New Aberdour Shore (see Fig. 1.41). Old Red Sandstone sediments rest unconformably upon Dalradian metasediments in the east whereas they are faulted againt Dalradian Andalusite Schists in the west.(by the New Aberdour Fault). As noted with sequences elsewhere, the trend is for finer sediments to occur at higher stratigraphic levels; this fining trend is displayed between Fleckies Meadow and Counter Head where it is terminated by faulting, the sequence being repeated between Counter Head and New Aberdour Shore.

Overall four facies associations have been recognised in a manner analogous to that employed further west.

4. Siltstone Facies Association
3. Sandstone Facies Association
2. Conglomerate Sandstone Facies Association
1. Conglomerate Facies Association

The Geological Survey offered no details of this section but recognised a basic three-fold subdivision of the sequence.

i.e.

3. Red sandstone, slightly conglomeratic, with shales and calcareous clay bands.
2. Red sandstone, partly conglomeratic.
1. Coarse conglomerate.

adding that "below Dundarg Castle the same section is repeated" implying that they either derived their section from Quarryhead (which they do not mention), or that their section originated from New Aberdour Shore. The present reclassifications would appear to compare favourably with that of the Geological Survey except that the basal conglomerate has been given a definite separate identity during the course of this study.

As with sections already discussed a formal classification on a Formation Member basis allows the following sequence to be proposed:

Facies Association	Formation
Siltstone Facies	New Aberdour Siltstone Formation
Sandstone Facies	Dundarg Castle Sandstone Formation
Conglomeratic Sandstone Facies	Dundarg Castle Conglomerate Formation
Conglomerate Facies	Fleckies Meadow Conglomerate Formation

A consideration of Fig. 1.41 indicates that due to faulting repeating much of the sequence the section may be easier considered in terms of:

1. Dundarg Castle - Counter Head subsection,
2. New Aberdour subsection.

1.5(ii) The Dundarg Castle/Counter Head Subsection

This short coastal strip illustrated in Fig. 1.41 represents the most important section for interpretation of sedimentation in the east of the Gamrie Outlier. The sequence exposed is incomplete due to inevitable faulting, but it is felt that no major omissions occur. Sediments are exposed from the repeat of the basal conglomerate resting upon Dalradian of Quarryhead section, up to the Siltstone facies of the Counter Head Silstone Formation. Lithological homogeneity is the prime concern in the stratigraphic subdivision of the section and again in the Dundarg Castle Sandstone Formation it has been necessary to employ a facies concept to separate stratigraphic units.

The following sequence is exposed in the sub-section:

Counter Head Siltstone (regarded as equivalent to the New Aberdour Siltstone Formation)

Dundarg Castle Sandstone

Dundarg Castle Conglomerate

Fleckies Meadow Conglomerate Formation

1.5 (ii)a Fleckies Meadow Conglomerate (Plate 1.13)

The lowest exposed deposits of the Eastern Section, compare very favourably with conglomerates exposed at Quarryhead both in lithology and marked angular unconformity with underlying Dalradian metasediments. The rocks may be equivalent to the Geological Surveys Bed 1 ..... "Coarse Conglomerate" but from their very brief description this cannot be confirmed.

Characteristics	A sequence of poorly-bedded, generally poorly-sorted coarse conglomerates.
Section	East side of Fleckies Meadow (east of Dundarg Castle) towards Pike Rock (see Fig 1.41
Equivalent Section	Lithologically similar sediments exposed in Quarryhead Bay and are suggested to be facies equivalents of this sequence.
Lower Boundary	Irregular angular unconformity with Dalradian.
Upper Boundary	Introduction of well-bedded sandstone and finer conglomerates.
Thickness	0 to 40 m at least

Fossils — None

Nature of Outcrop — Easily accessible broken cliff bounding the east side of Port an Doon embayment, accessible at all tides.

General Stratigraphy

Retaining the facies concept and terminology employed at Quarryhead only one facies is identified at Fleckies Meadow, i.e. a conglomeratic facies which has been directly assigned Formation status.

The conglomerate is variable throughout the vertical profile but shows little lateral change unlike the deposits of Quarryhead. Initially coarse, angular, poorly-sorted blocks (up to 3 m in length) within a fine, almost muddy matrix rest upon the Dalradian Basement represented by coarse psammitic rocks and interlayered micaceous Andalusite Schists. Erosion is apparent to a depth in the order of 40 m with local, steep, cliff-like terraces up to 5 m high (Plate 1.13). The coarse conglomerate infills these hollows but shows no internal stratification. At higher levels the conglomerate grade decreases and is accompanied by an increase in sand percentage. Laterally where the Basement terrain rises to its maximum original height the coarse conglomerate is absent, being replaced by the finer conglomerate, and in places even by sandy-conglomerate and conglomeratic-sandstone. Bedding is poorly developed in these higher levels, indicated only by sheets of cobbles etc. - no sedimentary structures or erosion being apparent (although exposure is very restricted at these high levels). Using the previous notation (see Quarryhead) the lowest 30 m show the development of lithofacies F with approximately 10 m of lithofacies E above - no lateral interchange of E and F, and no evidence of lithofacies A, B, C or D are recognised. No extensive carbonate cement is developed in the conglomerates either.

1.5(ii) Dundarg Castle Conglomerate Formation (Plates 1.14, 1.15, 3.1, 3.2, 3.3, 3.4, 8.5)

The Dundarg Castle Conglomerate Formation is difficult to locate in the Geological Survey nomenclature, and may therefore be equivalent to either their Bed 1 or Bed 2, i.e. "coarse conglomerate - Bed 1" or "Red Sandstone partly conglomeratic - Bed 2".

Two sequences are exposed and both are complicated by faulting i.e.

(i) from Fleckies Meadow towards Counter Head, a very short but well exposed section in which the lowest deposits of the facies association outcrop (0.2 km in length).

(ii) faulted against the previous section, a duplicate section of the conglomerate facies exposing all but the lowest sediments occurs from Counter Head to New Aberdour Shore (0.8 km in length).

<u>Characteristics</u> A sequence of interbedded conglomerate, gravel and coarse sandstones showing extreme lateral and vertical variations in grain-size bedforms and textures.

<u>Type Section</u> Two sequences exposed between Fleckies Meadow and New Aberdour Shore separated by the Counter Head fault. Both sequences demonstrate the highest sediments, but only the Dundarg Castle section exhibits the lowest deposits of the formation.

<u>Equivalent Section</u> None directly comparable although as noted in the discussion at the end of this chapter, sediments belonging to the Central Coastal

Section below Pennan Head may be equivalent to the Dundarg Castle Formation.

Lowest exposed Stratum — The Dundarg Castle Conglomerate Formation is observed to rest directly upon the Dalradian Basement on the east side of Fleckies Meadow to the south of the Bay whilst to the north the Fleckies Meadow Conglomerate Formation infills hollows within the Dalradian Basement and forms a base to the sequence. Exposure of the Fleckies Meadow Conglomerate is not continuous and therefore its relationship with the Dundarg Castle Conglomerate Formation cannot be observed.

Uppermost Exposed Stratum — Lateral impersistence is a characteristic feature of sediments belonging to the Conglomerate Formation - the upper boundary being the introduction of finer grained sediments belonging to the Sandstone Formation. The junction is marked by:

i) finer sediments,

ii) laterally persistent stratum, show in plate 1.16 a

Thickness — ~ 90 m measured at Dundarg Castle

~400 m to New Aberdour. See later discussion (page 85).

Fossils' — None

Nature of Outcrop — A broad wave-cut platform readily accessible at most tides, but transected by numerous fault and joint controlled gullies frequently preventing continued access to long sections except at low tides.

General Stratigraphy

The Conglomerate Formation consists of conglomerates, pebbly-sandstones and sandstones, and characteristically has a complete lack of fine-grained sediment. A few levels of conglomerate are very coarse, reaching sizes common in the basal conglomerate, but on the whole grain-size is reduced as part of the upward fining trend and much more sandstone is present in the sequence.

Seven lithofacies combine to make up the Conglomerate Formation and have been defined mainly on the basis of structure, but also including grain size sorting and texture.

i.e.

Lithofacies 1 - Channel Fill Conglomerate (Plate 1.15) Coarse grained channel shaped infills with variable grain size, ranging from boulder to gravel grade and generally poorly sorted. Units of channel fill conglomerate are often graded both vertically and laterally, lateral grading resulting often in the replacement of lithofacies 1 by lithofacies 2.

Lithofacies 2 - Inclined Bedded Conglomerate (Plate 1.15) Usually occurs laterally adjacent to Channel fill conglomerate, in the shallower parts of channel bodies. Grain size is lower than lithofacies 1 and sorting is better. Grading is again common and may take place either perpendicular to bedding, or parallel to bedding, or both. Matrix is more abundant, and therefore packing density is reduced.

Lithofacies 3 - Single Sheet Conglomerate (Plate 1.15) Follow planar erosive surfaces which may bear isolated scours. Internal bedding is absent, but units may be either normally or reverse graded. The conglomerate is finer grained than the channel variety, and poor sorting is common although the deposits are usually well packed. Generally single sheet conglomerates are laterally very persistent.

Lithofacies 4 - Multiple Sheet Conglomerate (Plate 3.2) As the name implies, a multitude of thin laterally impersistent fine grained poorly sorted conglomerates. Lithofacies 4 follows all previous deposits by gradation. Small scour and fill structures may be preserved, but no large scale bed forms are developed.

Lithofacies 5 - Small Scale Cross Stratified Gravel (Plate 3.5) Occurs in higher parts of fining sequences, and consists of moderately well sorted sandy gravels displaying a shallow trough cross stratification.

Lithofacies 6 - Large Scale Cross Stratified Gravel (Plate 3.5) Generally occurs in higher levels of channel shaped deposits, and consists of moderately well sorted sandy gravel with large scale trough cross stratification. Pebbles are commonly present along foresets.

Lithofacies 7 - Sandstone (Plate 3.1) A rare addition to the sequence, sandstone generally is medium to coarse grained, and laterally impersistent due to erosion by overlying lithologies. The sandstones are fairly well sorted but usually show no internal structure.

It is difficult to characterise the Dundarg Castle Conglomerate sequence by constructing lithoprofiles and tabulating lithofacies abundance data, as vertical and lateral variation is extreme. By rigidly adhering to one vertical line of section Table 1.18 has been constructed and illustrates lithofacies abundance in that section. Local variations may show fining-trends, coarsening-trends, or distinct lateral changes in lithofacies. With this in mind Table summarises the lithofacies abundance, but selected field logs (Fig. 1.42, 1.43) should be noted, as well as the facies relationships reconstructed in Fig.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Channel Fill Conglomerate	10.78	17	0.64	1.35	0.25	28	28.6
Inclined Bedded Conglomerate	1.95	5	0.39	1.05	0.17	8.3	5.1
Single Sheet Conglomerate	1.43	7	0.20	0.53	0.10	11.6	3.7
Multiple Sheet Conglomerate	16.37	15	1.09	3.6	0.22	25	43.1
Small Scale Cross-strat gravel	2.12	6	0.35	0.55	0.30	10	5.6
Larger Scale Cross-strat gravel	2.67	5	0.53	0.7	0.40	8.3	7
Sandstone	2.55	5	0.51	1.0	0.15	8.3	6.7
TOTAL	37.96						

Table 1.18 Thickness Parameters of Lithofacies in the Dundarg Castle Conglomerate Formation

Certain generalisations may be made from Table 1.18; the sequence is dominated by lithofacies 4 (multiple conglomerate sheets), both numerically and in thickness, while lithofacies 1 (channel fill conglomerate) follows close behind. Channel-fill conglomerates are laterally restricted and therefore a 29% thickness result rather over estimates the volumetric importance of such conglomerate. The remaining lithofacies occur in approximately equal abundance, except for the single sheet conglomerates which are numerically more abundant, but constitute a small total thickness, clearly demonstrating their small overall size.

A consideration of conglomerate bed thickness and sandstone bed thickness does not show any significant trend with increased stratigraphic height, although the frequency of occurrence of lithofacies

1 decreases markedly at highest levels being replaced by fine grained lithofacies 4.

The above details have been extracted from both of the mentioned sequences. Sedimentologically the sequences are regarded as comparable, but provenance studies demonstrate that only the Dundarg sequence contains the lowest sediments of the conglomerate sequence. Faulting in Fleckies Meadow shortens the succession by an indeterminable amount.

Between Counter Head and New Aberdour Shore a much longer sequence of conglomerates are exposed, and faulting again complicates any estimation of the total thickness of this sequence. Many of the faults are minor normal faults, and will only have caused minimal extension. The lack of marker horizons, or distinctive conglomerate compositions prevents the evaluation of faulting in Boat Shore and Little Haven, two localities where faulting may be of greater magnitude.

1.5(ii)c Dundarg Castle Sandstone Formation (Plate 1.16)

Characteristics	A sequence of alternating coarse and fine members - fine sandstone being the finest commonly occurring sediment. The Formation represents the passage from coarser conglomerates in the lower part of the succession into the siltstones and mudstones of the Counter Head Siltstone Formation and is characterised by laterally persistent bedding surfaces.
Type Section	20 m west of the small peninsular on which Dundarg Castle is sited - continuing west for a further 40 m.
Equivalent Section	West of the Central Sandy Bay of New Aberdour Shore an incomplete section.

Lower Boundary — Sharp passage from laterally impersistent conglomeratic sandstones, see plate

Upper Boundary — Incoming of red brown siltstone.

Thickness — 30 m.

Fossils — None. Rare trace fossils of "Plugged pipe" form have been found (see Chapter 5).

Nature of Outcrop — Fairly narrow wave platform with poor exposure in cliff behind. Easily accessible and not apparently complicated by faulting.

General Stratigraphy

The Sandstone Formation overlies the Conglomerate Formation, the passage being very sharp. The Sandstone Formation is separated from adjacent sequences in that:

1. A marked reduction in conglomerate occurs, and is associated with a decrease in erosive contacts, and an increase in lateral persistence of lithofacies.
2. New lithofacies are introduced, particularly fine grained sediments.
3. The base is sharply defined and laterally persistent, as is the top.
4. The lithofacies composition of the proposed stratigraphic unit is distinct, and differs markedly from adjacent sequences.

The sequence is characterised by the distinct alternation of coarse and fine members, five fine members and four coarse members, varying in thickness from 1 m to 10 m (fine members), 2 m to 9m (coarse members). These alternations are distinct in the following respects:

Fine Members	Coarse Members
1. Characterised by sharp contacts between lithofacies, but erosive contacts rare and minor.	1. Gradational changes common both vertically and horizontally, sharp contacts commonly erosive.
2. Gradational contacts common but vertically.	2. Lateral gradation common.
3. Fine grade sediments predominate.	3. Coarse sediment, often conglomeratic predominates.
4. Conglomerate rare, and usually not coarser than gravel.	4. Conglomerate abundant and up to cobble grade.
5. Units are laterally very persistent.	5. Units are laterally very impersistent.

The above details summarise the criteria (other than lithological) used to separate members, similar criteria also serve to demarcate the base of the Formation, as the coarse members are in many respects comparable to the preceeding Conglomerate Formation.

The fine members are made up of the following lithofacies:

1. Wavy-bedded fine sandstone
2. Cross-laminated sandstone
3. Coarse sandstone
4. Very fine sandstone
5. Fine sandstone
6. Flat-bedded sandstone
7. Massive sandstone
8. Interbedded granule and sandstone
9. Planer cross-stratified sandstone
10. Trough cross-stratified sandstone

Lithofacies 1 - Wavy-bedded Fine Sandstone

Fine moderately well sorted sandstone with an internal lenticular or wavy appearance due to ripple development. Ripple cross-lamination is only rarely developed, but rare occurrences verify this interpretation. Very fine sandstone veneers separate lenticular units.

Lithofacies 2 - Cross-laminated Sandstone

Fine red sandstone with well developed ripple cross-lamination.

Lithofacies 3 - Coarse Sandstone

Coarse, poorly sorted, and generally massive units of red coarse sandstone.

Lithofacies 4 - Very Fine Sandstone

Red very fine sandstone in thinly laminated units, and resting gradationally on previous lithofacies.

Lithofacies 5 - Fine Sandstone

Red fine sandstone may preceed lithofacies 4, and occurs in relatively thick units showing an internally flat-bedded or more commonly massive appearance.

Lithofacies 6 - Flat-bedded Sandstone

Thin units of flat bedded medium grained red sandstone often forming a base to erosive cycles, the flat bedding displaying primary current-lineation on bedding surfaces.

Lithofacies 7 - Massive Sandstone

Poorly sorted medium grained red sandstone, in thin units and often containing 'floating' granules or gravel.

Lithofacies 8 - Interbedded Granule and Sandstone Sheets

Thick units of granule and gravel grade material interbedded with medium to fine grained sandstone. No internal erosion is apparent.

Lithofacies 9 - Planar Cross-stratified Sandstone

One occurrence recorded of planar cross-stratified fine sandstone, laterally impersistent.

Lithofacies 10 - Trough Cross-stratified Sandstone

Small, shallow trough cross-bedded fine sandstone

Table 1.19 summarises the abundance of these lithofacies, and demonstrates clearly the contrast between conglomerate and sandstone formations.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Wavy-bedded fine sandstone	7.05	22	0.32	0.65	0.06	29.3	40.6
Cross-laminated sandstone	1.16	9	0.12	0.24	0.03	12	6.7
Coarse sandstone	1.60	7	0.22	0.47	0.05	9	9.2
Very fine sandstone	0.96	10	0.09	0.21	0.04	13	5.5
Fine sandstone	2.38	4	0.59	0.84	0.08	5	13.7
Flat-bedded sandstone	1.45	9	0.16	0.32	0.04	12	8.3
Massive sandstone	0.32	5	0.06	0.21	0.03	7	1.8
Interbedded granule and Sandstone	1.84	6	0.30	0.85	0.08	8	10.6
Planer cross-stratified sandstone	0.14	1	0.14	0.14	0.14	1	0.8
Trough cross-stratified sandstone	0.45	2	0.22	0.28	0.16	3	2.6
TOTAL	17.35						

Table 1.19 Thickness Parameters of Lithofacies in the Dundarg Castle Sandstone Formation - Fine Members

The fine members are clearly characterised by wavy-bedded fine sandstone, and fine sandstone. Logged sections through the fine members show that a vague cycle may develop which consists of:

1. Slight erosion
2. A coarse lag or string of granules

3. Coarse sediment

4. Wavy-bedded fine sandstone

5. Very fine sandstone possibly silt.

Generally such a cycle is dominated by the wavy-bedded sediment, the coarse sediment being quite variable - lithofacies 3, 6, 7, 8, or 10 may be present. Massive sandstone, and interbedded gravel and sandstone commonly occur in lenticular, channel-shaped bodies and are associated with cross-stratified sandstones. Ripple cross-lamination may develop in relationship to either coarse basal sediments or wavy-bedded deposits.

The coarse members within the Sandstone Formation comprise:

1. Wavy-bedded fine sandstone
2. Fine sandstone
3. Massive sandstone
4. Cross-stratified sandstone
5. Cross-stratified gravel
6. Flat-bedded sandstone
7. Flat-bedded gravel
8. Massive gravel
9. Conglomeratic sandstone

Lithofacies 1, 2, 3, 4, and 6 are equivalent to similar develpments in the fine members. Lithofacies 5, 7, 8, and 9 are distinct and reflect the conglomerate Formation, the titles are self explanatory.

The following table summarises the lithofacies content of the coarse members.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Wavy-bedded fine sandstone	0.26	3	0.08	0.12	0.06	7.7	1.9
Fine sandstone	0.67	3	0.22	0.27	0.18	7.7	5.1
Massive sandstone	1.53	8	0.19	0.34	0.08	20.5	11.6
Cross-stratified sandstone	1.37	3	0.45	0.52	0.40	7.7	10.4
Cross-stratified gravel	2.23	3	0.74	0.95	0.54	7.7	16.9
Flat-bedded sandstone	0.52	5	0.10	0.16	0.06	12.8	3.9
Flat-bedded gravel	1.83	5	0.36	0.40	0.08	12.8	13.9
Massive gravel	1.81	6	0.30	0.48	0.10	15.4	13.7
Conglomeratic sandstone	3.02	3	1.0	1.4	0.62	7.7	22.9
TOTAL	13.24						

Table1.20 Thickness Parameters of Lithofacies in the Dundarg Castle Sandstone Formation - Coarse Members

Table 1.20 clearly demonstrates the predominance of coarse lithofacies in the total composition of the profile, whilst at the same time showing the abundance of structures pertaining to higher energy regimes, for instance flat-bedded sandstone and cross-bedded gravel, and therefore clearly contrasting the coarse and fine members.

Along the New Aberdour Shore the previously noted facies associations 2, 3 and 4 are exposed. 2 and 3 are regarded as equivalent sections, facies association 3 is incomplete. Facies association 4 (the Siltstone Facies Association) also outcrops at Counter Head where it is incomplete due to faulting. At New Aberdour Shore the Siltstone Facies Association is well exposed, and although also terminated by faulting, is considered the type section.

1.5(iii) New Aberdour Shore Subsection

1.5(iii)a New Aberdour Siltstone Formation (Plates 1.17, 1.18)

The New Aberdour Siltstone Formation completes the exposed sequence in the Eastern Coastal Section and is largely equivalent to the Geological Survey's Bed 3, i.e:

"Red sandstone slightly conglomeratic	with shales and calcareous clay bands
	SILTSTONE FORMATION

Characteristics	A siltstone dominated sequence with subordinate developments of thinly bedded sandstone and siltstone arranged rhythmically.
Type Section	The western end of New Aberdour Shore (Fig.1.41, 45)
Equivalent Section	The western end of Counter Head - Dundarg Castle section. This is suggested as being a lateral equivalent, but may represent deposits lower in the sequence than those of New Aberdour Shore, faulting causes both sections to be incompletely represented.
Lower Boundary	The lower boundary is complicated by faulting and over majority of the section mentioned siltstone is faulted directly against the previous Sandstone Formation sediments. Further towards the sea, as illustrated in Fig. 1.45, the conformable junction between siltstone and sandstone Formations may be observed although the succession continues to be complicated by faulting. The base of the Formation is defined as the incoming of siltstone.
Upper Boundary	The Siltstone Formation is faulted against the

Dalradian andalusite schists at the westernmost end of New Aberdour Shore at a point below St. John's Well (Fig. 1.45).

Thickness — Clearly the section is incomplete due to faulting. 89 m of sediment have been logged along the type section without recognisable repetition. Although the sequence consists of monotonous repetitions of thick siltstones and very thin sandstones, each cycle has sufficient character to allow its repetition to be recognised.

Fossils — Poorly preserved spores, such as Dibolisporites and various smooth-walled azonate varieties. Plus trace fossils interpreted as possible Dipnoan burrows (see Chapter 5).

Nature of Outcrop — A low, broad wave-cut platform with very easy access. The soft nature of the sediments and numerous fault planes have produced numerous low areas crossing the foreshore imposing a very low tide restriction on the section.

General Stratigraphy

The Siltstone Formation is composed of alternations of coarse and fine members, the sequence being comprised the following lithofacies:

a) Siltstone

Thick, massively bedded, fine to coarse siltstones, red-brown to brown-grey in colour. Some horizons preserve sheets of isolated calcareous nodules whilst others record thin mud laminae. Desiccation cracks are uncommon but may be developed at the top and bottom of siltstone units.

b) Interbedded Sandstone and Siltstone

An association of sediments characterised by the alternation of distinct sandstone and siltstone sheets in approximately equal proportions and equal thicknesses. The units are thinly bedded and may incorporate thin mud veneers. Ripple cross-lamination is common in the sandstones while desiccation cracks are abundant in the silts. The siltstone portion of the unit may be replaced by dark grey laminated muds (although quite uncommon) showing the development of symmetrical ripple marks.

c) Mudstone

Thin alternations of dark grey mudstone, fine sandstone and levels of reddened mudstone. Such deposits are desiccated at numerous levels.

The previously mentioned coarse-fine member rhythm is repeated along New Aberdour Shore at least 25 times, see Fig. 1.46 (others have suffered minor faulting and are therefore incomplete). Fig. 1.47 illustrates the reconstructed vertical profile for an average cycle and indicates the relative dimensions. On average siltstone comprises approximately 69% of cycles whilst interbedded sandstone and siltstone make up 31%. Average cycle thickness is 2.6 m with an average of 1.8 m siltstone and 0.8 m interbedded sandstone and siltstone. Detailed measurements of the coarse members show that interbedded sandstone and siltstone occur in roughly equal proportions, 55% sandstone, 45% siltstone, Similarly the thickness of the interbedded units is comparable:

Average sandstone thickness	6.6 cm	Range 5-10 cms
Average siltstone thickness	6.0 cm	Range 2-11 cms

The cycle or rhythm described has been defined on the following grounds:

1. Sandstones are sharp based, or even slightly erosive
2. Sandstones may often grade upwards into siltstones
3. The complete coarse member commonly grades into the fine member by means of sand flasers and lenses.

From this it is implied that coarse and fine members are related as no significant break occurs between them, whereas a sharp passage exists between fine and overlying coarse members.

Basis for the Erection of the New Aberdour Siltstone Formation

The subdivision has been applied on the basis of the restricted and markedly different lithological assemblage displayed by the Siltstone Facies Association (compare Fig. 1.47 with Tables 1.19, 20). Although the New Aberdour Shore section is longest, the short Counter Head equivalent section does display the base of the Formation, demonstrating that a sharp change in lithofacies does occur. Primarily the introduction of siltstone defines the base of the Formation, and is accompanied by the loss of all previously recorded lithofacies. Although well exposed, the basal portion of the Siltstone Formation is considerably modified by pedogenic carbonate, preventing observation of details of structure (Chapter 7).

Siltstone Facies - Coarse Member

At the extreme west end of New Aberdour Shore the Siltstone Formation rapidly coarsens upward into a thin sandstone development, and form of this coarse member is illustrated in Fig. 1.49. The highest exposed deposits of the Siltstone Formation show the development of very thick siltstone dominated cycles, the uppermost cycle is abruptly terminated by interbedded red sandstone and siltstone which eventually results in the development of coarse sandstones with large scale cross-stratification. The coarse nature of the sediment, the large scale bedforms, and the thick sedimentary units make this horizon quite distinct. A thick unit of siltstone sharply overlies the coarse member before the sequence is truncated by the New Aberdour Fault. Although very distinct, the significance of this coarse member is open to question, as it may record the uppermost limit of the Siltstone Formation, or it may simply record an isolate coarse sediment incursion into the otherwise siltstone dominated sequence. Due to the location of the New Aberdour Fault this problem cannot be solved.

1.5(iii)b <u>Counter Head 'Equivalent' Section</u>

Although the maximum development of the New Aberdour siltstone sequence occurs along New Aberdour Shore, an incomplete but important 'equivalent' section of siltstones are displayed on the foreshore at Counter Head.

Essentially, the sequences are similar, but at Counter Head a rapid (but conformable) passage is apparent from the underlying Dundarg Castle Sandstone Formation. Few observations on the nature of the sequence can be offered for this portion of the succession as extensive accumulations of pedogenic carbonate (see Chapter 7) modify majority of the sediments. Nevertheless, the importance of the sequence remains in its conformable relationship with underlying sandstones.

1.5(iv) <u>Summary and Discussion</u>

As with sequences exposed to the west, the succession of sediments in the eastern coastal section is largely a simple fining upward sequence. The nature and order of the stratigraphic units is clear, the only complications being the amount of shortening or extension caused by the abundant faulting present within the sequence.

Studies of conglomerate composition (Chapter 4) demonstrate clearly that the Dundarg Castle sequence contains the lowest strata of the Dundarg Castle Conglomerate Formation, while at the same time, the upper boundary to this unit is clearly exposed. Between the base and top of the sequence at Dundarg Castle, 90 m of sediment are exposed, while in the equivalent sequence from Counter Head to New Aberdour Shore as much as 400 m may be exposed. Faulting within Port an Doon may shorten the sequence, but no estimation of the original thickness can be made.

Thus in conclusion, the following points may be summarised for the Eastern Coastal Section:

1. The sequence is based by the Fleckies Meadow Conglomerate, a facies equivalent of the Quarryhead Conglomerate.

2. The Dundarg Castle Conglomerate follows, locally resting directly upon the Dalradian basement.

3. The lowest deposits of the Dundarg Castle Conglomerate Formation are those exposed at Dundarg Castle.

4. Faulting may extend the apparent thickness of higher deposits to the west, or shorten the apparent thickness to the east, although at the same time a westward (basinward) thickening would not be unreasonable.

5. The Dundarg Castle Sandstone Formation and New Aberdour Siltstone Formation follow conformably.

6. The New Aberdour Siltstone Formation regarded to be a facies equivalent of the Crovie Siltstone sequence of the Western Coastal Section.

7. Overall, the Eastern Coastal Section is considered a facies equivalent of the fining portion of the Crovie Group sediments of the Western Coastal Section. The term Crovie Group is therefore applicable to the sediments of both the Eastern Coastal Section and Quarryhead.

Middle Old Red Sandstone of the Gamrie Outlier

1.6 . Middle Old Red Sandstone Unconformity

Strata of Middle Old Red Sandstone age have been recognised from the Gamrie Outlier since the establishment of a fauna from the Findon Fish Bed by Traquair (1896) which resulted in the comparison of this horizon with the Anchanarras horizon of Caithness and its numerous equivalents (placing the horizon near or just below the Eifelian - Givetian boundary). The relationship between these Middle Old Red Sandstone sediments and strata assigned to the basement group has only been considered by Westoll (1951) who suggested a Lower Old Red Sandstone age for the local Basement Group sediments on the basis of an unconformity between the two sequences. This unconformity has remained undescribed and in fact as mentioned previously some doubt initially existed as to its presence. During the present study the relationships between Middle Old Red Sandstone and Basement Group sediments have been observed at several more localities, i.e.:

1) 200 m west of Coral Haven, and in Coral Haven
2) Black Hill east of Pennan Village
3) Along the sea cliff between Pennan Head and Sandy Haven
4) Meal Girnel and Sidegate
5) West of Strabackie
6) West of Langlitterly

The distribution of these outcrops is shown in Fig. 1.33, 1.34 The above mentioned sections have been studied in order to provide a more complete picture of the relationships between the two rock groups. Particular attention has been paid to the form of the erosion surface and the time and duration of any such erosion. Finally, although implicit in the term unconformity, the nature of tectonic events responsible must be sought.

With respect to the above points, the cliff section ½ km to the west of Pennan (locality 1 above) offers evidence on all counts, it is also the only readily accessible outcrop of the unconformity. Two sections are exposed:

a) Coral Haven
b) An un-named embayment 200 m west of Coral Haven beneath the 'Lodge'.

(a) Coral Haven

Poor, restricted exposure, mostly covered by loose blocks on the foreshore. Below the unconformity, conglomeratic sandstones dip steeply to the north at about 45° while above the unconformity, slate rich conglomerate appears flat, with no surface irregularities or major erosive depressions. Laterally no great variation in the inclination is apparent in the conglomerate, whereas the dip of the conglomeratic sandstones decreases over 15 m until only a small angular discordance exists between upper and lower groups, suggesting that at least a minor amount of folding has taken place prior to erosion.

(b) Below 'The Lodge'

A very well exposed accessible section again showing sandy conglomerate, flat layered with mud drapes between strata in the finer sand portions, occasional widely-spaced oscillation ripples with mud drapes, the whole sequence being commonly affected by sand injection phenomena and penecontemporaneous minor faulting. Above these, coarse conglomerate and slate breccia rest with marked erosive unconformity. Plates 1.19 1.19A and 1.20 show the almost horizontal lower group overlain by a moderately inclined upper group. Tracing the unconformity to the west only a matter of 25 m shows a marked steepening of the dip of the lower group whilst the upper group remains unchanged (plate 1.19). Also in this part of the outcrop further faulting is apparent, only of minor downthrow but clearly predating the upper group conglomerate. This section of the unconformity gives valuable evidence as to the nature of the events leading up to the unconformity:

1. Sediment below the unconformity contains possible evidence of tectonism in the form of sand injection structures.
2. Variation in inclination of the lower group sediments points to a pre-Middle Old Red Sandstone tectonic event (folding).
3. Faulting, although on a minor scale, is of pre-upper group age, thus supporting the tectonic event of 2.
4. The erosion surface is irregular and channel like with hollows infilled by derived second cycle conglomerate clasts. This suggests that erosion of the lower sediments occurred quite early, almost predating extensive lithification.
5. Steep channel sides suggest partial cementation or a state of 'wet sand' whereby the sediment resisted slumping.
6. Plate 1.19A illustrates minor rotational faulting, a feature common to channels in unconsolidated recent sediments (Hemingway, pers. comm. and Reineck and Singh, 1973). The important feature in this instance is that the sense of rotation is of a reversed nature. The mechanism was therefore not one of slumping but probably differential compaction. Given that such structures require a soft sediment, (Reineck and Singh, 1973), this reverse rotation would imply that some degree of loading occurred prior to cementation (i.e. the upper group was deposited onto relatively unconsolidated sands and gravels).

The remaining exposures (localities 2-6) of the unconformity occur to the east of Pennan Village and are mostly inaccessible, all can be viewed from the sea, but little evidence can be added from the land. The exposures in Sidegate and in Meal Girnel may be observed directly, Meal Girnel offers difficult access from land, but Sidegate is only accessible by sea.

East of Pennan the first outcrop of the unconformity occurs high in the cliff below Black Hill (locality 2) where the red Pennan Sandstone is overlain with marked angular unconformity by slate rich breccia. This outcrop is totally inaccessible particularly following recent cliff erosion and may only be observed with binoculars.

From the sea the capping of breccia is notable between Pennan Head and Sandy Haven with exception of the lower cliffs of Buckies Pad. Most direct evidence exists in the large blocks of slate rich breccia which litter the foot of these cliffs and confirm the presence of the Middle Old Red Sandstone conglomerates in the cliffs high above. All of these sections are dangerously inaccessible and may only be observed at a distance from the sea.

The important feature of these sections is that they show the upper sediments with uniform inclination towards the east, usually at a very low angle, almost horizontal. In contrast the lower sediments have a variable dip and demonstrate further the pre-upper group folding. This feature is illustrated in plates

1.7(i) <u>Middle Old Red Sandstone Outcrop Distribution</u> (Plates 1.20,21,22)

Although the presence of Middle Old Red Sandstone strata has long been recognised, no detailed appraisal has been made as to the nature or extent of the sequence. The Geological Survey noted the Middle Old Red Sandstone of the Gardenstown section, referring it to the Findon Group with a three fold subdivision:

7. Conglomerate and breccia

---

6. Grey and red clay with limestone nodules, containing fish remains, and lenticular grey micaceous shales, yielding plant remains and some scales of fish.

---

5. Coarse red conglomerate with some intercalations of red sandstone with fish scales.

Unfortunately, the conglomeratic nature of the Middle Old Red Sandstone sequence apparently lead the early workers to compare this sequence with that of Pennan Head concluding an equivalence between the two sections. From studies of conglomerate provenance, and from observations to the east of Pennan Head along sections only accessible by sea the present study concludes that such interpretations were incorrect, the Pennan Head section being of Basement or Crovie Group equivalence.

Sediments of Middle Old Red Sandstone age are exposed:

1. in higher parts of the Den of Findon where the three Geological Survey divisions are developed;
2. at the Snook, where lowermost Middle Old Red Sandstone conglomerate is faulted against a variety of Lower Old Red Sandstone sediments;

3. between Lions Head and Pennan Village;
4. between Pennan and Langlitterty.

Exposure of the Middle Old Red Sandstone sequence is far from adequate, and combined with the monotonous nature of the conglomerate sequences precludes the establishment of a rigid stratigraphy. On lithological grounds the original Geological Survey subdivision has been retained, but the problems involved with adjacent sequences prevent any correlation and therefore form naming of the various sequences, serving no practical value, has been avoided.

Den of Findon (Plate 1.22)

At present exposure is very poor, and consideration of the Geological Survey comments (1890) suggest that conditions had deteriorated by then in comparison to the exposures referred to by Horne in 1890, but from earlier work. In the Den of Findon the following sequence is exposed:

Upper Findon Conglomerate

Findon Fish Bed

Lower Findon Conglomerate

The Findon Fault brings uppermost Crovie Group sediments of the Castle Hill Sandstone Formation into contact with the Lower Findon Conglomerate above the confluence of the Findon and Afforsk burns. As far as can be estimated approximately 25-30 m of the Lower Findon Conglomerate remain, but are poorly exposed in this section. The conglomerates are poor to moderately well sorted and range in grade from small boulder sized fragments to gravel. Gravel and pebble grade conglomerates predominate, the detritus being mostly slate (see Chapter 4).

Consideration of the Middle Old Red Sandstone conglomerates at other localities indicate that immediately overlying the unconformity a zone of reworked detritus exists up to 5 m in thickness. Over the whole of the scant exposure in the Den of Findon there is no evidence of such a zone and therefore it must be concluded that the Findon Fault has shortened both Crovie and Findon Group sequences. Minor, impersistent, thin sandstones are present within the sequence, but constitute a very small proportion of the exposed sequence. No further lithofacies have been recognised.

The Findon Fish Bed outcrops high in the east side of the Findon Ravine, and at present is in a very poor state of preservation (and rapidly worsening). Minor excavation demonstrates that the fine grained sediments comprising this unit rest conformably upon the Lower Findon Conglomerate, grading rapidly from it. The following section is exposed in the type and only section available (Grid Ref. NJ76. 796636) dipping at approximately 8° to the north east.

Upper Findon Conglomerate

Red mudstone + small red carbonate nodules	60 cm
Grey Mudstone	30 cm
Laminated grey mudstone and fish-bearing nodules	110 cm
Pale grey soft plant-bearing mudstone	40 cm
Red siltstone, locally sandy and gravelly	10 cm

Lower Findon Conglomerate

The Lower Findon Conglomerate fines rapidly to be replaced by the red sandy siltstone of the Findon Fish Bed which fill depressions in the conglomerate surface. Pale grey mudstones sharply overlie this level, and have yielded specimens of <u>Ptilophyton</u>

(Geological Survey, 1890). Present exposure does not permit examination of the relationships of this horizon with the overlying fish-bearing mudstones, but Prestwich's original work implies that the lower deposits (as recorded above) may be absent, and locally replaced by red micaceous sandstones, and in places the fish-bearing mudstones rest directly upon conglomerates.

The fish-bearing horizon dominates the Findon Fish Bed, and in many respects is similar to the underlying grey mudstone, differing slightly in the presence of fine graded laminae and the abundance of calcareous nodules. Although exposure is restricted, the nodules can be seen to be arranged in sheets rather than randomly distributed.

The lamination characteristic of the fish-bearing mudstone disappears rapidly, returning to the grey mudstones comparable to the lower plant bearing horizon. By gradation the grey mudstones become red, and show the development of clusters of red calcareous nodules comparable to calcrete developments in the Crovie Group.

The relationship of the uppermost mudstones to the overlying Upper Findon Conglomerate is vague at present, 60 cm of mudstone are exposed, and appear to be conformably overlain by the upper conglomerate without indication of marked erosion. Present exposures only display 70 cm of Upper Findon Conglomerate; attempts to locate the fish-bearing horizon using portable drilling equipment verified that at least 8 m of Upper Conglomerate are present.

Prestwich (1838) recorded outcrops of the fish bed in the Pishlin Burn, where he also records 38 feet (12 m) of the Upper Conglomerate, these are no longer exposed. The Geological Survey (1890) also record grey mudstones in the Cushnie Burn, and in a small ditch near South Cushnie. The former location is no longer exposed, but plant bearing grey mudstones have been sampled from the latter.

The Findon Fault may be traced as far as the Snook, where Middle Old Red Sandstone Conglomerate is faulted against a variety of Crovie Group sediments. At this locality the conglomerates are very coarse, and for the first 5 m have a mixed assemblage of detritus analogous to that observed immediately overlying the Middle Old Red Sandstone unconformity at Pennan, and interpreted as reworked detritus. On these grounds the lowest exposed deposits at the Snook are considered to be close to the basal unconformity, although the lowest deposits have been removed.

The effect of the Findon Fault appears to vary along its outcrop. Very little deformation is apparent in the Den of Findon, but at the Snook the Crovie Group sequence is folded against the fault, and the Findon Group Conglomerates are dipping steeply 60° to 80° to the south (Fig. 1.15).

Some sandy horizons are present in the lowest conglomerates at the Snook, but these are rare and the rapid increase in slate detritus is accompanied by a decline in the amount of sandstone.

As mentioned the dip ranges from 35° to 80° , the exposed thickness being 500 m; although the amount of strata removed by faulting cannot be reliably estimated.

The Findon Fault splays as it rounds the Snook, one branch skirting the base of the high cliff between the Snook and Crovie Village, eventually running inland to meet the Troup Head Fault near Crovie. These relationships are illustrated in Fig. 1.15 .

Fig. 1.34 demonstrates that the Middle Old Red Sandstone conglomerates are faulted against Dalradian metasediments at the western end of the Central Section and outcrop between Downie Shore and Pennan Village. The cliffs are inaccessible between Downie Shore and Lions Head, but from the sea they are observed to consist of almost horizontal slate rich conglomerate. No sandstone is observed in the sequence. The cliffs fall vertically to the sea and thus expose 65 m of unbroken conglomerate.

The conglomerates are accessible at Lions Head, Cullykhan, and Mill Shore, and traced in this direction increase in dip to about 30° at Mill Shore. No change in character is recognised. Between Mill Shore and Pennan the dip steepens to approximately 45°, the lower portion of the conglomerate sequence being exposed resting unconformably on Lower Old Red Sandstone sediments.

At the east of Pennan Village, Middle Old Red Sandstone slate conglomerates are faulted against red sandstone of the Pennan Sandstone facies, and are not accessible east of this until Meal Girnel and the Quaynan. (Plate 1.20)

Middle Old Red Sandstone sediments are faulted down to sea level in the east side of Sandy Haven, having been present at about the 100 m contour along most of the cliff top east of Pennan Village. The Quaynan offers the first readily accessible vantage point, and along with the slightly more arduous Meal Girnel display a monotonous sequence of conglomerate. The conglomerates are coarser grade, up to cobble and small boulder sizes are common, and although slate rich they are strongly influenced by granite, psammite, and quartzite. Sand is present in large quantities in the conglomerate matrix making these deposits even more of a contrast to the slate rich deposits further west. Thin sandstones are rare, (less than 1%) reaching a maximum thickness of 40 cm, other than this, bedding is as poorly defined as in the slate conglomerate.

In the Quaynan the conglomerates dip slightly towards due west, the dip increasing in the vicinity of the Sandy Haven Fault. The stratigraphic horizon of the Quaynan conglomerates is uncertain, but by comparison to those exposed in Meal Girnel of knownprox- imity to the unconformity it is apparent that the Quaynan examples are also quite low in the Middle Old Red Sandstone sequence.

Further exposures of Middle Old Red Sandstone sediments are accessible from the sea in the three bays of:

i) Sidegate

ii) Strabackie

iii) Langlitterty

The basal unconformity is readily visible in Sidegate and may be observed with difficulty in Langlitterty.

The conglomerates exposed in Sidegate and Langlitterty are identical to those of Meal Girnel in grain size and composition (see Chapter 4), although slightly more sandstone is present in the lowest deposits. In Strabackie the conglomerates are exposed over 127 m of inaccessible cliff, although the slight dip to the east does allow slightly higher conglomerate to be studied. The higher conglomerates are notably finer in clast size, and are compositionally comparable to the deposits at the Quaynan. Sandstone is absent in the higher deposits, leaving at least 100 m of montonous conglomerate.

In the middle of Langlitterty the Middle Old Red Sandstone is faulted against Dalradian metasediments, and although reported further east by the Geological Survey no exposure is available at the present day. Nevertheless the observation by the Survey that this conglomerate rested upon brown siltstones with calcareous nodules comparable to those exposed on New Aberdour Shore does have very important implications, and may allow estimations to be made of pre Middle Old Red Sandstone faulting.

1.7(ii) Summary

Stratigraphically the Middle Old Red Sandstone sediments propose an insurmountable problem due to poor exposure and the lack of distinctive marker horizons. The present study supports the Geological Survey's proposed 3 fold subdivision at Gardenstown, and confirms that Middle Old Red Sandstone conglomerate outcrops to the east of Pennan - recognising several previously unrecorded exposures of the unconformity between Lower and Middle Old Red Sandstone.

1.8 Stratigraphical Synthesis

1.8(i) Lower Old Red Sandstone

Following the General Stratigraphy of each of the six sections described an attempt was made to interpret the nature of the sequence, its continuity, and related problems. Very few problems exist as to the nature of these sequences, but the assembly of the coastal sections into a vertically and laterally coherent picture is very difficult, primarily due to the previously mentioned problems of lack of marker horizons and the distinct possibility of facies variation.

The proposed stratigraphic correlation is illustrated in Table 1.21 but in order to justify this revision several points must be considered. Basically the problem is the interrelationships of isolated and fault-bounded sections, i.e:

WEST				EAST
Cardenstown subsection Crovie subsection	Central Coastal Section	New Aberdour subsection	Counter Head subsection	Quarryhead section

The New Aberdour and Counter Head sequences contain indentical conglomerate, sandstone, and siltstone facies, and little doubt exists as to their direct equivalence.

At Quarryhead the sequence also fines up into siltstone, and as at Fleckies Meadow is resting unconformably on Dalradian

Section	WESTERN		CENTRAL			EASTERN			QUARRYHEAD
Sub Section	Gardenstown	Crovie	Pennan	Pennan Head	Strabackie	New Aberdour	Dundarg Castle	Fleckies Meadow	
MIDDLE O.R.S.	Upper Findon Conglomerate Formation Findon Fish Bed 4m. Lower Findon Conglomerate Formation 500m.+		M.O.R.S. Conglomerate	M.O.R.S. Conglomerate	M.O.R.S. Conglomerate				
LOWER O.R.S.	Castle Hill Sandstone Formation 300m.+ West Harbour Sandstone Formation 45m.+ East Harbour Fm. 94m.+	Crovie Siltstone Formation 94m.+ Crovie Sandstone Formation 45m.+ Crovie Conglomerate Formation 30m.+	Pennan sst. 7cm. Pennan Conglomerate sst. 150m	Need Haven Conglomerate 25m Pennan Head Conglomerate 30m Quarry Conglomerate	Sandy Haven Conglomerate	New Aberdour Siltstone Formation 90m.+ New Aberdour Sandstone	Counter Head Siltstone Dundarg Castle Sandstone Formation 30m.+ Dundarg Castle Conglomerate Formation 90-200m.+	Fleckies Meadow Conglomerate 0-40m.	Quarryhead Conglomerate and siltstone 0-40m.
		DALRADIAN						DALRADIAN	DALRADIAN

Table 1.21

rocks. Such a basal unconformity is no criterion for chronostratigraphical correlation, and neither are the basal conglomerates, they remain only facies equivalents. Both sequences fine upwards, and both have pedogenic developments of carbonate nodules in the basal portion of the siltstone sequence (Chapter 7). Calcretes are known to be well developed in certain regions and characterised by slow aggradation, and are frequently of wide lateral extent. In all the sequences at Gamrie only one zone of calcrete development has been recognised, and it may therefore follow that the Counter Head and Quarryhead sequences can be equated on the basis of this horizon of calcretes. This must remain conjectural, as certain dissimilarities exist between the calcrete sequences (see Chapter 7).

If the correlation is valid, sedimentation is either condensed at Quarryhead or started at a much later time. The latter explanation is acceptable, as palaeocurrent evidence suggests an east or south-east palaeoslope, and sediment would be expected to thin in this direction.

At Crovie, New Aberdour, Counter Head and Quarryhead a fining-upward sequence is developed, and as stated, the New Aberdour sequence is equivalent to the Counter Head sequence and possibly the Quarryhead sequence. The fining-upward sequence may also suggest a broad comparison of the Crovie sequence with those to the east, but a major problem is that none of the lower sediments are directly comparable, only the siltstone facies are equateable.

Equivalence of the siltstone facies across the area may be further supported by the developments of calcrete in the upper portions of the Crovie Sandstone Formation, and the lower member of the Crovie Siltstone Formation. Hence correlation of the outcrops of the lower portion of the fining upward sequence would appear to be:

Crovie Siltstone	New Aberdour Siltstone	Counter Head Siltstone	Quarryhead Siltstone
Crovie Sandstone		Dundarg Castle Sandstone	'sandstone'
Crovie Conglomerate		Dundarg Castle Conglomerate	'conglomerate'
		Fleckies Meadow Conglomerate	'conglomerate'

In the eastern sections exposure is terminated at the level of the Siltstone Facies and therefore no correlation can be made with the coarsening upward sequence in the west.

However, the greatest problem still remains in attempting to locate the relative stratigraphic position of the sediments of the Central Coastal Section. The sequence is almost totally conglomeratic, the lowest accessible rocks having a conglomerate composition similar to that of the Dundarg Castle conglomerates (Chapter 4). At higher levels, a quartzite-rich conglomerate prevails and is unlike any so far recorded in the area. The highest conglomerates observed become slate-rich, and are thus comparable to the conglomerates of the western section. Several possibilities thus exist:

1. That the lowest conglomerates may be comparable with the Dundarg Castle and Counter Head conglomerate sequences;

2. That the upper slate-rich conglomerates may reflect a relationship to the western conglomerate sequence, either in the:

   a) lower fining portion

   b) upper coarsening portion;

3. That the quartzite-rich conglomerates may have no comparable facies or conglomerates of the same composition.

This leaves at least two alternatives:

A. That the lower conglomerates of the Central Section are comparable with those further east, whilst at the same time higher conglomerate levels are influenced by the westerly Crovie slate-rich conglomerate sources.

This would produce a situation illustrated in Fig. 1.51A where the deposits of the Central Section exist beneath the main siltstone development:

B. If the slate development in the upper conglomerates of the Central Section is equivalent to the coarsening portion of the Gardenstown sequence then the central section sediments would be above the main siltstone development as shown in Fig. 1.51B.

Petrographically the Pennan Sandstone formation does not compare with rocks of either east or west sections following either of the above methods of correlation (Chapter 4, and this Chapter, page 57), but being quartz dominated may belong to a similar source area to the quartzite-rich Pennan Head Conglomerate. If this is so, then the sequence of sediments in the Central Section may be considered a fining-upward sequence, in which case the sequence would be anlogous to the lower fining-upward trend in eastern and western sections and alternative A outlined above would be favoured. At the present state of knowledge, alternative A appears most favourable, but alternative B cannot, as yet, be overlooked.

1.8(ii) Middle Old Red Sandstone

As mentioned, correlation within the Middle Old Red Sandstone is impossible, and a reconstruction of the stratigraphy is out of the question. The unconformable relationships have been described, and from the various levels of strata encountered by the unconformity it is readily apparent that considerable tectonism and faulting occurred during the period of this unconformity.

1.9 Regional Setting

The Devonian sediments of the North East of Scotland, being largely coarse clastic sequences, pose as yet unsolved problems in the determination of their relative ages. Lithostratigraphical correlation over the large distances involved is to be avoided considering the nature of most of the sediments. Nevertheless the regional setting must be considered, as the Old Red Sandstone of North East Scotland has several important features only recently apparent following the recognition of Lower and Middle Old Red Sandstone strata in several of the Outliers previously considered to be entirely of Middle Old Red Sandstone age.

By comparison of spore assemblages from the Basement Group of Scotland with those of other British Lower Devonian sequences, Richardson (1967) suggested that a Lower Devonian age was likely for the Basement Group. Westoll (1951, 1964) had already noted the unconformity between known Middle Old Red Sandstone and Basement Group in North East Scotland and suggested that the Basement Group was in fact of Lower Old Red Sandstone age. He also postulated a Basement Group equivalence for the deposits of the Rhynie Outlier (Westoll, op. cit.). Spores extracted from the lower deposits of silts and shales and also from the chert in the Rhynie sequence have yielded poorly preserved, azonate, smooth and apiculate spores of the genera Retusotriletes and Apiculiretusispora (Richardson, 1967), and are thus comparable with assemblages from the Ousdale Mudstones both in type of spore and the lack of variety compared with other Devonian assemblages. The main difference is that the Ousdale assemblage contains undoubted specimens of Emphanisporites whereas the Rhynie Outlier has to date only offered rare specimens possibly of the same genus (Richardson, op cit.). From Strathpeffer the assemblage suggests a range of possible age from upper Lower Devonian to lowermost Middle Devonian, the former being most likely (Richardson, op. cit.). Although the spores from the Rhynie Outlier do not show a level of complexity equivalent to those seen in the Middle Old Red Sandstone, neither are they comparable with the Basement Group assemblages from Strathpeffer (Richardson, op. cit.). Richardson explains this as being a reflection of the *in situ* flora and thus no indication of the total spore spectrum at that time. However, he continues, the Rhynie spores resemble forms from the Basement Group at Ousdale providing at least some evidence to suggest that the Rhynie deposits are of Basement Group Age. Furthermore, the size-range of the Rhynie spores compares more favourably with Midland Valley assemblages than with those from the Middle Old Red Sandstone, and as the Midland Valley assemblages are probably Siegenian to Emsian in age there is some evidence for a Lower Devonian age for the Rhynie deposits. Recent work (pers. comm. to Westoll, 1975, from Richardson) implies that a Siegenian age is more likely for the Rhynie sediments.

During the course of this study acid-insoluble residues from dark fine grained sediments belonging to the Crovie Siltstone, and New Aberdour Siltstone Formations have been studied, and poorly preserved spores extracted. Only *Dibolisporites* and various smooth-walled azonate spores have been recognised, no apiculate examples being present. This work was carried out in conjunction with Mr. A. Collins, in whose opinion the assemblage suggested an Emsian to Eifelian age for the Basement Group, and although not as conclusive as would be desired it does to a large extent support Westoll's (1951, 1964) ideas of a Lower Old Red Sandstone Basement

Group at Gamrie.

To the west of Rhynie lie restricted developments of coarse clastics at Cabrach and Tomintoul. As yet these outliers have not been studied in detail, and only the Cabrach Outlier can be related to strata of known age, and then only tentatively on the presence of thin lava flows comparable to those at Rhynie, in the lower portions of both sequences. The Tomintoul sequence offers no means of correlation, but its location close to Cabrach and Rhynie does not preclude a Lower Old Red Sandstone age, although the 'replacement' of Lower Old Red Sandstone by Middle Old Red Sandstone along the Moray Firth coast does cast doubt on 'guesses' as to the age of such deposits.

Along the Moray Firth coast to the west of Gamrie several small outcrops of Old Red Sandstone, originally recorded as Middle Old Red Sandstone in age exist.
i.e. At Sandend Bay, Cullen, and Buckie

The validity of this Middle Old Red Sandstone age is open to question. Peacock et al (1968) have recently supported this date suggesting that at Buckie the 'Buckie Beds' are of Middle Old Red Sandstone age. They offer no explanation as to the nature or significance of this unconformity. If such an interpretation is valid it would demonstrate a marked thinning of the Lower Old Red Sandstone westwards, from at least 300 m at Gamrie to zero at Buckie. Peacock's (et al, 1968) argument cannot be accepted without question, but in the light of Donovan's (1975) discussion of a Middle Old Red Sandstone marginal lacustrine limestone in North Caithness, a situation exists which may be analogous to that at Buckie, and would allow for the whole of the Buckie sequence to be regarded as Middle Old Red Sandstone in age. Although the sequence has not been studied in detail the present author has observed the 'calcareous deposits' comprising the Buckie Beds and following the recognition of algal or similar structures

regards the similarity to Donovan's (1975) description as being highly likely, and thus it is considered that the conclusions reached by Peacock et al (that the Buckie Sequence is of Middle Old Red Sandstone age) are likely to be correct.

At Cullen and at Sandend Bay short sequences (10 m) of coarse clastic sediments are exposed but offer very little information as to their relative age. Both sequences are of local derivation preventing an assessment of their age in terms of conglomerate provenance. At Sandend Bay a remarkable unconformity exists between Old Red Sandstone and Dalradian Limestones resulting in the development of a 'fossil karst' structure, (see plate 1.23).

Whether such a structure is indicative of less arid climates than those implied further east is open to argument, but must remain doubtful grounds on which to date the Outlier. The only useful evidence which may be employed in paleogeographic reconstruction is the N.W.-S.E. trend of irregularities in the basement, and imbrication suggesting a N.W. direction of transport.

The distribution of Middle Old Red Sandstone sediment in N.E. Scotland is of great importance, particularly as the common presence of a reliable fauna allows correlation of the isolated sequences. At Gamrie at least 200 m of Middle Old Red Sandstone slate-rich conglomerates are recognised and when traced to the west of the Outlier Middle Old Red Sandstone sediments are noted to overlap the Lower

Old Red Sandstone deposits to eventually overstep onto the Dalradian and Moine basement. Even accepting the doubtful position of the Buckie Beds no Lower Old Red Sandstone strata are recognised west of the River Spey, whilst Middle Old Red Sandstone deposits are relatively common, the five fold division applied by the Geological Survey totalling at least 900 m of sediment in the Nairnside-Inverness area.

Lithostratigraphic correlation is out of the question, but comparison may be made between the faunas of the many fish beds of these Middle Old Red Sandstone deposits. At Gamrie, Traquair (1895) listed the following species from the Findon Fish Bed:

Diplacanthus striatus

Rhabdinacanthus longispinus

Cheiracanthus murchisoni

Cheiracanthus latus

Pterichthys milleri

Pterichthys productus

Glyptolepis leptopterus

Coccosteus decipiens

Cheirolepis trailli

Diplacanthus tennistriatus

Diplopterus agassizi

Osteolepis macrolepidotus

Gyroptychius microlepidotus

From this assemblage the Findon Fish Bed has long been equated with the Achanarras horizon of Caithness. More specifically it allows correlation between Gamrie, Tynet Burn, and the Nairnside fishbeds at Clava, Nairn and Lethen Bar and also north to the Cromarty fish beds, Edderton Burn, and as far north as Orkney (Sandwick Fish Bed) and Shetland (Melby Fish Bed), thus allowing considerable paleogeographic speculation as to the nature and extent of the Orcadian Lake during both Lower and Middle Old Red Sandstone times. Although the age of these horizons was initially based on vertebrate faunas (see Westoll, 1951, Miles and Westoll, 1963) it has since been confirmed on palynological data (Richardson, 1965, 1967).

As mentioned this correlation has important paleogeographic implications, indicating that whilst the general region of maximum lacustrine sedimentation probably existed in the offshore Caithness-Orkney region, the basin itself was extending in a N.E.-S.W. form, overstepping Lower Old Red Sandstone sediments to the south-west. Eventually of course overlap occurred to the north, west, south and south-east. As well as having important paleogeographic significance, this evidence has recently been employed by Donovan, Archer, Turner and Tarling (1976) to confirm magnitudes and timings of Great Glen Fault activity. Attempts have been made to support or refute the Lower Old Red Sandstone age suggested by field relationships and supported by sparse palynological evidence. Attempts to obtain a K-Ar. age date from the volcanic deposits at Rhynie (although not assisting the dating of the Gamrie Outlier) proved impossible due to the state of decay of the feldspars (Mitchell, pers. comm.). Magnetic studies (Turner and Archer, 1975) do give some support towards a Lower Old Red Sandstone age by comparison of pole positions with known Lower Old Red Sandstone positions, in contrast with Middle Old Red Sandstone positions.

CHAPTER 2

CHAPTER 2 - STRATIGRAPHY OF THE RHYNIE OUTLIER

2.1 Introduction

The Rhynie Outlier consists of a narrow faulted strip of Lower Old Red Sandstone occupying the valley of the 'Water of Bogie' and other tributaries of the River Don. The location of the Outlier relative to the Gamrie Outlier is shown in Fig. 2.1.

The sediments enclosed within this small Outlier rest unconformably on a range of Dalradian rocks along the eastern margin, but are terminated to the west by a series of major faults (Fig. 2.2).

2.2 History of Previous Research

Although the Rhynie Outlier is widely known for its plant bearing deposits, the overall geology and stratigraphy have received little attention later than the brief description offered by Hinxman (1888) and the Geological Survey (Grant, Wilson and Hinxman, 1890) in their description of Sheet 76. Their work offers the only outline of the sedimentary sequence, and is itself based on work previously carried out and noted by Geikie in his major publication in 1878 where he made a six fold subdivision of the sequence:

(6) Greenish grey shales, with beds of flagstone. Dryden

(5) Thick group of hard pale grey and reddish or purplish sandstones, with occasional pebble beds, and numerous pipes, 'galls', and irregular veinings of red clay. Rhynie Quarries, Burn of Craig

(4) Band of Diabase Porphyrite, seen between Contlach and Auchindoir Manse.

(3) Very soft and crumbling, grey and red, pebbly sandstones and conglomerates of well-rounded pebbles, with bands of red shale, seen below Glenbogie where the valley is cut out of this soft series.

(2) Red shales, with calcareous red nodules seen in small ravine to east of Glenbogie.

(1) Band of red and yellow conglomerate and breccia, sometimes with calcareous cement. This lowest deposit immediately underlies the shales at the last named locality and rests on the crystalline rocks.

Realising the difficulty in tracing units laterally with the often poor exposure, the Geological Survey used the term 'zones' for areas of the Outlier showing similar deposits. Only five zones were recognised:

Zone 5 - Dryden Flags and Shales

Zone 4 - Quarryhill Sandstone

Zone 3 - Tillybrachty Sandstones with Volcanic Zone

Zone 2 - Lower Red Shales with Calcareous bands

Zone 1 - Basal Breccia and Conglomerate

The term 'zone' brought together the numerous outcrops available, and the Geological Survey considered that these 'zones' were "generally persistent throughout the greater part of the basin".

They commented briefly on the structure of the area, and drew attention to the existence of a very small outlier of presumed Old Red Sandstone in the bed of the River Don at Towie (see Fig. 2.2).

In reducing the subdivision to five they acknowledge Geikie as having successfully demonstrated that the 'diabase-porphyrite' was interbedded with deposits of the upper Tillybrachty Sandstones. They thus included the lava in their zone 3, along with the more extensive lavas occurring in the north of the Outlier.

The Rhynie Cherts (a restricted facies developed within the Dryden Flags and Shales subdivision) have received most attention. They were discovered in 1914 by Mackie and immediately aroused heated discussion

Mackie regarded the deposits as 'older than the Old Red Sandstone of the Outlier'. The deposits were subsequently studied by Horne et al in 1916 who concluded that the sequence was in fact of Old Red Sandstone age. In 1917, Kidston and Lang published the first of their classic papers on the flora of the Rhynie Cherts identifying Rhynia Gwynne-Vaughani and subsequently (1921) Asteroxylon Mackiei. Kidston and Lang (1917) considered the sequence "... cannot be younger than Middle Old Red Sandstone in age". Hirst (1923) recorded the presence of small arachnids in the chert and thus greatly extended the field of interest, and Scourfield (1926) offered detailed descriptions of Lepidocaris Rhyniensis a small crustacean also found in the cherts. Hirst and Maulik (1926) added details of arthropod remains found in the cherts. Very little attention followed until 1959 when Croft and George remarkably identified (petrologically!) three species of blue green algae from thin chips of chert.

A wealth of botanical information has since been extracted from the cherts, and interest has even extended to a study of the hydrocarbons present (Dungworth and Schwartz, 1971).

Westoll (1951, 1964) drew attention to the presence of two sub-divisions in the Old Red Sandstone of north east Scotland separated by an unconformity. The upper division was reliably dated as being of Middle Old Red Sandstone age, while the lower was until quite recently regarded as 'barren'. Westoll (op. cit.) suggested that the lower division was probably of Lower Old Red Sandstone age, and further suggested, on paleobotanical evidence, that the Rhynie deposits were probably of the same age. Richardson (1967) offered the first direct evidence to support Westoll's views by comparing spore assemblages from the Rhynie deposits with spores from other Basement Group deposits. He concluded that the Rhynie deposits were probably of Seigenian to Emsian age, recent work

(Richardson pers. comm.) supporting a Siegenian age.

2.3 Stratigraphy

During the present study, the great lack of outcrop in the Rhynie Outlier (many of the original localities having disappeared) prevents any extensive elaboration on the stratigraphy proposed by the Geological Survey. It is suggested from the present study that the 'zonal' sub-division erected by the Geological Survey is as good as can be achieved from the limited evidence available, and with further outcrop it is presumed that these zones would confidently be raised to the Formation status, but at the present state of knowledge zones 1, 2, 3 and 5 cannot be observed in sufficient detail to warrant such a move. (In the following discussion numbers in parenthesis following localities refer to Fig. 2.2)

2.3 (i) Basal Breccia and Conglomerate

The Geological Survey (1890) record "brecciated conglomerate" forming a local base to the sequence with a maximum thickness of 50 feet. Initially this basal deposit was exposed in:

(i) the bank of the River Don at Milltown of Kildrummy (27)

(ii) the Linthaugh Burn (24)

(iii) the Carlinden Burn (23)

(iv) the Slughallen Burn (20)

Local residents confirm the first locality, but indicate that it was 'removed by the river many years ago'. Similarly the remaining three outcrops no longer exist, but augering in the Linthaugh and Carlinden Burns has confirmed the presence of a dark, pebble/gravel rich conglomerate largely composed of local Dalradian fragments.

There remains no direct evidence to confirm the basal unconformity, or indicate its magnitude and form.

2.3 (ii) Lower Red Shales with Calcareous Bands

According to the Geological Survey, 'red shales with calcareous bands' follow all of the above sections and are particularly well exposed in a deep ravine known as the Corbiestongue (21). They describe "... red, greenish, and purple sandy shales with intercalated calcareous sandstones and layers of oval flattened concretions".

During the present study small excavations in the Corbiestongue have provided red and purple sandy shales with numerous non-laminated, red brown calcareous nodules. No grey calcareous deposits have been observed. This latter point is of great significance as Hinxman (1888) and Grant Wilson and Hinxman (1890) record the presence of 'fish remains' in grey limestone nodules from this horizon.

Similar deposits have also been found during the present study in the Carlinden Burn where red-brown siltstones intercalate with thin sandstones, but very little detail could be extracted from this temporary exposure (a farm ditch) as the rock head was deeply weathered.

Thin sections of the calcareous nodules (see Chapter 7) lead to their interpretation as products of the development of calcareous soil profiles, such calcrete horizons being common in lower portions of the Gamrie Outlier, and clearly fish remains would not be expected in such nodules. Rather than contradict these authors on negative evidence it must be pointed out that the mudstones overlying the Findon Fish Bed at Gamrie are in fact reddened, and calcrete nodules although small are abundant. However, the Gamrie deposits are of Middle Old Red Sandstone age.

If such deposits <u>are</u> fish bearing it is of great importance in the implication of a Lower Old Red Sandstone connection to a major lacustrine development. From the present study of the Gamrie Outlier it is concluded that such a development in the Orcadian Lake did not extend south until Middle Old Red Sandstone times, and Lower Old Red Sandstone sediments contain no record of anything larger than shallow ephemeral lakes. It is thus tempting to assume that Hinxman (1888), and Grant Wilson and Hinxman (1888) were in error in their observation, particularly as Westoll (pers. comm.) having studied all the Moray Firth fish bearing nodules regards them as unlike anything he has observed from the lower deposits at Rhynie.

2.3(iii) <u>The Tillybrachty Sandstones</u> (Plate 2.1)

The Tillybrachty Sandstones are regarded by the Survey as following the lower red shales, although no passage can at present be observed. As noted by the Survey they are "... composed of soft, crumbling incoherent sandstones".

The sequence is best exposed in the Corbiestongue and the banks of the River Bogie in the Craigs of Tillybrachty (19) south of Rhynie with similar deposits observed at Mill Farm (17), Auchinleath (22) and in the road side south of Kildrummy Castle (30).

(a) <u>Corbiestongue</u> - Small exposures of very soft conglomeratic sandstone occur in the Corbiestongue in close proximity to the previously mentioned red nodule rich siltstones. The conglomerates and sandstones are coarse (up to large cobble grade) and occur in relatively thick units (up to 0.5 m).

(b) <u>Craigs of Tillybrachty</u> - This series of outcrops, cut into by the River Bogie, are largely obscured by sand washed from the crumbling surface of the poorly cemented sandstone. Nevertheless, the crags do demonstrate the development of the Tillybrachty sandstones and their passage almost into the Quarryhill Sandstone.

In the lowest part of the sequence the Tillybrachty Sandstones consist of reddish conglomeratic sandstones and thin impersistent pebble and cobble grade conglomerates. Erosion surfaces are common, and extend over long distances although sandstone features frequently change rapidly. Bedding is largely obscure in these lowest deposits. Two thin siltstone horizons have been observed but are laterally impersistent due to erosion by overlying conglomerate.

In the uppermost part the Tillybrachty Sandstones show a marked reduction in grain size and unit thickness. Conglomerates are restricted to small pebble lags overlying numerous scoured surfaces. Siltstone films occur but are rare, mudclasts present on foreset laminae attest to the presence of fine grained deposits elsewhere at this level. Cross-stratification is patchily developed and laterally impersistent.

Figs. 2.3 and 2.4 compare the sequences exposed in the upper and lower parts of the crags. Note the development of apparently large channelled surfaces.

Clearly a reduction in grain size and unit thickness, plus the introduction of siltstone and mudclasts heralds the close proximity of the overlying Quarryhill Sandstones. The Tillybrachty Sandstones differ from the Quarryhill Sandstones principally in:

1. Their higher conglomerate and pebbly sandstone content
2. Their lower siltstone content and absence of discrete developments of intraformational conglomerate.
3. Units are still laterally quite impersistent

(c) Mill Farm, Auchinleath and Kildrummy - In these localities exposure is extremely poor, but considered adequate to identify the sediments exposed as belonging to the Tillybrachty Sandstone sequence.

At Mill Farm a heavily overgrown exposure of poorly conglomeratic red sandstone with mudclasts occurs, and is regarded as belonging to the upper portion of the Tillybrachty Sandstone unit. They are in fact overlain in Craig Burn quite nearby, by sediments assigned to the Quarryhill Sandstones by the Geological Survey.

At Auchinleath, coarse conglomerate occurs in a farm ditch and although the Geological Survey record clasts of two feet in diameter only pebble and cobble grade sediments now remain. Although difficult to allocate due to lack of apparent structure, the sediments are considered from this study to belong to the middle or lower part of the Tillybrachty Sandstone sequence.

Near Kildrummy, conglomeratic sandstones can be excavated from road-side cuttings, the maximum clast size is quite small, and the occurrence of mudclasts would suggest a high position in the sequence. The deposits in these roadside outcrops are overlain quite closely by the Quarryhill Sandstone outcrops in the quarries below Kildrummy Castle.

2.3 (iv) Interbedded Volcanics (Plates 2.3, 2.4)

Geikie (1876) noted the presence of a band of "diabase-porphyrite" near Contlach (18) and Auchindoir Manse, and later the Geological Survey included these deposits in their zone 3 (the Tillybrachty Sandstones). The Geological Survey also drew attention to similar deposits outcropping in the Glen of Cults (3), and in the northern prolongation of the Outlier near Gartly (2). Unfortunately, the Survey introduced an element of confusion by not conforming to their zone system (used for the main part of the Outlier) when they described the northern portion of the Outlier outcropping in the area of sheet 86 . Essentially, the volcanic deposits of the main part of the Outlier were considered to follow the basal zones conformably, and were considered to occur at the base of the Tillybrachty Sandstone sequence, (i.e. zone 3). In the Glen of Cults, the numerical subdivision is retained, but the zonal arrangement is abandoned, hence the lava rests on "red sandy shales" assigned to a group 3 but apparently equivalent to zone 2 further south. It would therefore appear from the Geological Surveys evidence that the lavas described in these two localities are either one and the same, or closely comparable.

Exposure is extremely poor, and the only guide available remains the field evidence provided by the Geological Survey. They note outcrops at three main localities:

(i) Contlach (18)

(ii) Glen of Cults (3)

(iii) Near Gartly (1 and 2)

(a) <u>Contlach</u>

The Geological Survey observed a hard, fine grained, bluish-black, diabase porphyry which they interpreted as the inner portion of a lava flow. They offered no further details, and none can be added from the present study as the original small quarry at Contlach has now been infilled. Only loose debris could be sampled

From information provided on original Survey field slips it is apparent that the lava outcropping at Contlach also belongs to the Tillybrachty sequence, but does not appear to be anywhere near the base of this sequence. Lava certainly existed during early Tillybrachty Sandstone deposition as fragments of purply-brown vesicular lava are included in the lowest exposed conglomerates of this unit.

(b) <u>Glen of Cults</u>

In the neighbourhood of the Glen of Cults the lava is notably vesicular, and is locally termed 'the cork rock'. As mentioned, the Survey have pieced together fragments of exposure and indicate that the lava rests upon red sandy shales. In this locality the lava is regarded as occurring at the base of the Tillybrachty Sandstone sequence, and was described as a 'slaggy, acid-andesite'. During the present study no outcrop was found in the Glen of Cults, but thin sections of loose debris are illustrated in plate 2.3.

(c) Gartly

The survey note a purplish slaggy lava outcropping near to Gartly, and observed it resting upon both red shales and red sandstones. The initial roadside exposures have been lost, but small outcrops are still available to the extreme north of the Outlier where road improvement schemes have not occurred. Further exposure has also been noted during the present study on the western side of Gartly Village where a small quarry has been used as a road gravel dump. Here the lava is a non-vesicular bluish-black variety. Similar outcrops have been commented on by the Survey who described the lava "... as a compact dark green olivine basalt/olivine andesite".

From the Surveys field slips the lava is clearly somewhat local in its outcrop, its thickness is difficult to assess as the Survey do stress that boundaries are conjectural, nevertheless the development would appear to be in the order of 10 to 20 metres. Also, from the position of the Contlach lava at least two horizons are probable.

2.3 (v) The Quarryhill Sandstones (Plate 2.1)

The Quarryhill Sandstones are perhaps the best exposed deposits of the Rhynie Outlier due to their past exploitation as a local building stone. They are primarily exposed in a series of quarries on the south east side of Quarryhill (10, 11, 12), other exposures occurring at Broadley (25), Kildrummy Castle (28) and in the banks of the Burn of Craig (14, 15, 16). The Geological Survey record "... good sections" in the Mossat Burn near Wester Clova (east of Lumsden) although these are no longer apparent.

The total exposure of the Quarryhill Sandstones comprises alternations of the following seven lithofacies:

(i) cross-stratified sandstone

(ii) flat-bedded sandstone

(iii) massive sandstone

(iv) cross-laminated sandstone

(v) mudflake conglomerate

(vi) conglomerate

(vii) siltstone

2.3 (v)a Quarryhill

At Quarryhill a series of quarries have worked sandstone at three principal horizons. Each horizon shows distinct lithological features, and although there is no indication of intermediate horizons the lower, middle and upper quarries are regarded as adequately showing the development of the Quarryhill Sandstone sequence. The exposure at Quarryhill is very much incomplete, only middle and upper portions of the Geological Survey's zone 4 are exposed.

Lower Quarry

Fig. 2.5(a) illustrates graphically the nature of the sequence exposed in the lower quarry, the details of lithofacies abundance and thickness are summarised in Table 2.1.

The lower portion of the Quarryhill Sandstone sequence is clearly composed of large amounts of flat bedded and massive sandstones, but also has significant amounts of cross-stratified sandstone and mudflake conglomerate. The average thickness of these units is generally high, and reflects the nature of the uppermost Tillybrachty Sandstones both in thickness and lithofacies content. The sequence is distinct from the

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Cross-strat. Sst.	2.65	2	1.33	1.6	1.05	5	13
Siltstone	0.15	6	0.03	0.02	0.01	15	7
Massive Sst.	6.49	10	0.65	2.11	0.40	25	31
Mudflake conglomerate	2.55	7	0.36	0.80	0.12	18	12
Cross-laminated Sst.	0.59	2	0.30	0.35	0.24	5	3
Flat-bedded Sst.	8.45	13	0.65	2.8	0.1	33	40
Conglomerate	-	-	-	-	-	-	-
TOTAL	20.88	40					

Table 2.1 Thickness Parameters of Lithofacies in the Quarryhill Sandstones, Lower Quarry

from the Tillybrachty Sandstones in the relative abundance of siltstone, the presence of cross-laminated sandstone, and the absence of conglomerate horizons.

The sequence at this horizon still retains a significant amount of distinct channel-shaped horizons, frequently overlain by cross-stratified sandstone, but often infilled with thick poorly sorted mudflake conglomerate. Much of the sequence is problematical, bedding is never distinct and it is considered quite possible that the thick units of flat bedded sandstone are in fact very low angle cross-stratification. Similarly, truly massive sandstones are rare in nature tending to be restricted to finer sediment grades or the products of density currents. The abundant massive units in this sequence are therefore presumed to be lacking apparent structure.

The lower quarry contains the first of the recorded trace fossils present at Rhynie which here occur as thin but densely packed red mud filled tubes originating in siltstone units overlying thick sandstone horizons.

Middle Quarry

Fig. 2.5(b) illustrates parts of the logged sequence, lithofacies data are summarised in table 2.2

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Cross-strat. Sst.	-	-	-	-	-	-	-
Siltstone	0.23	2	0.12	0.15	0.08	8	3
Massive Sst.	3.17	8	0.40	0.70	0.14	33	43
Mudflake conglomerate	1.66	5	0.33	0.60	0.16	21	23
Cross-laminated Sst.	0.24	3	0.08	0.12	0.05	13	3
Flat-bedded Sst.	2.06	6	0.34	0.75	0.10	25	28
Conglomerate	-	-	-	-	-	-	-
TOTAL	7.36	24					

Table 2.2 Thickness Parameters of Lithofacies in the Quarryhill Sandstones, Middle Quarry.

In the middle quarry massive and flat-bedded sandstones are abundant, the most striking feature being the frequent thick mudflake conglomerate units. Furthermore the absence of cross-stratified sandstones makes the sequence quite distinct.

The nature of the lithofacies assemblage is similar to that described for the lower quarry except for mudflake conglomerate which occurs as large channel infills. Mudclasts are large, often reaching 40 cm. in dimension. Siltstone is a relatively small component of the sequence, but often occurs as thin drapes over individual sandstone horizons.

Rootlet horizons (mud filled tubes) described in more detail in Chapter 5 are also a common feature in the middle quarry, occurring in the upper portions of most sandstone units overlain by siltstone.

Upper Quarry

Fig. 2.5(c) illustrates the form of the sequence exposed in the upper quarry. This upper level appears to have offered the most useful building material as the quarry is the largest of the three.

The upper quarry also shows two distinct levels of working, and thus the summary of lithofacies abundance has been listed separately in tables 2.3 and 2.4.

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Cross-strat. Sst.	1.96	7	0.28	0.38	0.15	15	19
Siltstone	0.72	13	0.55	0.08	0.01	27	7
Massive Sst.	1.65	7	0.24	0.45	0.08	15	16
Mudflake conglomerate	-	-	-	-	-	-	-
Cross-laminated Sst.	2.82	11	0.26	0.85	0.03	23	28
Flat-bedded Sst.	2.79	8	0.35	0.65	0.13	17	28
Conglomerate	0.14	2	0.07	0.10	0.04	3	1
TOTAL	10.08	48					

Table 2.3 Thickness Parameters of Lithofacies in the Quarryhill Sandstone, Upper Quarry (lower portion).

LITHOFACIES	TOTAL T. m	NO.	MEAN T. m	MAX. T. m	MIN. T. m	PERCENT NO.	PERCENT T.
Cross-strat. Sst.	0.2	1	0.2	0.2	0.2	2	2
Siltstone	0.33	7	0.05	0.08	0.02	19	3
Massive Sst.	6.69	13	0.51	1.9	0.07	35	65
Mudflake conglomerate	-	-	-	-	-	-	-
Cross-laminated Sst.	1.78	9	0.02	0.4	0.06	24	17
Flat-bedded Sst.	1.38	7	0.20	0.39	0.02	19	13
Conglomerate	-	-	-	-	-	-	-
TOTAL	10.38	37					

Table 2.4 Thickness Parameters of Lithofacies in the Quarryhill Sandstones, Upper Quarry (upper portion).

In many ways, the upper quarry is a reflection of the lower quarry, and therefore suggests that the sequence exposed in the middle quarry is anomalous. The upper sequence differs in that although massive sandstone is still quite abundant, flat bedded sandstones are diminished while cross-stratification is increased. Cross-lamination is significantly higher, and most distinctive - mudflake conglomerate is not recorded forming distinct horizons (mudflake being only recorded on bedding planes).

A surprising feature of the upper sequence is the relative paucity of siltstone. The Quarryhill Sandstone is overlain quite close to the upper quarry by the Dryden Flags and Shales, and a higher proportion of siltstone would be expected to accompany this transition. The development of the Dryden Flags and Shales must therefore be either rapid, or have been formed in a sub-facies of the environment producing the Quarryhill Sandstone. In the latter case major changes in lithofacies abundance would not need to preceed what would in fact be only a temporary facies change.

The upper quarry shows the greatest development of trace fossils occurring at Rhynie. Rootlet horizons, burrows and locomotion trails all occur in this upper level.

2.3 (v)b Kildrummy Castle Quarry (Plate 2.1)

Approximately 20 m. of sediment are exposed in the small quarry behind Kildrummy Castle, the quarry itself having now been converted into an admirable ornamental garden. The base of the quarry wall has been built up and landscaped and houses an extensive collection of Alpine plants. Much of the quarry wall is covered by an attractive but rock obscuring foliage!

Nevertheless, the sequence clearly consists of:

(i) cross-stratified sandstone

ii) massive sandstone

(iii) thinly bedded fine sandstone and siltstone

(iv) thin gravel-grade conglomerates

In many ways the sequence is comparable to the upper deposits of the Tillybrachty Sandstone sequence. The most prominent features are:

(i) the listed lithofacies occur in thick indivisible units comparable with sequences in the Tillybrachty Sandstones,

(ii) true siltstones are absent, but fine sandstone/siltstone levels break up the sequence and distinguish the deposits from those of the Tillybrachty Sandstones,

(iii) conglomerate is present in the sequence, but the units are small and the grade is small. Their presence makes the sequence more comparable with the underlying Tillybrachty Sandstones than the overlying sandstones exposed in the Quarryhill sequence. It is concluded therefore that the sediments exposed at Kildrummy are perhaps close to the upper boundary of the Tillybrachty Sandstone,

(iv) a further feature indicating that the sequence is close to the Tillybrachty Sandstones is the lack of mudflake conglomerate, and the lack of rootlet horizons so common in the deposits at Quarryhill.

2.3 (v)c <u>Broadley</u>

Several small quarries exist near the farm of Broadley, but all are partially infilled at present. Thick units of massive and cross-stratified sandstone occur in these quarries and gravel strings occur frequently at the base of sandstone units and along foresets. Mudflakes occur on foresets, but are uncommon. The presence of thin siltstone veneers implies that the sediments genuinely belong to the Quarryhill Sandstone sequence, and are probably higher in the succession than the previously considered Kildrummy Castle quarry deposits, yet lower than the Quarryhill sequence itself.

2.3 (v)d Burn of Craig

Small exposures of thickly bedded gravel rich massive sandstone occur in the banks of the Burn of Craig, but it is only the presence of thin siltstones (veneers) which allow this series of exposures to be regarded as Quarryhill Sandstone and not Tillybrachty Sandstone. The Geological Survey initially regarded these exposures as belonging to the Quarryhill Sandstone zone.

2.3 (vi) Dryden Flags and Shales

The Dryden Flags and Shales are a poorly exposed but important sequence of sediments as they include the well known and botanically important Rhynie Cherts.

The sequence follows the Quarryhill Sandstones and is so named from small exposures in farm ditches at Dryden Farm (7, 8) where thinly bedded dark grey micaceous siltstones outcrop.

The most extensive outcrop occurs in the Den of Wheedlemont (9) and consists of a short sequence of thinly interbedded sandstones and laminated grey brown micaceous siltstones and mudstones. The nature of the sequence is illustrated in Fig. 2.6. Poorly preserved plant remains are quite common in the grey mudstones, and poorly preserved spores have been extracted from the mudstones and micaceous siltstones.

2.3 (vii) Chert Bearing Deposits (Plate 2.5)

In the early part of this century deposits belonging to the Dryden Flags were studied to the west of Rhynie. Mackie (1912) studied a series of rocks consisting of cherts, silicified grits, conglomerates, and a silicified rhyolite, and concluded that the deposits (which included the famous Rhynie Chert) were older than the Lower Old Red Sandstone forming the Outlier.

Subsequent investigation by Horne et al (1916) included a study of the plant bearing cherts, resulting in the conclusion that:

(i) the plant bearing cherts are of Old Red Sandstone age

(ii) the plant bearing cherts are interbedded in the Dryden Flags and Shales.

The plant bearing cherts were intially studied in a series of trenches dug in farm fields south of Windyfield (4) near Rhynie. Exposures also existed in the roadside adjacent to this field, and in the nearby Easaiche Burn (5, 6). At present no exposures are apparent in the Easaiche Burn, road improvements have removed the roadside exposures and the trenches by necessity are long infilled. Material for the present study has come solely from debris in the field. Clearly this is an important section, but unfortunately the only sections available are those logged during early studies and a section contributed by Dr. Lyons - a botanist and owner of the chert deposit. These sections have been redrawn and are compared in Fig. 2.7.

Quite clearly from this figure the sequences comprise sandy cherts/cherty sandstones and clays, with relatively thin but quite pure intervening dark cherts. Both the cherts and sandy cherts have been observed during this study, but only from loose material occurring near previous trench sites. The 'clays' and any other interbedded fine grained non-siliceous deposits could not be sampled, and apparently were not sampled even during the more recent trenchings (Lyons pers. comm.). This latter point is unfortunate, particularly as Horne et al (1916) in describing the sequence of Dryden shales exposed along the Rhynie-Cabrach roadside noted the presence of at least four 'ashy' horizons (see Fig. 2.6). Generalisations about the origin and remarkable preservation of material within the Rhynie Chert frequently invoke contemporaneous volcanic activity which result in the silicification of local peat swamps. The presence of 'ashy' bands would certainly assist such a concept, and samples of these horizons may in future prove fruitful.

An attempt was made during this study to sample at least part of the chert sequence, using a 'Packsack' portable drilling rig. The hardness and brittleness of the chert caused the project to be abandoned at the expense of several diamond impregnated bits. In several hours only 8 inches of chert were penetrated! Hopefully, at some later date the trenches will be re-opened and geologists (other than paleobotanists) will be invited to study or at least record and sample the sequence fully.

Much of the chert material collected is of a brecciated nature and shows no clear structure. Small samples have been observed with clearly preserved plant material in growth positions.

For the purpose of this stratigraphical study, the clay horizons confuse the evaluation of the sequence. Horne et al (op. cit.) certainly record ashy bands, but other logs simply refer to the presence of clay bands, making no distinction between recent clay and weathered shale and mudstone. The clays have generally been reported as being grey clays, and drilled portions of Dryden Shales certainly proved to be grey micaceous siltstones - perhaps these could easily weather to produce the mentioned grey clays. Unfortunately Lyons (pers. comm.) has observed in a recent trenching that the chert appears to stand proud and is surrounded by recent clay (the nature of which is unrecorded). It may also be possible therefore that the grey clays are simple infillings of recent material.

2.4 Relationships with Adjacent Sequences

The Rhynie cherts have yielded the famous flora Rhynia, Asteroxylon Mackiei, and Horneophyton etc. plus numerous invertebrate species such as the arachnid Paleocharinus rhyniensis, the crustacean Lepidocaris rhyniensis, the Merostome Crania rhyniensis, plus primitive insects Rhyniella praecursor and Rhyniogratha misti (also including early but less well documented finds of Pachytheca from lower deposits in the Glen of Cults). Although this fauna and flora appear somewhat rich it was the palynological studies made by Richardson (1967) that strongly indicated that a Siegenian age for the deposits in place of the original belief that the deposits were of Middle Old Red Sandstone age. As mentioned in Chapter 1, the present study has obtained poor palynological evidence to suggest (but not confirm) that the lowermost deposits at Gamrie are of Emsian age.

Chronostratigraphically, therefore, the two Outliers may be closely comparable, but Lithostratigraphically no comparisons can be made. This however must not be taken as evidence against correlation, as in such marginal alluvial environments (Chapter 3) extreme facies change would be common, and sediment composition closely controlled by local supply area.

It seems reasonable that the deposits of the Rhynie Outlier, being amongst the oldest Old Red Sandstone in North East Scotland, is equivalent in age to the lowest deposits at Gamrie, and is also a close equivalent to the small deposits further west at Cabrach and Tomintoul although it is unlikely due to the coarse nature of the deposits of the latter two Outliers that confirmation of this view will be possible. The possibilities of a more significant relationship between the Gamrie and Rhynie Outliers is discussed further in Chapter 4, where, although largely speculation, an attempt is made to draw together paleocurrent, sedimentological, and structural evidence in order to produce a paleogeographic reconstruction.

2.5 Summary and Conclusions

1. The stratigraphical subdivisions employed by the Geological Survey are retained.

2. The sequence is of Lower Old Red Sandstone age, and belonging to the Basement Group of north-east Scotland, it is probably comparable (a facies equivalent) to the Crovie Group sediments to the north. In the absence of direct evidence of such an equivalence, the term Rhynie Group is proposed for the sediments of the Rhynie Outlier.

CHAPTER 3

CHAPTER 3

Facies Analysis of Sediments of the Gamrie and Rhynie Outliers

PART 1 - Gamrie Outlier

3.1 Introduction

The subdivision of the sediments of the Gamrie and Rhynie Outliers on a Formation/Member basis (Chapters 1 and 2) relied on lithostratigraphical techniques, and the subdivisionsproposed are sedimentologically important. A study of the facies present and their interrelationships has been undertaken, primarily to assess objectively, and illustrate, the differences between the stratigraphic subdivisions, and hence provide justification for the stratigraphy. For this purpose a continuous field record of lithology, colour, grain size and sedimentary structures has been made. Facies content and variation within stratigraphic units have been largely considered by constructing facies profiles as described by Selley (1968), a technique allowing large amounts of data to be summarised, and providing a useful means of illustrating differences between stratigraphic levels. Facies profiles represent the graphical display of large amounts of field data, and must be considered in conjunction with field logs and bed-thickness histograms. It is essential, therefore, that much of the following discussion be complimented with data incorporated in the previously discussed stratigraphy (Chapters 1 and 2).

Vertical relationships are an important consideration in any attempt to evaluate the genesis of sequences of sediments, and the recognition and interpretation of cyclic and rhythmic sequences may often be of crucial importance. Several authors have outlined ways in which such relationships can be objectively assessed (see Duff and Walton (1962), Duff (1967), Krumbein (1967), Potter and Blakely (1968), Allen (1970a), Selley (1970), Anderson and Goodman (1957), Read (1964) and Doveton (1971). Where possible the techniques employed by these authors have been kept in mind during evaluation of sequences, but unfortunately most sequences in the present study and either too short, or show complex lateral variation, or are vertically gradational, preventing wide application of such techniques. Only is Subfacies C2 have such techniques proved to be of practical value in assisting to characterise a complex sequence more fully (see page 202).

As outlined in Chapter 1, the Gamrie Outlier consists of three time related but lithologically dissimilar coastal sequences which show an initial upward fining Megacycle followed by a coarsening Megacycle. The coarsening trend continues to the Middle Old Red Sandstone unconformity, and is followed by very coarse Middle Old Red Sandstone conglomerate. These Megacycles are regarded as consisting of sediments belonging to four major facies or environments, here termed Megafacies. The succession is wholly continental in origin, and is interpreted as deposits in an almost enclosed Intermontain Basin including the following four Megafacies:

A. Alluvial Fan Megafacies

B. Braided Stream/Wadi Megafacies

C. Piedmont Floodplain/Playa Megafacies

D. Lacustrine Megafacies

These subdivisions are regarded in the broadest sense only, and are intended as working terms to assist in the description and evaluation of the facies of the study area. Fig. 3.1 is an attempt to illustrate and interrelate the Megacycle/Megafacies and stratigraphy concepts briefly mentioned above.

3.2 Alluvial Fan Megafacies (A)

3.2(i) Introduction

During the lithostratigraphical evaluation of sediments belonging to the Alluvial Fan Megafacies, three subfacies were separated:

Subfacies A1 - Colluvium/regolith

Subfacies A2 - Alluvial Fan s.s. (Lower Old Red Sandstone)

Subfacies A3 - Alluvial Fan (Middle Old Red Sandstone)

3.2(ii) Alluvial Fan Subfacies (Colluvium/regolith) (Plates 1.11, 12, 13)

Sediments assigned to this grouping outcrop in two sequences at Quarryhead and at Fleckies Meadow, and in both instances rest directly on Upper Dalradian metasediments with a marked unconformity.

In both localities Old Red Sandstone/Basement relationships are complex but serve to demonstrate that at least 45 m of relief occurs locally, with steep-sided gullies up to 15 m deep and 30 m wide. Fleckies Meadow shows 5 m cliff-like terraces.

A strong relationship exists between deposits of subfacies A1 and this basement relief, the coarsest deposits being essentially restricted to the gullies and cliff-terraces.

3.2(ii)a Facies Description

A variety of lithofacies are displayed at Quarryhead and Fleckies Meadow, details have already been considered in Chapter 1. The general relationships, both spatial and temporal, are illustrated in Fig. 3.2 (a reconstruction of interrelationships found at Quarryhead).

Basement depressions or gullies are infilled by very-coarse very poorly-sorted conglomerate (Fig. 3.2A) which is always confined to such situations, being replaced laterally by finer often non-conglomeratic deposits. The coarse conglomerate consists entirely of local rock types, suggesting that transport has been minimal. For example, the Upper Dalradian sequences at both Quarryhead and Fleckies Meadow are closely comparable, being made up of psammitic-schists, meta-conglomerate, pelitic-schists and andalusite mica-schists. At Quarryhead psammitic-schists dominate the conglomerate with minor additions of meta-conglomerate. At Fleckies Meadow psammitic-schists again predominate, but andalusite-schist is only a minor accessory. These two accessory pebble types are restricted to locations where the rock types occur in the immediate basement sequence. Andalusite-schist is notably unstable, being recorded only in the conglomerates close to the basement outcrop of andalusite-schist.

The deposits are clearly proximal , a conclusion supported by the very poor rounding of all rock types, and also by their very poor sorting. The size of rock fragments ranges from gravel to boulders up to 3.5 m in length, and set in a matrix ranging from sand to mud. In no instances in the main conglomerate units has winnowing taken place, and no internal-bedding is apparent.

At higher levels the Quarryhead sequence shows the development of wedge-shaped conglomerate units (Fig. 3.2B). Sorting is still poor, although maximum clast-size is reduced. Adjacent to these higher conglomerates, wedges of well-sorted conglomerate occur (Fig. 3.2c) apparently being re-worked sediment from the main conglomerate units. The highest conglomerate units are carbonate cemented.

3.2(ii)b Spatial and Temporal Relationships

In both localities coarse conglomerate rests directly upon the Dalradian Basement, and is replaced laterally and vertically by finer deposits.

Coarse conglomerate is intially confined to gullies (at Quarryhead) or occurs adjacent to small cliff-like terraces (at Fleckies Meadow).

Exposure is restricted at Fleckies Meadow, but at Quarryhead higher levels of conglomerate occur as thick but internally-massive units of poorly-sorted conglomerate having an overall wedge-shape or lobate form. The units are non-erosive.

In general conglomerate grade decreases with height at both localities, and sorting improves (although large blocks, often isolated, are still present in higher deposits - see plate 1.12).

Laterally the conglomerates at Quarryhead are replaced by conglomeratic sandstones, sandstones, and eventually by siltstones and mudstones (see Fig. 3.2E).

3.2(ii)c Interpretation

The coarseness, poor-sorting, poor rounding, poor packing, and compositional immaturity of the deposits are features suggesting a near-source deposit and are commonly attributed to alluvial fan sediments (Sharp and Nobles 1953, Blissenbach 1954, Bluck 1967, Miall 1970).

The small scale of the deposits and their intimate relationships with basement topography precludes an interpretation in terms of normal alluvial models. The general restriction of coarse conglomerate to gullies implies that these basement features probably acted as conduits, channelling coarse detritus onto a floodplain surface. These features, plus poor stratification are typical of slope deposits (for example colluvium, talus and scree). Movement of detritus in such environments has been given much attention by geomorphologists, and several classifications have arisen (see Varnes, 1958 and Leopold et al, 1964). A recent simplification by Cooke and Warren (1973) based on the controlling processes outlines three general modes of deposition:

(i) gravity-controlled slope deposits,
(ii) debris-controlled slope deposits (where mass movement of detritus is characteristic),
(iii) wash-controlled slope deposits.

The conglomerates at Fleckies Meadow are regarded as having formed essentially under the influence of gravity, with no subsequent movement of debris being apparent. Orientation studies of blocks in this conglomerate (see Chapter 4) suggest an accumulating slope inclined at about 21° to Dalradian cliff-like terraces. Melton (1965a, b) considered slope deposits in Arizona, and found that slopes were inclined at 12 to 37.5° for granitic rocks, and from 17.5 to 34° for volcanic rocks. Both had a mean slope of approximately 26°, closely comparable to the present example.

The deposits at Quarryhead are clearly more complex. It is presumed that gravity-deposits have been 'funnelled' into pre-existing gullies, a phenomenon common in present day Scandinavian slope-deposits (Rapp, 1963). They have subsequently been modifed by 'debris-controlled' slope processes such as infiltration of fine sediment, and perhaps even re-mobilisation as mudflows or less miscous debris-flows (see Leopold et al, 1964). Such an interpretation would be consistent with the restriction of conglomerate to gullies, and also with the lobate form and sharp boundaries of higher non-erosive conglomerate units (see Fig. 3.2B).

The transition from 'debris-controlled' slope deposits to 'wash-controlled' slope deposits is regarded as being recorded in the small bodies of re-worked conglomerate adjacent to the previously mentioned lobate deposits. Further evidence for this interpretation lies in the fact that although the gully debouched onto a piedmont floodplain, the coarse conglomerate is surrounded almost in delta fashion by a local sand-apron on the playa surface, (such features are very common in modern playa environments - see Cooke and Reeves, 1976).

The gullies clearly did not accommodate channelised flow, and perhaps periodic sheet-flooding represents the maximum transfer of sediment onto the floodplain surface. Transfer of detritus onto the floodplain was clearly minimal as the rate of accumulation kept pace with laterally equivalent siltstones and mudstones in which extensive calcretes confirm long periods of non-deposition.

Carbonate cementation is extensive in the conglomerates laterally adjacent to calcretes, and although a connection is implied, the lack of extensive studies (see Lattmann, 1973) of carbonate cemented coarse-clastic material precludes detailed interpretation, although Stalder (1975) has described rapid phneatic and vadose cementation in coarse-clastics in the Oman Mountains. At Quarryhead the conglomerates have an extensive micritic matrix cement, but show none of the structures and textures noted by these authors.

Both authors recorded laminated horizons, and Stalder (op cit) in particular detailed 'dripstone' or 'stalactica-asymmetric' microcrystalline vadose cements. The existence of extensive microcrystalline carbonate cement probably suggests a vadose origin, and Pettijohn et al (1972) regards the micritic cement in such a location as suggesting a rapid development.

3.2(iii) Alluvial Fan Subfacies A2 (Sheetflood Conglomerates)

3.2(iii)a Facies Description (Plate 1.1)

Subfacies includes the lowest exposed strata in the west of the outlier (Crovie conglomerate) and consists of an alternation of three lithofacies, i.e:

(i) conglomerate

(ii) massive-sandstone

(iii) flat-bedded sandstone

Reddish-brown slate conglomerate dominates the sequence, being very poorly-sorted and ranging in grade from cobbles (8-10 cms diameter) to silt or mud-grade matrix. Bedding is always poorly-defined, sequences being typically massive or showing only vague and discontinuous internal textural changes.

Exposure is poor and repeatedly broken by minor faulting, yet as far as can be observed conglomerates exist in laterally-persistent thick tabular-units. Erosion surfaces are not evident in the conglomerates, nor the sandstones. Bedding is more reliably displayed by the rare interbedded red sandstones which may be internally massive or flat-bedded, and range from medium to coarse grained, moderately well-sorted sandstone. Sandstones commonly overlie a graded portion of conglomerate, and are seemingly related to underlying conglomerate depositional phases.

Not all conglomerate units have sandstone tops, finer-grained graded-conglomerates commonly do. Significant changes in clast size, packing and fabric have been noted and are considered to be a record of individual depositional events. Individual horizons tend to be uniform in terms of grain-size and fabric, but these parameters may vary considerably between successive horizons. Packing has been considered to be open or close depending on the presence or absence of a supporting framework of coarse particles. The conglomerates showing the poorest packing thus show the least well developed framework and vice-versa. Similarly poor-packing is displayed in poorly-sorted deposits. In no cases is a purely fine grained matrix developed, and clasts are never recorded floating in fine grained matrix. Framework supported conglomerates show the greatest tendency to be graded.

Clast shape enrichment is noted in better-sorted deposits, disc-shaped fragments being more abundant in well-sorted framework-supported conglomerates. Shape enrichment is an important problem to be considered, but the predominance of disc-shaped slate clasts introduces great problems to such a study in the present case.

Imbrication has not been observed, but poorly-sorted conglomerates show disc-shaped clasts with long axes oriented parallel to bedding surfaces.

3.2(iii)b Interpretation

The coarseness, poor sorting and compositional immaturity suggest that the sediments are relatively proximal deposits. The lack of fine-grained deposits and lack of erosive surfaces precludes an origin by the more normally accepted fluvial processes of high and low sinuosity streams and braided streams.

Miall (1970) describes similar coarse poorly-sorted conglomerates with little clast orientation and poor pebble-framework, interpreting them as debris-flood deposits of an alluvial fan. Poor-sorting, poor stratification, and loose packing are features commonly attributed to alluvial fan sediments (see Sharp and Nobles 1953, Blissenbach 1954, Bluck 1967, and Miall 1970) while at the same time Blissenbach (op cit) also notes that such features are not consistently found in stream sediments.

In modern alluvial fans, sedimentation is quite variable. The processes in operation being a function of climate, source-rock type and, more important, the location within the fan complex. From fan-head to fan-toe an increase in depositional processes exists, with erosion being more common towards the fan-head (Bull 1964)

The sediments of subfacies A2 clearly lack the erosive properties attributed to fan head sediments and therefore more distal situations must be considered.

At lower levels on alluvial fans sedimentation occurs by means of a spectrum of processes, with viscous mudflows at one end (i.e. a medium of low Reynolds number with insignificant turbulence, Blackwelder 1928, Blissenbach 1954, Sharp and Nobles 1953), and aqueous deposition at the other (Hooke 1967). Three mechanisms dominate the aqueous processes:

a) sheetflood

b) streamflood

c) stream-channel

Each of these processes may grade into the next (sheetfloods verging towards mudflows at high sediment loads), but the mechanisms characteristic of each process lead to distinct types of deposits. Although a single depositional process may characterise one position on the fan, Blissenbach (1954) notes that vertical sections may frequently show an intimate interbedding of sediments produced by all of the above processes.

The vertical and lateral lithological consistency of subfacies A2 suggests that the sediments originated by only one of these processes, and not a mixture as observed by Blissenbach. A detailed consideration of the sediments allows some speculation as to this process.

The frequent failure of conglomerate horizons to erode either sandstone or conglomerate is anomalous, particularly as Hjulstrom (1935) from theoretical considerations, and Fahnstock (1963) from field observations deduced that a normal stream capable of transporting fragments in the order of 10 cms diameter could erode material -up to 4 cms diameter.

As mentioned this lack of erosion surfaces, and the lack of fine-grained deposits, preclude an origin by normal fluvial processes of channel and floodplain character, and also exclude the stream-flood and stream-channel mechanisms common to alluvial fans, as these are typified by marked erosion. The lack of channelling, and the lateral persistence of the units implies that instead of being confined to a channel, flow was deployed quite uniformly over a broad planar-surface in a manner similar to that described by Hooke (1967). At the same time, although the process responsible was capable of transporting a large volume of coarse detritus, it was incapable of eroding previously deposited sediment, and therefore must either have been loaded to capacity or water rapidly infiltrated into the poorly-packed substrate producing a 'seive-deposit' (see Hooke 1967). Such unchannelled surfaces and laterally -extensive beds are produced during sheetflood episodes (Davis 1938) but not during streamflood and stream-channel phases (Blissenbach 1954).

Although few in number, sandstone horizons do punctuate the conglomerate sequence at several levels, commonly following a graded conglomerate unit. Such an apparent relationship to the conglomerate is useful in evaluating flow conditions, the above mentioned profile implying that flow decreased in competence during later stages in the flood episode. Blissenbach (1953) is not alone in noting that in modern sheetfloods a similar interbedding of coarse and fine deposits may result, a relationship considered due to late-stage run-off following a main flood episode, (see also Sharp and Nobles 1953, Fahnstock 1963, Bluck 1967) such run-off frequently being a more persistent event than the initial sheetflood (Blissenbach op cit).

Such sandstones that do occur are moderately well-sorted and may develop flat-bedding, they are considered to record a greater degree of reworking, and certainly a higher fluidity allowing the velocity gradients necessary for the establishment of upper flow-regime conditions and the development of flat-bedding.

Clast packing, as mentioned, is very variable and may either be a record of separate depositional events, or variations or pulses within a single flow. Fisher (1971) notes that velocity pulses are a common feature of modern sheetfloods. Although temporally variable the clast fabric tends to be laterally consistent, which may imply that processes were fairly constant for any one horizon, and that conglomerate fabric formed in response to physical conditions which varied with time but not space. This property adds further support to the concept of a more viscous type of flow such as a sheetflood or debris-flood. The conglomerates clearly did not develop through the action of highly viscous mudflow processes as pure fine-grained matrix and floating clasts are not recognised, but are regarded as typical of such high density deposits.

There is some evidence in the wide variation in sorting and packing that a range of sediment concentrations and flow durations must have existed. The more viscous flows would result in poorly-sorted deposits, and would be of rather short duration (Fisher 1971). Conversely the better sorted deposits were probably much less viscous and of longer duration allowing increased winnowing of fine material; a noticeable feature of the well sorted conglomerates is the marked depletion of sand-grade material.

Framework supported conglomerates also show the greatest tendency to be graded, and thus support the notion that they were deposited from a more turbulent flowing medium in which competence could vary with time.

The common orientation of disc-shaped clasts parallel to bedding in poorly-sorted deposits confirms their origin from more viscous sources, Fisher (1971) observed this phenomena in high viscosity flows and attributed it to the development of laminar flow-conditions common in highly concentrated dispersions.

The clast-shape enrichment recorded earlier is difficult to interpret, as the clast lithology (pelite) preferentially produces disc-shaped clasts. Nevertheless, the decrease of disc-shaped clasts relative to equant shapes in better sorted deposits does reflect a higher fluidity in the better sorted deposits where the settling velocity of blades and discs is lower due to their much lower effective settling sphericity (Sneed and Folk, 1958).

In summary the deposits are attributed to sheetflooding on an alluvial fan and although the immature clast assemblage suggests a proximal deposit, the lack of erosion within the sequence implies that the sediments formed in a more distal position, beyond the region of fan-head incision.

The predominance of sheetflooding over any other depositional process is perhaps unusual and may reflect either climatic control where precipitation was an intense but rare event, OR the absence of sand, having left a porous surface of fairly open conglomerate, causes water to infiltrate rapidly as in the generation of seive deposits (Hooke 1967) thus leaving little or no surface run-off for the development of channelled flow.

3.2(iii)c Comparison with Recent Deposits

Much of the limited work carried out on alluvial fan sediments has been referred to in the previous interpretation, futher comments may be relevant and help to confirm the interpretation.

Davis (1938) studied sheetflood processes in the Mojave Desert, he noted their short duration, and observed laminar non-erosive flow of the heavily-laden flood medium. Analogous poor-sorting and absence of cross-stratification has been referred to by Chawner (1935), Sharp and Nobles (1953), Fahnstock (1963) and Bull (1964).

Bluck (1967) considered alluvial fan sediments, and for sheetflood deposits he found that maximum clast-size and bed-thickness had a positive correlation. As particle size is known to increase towards source he concluded that bed-thickness must increase towards the source also and therefore sheetflood deposits must be wedge-shaped (this has been demonstrated by Sharp and Nobles, 1953, Bull, 1964).

3.2(iii)d Sedimentation Trends

A vertical profile through the conglomerate sequence may provide useful information as to fan processes with time. Unfortunately such a sequence is not exposed, but the overlying sandstone facies does have minor conglomerates towards the base of the succession. The gradual depletion of conglomerate is regarded as a continuation of the above mentioned distal thinning (a wedge-shaped deposit), the decrease in particle size (although small) is also recorded and confirms that with time, fan deposits contribute less and less sediment to the piedmont surface. This in turn imples that either:

(i) the source-area was reduced significantly,

(ii) climatic conditions were unfavourable for fan construction,,

(iii) the fan was only a small local deposit which rapidly equilibrated with its surroundings.

A reduction in source area cannot be confirmed, although the Lower Old Red Sandstone sequence does show a major fining trend which would be expected if relief were reduced and sediment supply caused fan recession. Climatic conditions were apparently semi-arid, allowing calcrete development at higher levels; whether climate changed or not also cannot be confirmed as calcrete distribution would also be environmentally sensitive to a large extent. If the fan was a small localised deposit it would be expected to mature rapidly, and eventually equilibrate with supply of detritus. If no further relative elevation of relief occurred, then fan advance would cease. The lack of channel deposits may indicate that fan slope was too steep to allow any other than sheetfloods, if so, this may confirm that the fan was only of local extent; smaller recent fans being widely observed to have steeper slopes (Eckis 1928, Melton 1965a, b). Unfortunately, yet again this cannot be confirmed as fans derived from fine grained rocks are often 35-75% steeper than fans of similar area and derived from coarse rocks (Bull 1964).

3.2(iv) Alluvial Fan Subfacies A3 (Sheetflood conglomerates)

3.2(iv)a Facies Descripton (Plate 1.20, 1.21)

Subfacies A3 consists of the slate-rich Middle Old Red Sandstone conglomerate sequence outlined in Chapter 1. Although probably in excess of 300 m in thickness, the monotonous nature of the conglomerate sequence prevents any further subdivision.

The conglomerates of subfacies A3 are dominated by local Macduff Slate detritus, the only significant variation occurring immediately above the Middle Old Red Sandstone unconformity where considerable reworking of the Lower Old Red conglomerates has contributed granitic detritus to the otherwise slate-rich sequence. The conglomerates are generally poorly-sorted, with detritus ranging from fine sand to cobble grade. Discrete units of sandstone are extremely rare, and fine gravel rather than sand tends to form a matrix for the abundant pebble and cobble grade material.

Bedding is always poorly defined, and displayed only by vague internal textural changes. Erosion surfaces are practically non-existent, only two having been recognised in the whole sequence.

Texturally the conglomerates are regarded as very immature in that although a framework of coarser material may develop, larger clasts are normally supported in gravel matrix. This apparent textural immaturity is also supported by a structural immaturity in which clasts show no apparent preferred orientation in vertical and bedding plane sections. In these features the conglomerates closely resemble the slate-rich subfacies A2 conglomerates of the Crovie Conglomerate sequence. The most significant difference is that the conglomerates of subfaces A3 show occasional distinct structural and textural features not recorded in the subfacies A2 conglomerates.

These features include improved sorting/clast size enrichment, whereby a reduced pebble assemblage generally occurs supported by a well sorted gravel matrix. Such horizons are occasionally associated with improved packing and distinct developments of imbrication, clast orientation, and crude cross-stratification.

Anomalous horizons have been recorded showing vertically-inclined fragments, these will be discussed in a following section.

Although the conglomerates clearly show a greater diversity than in subfacies A2, indicated earlier, erosion surfaces are rare, only one distinct channelled surface has been recorded, the other erosion surface observed was related to cross-stratified conglomerates.

An exception from the norm occurs in the vicinity of Mill Shore near Pennan where conglomerates commonly show the development of zones of vertically oriented clasts extending for up to 1 m horizontally and 40 cm vertically. In all instances a moderate amount of clast-size enrichment is apparent with pebble sized clasts occurring in well packed conglomerates but still retaining a significant fine gravel matrix (see Plate 1.21d).

3.2(iv)b <u>Spatial and Temporal Relationships</u>

The failure to establish a detailed stratigraphy based on either sedimentological criteria or conglomerate composition prevents a specific consideration -of such variations.

In general, variations in conglomerate composition and form are most apparent in the lower deposits of subfacies A3 only. Immediately overlying the Middle Old Red Sandstone unconformity, the composition of the conglomerates strongly suggests that much of the material involved has been derived from Lower Old Red Sandstone conglomerates. In these conglomerates sandstone horizons are common and the conglomerates themselves quite well sorted. Plate shows perhaps the most accessible of these conglomerates at The Snook near Gardenstown where there is a strong indication that detritus was moved as a series of shallow braid-bars. Whether such conditions prevailed into the slate-rich conglomerates cannot be decided with confidence although in the previous discussion the evidence was regarded as being weighted against this possibility.

The lowermost conglomerates are not well exposed, but where present they do tend to reflect the conditions apparent at The Snook both in the development of braid-bars, and in the strong re-worked component.

3.2(iv)c Interpretation

The overall coarseness, poor-sorting, compositional immaturity, lack of fine grained deposits, and virtual absence of erosional surfaces precludes the majority of fluvial environments and suggests a relatively proximal deposit. Alluvial fan deposits have been discussed in some detail in the previous section under subfacies A2 (Crovie Conglomerate), and in many ways the conglomerates of subfacies A3 are comparable in that the lack of erosion precludes streamflood and stream-channel environments, whilst a gross vertical and lateral lithological consistency implies that sedimentation was dominated by one general mechanism for long periods of time.

By analogy with arguments put forward during consideration of subfacies A2, a sheetflood mechanism would again receive strong support for the poorly-sorted texturally immature conglomerates of subfacies A3.

During sheetflood processes, flow would be deployed somewhat uniformly over broad planar surfaces, and lack of erosion during this event is generally taken to indicate that the depositing medium was either loaded to capacity or else water rapidly infiltrated into the 'open' substrate producing 'sieve deposits' (Hooke 1967). In such instances a well developed fabric would not be expected. The development of framework supported fabrics and improved sorting imply increased fluidity of the depositing medium, and sufficient energy available to transport and winnow the coarse sediment. The poorly defined bedding implies that such conditions were occasionally persistent, and changed slowly, thus preventing the development of distinct breaks and erosion surfaces. These implications contrast quite strongly with the normal concept of flow conditions during sheetflood episodes, as periods of high fluidity are normally late stage run-off events following a main flood. Late stage run-off is generally accepted as a less competent phase of sheetflooding and responsible for finer sediments often interbedded with sheetflood conglomerates.

The lack of interbedded sandstones at first detracts from this possibility, but as the conglomerates are derived from local pelitic schists and Pettijohn (1975) considers that grain size ...."is inherited from parent rock" and that the breakdown of such parent rock .... "will lead to the liberation of particles from an earlier phase of primary production" - sand would probably not have been available in subfacies A3 for such a late stage run-off episode. Instead the abundant fine gravel may record periods of winnowing during late stage run-off, when, due to a reduced traction carpet caused by lack of sand in suspension an increased bed shear-stress would make considerable energy available for erosion of the finest-grade of sediment. The reduced bed-thickness, regarded by Bluck (1967) as indicative of reduced water depth would also aid such a process.

A consideration of graphs relating velocity and particle size to erosion, transport, and deposition (e.g. Hjulstrom, 1935) also would indicate that erosion and deposition of coarse sediment are separated by only a small velocity change. Similarly, high velocity flows are capable of eroding and transporting a broad spectrum of sediment grade making theoretical considerations of transportation open to question.

Alternatively, the abundance of crude horizontal bedding may fit into a proximal braided-stream model where a predominance of longitudinal bars would typically produce such bedding. Unfortunately a high suspended load would reduce the critical shear-stress and favour bar development, but on the other hand the paucity of sand in the present example would not favour this. Also, low-stage dissection of such bars would be likely and would result in extreme lateral discontinuity - a factor normally regarded as aiding recognition of braided-stream environments, but lacking within subfacies A3 sediments.

The only major erosive surface recorded in subfacies A3 shows steep downcutting of 1.6 m and could quite easily be a single rare stream-channel episode more common in proximal alluvial fan environments.

It is concluded that although interpretation is complicated by a strong possibility that a restricted sediment grade would modify normal concepts of conglomerate deposition, the conglomerates are comparable to those described in the literature and interpreted as Alluvial Fan sheetflood conglomerates. The relatively common levels of imbrication and well sorted conglomerate may attest to larger run-off episodes, or they may be a result of the scarcity of fine sediment. Perhaps the lack of fine sediment may even modify distal-fan environments and allow braided environments to develop with very broad shallow channels and low longitudinal bars.

At higher stratigraphic levels variation in composition and form are not readily apparent, and even when the Alluvial Fan environment was overstepped by the Lacustrine development in the region of the Den of Findon (subfacies D1), no advance warning of this exists in the Lower Findon Conglomerates, and no differences are apparent in the overlying Upper Findon Conglomerates. The Lacustrine advance has interdigitated with the Alluvial Fan environment without significant gradation, the change occurring over as little as 25 cm.

Vertically-packed sediments as noted earlier have been described from numerous environments ranging from offshore marine (Greensmith and Tucker, 1968, 1969), to Estuarine (Weidemann, 1972) and marine and Lacustrine beaches (Mii, 1957, Sanderson and Donovan, 1974, Dionne, 1971). In these instances the action of low energy waves on disc and blade shaped fragments is regarded as being responsible for the production of such textures. Clast shape enrichment is prominent, but unfortunately this cannot be confirmed in the present situation as blade and disc-shaped slate fragments predominate overall. Documented examples also record a high degree of size-sorting, with very little fine matrix present - this feature constrasts with the vertically-packed conglomerates of subfacies A3.

The occurrence of such an unusual texture is of interest, but its interpretation is difficult in this instance as no direct evidence exists to indicate that low energy waves may have acted upon the conglomerates. The rapid replacement of the fan environment by Lacustrine conditions in the Den of Findon may offer slight support by demonstrating the ease by which such conditions could develop, and also the lack of influence they had on the fan environment both before and after the change. It may be possible therefore that the Orcadian Lake remained close to the present Middle Old Red Sandstone outcrop and at times even interdigitated with fan conglomerates without leaving significant record other than these possible re-worked beach deposits.

Although specific interpretation is difficult, the general form of the conglomerates does in many ways fit into the criteria outlined by Bull (1964) for the recognition of Alluvial Fan environments. In particular, Bull stressed that each horizon is commonly a record of a unique set of hydraulic conditions which determine such properties as grain-size, bed-thickness, clast orientation, and the presence or absence of erosion. As the bulk of fan deposits are deposited as sheets or lobes, these conditions generally prevail over distances in excess of most outcrops, thus bedding in fan deposits is frequently observed to be 'laterally consistent'. Variationsin bedding are most distinct when differing mechanisms have contributed to a sequence of sediments, for example interbedding of sheetflood - debris flood - and mudflow deposits. Laterally, bedding is probably most distinct in water-lain deposits, but even here thickness is a function of relief between shallow-channels and low bars and erosional and post-depositional modification. Bull also indicated that ephemeral conditions may contribute thin clayey gravels during the waning stages of flow, the less well sorted finer grained horizons may represent such conditions.

3.3 Braided Stream/Wadi Megafacies (B)

Introduction

Sediments regarded as belonging to Megafacies B follow Megafacies A alluvial fan sediments in the east of the Outlier (Dundarg Castle Conglomerates and Dundarg Castle Conglomeratic Sandstones), and include the whole of the sequence accessible in the Central Coastal Section - here interpreted as being laterally equivalent to the Megafacies B sediments in the east. Megafacies B type sediments are not developed in the lower part (the fining megacycle) of the Western Coastal Section, but dominate the upper coarsening megacycle in this section.

The megafacies is subdivided into the following three broad subfacies:

Subfacies B1 - ephemeral-stream/wadi environment represented by:

- Subfacies B1a - Dundarg Castle Conglomerate Formation
- Subfacies B1b - Pennan Head Conglomerate
- Subfacies B1c - Pennan Conglomeratic Sandstone

Subfacies B2 - predominantly fine-grained braided-stream environment at times ephemeral flow, represented by:

- Subfacies B2a - Castle Hill Sandstone Formation
- Subfacies B2b - Pennan Sandstone

Subfacies B3 - coarse-grained braided-stream environment represented by:

- Subfacies B3a - Need Haven Conglomerate

3.3(i) Braided-stream/Wadi Subfacies B1a

3.3(i)a Introduction

In contrast to the western portion of the Outlier, the lower sediments of the east are coarse and completely lacking in finer grades of sediment so common in the Crovie section. The Dundarg Castle Conglomerate Formation overlies the coarse basal conglomerates (Subfacies A1) conformably and in places oversteps these lowest deposits to rest unconformably on the Dalradian Basement. Although no unconfirmity necessarily exists between these two lower sedimentary units a great dissimilarity exists in sediment type and consequently in presumed environment of origin.

The transition from the basal conglomerate (Subfacies A1) to Subfacies B1a is exposed between Fleckies Meadow and Dundarg Castle and involves:

(i) an overall decrease in the predominant grain size component with a concomitant increase in the percentage of sandstone,

(ii) an increase in the proportion of coarse matrix and gravel size sediments,

(iii) an increase in well defined bedding surfaces accompanied by a marked development of erosional features and internal stratification,

(iv) a marked increase in clast roundness, and

(v) a marked change in clast composition.

The majority of the subfacies is exposed between Fleckies Meadow and New Aberdour Shore, although the sequence is complicated by faulting at Counter Head. The subfacies consists essentially of conglomerates, pebbly-sandstones and sandstones, and characteristically a total lack of fine-grained sediment. A few levels of conglomerate are as coarse as the basal conglomerate, but the majority are much finer and more sandstone is present in the sequence.

The facies has been subdivided into eight lithofacies mainly on the basis of structure, but also including grain size, sorting, and texture. Fig. 3.3 is an attempt to reconstruct the relationships between these lithofacies and is compiled from numerous field logs. Lateral and vertical variation is very significant and therefore this reconstruction is by no means definitive, it is merely an apparent relationship of lithofacies as exposed.

3.3(i)b Facies Description (Plates 3.1 to 3.5)

Lithofacies A - Channel Fill Conglomerate

Channel shaped erosion surfaces are abundant and may range in size from a mere 40 cm wide to large channels 1.5 m deep and over 20 m wide. The nature of channel infills is as variable as are the dimensions mentioned. Smaller channel forms are invariable infilled by moderately well packed coarse conglomerate, whilst larger channels, tending to be asymmetric in shape, have coarse conglomerate situated in the deeper, more steeply eroded portion of the hollow.

Step-like low relief terraces frequently occur on the steeper edges of large channels and may correspond to structural differences within the channels themselves. Lateral migration of channel deposits is evident in many sections, but primarily by distinct and discrete movements of position (Fig. 3.4) rather than by gradual lateral migration as is common in modern and ancient high sinuosity systems. In a few instances migration has taken place along a horizontal plane (Fig. 3.4), whereas in the majority of situations adjustments occur in height also and therefore are even less analogous to lateral accretion described elsewhere (Allen, 1965a, b).

A salient feature of channel conglomerates is their abundance throughout the stratigraphic unit, scattered examples occur in most of the short coastal sections available, but it is only at restricted horizons that developments of channels are abundant. It therefore appears that stream development in any one area may have been somewhat ephemeral, a problem discussed later when channel infilling is considered (see page 162).

Channel fill conglomerates are always coarse grained infills roughly increasing in grade with increasing channel size (see Fig. 3.6). Sorting is generally poor although exceptions do exist (mainly at smaller channel sizes). Packing density is high and results in a predominantly 'grain' supported fabric. The matrix may often be fine grained, and relatively well sorted, although in many cases a gravel mode is present. Gravel abundance appears to be strongly related to the amount of matrix present, whilst at the other end of the scale when matrix is very low, very coarse gravel and small pebbles may occur in the matrix cavities. Grain size within channels shows a lateral grading towards finer deposits in lateral positions, particularly towards the shallow edge where replacement by lithofacies B bedded conglomerate may occur. Vertical fining occurs and is rapid, channel deposits may frequently be replaced by single thin sheets of conglomerate which overlie planar erosion surfaces. A lateral decrease of grain-size occurs in such instances, the conglomerate being replaced by gravel with irregularly bedded coarse and fine portions. Fining in a similar manner has been described by Smith (1974) from longitudinal-bars in a braided outwash stream and is analogous to coarsening upward sequences described by several authors, and regarded as being due to the downstream migration of longitudinal-bars allowing coarser bar-head gravels to overstep the finer bar-tail sediments, such structures are commonly related to erosion structures at Gamrie.

It is notable that the lower finer portion of such bars shows a better degree of sorting than the poorly sorted upper deposits. Ore (1964) included such evidence in his criteria for the recognition of braided-stream deposits.

Lithofacies B - Cross-stratified Conglomerate

Inclined bedded conglomerate sheets occupy the shallower portions of many channel shaped depressions and grade into both channel fill conglomerates and the single and multiple sheet varieties. The conglomerates are characterised by finer grain sizes generally, and a low to moderately steep inclined bedding with grain size variations both parallel and perpendicular to the inclined laminae such that individual laminae fine upwards perpendicular to the bedding and also fine upwards along the individual laminae (see Fig. 3.3). Sorting is moderate and increases away from the channel base, and away from the channel fill conglomerate. A higher proportion of matrix is present, resulting in significantly lower packing densities, framework supported fabrics are rare, but not totally absent.

These conglomerates may pass sharply into single sheet conglomerates, or multiple sheet conglomerates, the latter case being by far less common, such passages occurring in a direction away from the channel. Within the channel area Lithofacies B conglomerates are often overlain by either irregularly bedded gravels, or cross-stratified gravels.

Lithofacies C - Single Sheet Conglomerate

Single sheet conglomerate occurs immediately overlying a planar erosion surface which is sometimes cut by deep conglomerate filled scours. Single sheet conglomerates are characterised by a lack of internal bedding, but often show either fining upward or more interesting reverse grading. The conglomerates are frequently finer grained than many of the channel varieties and show a relatively low packing density, although still generally higher than Lithofacies B. Poor sorting is typical although graded portions show a variation in this parameter, finer portions being better sorted than the coarser. Sorting within the coarse mode of Lithofacies C is better than in the previous examples.

Lithofacies C is always erosively based and always overlain by irregularly bedded gravels or multiple sheet conglomerates. Laterally such sheets may persist for tens of metres and become lost due to lack of exposure; many cases demonstrate a clear relationship to channel deposits where a lateral decrease in grain-size is apparent away from such a channel.

Lithofacies D - Multiple Conglomerate Sheets

Multiple conglomerate sheets with restricted lateral extent occur in laterally persistent thick units. Such conglomerates follow all previous deposits by rapid gradation, but never erosively. Internal bedding is poorly developed and generally of no great lateral persistence, although small scour and fill structures are common, as is very low inclined planar cross-stratification.

Clast size is small, but well sorted with regard to the coarse mode. Overall sorting is poor, the matrix generally containing abundant gravel. No apparent relationship exists between unit thickness and maximum clast size, although this is discussed at a later stage (page 165). Lithofacies D includes the bulk of subfacies B1 sediment.

Lithofacies E and F Cross Stratified Gravel.

Lithofacies E and F are related in that both occur in the higher, finer portions of fining-upward units and also frequently occur at similar horizons.

In areas overlying channel deposits a low cross-stratification is developed with grouped sets up to 20 cm deep and 1 m wide common. Laterally these may become larger and often solitary sets up to 60 cm deep are found. Such forms are several metres wide and tend to become more planar in form. Such cross-stratified sets develop in gravels ranging from poor to well sorted, the larger varieties occurring in the better sorted sediments. Pebbles do occur in foresets, but are uncommon constituents in such deposits.

Lithofacies G - Sandstone

Sandstone is rare within these deposits and when present is rarely persistent for any great distance. The grain-size ranges from medium to coarse, the sediment being moderately well sorted. No internal bedding has been recorded from such deposits.

Variations

Certain variations do occur, but tend to be structural variations rather than the introduction of a new grade of detritus, for example, as a final channel infill, the multiple-conglomerate or gravel sheets may develop as curved surfaces mirroring the original channel shape, and causing an infilling of the channel form in which the final channel form is deflected towards the deeper portion of the original channel (see Fig. 3.4). Fig. 3.4 also shows that coarse poorly-sorted conglomerate may occur in positions adjacent to the channel fill varieties, appearing as 'bars' overlying planar erosion surfaces.

3.3(i)c Interpretation

Structural Variability within Subfacies B1a

Within the conglomerate facies channelling is ubiquitous, and a maximum recorded depth of 1.5 m may be a reasonable approximation of maximum channel depth. More commonly channels are less than 1 m deep, with widths in the order of 25 m, giving an average width/depth ratio in excess of 25:1. Erosion surfaces change in form laterally and may commonly pass into non-eroded junctions and illustrate the restricted extent of many channels, drawing attention to the frequent proximity of erosion and deposition, (the latter being an important factor which must be taken into account when bed thickness is used as a measure of capacity or competence, see page 165).

Abundant scouring exists indicating that channelling is important (Moody Stuart, 1966) while low relief terraces indicate successive margins of shallow channels cut during the falling stages of stream flow (see also Krigstrom, 1962, Doeglas, 1962, and Williams and Rust, 1969). Channels appear to migrate by distinct steps rather than by gradual changes, and therefore lateral accretion deposits are unimportant. Although not directly comparable, Moody-Stuart (1966) concluded that a significant feature of low sinuosity stream systems was the development of channel fills by vertical accretion rather than by lateral migration and accretion.

Coarsening upwards and fining upwards units do occur and may record periods of increasing and decreasing competence of flow during accumulation. Coarsening upward units are commonly found in close proximity to channel conglomerates and occur within short vertical distances of planar erosion surfaces. Laterally these sequences gradually fine and are replaced by irregularly bedded gravels and coarse sandstones, often with a low internal cross-stratification. Internal bedding is rare in all coarsening upward units, but when recognised is always of very low angle. Such relationships may record the downstream migration of longitudinal bars, (Doeglas, 1962, Leopold and Wolman, 1957, Bluck, 1971). Longitudinal bars have a downstream reduction in grain size and consequently their downstream migration results in the movement of coarse sediments over fine (see Bluck, 1971, and Smith, 1974). It is interesting to note that in dealing with the problem of paleocurrents around longitudinal bars Rust (1972a) illustrates a model of bar and channel section showing many features typical of sections recorded at Gamrie (see Fig. 3.5). During high flood stage coarse detritus is transported and dumped at certain sites, any initial grouping of such tends to preserve the concentration and promotes the formation of a gravel bar (Leopold et al 1964, and Raichlen & Kennedy 1975). At lower flow stages water movement is concentrated into channels and slight lateral adjustment is likely, presumably the stage when terracing occurs. Accompanying this lateral divergence of flow, finer sediment accumulates at bar margins and builds outward to form sets of high-angle cross-strata (Rust, 1972, Smith, 1974). Rust (op cit) goes on to describe ultimate stages of ripple development and suspension fallout, the latter he adds occurs rarely or never in active channels. Such deposits are never recorded in subfacies B1 deposits. Similarly Schumm (1961) found that in streams with ephemeral flow aggradation may begin at localised points, and as the channel fills the zone of major deposition migrates up stream causing two distinct deposits, (a) coarse sediment overlying fine upstream, and (b) fining sequences downstream.

Thus it seems possible that channel development may be related to bar development, or simply ephemeral stream flow. Trough cross-stratification is limited in all cases to small restricted examples within finer gravel fills to channels. Larger examples occur, but are very rare, thus suggesting a preponderance of longitudinal bars over transverse bars as the latter would be expected to produce significant contributions of either trough bedding or planar cross-stratification recording avalanching down lee faces of migrating curve or straight crested dunes. Such a dominance of longitudinal bars implies a proximal site of deposition with associated implications of higher paleoslopes.

Smith (1970) substantiated Ores (1964) conclusions that braided patterns are created mainly by accretion of longitudinal bars, and dissection of transverse bars, noting that coarser poorly sorted sediments favoured the development of longitudinal bars.

Lithological Variability within Subfacies B1a

The coarse nature of the conglomerates plus their common internal planar bedding is indicative of high velocity competent flows (Nevin, 1946, Helley, 1969, Fahnstock, 1963). A direct evaluation of current flow cannot be made (but Eynon and Walker, 1974, demonstrated that with certain assumptions an order of magnitude may be determined), although data from modern streams suggests that larger clasts may only be moved during flood conditions. Leopold et al (1964) suggest that even so large floods may be incompetant at moving large clasts and that small surges may be more effective, or the initial and falling stages of major flood.

A large amount of coarse detritus is present in the facies described implying that the environment was probably quite proximal and of relatively high slope. Floods must have occurred frequently being controlled by the high slopes and vegetation deficiency (Schumm, 1961). High flow conditions are verified in the presence of cross-stratified conglomerates (Simons et al, 1961). Pebbly sandstones and sandstones retain a horizontal or massive stratification in most instances and may record lower flow velocities (Helley, 1969, Fahnstock, 1963) but only if a source of coarse detritus was always present; as pebbly lithologies interbed with coarse conglomerates a coarse clast source is assumed to have always been present. Siltstone is notably absent except at the very highest levels (in the overlying sandstone facies) at a position where the transition into the Siltstone Facies is initiated. In braided river systems on alluvial fans siltstone is only recorded in low energy areas (Doeglas, 1962), normally being removed by the lateral migration of channels and bars (Krigstrom, 1962). In the present situation the lack of siltstone is probably a function of non-deposition on originally high paleoslopes rather than deposition and subsequent removal, as the evidence at hand does not indicate that the channel systems suffered major lateral shifting in all but a few cases.

Textural Variability within Subfacies Bla

Several aspects of conglomerate bedding and textures have recently been studied by Bluck (1967) in an attempt to evaluate more precisely the genesis of alluvial conglomerates. In the Gamrie Outlier outcrop prevents the widespread application of such techniques, but reasonable exposure of the Subfacies Bl sequence allows such a study to be made. Primarily, Bluck (op cit) attempted to evaluate flow-power and discharge by considering easily measured parameters such as bed thickness and grain size. Several authors (Nevin, 1946, Hjulstrom, 1939 , Fahnstock, 1961) have already used values of maximum particle size as an expression on minimum flow velocity, and hence competence (Fahnstock op cit). For example, tractive force, recorded by the relationship between maximum particle size and ground slope was considered by Lustig (1965) as an alternative measure of flow velocity. In Blucks (1967) studies maximum particle size was considered in relation to be thickness; a parameter regarded as indicative of the discharged sediment load, (this assumption must be supported by field observation with evidence of the lack of erosion and reworking, before bed thickness may be regarded as recording the magnitude of a depositional event).

Fig. 3.6 illustrates the data obtained from Subfacies Bl. No significant correlation is apparent. The distribution compares favourably with Blucks (1967) figure 8, - fluvial channel deposits, a situation where neither maximum clast size or bed thickness are regarded as reliable indicators of competence or discharge.

Throughout Subfacies B1a clast packing and sorting are as variable laterally and vertically as are grain size and structure, indicating that the processes of winnowing and lagging clearly operated to quite different degrees on closely associated sediments. The common occurrence of moderate to good clast packing associated with some imbricate developments suggests the attainment of a moderate degree of textural maturity (Bluck, 1967), but a comparison with many associated horizons clearly demonstrates that such processes were limited in their distribution. The presence of poorly-sorted conglomerates implies that a whole range of sediment grade was available for transportation at times, and the preservation of such a spectrum of detritus may suggest that deposition in such sites was rapid. Rapid reductions in flow velocities are typical of many ephemeral streams where high percolation causes floods to be of short duration (Leopold and Miller, 1956). Size sorting is variable in both conglomerates and sandstones and is indicative of diverse depositional environments. At times the stream system had the potential for considerable reworking, while at others it could not separate sand and gravel grades.

A reconsideration of Fig. 3.6A with the grouping of data with regard to clast packing, sorting and shape of the deposit leads to the clear distribution of Fig. 3.6B.

Good correlation is observed only in the conglomerates of group A, single sheet conglomerates. The deposits are distinguished on the grounds of their lateral persistence but only minor associated erosion. Bed thickness is very restricted, but clast size shows a great spread. Clast sorting is poor overall, but good within the coarse-mode. Packing is variable, moderate to good..

Group B conglomerates, channel conglomerates, are distinct in the association of erosive units, coarse grain sizes, poor sorting, but good clast-packing.

Group C, multiple-sheet conglomerates, are also distinct in their small clast size, very poor overall sorting, but good sorting of the coarse mode, lack of erosion, internal bedding and very poor clast-packing.

In single-sheet conglomerates A bed thickness correlates with average maximum particle size implying that coarser detritus may only be transported during larger flood events when stream power is high enough. Unit thickness correlates with stream competence suggesting that either more powerful flood events discharged larger volumes of detritus or that the more competent flows were more persistent events.

Texturally two separate modes exist, a coarse tractive-mode and a finer-mode presumably transported within the tractive-mode and also in suspension (Bluck, 1967). In comparison to the channel deposits considerable suppression of the coarsest material occurs, and is enhanced by the distribution of maximum clast sizes being skewed towards finer grades. The competence of the system must have been such that restricted coarse mode transport was possible, and was associated with considerable transport and deposition of sand-grade detritus while at the same time winnowing of fine sediment was only localised.

Bed thickness is notably reduced, and may provide information as to the flow depth as Bluck considers that reduced water depths cause a reduction in the thickness of the traction carpet and hence a reduction in conglomerate thickness. The sparce framework developments point to periodic reworking of fine detritus as competence declines. The magnitude of the fine population is normally high, and high concentrations of sand would reduce the critical shear on the bed (Bluck, 1967); this would serve to enhance the smaller pebble grades as much of the streams' energy would be occupied in sand transport.

Bar top environments (see Eynon and Walker, 1974) provide suitable conditions for the development of such deposits, having reduced water-depth and also, being inundated during flood episodes only, they provide a situation where suspended load is high also. Normal and reverse grading have been noted, reverse grading being a common feature of the downstream migration of coarse detritus over fine in longitudinal bars.

Channel conglomerates B show a less well-defined correlation between competence and discharge presumably due to the failure of one or both parameters (i.e. maximum clast size and bed thickness) to record competence or discharge. Understandably, thickness relates to total channel depth, and not to individual discharge events, whereas maximum clast size will give some idea of competence although selective removal of finer grades will enhance this value. Competence is thus recorded as the maximum competence over a long period of time.

Framework supported conglomerates are patchily developed, and demonstrate that deposition was pulsatory, with reworking taking place during depositional pauses (Jopling, 1964). Augustinus and Reizebos (1971) record similar variations in outwash plain deposits, while Bluck (1971) described well-packed conglomerates from deposits of meandering streams.

As particle size correlates with bed thickness, and bed thickness generally indicates channel magnitude, the evidence would seem to imply that channel magnitude would increase towards source, as particle size is regarded as increasing towards more proximal locations. This inference is considered false, thus pointing to the invalidity of one or both of these parameters.

Erosion surfaces form the base of channel units, and may be traced laterally and are observed to be equivalent to adjacent channel erosion surfaces. To some extent this suggests that a network of channellised flow was operating. Braided streams are known to function on alluvial fan surfaces (Hoppe and Eckman, 1964), generally in distal positions. The present situation appears to be one of a network of low-relief channels separated by large longitudinal bars over which sediment was distributed only during flood events. Flow may have been more permanent in channel areas allowing winnowing and reworking to continue; flow was of greater competence overall, presumably due to increased flow depth. Poorly sorted channel conglomerates may record sudden depositional events, for example, percolation of water into the substrate is a common phenomena in ephemeral streams, and results in the rapid deposition of poorly-sorted conglomerate. In contrast, reworking would occur in such channel areas when lower flow powers prevailed due to the transition from braided to meandering stream systems during low-discharge phases (see Fahnstock, 1963).

Multiple sheet conglomerates C show no relationship between maximum clast size and bed thickness, and therefore one or both of these parameters must not approximate to competence or discharge. To a large extent clast size is considered to reflect competence, but the internal bedding within such conglomerates records periodic lagging, due to reworking of finer grades, and thus bed thickness records a sequence of depositional events and not simply one discharge. Local developments of good clast-packing confirm limited reworking as the large fragments resist movement whilst fines are winnowed.

The slight bias in the maximum clast size distribution towards coarser deposits does add further evidence to the notion of winnowing of smaller pebbles. Bluck (1967) noted that during periods of high discharge streams pick up large amounts of sand from the stream bed in preference to coarser grades. The more sand eventually in suspension, the more energy expended in transportion of this load, and thus by reduction of the critical shear stress acting on the bed only finer grains can be moved. This phenomena would explain the abundance of sand and finer gravel, and the well-sorted nature of the coarse mode. The suppression of coarse detritus may thus be due to decreased competence, magnitude of suspended load etc.

Environmentally the multiple sheet conglomerates are considered to represent a lower energy environment, although their common association with cross-stratified gravels does suggest relatively high flow powers. Multiple conglomerate sheets probably record what is effectively the 'braided stream floodplain', being inundated only during large floods, but not forming an active migrating part of the braided stream system. The sequence accumulates principally by vertical accretion, and may be analogous to either side-channel or shallow braided environments described by Eynon and Walker (1974). Low-angle planar erosion surfaces, with impersistent granule and gravel lags, also bear features similar to deflation structures (McAlpine, 1978), and may support the notion that these deposits are formed on an inter-channel area, exposed for long periods.

Overall the structure and textures described imply frequent attainment of high velocity flows, which in turn imply that deposition took place on or near to steep slopes, (Leopold and Wolman, 1957, Chien, 1961, Brice, 1964) and support the idea that these streams, braided at time, operated on alluvial fans adjacent to the Caledonian Mountain front.

The poor-sorting recorded in many of the conglomerates may be a result of rapid aggradation and bar and channel migration commonly found in modern braided systems (Doeglas, 1962, Fahnstock, 1963, Shantzer, 1951, Chien, 1961, Krigstrom, 1962).

3.3(i)d Summary and Discussion

The sediments are red, coarse-grained, and have textures and structures including cross-stratification and channelling of fluvial type. The presence of poorly-sorted coarse grained deposits with abundant high velocity structures implies deposition mainly of bed-load material from strong turbulent traction currents (Sundborg, 1956) and probably on a moderately high slope (Fahnstock, 1963, Rust, 1972a). Paleocurrent data is sparse and cannot be used to imply unimodal sediment transport directions although the sparse data available does suggest a rather limited spread (Chapter 4). Fluvial systems belong to a series (Schumm, 1963) the end members of which are high and low sinuosity streams (see Brice, 1964), the low sinuosity member often being braided. Different physical conditions operate in these end member situations and it should therefore be possible to characterise the two different types of deposit and thus determine the stream type dominant in the rocks described, compare Doeglas (1962), Williams and Rust (1969), Smith (1970), with Frasier and Osanick (1961), Harms et al (1963), McGowen and Garner (1970), Bluck (1971). Deposits of subfacies B2 show a marked lateral and vertical variability of lithology, texture, and structures indicative of a stream system capable of responding rapidly to changes in flow conditions such as water depth/velocity relationships, competence and discharge. The great variability of grain size implies that not only were such fluctuating conditions frequent, they were also extreme and spatially and temporally highly variable. Lateral and vertical changes in textural maturity confirm the variability of the system, inferring a varying capacity to rework the sediment. Such features are typical of modern low-sinuosity streams in which great velocity fluctuations are recorded with similar variations in competence and discharge (Krigstrom, 1962, Doeglas, 1962, Williams and Rust, 1969, Smith, 1970, Collinson, 1970) but are typical of the high-sinuosity stream types with their quasi-cyclic sequences of sediments and relatively uncommon fluctuations in velocity and discharge which rarely reach extreme values.

Perhaps due to the complexities involved "the braided model is poorly developed" (Eynon and Walker, 1974) and examples tend to relate specifically to individual cases. Generalisations are restricted to the following indicators of proximal positions. Proximal deposits have a very low proportion of fine-grained sediments partially due to their non deposition on high slopes but also related to their low preservation potential amidst the actively migrating channel and bar systems. Coarser grain sizes are more abundant in more proximal situations whilst horizontal stratification also predominates over cross-stratification more typical offdistal reaches.

Longitudinal bars dominate over transverse bars in proximal situations and the bed relief index increases towards the source, (Eynon and Walker, 1974, and see Krigstrom, 1962, Ore, 1964, Williams and Rust, 1969, Collinson, 1970, Smith, 1970, Rust, 1972). The marked lack of overbank sediment alone has been used to imply low sinuosity braided systems (Doeglas, 1962, Williams and Rust, 1969, Smith, 1970) where, due to higher slopes, coarser material is transported and fine overbank deposits are inhibited. Yeakel (1962) points out that meandering streams suffering only slow aggradation may comb across their floodplains and thus remove fine grained deposits. Sequences of bedforms are grossly dissimilar in such meandering deposits (Smith, 1970) and the lateral variation alone in the present examples precludes such a mechanism.

As detailed in later chapters the sediments studied are inferred to have a marginal position in the Orcadian Cuvette and were thus in close proximity to the rising Caledonian Mountain Chain. Alluvial fan deposits would therefore be expected in such a situation and have been recorded from other marginal sites (Mykura, 1975 pers comm., Stephenson, 1972). As previously considered alluvial fan processes are characterised by three dominant mechanismsof deposition, i.e. debris flood, streamflood, and sheetflood. Subfacies B2 deposits are attributed to more fluid type of process than the debris flood and sheetflood mechanism described for subfacies A2 at Crovie. The abundance of channel forms and broad erosion surfaces suggest that processes operating were more permanently established. The fluid nature of the processes is evident from the abundant record of winnowing, reworking and various transport processes involved. The complex structures and lateral relationships exhibited by this facies are more consistent with stream channel and stream flood deposits rather than sheetflood processes (Blissenbach, 1954, Bluck, 1964, 1965), but the predominant vertical accretion and re-activation strongly implies that such stream flood events were of an ephemeral nature.

3.3(ii) Subfacies Blb (Plates 1.8, 1.9).

3.3(ii)a Introduction

Subfacies Blb, represented by the Pennan Head Conglomerate, is a relatively thick sequence of conglomerates, conglomeratic sandstones, and sandstones. As noted in Chapter 1 much of the Central Coastal Section is quite inaccessible and in this instance only the upper portion of Subfacies Blb can be observed in any detail and therefore it must be stressed that much of the following facies description is somewhat generalised.

3.3(ii)b Facies Description

Throughout the sequence five lithofacies have been recognised:

(i) poorly-sorted conglomerate,

(ii) moderately well sorted conglomerate,

(iii) well sorted conglomerate,

(iv) conglomeratic sandstones,

(v) sandstones.

The sequence of conglomerates and sandstones in many ways resembles the deposits of Subfacies Bla in that a wide range of sediment grade is present showing an equally wide range of sorting and texture.

Poorly-sorted conglomerates are most abundant in the lower portions of the sequence, they show the widest range of sediment grade and occur in thick laterally inconsistent units. Sediment grade ranges from fine sand to cobble grade, with grain size being skewed toward finer sizes leaving coarser detritus generally floating in a matrix of sand and gravel. The conglomerates are impersistent laterally, and frequently show features such as erosion surfaces and poorly developed cross-stratification. These are the most variable deposits of the subfacies, but being predominant in the lower portion of the sequence they are unfortunately the least well exposed.

Moderately well sorted conglomerates occur in quite thin sheets, and are laterally persistent. Small scours may be present on the basal surface, but larger erosion features have not been observed, other than the probability that very broad discontinuities exist between adjacent conglomerate sheets. When such conglomerates are abundant in the sequence, discontinuities are more readily apparent. The moderate sorting is apparent as a separation of the coarse and fine modes, with each mode being relatively well sorted. The fine mode comprises sand with a high proportion of gravel, while the coarse mode is restricted to pebble and cobble sized fragments.

Well sorted conglomerates occur in the highest parts of the sequence, and occur due to a considerable reduction in the fine population. The conglomerates show an abundance of pebble grade material forming a framework to the conglomerate and supporting a fairly abundant cobble population. Sand and gravel, although considerably reduced are still present. Well sorted conglomerates only occur in relatively thin sheets, they show no apparent erosive relationships to adjacent sediments (or, erosion has occurred over broad planes in each instance), and individual conglomerates are laterally persistent and consistent.

Conglomeratic sandstones are recognised as fairly thick units of medium and coarse sandstone with frequent impersistent conglomerate strings, and an abundance of gravel grade sediments. In many respects the conglomeratic sandstones of subfacies B1b are very similar in appearance to the 'multiple conglomerate sheets' of subfacies B1a . Such a similarity may be significant as the deposits most commonly occur in association with poorly-sorted conglomerates also quite similar to the conglomerates of subfacies

Sandstones are always thin, coarse grained, and generally lacking in structure. They are most frequent in association with conglomeratic sandstones and are either internally massive or show a crude horizontal bedding. Sandstones usually appear to grade from underlying conglomerates rather than showing distinct break in sedimentation.

3.3(ii)c <u>Interpretation</u>

As mentioned, the sediments of Subfacies B1b are closely comparable to those of Subfacies B1, and are thus interpreted in a similar manner. A comparison is considered as follows:

Lithofacies 1 - comparable to some channel and single sheet conglomerates of Subfacies B1.

Lithofacies 2 - closely comparable to single sheet conglomerates.

Lithofacies 3 - comparable to conglomerates in the overlying Subfacies B5.

Lithofacies 4 - very closely comparable to the multiple sheet conglomerates of Subfacies B1.

Thus Subfacies B1b is comprised deposits formed in bar-top and ephemeral stream channel environments, with progressive introduction of Subfacies B5 conglomerates representing more permanent braided stream episodes.

Thus in summary the deposits of Subfacies B1b are considered to have formed due to the vertical accretion of longitudinal bars in a shallow braided stream environment.

3.3(iii) Subfacies B2a (Plates 3.6, 3.7, 3.8)

3.3(iii)a Introduction

Subfacies B2a (the Castle Hill Sandstone Formation) outcrops to the west of Gardenstown Village towards the Den of Findon. The sequence is gradational, being sandstone dominated overall, but increasing in sediment-grade with rising stratigraphic level.

The sequence has been divided into two members:

a) a lower member dominated by cross-stratified sandstones,

b) an upper member dominated by conglomeratic sandstones.

3.3(iii)b Facies Description

The lower member comprises thick red sandstone units resting with sharp erosive bases, initially on brown siltstones or red mudstones, but more commonly (and particularly with rising stratigraphic level) upon previous sandstones. The sandstone units attain thicknesses in the order of 200 cm max., with cross-stratified portions in the order of 70 cms.

The sharp sandstone bases are generally smooth channel-shaped surfaces and may occasionally show small pebble-filled scours. This surface is commonly overlain by coarse sandstone or medium sandstone containing pebbles, cobbles, and often abundant red and brown mudflakes. Rarely, the basal sandstone portion may show flat bedding.

The main portion of the sandstone member consists of fine to medium grained cross-stratified sandstone. Trough and planar cross-stratification have been identified. Occasional clay drapes occur in the cross-stratified portions, but generally grain size shows no reduction until at highest levels where wavy or poor cross-lamination develops. Rarely, ripple-lamination or climbing-ripple lamination may be preserved in these highest, finest portions. Small scours infilled by coarse detritus have also been recorded in the highest parts of cycles. In many instances particularly at higher levels in the sequence, convolute-bedding is common in the cross-stratified portion of the cycle.

In the lowest portion of the sequence cycles are capped by red mudstone or brown siltstone, these deposits being generally quite massive, Desiccation cracks have not been recorded, and in contrast to the coarse fine sediment alternations of Subfacies C4 carbonate nodules are conspicuously absent. At higher levels in the sequence such fine deposits no longer occur.

The upper member contrasts strongly with the lower member in many ways; principally, coarse sediment predominates with red medium-grained sandstones occurring in laterally persistent sheets and containing abundant pebble grade conglomerate sheets and lags overlying frequent scoured surfaces.

Cross-stratification is rare, being only preserved as planar or 'avalanche front' cross-stratification infilling deep scours. Bedding is in most cases only apparent as pebble and gravel strings, the remainder appearing massive or irregularly bedded.

Although fine sediment is totally absent from this part of the sequence, mudflake conglomerates still occur, and often with abundant mudclasts. (Plates 3.6, 3.7).

Deep channelling has been observed in one instance, displaying steep cut banks and collapsed, re-worked bank material. (Plate 3.8c)

Interpretation

By comparison with modern alluvial sediments (see Allen, 1965a) the deposits are regarded as being fluviatile in origin, and although the existence of 'cycles' is based on a small amount of evidence, the apparent fining upwards sequences with coarse and fine-members in alternation may record the establishment of some kind of channel system (coarse units) and its subsequent burial beneath a floodplain (fine units). Such cycles have been considered by many authors, and attributed by Allen (1962b, 1965a,b), Allen and Tarlo (1963), and Allen and Friend (1968) to factors intrinsic to the fluvial regime, i.e. the autocyclic factors of Beerbower (1964).

The thick sandstones with large scale cross-stratification probably record the establishment of channelled flow with associated basal scouring and overlying coarse lag deposits. The sets of large scale cross-stratification presumably represent the deposition of bedload sediment by migrating subsqueous dunes during the main flood episode, while clay drapes and interbedded ripple-laminated sediment represent deposition during low flow stages. Ponded-water conditions would be necessary for the deposition of thick siltstones and mudstones in the lower part of the sequence. Such a situation compares favourably with that described by Harms and Fahnstock (1965) from recent fluvial sediments.

Several important features must be noted with regard to the interpretation of these deposits:

1. Initially (lower member) the sandstones occupy distinct channel-shaped bodies, no lateral accretion is apparent. Upward fining of grain-size is not gradual, but cross-stratified sandstones are overlain by finer ripple-laminated sandstones. For this reason, the system was probably of low sinuosity, and initially comparable to the system described in lithofacies association C5 (the West Harbour Formation). Where sediment is considered to have been distributed by a series of shallow ephemeral channels which eventually choked to be overlain by finer 'floodplain' sediments.

2. With rising stratigraphic level, ripple-laminated sandstones and siltstones become scarce, and the sequence becomes dominated by cross-stratified and massive sandstones. At this level, the sequence is considered to represent the replacement of low sinuosity ephemeral channels by more normal braided channels. There is insufficient evidence to indicate whether such a system was also ephemeral, but a consideration of succeeding and preceeding (ephemeral) deposits would suggest that these also were.

3. In the uppermost part of the sequence (the upper member) cross-stratification is very rare and the sediments show many features comparable to those of Subfacies B1, particularly the multiple conglomerate sheet type of deposit. Small 'choked' channels confirm

the local periodic transport of sediment and indicate the ephemeral nature of such channels. The environment is considered closely comparable to that of Subfacies B1 where shallow low-sinuosity ephemeral stream channels crossed a distal alluvial fan surface, at times choking and splaying sediment in sheets across large 'bar-top' or interchannel areas.

3.3(iv) Subfacies B3 (Plate 1.9)

3.3(iv)a Facies Description

Subfacies B3, the Need Haven Conglomerate, succeeds a previously considered Subfacies B1b in the Central Coastal Section by rapid vertical gradation. The subfacies is unique in the sequence in that although it is not extensively developed it is dominated (99%+) by quartzite-rich well sorted conglomerate.

The well sorted conglomerate apparently occurs in one thick unit, only two thin sandstone units have been observed breaking up the sequence. The sediment ranges from small boulders to sand, but is dominated by cobble-grade material. The paucity of fine grades ensures that a framework is developed throughout, and this framework has a minimum of sand and gravel as matrix filling giving the conglomerate a high packing density.

As mentioned, bedding is indistinct as sandstones are extremely rare in the sequence and conglomerate grade, sorting and texture do not vary appreciably through the short sequence. The subfacies develops as an extension of subfacies B1b by rapid increase in the content of well sorted quartzite-rich conglomerates common in the upper portion of subfacies B1b Similarly the subfacies declines very rapidly and is replaced by subfacies B1c by replacement of the well sorted conglomerates by less well sorted granite-rich conglomerates and conglomeratic sandstones (further consideration of the significance of these composition changes is given in Chapter 4).

3.3(iv)b <u>Interpretation</u>

Interpretation of such coarse grained deposits is generally quite difficult as most previous studies of fluvial conglomerates have concentrated upon systems transporting finer grades of sediment. Recent environments in which coarse detritus has been transported have been described by McDonald and Banerjee (1971), Martini and Ostler (1973), Gustavson (1974), and Boothroyd and Ashley (1975), and it is readily apparent from such studies that a major difference between rivers carrying coarse rather than fine loads is the failure of systems carrying little sand to develop discrete bedforms. In pebble/ gravelly systems, longitudinal bar formation is predominant with coarse loads transported in deeper channels (Boothroyd and Ashley, 1975), while deposition takes place over bars where competence is reduced due to a reduction in water depth. Such longitudinal bars are large features, but of low amplitude and therefore result in very low depositional dips. The lack of apparent bedding in the conglomerates of subfacies B5 is consistent with such an origin, as bar development occurs by clast by clast accretion, fines being eventually trapped or filtering into the small matrix cavities. Clast supported conglomerates would be expected from such environments, and the mechanism of bar development would not be conducive to the development of a well defined internal bedding unless other processes such as low-water accretion or flood stage fluctuations in velocity occurred.

The overall consistency of the conglomerates of subfacies B5 suggests that flow conditions remained uniform for long periods of time, and even when rare conditions permitted the deposition of thin sandstone units a return to conglomerate deposition apparently meant a return of previous depositional conditions. Such interbedded sandstones are presumably a result of low-water accretion processes. Miall (1977) has noted that a multitude of 'subfacies' may develop during low-water stages. Most of these would involve modification of the bar surface and would consequently leave a record of such in suspension deposits, minor channel developments, bar front accretion, or reactivation surfaces. Smith (1971, 1972) described the development of low amplitude sand waves forming in shallow water over bars and resulting in the development of almost horizontally bedded sands. The thin sandstone developments are presumed to be of such an origin.

3.4 Piedmont Floodplain/Playa Megafacies (c)

3.4(i) Introduction

Three subfacies comprise the Piedmont floodplain/Playa Megafacies and are represented by:

Subfacies Cla - Crovie Siltstone Formation

Subfacies Clb - New Aberdour Siltstone Formation

Subfacies Clc - East Harbour Formation

Subfacies C2 - Crovie Sandstone Formation

Subfacies C3 - West Harbour Formation

Subfacies C4 - Dundarg Castle Sandstone Formation

Subfacies Cla, b and c are closely comparable in form and interpretation, but occur widely separated; Cla and Clb separate in distance, Cla and Clc separate in time. In the following section subfacies Cla, b and c have been considered as one broad subfacies, with specific details added where relevant.

In recent environments, the Piedmont floodplain/Playa situation may be very complex in form, a feature also reflected in the present examples. Subfacies Cl is considered to represent the Piedmont floodplain *sensu-stricto* being quite distinct and remote from the adjacent but distant alluvial fan complex. Sufacies C2, C3 and C4 are complex in that they are considered to represent marginal floodplain sites and bridge the gap between true floodplain and alluvial fan deposits. These latter two subfacies are regarded in many ways to be similar to modern 'Oueds' (ephemeral stream channels) and represent the transport of sediment from the distal alluvial fan onto the marginal floodplain surface.

3.4(ii) Subfacies C1 (1a, 1b, 1c) (Plates 1.4, 1.5, 1.17, 1.18)

Throughout the three representatives of subfacies C1, the sequences are comprised alternations of the following lithofacies:

(i) Siltstone,

(ii) Sandstone,

(iii) Laminated Mudstone,

(iv) 'Wavy-bedded' Sandstone and Siltstone

3.4(ii)a Vertical Facies Relationships

Lateral persistence of lithofacies is perhaps the most striking feature of Subfacies C1, a feature which makes evaluation of vertical sequences quite a simple matter. As shown in the lithoprofiles of the representative sections (Figs. 3.7, 3.8, 3.9) the sequence consists essentially of alternating coarse and fine members. In the Crovie and New Aberdour examples (subfacies C1a and C1b) the coarse member consists entirely of interbedded sandstones and siltstones alternating with relatively thicker siltstone units.

At Crovie, the sequence (being gradational from the underlying sandstone-dominated subfacies C2) initially contains a large amount of thin sandstone units, whereas at higher levels, namely the Middle and Upper Crovie Siltstone Members (shown in Fig. 1.12) the lithological content of the sequence is reduced to simple alternations of two lithofacies, siltstone and thin sandstones.

Figs. 1.12, 16, 17, 46 are typical field-logs from the three sequences, and they demonstrate that siltstone units are wholly massive and very thick. Thin siltstones are rare, but may occur in alternation with thin sandstone developments. Sandstones are fine grained, grey, micaceous, and always have sharp or slightly erosive bases. Internally, ripple cross-lamination is common, but may be replaced laterally or vertically by massive or flat-bedded sandstones. Flat-bedding may replace ripple-lamination in graded fining upward units. The initial phase of ripple-lamination may also be replaced rapidly by climbing-ripple/lamination, again generally in fining upward units.

The basal portions of siltstone units frequently contain very thin sandstone sheets or lenses comparable in form to lenticular bedding described by Reineck and Wunderlich (1968). Desiccation features are abundant within these deposits, and can often be easily dated as occurring between successive events depositing sand, and also following the deposition of the thin sand sheets or lenses in the siltstone units.

Although the siltstone portions of the sequences are regarded as forming thick units (i.e. 90 to 570 cm in the Middle Crovie Siltstone Member) the removal of part of the gravel beach at Crovie due to storms indicates that on freshly scoured surfaces internal bedding is readily discernable, being picked out by either subtle grain-size changes, or desiccation events. Individual silt units were measured to range from 1.5 cm to 21 cm, averaging 5.6 cm, and are probably a record of individual flood events.

3.4(ii)b Sedimentation Trends

Subfacies Cla

Lithological Trends

The litholgical trends already noted for subfacies C2 continue into subfacies Cla. Towards the top of subfacies C2 siltstone is noted to continue at the expense of declining amounts of cross-stratified sandstone units. In the lower part of the subfacies Cla sequence siltstone dominates and occurs in conjunction with minor amounts of 'wavy-bedded' sandstone and siltstone, and small amounts of sandstone and laminated mudstone. With rising stratigraphic level the wavy-bedded sandstone and siltstone and laminated mudstone deposits cease to occur.

Thickness Trends

Only siltstone units show any significant variation in thickness with time. In the lower portion of the sequence average siltstone thickness is low (c. 30 cm), upon removal of wavy-bedded sandstone and siltstone and laminated mudstone from the mid and upper parts of the sequence siltstone thickness increases dramatically to c. 220 cms. before declining again to c. 120 cm at the top of the succession.

Subfacies Clb

Lithological Trends

In subfacies Clb no vertical lithological trends are apparent although the introduction of cross-stratified sandstones towards the top of the sequence does indicate that the Piedmont plain may have been repeatedly traversed by small but persistent channels. The development of a thick dark laminated mudstone also suggests that temporary lakes may have developed in more distal floodplain sites.

Thickness Trends

Temporal variations in lithofacies thickness are not distinct in the major portion of the succession (Fig. 3.10.) although at highest levels a sudden increase in siltstone thickness occurs temporarily.

Subfacies Clc

Lithological Trends

Subfacies Clc shows no temporal changes in lithofacies content although significant changes in abundance of lithofacies does occur. Principally, the sequence suffers a coarsening upward trend in which siltstone, initially abundant (59%) is gradually replaced by increased amounts of wavy-bedded sandstone and siltstone, and sandstone, i.e. wavy-bedded sandstone and siltstone 33% to 48% and sandstone 2% to 20%.

Thickness Trends

The above noted variations in lithofacies content are accompanied by:

(i) a decrease in thickness of siltstone units,

(ii) an increase in the number and thickness of both wavy-bedded sandstone and siltstone, and sandstone beds,

(iii) siltstone bed thickness decreases from c. 112 cm to 45 cm,

(iv) sandstone increases from c. 5 cm to 9 cm,

(v) wavy-bedded sandstone and siltstone decreases in thickness from c. 110 cm to 47 cm.

The increase in abundance of wavy-bedded sandstone and siltstone combined with its decreased bed thickness is accompanied by an overall increase in its frequency of occurrence.

3.4(ii)c <u>Interpretation</u> (See figs 3.7, 3.8, 3.9).

Above the conglomeratic and sandstone sequences in both east and west sections fine grained sediments dominate and the available evidence suggests that accumulation took place predominantly by processes of vertical accretion. The facies is distinct in the significant lack of erosive surfaces, the marked depletion of sand and coarser grade detritus, the lateral persistence and consistence of individual horizons, and the predominance of low-energy bedforms.

Subfacies C1a, C1b and C1c are closely comparable to modern floodplain sediments distant from a main channel (Fisk, 1944, Allen, 1965a, Coleman, 1967), particularly in the lowest portions of such sequences where calcrete developments are a common feature (Chapter 7). Similar associations of sediment have been described by Allen (1966), Allen (1970a) and Allen and Friend (1968) and attributed to overbank flooding of fluvial channels.

Consideration of the magnitude and geometry of the sequence leads to the conclusion that although the sediments may have originated by processes analogous to those operating on modern floodplains, the lack of channel deposits suggests that the sequence may be more analogous to the less well described but more accomodating Piedmont plain situation described by Williams (1970, 1973). Similar deposits have been described by Leeder (1972) and observed by Horne (Irish Geol. Survey pers. comm, 1975) both of whom now favour the latter explanation.

Basically the fine grain size, low energy bedforms, and evidence of repeated exposure suggest that deposition largely took place in an area quite remote from a main distributary channel. The predominance of fine grained sediment in poorly-bedded, often graded units indicates that deposition in the finer portion of each cycle was essentially from suspension fallout (Allen, 1965a). The interbedded coarse and fine sediment indicates that the grain size of the deposits ranges across the suspended and bed load fields of Sundborg (1956) whilst their intimate interbedding probably indicates the combination of deposition of suspended load via a bed load phase. Ripple-bedding is the most common structure and points to relatively low intensity lower flow-regime currents, carrying suspended sand, while fluctuations in either suspended load or flow velocity at times lead to the development of a climbing-ripple bedding, or washed out ripples. At times current velocity was high, upper flow regime conditions being suggested by flat-bedded sandstones with parting lineations.

In the coarser members, the occurrence of mud-veneers over ripple-laminae record frequent cessation of bedform movement and subsequent suspension fallout from shallow ponds or lakes. Erosion of such laminae prior to desiccation confirms that flow was pulsatory within coarse members.

Sandstones are poor to moderately well sorted, graded units being less well sorted than rippled units. Graded units are also massive, indicating that high sediment loads may have been dispersed upon the floodplain area, graded massive units being analogous to turbidity current deposits, although Kuenan (1967) has produced sequences showing erosion - current ripple - climbing ripple - silt from the deceleration of experimental suspension currents.

In the present case it appears that sediment laden floodwater was probably dispersed rapidly in large quantities, but was equally rapidly ponded. Coarse detritus fell from suspension as a graded deposit, followed by the suspended silt detritus. Such graded units are always desiccated as a couplet rather than as individual layers as may be common with rippled sandstone sheets.

A variety of ripple forms has been identified, ranging from straight crested asymmetric to linguoid forms, and demonstrates a variability of flow conditions, but all well within the lower flow regime. Oscillation-ripples record periods of shallow ponded-water, and are frequently preserved in the finest grade sediments, suggesting that shallow ponded water conditions may have prevailed at times, but the restricted lateral extent of fine deposits indicates that such areas may have been very small indeed. A flood event may thus be recorded in several ways:

(i) the flood surge may at times have been a rapid sediment laden event causing graded units which were later desiccated as one couplet, confirming their origin by one depositional event. Rapid deposition is partially confirmed by the close association of graded units, and convolute horizons;

(ii) flat-bedded sandstones with parting lineations frequently initiate sandstone units indicating that some flood events had an initial high velocity, but being spread out over a wide lateral extent the increased resistance to flow caused a reduction of this velocity allowing suspension fallout and ripple development. This plane bed to ripple transition has been recorded by McKee et al (1967), Allen (1971) and Stanley (1968) from modern flood deposits. Pulses in flow are evident with repeated sand-silt alternations, the silt or even mud being only a thin veneer verifying that fallout from suspension was only a temporary event. Climbing-ripple bedding is uncommon, but does record periods of increased suspension fallout, possibly confirming flow variations. Sandstone and siltstone may alternate, but may not always be related to the same flood event, as sandstone and siltstone may be desiccated individually;

(iii) thick siltstone units show evidence of wavy or slight ripple-bedding confirming that at times suspension fallout was from slowly moving floodwater. Thin mud lamellae may record stilling of this floodwater. Thus either repeated flood events, or repeated flood surges may be recorded in such thick siltstone deposits. Such units are desiccated, but their soft nature prevents the detailed dating of such desiccation events.

The ultimate process of desiccation often produced polygonal crack patterns, although more commonly a small scale irregular pattern is evident suggesting that desiccation was advanced (c.f. Donovan and Archer, 1975). Frequent desiccation verifies that periods of submergence and desiccation alternated. The environmental interpretation of such deposits will probably be clearer with the following comparison of recent and ancient examples.

3.4(ii)d Comparison with Recent Deposits

Sediments analogous to those described here have been described by Allen (1966), Allen (1970a), Allen and Friend (1968), and Leeder (1972) and attributed to overbank flooding of fluvial channels, and modern floodplains distant to the main stream channel contain similar sediments (Fisk, 1944, Allen, 1965a, Coleman, 1967, Coleman et al, 1964). Although sequences of sediments directly comparable to those described are not available in the floodplain literature, some comparisons may be made.

'Floodplain deposits' is a term initially proposed by Allen

(1965a) to separate that sediment deposited beyond the confines of a channel by a process of overbank flow from the all embracing term 'alluvium', which is generally accepted to include all aspects of fluvial deposits.

Initially Happ et al (1940) separated alluvial deposits into six genetic types:

1. vertical-accretion deposits
2. channel-fill deposits
3. crevasse-splay deposits
4. lateral-accretion deposits
5. channel-lag deposits
6. colluvium deposits

and Fenneman (1906) first summarised these environments and indicated a major two fold grouping, i.e:

1. lateral-accretion deposits
2. vertical-accretion deposits

(see also Wolman and Leopold, 1957)

Allen (1965a) summarised the literature and strengthened the above subdivisions and with regard to vertical accretion deposits he recognised:

1. levee
2. crevasse-splay

and 3. floodbasin environments,

adding a further depositional site responsible for 'undivided topstratum' or simply overbank deposits. A wealth of information has evolved since the early pioneers Mansfield (1938), Happ et al

(1940), and Fisk (1944, 1947) directed their attention towards floodplain deposits.

Levee deposits are recognised as highly variable sediments, tending to form prismatic units parallel to the stream channel. They are probably the coarsest overbank deposits, a reflection of their proximity to active stream channels. Fisk (1944, 1947) noted that levee sediments of the Mississippi were interbedded coarse and fine, generally sandy silts being the coarsest sediment. The scale of interbedding is a function of flood magnitude, period, and the nature of the channel. Suspended load tends to vary downstream. Fisk (1947) noted a downstream decrease in sediment grade and scale of interbedding. Overall in the Mississippi alluvial valley interbedding ranges from inches to one foot. A similar scale and type of interbedding is also described by Anderson (1961). Such a rapid interbedding of coarse and fine sediment is widely reported, (see Allen 1965a) and taken as characteristic of levee type sediments (see Anderson, 1961, Lattman, 1960, Fisk, 1944, 1947, Shepard, 1956, Allen 1964a, 1965a,b). Sedimentary structures in levee deposits are usually low energy bedforms, Allen (1964a, 1965a,b) records small scale cross-stratification and even lamination. Levee sediments contain abundant desiccation cracks, as aggradation is usually slow, levee areas being inundated only infrequently.

The interbedded sandstone and siltstone, and the wavy-bedded or heterolithic lithofacies may be regarded as closely comparable with sequences of levee deposits in many ways, except in the lack of lateral variation. In the East Harbour Formation almost 100 m of sediment contain wavy-bedded developments, and apart from vertical thickness changes no suggestion of greater or lesser proximity to an active channel is suggested.

Flood basin deposits occur in more distal floodplain sites, and represent the long continued accumulation of suspended fine material from floodwaters. Deposition is slow, and characteristically consists of the finest grained detritus available. Fisk (1944, 1947) describes clayey silts and silty clays from the Mississippi flood-basins, while Glenn and Dahl (1959) record sandy silts, but mainly silty clays from the Missouri. Many other authors confirm these findings (see Bernard et al, 1963, Happ et al, 1940, Anderson, 1961, Lorens and Thronson, 1955).

Anderson (1961) described alluvium of the Rufuji River, and noted two groups of sediment, a coarse deposit of sandy silt and a fine group of silty clays, which may be comparable to the present situation.

Floodbasin deposits rarely show strong bedding features, Fisk (1947) observed 'thin laminations', but Happ et al (1940) commented that stratification was mainly due to the interbedding of crevasse-splay sands. Although Anderson (1961) noted a bimodal grain-size, he only detailed thin sandy layers, and pointed out that floodbasin sequences up to 2 m had been observed with no pronounced lithological contrasts. Similarly Bernard et al (1963) observed little variation in detrital lithologies in the Brazos River floodplain. Other than the lack of internal stratification repeated exposure may cause extensive desiccation of such deposits, particularly in more arid regions where calcrete profiles may also develop. Present day analogies are somewhat restricted, as vegetation frequently complicates the significance of any comparisons.

The thick siltstone units characteristic of the Crovie Siltstone sequence, and commonly recorded in the New Aberdour and East Harbour sections may be ascribed to environments similar to alluvial flood-basins. Interbedded sandstone sheets may record the interdigitation of adjacent coarser environments, for example crevasse-splays, as recorded by Happ et al (1940). Sheets of calcareous nodules, considered to be a form of calcrete are common at New Aberdour and in the East Harbour sequence, and may be compared with similar developments described from recent deposits (Allen, 1964a, Steel, 1974).

Deposits occurring environmentally between levee and flood-basin or backswamp were termed 'undivided topstratum deposits' by Allen (1965a, see also Allen and Friend, 1968) when such overbank deposits accumulate in unrestricted areas, i.e. areas of floodplain with low relief.

Deposits falling into this category have been described by Happ et al (1940) from the Rio Grande, by Mansfield (1938) from the Ohio River, and Jahns (1947) described two flood episodes of the Connecticut River. Other examples worthy of inclusion are: the Kansas River (Carlson and Runnels, 1952), the Brandywine Creek (Wolman, 1955), the Klaralven River (Sundborg, 1956). In several of these examples, topstratum deposits are fine grained, but Mansfield op cit, Jahns (1947), Sundborg (1956), and Wolman (1955) all record large amounts of fine sand or sandy silt. Jahns (1947) observed sediment up to gravel grade interbedded with fine grained detritus.

A repeated interstratification of coarse and fine sediment is characteristic of topstratum deposits formed on topographically unrestricted floodplains, where floodwaters are not impeded.

Interstratification similar to that observed in sequences described here has been observed by Mansfield (1938), McKee (1939), Jahns (1947), and Schumm and Lichty (1963), although the example quoted by McKee is coarse sediment dominated.

The dominance and scale of coarse or fine detritus is related to several factors, mainly:

a) proximity to channel

b) flood duration

c) flood magnitude

d) flood load calibre

For example, coarse units dominate in the Cimmaron River while fine units dominate in the Connecticut River (Jahns, 1947). Sequences of bedforms are variable but commonly include small-scale ripple-bedding asymmetric-ripples, erosive based sand units and desiccation, all of which are common in the sequences described here.

Little information is available as to the nature of crevasse-splay deposits, Happ et al recognised their importance in floodplain areas, Russel (1954) offered a geomorphological observation, while good descriptions are given by Coleman (1969) from the Brahmaputra River. With the lack of comparative information it is difficult to summarise the deposits, but channellised flow, and the introduction of coarse detritus into fine floodplain sequences may be expected. Allen (1964) interprets thin sandstones interbedded with siltstones as distal crevasse-splays, while Singh (1972) describes channel infills from the Gomti River crevasse-splays. Considerable proximal-distal changes are to be expected, in the more distal sites the crevasse-splay mechanism contributes to the topstratum deposits, and may be an integral mechanism in the production of such deposits.

In areas where channels are rapidly migrating, velocities of overbank flow may be rapid, Leopold and Wolman (1957) record velocities up to 40 to 50 cms. per second. In such circumstances it is appreciable that even thin sheets of sediment may show the development of upper flow regime bedding, whilst also enabling large amounts of sand to be introduced into an otherwise fine grained environment. In such cases interbedded sand and silt has been attributed to crevasse-splay or levee modes of origin (Allen, 1964) as noted above.

The repetition of coarse and fine beds typical of many overbank situations has been widely observed, and attributed to fluctuations in flow during individual floods (Allen, 1965).

Small-scale bedforms are typical throughout, horizontal and ripple bedding are regarded as typical by Allen (1965); McKee (1939) noted that 80% of the floodplain sediment of the Colorado Delta was composed of climbing-ripple lamination, the Indus River being similar (McKee, 1966), whilst the Bijou Creek (Colorado) displayed over 90% horizontal bedding (McKee, 1967). McKee (1966) also noted convolute bedding in floodplain deposits.

Jahns (1947) believed that floods of large magnitude were rare events (see also Dury, 1971) and that interbedded sandstones in otherwise fine deposits were a record of such events.

It is clear from this brief review that the siltstone facies associations have features in common with modern overbank sediments. Whether such a comparison is valid is open to question, and warrants further discussion.

In all of the recent examples cited, and in ancient analogues there exists a cause and effect relationship between vertical and lateral accretion deposits. Allen (1965) noted that floodplain deposits may be well developed in some cases, poorly developed in others, but 'lateral accretion deposits however are common to <u>all</u> floodplains'. In the present example, sediments considered to be vertically accreted are exposed for an unbroken thickness of 100 m, and stratigraphical interpretations suggest that this may be up to 180 m or even more. A consideration of ancient examples (e.g. Allen, 1964a) shows floodplain developments consistently under 10 m in thickness, and recent analogues only extend this value to about 30 m. Clearly, therefore, although the sequence of sediments, bedforms and interrelationships may be comparable to an origin by mechanisms common to the floodplain environment, the interpretation must cease at the mechanism, and a comparable environment must be sought elsewhere.

The underlying deposits in eastern and western sections are considered to be of alluvial fan origin, and the absence of laterally accreting fluvial processes necessitates that our attentions be directed towards an environment related to such fans.

Williams (1970, 1973) describes two similar regions, one in North Africa, the other in Australia, where thick fine-grained sequences occur beyond alluvial fans. The climate is semi-arid to arid resulting in predominantly ephemeral processes; braided streams and debris flows have constructed the alluvial fans under conditions of brief high rainfall. In his Australian example (Williams, 1973) Lake Torrens is the focal point of an internal drainage system, and beyond the coarse alluvial fan sediments aeolianites (predominantly seif-dunes) occur as a passage into a thick sequence of silts, clays, laminated silts, with local sandy developments. Borings (Johns, 1968) have proved that at least 80 m of this sediment are present yet still within 10 km of the alluvial fan apex. Calcrete profiles are recorded in a situation adjacent to the distal alluvial fan (fan toe).

A more complete description of a similar situation is given by Williams (1970) concerning the Biskra region of the Algerian Sahara.

A broad Piedmont alluvial plane exists having aggraded by braided stream and debris flood processes, again during periods of high but impersistent rainfall. Today extensive alluviation is taking place in distal portions of the plain by means of sudden flooding. Sediment is initially carried across more proximal reaches by oueds, ephemeral stream channels. Floodwaters spread out over the Piedmont plain surface, often up to 6 m of floodwater may occur, and deposit thick silts, muds and thin rippled sandstone sheets. Borings have indicated that at least 400 m of such fine grained sediment is present, and still quite close to the alluvial fan area.

Fig. 3.11 is a reconstruction of profiles measured by Williams (1970) in the Biskra region, and these are compared with profiles measured at various stratigraphic levels with subfacies C1.

3.4(ii)e <u>Significance of Sedimentation Trends</u>

Subfacies C1a is considered to record the establishment of a Piedmont floodplain environment, channellised flow being replaced initially by thin sandstone sheets and units of wavy-bedded sandstone and siltstone due to channel widening eventually causing floodwater to be deployed in sheet form over the Piedmont surface.

The decline of wavy-bedded sandstones and siltstone deposits probably corresponds to the more distal Piedmont plain 'flood basin' sites beyond the reach of the bedload laden floodwaters.

Siltstone thickness is initially low, because at the top of subfacies C2 sequence flow was channellised and therefore inundations of the floodplain surface were less frequent in such areas. In the lower parts of subfacies C1a sequence, the wavy-bedded sandstone and siltstone deposits (probably analogous to levee deposits) indicate that floods spread over greater lateral extents and hence although flood frequency need not have changed, areas subjected to flooding are increased and therefore in profile flood frequency is more apparent.

Due to a small floodplain relief, small areas of ponded water allowed the development of laminated mudstones, but these decline at higher levels as the sequence eventually represents more and more distal situations where floodplain relief would be much smaller. In such regions, beyond the limit of bedload transport, siltstone accumulates in thick units, with coarse detritus being introduced only by very infrequent floods of exceptionally large magnitude.

Within subfacies C1b the interpretation of trends would be similar to above, with initial proximal sites being replaced at higher stratigraphic levels by more and more distal floodplain sites. The development of calcrete is most distinct in subfacies C1b, and fits well into the above picture. In both Subfacies C1a and C1b calcrete occurs in lower parts of the succession, in positions considered here to represent more proximal locations in the floodplain environment. In such locations conditions would in fact be more conducive to extensive calcrete development (see Williams, 1970). At higher levels only isolate sheets of nodules occur, recording the more permanently developed water table rather than the fluctuating water table to be found in marginal situations.

In subfacies C1c a much different and very significant development is recorded in the sedimentation trends. The increase in abundance of coarser lithofacies is considered to herald the decline of the Piedmont floodplain environment and the subsequent advance of proximal facies over the more distal floodbasin environments. Eventually this trend is completed by the overstepping of the floodplain by alluvial fan sediments of subfacies B.

Such trends are considered to be recorded in the increase in sandstone and wavy-bedded sandstone and siltstone deposits, and in the upwards decrease in siltstone thickness.

Why wavy-bedded sandstone and siltstone units should be thicker but less abundant in lower parts of the sequence in situations considered to represent distal floodplain environments remains problematical. This may be partially explained because of the tendency for wavy-bedded deposits to equate with interbedded sands and silts in such distal sites as in subfacies C1a and C1b.

Further confirmation of the aggrading nature of the profile is provided by the very rapid decline in the presence of calcrete nodules with increasing stratigraphic level in subfacies C1c.

3.4(iii) Subfacies C2

3.4(iii)a Facies Description (Plates 1.2, 1.3)

Subfacies C2 occurs faulting against subfacies A2 in Crovie Village, and is comprised alternations of sandstone and siltstone. Six lithofacies make up the sequence, i.e:

(i)	conglomerate	Sandstone Member
(ii)	flat bedded sandstone	Sandstone Member
(iii)	massive sandstone	Sandstone Member
(iv)	cross stratified sandstone	Sandstone Member
(v)	cross laminated sandstone	Sandstone Member; Siltstone Member
(vi)	siltstone	Siltstone Member

It was noted in Chapter 1 that subfacies C2 (or the Crovie Sandstone Formation) is in fact a gradational sequence in which the relative abundance of the above lithofacies is quite variable, and for this reason it is difficult to characterise the sequence (although in Chapter 1 an attempt has been made in Fig. 1.9).

Brief details of the above lithofacies have been given in Chapter 1 but more specifically the sandstone siltstone alternation may be as follows: sandstone units are commonly erosively based, and in lower parts of the sequence may be initiated by relatively coarse moderately well sorted slate-rich conglomerate. Such conglomerate usually infills erosive hollows, and in isolated examples shows the initiation of a crude cross-stratification. The erosive sandstone bases may preserve step-like erosion surfaces.

In the majority of cases the conglomerate portion of each unit is no more than a thin gravel lag overlying an erosion surface, and at higher levels such lag conglomerates often include cornstone fragments. Red and green mudclasts are a common constituent at most levels. Flat-bedded or massive sandstones may occur in thin units overlying conglomerate or erosion surfaces, the flat-bedded portion has been observed to preserve parting lineations of upper flow regime origin, whilst the intimate association of flat-bedding and massive sandstone may suggest that at times high sedimentation rates allow the development of sandstone horizons with no internal bedding.

The bulk of most sandstone horizons is made up of cross-stratified fine to medium grained sandstones. The poor exposure almost always prevents a three dimensional form to be established for this cross-stratification, but in several instances planar and trough forms have been recognised. Cross-stratal sets occur as multistorey units, and may or may not be interspaced by siltstone veneers. Gravel and mud flakes are common additions to foresets. Finally a sandstone unit may become finer in grain size, or simply develop ripple or lower flow regime horizontal bedding. Sandstone units are notably of asymmetrical channel form, being erosively based, and flat topped, and laterally show a marked thinning and replacement of cross-stratified sets with cross laminated sandstones.

Siltstones sharply overlie sandstone units, and may often contain thin massive or ripple laminated sandstones. Although siltstones are generally massive, a crude horizontal lamination may be created by thin mud laminae. Where mud laminae are most persistent extensive desiccation is apparent, and may often be superimposed upon symmetrical ripple developments.

Calcareous nodules develop throughout the sequence in these siltstone levels.

3.4(iii)b Vertical Facies Relationships (See fig 3.12)

As noted in previous paragraphs a simple alternation of sandstone and siltstone typifies the sequence, while internally the sandstones may fine or show common sequences of bedforms. Subfacies C2 is one of the few sequences at Gamrie suitable for the application of statistical techniques, and these have been applied, initially in an attempt to characterise the sequence objectively.

The tally matrix presented in Table 3.1 shows the number of upward lithofacies transitions in subfacies C2.

Lithofacies	1	2	3	4	5	6	
1	0	9	7	5	1	0	22
2	7	0	2	3	11	7	30
3	6	5	0	0	4	3	18
4	1	7	3	0	12	14	37
5	1	5	3	6	0	16	31
6	8	5	4	22	5	0	44
	23	31	19	36	33	40	182

Table 3.1 Subfacies C2 - Tally Matrix

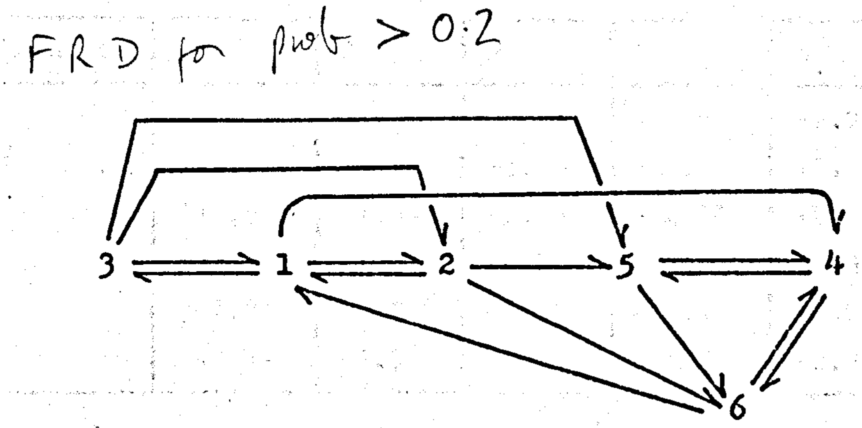
The corresponding transition probability matrix is illustrated in Table 3.2.

Lithofacies	1	2	3	4	5	6
1	0	.41	.32	.23	.05	0
2	.23	0	.06	.1	.36	.23
3	.33	.27	0	0	.22	.16
4	.03	.18	.08	0	.32	.37
5	.03	.16	.09	.19	0	.52
6	.18	.11	.09	.5	.11	0

Table 3.2 Subfacies C2 - Transition Probability Matrix

To avoid complication, transitions were only recorded between differing lithofacies, i.e. transitions from one lithofacies into itself were not recorded, and this accounts for the zero elements in the main diagonal. Transitions of this nature do occur, but only within the cross-stratified and siltstone lithofacies. Justification for omitting these transitions is felt to be that although within the cross-stratified sandstones silt veneers may separate cross stratal sets, this is not always the case, and many cross-stratified sandstone units may simply be multiple cross stratal sets. Similarly many of the siltstones at higher levels have been shown to be composed not of massive sequences, but thin desiccated units of siltstone which in most instances would be impossible to log as facies transitions, either due to exposure or the degree of desiccation rendering them effectively thick massive units.

The following diagram is a facies relationship diagram constructed from table 3.2 and shows those transitions having a probability of greater than 0.2. The starting state of the diagram is facies 1 and it can be seen that a variety of paths lead back to the same facies state, indicating clearly that the overall lithofacies arrangement is cyclic.



Clearly the vertical organisation of lithofacies may be complex. In order to indicate where variation in the facies transitions lies, a predicted data array and residual data array were calculated (Table 3.3 and 3.4). These allow a corrected facies relationship diagram to be constructed, representing transitions which are most likely to occur after allowing for those transitions expected had the process been random.

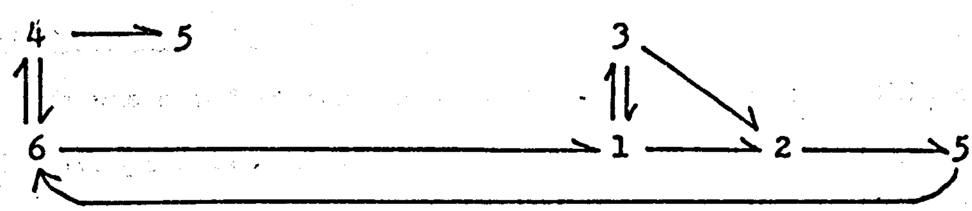
Lithofacies	1	2	3	4	5	6
1	2.78	3.74	2.29	4.35	3.98	4.83
2	3.79	5.1	3.13	5.93	5.44	6.59
3	2.27	3.06	1.87	3.56	3.26	3.95
4	4.67	6.3	3.23	7.31	6.7	8.13
5	3.91	5.3	3.24	6.33	5.62	6.81
6	5.56	7.5	4.59	8.7	7.97	9.67

Table 3.3 Subfacies C2 - Predicted Data Array

Lithofacies	1	2	3	4	5	6
1	-2.78	+5.26	+4.71	+ 0.6	-2.9	-4.8
2	+3.21	-5.1	-1.13	- 2.93	+5.56	+0.4
3	+3.73	+1.94	-1.87	- 3.56	+0.74	-3.59
4	-3.67	+0.7	-0.23	- 7.31	+5.3	+5.87
5	-2.91	-0.3	-0.24	- 0.13	-5.62	+9.19
6	+2.44	-2.5	-0.59	+13.3	-2.97	-9.67

Table 3.4 Subfacies C2 - Residual Data Array

Corrected Path Diagram



The corrected path diagram shows essentially two basic sequences one loop from siltstone through cross-stratified sandstone, cross laminated sandstone back to siltstone; the other from siltstone into conglomerate flat and massive sandstone into cross laminated sandstone and then back to siltstone. These two loops are believed to represent:

i) sections through central portions of channels where cross-stratified sandstone is typical, and

ii) sections through marginal sites where cross laminated sandstone alternates with siltstone.

Although certain cycles may thus be detected from the lithofacies relationship diagrams, it does not tell us whether the controlling process was of an independent trials or Markov type. This has been achieved by applying a χ^2 test as described earlier. The tally matrix was treated as a contingency table, and yielded a χ^2 obs. of

130.2 against a χ^2 0.05 of 35.17 with 23 degrees of freedom. The null hypothesis of an independent trials process was therefore strongly rejected. Consideration of the sequence as a regular transition matrix with fixed spaced intervals was not attempted in the light of Turners' (1974) conclusions that although similar ends may be reached, the latter method may create large positive diagonal elements leading to considerable variation and unrealistically large χ^2 obs. values.

3.4(iii)c <u>Sedimentation Trends</u>

<u>Lithological Trends</u>

It was noted in the stratigraphical description of this subfacies (Chapter 1) that lithofacies composition varied with stratigraphic height. This variation was summarised in Fig. 1.9 and demonstrated clearly that the following trends occurred with rising stratigraphic level:

i) conglomerate rapidly thins and becomes only a minor constituent,
ii) flat-bedded sandstone also declines in abundance,
iii) massive-sandstone, cross-stratified sandstone, cross laminated sandstone and siltstone increase in abundance toward the middle of the sequence,
iv) cross laminated sandstone remains uniform in abundance while at higher levels cross-stratified sandstones rapidly disappear,
v) the decline of cross-stratified sandstone is accompanied by a marked increase in the proportion of siltstone,
vi) toward the top of the sequence conglomerate makes a temporary return in several quite thick units.

Thickness Trends

Variations in bed thickness are indistinct in subfacies C2. As mentioned, conglomerate thickness declines rapidly, but apart from this neither sandstone nor siltstone show any significant temporal variations.

3.4(iii)d Interpretation

The simple statistical tests applied to the succession indicate that a Markov 1 type process controlled the vertical arrangement of lithofacies, with cycles essentially comprised a simple alternation of sandstone and siltstone units in a fining upward order. The lithofacies content, and their interrelationships compare favourably with certain aspects of modern and ancient alluvial sequences (see Allen, 1965a), the coarse and fine interrelationship being interpreted as channel and topstratum deposits respectively.

The erosive sandstone bases often showing marked downcutting are considered equivalent to the scoured surfaces of Allen (1962b, 1965b) and Williams (1968) and are ascribed to erosional processes operating in the scour pools of stream channels (Arnborg, 1958). A variable thickness of conglomerate may follow this erosion surface, and discoidal shale and mudclast are often common accessories. The coarse grain-size of the sandstones indicates that the streams were bedload streams (Sundborg, 1956), the mixture of basal lag conglomerate (Sundborg op cit, Arnborg, 1958, Williams, 1968) being a record of the coarsest bedload available and in transport (Sundborg, 1956, Happ et al, 1940). The silt and mud clasts are of intraformational origin and confirm erosive processes such as bank caving and channel-floor erosion (Happ et al, 1940, Fisk, 1947, Lugn, 1927, Pettijohn and Potter, 1963) all of which are apparent at lower levels in the sequence as step-like erosion surfaces, i.e. reactivation surfaces

(Picard and High, 1973), providing a record of periodic rejuvenation of erosion, perhaps as renewed flood-surges. At higher stratigraphic levels floodplain erosion is confirmed by the inclusion of cornstone fragments (Allen, 1960) in the basal lag deposits.

The poorly sorted nature of some of the thicker basal-conglomerates may suggest that in a similar manner to the sheet-flood deposits of subfacies A2, the floodwater was heavily laden, and thus unable to sort and erode. Occasionally cross-stratified conglomerate forms a base to coarse members, recording very high flow-powers (Simons et al, 1961). Further evidence is available as to the bedload character of these streams, in that the cross-stratified major portion of each unit was deposited under conditions of net deposition but moderately high flow-powers (Allen, 1968a) by migrating subaqueous straight or curve-crested sand dunes (Allen op cit.), the lag gravels in many instances may be concentrated due to backflow in the lee of such dunes (Williams, 1968) and not due to declining flow-power. At times sedimentation was apparently high, resulting in gravity shearing of dune foresets (Simons et al, 1961, 1965)

Sedimentation is often initiated with flat-bedded sandstone, rapidly being replaced by cross-stratified sandstones and finally cross laminated sandstones. Such an upward sequence of bedforms indicates a gradual decline in flow-power from upper flow-regime conditions responsible for the deposition of traction-load sediments in flat sheets (Allen, 1968a), or even cross-stratified conglomerate, to bedload deposition and dune migration in the upper part of the lower flow-regime (Allen op cit.), prior to the final ripple-migration upon a surface undergoing net deposition at low flow-powers (Allen op cit.). Such an interpretation of declining flow-power is particularly applicable as no significant decrease in grain-size occurs in many of the cycles. Breaks do occur within the sandstone part of each cycle, and are represented by silt-veneers between cross-stratal sets. At times flow must have been rapid, but easily ponded in order to allow suspension fallout directly onto the dunes prior to a resurge or following flood event. Some of these silt-veneers have been desiccated, and the sequence of: cessation of flow - suspension fallout - desiccation - flood repeat - must be a record of at least some ephemeral-flow within these channels.

Above each sandstone unit a thick massive siltstone unit occurs, its sharp-base suggesting a significant break in sedimentation between coarse and fine members. In grain-size the siltstone deposits range across the suspended and bedload fields (Sundborg, 1956) and are thus comparable with modern floodplain topstratum deposits (Wolman and Leopold, 1957). Lower flow-regime and relatively low flow-intensities are implied and the thick uniform silts have an appearance similar to backswamp silts of the Mississippi described by Fisk (1944). The lack of desiccation cracks is a problem, but the general absence of structure may be due to alternate wetting and drying (Brewer, 1964).

Sandstone and siltstone thickness in any cycle bear no relationship to each other (see Fig. 3.13), and it may follow that a cause and effect relationship does not exist. Siltstone units always rest sharply upon sandstones, and are never gradational from them. Thin ripple-laminated sandstones occur interbedded within the lower portion of many of the siltstone units, but no desiccation has been directly recorded, although it may be inferred from the lack of structure within the siltstones. Remnants of a thin graded-lamination are commonly present in the siltstones but never extensively developed. At higher stratigraphic levels siltstone units commonly show an extensive development of calcareous nodules believed to be the result of the development of calcareous soil profiles in a semi arid environment (see Chapter 7). A slowly aggrading soil-profile is implied, with frequent desiccation. The inferred ephemeral nature of the stream system fits well into this type of environment.

Laterally, as well as vertically, large scale cross-stratification may be replaced by smaller low-energy bedforms, principally ripple cross-lamination. Sandstone units persist laterally for up to 10 metres, and are notably channel-shaped, with broad, symmetrical, gently erosive lower-surfaces, and planar 'horizontal' upper surfaces. Smaller channels may be infilled by smaller bedforms, whereas larger channels pass laterally into smaller forms and eventually may wedge out and be replaced by thin impersistent sheets of ripple-laminated sandstone, the notable feature being the absence of such deposits immediately overlying channel type deposits.

The mechanism of channel infilling appears to be one of predominantly vertical-accretion caused by declining flow-powers, No evidence exists to suggest that the channels underwent lateral-migration of any great significance, although the sequence of bedforms, indicating a declining flow-regime is comparable to that proposed by Allen (1963) for high-sinuosity stream systems which are regarded as accreting principally by lateral-migration. For channel-shaped sand bodies to develop principally by vertical-accretion would also require that flow in the channels was of an ephemeral nature.

The overall form and relationships suggest that the deposits are fluvial in origin, consisting of both channel and floodplain deposits repeatedly formed in one section. The shape of the sandstone bodies, their eventual decrease in grain-size and sequence of decreasing-energy bedforms implies a gradually choking stream-channel. Migration was probably by avulsion rather than lateral-migration, although temporary periods of suspension-fallout indicate that ephemeral flow conditions were common, sand sedimentation and avulsion were not continuous processes as in braided-stream systems. Low-sinuosity streams suffer such processes, but are commonly braided, their deposits being markedly different to those described. Moody-Stuart (1966) describes deposits of low-sinuosity streams with a non-braided form and characterises them by:

a) channel-shaped sand bodies,
b) horizontal tops to channel units,
c) upward-fining nature,
d) upward decrease in energy implied by bedforms, and
e) typically a lack of evidence of lateral-migration as migration is essentially downstream (see also Doeglas, 1962, Krigstrom, 1962, Williams and Rust, 1969, Smith, 1970, Collinson, 1970).

In such a system, levee-deposits are only developed laterally to channel bodies, and would not be predicted above a channel sandstone in vertical-profile as they may in high-sinuosity stream deposits. In the present situation the wedging out of channel sandstones and their replacement by impersistent sheets of ripple cross-laminated sandstone is probably a representation of levee-type deposits forming adjacent to a single channel. Interbedded cross-laminated sandstones occurring within siltstone units may represent levee deposits of adjacent channels developed at later stages.

Levee preservation is normally quite rare in low-sinuosity stream deposits due to the common development of a high braiding-index (Doeglas, 1962, Fahnstock, 1963). The fine sediment is deposited evenly by spreading across the whole surface, and thus silt rests upon horizontal upper channel surfaces, channel avulsion having occurred by widening and shallowing of the channel by aggradation. Such widening and shoaling would lead to a suite of structures representing declining flow-regime comparable to that proposed by Allen (1963). The evidence therefore combines to suggest that subfacies C2 represents a sequence of sediments deposited by the action of small, low-sinuosity, essentially non-braided, ephemeral-streams.

The high proportion of fine-grained sediment suggests that the deposits, although initially conglomeratic and possibly influenced by alluvial-fan stream-floods of subfacies A, were in fact deposited upon a surface of relatively low-angle, allowing the formation and preservation of flood deposits. Similar sequences of deposits although on a larger scale have been described by Leeder (1972) who proposed a mechanism of crevasse-splay or crevasse-flooding.

The development of channel and floodplain deposits may be analogous to that described by Schumm and Lichty (1963) in which channel widening occurs instead of channel degradation during early high-peak discharge; floodplain construction by overbank flow is performed instead of marked channel-aggradation during later phases of discharge. Discharge is considered to be brief, and the above mechanism would allow initial dune-migration, followed by the spreading out of ripple-bedded sandstone over larger areas (a model also largely confirmed by Williams', 1970, observations).

Fine-grained floodplain bank material is known to encourage channel deepening and vertical aggradation in recent streams (Schumm and Lichty, 1963, Wolman and Brush, 1961), and therefore it follows that the streams traversing the distal fan-slope must have been of short duration, carrying large amounts of coarse detritus, and not having time to equilibrate with surroundings. Schumm (1961) confirms this notion, concluding that ..."the ability of streams to adjust to varying and changed conditions does not apply to ephemeral streams in channels that are being rapidly aggraded." Channel-widening in the rapidly deposited non-cohesive sand would occur instead of channel-deepening in the cohesive floodplain-silt.

The notion that the coarse members in subfacies C2 are flood deposits, and therefore were not in equilibrium with their surroundings, may be further apparent from studies made by Schumm (1960a,b 1968) from which he concluded that the type of sediment transported by a stream influences the character of that stream. Essentially, in fine-sediments channels will be deep and narrow in comparison to coarser deposits where wide shallow channels prevail.

Schumm (1968) went on to classify stream systems in a manner analogous to Sundborg (1956) and concluded that during the long prevegetation period sediment would have been provided at high rate, and bedload-channels would be abundant in many locations. Fluvial systems would not suffer channel confinement as in vegetated terrains, but would be free to 'spread across Piedmont areas' (also see Stokes, 1950).

3.4(iii)e <u>Comparison with Recent Deposits</u>

Recent deposits of this nature have been described by Russell (1954) and Coleman (1969). In the present case a comparison with these examples is unlikely as no evidence is available for the presence or even proximity of a major channel system which would be capable of carrying such coarse bedloads. The conglomerates present are quite immature and are closely comparable to those of the adjacent conglomerates of subfacies A. There is no evidence of increased transport, and no evidence of an increased area of provenence as would be expected with a larger river system.

Conglomerate is common at several horizons throughout the sequence, and such an abundance would require frequent tapping of the coarse bedload of a major channel whereas Dury (1971) points out that floods of exceptional magnitude are rare events in modern rivers and therefore such a mechanism would probably be uncommon.

A better recent analogue to the present example is the channel and floodplain deposits of an alluvial floodplain in Algeria described by Williams (1970) where a gently sloping distal fan surface is traversed by numerous moderate to low sinuosity non-braided shallow ephemeral stream channels which transfer floodwater and detritus beyond the fan slope (Leeder pers comm, now considers this a viable mechanism for at least some of the Border Group sediments).

The system is in several ways analogous to the crevasse-splay mechanism but instead of a major river breaking its retaining bank, the distal fan surface is traversed by numerous shallow channels which periodically transfer floodwater directly from more proximal sites on the alluvial fan beyond the fan slope, and onto the flood-basin beyond.

Such a mechanism would be quite applicable to the interpretation of the present deposits as the evidence available suggests that relatively large volumes of detritus have been released periodically, and often onto floodplain or flood basin siltstones. In many instances the medium was so loaded with detritus that erosion could not take place. Floods were probably short events (thin units, and poorly sorted conglomerate) and any succeeding runoff was incapable of any further modification to the conglomerate. Fig. 3.13 relates conglomerate and sandstone thickness to siltstones, and no relationship is apparent. It is suggested, therefore, that the conglomerates of facies association B are a logical continuation of those in facies association A, which are probably comparable with the alluvial fan deposits described by Williams (op cit.), i.e. "the gently sloping distal fan surface". The minor channel systems associated with such an environment are probably recorded in the sandstone members of each cycle.

3.4(iii)f <u>Significance of Sedimentation Trends</u>

As noted previously, the presence of conglomerate at the base of the subfacies C2 sequence may be regarded as indication of a relationship with adjacent alluvial fan deposits. The lithofacies abundance trends are considered to add further support to the concept that subfacies C2 environmentally belongs to a situation partially related to an alluvial fan, and partially to a Piedmont floodplain.

The initial presence of conglomerate indicates a declining influence upon sedimentation by alluvial fan processes. The subsequent restriction of conglomerate to channels clearly indicates that sheetflood processes were replaced by channel processes. The sequence records the increasing importance of channelled flow with abundant cross-stratified sandstones. Flow was ephemeral, and the abundance of siltstone in alternation with sandstones demonstrates that slopes were either gentle enough to allow large scale ponding of floodwaters (see Williams, 1970) or sandstone deposition caused an irregular floodplain relief which allowed ponding of floodwater in depressions. Eventually, siltstone deposition predominates and records the establishment of a more permanent, less proximal floodplain environment.

The changes listed and discussed above are displayed in the steeply dipping Crovie Sandstone Formation at Crovie, and being steeply dipping, the changes recorded are virtually vertical changes in facies. Thus the replacement of alluvial fan processes by Piedmont floodplain processes in vertical sequence demonstrates that the alluvial fan (an environment laterally adjacent to the Piedmont floodplain) was in fact receding and being overstepped by the rapidly aggrading floodplain, which was gradually increasing in area.

Further confirmation of this opinion is provided by the distribution of calcrete within subfacies C2. The developments of calcrete are considered in more detail in Chapter 7, where a five fold genetic sequence is recognised. The distribution of these genetic types is illustrated in Fig. 3.14 where the following points are displayed:

i) immature calcrete is predominant in lower parts of the sequence,

ii) mature calcrete predominates in the middle of the sequence, and

iii) isolated nodules in sheets occur in highest parts of the sequence.

The presence of immature calcrete in lower parts of the succession relate to the areas strongly influenced by alluvial fan processes where either run-off or aggradation was in excess of that required for maturation of the calcrete profile. The flood events of the mid portion of the sequence cover a greater area of floodplain, and therefore aggradation is reduced. The area is frequently provided with floodwater, assisting in generating a fluctuating water table necessary for mature calcrete formation. In higher levels, more distal floodplain sites are represented. Here, floodwater would be held for longer periods, and the water table would be more stable, this environment could only generate the laterally persistent sheets of isolate nodules.

Thus several lines of evidence converge to support the environmental interpretation envisaged and help to confirm that the vertical profile was generated solely by autocyclic processes (Beerbower, 1964).

3.4(iv) Subfacies C3

3.4(iv)a Facies Description (Plates 1.6, 3.9, 3.10, 3.11)

Sediments grouped into subfacies C3 are exposed only in the Western Coastal Section at Crovie and Gardenstown (i.e. the West Harbour Formation). Details of the nature of these sediments have largely been considered in Chapter 1, where a two fold subdivision of the sequence was proposed.

Essentially, subfacies C3 consists of cyclic sequences comprising the following six lithofacies:

i) cross-laminated sandstones,

ii) flat-bedded sandstone,

iii) siltstone,

iv) laminated mudstone,

v) mudstone,

vi) cross-stratified sandstone.

The lower member is typified by an abundance of fine/very fine micaceous sandstone in alternation with siltstone and laminated mudstone. Cycles are laterally persistent, with little change occurring over 15 m. The units are comprised minor fining upward cycles, sharp based sandstone units resting with slight erosion on previous mudstones.

The cycles may be based by thin intraformational conglomerates, but generally consist of ripple cross-laminated fine sandstones with abundant developments of climbing ripple-lamination. Ripple development varies from well developed asymmetric ripples to ripple-drift, washed out ripples and climbing ripples. Ripple size is generally quite consistent, but may vary with level within sandstone units, increasing towards the top.

Vertical changes between ripple forms usually occur quite rapidly, as do changes between lithofacies, for example, sandstone grades rapidly into siltstone, and mudstone rapidly replaces siltstone.

Fig. 3.15 shows the general form of the sequence, and illustrates the common interrelationships of lithofacies. Fig. 3.16 allows comparison of the Upper Member. The major differences are increased unit thickness, and the development of distinct channel-shaped bodies rather than the laterally persistent levels common in the Lower Member.

3.4(iv)b Vertical Facies Relationships

The most striking feature of subfacies C3 is the simple alternation of coarse and fine units, particularly apparent in the deposits below the West Harbour Fault, and demonstrated in Fig.

Although no significant relationship exists between coarse and fine unit thicknesses, each coarse unit is related to the overlying fine unit by gradation, coarse and fine units forming couplets and being approximately equal in total thickness in the lower section (57% sandstone : 43% fines).

Figs 3.15, 3.16 illustrate the 'composition' of upper and lower portions of the sequence and also serve to illustrate the common facies relationships involved.

The sharp or erosive base, may or may not be overlain by intraformational conglomerate. Approximately 5% of transitions involve such mudflake breccias in the lower portion of the sequence, whereas in the channel-shaped sandstones of the upper portion of the sequence 80% show the presence of mudflakes. Isolated mudflakes are common in the lower sequence, whereas dense mudflake conglomerates are present at higher levels.

Flat-bedded sandstone may follow the mudflake level or the basal surface, but again this is rare (less than 5%). The most common deposit in either portion of the sequence is ripple-laminated sandstone (51% and 61% in lower and upper portions respectively). Ripple-drift cross-lamination is by far the most common, and often associated with extensive developments of climbing-ripple cross-lamination (most commonly developed toward the top of sandstone units). Occasionally, climbing ripple-lamination appears to constitute the whole coarse member, but careful examination usually indicates a lower sheet of ripple cross-lamination, and either parallel lamination or further ripple-lamination towards the top.

Ripple size has been noted to increase upwards, but lateral changes in form are most common. The most common variations are changes from ripple-drift lamination to climbing ripple-lamination, although several examples show ripple-lamination changing to small tabular cross-stratified units.

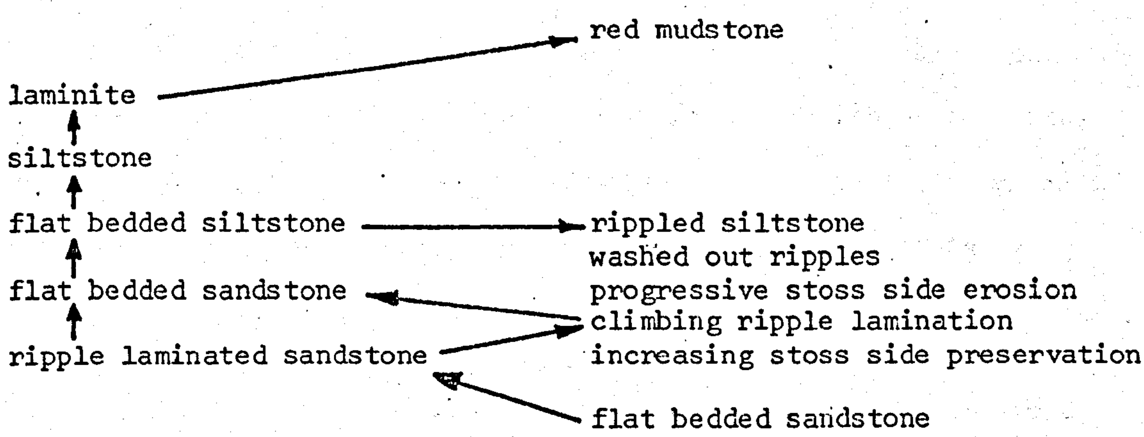
With continued fining of sediment grade, ripple-lamination is commonly replaced by flat-bedded very fine sandstone and siltstone. Climbing ripple-lamination often develops a shallower angle of climb, and ripples may continue into the siltstone portion.

The lowest portion of siltstone units may show ripple-lamination, but largely shows the development of an irregular flat-bedding. Thin sandstone lenticles may develop, decreasing in abundance vertically.

Thin rippled sandstone sheets are common in the lower siltstone portion of the cycles and mimic the major units in having sharp bases but graded tops. In the upper third of the siltstone portion sand is absent, the siltstone showing a very fine flat parallel-lamination, and with increasing height the finest mud-lamallae show a red coloration. Initially such mud-lamallae may be isolate, but rapidly become more abundant until they eventually equal the laminite in importance.

The laminite horizon shows abundant desiccation cracks, but none of these originate from within the laminite unit, all are infilled by red mud or sandstone depending on the overlying deposit.

Red mud, where present, is the final capping to a cycle, but tends to be rare at lower levels and generally is restricted to impersistent lenticular units. A summary of these relationships is given below:



The vertical elements in this summary are regarded as the most common transitions, oblique lines represent less common variations.

3.4(iv)c Sedimentation Trends

Lithological Trends

Overall, six lithofacies comprise subfacies C3, but as noted in Chapter 1 mudstone and cross-stratified sandstone only occur in the upper portion of the subfacies. Numerically, the occurrence of siltstone decreases with increased stratigraphic level, as does cross-laminated sandstone. Laminated mudstone remains fairly consistent throughout the sequence, but mudstone and cross-stratified sandstone increase with increasing stratigraphic level.

Thickness Trends

Fig. 3.18 shows thickness variations of sandstone units throughout the sequence, and demonstrates that in the lower member where cross-lamination prevails, unit thickness is reasonably consistent. Towards the top of the Lower Member and throughout the rest of the sequence considerable variation exists but is associated with a general thickening of sandstone units.

3.4(iv)d Interpretation

Subfacies C3 supercedes the previously interpreted flood-plain deposits in a coarsening upwards sequence at Gardenstown.

The facies is distinct in the abundance of fine grained micaceous sandstone with abundant ripple bedding. Consideration of sequences of lithofacies, and arrangements of bedforms leads to the conclusion that the deposits represent channelled distribution of sediment laden floodwater as a sequence of ephemeral events.

The sequence is characterised by a dominance of fine grained sediment (fine sandstone, siltstone, and mudstone) with abundant sedimentary structures, mainly small-scale or ripple cross-lamination, horizontal lamination, mudcracks and burrows. The sediment and cross-stratal types are similar to those of modern river sediments, deposition from traction loads being suggested by many structures (Sundborg, 1956) in the coarser portions (e.g. flat-bedding, with parting lineations) while the overlying finer sandstones are characterised by structures indicative of deposition from suspension, e.g. ripple-lamination. Such a bipartite mode of sedimentation is typical of many fluvial systems in which segregation of grain-sizes takes place on the depositional surface as a response to varying flow conditions. The fine grained sandstones, occurring in distinct laterally persistent sheets, show only slight lateral variability and their occurrence in alternation with siltstones and mudstones closely resembles modern floodplain sediments in possessing proof of repeated submergence and emergence of the sedimentary surface, (indicated by the red colour and abundant evidence of subaerial desiccation conditions) and also evidence of sediment deposition mainly from suspension.

Close comparison can be made here with deposits described by Jahns (1947), Happ Rittenhouse and Dobson (1940), McKee (1939, 1938) McKee, Crosby and Berryhill (1967) and Shantzer (1951).

Further indications of the depositional environment can be obtained from a consideration of the dominant ripple and climbing ripple laminated structures. Ripple-lamination forms only under relatively weak hydrodynamic conditions, climbing-ripples developing when large quantities of suspended sediment are available for deposition (McKee, 1966, Allen, 1970b, 1971). Ripple-lamination forms in many modern environments but climbing ripple-lamination has somewhat more specific implications. McKee (1966) notes that river floodplains and areas of overbank flow are especially favourable for the development of such deposits as they are capable of providing the considerable sediment supply necessary. As examples McKee quotes the Colorado, Mississippi and Indus Rivers.

Although an initial consideration of the available evidence suggests that the deposits considered may be assigned to an origin due to overbank flow upon a floodplain of some nature, a further, more detailed consideration of the evidence must be undertaken in order to characterise this environment more fully.

As each fining upward cycle has a lower coarse-member preceding a fine-member it may follow that each cyclothem records the establishment of some kind of channel system and its ultimate abandonment and burial under floodplain sediments. As repeated cyclothems are developed such a construction must have been repeated many times at a given site. The restricted thickness and great lateral extent of majority of the sandstone horizons does not favour the above concept in the lower part of the sequence, but may be applicable within the upper member where channellised flow does occur. Instead, for the lower member, the persistent sheets of sandstone imply that deposition occurred over wide essentially flat areas with a complete lack of channel erosion. The initial fining of the sediment, plus the record of flat-bedding changing into ripple-lamination is evidence of varying flow conditions recorded as a change from deposition often within the upper flow-regime (Allen, 1968) to deposition by moderate flow-powers within the lower flow-regime (Simons et al, 1965), and implies that floodwaters may initially have been of quite high energy in many cycles but that flow rapidly diminished as deposition from traction loads gave way to deposition from suspension.

The sandstone units fine upwards and grade into the siltstone and mudstone portions of each cycle, no breaks in this fining sequence have been recorded implying that each fining cycle is a record of a single flood event. Although the tendency is for cycles to fine upwards, very thin sandstone sheets within the lower siltstone portion record the presence of temporary surges, perhaps repeated flood peaks at a late stage (see Wolman and Leopold, 1957).

Ripple size remains fairly constant throughout the sandy portions of graded members, however an upward increase in ripple size has been detected in several instances, suggesting that flood conditions, although remaining uniform during deposition of the majority of the sand units, suffered a rapid change toward the top of the coarse portion. The upward increase of ripple size implies that sand deposition may have imposed a restriction on water depth, shoaling of the water resulting in increased current strength and hence larger ripples (McKee,1957,1965).Alternatively shoaling may be externally controlled, for example, floodwaters having poured into a floodbasin may not become ponded and as a result would rapidly shoal as the waters migrated across the flood-basin. The latter idea is less likely in the present instance as overlying siltstones record continued deposition from suspension, whilst laminite and mud sheets record continuing suspension fall-out from ponded waters. An increase in current strength as a result of rejuvenated activity from the sediment source, for example repeated flood surges would also cause larger ripple bedforms. This is also unlikely in the present case as a retro-gressive sequence of bedforms would be expected in such an instance.

Thus a decrease in water depth due to suspension fallout during waning flood conditions is most likely. Water depth within the flood basin would remain fairly consistent, but relative depth would be decreased due to sedimentation in the vicinity of local 'fluvial delta splays'. Laterally in-phase ripple laminae have been observed to develop into climbing ripple-lamination suggesting increased current strength with associated suspension fallout, (Jopling and Walker, 1968).

Sheets of ripple laminae have been noted to transform into short impersistent normal planar 'foreset' beds. Such foresets may be produced as a result of a downstream increase in water depth, perhaps downstream of a sediment mound. Effective bed shear stress is thus reduced as the rapidly moving waters impinge on the slower moving deeper portions causing sediment to be dumped as foresets (Reineck and Singh, 1973). Several such examples have been noted with varying angles and basal contacts of foresets, all of which vary in response to local flow-powers (Reineck and Singh, 1973). Such features as deepening of floodwater would be expected at the termination of splay type deposits where a limit exists to the capabilities of sediment transport as ripple sheets, and would produce sheets of sediment moving as tongues across the floodplain.

The transition of ripple laminae to horizontal laminae again probably forms in response to extensive shoaling of water depth, resulting in a change from lower to upper flow-regime conditions and a resultant modification of suspension fallout in moderate to low currents to transport of sediment as a traction load in moderately high flow-powers. Such transitions are not normally followed by extensive suspension deposits, and this supports the proposed interpetation. Such a transition from small ripples to plane bed phase of the upper flow-regime usually involves a phase of mega-ripples; the generation of mega-ripples apparently requires a significant water depth of several decimetres to one metre (Singh, 1972) and the by-passing of this large scale bedform may be some indication of the shallow water depths involved.

Vertical changes in cross-lamination within sandstone portions of each cycle are commonly as follows:

a) trough cross-lamination characterised by incomplete preservation of the ripple form,

to b) climbing ripple cross-lamination with tabular form and no preservation of stoss side laminae,

to c) climbing ripple cross-lamination with complete preservation of both stoss and lee-side laminae.

The final stage (c) is frequently absent, presumably replaced by the graded portion of the sandstone unit and recording the cessation of sediment supply from suspension.

From considerations of the significance of cross-lamination, the above mentioned sequence is important in its record of increasing net sediment deposition from suspension which in turn lends credance to the notion of sediment laden floodwaters pouring onto a broad, relatively flat, floodplain surface and rapidly depositing their suspended sediment, probably in close proximity to their origin. Deposition was probably rapid, many of the cross-laminated sets examined show the development of straight crested asymmetric ripples. Experimental evidence suggests that straight-crested ripple-drift structures may have such a form because of the transitory nature of the flow in which they formed (Raichlen and Kennedy, 1965). The rapid burial of climbing-ripples could have preserved the straight crested morphology preventing the full development of more complex forms - linguoid etc. (Middleton, 1970).

The angle of climb of climbing-ripple lamination frequently decreases towards the top of a sandstone unit, and as "... the rate a moving ripple surface builds up is directly proportional to the rate at which sediment is deposited on it from an external source" (Allen, 1971) this decline probably records a decline in fallout from suspension either due to a genuine lack of suspended sediment or an increase in flow-power. The latter is unlikely as such portions are commonly gradationally overlain by siltstone. Siltstone deposition was effected intially in slowly moving water, although during later stages this may have been ponded. Minor surges took place causing the temporary introduction or remobilisation of sand into thin rippled sheets.

The deposition of laminite also records the deposition of the finest grade sediment in thin graded units. The numerous sharp based laminae within each bed suggest that bottom scour and deposition occurred in small discrete episodes, a suitable model being a succession of minor ebbs and surges during the course of a major flood episode. A useful analogue is provided by Larrabee (1962) in his record of the flood deposits of the Shenendoah and Potomac Rivers. He records over 100 thin laminae 0.1 to 0.5 cms thick which were deposited in 'not more than 12 days of flooding'. The laminite deposition was accomplished prior to any drying out of the sediment, as desiccation always postdates the whole laminite unit.

Thus in summary the lower sequence of sediments records a sequence of:

a) sudden incursion of sediment laden floodwater moving with high flow-power allowing deposition of traction loads,
b) deposition of sand from suspension as ripple laminae,
c) increased suspension fallout due to reduced velocity of flow causing climbing ripple laminae to develop,
d) shoaling of water causing increased ripple sizes,
e) considerable decrease of flow-power allowing total suspension fallout in (at the most) slowly moving water, with minor temporary surges,
f) bioturbation, exposure, oxidation, desiccation, and
g) repetition of the above sequence.

In the case of the upper sequence of sediments of subfacies C3 sand and siltstone units still alternate, but deeply erosive contacts and multistorey sandstone units dominate at the expense of much diminished fine sediment (Fig. 3.17)

The thick sandstone members represent channel infill deposits, the elongation of which is only rarely apparent but is confirmed by the unidirectional paleocurrent data. The observed channels are quite small (50 cm deep, 15 m wide) and are essentially symmetrical in form, (see also Stokes, 1961), sediment grade, and internal structures. Channels taper out laterally and vertical walls representing cut banks are not observed. Such observations, together with the lack of heterolithic epsilon cross-stratification (Allen, 1965b) suggest that deposition of the coarse sediment did not occur in channels with laterally migrating point bars (Moody-Stuart, 1966) and implies a lack of high sinuosity meandering streams but supports the notion of moderately low sinuosity streams.

Channels with an overall lateral symmetry probably migrated by avulsion rather than by continual shifting. Measured channel sections have a width depth ratio of at least 25:1 and are thus typical of modern low sinuosity ephemeral streams (Leopold and Miller, 1956, Schumm, 1961, Schumm and Lichty, 1963), i.e. a situation where channel profile remains a function of bank stability. No evidence exists to confirm that the channels were anabranches of a braided system, in fact the mechanism of channel infilling contradicts such a notion; even so this does not preclude the possibility that flow within the channels may have been braided at times (Leopold and Miller, op cit.). The abundance of desiccation structures and mud laminae between many of the channel deposits confirms the ephemeral nature of the flow within such channels. Sediments were subject to desiccation prior to further infilling, implying that channel infilling was effected by quite distinct and separate flood episodes followed by periods of no flow, Water must have been ponded as a final stage in sedimentation, to allow the deposition of mudstones.

Although channel infillings are usually confused by the erosive nature of overlying channel deposits several examples are complete enough to confirm the existence of similar profiles to those developed in the lower section; instead of laterally persistent sheets the sediments are restricted to the broad confines of channels.

Channel symmetry and the concentric infilling together with the absence of steep channel walls implies that channel forms were cut prior to the depositional phase. The abundance of reddened siltstone clasts lying above the erosive bases is evidence of the destruction of cohesive channel floor and walls. Erosion is slight when based by mudstone, but quite deep when cutting a sandstone unit clearly illustrating the ease of which the fine sand could be eroded in comparison to the cohesive mud-based channels.

Channel margins are smooth and tapering, strongly suggesting that the bank material possessed little resistance to erosion (compare with Leopold and Miller, 1956, Arroyos of south west U.S.A.) such a phenomena is typical of high width-depth ratio streams (Schumm and Lichty, 1963) but is very unusual with regard to the high proportion of silt and mud forming many of the banks (Schumm, 1960). The reason for this is uncertain, but may be related to the ephemeral nature of the flow, (i.e. flow duration was probably too short for the stream system to approach equilibrium with the environmental controls).

As channel deposits have a maximum thickness of 1·4 m they probably reflect the lack of significant relief on the floodplain surface (a feature implicit in the laterally persistent sheets of sediment common in the lower sequence). Vertical sequences of grain size and bedforms closely follow the nature of the lower sequence and confirm a decrease in competence and flow-power with time and suggest that the two sequences of deposits may in fact be related. Overall the upper sequence with higher energy structures appears to be more proximal than the relatively non erosive sheets of the lower sequence. It may follow, therefore, that the deposits are environmentally lateral equivalent facies.

3.4(iv)e Recent Analogues

The nature of recent floodplain sediments has been discussed on pages 190 to 198 and clearly deposits of the magnitude and structure noted here are not common. The only floodplain environment contributing such deposits is that within the crevasse-splay category. Recent descriptions of floodplain sediments commonly restrict their details of crevasse-splay deposits to purely morphological aspects. Singh (1972) offers the only detailed study of such a recent deposit, and a consideration of his results are of great interest here.

The situation Singh describes consists of a meandering river subject to seasonal flooding. Conveniently for this comparison, overbank floods provide 'fine sand to silty fine sand with a very high proportion of mica' (compare the sandstones of facies association D - very fine to fine sandstones with a very high percentage of mica).

Singh noted sandstone units in the order of 20-30 cms thickness associated with 10-20 cms of laminated mud and up to 5 cm of mud. Small scale cross bedding, climbing ripple lamination and horizontal bedding are abundant. In a number of locations the floodplain is transected by channels cutting across the levee. These channels serve to drain extra water into floodbasin areas during high water flood periods, and during flood recession eventually choke with 'channel fill cross bedding' (Singh op cit.)as abundant sediment falls rapidly from suspension, and is combined with a modicum of bed load. The resulting laminae conform to the shape of the channel producing trough shaped channel fills. Such structures may remain as relative topographic lows and continue to serve as channels during future floods allowing limited erosion and subsequent development of multistorey channel fills.

Singh noted further features interpreted in a similar manner here in subfacies C5, he considered that the alternation of horizontally laminated sediment and ripple cross lamination recorded pulsatory conditions of flow. He also regarded upward change from small ripple to upper flow-regime plane bed conditions feasible in very shallow water when it seems that the mega-ripple phase may be by-passed. If the analogy with facies association D is close, it may thus allow an estimation of water depth, as Singh regards 'very shallow' as being in the order of 'several decimetres to one metre'.

Although McKee et al (1967), Allen (1971), and Stanley (1968) recorded plane bed to ripple transitions in modern floodplain deposits, much of the lower horizontal laminated fine sandstone recorded at Gardenstown, lacking in parting lineation and showing abundant mica on bedding planes, may be explained by Singh's suggestion that they originate in sites of reduced turbulence as suspension fallout, perhaps from suspension clouds as noted by Reineck and Singh (1971). The sequence - erosion - current ripple - climbing ripple - silt - has been produced by Kuenan (1967) by the deceleration of experimental suspension currents.

The comparison noted above is remarkably close, and may allow further interpretation. It seems reasonable that the lower horizontally bedded units are deposited in lower energy conditions and may record the rapid introduction of floodwaters. The subsequent development of ripple and climbing ripple lamination may thus record the flood stage containing the maximum concentration of suspended load, a stage recognised to frequently lag behind the maximum water or bankfull stage (Wolman and Leopold, 1957). This consideration thus allows bias towards the concept that flow velocity and suspended load were both variable parameters rather than one varying at the expense of the other.

3.4(iv)f <u>Significance of Sedimentation Trends</u>

In the interpretation of subfacies C1c the re-advance of alluvial fan processes was considered to be recorded in the initiation of a coarsening trend throughout the subfacies; subfacies C1c was considered to record more and more proximal floodplain environments with higher stratigraphic level. Subfacies C3 continues this trend, coarsening upward by means of increasing predominance of fine sand detritus.

In the lower part of the sequence, small fining upward units of sandstone predominate and record 'fluvial delta splays' of sand debouched from a distal alluvial fan surface onto the margin of the Piedmont floodplain.

In the upper part of the sequence, the deposits are more proximal in that the channelled surface is recorded from which the more distal splays originated.

The development of a channel system would introduce a significant relief upon the floodplain surface, and may account for the introduction of mudstone deposits by allowing shallow ponded water conditions to be more persistent than in the more distal regions. Such areas of ponded water would be more persistent, and also would be less likely to receive the repeated inputs of sediment laden floodwater which produced the laminated mudstones in more distal sites.

3.4(v) Subfacies C4

3.4(v)a Facies Description (Plates 3.12, 3.13)

Subfacies C4 (The Dundarg Castle Sandstone Formation) outcrops exclusively in the east of the Outlier and forms part of the fining megacycle, being intermediate between the coarse braided stream subfacies B1 and fine playa subfacies C1.

Subfacies C4 is distinct from its underlying ephemeral braided stream sediments in that a marked reduction in coarse sediment is apparent. The sequence is comprised an interdigitation of fine and coarse members (five fine members and four coarse members), see Fig. 3.19

Details of subfacies C4 have already been considered in Chapter 1, where it was demonstrated that:

i) 'fine members' are dominated by wavy-bedded fine sandstones and massive or flat-bedded fine sandstone. Sharp-based units are common, but erosion is minimal. Graded units are common, particularly in gravel rich sediments, and overall - sedimentary units show great lateral persistence;

ii) coarse units are a direct reflection of subfacies B1, and need no further detailed considerations.

With subfacies C4 several forms of cycle are commonly repeated in fine-members, these are:

i) desiccated very-fine sandstone or siltstone
wavy-bedded fine sandstone
massive sandstone
lag-deposit of granules or gravel

slight erosion.

ii) desiccated siltstone
cross-laminated fine-sandstone
cross-stratified medium sandstone
erosion

iii) gravel rich coarse sandstone (floating gravel)
massive coarse to medium grained sandstone
sharp non-erosive base

Lateral persistence is a common feature of subfacies C4 sediments in all cases except cross-stratified units, which show the development of broad shallow channels. A final type of deposit, also being of channel form, is of massive sandstones with abundant 'floating' gravel and granule grade material.

Throughout the sequence, cycles are thin and laterally persistent. Ripple-lamination is the most frequently observed structure, forming within wavy-bedded fine sandstone units. These wavy-bedded sediments are comprised up to 4 cm. units of crudely ripple-drifted fine sand, culminating with very thin veneers of very fine sand or siltstone (see Fig. 3.20). Occasionally symmetrical ripples, with silt veneers, are preserved within these wavy-bedded units.

Gravel and granule strings up to 2 cm. thick are common throughout the sequence, often persisting laterally for up to 4 m. Small erosive scours may be present in such units.

3.4(v)b <u>Interpretation</u>

The reduced grain size, low energy bedforms, and evidence of exposure and desiccation combined with the lack of evidence of extensive channellised flow and erosion suggest that deposition occurred in areas remote from distributary channels. The predominance of fine-grained, often graded sediments, and the abundance of ripple-drifted units with fine sediment veneers suggest that deposition occurred largely from out of suspension.

The predominance of low energy, bedload, transport structures, points to abundant low intensity, lower flow-regime currents carrying large amounts of bedload sand probably for reasonable lengths of time. Eventual fine veneers confirm suspension fallout from ponded waters. Several examples of thicker silts imply more extensive but still ephemeral water bodies, as the silts are invariably desiccated. Oscillation ripples record periods of shallow water.

The sediments are in many ways analogous to the sediments of subfacies C1c, and are comparable to sediments described by many authors (Allen, 1966, Allen, 1970a, Allen and Friend, 1968, and Leeder, 1972) and interpreted as overbank deposits. Modern flood-plains do contain such sediments, but generally in levee positions (Fisk, 1944, Allen, 1965, Coleman, 1969, Coleman et al, 1964); pages 190 to 198 have already considered in detail some aspects of such environments.

Throughout the sequence small channels are in evidence, but are regarded as being too small to be solely responsible for thick 'levee' type deposits. A detailed consideration of such channels indicates that in early stages of development high energy bedforms are present, but are rapidly replaced by low energy ripple-lamination. Thus, just as in subfacies B1, channels only transported ephemeral flood events and were eventually choked with sediment. At times flood events were apparently heavily laden with sediment, channels being infilled with very poorly-sorted gravel-rich sandstone, the gravel occurring floating in medium grained sandstone and indicating a distinct lack of reworking, and certainly the absence of a tractional phase during deposition. It is probable that such deposits result from the rapid deposition from suspension from highly concentrated sediment dispersions.

It is considered that the ephemeral flood events recorded in subfacies B1 eventually reached the Piedmont floodplain/Playa and spread out almost in delta fashion as an apron of sand around the distal portion of the alluvial fan (a feature common in modern playa environments, see Cooke and Reeves, 1976). On the whole, floods dispersed as sheets of sediment laden water depositing thick units of wavy-bedded sediment in proximal positions. Occasional channels served to transfer much of this water and sediment into more distal locations, and probably choked with sediment during each event.

In this manner the vertical accretion deposits of subfacies C4 are logical predecessors of the rippled sand sheets common in floodplain sediments of subfacies C1, and in particular C1b which record the eventual transfer of floodwater to more distal floodplain sites where suspended sediment predominates over bedload material.

3.5 Lacustrine Megafacies D

3.5(i) Subfacies D1

3.5(i)a Introduction

The Findon Fish Bed, of Middle Old Red Sandstone age, represents the only true Lacustrine incursion into the Gamrie Outlier. Its undoubted faunal correlation with other horizons regarded as 'Achanarras Limestone' equivalents makes it presence one of great importance.

Paleogeographically, the Findon Fish Bed provides evidence of the extension of the Orcadian Lake during early Middle Old Red Sandstone times (fig 3.22), but the nature of the fish-bearing sediments implies that a marginal site in this lake is most probably at Gamrie.

3.5(i)b Facies Description

The Findon Fish Bed, as its name suggests, outcrops primarily in the steep east side of the Den of Findon (Plate 1.22). At present this outcrop is heavily vegetated and rapidly worsening. Initially Prestwich (1838) was able to trace this outcrop into the nearby Pishlin Burn, whilst the Geological Survey (1890) recorded grey mudstones in the Cushnie Burn and near South Cushnie. Of these latter localities, only very weathered plant-bearing grey mudstones have been extracted from a farm ditch at South Cushnie during the present study. + fish scales common 1994 BGS

The nature of the Findon Fish Bed sequence is illustrated in Fig. 3.21. An irregular surface of the Lower Findon Conglomerate forms the base of the sequence, with irregularities up to 45 cms in depth infilled by greenish silty gravels, and red siltstones (Plate 1.22d). Massive grey mudstones follow the initial coarse deposits (Plate 1.22c) and in places rest directly upon the Lower Findon Conglomerate. These grey mudstones are laterally persistent and consistent in form, but are overlain locally by a thin massive grey-green plant bearing mudstone. Over most of the outcrop the grey mudstones are overlain by mudstones with a poorly developed fine lamination, which in thin section proves to be composed of organic rich carbonate-clastic laminae. At this same horizon, nodules become abundantly developed, ranging from 3 cm to 40 cm in diameter. They are generally oval in shape, and often contain fish remains. Other concretionary forms exist, generally long tubular forms up to 50 cms in length and up to 10 cms in diameter. The latter forms are apparently unrelated to specific organic remains.

The lamination poorly preserved in the host sediment is excellently preserved within all nodules at this horizon, although generally expanded and often deformed by extensive carbonate re-crystallisation and development of cone-in-cone structures (Plates

The nodules are arranged along specific levels, rather than being randomly disposed within the sediment.

The abundance of nodules decreases upwards, and the presence of lamination in the mudstones disappears. The laminated mudstones are replaced by massive grey-green mudstones, which over much of the outcrop have subsequently been extensively reddened below the overlying Upper Findon Conglomerate. Within this reddened sediment calcareous nodules are abundant, and in thin section the carbonate shows displacive textures comparable to nodules developed in lower parts of the Crovie Group sediments and interpreted here as being calcrete developments.

The Findon Fish Bed is sharply overlain by the Upper Findon Conglomerate, which over the small outcrop available shows considerable downcutting relationships.

3.5(i)c Interpretation

The sequence, although quite short, shows significant phases in its development. These phases are illustrated in Fig. 3.21, and clearly record:

i) rapid establishment of marginal Lacustrine sedimentation initially incorporating alluvial gravels and local plant debris;

ii) Lacustrine conditions became better established with the development of grey siltstones and the eventual 'typical' carbonate-organic-clastic laminites forming in deeper water, now best preserved in fish-bearing nodules;

iii) the Lacustrine environment was subsequently abandoned, the siltstones being extensively oxidised and reddened in the upper portion of the sequence. Existing carbonate material was re-mobilised at this stage and assisted in the development of nodular calcrete;

iv) alluvial fan sedimentation returned to the area.

Throughout the Moray Firth Basin an expansion of the Orcadian Lake during Middle Old Red Sandstone times is evident. A major extension of the lake area is apparent at the 'Achanarras' horizon when the area covered by the lake extended certainly from Gamrie to the Black Isle, through Caithness, Orkney, and at least into Shetland.

During this expansion, two major types of sediment developed, (Donovan pers. comm.):

i) dark grey 'deep water' carbonate laminites,

and ii) grey and greenish grey 'shallow water' flagstones.

Outside of Caithness the Tarbet Ness and Clava regions appear to have suffered the greatest inundation, bearing record of deep water Lacustrine laminites.

Infrequent inundations are more likely to have occurred in Shetland, Edderton Burn, Tynet Burn, and at Gamrie, as laminated deep water sediments are not evident. Lamination does exist to some extent at Gamrie, but not to the extent of the true deep water laminities of Caithness

A striking feature of such inferred marginal sites is the common development of abundant, and often quite large, carbonate nodules. At Gamrie, the bulk of the Findon Fish Bed is non-laminated, but a distinct carbonate-organic-clastic lamination is well developed in fish bearing nodules and also poorly developed in surrounding sediments. (See Plate 3.14)

It would appear from the presence of such laminites that perhaps deeper water conditions than at first apparent were in existence at Gamrie. Paleogeographically, such a conclusion would hold great significance, and it is therefore most important that the diagenetic history (particularly the early diagenetic processes) be considered as a means of preserving or destroying such organic laminae.

The origin of the Lacustrine laminated sediments has been considered in some detail by Rayner (1963) and Donovan (1972), who concluded that with deepening of lake waters, permanent stratification would develop, allowing an upper layer (epilimnion) warmed by the sun to separate from a lower, cool, dense layer (hypolimnion), The epilimnion is photic and life supporting, whilst the hypolimnion is darker and oxygen depleted.

Carbonate deposition is induced in the epilimnion by photosynthesising algae, with seasonal algal blooms leading to increased photosynthesis, a rise in pH, and carbonate precipitation. Upon death, the algae sink and accumulate as organic matter on the lake floor along with a continual or sporadic influx of clastic material.

In the warmer lake margin sites an increased activity of photosynthesising algae would be expected, and greater amounts of carbonate would be produced than in the cooler, darker, deeper offshore waters. In Caithness, lake margin limestones may in fact reach 3 m. in thickness (Donovan pers. comm.).

The absence of a hypolimnion in such sites is attested by the absence of organic laminae, and the frequent destruction of any original lamination by birdseye structures formed by gas bubbles resulting from the decay of organic matter.

In the Gamrie Fish Bed and other nodular fish bearing horizons of the Orcadian Basin, vertebrate organic material is generally preserved with excellent and often three dimensional detail.

For the excellent preservation of organic matter in sediments, the organism must have been introduced very rapidly into a reducing environment. Perhaps at this very early stage a hypolimnion may have been developed at Gamrie, or, the sediment/water interface closely corresponded to the O_2/H_2S interface of Krejci-Graf (1963), providing enough oxygen for algae to flourish above the sediment, but still allowing organic material to be rapidly introduced into a reducing environment within the sediment.

Oxygen would be rapidly depleted within the sediment whilst the amount of CO_2 would increase due to energetic bacterial activity (Strakhov, 1969, Berner, 1968, Lalou, 1957 and Sisler, 1962) support this notion of carbonate precipitation assisted by the action of sulphate reducing bacteria. and note the early development of sulphide minerals.

There is at least some support for this hypothesis at Gamrie in that early diagenetic pyrite and marcasite have been recorded. Galena has been recorded by Prestwich (1838), but has not been identified during this study. Marcasite crystallisation would require a pH 7, lower than pyrite, and pre carbonate precipitation. Berner (1969) regards marcasite as a late forming mineral, certainly post carbonate. In the present instance its displacement of laminae is regarded as evidence of a pre-compaction origin.

Overall, within the sediment, CO_2 accumulates and calcium is retained as a bicarbonate. There is some contention over the release mechanism of such carbonate. Increase of temperature or decreasing pCO_2 could help to liberate $CaCO_3$, but in the vicinity of decaying organic matter the liberation of ammonia or amines would allow a local pH increase. This would then allow either direct precipitation of calcium carbonate (Strakhov, 1969) or the formation of calcium fatty acid salts which could then at a later stage be converted to calcium carbonate (Berner, 1971). Studies in recent environments have shown that the pH may be increased to approximately pH 8 within 6 months, with the formation of adipocere (a calcium fatty acid) within as little as 10 years.(Weeks 1957).

The local enrichment of calcium carbonate would lead to the rapid accumulation and crystallisation of calcite with further carbonate rich interstitial fluid diffusing towards the organic remains.

The nodules in the Findon Fish Bed frequently show an internal septarian fissuring implying that the outer regions crystallised first, the crystallisation and contraction of the inner material occurring sometime later. This mechanism would allow good preservation of organic remains, by providing immediate protection against compaction (whilst also supporting the adipocere replacement concept).

Hence a mechanism for the preservation of both vertebrate remains and finely dispersed organic matter seems feasible, but wholly dependent in this instance on the early diagenetic environment.

The crucial question which cannot be answered from the present study is whether organic laminae can develop significantly in marginal sites, or whether in fact they may commonly develop but are not usually preserved. An answer to this question will allow greater speculation as to water depth and area of the Orcadian Lake.

PART B - Rhynie Outlier

3.7(i) Introduction

Although the sedimentological interpretation of the Lower Old Red Sandstone sediments of the Rhynie Outlier would be an important contribution towards the reconstruction of the early Devonian paleogeography of north eastern Scotland, such an evaluation is considerably hampered by inadequate exposure.

The remainder of this chapter is an attempt to summarise and interpret the sedimentology of the Rhynie Outlier. As the available evidence is provided by an extremely small portion of the total sequence, the resulting conclusions must be open to speculation. In many cases interpretation has been made by comparison with sediments of the Gamrie Outlier where greater exposure has allowed a more realistic comparison with recent literature.

In comparison with the previous analysis of the sediments of the Gamrie Outlier, the Rhynie sequence has been subdivided into the following five subfacies (tabulated in stratigraphic order):

Dryden Flags and Shales	Subfacies C5
Quarryhill Sandstones	Subfacies B4
Tillybrachty Sandstones	Subfacies Blc
Lower Red Shales	Subfacies Cld
Basal Conglomerate	Subfacies A4

3.7(ii) Subfacies A4 : Basal Conglomerate

As indicated in Chapter 2, the basal conglomerate is not exposed naturally in the Rhynie Outlier although minor excavation and augering have provided small samples and confirmed its presence. In all of the few available sites, the Basal Conglomerate has consisted of a pebble/gravel grade conglomerate comprising essentially very local Dalradian semi-pelitic and psammitic schist. Very little sand grade material is present within the conglomerate, and in appearance the deposits are closely comparable to much of subfacies A2 and A3 (Crovie Conglomerate and Middle Old Red Sandstone Conglomerate) at Gamrie. The Gamrie deposits have been interpreted as alluvial fan sediments, deposited essentially by sheetflood processes. It is possible that the basal deposits at Rhynie are also of this nature, but the limited evidence available prevents a more specific interpretation.

3.7(iii) <u>Subfacies Cld</u> (Lower Red Shales)

The deposits of Cld are assumed to follow subfacies A4 in all parts of the Outlier, but as with subfacies A4 they are at present very poorly exposed. Minor excavations have also provided much less evidence than for A4. As far as can be established, subfacies Cld consists largely of reddish brown siltstones, with occasional quite coarse structureless sandstones. The Geological Survey record calcareous nodules, and one excavation during the present study has produced small reddish-brown calcareous nodules.

Clearly on such scant evidence interpretation is difficult, but in general form the sediments are comparable to parts of subfacies Cla and Clb at Gamrie. If such a comparison is reasonable, the sediments of subfacies Cld may represent a relatively stable Piedmont floodplain, occasionally inundated by ephemeral sheet floods, but generally with a low accretion rate conducive to the development of calcrete nodules.

3.7(iv) <u>Subfacies Blc</u> (Tillybrachty Sandstones)

3.7(iv)a <u>Description</u> (figs 2.3, 2.4: Plate 2.1)

The Tillybrachty sandstones (see Chapter 2), although only poorly exposed over a short sequence, display many features comparable with those already included in the consideration of subfacies Bla (The Dundarg Castle Conglomerate) in the Gamrie Outlier.

The sediments are coarse, with cobble grade conglomerates being common in lower portions of the sequence. Lateral and vertical facies variations are significant and although poor exposure prevents the characterisation of the sequence in terms of specific lithofacies, many distinct features are apparent.

Erosion surfaces are distinct and laterally persistent and small channels are evident, infilled by cobble/pebble/gravel grade detritus. The bulk of the sequence is made up of poorly bedded thick pebble/gravelly sandstones.

At higher stratigraphic levels, the conglomerate component declines and is replaced by abundant cross-stratified sandstones with thin mudflake conglomerates. Siltstone veneers may occur locally, but are never persistent.

3.7(iv)b <u>Interpretation</u>

The predominance of coarse grade sediments, frequent erosion surfaces, but lack of distinct stratification makes the lower part of the Tillybrachty sequence quite comparable in form to Subfacies Bla in the Gamrie Outlier. The environment is envisaged as one where small, possibly ephemeral channels, crossed a distal alluvial fan surface. The coarse sediments accumulated primarily by vertical accretion in interchannel areas as thin 'sheet flood' episodes submerged the majority of the fan surface.

Unlike subfacies Bl at Gamrie which is considered to grade into a distal fan Piedmont plain, the Tillybrachty sandstones show the presence of more permanent, relatively high energy processes within higher levels. Clearly, although ephemeral events may have existed during the earliest history of the deposits, they were certainly not maintained. Instead, the increasing abundance of cross-stratified sandstone units, although initially small, confirms the existence of an environment where large quantities of sand were transported as small subaqueous dunes. Even so, flow was clearly variable as thin silt veneers indicate periods when fine sediment was deposited from out of suspension. The presence of even small amounts of mudflake conglomerate suggest that the river system was actively re-working its floodplain, a feature very common in modern braided stream environments.

The interbedding of vesicular lava and sandstone noted in Chapter 2 implies that contemporaneous volcanic activity existed within the Caledonian Highlands and poured thin lavas onto the Piedmont plain.

The apparent introduction of sediment transport as subaqueous dunes mixed with evidence of channelling strongly suggests that the fluvial system was becoming more permanently established, and possibly shallow and braided in form. Such an environment would occur in relatively distal alluvial fan regions. The intimate relationships between such a system and volcanic rocks may imply that transport occurred axially along a valley or depression, flanked possibly by subfacies A4 and even Cld, and also thus within easy reach of Highland volcanicity.

3.7(v) Subfacies B4 (Quarryhill Sandstone)

3.7(v)a Description (fig 2.5 : Plate 2.2)

Due to its former use as a building stone, the Quarryhill Sandstone provides quarry exposures at several localities and levels within its sequence. These are detailed and summarised in Chapter 2. The sequence shows significant changes throughout its development, which may be summarised as follows:

(i) The lowest deposits are dominated by thick, massive and (more rarely) cross-stratified sandstones with occasional fine sandstones and thin gravels. Channelling is apparent, but on a large scale (up to 1.7 m deep and at least 30 m wide).

(ii) At higher levels, distinct persistent siltstone horizons occur and show rootlet horizons and burrows. The sandstones no longer show distinct channel forms, except when deep erosion occurs with a subsequent infilling of coarse mudflake conglomerate.

(iii) Towards the top of the sequence cross-stratification is quite rare, bed thickness is much reduced, and massive sandstones predominate.

3.7(v)b Interpretation

The lowest portion of subfacies B4is a direct reflection of the trends apparent in subfacies Blc and interpreted as showing the development of shallow braided channels. In the Quarryhill Sandstone sequence, such braiding could have existed as the deposits are comparable to recent braided systems discussed in more detail in Chapter 3.

Unfortunately, the destruction of floodplain material is often regarded as typical of braided stream systems (Dceglas, 1962), and although the lowest deposits show very little floodplain sediment, (but do contain mudflakes as confirmation of erosion of floodplain or bank material) the higher deposits do show well developed floodplain sediments.

In highest deposits, erosion of floodplain material is occasionally extreme, but overall with increasing level the chances of floodplain preservation are very good, and in most instances floodplain sites were conducive to the development of a substantial fauna and flora (see Chapter 7).

An alternative model must therefore be sought in place of a simple braided system, and an anology with Moody Stuart's (1966) low sinuosity non braided model is considered more likely.

Basically, it is considered that the channel sandstones may have formed analogous to common braided stream sandstone units, but the braiding was probably confined to a broad major zone or channel thus allowing development of floodplain deposits in adjacent areas. The accretion rate was probably quite high, but each braided unit was able to overlie floodplain without marked erosion, except in rare instances when a form of crevasse-splay breached portions of floodplain close to the main channel system and formed the thick mudflake conglomerate deposits.

As noted earlier, the Rhynie sedimentary basin may have been confined within a narrow depression within the Caledonides with transport axially along such a 'valley'. Such a restriction would assist in the development of a low sinuosity non-braided model by concentrating deposition within a small area.

The reduction in thickness and amount of cross-stratified sandstone is assumed to be an indication that the system declined in magnitude, and was eventually replaced by more typical floodplain deposits - eventually subfacies C5 - Dryden Shales.

3.7(vi) Subfacies C5 (Dryden Flags and Shales)

3.7(vi)a Description

As indicated in Chapter 2, the Dryden Flags and Shales are very poorly exposed at Dryden and in the Den of Wheedlemont. A logged profile of the main exposure in the Den of Wheedlemont is illustrated in Fig. 2.6 and clearly indicates that the sequence is dominated by siltstones and thin sandstones. The siltstones are reddish brown to grey, micaceous and generally internally massive, although where poorly developed horizontal bedding is preserved, plant fragment may occur on bedding surfaces.

The thin sandstones are rarely coarser than fine sand grade and most commonly are pale grey to buff and highly micaceous. Ripple lamination, massive beds, thinly flat bedded sandstones and lenses of sandstone are most common. Erosion is rare, generally confined to scouring at the base of ripple laminated units. Erosion on a greater scale is implied by relatively large mudstone intraclasts within a single sandstone unit showing a low angle cross-stratification. Surprisingly, the sequence shows no evidence of desiccation or the development of burrows or rootlet horizons quite common in lower parts of the Rhynie succession.

3.7(vi)b Interpretation

In an earlier section (Chapter 3, page 190) the common features of floodplain deposits were reviewed in some detail, and many of the conclusions are relevant here.

The sediments of the Dryden Shales are considered to have been deposited in a floodplain environment as the available evidence suggests that accumulation was predominantly by vertical accretion of low energy bed-forms. Calcrete nodules are absent, and probably indicate a relatively high accretion rate. Many authors (see page 190) have described similar sequences of sediments, and have attributed their origin to overbank flooding of fluvial channels.

In the earlier discussion about subfacies Cla, Clb and Clc in the Gamrie Outlier thick sequences and large volumes of siltstone were taken to imply that the site of deposition was perhaps a Piedmont floodplain or Playa environment.

Insufficient evidence is available from Rhynie to give strong support to such conclusions, and furthermore although low energy bed-form predominate much larger proportions of ripple laminated sandstones are present, and although again there is no evidence of channel deposits, the sediments are much more comparable to levee or topstratum deposits (see Allen, 1965a) than to Piedmont/Playa deposits (see Williams, 1970).

It is therefore concluded that the deposits of subfacies C probably represent the local and somewhat extensive preservation of floodplain deposits, in an area adjacent to a more permanent channel system (perhaps subfacies B, the Quarryhill Sandstones, although as mentioned the available evidence does suggest that with time this subfacies was declining in magnitude).

Perhaps the most interesting deposits of the Outlier, the Rhynie Cherts, occur within the Dryden Shale sequence, and as noted in Chapter 2 are renown for their well preserved fauna and flora (Plate 2.5).

Published sections through the Rhynie Cherts fig 2.7 indicate that sandstones, cherty sandstones, mudstones and cherts make up the sequence but have unfortunately been logged by early Geological Survey geologists or botanists. In consequence, no detailed structure of the sequence is available.

During the present study only loose, waste debris, from early trench sites could be studied, but nevertheless, significant points do arise.

The sandstones and cherts contain abundant organic material, and most important is extremely well preserved in the chert horizons where plant material is often preserved in a growth position. In thin section, preservation of plant material is most striking. Plant cross-sections occur undeformed, cell structure is preserved in excellent detail, and spores and sporangia are quite common. (Plate 2.5)

Generally, the cherts consist of microcrystalline, cryptocrystalline and opaline silica showing broad regions of undulose extinction, and cracks and pores infilled by opaline silica.

The formation of the cherts would appear to be a relatively simple procedure, as the mechanisms are generally agreed. Most silica is considered to be transported in solution as H_4SiO_2 (Krauskopf, 1967), and the production of a supersturated solution of silica may rapidly lead to the formation of a colloid.

Silica precipitating from a supersaturated solution aggregates as small SiO_2 molecules which are rapidly surrounded by a lyosphere of water molecules serving to stabilize the charge on the SiO_2 aggregates. This results in a colloid where the silica, the dispersed phase, is surrounded by water molecules, the continuous phase.

Dehydration of such a colloid would simply reduce the continuous phase and lead to the formation of a gel which would eventually crystallise an amorphous silica.

Such a standard mechanism of chert formation would easily allow:

(i) the rapid production of a SiO_2 gel capable of supporting the plant structure in growth position,

(ii) preservation of excellent cellular detail, as the resulting SiO_2 is cryptocrystalline,

(iii) the colloid/gel would easily support dispersed organic matter and ferruginous staining common within the cherts,

(iv) dehydration would give shrinkage cracks and allow eventual infills of opaline (hydrated SiO_2) silica,

(v) shrinkage would also cause a certain amount of distortion causing the slight undulatory extinction recognised in some cherts.

Although there is probably nothing unusual about the mechanism of chert formation, the major problem remaining (as with most cherts) is the origin of the silica, and its concentration to supersaturated levels. Most chert studies have a convenient source of silica from microorganisms (diatoms, sponge spicules etc.). In the present instance no such assistance can be called upon.

The presence of volcanism in the lowest deposits of the Rhynie Group may be significant, as volcanic activity is often considered to elevate the SiO_2 content of ocean waters and allow chert precipitation. At the present stage no conclusions can be made, except that the lavas produced by the early volcanism were certainly not acidic, and no evidence of hydrothermal fluids have been recorded in the vicinity, whether the latest stages of the Caledonian Orogeny could have generated silica rich fluids must remain open to speculation.

CHAPTER 4

SOURCE AND DISPERSAL OF SEDIMENTS OF THE GAMRIE AND RHYNIE OUTLIERS

PART A - PALEOCURRENTS

4.1 Introduction

During the course of this study an attempt has been made to establish the depositional environment of the sediments with an eventual aim to reconstructing the local Old Red Sandstone paleogeography. With this in mind it is important to recognise the source of detritus, both as an indication of source area composition and regional paleoslope. Temporal changes in paleoslope may thus be recorded and provide useful information as to the initiation and heirarchy of tectonic events.

Previous studies of Orcadian sediments have relied mainly on sedimentary structures and detrital mineralogy for evaluating source area. In the present study, sedimentary structures are only locally abundant, and in no way can be regarded as fully adequate. Use has therefore been made of all, possible information including sedimentary structures, conglomerate composition and detrital mineralogy.

4.2 Paleocurrents in the Sediments of the Gamrie and Rhynie Outliers

Sediments of the Gamrie and Rhynie Outliers range in grain size from coarse boulder-grade conglomerates to mudstones, and show a similar wide range of sedimentary structures from which evidence may be derived as to the direction of transport of sediment and hence local paleoslope.

The restricted exposures, and lack of laterally equivalent sections, prevent the analysis of paleocurrents by conventional statistical techniques and hence many of the results presented here lead to conclusions which it must be acknowledged are tentative, particularly in an environment where a high degree of spatial and temporal variation may be expected.

Geologists have long recognised the value of sedimentary structures in the interpretation of flow directions since the early work of Sorby (1859) when small-scale cross-bedding structures were recognised as being the product of ripple migration.

Structures involved in this study include both symmetrical and asymmetrical ripple marks, small and large scale cross stratifications, scour marks, and parting lineation. In the conglomeratic sequences paleocurrent evidence is sparse and attempts have been made to employ clast orientation to assist in the study.

Recently Barret (1970) considered fluviatile paleocurrent indicators, noting the reliability of certain structures. Reliability was considered in terms of:

(i) ease of measurement of a structure

(ii) the efficiency of the depositing system in generating a structure.

(iii) local variations in current variation related to a structure

He ranked the structures he used in order of decreasing reliability. Parting current lineation, initially taken to imply flow parallel to the lineation (Sorby 1859, 1908) and later established by Allen (1966) from flume studies to develop during flow in the lower part of the upper flow regime, was considered to be of highest reliability being easy to measure, and being derived from high velocity currents suffered very little internal variation. Parting current lineation unfortunately is rare in the Gamrie sediments, being most commonly developed in the flat-bedded sandstones occurring within the finer parts of the sequence.

Ripple cross-lamination was considered of high reliability, but ranked lower than parting current lineation because of the difficulty in obtaining measurements. Sorby (1859) recognised such bedding as being the product of ripple migration, the mechanics of formation being evaluated by Simons and Richardson (1961), Allen (1966), and McKee (1965) who confirmed Sorby's views and established that such structures originated in the lower part of the lower flow regime. A greater variability in flow occurs, and this combined with the difficulty in accurately measuring such structures lead Barret to rank them lower than parting lineation.

Ripple cross-lamination is abundant in the finer grained sediments at Gamrie, both symmetrical and asymmetrical forms being developed. These two broad groups of ripple form are frequently used by geologists, with the notion that the former records wave action, whilst the latter records current direction, even though McKee (1965) demonstrated that both wave and current action could produce symmetrical and asymmetrical forms. During the present study ripple-marks used as paleocurrent indicators were only measured on bedding plane surfaces, ripple cross-sections being used in as many instances as possible only to record symmetry or asymmetry.

Larger scale cross-stratification, was rated low by Barret, flow variation is greater, and outcrop difficulties increase the error present in obtaining accurate results. Such bedforms are rare in the Gamrie sediments, and in the majority of examples recorded accurate results were impossible due to the nature of the outcrop. Well developed planar cross-stratification has in several cases only confirmed the 'quadrant' from which currents originated. Reliable results were only considered from well exposed planar foresets, or when trough or scour axes could be measured.

Of lowest reliability, Barret considered slump folds and drifted material, both of which are of very restricted development at Gamrie.

The recognition of such a hierarchy of bedforms is an important step in evaluating the significance of paleocurrent results, but the author feels that other factors must be taken into consideration, that is to say, the significance of the paleocurrent trends must be considered in terms of the sedimentary environment. Ripple cross-lamination may reliably record local flow directions and hence local paleoslope, but in floodplain sites may offer no information relevant to regional paleoslopes. In contrast, vectors means of cross-stratification data from coarse members laid down by meandering and braided streams are considered a reliable estimate of paleoslope (Bluck 1971, Williams 1969). Slump folds are present at Gamrie, and although Potter and Pettijohn (1963) consider that such structures reflect paleoslope, the slope concerned is probably of very local significance only, for example, point bar or dune foresets.

Similar structures of restricted value have been considered by Donovan and Archer (1975) who recognised relationships between mudcrack patterns and slope; slope frequently being no more than floodplain undulations. Wave-ripples were also considered by these authors, who observed that although wave-formed symmetrical ripples commonly were reliable indication of proximity of shore lines (i.e. symmetrical ripples formed parallel and close to the shore) under more intense conditions, such as stronger winds, oscillation ripples were frequently perpendicular to wind direction and hence unrelated to shoreline and paleoslope. Similar phenomena have also been recorded by the present author in other recent shallow lakes.

4.3 Gamrie Paleocurrents

4.3 (i) Eastern Section

In the lowest deposits of the eastern section the coarse nature and mode of origin of the sediments prevents the development of bedforms useful for paleocurrent studies.

At Fleckies Meadow an alternative approach has been attempted involving measurement of the orientation and inclination of large blade and disc shaped blocks (nomenclature of Zingg 1935, and corresponding to an elongation index of Johanssen 1965 greater than 2). The deposits have been interpreted as forming purely under the influence of gravity (Chapter 3, page 137), and similar although finer grade deposits have been observed by the author and Donovan (pers comm) who conclude that clast orientation in such deposits is largely bimodal. A dominant mode almost parallel to the accreting slope was found, with a minor mode dipping into the slope at a low angle. Clast orientation generally reflects maximum slope.

The results of the present study are illustrated in Fig. 4.1, a stereographic projection of clast orientation and inclination in which the data has been corrected for tectonic dip. A major mode is developed with a corrected mean orientation of 290° N and a mean inclination of 21°. A minor mode inclined at 7° into this slope occurs towards 116° N, almost diametrically opposite. By comparison with the recent analogues the major trend is interpreted as recording the direction of dip of the 'scree', being also confirmed by the minor mode. The inclination of the blocks is approximately 15° and this may be a reliable estimate of the order of the slope of the original conglomerate surface. The low angle of spread of the data is interpreted as confirming a wedge shaped scree rather than a cone shaped fan at this locality, a detail perhaps confirmed by the 200° N strike of the cliff like buried landscape at Fleckies Meadow, i.e. perpendicular to the computed maximum slope (200° v 290°).

At Quarryhead, conglomerates are observed to wedge out to the south, but as only one section is available, and as the original shape of the deposit is unknown, no inference can be made. At higher levels at Quarryhead fluvial deposits do develop, and limited cross-stratification and parting lineation suggests an easterly or north easterly origin for paleocurrents, becoming south easterly in origin at highest levels. These results are illustrated in Fig. 4.2 but the very limited data available prevents the change in source from being reliably regarded as a trend.

The overlying Dundarg Castle Conglomerate sequence offers very little paleocurrent evidence, figure 4.2 summarises the sparse data available. Although several authors have attempted to relate pebble orientation to direction of stream transport, as a paleocurrent tool the idea has numerous drawbacks. Nevertheless due to the lack of an alternative, orientations of pebbles were measured on bedding plane surfaces at several points throughout the conglomerate sequence. Well-sorted conglomerates were chosen, presumably having been longer in the transporting system, and in particular, poorly packed conglomerates where adjacent particles exert less influence on each others' orientation. In all cases the long axes of 50 pebbles from each site were measured.

Recent studies of fluvial pebble fabrics have demonstrated that a bimodal distribution of long axes is common, interpretations of this bimodality are controversial. Essentially the orientations are taken to be parallel and perpendicular to flow (demonstrated by Carver (1971) from theoretical considerations, and confirmed experimentally by Johanssen 1965). Ruchin (1958) and Sengupta (1966) resolved the problem into one of stream gradient, high slopes were claimed to result in the orientation of long axes parallel to flow low slopes allowing the alignment of long axes perpendicular to flow. The interpretation of the Dundarg Castle Conglomerate sequence as a distal alluvial fan deposit places them within the low gradient class where a dominant mode would be expected perpendicular to flow. The results of the present study (Fig. 4.3) do show such an arrangement, if the limited cross-stratification data available suggesting a south easterly source is reliable.

More recently, evidence provided by Gustavson (1974) from Alaskan glacial outwash fans contradicts the notions of Ruchin (op cit) and Sengupta (op cit) demonstrating that of twenty seven clast fabrics measured, all showed clasts oriented with their long axes perpendicular to flow even at steeper stream gradients. Similar observations have been made by Lane and Carlson (1954), Doeglas (1962), and Boothroyd (1972). With this wealth of evidence arguing against the 'stream gradient' concept it is concluded that irrespective of the accuracy of the present environmental interpretation, the orientations recorded do confirm the limited cross-stratification evidence in showing a consistent dominant mode implying a general north-west/south-east axis of flow, cross-stratal sets and trough axes indicating a south easterly origin.

In the overlying fine grained sequence a mixture of mainly symmetrical and asymmetrical ripples occur, associated with rare parting lineations and very rare large scale cross-stratifications. Fig. 4.2 illustrates this combination of paleocurrent indicators, asymmetrical ripple marks, and a thin fluvial incursion with common trough cross-stratification confirming that the passage of the sediment laden floodwaters still essentially originated from the south east.

4.3 (ii) Western Section

Data for the western section are illustrated in Figs. 4.4 and 4.5. No information is available for the lowest deposits, the Crovie Conglomerate, but the Crovie Sandstone Formation has been interpreted as a distal representation of the conglomerate and sparse cross-bedding indicates a southerly origin for this sequence (Fig. 4.4).

The Crovie Siltstone sequence (Fig. 4.4) continues to reflect this southerly origin although data is not abundant, the evidence displayed in Fig. 4.4 being a combination of symmetrical and asymmetrical ripple marks.

Similar implications from similar structures are further supported by directions obtained from the East Harbour Formation, but the limited evidence available implies that a wide spread of paleocurrent trends existed throughout the sequence, possibly a reflection of the floodplain type of environment in which sediments were deposited.

Unidirectional paleocurrents are not recognised during these finer grained deposits until the introduction of thick ripple cross laminated sandstones in the West Harbour Formation. Fig. 4.5 illustrates the south or south easterly origin for sediments of the lower West Harbour Member while higher deposits of this Formation (Fig. 4.5) show a swing to the south west. This swing to the south west is accentuated by cross-stratification in the highest deposits of the western section, the Castle Hill Sandstone Formation, where planar cross-stratification in the lower portion is derived from west of south, becoming more biased to the west at higher levels with the introduction of trough cross-stratification.

4.3 (iii) Central Coastal Section

Although the sediments of the Central Coastal Section appear to be one of the most controversial portions of the Gamrie sequence due to their unique facies content and unique conglomerate composition (see page 273),

they provide little in the way of paleocurrent indicators to confirm any hypothesis about sediment origin.

The majority of evidence is crude, coming from parameters such as pebble imbrication and lag deposits. Cross-stratification is only rarely developed, and as the sea cliffs rarely offer such structures in three dimensions assessment of flow direction must be made with caution.

Overall, a southerly origin is apparent, with very little indication of any strong east or westerly influence.

4.3 (iv) Middle Old Red Sandstone

The abundance of conglomerate throughout the Middle Old Red Sandstone sequence precludes the development of abundant and reliable paleocurrent indicators. Nevertheless, some portions of the sequence particularly near Mill Shore do show poorly developed cross-stratification and imbrication supported by frequent lag gravels in the lee of larger clasts. Even so the evidence is sparse, and illustrated in Fig. 4.5.

The results show a considerable spread, but significantly a marked swing towards western quadrants is apparent, a feature which supports the similar trend developed beneath the Middle Old Red Sandstone unconformity, and also supports evidence presented later during conglomerate source area reconstruction.

4.3 (v) Summary and Conclusions (Gamrie Outlier)

Paleocurrent evidence suggests that in many respects the Gamrie Outlier was an intermontain basin during Lower Old Red Sandstone times, with drainage originating from the east, south and western quadrants at various times throughout the history of the Outlier.

In the eastern section a local easterly source was rapidly overtaken by drainage from a general south easterly direction.

Analogous sediments in the west show a south to south westerly origin and may be comparable to the southerly trends observed in the Central Section, although as noted later conglomerate composition strongly suggests that the sediments of the Central Section are in fact stratigraphically much higher than the Crovie or Dundarg Castle sequences. A westerly swing in drainage is apparent with ascending stratigraphic level, culminating in the Middle Old Red Sandstone conglomerates which show a strong westerly derivation.

In the east, paleocurrent trends are relatively stable above the basal conglomerate, suggesting that this initial upward variation was not a gradual change, but instead was the result of a more vigorous south easterly supply actually overlapping the initial localised basal conglomerate supplied directly from the east. (The interdigitation of the two facies does confirm this view - Chapter 3).

The Siltstone facies at New Aberdour only provides evidence from symmetrical ripples, asymmetric ripples, and occasional parting lineations, and although Barret (1970) considered the two to be reliable paleocurrent indicators the significance of the paleocurrents themselves in floodplain facies (see Chapter 3,) must be open to question. The sediments have been regarded closely comparable to modern floodplain sediments and the movement of floodwater over such sites may bear no relation to regional paleoslopes except in the very broadest sense. Fortunately, a fluvial incursion is recorded at the top of the Siltstone sequence exposed at New Aberdour Shore, and confirms that drainage was still originating from the south east, although the admittedly scant evidence does suggest perhaps a more southerly source.

From the semi-radial pattern of paleocurrents it has been assumed that an intermontain basin situation existed during Lower Old Red Sandstone times. At higher stratigraphic levels a westerly source becomes more and more apparent in the coarsening-upward profile. Sedimentological considerations suggest that sediments at higher levels belong to more proximal locations, and together with paleocurrent evidence may combine to suggest that during the Lower Old Red Sandstone period tectonic events were initiated which led to the development of a paleoslope to the west or south west, strongly influencing the Crovie Group sediments. The perpetuation of the westerly source into the Middle Old Red Sandstone may also imply that the initial tectonic events were merely the precursors to those eventually causing uplift and deformation of the Lower Old Red Sandstone sequence prior to the advance of the major Middle Old Red Sandstone alluvial fans.

4.4 (i) Rhynie Paleocurrents

As with most aspects of the geology of the Rhynie Outlier, the source and transport of its sediments is difficult to ascertain due to very poor exposure. Of the major stratigraphic groups recognised during this study the Basal Conglomerate and succeeding Red Shales etc. plus the Dryden Shales offer no paleocurrent information of any form. The Tillybrachty Sandstones offer only three cross-stratified units which suggest that immediately prior to the deposition of the Quarryhill Sandstones at least some transport was from south-east quadrants.

The majority of the information at present available comes from the Quarryhill Sandstones, which during the present study have provided information from the following sources:

(i) channel axes,

(ii) asymmetric ripple-marks,

(iii) symmetric ripple-marks,

(iv) cross-stratification,

(v) parting lineation,

(vi) drag or tool marks,

(vii) mudclast imbrication,

(viii) mudcrack orientation.

The results from these sources are illustrated in Fig. 4.6. Perhaps the most significant point to arise is that the general direction of transport is from south to northerly quadrants, as indicated by channel axes and confirmed by cross-stratification and asymmetric ripple marks. Unfortunately, though parting lineation and drag marks would normally be expected to add support to these conclusions, no support is given by the present results. Only two sets of symmetrical ripple marks have been observed, these are of no value to the present study partly due to the small number of readings, but also symmetrical ripple marks are a poor indicator of paleoslope (Donovan and Archer 1975). Mudcrack orientation offers further support of the prevailing direction of channel axes, the major crack direction being approximately north south with minor cracks at 70° to this. In recent floodplain muds Donovan and Archer (1975) recognised the preferential orientation of mudcracks parallel and perpendicular to the local paleoslope. A major crack pattern was developed along the strike of the slope, with minor cracks developed perpendicular to this. It is considered that the crack patterns recognised at Rhynie probably conform to this arrangement.

4.4 (ii) Summary and Conclusions (Rhynie Outlier)

Clearly, the amount of evidence obtained from the sediments of the Rhynie Outlier is far from adequate. It is considered that the only meaningful conclusions that can be drawn from the present study are that the river systems transporting the majority of the Rhynie sediments were flowing in general northwards toward the 'Orcadian Basin', and more significantly not towards the Midland Valley Graben.

PART B - SEDIMENT COMPOSITION

4.5 Introduction

In order to achieve a more complete palaeogeographic reconstruction, evidence must be sought which aids not only the delineation of the basin of deposition, but also the limits and size of the source area including where possible information on the relief and climate.

Many attempts have been made to utilize detrital mineralogy as a guide to provenance (see Blatt and Christie 1963, Blatt 1967a, b, Connolly 1965, and Pittman 1963). Both light and heavy minerals have been applied to this end, but most workers outline a complexity of problems including re-cycling of grains, intra-stratal solution, and the effect of different relief and climate upon the resultant mineralogy.

In the Gamrie Outlier conglomerates are abundant in both Lower and Middle Old Red Sandstone sequences, and have been studied in detail in an attempt to provide more information to supplement the previously discussed palaeocurrent evidence and aid source area reconstruction.

Detrital mineralogy has been looked at in less detail for several reasons. Primarily, when an abundance of rock fragments exist in the sediments sandstone petrography can hardly add further evidence as to source area composition. Also, the majority of the sequences in the Outlier show very significant changes in grain-size with ascending stratigraphic level making an analysis of petrographic composition very much open to criticism. A brief consideration of the distribution of heavy minerals occurring in the basement in the immediate vicinity of the outlier demonstrates that the most resistant species could easily be derived from all around the area. The less resistant, but more useful varieties such as kyanite, andalusite, and cordierite either have not been in the source area (which is highly unlikely) or diagenetic processes have reduced their chances of survival to a minimum.

4.6 (i) Conglomerate Composition (Gamrie Outlier)

A variety of rock types characterise the conglomerates of the Gamrie Outlier, and during the present study thirteen rock types have been identified.

4.6 (ii) Total Pebble Assemblage

1. Granite - A variety of granitic rock types occur, most common being an equigranular feldspathic granite. Porphyritic granite and microgranite have been observed, but their abundance does not warrant individual classes for these rock types. Several specimens of a foliated granite have been identified, but these are also extremely rare. Granitic fragments usually occur highly weathered and corroded, making a subdivision into specific types a difficult and undesirable proposition.

2. Felsite - A reddish orange felsite, frequently containing large quartz or feldspar phenocrysts, forms a resistant and readily identifiable rock type. Granite and felsite dominate the igneous components of all conglomerates studied.

3. Andesite - A rare and always highly weathered constituent. Andesite pebbles tend to be very small, and of a purple vesicular variety.

4. Dolerite - Several specimens of an apparently fine grained basic igneous rock presumed to be a dolerite have been observed, but being highly weathered this is difficult to confirm. The abundance of this material is also so low as to make its presence somewhat insignificant.

5. Gabbro - As with dolerite, several highly weathered specimens of a garnetiferous gabbroic rock have been found, having a similar appearance to weathered Gabbro/Norite in the vicinity of Huntly. Although confusing when deeply weathered, the igneous rock types are somewhat easier to classify than the metamorphic rock types which dominate all conglomerates. For this reason metamorphic rock fragments have been allocated to seven

groups during this study.

6. <u>'Pure' Quartzite</u> - A variety of clean 'vitreous' quartzite, occurring in well rounded resistant easily identifiable pebbles.

7. <u>Granular Quartzite</u> - A dark granular gritty looking quartzite.

8. <u>Vein Quartz</u> - Vein Quartz is a common addition to all conglomerate sequences, and occurs as white and milky varieties.

9. <u>Psammite</u> - A large proportion of metamorphic assemblage consists of grits, quartzose and feldspathic flags, and psammitic and semi-psammitic schists. An apparent spectrum of rock types fall into this category, and it is felt that without specialist knowledge of these rock types further subdivision would possibly prove meaningless or even misleading.

10. <u>Pelite</u> - A pale grey variety of semi-pelitic schist, very similar to the local Dalradian Macduff or Banffshire slate, occurs in many sequences as small elongate fragments.

11. <u>Andalusite Schist</u> - A semi-pelitic schist with abundant large andalusite and cordierite porphyroblasts. Andalusite schist is restricted in its occurrence in conglomerates, and tends to occur either as very large, or small angular, fragments.

12 <u>Mica Schist</u> - A rare addition, always in extremely small fragments, and possibly are of the above andalusite schist with no readily apparent prophyroblasts. This is certainly not always the case, as some specimens are clearly more psammitic varieties than any true andalusite schist that has been observed.

13. <u>Meta-Conglomerate</u> - A variety of metamorphosed gravel common in the local Dalradian basement, and characterised by abundant blue gravel sized quartz grains and abundant feldspar.

4.6 (iii) Pebble Suites

Of the thirteen pebble types recognised, a maximum of five form the bulk of most conglomerates, i.e. granite, felsite, quartzite, psammite and pelite. The remainder occur only as minor additions. Although individual rock types may provide valuable evidence as to the source area, a consideration of figure 4.7 shows that many of the rock types listed virtually surround the Outlier. For this reason it is considered more important to look at the distribution of assemblages or suites of rock types in the conglomerates.

A consideration of Figs. 4.8, 9, 10 allows the separation of at least five pebble assemblages or suites.

1. A Psammitic suite
2. A Granitic suite
3. A Quartzitic suite
4. A Slate suite (A)
5. A Slate suite (B)

Both the granitic suite and the slate suite (B) may be subdivided further, but for simplicity this has been avoided, instead such subdivisions will be discussed later.

1. The Psammitic suite is dominated by quartzose and feldspathic psammitic metasediments, with minor additions of andalusite schist and meta-conglomerate. The assemblage is totally restricted to the Quarryhead and Fleckies Meadow series of outcrops, and thus only includes the scree, talus, and gully fills immediately overlying the Dalradian Basement. The very nature of these deposits, and the sensitivity of the composition of the conglomerates to the local basement composition confirms the close proximity of the conglomerates to source.

2. The Granitic suite is dominated by psammitic, pelitic, and semi-pelitic schists, but contains an abundant supply of granite and felsite

pebbles plus a vast amount of feldspar gravel. The distribution of the granitic suite is restricted to:

(i) The Dundarg Castle to New Aberdour coastal section,

(ii) Parts of the Central Coastal section, both east and west of Pennan.

The Dundarg Castle Conglomerate granitic suite sequence offers the most complete conglomerate sequence in the Outlier, and demonstrates some interesting features.

The conglomerates of this sequence are initially dominated by psammitic, pelitic and semi-pelitic schists and perhaps should ideally be separated as a separate 'sub-suite'. Porphyritic felsite is introduced first, initially in small quantities and associated with a small amount of feldspar gravel. The amount of feldspar gravel increases dramatically, and then granite is introduced. Both granite and felsite increase in abundance rapidly before continuing relatively unchanged throughout the remainder of the sequence. Initially the size of both granite and felsite pebbles is small, the size increasing with increasing abundance.

In the Central Coastal section, the Sandy Haven Conglomerate (although inaccessible - see Chaper 1, pages 51-58) appears to be rich in feldspar gravel, and is presumed to be granitic in composition. The overlying Pennan Head Conglomerate has a composition closely resembling the granitic suite exposed in the east, but the uppermost conglomerates of this section, the Pennan Conglomeratic Sandstone sequence, is essentially of granitic suite composition, but with a significant admixture of grey slate strongly resembling the slate rich conglomerates exposed in the west, and presumed to be Macduff or Banffshire Slate.

To the west of Pennan, the conglomeratic sandstones beneath the Middle Old Red Sandstone unconformity are again of a granitic composition, but significantly lacking any of the grey slate.

3. The <u>Quartzitic suite</u> contains large amounts of a clean 'vitreous' quartzite, and is entirely restricted to the Need Haven Conglomerate in the Central Coastal Section to the east of Pennan. Several important features are associated with this conglomerate; firstly, the pebble assemblage is quite unique in its high content of quartzite, the variety of quartzite is uncommon in all other conglomeratic sequences, granitic material is rare, and finally as discussed in Chapter 3 (page 180) a significant change in facies takes place with the transition into the Need Haven Conglomerate.

4. <u>Slate suite (A)</u> occurs only in the Crovie Conglomerate and overlying Crovie sandstone sequence, and it is almost entirely composed of grey slate similar to the local Macduff or Banffshire Slate. Granitic and felsitic detritus is absent from this suite.

5. <u>Slate suite (B)</u> is also dominated by the same grey slate as in suite (A) but in addition a small but significant amount of granite and felsite is present in this assemblage. Slate suite (B) is first recognised in the coarsening portion of the Lower Old Red Sandstone in the west of the Outlier in the Castle Hill Sandstone sequence. Conglomerates of a very similar composition occur in the immediately overlying Findon Conglomerates of Middle Old Red Sandstone age, and also in the Middle Old Red Sandstone conglomerates further to the east. The slate suite (B) conglomerates of the east are slightly different in that much higher proportions of granitic, felsitic and the metamorphic rocks common to the granitic suite are present in the assemblage.

The 'minor constituents' previously mentioned tend to strengthen the above sub-division, for example:

(i) Meta-conglomerate is only abundant in the conglomerates belonging to the psammitic suite. Isolated fragments are found in the granitic suite, but always in amounts much less than 1 percent.

(ii) Andalusite schist occurs only in small quantities, and is essentially restricted to the psammitic suite. Again, isolated fragments do occur in the granitic suite, but andalusite schist only occurs in abundance within a few metres of the basal unconformity, and even then only in situations where such rocks are abundant in the Dalradian basement.

(iii) Gabbro and Dolerite have only been found in the Need Haven Conglomerate, i.e. Quartzite suite.

(iv) Andesite has only been observed in a rather mixed assemblage at the base of Slate suite (B) conglomerates immediately overlying the Middle Old Red Sandstone unconformity. (This mixed assemblage also probably deserves the status of a separate suite, but for the sake of simplicity this has been avoided.

(v) Mica-schist has only been recorded in the granitic suite.

(vi) Two major varieties of quartzite have been observed; a dark granular variety common to the granitic suite, and a clean vitreous variety restricted to the quartzite suite.

(vii) Vein quartz is ubiquitous, and therefore of no value in the present study.

4.6 (iv) Spatial Distribution of Conglomerate Assemblages

It is clear from Figures 4.8, 4.9 and 4.10that the pebble assemblages just listed are not vertically and laterally consistent. Two completely dissimilar sequences exist during Lower Old Red Sandstone times. In the east, the lowest conglomerates rest directly upon the Dalradian basement and strongly reflect the immediate basement composition. Little transport has taken place, resulting in a very immature assemblage of detritus, the psammitic assemblage. Although these lowest conglomerates are overlapped by sandstones and conglomeratic sandstones, the conglomerate composition does not alter initially (other than a decline in unstable andalusite schist fragments). With ascending stratigraphic level, granite is introduced, then felsite, plus a new assortment of pelitic and psammitic schists, forming the granitic assemblage.

In the west, all conglomerate occurrences in the fining upward portion of the sequence are slate rich, no granite, felsite or the metamorphic assemblages common in the east are recorded. In the coarsening part of this sequence, slate still predominates, but minor additions of granite, felsite, quartzite and vein quartz are common.

The implications are therefore that:

1. the earliest sediments were locally derived, a phenomena confirmed by sedimentological considerations.
2. the major part of the sequence in both east and west is derived from different and contrasting source areas. In the east a granite/felsite rich, psammitic metamorphic terrain provided detritus, whilst in the west pelitic rocks predominate in the source area.
3. these results are consistent with the basic results of the paleocurrent study.

4.6 (v) Source Area Reconstruction

At present North East Scotland is dominated by a diverse assemblage of Dalradian metasediments. Bounded to the west by highly deformed Moine rocks and penetrated at numerous points by granitic and gabbroic intrusions, the region may be loosely considered as a synclinal arrangement with the Gamrie Outlier in the centre, flanked by Upper Dalradian which itself is surrounded by Lower Dalradian metasediments.

The present day outcrop may not be an accurate representation of the Devonian rock type distribution, but it must remain the only guide to the evaluation of the Devonian source area and paleogeography. An attempt has been made in Fig. 4.11 to summarise the geology of north east Scotland, and to indicate the present day distribution of rock types encountered in the Old Red Sandstone conglomerates. In most cases these maps demonstrate that similar rock types may be obtained from past distribution, then many of the rock types may be of little value in source area reconstruction.

Even so, with this in mind, the Moine far to the west could provide little detritus of the nature of that preserved at Gamrie, being composed of very 'high grade' metamorphics, granulites, schists, migmatites, and widespread calc-silicates (Anderson and Owen 1968). The limited paleocurrent evidence helps to reduce the source area possibilities, but can probably do no more than indicate that the depositing currents in the east are biased towards the east of south, whilst those in the west are biased to west of south.

Mackie (1925) carried out extensive, detailed work in the north east of Scotland, and fortunately he applied his great experience to the problem of the origin of the conglomerates in the Gamrie Outlier. His conclusions were simple but to the point, "... sandstones and granites provided pebbles", the sandstones (presumably Dalradian metasediments) he felt were no indication of the source area. He considered granites to be of great value, and claimed positive identification of the following types:

1. Rubislaw granite (more specifically he claimed Rubislaw granite from Donmouth near Aberdeen)
2. Correnie granite.
3. Bennachie granite.
4. Vein material from the Correnie massif.
5. Garnetiferous norite comparable to that of Battle Hill near Huntly.

The location of these sites are shown in Fig. 4.12. Unfortunately the stratigraphic horizons of these samples are unknown, the only real assumption that can be made is that due to the lack of granite in the Middle Old Red Sandstone conglomerates his samples must have been derived from Lower Old Red Sandstone conglomerates. There is some implication from Mackie's report that they may have been derived from the conglomerates of the Central Coastal section.

Mackie's results would clearly indicate an origin of detritus from a south or south east quadrant. Unfortunately, Mackie also collected several sphene bearing granites which he considered were derived from the Abriachan or Helmsdale granites, and the Inchbrae granite. Both of these granites are situated far to the west, and are actually beyond the Great Glen Fault zone. Although Mackie had great experience of local geology it is felt that the latter identifications are eroneous as:

1. Recent work (Stephenson 1972, and Mykura, pers. comm.) along the Great Glen suggests that the fault was active during Lower Old Red Sandstone times, the area being a graben with sediments derived from north west and south east. Such a situation would prevent transport of detritus across such a rift towards Gamrie.
2. No Moine detritus has been recognised at Gamrie, but would be expected to accompany any granite derived from west of the Great Glen.
3. The Lower Old Red Sandstone conglomerates at Gamrie are rich in feldspar detritus, suggesting that granite was unstable under the existing conditions. Also ephemeral flow conditions prevailed in the lower granite rich sequences, and hence detritus would not be expected to be transported over such great distances.

In conclusion, therefore, although it may appear 'convenient' for the purpose of the present study, the westerly source implied by Mackie is rejected, but his evidence supporting a south east source is retained.

From megascopic comparisons the author has noted a distinct similarity between the granite clasts and the local granites of Peterhead and Correnie, but variation within such granites is large and casts doubt on the value of such visual comparisons.

Fig. 4.11 is a series of maps illustrating the present day distribution of the major rock types in north east Scotland, and a consideration of this map and the five defined conglomerate assemblages allows the following conclusions to be drawn.

1. The granitic assemblage could theoretically be drawn from east, south or western quadrants (Fig. 4.11), but the occurrence of andalusite schist tends to favour an easterly or southerly source. The southern outcrops of andalusite schist are intimately associated with gabbro and garnetiferous norite which would have presumably been transported with such schist had these regions been in the catchment area. Schistose and quartzitic grits occur in both east, west, and south. The southern exposures were probably beyond the watershed supplying the Midland Valley with detritus instead, while the western exposures would presumably supply Banffshire slate. (Slate of this nature is never recordeed in the granitic assemblages) Thus an east or south easterly source of detritus would allow a pebble assemblage comparable to that of the granitic assemblage to accumulate.

2. The slate assemblage (B) is comprised largely of Banffshire slate (Fig. 4.11) and supports the paleocurrent evidence suggesting its derivation from the west of south. Some mixing of granitic detritus with slate detritus had occurred but feldspar gravel is very restricted in its abundance, and granite fragments are very small. Both of these observations may combine to suggest that granitic material was either re-worked, transported over large distances or very rare in the source area.

3. A local supply of detritus is envisaged for slate assemblage (A) as no extra material is added to this conglomerate. Paleocurrent evidence from adjacent sequences suggests that fluvial channels may have originated

from the south.

4. The Psammitic assemblage is again of local origin, and consists of detritus which may originate from the Dalradian basement immediately to the east. Paleocurrent evidence supports this.

5. The quartzitic assemblage is slightly more problematical in that it could theoretically be derived from east, west or south of the present outcrop. Paleocurrent evidence implies that its derivation was from the south, and the well rounded appearance of the fragments suggests that transport may have been considerable. The lack of granite and local slate detritus precludes east and west supplies, and most of the quartzite outcropping in the south was probably within the catchment of the Midland Valley sedimentary basin. Similar quartzites do occur in the Rhynie conglomerates associated with small amounts of schist. It has been concluded that the Rhynie conglomerates may have been derived from west or south westerly sources (see page 267) and also that a connection between the Rhynie and Gamrie Outliers is not unlikely (see page 309). It may therefore be possible that the quartzite assemblage has been transported from well south of the Outlier, perhaps even from beyond the Rhynie Outlier.

4.6 (vi) Discussion and Interpretation

The psammitic suite is clearly of local derivation, and of very restricted local extent. A marked change in pebble composition between the Fleckies Meadow (psammitic) conglomerate and the overlying Dundarg Castle (granitic) conglomerate confirms the earlier paleocurrent implications of changing source areas. The change is not regarded as being a tectonically activated change, instead, local screes and gully fills having been overstepped by the more rapidly advancing 'granitic' fans from the south east. The lowermost Dundarg Castle conglomerate initially lacks granitic detritus and felsite, but consists of the same metamorphic rock fragments as the higher granite bearing conglomerates. The introduction of felsite, then felsite plus feldspar gravel, and finally felsite plus granite plus abundant feldspar gravel is regarded as being a record of the progressive unroofing of the granitic source area to the south east.

The presence of a granitic suite of pebbles in the conglomerates of the Central Coastal section implies that the piedmont plain/playa facies overstepped by slate (B) conglomerate suite in the west is overstepped by a granitic suite of pebbles in the east and central sections, as the highest conglomerates (the Pennan Conglomeratic Sandstones) show a significant influx of Banffshire Slate which is consistent with the advancing slate fans of the west (see fig 4.13). This conclusion has significant implications as at present there is no evidence of sedimentation after the piedmont floodplain/playa facies in the eastern section. It would seem therefore that the extensive siltstone deposits were probably overlain by granitic conglomerates and sandstones in a coarsening upward sequence in a manner similar to that occurring in the western sections. Furthermore, the presence of Middle Old Red Sandstone conglomerate resting directly upon the siltstone facies and observed by the Geological Survey would imply that a considerable amount of erosion was related to the development of this unconformity.

The presence of a granitic suite of pebbles beneath the unconformity at Pennan implies that considerable downcutting also occurred in this region, removing the uppermost slate rich granite suite conglomerates.

In a later section (see page 310) the detailed paleogeography of the northern portion of the Gamrie Outlier is discussed, and with reference to this section many aspects of paleocurrent trends and conglomerate composition can be explained.

The eastern Coastal Section stands as outlined above, but the Western Section could easily (from Fig. 4.11) have had a simple local supply area from the south which was eventually encroached upon by detritus from and including the unroofing of the nearby Longmanhills Granite. The present day outcrop is small, and presumably an even smaller Old Red Sandstone outcrop would only provide minor amounts of granite which are in fact present in the sequence.

In the Central Coastal Section it was concluded that the quartzitic assemblage was most likely derived from quite long distances to the south. The probable link with the Rhynie Outlier (page 309) assists this conclusion whilst the detailed paleogeography illustrated in Figs. 4.13, 22 and 24 would also explain how the varying influence of east and westerly fans could provide conglomerates in the Central Section with either granitic or slate rich composition. The eventual predominance of westerly derived slate in the highest conglomerates of this sequence is also consistent with the view that the source area swung to the west in late Lower Old Red Sandstone times. Such a conclusion has further reaching implications in that it does suggest that the conglomerates of the Central Section do in fact belong to the coarsening portion of the Megacycle fully evident only in the Western Section. Thus conglomerate composition may assist stratigraphic dating of at least small portions of the sequence.

4.7 Conglomerate Composition (Rhynie Outlier)

As already mentioned, conglomerate composition is regarded as providing the most significant evidence for source area evaluation. The sediments of the Rhynie Outlier unfortunately offer only a small amount of such evidence.

The basal Conglomerate would normally be expected to show significant local variations in composition due to variations in Basement composition, but only one outcrop has been located, and in this the basal conglomerate comprised only pelitic and semi-pelitic detritus.

The Tillybrachty Sandstones contain the most conglomerate material but even so this is still unsufficient. In the lower portion of the sequence one major conglomerate horizon exists with a total assemblage of:

(i) vein quartz

(ii) porphyritic felsite

(iii) quartzite

(iv) pelitic schist

(v) psammitic schist

(vi) vesicular and amygdaloidal andesite

At higher levels the abundance of coarse detritus declines markedly, and the scant evidence provided by these levels must be viewed with caution as it may represent a simplified resistant residual population.

The significance of the Tillybrachty Sandstone detritus is considered as follows:

(i) no granite detritus is readily apparent

(ii) a clear quartzite is abundant and comparable to that recorded in the Central Coastal Section of the Gamrie Outlier

(iii) a purple vesicular and amygdaloidal andesite is quite common in the lowest conglomerates

The lack of granite is difficult to understand as abundant granite is present virtually all around the Outlier except in western quadrants. If sediment was initially derived from the western quadrants, then as well as containing little or no granite material, the sediment would be expected to contain large amounts of quartzite, schist, and gneiss. As indicated above, the conglomerate of the Tillybrachty Sandstones contains a large amount of quartzite and schists of various forms. Therefore although evidence is scant, it does seem possible that a small amount of evidence does exist to support the notion that sediment was derived from the west or south west.

The presence of vesicular andesite at the base of the Tillybrachty

Sandstone sequence adds further information to the timing of the extrusion of this lava. The Geological Survey initially indicated that the andesite occurred within the Tillybrachty Sandstone sequence, but added that it was in fact interbedded with the upper deposits of the Tillybrachty Sandstones. The evidence provided by conglomerates at the base of the Tillybrachty Sandstone sequence confirm that within the catchment at that time (regarded earlier in this chapter to lie to the south or south west) andesitic lavas were extruded and eroded during early Tillybrachty Sandstone times, and therefore the lavas may possibly have been extruded onto the floodplain areas developed during the deposition of the Lower Red Shales.

Later in this chapter the possibility of a connection between the Rhynie and Gamrie Outliers is considered. From the study of conglomerates in the Gamrie Outlier, it was concluded that quartzite rich conglomerates within the Central Coastal Section were probably derived from areas to the south of the present outcrop. If such a link existed between the two Outliers then clearly, the quartzite rich conglomerates of the Rhynie Outlier could clearly have provided or shared a source of detritus for the deposits in the Central Coastal Section at Gamrie. This is discussed further in later sections (see page 310).

4.8 Sandstone Classification

4.8 (i) Introduction

Okada (1971) reviewed the great variety of schemes available for the classification of sandstones, and indicated that as the proportion of matrix (important in many schemes) increases with decreasing grain size, Folk's (1968) concept of textural maturity is not applicable. He also convincingly demonstrated that mineral composition was a function of grain size, and therefore sandstone composition data should always be accompanied by grain size data. Although only briefly considered, the classification scheme proposed by Okada (op. cit.) has been adopted here. It has a three fold organisation:

(i) grain size

(ii) clay matrix and cement

(iii) composition of framework constituents

The sandstones are divided into wackes and arenites depending on whether they have more or less than 15% matrix. The subdivisions of arenites and wackes are illustrated in Fig. 4.14.

Generally, the object of classifying sediments is to provide a basis for the study of regional and stratigraphical variations in composition. As mentioned already, during the present study conglomerates are abundant and regarded as a better indication of source rock composition than detrital mineralogy. Nevertheless, detrital mineralogy has been considered briefly in order to support, if possible, the conclusions already drawn from the study of conglomerate composition. For this purpose some modifications have been made to Okada's basic scheme. Basically, as Okada demonstrated that mineral composition varied with mean grain size, and the sediments of the study area offer a whole range of sediment grades, sandstone composition has been evaluated from a restricted grain size range. Only medium and fine grained sandstones have been considered. Furthermore, as the present study is only concerned with source area implications, the abundance of matrix (either clay or cement) is not regarded as relevant and has therefore been omitted from the composition diagram.

4.8 (ii) Sandstone Composition (Gamrie Outlier)

The results of the present study are illustrated in Fig. 4.15 and 4.16, and are considered to offer reasonable support to the evidence provided by analysis of conglomerates.

In the eastern coastal section, the low feldspar content of the Quarryhead sandstones compared to the Dundarg Castle sandstones and sandstones within the New Aberdour Siltstone sequence, is a direct consequence of the lack of granite in the source area of the Quarryhead sediments. The predominance of quartz reflects the abundance of psammitic metasediments and the weakness of the pelitic schists failing to produce rock fragments in any great quantity. The greater abundance of feldspar in the Dundarg Castle sediments indicates the strong influence of the granitic source area, while the apparent reduction in the New Aberdour Siltstone sequence is considered largely related to differences in grain size of the samples. The apparent increase in rock fragments in the New Aberdour sediments is directly related to the abundance of mica (A clear indication of the influence of even the mode of deposition on sediment composition within the same basin).

In the western coastal section similar conclusions may be drawn. The Crovie sediments are deficient in feldspar, and lack granitic material in their conglomerates. At higher stratigraphic levels, with the introduction of granitic detritus, feldspar content increases. More significantly in this instance, the increase of feldspar content during the East Harbour sequence confirms the presence of granitic material in the source area long before conglomerates occur in the sequence to offer direct evidence. Again, the increase in rock fragments in the

East Harbour sediments is directly related to the abundance of mica.

In the Central Coastal Section, sediments of the Pennan Head and Pennan Conglomerate sequences demonstrate a granitic influence by their feldspar content, but do not show any changes related to the increasing abundance of pelitic detritus in the higher sediments. They do, however, contrast strongly with the Pennan Sandstones, which, being dominated by only quartzite clasts show an almost monomineralic composition. Two points complicate this latter observation. Firstly, conglomerate is rare in the Pennan Sandstone sequence, quartzite being stable would be expected in preference to other rock types. Secondly, the occurrence in the sequence of iron/manganese rich horizons or 'pans' (see chapter 7) may indicate abnormal early diagenetic conditions which may have proven unfavourable for the preservation of feldspar minerals.

On the whole, detrital mineralogy is considered a useful addition to conglomerate analysis in the study of source area composition, the nature of its usefulness being demonstrated in the detection of granitic influence in the East Harbour sediments too fine to offer conglomerate evidence.

As will be discussed in the following section, the value of detrital mineralogy alone is considered very limited.

4.8 (iii) <u>Detrital Mineralogy</u>

Three broad mineral groups have been considered during the present study. The abundance and details of mineral types have been observed in an attempt to evaluate the possible support detrital mineralogy can give towards source area reconstruction. The mineral groups considered are:

(a) quartz

(b) feldspar

(c) mica

4.8 (iii)a Quartz

Throughout the sediments studied a variety of quartz types occur and the proportions of strained, unstrained, and composite grains have been estimated. In all cases the sediments are dominated by monocrystalline quartz, the proportions of strained and unstrained varieties varying throughout the succession and tending to support the interpretations made from analysis of conglomerate clast compositions.

As mentioned, grain size plays an important role in studies of detrital mineralogy, in the case of detrital quartz, coarser sediments were observed to have higher proportions of polycrystalline fragments than equivalent finer-grained sediments, and similarly, strained quartz grains were more abundant in coarser deposits than in their finer grained counterparts.

Inclusions are common in quartz grains throughout the total sequence, and therefore are unlikely to be of value in source area reconstruction. Fluid gas inclusions are most common rutile, chlorite, and muscovite also having been recognised

Quartz grains are commonly attacked by carbonate cement and are heavily fretted.

In the past many attempts have been made to relate the nature of quartz type to its igneous or metamorphic precursor. Blatt and Christie (1963) virtually ended such studies by concluding that the nature of quartz extinction was an unreliable criterion for source determinations. Part of their argument was based on the argument that undulatory extinction could only be successfully evaluated by study with a universal stage. Furthermore, they pointed out that most rocks were capable of supplying strained quartz grains, and only certain volcanic extrusives were reliable sources of unstrained grains. Polycrystalline fragments are possibly of greater value, but even so, much work is still required in order to characterise the various optical criteria such as suturing, inclusions, grain shape, and crystal size (Potter et al 1972). Blatt (1967) attempted this suggesting that crystal size and morphology may help to distinguish gneissic and granitic polycrystalline quartzes.

In the present examples, polycrystalline quartz varieties are reasonably common and three distinct forms have been found to be most common:

Type I Large composite fragments showing marked undulose extinction and interlocking sometimes sutured grain boundaries, crystal size is generally large.

Type II Large composite fragments with strained or unstrained extinction and sharp, straight crystal boundaries. Crystal size is again large, and inclusions are abundant.

Type III Smaller composite fragments with small internal crystal size and polygonal boundaries producing an interlocking mosaic of fairly uniform sized crystals. This latter grouping may show some slight elongation and suturing of crystals, but not on any marked scale.

The first variety of quartz (Type I) is more abundant in the lower portion of the Dundarg Castle Conglomerate Formation and is considered to correspond to the higher proportion of metamorphic rock fragments present.

The second variety (Type II) dominates the majority of the sequence in the east and equates with abundant granitic detritus in this portion of the sequence.

The third variety (Type III) is common throughout, but mostly in lower parts of the sequences, related to grits and psammitic schists.

Although this relationship has not been studied in any great detail a series of diagrams (Figures 4.17 and 4.18) summarise the general distribution of quartz types throughout the Outlier.

In the eastern coastal section at Quarryhead (Fig. 4.17) unstrained quartz is uncommon, a significant point considering the strong metamorphic influence of the source area. The high proportion of composite grains is attributed to the abundant psammitic metasediments in the source area. Composite grains are frequently attributed to igneous sources, but in this instance the fragments are of types I and III, sutured grain boundaries confirming the metamorphic origin.

In the Dundarg Castle sequence (Fig. 4.17) composite grains are less frequent, monocrystalline strained grains predominating. This feature would be expected from the plutonic igneous rocks of the source area, but the apparent trend towards higher proportions of unstrained grains at higher stratigraphic levels (Fig. 4.17) is difficult to explain as conglomerate evidence does not indicate any significant change in the source area. Several factors must be considered:

(i) Granite detritus would intially rapidly produce strained quartz grains.

(ii) Felsite being more durable would produce quartz grains more slowly, adding more unstrained grains, in distal sites.

(iii) Felsite would therefore produce a greater proportion of slightly strained or at least less strained quartz grains in distal sites.

(iv) It is also possible that the inevitable decrease in grain size in the higher deposits (distal sites) means that strained grains will be less apparent in thin section. Also, it is well known that strained and composite grains are less durable and would therefore be expected to decrease in abundance in more distal sites.

In the eastern coastal section it is concluded that quartz type can compliment the evidence provided by conglomerate analysis, but this relies more on specific typing of the polycrystalline or composite varieties.

In the western coastal section (Fig. 4.16) a similar trend exists, but as felsite is not present in any great quantity it cannot be responsible for the trend towards higher proportions of unstrained grains in the East Harbour Formation. It is concluded that such a trend is due to the overall finer grain size of these deposits.

In the Central Coastal Section (Fig. 4.17) evidence is sparse, but the Pennan Head and Pennan Conglomerates have a composition reflecting their granite rich source area. More specifically, the composite grain type II is abundant and reflects this granitic source. At higher stratigraphic levels pelitic material is introduced into the conglomerates, but this trend is not reflected in the quartz grain types. In the highest deposits, the Pennan Sandstones, the distribution of quartz types is similar to the underlying granite rich sequence, yet the Pennan Sandstones are quartzite rich. A consideration of composite grain types resolves this problem in that the type III grains are most abundant and reflect this quartzite source rock. Suprisingly, although quartzite has made a significant contribution to the Pennan Sandstone composite grains are quite rare.

In summary, the overall value of quartz type in the evaluation of source rocks appears to be quite restricted, its greatest potential being in the study of varieties of composite grains (a region very close to the study of rock fragments themselves!). It would appear that quartz type is very sensitive to grain size variations in samples, and possibly also to degree of transport. If the complex variables can be resolved, then perhaps quartz type may be of greater value. In proximal environments such as in the present study, the technique is regarded as too sensitive to many variables.

4.8 (iii)b Feldspar

Orthoclase feldspar is the most abundant feldspar throughout the succession, occurringin a wide range of weathering states from complete 'ghost' grains to slightly sericitised forms. Numerous grains show simple twinning. Microcline is a common constituent and demonstrates its greater resistance to weathering by its frequent lack of alteration. Many feldspar grains show perthitic intergrowths.

Feldspar content is quite variable, ranging from 47% in the Dundarg Castle Conglomerate sequence to zero in the Pennan Sandstone Formation.

The potassium feldspars observed are cloudy, generally twinned orthoclase feldspar. Plagioclase feldspars are mostly albite and andesine compositions, they are quite uncommon, but show very little alteration when present suggesting that their absence is lack of availability rather than subsequent destruction. Untwinned plagioclast feldspars, although easily confused with quartz, are uncommon.

Feldspar is a potentially valuable tool in source rock evaluation, for example, acid plutonic igneous rocks should provide a large amount of simple carlsbad twinned orthoclase feldspar (possibly zoned) along with a variety of twinned plagioclase feldspars. This contrasts sharply with metamorphic sources which supply unzoned orthoclase and untwinned plagioclase (Blatt et al 1972). Because of the wide range of temperature/pressure conditions prevailing, metamorphic rocks theoretically provide somewhat distinctive plagioclase feldspar assemblages. For example Blatt et al (op. cit.) regard feldspars with compositions An 0-7 to be low grade greenschist facies, An 15-30 to be epidote-amphibolite facies, whilst the range An 8-14 is absent or low in medium grade schists. Plagioclase of this latter range is regarded as abundant in granites. Granulites show small amounts of plagioclase with a composition in the An 30-40 range and are frequently associated with perthitic orthoclase feldspars. Orthoclase should predominate over microcline in high grade metamorphic facies except migmatites.

In the present situation, in the light of such comments, feldspar would certainly appear to be of very little value. Orthoclase feldspar is in many cases abundant, certainly dominating microcline and occasionally zoned. Perthitic intergrowths are frequent, but never abundant. Plagioclase feldspar has been studied only briefly, and without the use of the universal stage, and shows compositions ranging between An 10 and An 45, with values in the order of An 35 being most common. The majority of plagioclase feldspars are twinned.

Clearly the orthoclase feldspar could suggest that derivation was from a granitic source, or a high grade metamorphic source. The plagioclase implies possibly high grade metamorphics, but such rocks (Granulites) would provide a lot of perthite, and the proportion of perthite is certainly not high. The paucity of plagioclase with low An values does not support the idea thatgranite was a major contributor yet in the Dundarg Castle Conglomerate sequence where granite pebbles are abundant, the values of plagioclase composition would not appear to support their presence!

A consideration of the immediate and most probable source area adds further confusion in that plutonic igneous rocks, a range of metamorphic rocks and possible migmatites all may have contributed to the sediments at any one time. Clearly, in such an assembly (apart from true migmatites, an assembly which is supported from clast composition) a whole range of feldspars would be ubiquitous (see also Pettijohn et al 1972). Therefore, although the present study has indeed only been brief, the value of feldspar as an indicator of provenance is regarded as being low, particularly in regions such as the Scottish Caledonides where the 'feldspar producers' offer fairly wide but similar ranges of composition.

Perhaps the most valuable, but again restricted type of conclusion to arise, is that the total absence of more calcium rich feldspars implies that the few basic intrusions possible in the source area did not contribute detritus in any great magnitude. The restriction to such a conclusion is unfortunately a severe one - calcium rich feldspar is extremely unstable relative to other plagioclase feldspars, and would not be expected to survive even mild soil forming processes.

4.8 (iii)c Mica

Although the proportion of muscovite, biotite, and chlorite present within the sandstones has contributed to the 'rock fragments' component of the sandstone classification diagrams, the interpretation of the significance of these minerals is quite difficult as no major studies have been made of the relationship to source rocks.

In general, granites are considered to produce mainly biotite with smaller amounts of muscovite. Pegmatities probably offer the reverse. Metamorphic rocks may offer all three, but in the present instance the local source area would be expected to contribute mainly muscovite and chlorite.

Folk (1974) considers that many factors may influence the availability of mica in sediments, and for this reason it is considered that mica is of little value in source area reconstruction. Folk (op. cit.) points out that biotite is probably the most abundant mica in source rocks, yet, in sediments muscovite is on average four times more abundant. The abundance of the three micas is dependent upon:

(i) their differing durability

(ii) their differing chemical stability

(iii) their differing depositional characteristics due to their shape making them act hydraulically differently to other minerals.

(iv) the possibility of the early introduction of authigenic mica.

In the present instance, biotite and chlorite have suffered extensive hematisation, whilst muscovite remains relatively unaltered. The size of biotite and muscovite grains is quite variable, but in general biotites occur in larger flakes than do muscovite. Chlorite always occurs in very small flakes only. No authogenic micas have been observed.

While large biotites have been observed in sediments such as the Dundarg Castle sequence which have a known granite rich source area, large biotites have also been found in the Crovie Sandstone sequence, a sequence containing no granite material. In the latter instance, large biotites have been observed in composite quartz grains of type I, regarded as being of metamorphic origin.

While biotites may not directly assist source area reconstruction, it may give indirect evidence. For example, in the West Harbour and Castle Hill Sandstone Formations, biotite is abundant, often in quantities greater than the normally dominant muscovite. Granitic material is uncommon in sediments of this part of the sequence, but the relative abundance of biotite may indicate that granitic material has been rapidly destroyed to liberate the high quantities of mica, and therefore that granite may have been a far more important component in the source area than at first apparent from a study of conglomerates alone. Unfortunately very little conglomerate material exists to allow a study of the possibility of a metamorphic source of the biotite to be considered.

Overall, in the present study, mica is regarded to be of little value in source area reconstruction being variably susceptible to many different factors. If such factors can be evaluated and allowances made, biotite may offer information in addition to conglomerate evidence (such as the example in the previous paragraph) but alone is probably of little value.

4.9 (i) Sandstone Composition (Rhynie Outlier)

Figure 4.18 summarises the results of the present study, again analysis has been restricted to medium and fine grained sediments.

The earliest sediments represented in Fig. 4.19 are from the lower red shales. Compositionally, these lowest deposits are distinct in their high rock fragment component, being comprised of a variety of pelitic, psammitic and schistose metasediments, with an even larger component of quartzitic fragments. On top of these 'genuine' rock fragments, the total rock fragment component in the figure is boosted by quite a large amount of mica - predominantly muscovite and chlorite, no biotite having been observed.

Orthoclase is common, but 'simple' untwinned orthoclase is common, no microcline or perthite have been observed. In addition, much of the orthoclase appears as large strained grains.

The overlying Tillybrachty Sandstones have a high quartz content presumably in direct response to the high quartzite content of the conglomerates. The rock fragment component is low, due to the virtual absence of any form of mica. Although quartzite contributes significantly to the conglomerates, rock fragments are uncommon in the sandstones, those present are regarded as being of quartzitic origin as they show highly sutured composite quartz forms.

Plagioclase is quite high, but orthoclase still predominates with large amounts of mircrocline and perthite being present.

The Quarryhill Sandstones are quite comparable with the underlying Tillybrachty Sandstones, but differ in a higher feldspar content, with notably higher plagioclase. Rock fragments are boosted by a large mica content. In particular a vast increase in the proportion of biotite. Rock fragments sensu stricto are very rare.

The Dryden Shales again compare very favourably with underlying sediments, but differ in a lower feldspar content and a high rock fragment component due solely to the abundant mica present.

4.9 (ii) Discussion and Conclusions

The detrital mineralogy of the Rhynie sediments is considered to offer little information of value towards source area reconstruction. A major point of interest however has been the presence in quantity of strained orthoclase feldspars in the lowest sediments. This evidence, combined with quartzitic composite quartz fragments combines with a distinct lack of mica to suggest that earlier indications that the sediment may have been derived from the west or south west could have some support in the detrital mineralogy. Firstly, the strained feldspars could have been derived from earlier forceful granitic intrusions which may have suffered further deformation during later stages of the Caledonian Orogeny, or, secondly, the strained feldspars may have been derived from gneisses or migmatites. Early permissive granites occur both east and west of the present outcrop of the Rhynie Outlier as do migmatites, but the western region could provide both migmatitic material, early Caledonian granite and quartzite. Such evidence therefore although hardly conclusive does add at least some support to the views made earlier.

PART C - PALEOGEOGRAPHIC RECONSTRUCTION

4.10 (i) Introduction

In recent years much work has been carried out on the sedimentology of the Orcadian Basin (see Donovan 1971, Foster 1973, Plimmer 1974, McAlpine 1978), but to date no attempt has been made to reconstruct the paleogeography of the basin as a whole. This omission is partly due to the problems involved in the interpretation of paleoslopes in marginal and distal lacustrine sediments.

The object of this section is to attempt to delineate more precisely the limits and paleogeography of the Orcadian sediments of the south eastern Moray Firth, and to place these deposits into some regional context.

Broadly speaking the Lower Old Red Sandstone sediments of the Gamrie Outlier were deposited in a series of continental alluvial environments marginal to both the Orcadian Lake and the 'Caledonian Mountain Massif'. Deposition was initiated by Alluvial Fan coarse clastics, but with successive deposition aggradation of the alluvial depositional surface resulted in fan recession and the establishment of a broad piedmont surface which was stable for long periods of time. In many places aggradation was slow and extensive calcrete profiles developed. Earth movements towards the end of the Lower Old Red Sandstone times caused an advance of rejuvenated fans across this piedmont plain, and heralded the initiation of earth movements which eventually caused the folding and faulting of the Lower Old Red Sandstone sediments prior to the deposition of thick Middle Old Red Sandstone conglomerates. The Middle Old Red Sandstone deposits of the area confirm that alluvial processes were renewed, and rapidly dominated the scene. Some evidence suggests that these fan deposits may have flanked a lacustrine environment, and toward the top of the exposed sequence the southernmost extent of the

Orcadian Lake is apparent in the Findon Fish Bed.

The previous considerations of sedimentology, paleocurrent trends and conglomerate composition concluded that the Gamrie Outlier existed essentially as an intermontain basin open to the north.

4.10 (ii) Cause and Timing of Uplift

Dewey (1969 and 1971) and Dewey and Pankhurst (1970) provide details of the Caledonian Orogenic events, including envisaged cross-sections through north Britain up to and including the Devonian period. They demonstrate a hypothesis that the initiation of a Bennioff zone, and eventual closure of the Lower Paleozoic 'proto-Atlantic Ocean' (Iapetus) resulted in the Caledonian earth movements responsible for the uplift of what eventually became the Old Red Sandstone continent. Bott (1964, 1965) had previously provided a working hypothesis for basin origin, recently applied by Leeder (1972) in his outline of Border Paleogeography, largely based on the presence of crustal tensional stress set up during upper mantle flow northwards towards this newly developed Benioff zone.

The orthotectonic zone of the Scottish Highlands remained relatively stable, and bears evidence of a long and involved thermal history, during which time rising magmas ascended from the underlying Benioff zone. This rise of magma is well demonstrated by the abundant 'newer granites', and contemporaneous volcanic outpourings of the Lorne lava plateau.

Post-tectonic activity has been dated by Brown et al (1968) based on granite crystallisation dates. He concluded that the period of maximum intrusion was 400 - 390 m.y. ago, although the range of events covers the period 430 - 370 m.y., and points to the long term availability of granitic magmas. Brown noted that the climax of granite emplacement was some 20 m.y. after the regional metamorphic country rock was 'closed' to argon, concluding that magma remained at depth until the end of the main tectonic event, after which they permeated to higher levels simply due to isostatic processes.

Modern petrographic and structural analysis of the Scottish Dalradian has resolved the Caledonian orogenic event into a number of episodes of deformation and re-crystallisation, the culmination being migmatisation (Sutton 1965). Recent K - Ar dates suggest that radiogenic Argon was accumulating by 470 m.y. and hence the Dalradian metamorphic peak was pre 470 m.y. ago (Harris et al 1965). Harper (1967) recognises accelerated cooling of Dalradian metasediments between 450 and 430 m.y. and relates this to post-metamorphic uplift and folding. This uplift was associated with the intrusion of 'forceful' granites such as those of Kennethmont, Auchedly, Ben Tirrel etc. (Pankhurst 1970) and followed at around 400 m.y. by the introduction of the Aberdeenshire newer granites - for example Peterhead, Aberdeen, and Bennachie (about 404 m.y.). These late permissive intrusions form the bulk of the Grampian intrusions and demonstrate the extension of deep seated thermal activity into the Devonian.

In the Midland Valley of Scotland sedimentation began in the Gedinnian (Friend 1967) or slightly earlier (Westoll pers. comm.) and thick sediments accumulated there are proof of the significant downwarp relative to adjacent areas. Thin sediment accumulation on bounding blocks associated with thin lava flows confirm the relative uplift of these areas.

Richardson (1967) has provided valuable palynological evidence relating to the timing of Old Red Sandstone sedimentation north of the midland Valley Graben. The Dryden shales containing the Rhynie Cherts are now considered to be of late Siegenian age (Richardson pers. comm.), possibly early Emsian, whilst an Emsian age for the Strathpeffer sediments is proposed (Richardson 1967). Emsian ages have been suggested on similar grounds by Collins and Donovan (1978) for the Ousdale Mudstones of south

Caithness; and as mentioned previously an Emsian age has been suggested (Collins pers. comm.) from poorly preserved spores extracted from lowermost deposits of the Crovie Group at Gamrie.

It seems, therefore, that the Old Red Sandstone sediments began to accumulate in the post-Caledonian orogenic episode as early as late Silurian in the more rapidly downwarping Midland Valley Graben, whereas to the north the deposits at Rhynie appear to have lagged until at least late Siegenian times, or even later at Gamrie. At Rhynie and at Gamrie the thickness of the sequence is much reduced in comparison to that of the Midland Valley (estimated to exceed 10,000 m). Rhynie and Gamrie may thus represent condensed deposits, calcrete development does indicate long periods of slow aggradation in both areas, but probably not sufficient to accommodate some 10 to 20 m.y. It does seem likely on these grounds that sedimentation began somewhat later in areas north of the Midland Valley.

Towards the middle of the Crovie Group sequence the fining upward trend reverses and progressively coarser sediments approach from the west. As calcrete developments are abundant in the lower Crovie Group succession this portion may be regarded as occupying longer time than the rapidly accumulating coarser upper portion. Tectonic events causing this coarsening probably occurred during late Emsian times, and eventually caused uplift and folding of the Lower Old Red Standstone sequence. Although sedimentological evidence suggests that Middle Old Red Sandstone deposition followed shortly after, the time gap cannot be estimated. The thickness of the conglomerate following is uncertain, certainly in excess of 400 m, but accumulating up until late Eifelian times when an extension of the Orcadian Lake allowed deposition of the Findon Fish Bed. There is no evidence at Gamrie to suggest that deposition continued for any length of time into the Givetian.

4.10 (iii) Limits of Sedimentary Basin

As mentioned previously (page 264) paleocurrent and sedimentoligical studies conclude that the Old Red Sandstone of the Gamrie Outlier was essentially derived from the Caledonian Continent immediately to the south. It is important that the limits of this basin are recognised in order to reconstruct a regional paleogeography, and in particular to evaluate the relationships between the sediments of the Gamrie Outlier and those further east. A more important problem is the relationship between the eastern Moray Firth sediments, and those of the Midland Valley Graben.

The eastern limit of the Gamrie Outlier probably extended little further to the east than the present day outcrop, although the south easterly derived alluvial fans may have extended further into the Caledonian Highlands in the south east of the area. The general southern derivation of Lower Old Red Sandstone detritus indicates that closure occurred to the south, whilst the extent of sedimentation to the west remains difficult to estimate. Ashcroft and Wilson (1976) consider that the western edge of the basin may have been controlled by the influence of the Longmanhill Granite, they suggest a degree of fault control, and in particular that the Afforsk Fault was active during Lower Old Red Sandstone sedimentation. The evidence used in support of this claim, slumped beds in the Castle Hill Sandstone Formation, is here regarded as invalid. The slumping present in these sandstones is of two forms: (1) slumped foresets on the lee side of subaqueous dunes, and (2) bank caving in higher parts of the sequence. Neither of these phenomena require tectonic instability for their development. In fact Potter and Pettijohn have used slump folds as a paleocurrent indicator (1963).
Nevertheless, the present study concludes that in the west of the Outlier sedimentation was controlled by an increasing westerly influence. The conclusions reached were that the Macduff Slate material, initially locally

derived in the lower part of the sequence was eventually superseded by a restricted assemblage dominated by slate, but with additional small amounts of granitic material. With the increasing coarse nature of the sequence a greater westerly influence is recognised until eventually Middle Old Red Sandstone fans dominate. Faulting may have influenced this development but movement along the Afforsk Fault cannot be confirmed, and cannot be supported from the nature of the sediments adjacent to this fault in the Den of Findon.

It is concluded from the present study that the Gamrie Outlier was terminated quite close to the present western margin, and as slate rich alluvial fans may be up to 75% steeper than those derived from coarse grained rocks (Bull, 1964) it may be reasonable that the Longmanhill Granite did form the western boundary to the basin. If this point is valid the influence of this granite was clearly minimal as granite content is small.

A more detailed appraisal of the local paleogeography is not so easy, Friend (1967) considered criteria such as sediment thickness and grain size parameters of Old Red Sandstone sediments in the Midland Valley Graben, and was able to evaluate relative uplift of the source area. He was able to indicate the relatively small uplift of the Southern Uplands in comparison to the Grampian Highlands, and from sediment thickness trends he concluded that the order of uplift in the Grampian Highlands was greater towards the north east.

Kennedy (1948) probably opened a path to the further evaluation of the nature and magnitude of the Caledonian Highlands by pointing out that the Highland metamorphic zones were arranged in a major 'southwestward plunging thermal anticline' in which hydrous zones (chlorite and biotite) give way regionally to kyanite towards the interior, and indicate a greater depth of overburden towards the northeast. In northeast Scotland andalusite characterises the Buchan assemblage and is regarded as coeval with kyanite development (Chinner 1966) representing high grade metamorphism at higher crustal levels. Thus by such means it may be possible to interpret the regional form of the Caledonides and hence predict the general form of the early Orcadian Basin.

Dewey and Pankhurst (1970) estimate a 12 km mean depth for the high level Buchan assemblages, and up to 20 km for Barrovian assemblages. The authors add that appeals to tectonic overpressures could not reduce these depth estimates significantly, although Fyfes (1967) re-estimation of the position of the triple point may reduce the estimates by half. Fig. 4.20 illustrates the disposition of the metamorphic isograds, and if they can reasonably be assumed to reflect pressure and temperature relationships then their present day exposure may be regarded as a measure of burial and hence topography. As mentioned some confirmation of this exists in Friend's conclusions that increased sediment thickness towards the northeast of the Midland Valley reflect greater uplift in the adjacent northeastern portion of the Grampian Highlands.

Further support for this comes from the distribution of the older forceful granitic intrusions of the region, the location of which will be a reasonable guide to regions of uplift. Migmatites also follow a similar distribution, and are reasonable evidence of deep seated processes (Turner and Verhoogen 1960) and may thus be taken as representing greater thicknesses of crust, and hence possibly topography.

Recently, much attention has been focused on potassium-argon dating of Highland metamorphic rocks. Radiometric dates relate to time and temperature during cooling and records the cessation of diffusion of radiogenic nuclide out of the system (Moorbath 1967).

Harper (1967b) considered that in general Phanerozoic K-Ar ages could be interpreted in terms of orogenic processes, in that following metamorphic re-crystallisation retentive minerals begin to accumulate radiogenic argon and with further cooling higher level metasediments accumulate radiogenic argon earlier than lower level metasediments (Harper 1967a). Dewey and Pankhurst (1970) illustrate the concept of argon fixing in terms of pressure and temperature relationships, and thus demonstrate that radiometric ages determined from argon measurements may be a reliable indication of pressure and temperature at a certain time, but more important they may allow speculation as to depth of burial.

It this concept is acceptable, then old dates will indicate metasediments which cooled early and were therefore shallowest. Younger ages would belong to deepest metasediments, having cooled latest. This concept has been termed the 'uplift cooling hypothesis'
and is regarded by Fitch Miller and Mitchell (1970) as being demonstrated "beyond reasonable doubt" in some cases. As examples they refer to the British Caledonides, the Western Alps, Eastern Alps, Appalachians, Western U.S.A., New Zealand, and the Grenville Province of the Canadian Shield.

The idea is further supported and adequately summarised by Harper (1967) who considers that the spread of K-Ar ages in any one area is specifically related to the post metamorphic cooling history, and such ages actually date a time of cooling related to uplift such that the constituent minerals of higher level sediments accumulate radiogenic argon earlier than those of lower levels.

Figure 4.21 is a reconstruction of the distribution of the 'chrontours' (K-Ar age dates) produced by Dewey and Pankhurst (1970). The age dates clearly support the implications of the metamorphic isograds, namely that the north eastern Grampians suffered relatively more uplift than the south west portions. The implications are in full agreement though that the maximum overburden appears to have been in the Inverness region, a region where early deposition of Old Red Sandstone is known to have occurred.

In relation to the present study, the metamorphic isograds combine with the K-Ar date evidence to indicate that the Gamrie and Rhynie Outliers were located within and on the axis of the chlorite metamorphic zone, and are surrounded by successively higher zones implying the presence of former mountain roots.

This evidence is significant in that:

(i) It adds support to the earlier view that the Gamrie Outlier was in fact an enclosed basin open only to the north.

(ii) It provides evidence for the possible topographic high located to the immediate west of the Outlier and apparent in the sediments of the Gamrie Outlier as a swing of paleocurrents towards the west at the end of Lower Old Red Sandstone times.

(iii) It adds support to the idea that the Gamrie and Rhynie Outliers belonged to the same intermontaine basin, and that the Rhynie Outlier probably did not drain towards the Midland Valley. This latter point would normally be apparent from paleocurrent trends, but in the present case data is sparse and acts only as a guide to paleoslope.

The relative elevation implied from such evidence also allows certain other broader points to be raised:

(i) From the implied elevation of the Grampians in the north east it would seem unlikely that a simple connection with the Midland Valley Graben could be possible. (Such a connection is implied in recent geological maps produced by the Geological Survey) Cheshire (pers. comm.) supports this conclusion and indicates that there is evidence to show that paleocurrents in the Old Red Sandstone of the Midland Valley initially show a derivation from the Grampian Highlands, but towards the north east a strong axial component is present implying closure of the Graben to the north east.

(ii) The relative high region in the Inverness area was probably weakened by the early movement along the Great Glen Fault. Stephenson (1972) and Mykura (pers. comm.) record Lower Old Red Sandstone sedimentation into the axis of the depression eroded along this fault zone, sediment being transported from both north and south of the fault.

(iii) Such a weakness was presumably responsible for the localised Lower Old Red Sandstone basins in that region, for example - Strathpeffer, where the only truly lacustrine conditions prevailed during these early times. It must be noted that such minor basins are in fact actually off the axis of the fault zone, the Great Glen Fault zone did not act as a major basin of deposition until Middle and Upper Old Red Sandstone times.

(iv) The occurrence of Lower Old Red Sandstone on the southern margin of the basin combined with a considerable gap in time before inundation by the Middle Old Red Sandstone Lacustrine development is problematical, particularly as Middle Old Red Sandstone lacustrine deposits flank the northern extension of the Highlands into Caithness. This may be related to the late Caledonian/early Lower Old Red Sandstone phase of 'isostatic' readjustment whereby numerous permissive granites were emplaced. The Grampian region appears to have been the leading plate margin, and has suffered greatest permeation of acid magmas. It would therefore be expected to suffer greatest isostatic elevation during this late orogenic episode. It is therefore possible that Lower Old Red Sandstone sediments were continually flushed from the Grampian Highlands in response to such repeated adjustments and as evidence from the Gamrie Outlier shows in its rejuvenated fans overlying

Piedmont Plain deposits. On the other hand intense adjustments to the north may be expected and thus Lower Old Red Sandstone sediments would be buried and overstepped by Middle Old Red Sandstone as the sedimentary basin subsided. It is suggested therefore that at least some of the apparent difference in elevation of the deposits of the Orcadian Basin may be due to differential subsidence in the post orogenic episode.

(v) The extension of the 'chrontours' beyond Caithness would imply relative topographic highs to the west of Orkney, and in fact such a feature is confirmed both in this region and further north in Fair Isle and in Shetland, where the author has observed a local basin margin to the west on the Isle of Foula.

(vi) Perhaps a more regional implication to arise from the present study is that as the Rhynie and Gamrie Outliers drained to the north, and this would leave only a very thin strip of the Caledonides to supply the Midland Valley Graben. This portion of the Caledonides is regarded as having suffered maximum uplift, and in fact provided as much as 15,000 m. of sediment to the northern end of the Graben. For the Caledonides to have such a relative elevation, it would seem to imply that the Rhynie and Gamrie Outliers were probably 'perched' basins.

Thus in summary, it would appear that the Orcadian Basin consisted of a subsiding elongate basin flanked by Caledonian Mountains which were broken by the Great Glen Fault, and probably subsiding slightly in the north. Sediment was derived from these highlands, transported northwards from the Grampian region and east/northeast from the North of Scotland. A major disagreement is the Mykura (pers. comm.) considers that the lacustrine environment existed to the north, and sediment derived from the highlands and the Great Glen were transported eastwards along a broad alluvial plain. From the present study the elevation of the region to the west of the Gamrie Outlier is regarded to be a significant topographic feature, and would prevent the existence of a broad easterly paleoslope from Inverness. The small outcrops of Old Red Sandstone along the south of the basin add slight support to this in that they appear to indicate that sediment transport was either northerly, or biased to the west (the evidence in support of this must be stressed as being very weak!). It is therefore considered that the more logical conclusion is that these regions supplied the northerly Orcadian Lake more directly.

Sediments began to accumulate at a very late stage of the Caledonian Orogeny when periods of prolonged stability allowed extensive calcrete development. Movement along the Great Glen Fault was also an early event, Sediments to the north of the zone having yielded Seigenian spores (Mykura pers. comm.). As the trends of the Great Glen and Gamrie and Rhynie boundary faults have a somewhat common direction, it may be possible that the faults originated during the same period of stress.

Toward the end of Lower Old Red Sandstone time, tectonism was rejuvenated, causing folding and faulting of Lower Old Red Sandstone sediments and a swing in source area to the west. This period of deformation may be analogous to the event which caused extensive folding in the north of the basin in the Walls Formation of Shetland (regarded as being of late Lower or very early Middle Old Red Sandstone age), and also, the compressive episode responsible for the development of the Struie Thrust near Inverness (also regarded as being of the same age as the Walls deformation).

4.10 (iv) Possible Connection Between The Gamrie and Rhynie Outliers

Although paleocurrent evidence is weak (particularly from the Rhynie Outlier) it has been concluded from the present study that both the Gamrie and Rhynie Outliers drained in general to the north toward the 'Orcadian Lake' or its Lower Old Red Sandstone precursor.

Recent geophysical evidence provided by Ashcroft and Wilson (1976) (discussed in more detail on page 310) indicates that the Gamrie Outlier is largely fault controlled on both east and west margins with major 020^{o} faults paralleling the regional Dalradian strike. The authors consider that such faults are Old Red Sandstone in age, and may therefore have been syndepositional. This major fault trend is similar in both Outliers, and although Ashcroft and Wilson did not extend their study as far as the Rhynie Outlier it may be possible that similar Old Red Sandstone faults also governed the shape of the Rhynie basin.

More recent studies by Ashcroft and Muir (1978) draw attention to the similarities between fault trends at Rhynie and Gamrie. If late cleavage trends are included in the consideration and taken to indicate late Caledonian structure, then they would indicate that both Outliers could easily have a common axis paralleling the axis of the Boyndie Syncline and perhaps even influenced by the 'younger basic' suite of intrusions. These latter points are illustrated in Fig. 4.22

Although no direct evidence exists, it may be pertinent to consider the Cabrach and Tomintoul Outliers in relation to the present study area. It has been indicated that the source area for the Rhynie Outlier may have lay to the west or south west of the present outcrop, it is suggested from the present study that a consideration of the composition of these outliers may provide information relative to the possible connection of these with the Rhynie Outlier. George (1965) considered that much of the Grampians initially had a covering of Old Red Sandstone, it is possible that the remaining outcrops simply represent the roots of major depressions in existence at that time.

4.10 (v) Detailed Paleogeography of the Northern Part of the Gamrie Outlier

Sedimentological studies assisted by analysis of detrital mineralogy and paleocurrent evidence are regarded to indicate a somewhat restricted sedimentary basin closed on all but the northern side. Throughout the present study similar trends in facies development have been noted in different parts of the Outlier, but significant differences in composition of detritus have served to isolate such similar facies from each other. Sedimentological evidence could provide no answer to the problems of the interrelationship between the three coastal sections at Gamrie.

Fortunately, Ashcroft and Wilson (1976) carried out a detailed geophysical study of the Gamrie Outlier and were able to provide evidence which in many ways supports the conclusions made during the present study.

Essentially, it would appear from the geophysical evidence that both the Strichen and Longmanhill granites may have influenced the local Devonian paleogeography, and also, several major faults have been identified running almost parallel with the present outcrop. These faults serve to step down the margins of the Outlier in Graben style and allow up to 1 km of sediment to accumulate in the axial regions.

In the north of the Outlier Ashcroft and Wilson (op. cit.) indicate a basement structure which could conceivably have had a strong influence on the Old Red Sandstone paleogeography. The authors were able to combine several lines of geophysical evidence to indicate that the simple Graben like structure of the southern portion of the Outlier became more complex to the north, being replaced by a series of interrelated faults modifying the trend of the axis of the basin. The structural interpretation of the basin as indicated by Ashcroft and Wilson is reproduced in Fig. 4.23, 24 and

Accepting the influence of the two granites on sedimentation, the Strichen granite providing abundant granite rich debris to the eastern section while the less well exposed Longmanhill Granite merely provided a topographic high in the Macduff Slate allowing a slate rich supply to the west. The deeper axis provided by Ashcroft and Wilson would provide a solution to the previous mentioned problems by providing a means of channelling detritus from the south of the Outlier into the Central Coastal Section. A possible reconstruction of the region summarising the evidence of the present study, but largely assisted by the basement evidence provided by Ashcroft and Wilson is illustrated in Fig. 4.24.

4.10.(vi) Destination of Drainage

Three major areas of Lower Old Red Sandstone sedimentation are apparent from the present outcrop:

(i) Sarclet region (Caithness)

(ii) Strathpeffer region (near Inverness)

(iii) Gamrie region (north east Scotland)

At Strathpeffer, alluvial fan conglomerates rapidly give way to highly bituminous laminated lacustrine limestones. Donovan (1971 and pers. comm.) considers the north east transport of large amounts of sediment in the Sarclet Group and the replacement of this facies by playa lake facies towards the north east, as evidence supporting the hypothesis of a Lower Old Red Sandstone 'Orcadian Lake' under the present Moray Firth north east of Caithness. With this hypothesis, Strathpeffer exists as an early but very localised lacustrine development.

It must be concluded from the present study that although the Gamrie and Rhynie Outliers drained in general to the north, the ultimate destination cannot at this stage be confirmed.

Sedimentological considerations (chapter 3)   probably raised an important issue. The lowermost deposits indicate that ephemeral rivers debouched onto a piedmont floodplain. Initially this may have been their ultimate destination, as the evidence suggests that floodwaters were commonly ponded in this region. In the later part of the Lower Old Red Sandstone at Gamrie, the mechanisms of sediment transport were of greater magnitude and persistence. Perhaps at this time a link may have been developed with an 'Orcadian Lake' to the north.

4.10 (vii) Climatic Conditions

The interpretation of extensive carbonate developments in various parts of the sequence (chapter 7) as calcretes is probably the best climatic indicator available in the sediments studied.

Calcretes at present are a world-wide feature of arid and semi-arid regions, and Goudie (1972) has noted that Tertiary/Quaternary calcretes are also largely restricted to semi-arid regions. Even so, care must be taken. Goudie (1972) draws attention to the fact that "... caution needs to be exercised in the use of calcrete as a paleoclimatic indicator..." "... for climate is but one of the factors in its development...". As considered in chapter 7, precipitation, run-off, relief, and temperature are important factors in calcrete development, and contribute to the difficulties in evaluating climatic conditions. Nevertheless, it is probably reasonable to assume the vague implications of recent calcrete distributions, i.e. that a dry climate existed with periodic rains.

These implications hold for the lowermost Old Red Sandstone of the Gamrie Outlier, and are supported in part by the nature of the sediments in which the calcretes are developed. In chapter 3, the sequences comprising this lower fining upward sequence were interpreted as largely forming by ephemeral events, allowing slow aggradation of floodplain areas. Flood events were regarded as infrequent, but possibly large in magnitude. This hypothesis would tend to support the suggestion of 'a dry climate with periodic rains'.

In the upper portion of the Lower Old Red Sandstone at Gamrie the sediments are interpreted as recording significant changes in both magnitude and persistence of depositional processes. Aggradation became quite rapid, and significantly, calcretes are absent from the coarsening portion of the sequence. The important questions which must be considered are:

1. Does this coarsening sequence record climatic change.
2. Or, Could such changes by purely a response to greater catchment area?

These are difficult questions to answer. Certainly the coarsening portion of the Lower Old Red Sandstone sequence as exposed is derived from a more westerly and hence different catchment area, but whether this could be solely responsible for the change in sequence is difficult to evaluate. The conclusions of the present study are that the ephemeral streams predominant in the lower sequence are incompatible with the apparently 'more permanently established streams' of the upper sequence, and may thus record at least some increased precipitation. Mykura (pers. comm.) has noted that certainly in the Middle Old Red Sandstone a greater catchment and run-off is indicated. It may follow that climatic changes initiated during the Lower Old Red Sandstone times became well established during Middle Old Red Sandstone sedimentation and were an important factor in the vast expansion of the Orcadian Lake. This expansion was initiated during late Lower Old Red Sandstone times, reaching a climax at the Achanarras horizon during the Middle Old Red Sandstone.

This apparent change may in fact be the initiation of a cycle of change which ultimately culminated in the certainly more humid Carboniferous Period.

CHAPTER 5

TRACE FOSSILS IN THE GAMRIE AND RHYNIE OUTLIERS

5.1 Introduction

The recognition of several apparent forms of trace fossil is regarded as important, being at present the only clue to the Lower Old Red Sandstone fauna in North Eastern Scotland. Five structural forms have been recognised, three of which are confidently regarded as of biogenic origin. The fourth and fifth remain problematical.

(i) Large scale vertical and horizontal meniscus-filled structures.

(ii) Small scale inclined "burrows".

(iii) Small scale surface markings.

(iv) Mud-lined vertical "tubes".

(v) Branching carbonate-filled "tubes".

5.2 Vertical and horizontal meniscus-filled structures

5.2.(i) Introduction

Unusual vertical cylindrical and horizontal pipe-like meniscus-filled sedimentary structures have been observed in the siltstone and sandstone members of the New Aberdour Siltstone Formation, and the West Harbour Formation. Allen (1961) described structures similar to those described here from a number of localities in the Welsh Borders. He referred to these structures as "sandstone plugged pipes" and suggested that they formed purely as a result of physical processes. From the present study a biogenic origin is strongly favoured, but throughout the discussion the term "sandstone plugged pipe" has been retained (for descriptions) and is intended to have morphological implications only.

5.2.(ii) Description

At Gamrie two forms of structure have been differentiated on the basis of their attitude and internal structures.

(i) Vertical structures, here termed cylinders,

(ii) Horizontal and inclined pipes,

The general form and relationships observed are schematically illustrated in Figure 5.1.

Cylinders

Cylinders are restricted to sandstone horizons and show little diversity in general form. They are inclined normal to bedding and show a circular to sub-circular section (Figure 5.2a) with occasional minor swellings along their length. The sediment infilling is similar to that of the host sandstone except for rare silty films parallel and close to the vertical walls which suggest minor adjustments of shape and size during formation of the structure. The cylinders always cut the host sandstones cleanly and have never been observed to branch. Unfortunately the upper termination of such cylinders have never been observed, the lower termination being seen only in two cases where it consisted of a smooth, rounded concave upward sandstone projection into the underlying siltstone. In one of these examples the lower termination had a short horizontal side projection (Figure 5.1).

The cylinders are commonly isolated, widely spaced and in thicker sandstone units, but at Counter Head (Figure 5.3, locality D) they frequently show interlocking relationships (Figure 5.2a), suggesting slight lateral migration of their position. Less commonly they are cut by horizontal pipes, or, as shown in Figures 5.1 and 5.2a, pipes appear to originate or terminate at the sites of cylinders. The dimensions of cylinders from Gamrie are listed in Table 5.1. As no cylinders have been

	Locality																		
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
avge. dia. cms	10	-	-	-	8.5	-	9	-	-	-	-	8-10	-	6	8.9	8.3	10.5	7.7	4.8
range. cms	-	6-15	12	6-10	6-22	-	3-25	5-10	4-7	15	5-12	3-15	1-11	-	5-12	5-14	7-13	4-12	3-6
avge. l. cms	-	-	-	-	-	-	-	-	-	-	-	60-90	-	-	-	30	-	40	30
max. l. cms	-	30	-	-	40	-	-	-	23	41	46	100	170	-	-	50	70	170	70
No.	3	4	-	4	23	156	-	-	-	-	-	-	-	1	23	16	40	66	31

(A) Ditton Priors. Allen. 1961

(B) Middleton Scriven "

(C) Bitterly. "

(D) Stoke St. Milborough. "

(E) Tugford 1. "

(F) Tugford 2. "

(G) Swanlake Bay. Pemb. "

(H) Arroyo Fm. Mexico. Romer and Olsen. 1954

(I) Lower Permian New Mexico. Vaughn. 1964

(J) U. Carboniferous Michogan. Carroll. 1964

(K) U. Dev. Pennsylvania. Woodrow and Fletcher. 1968

(L) <u>Beaconites antarcticus</u>. Gevers et al.

(M) New Red Sandstone. S. Devon. Ridgeway. 1974.

(N) Upper Old Red. Orkney. McAlpine. 1977 (pers comm.)

(O) New Aberdour Shore. Emsian. This Study. (cylinders).

(P) New Aberdour Shore. Emsian. " (pipes).

(Q) Counter Head. Emsian. " (cylinders).

(R) Counter Head. Emsian. " (pipes).

(S) Mousa. Shetland. Givetian. " (pipes).

Table 5.1 Summary of physical dimensions of 'plugged pipe' type structures from the present study, and from the recent literature.

observed to traverse the thicker interbedded siltstones the maximum length is probably c. 60cms (i.e. maximum sandstone thickness). However the maximum observed length is 24cms.

Horizontal and inclined pipes

These have a similar surface form to the sandstone plugged pipes described by Allen (1961), but differ significantly in section. In the Gamrie forms an internal layering or meniscus fill is developed, consisting of sharp alternations of sandstone and equal or greater thicknesses of silty sandstone, the latter being commonly laden with angular siltstone clasts, (Figure 5.3). A comparison of Figure 5.1 with Allen's (1961) Figure 5 shows that at Gamrie the surface form of long pipes with colinear curved features is much shallower than those of the Welsh borders.

The greatest number of pipes occur as individual horizontal structures, although quite a large number show a tendency to coalesce (Figure 5.2b). A small number of pipes are related to cylinders, apparently originating or terminating at such sites (Figure 5.2a). It may be fortuitious that this latter relationship is seen; pipes may predate cylinders which were sited coincidentally at the ends of pipes.

The dimensions of pipes may show slight variations along the length and although it is difficult to observe and quantify, pipes may also become gently inclined along their length (Figure 5.2c) but to what degree and over what distance is impossible to estimate from the exposure available.

The curved internal bedding illustrated by Figure 5.3 show no preferred sand grain orientation, although siltstone clasts do occur with their longer axes parallel to the curved internal bedding.

The inclination of each set of internal bedding surfaces is variable within a pipe (Figure 5.3). At the base the bedding surfaces are tangential to the erosive lower surface of the pipe but the inclination increases with increasing height within a pipe until at a position near to the top of the pipe the bedding surfaces stand vertical or may even be overturned by up to 15^{o} from vertical. Occasionally, as shown in (Figure 5.3a) the internal bedding surfaces when overturned may be packed by the next unit, bending double before being covered by the next unit, giving a sense of direction during formation.

The inclination of the internal bedding shows no preferred orientation except where the pipes are connected to cylinders, or where they are inclined. In the former case the sets are inclined such that they dip towards a connecting cylinder whilst in the latter instance the dip is always "up the pipe". Significantly, each internal bed continues to the roof of the pipe and effectively seals the conduit. As internal bedding appears related to the position of a cylinder, and as the latter never cut pipes but may themselves be cut by pipes, a genetic relationship between pipes and cylinders is probable. Contrary to this genetic sequence is the evidence displayed in Figure 5.2a where a cylinder, apparently related to a pipe, is cut by a later cylinder; thus proving that cylinders may in fact post date pipes.

At Counter Head (Figure 5A locality D), the sandstone host to the pipes and cylinders is extensively subaerially desiccated, but in none of the examples studied does this desiccation post-date these irregular surface markings, except in that desiccation cracks originate from cylinders and pipes (Figure 5.2a). Major desiccation features do not traverse the structures. In all cases the pipe structures cut the host sediment cleanly and in the majority of cases do not modify it in any way. However at Counter Head bedding adjacent to pipes may be curved slightly below the pipe (Figure 5.2d), suggesting that compaction has occurred during the production of the structure.

5.2.(iii) Distribution

The pipes and cylinders in the Gamrie Outlier occur throughout a wide variety of lithologies and a total thickness of about 150 metres within which isolated pipes are only found at a few horizons. They are particularly abundant at one horizon and their maximum density of occurrence is restricted to 3m of sediment, laterally of quite variable lithology.

At Gardenstown (locality A, Figure 5.3) and Crovie (locality B, Figure 5.4) only about ten pipes (no cylinders) have been noticed in a sequence of fine grained, very micaceous, sub-arkosic, ripple cross laminated red and buff sandstones commonly less than 40cm thick which fine upwards into flat laminated siltstones and eventually into laminated red muds with abundant desiccation cracks. A few infilled casts resembling small worm burrows have been recorded from this sequence. (See 5.3, page 329).

At New Aberdour Shore (locality C) the host lithology is markedly different, consisting of 120cms of medium to coarse reddish sandstones showing abundant small trough cross stratified sets with numerous gravel lags and pebble strings. Pipes and cylinders occur here in abundance showing no obvious preference for sediment grade or bedding type except that their development is in the upper 60cm and greatest on the top surface of this unit.

At Counter Head (locality D), siltstones with a considerable development of pedogenic carbonate are overlain by thin flat yellowish buff, fine grained sandstones, which pass up into thin interbedded sandstones and siltstones. The thinly bedded sandstones (c. 3cm units) show a very dense development of all forms described, and also illustrate the greatest variation in interrelationships. The thicker basal unit shows the development of horizontal pipes and cylinders only in the upper 10cms, by far the greatest development occurring in the thinly interbedded sandstones and siltstone units.

5.2.(iv) Other Occurrences

The distribution of plugged pipes has received little attention other than Allen's description (Allen op cit); casual reference has been made to their presence only in the Old Red Sandstone of Spitzbergen (Dineley 1960, Friend 1965) where structures similar to those described here occur in comparable sediments (Dineley and Friend pers comm). An individual 6cm pipe has been recorded by McAlpine (pers comm) in floodplain sediments of the Upper Old Red Sandstone of Dunnet Head.

Horne and Gardiner (1973) describe isolate, tubular, radially symmetrical structures 6cm to 12cm in diameter in reddish micaceous siltstones and medium sandstones at several levels in non marine late Devonian or early Carboniferous sediments of south west Ireland. Although apparently uncommon, they also record associated "elongate burrows and trails" of a similar size to the circular structures. They conclude that a biogenic origin is likely and prefer an interpretation as dwelling burrows rather than feeding or escape burrows. Seilacher (pers comm to Horne and Gardiner) suggests that burrowing coelenterates are a most likely organism. More recently Ridgeway (1974) has described 'problematical' trace fossils from the New Red Sandstone of South Devon. In many ways the structures described are very similar to those described here, particularly in shape, size and internal form and cross cutting relationships (Ridgeway op cit plate 17A,B, Figure 1) plus the ability to pass through coarse clastic sediments. Diameters up to 11.0cm compare favourably whilst maximum lengths of 170cm and depth of 40cm are very close. Unlike many of the other examples cited, the South Devon examples also include inclined forms. Ridgeway supports a biogenic origin but rejects annelids and arthropods in favour of a reptilian origin. It is interesting to note that lungfish and hagfish were considered as possible sources.

The present author has observed plugged pipes in the Upper Middle Old Red Sandstone on the Isle of Mousa, Shetland, where numerous pipes occur in a shallow water lacustrine facies similar to that described in the Orcadian Basin by Donovan and Foster (1971). Subaqueous shrinkage cracks are abundant, suggesting quiet water conditions with fluctuating salinity (Donovan & Foster, op. cit.). The absence of large desiccation polygons suggests that drought conditions were never as far advanced as at Gamrie.

Small, vertical, cylindrical, internally massive, sand filled structures have been described from the Permian and Carboniferous of the U.S.A. and attributed to the diverse species of aestivating dipnoan fish which evolved rapidly during the Palaeozoic era.

Carlson (1955) describes a Permian lungfish and offers details of their aestivation burrows which are comparable to the structures described here. He records cylindrical burrows 1 - 10cms in diameter (45cms max. length) with well defined walls and a hemispherical base often extending into the shale below. Majority are vertical and many show concentric internal meniscus structure (cf. Figure 5.1) and commonly burrows occur closely packed (cf. Figure 5.2a).

Romer and Olsen (1954) describe aestivation burrows of Permian lungfish in the Arroyo Formation of New Mexico. They report vertical cylinders with smoothly rounded lower terminations. Their dimensions of 5.5 to 10cms compare favourably with the Scottish examples and those of the Welsh Borders.

The Lower Permian of north west Mexico exhibits vertical or slightly inclined circular cylinders of 4.5 to 6.5cms diameter and up to 23cms length. Vaughn (1964) describes these and notes that the lower termination may bend to the horizontal. His examples were not true cylinders, their tops being dilated and with a bulbous base causing a flask-shaped appearance. Vaughn suggests that the lack of fossil remains in most burrows is explained because firstly the conditions necessary for aestivation by lungfish would be unfavourable for the preservation of bone, and secondly because lungfish were probably highly successful in survival by aestivation. Modern examples have been estimated to be capable of survival for periods in excess of 18 months (Smith, 1931). Vaughn thus contemplates an "environmental calamity" as the cause of the high bone contents in the cylinders of the Texas and New Mexico Arroyo Formation, concluding that the lack of skeleton parts" ... does not seem to be strong evidence that these fish were not there, when it is remembered that the remains of lungfish are exceedingly rare even in the Arroyo Formation of Texas". The Carboniferous of the Michigan Coal Basin has yielded large, essentially straight cylinders of c.15cms diameter and 41cms length with spiral patterned sides caused by tail movement of the fish (Carroll, 1965). Carroll suggests that the earlier Dipnoi burrowed and remained straight rather than having the coiled tendencies of modern examples.

Woodrow and Fletcher (1968) report cylinders 5 - 15cms in diameter from the Upper Devonian of North East Pennsylvania. In section the structures are subcircular to oval and have their long axes normal to bedding. The bottoms of the cylinders are rounded and concave upwards, and, as in the present study, the cylinders only occur in the top 1.5ft (45cms) of sediment units. They may occur grouped or separated by several feet. No fish remains have been found associated with the cylinders, although bone has been found in interbedded lithologies. The environment of deposition of the host sediments is interpreted by Woodrow and Fletcher as being a broad fluvial plain or estuarine region with a development of pedogenic carbonate, subjected to seasonal drought during which time the Dipnoans burrowed into the exposed river mud to aestivate.

Although a number of structures comparable to the vertical cylindrical forms described here have thus been noted, no horizontal or pipe like structures ever relate to these examples.

Gevers et al (1971) describe a Devonian trace fossil from Victoria Land, Antarctica, and although they do not offer detailed sections their descriptions and photographs prove very comparable to those described here. The trace fossil they describe has been named Beaconites antarcticus, and typically may show a sinuous surface form, with curved internal bedding or septa as described from the present example. Branched forms are common, as are inclined forms. They range in size from 2.7 to 10.3cms, 7.7 to 10.3 being the most common, and are thus very comparable to the Gamrie pipe structures. Steeply inclined or vertical burrows were noted, but few details offered that would allow comparisons with the cylindrical forms described here. Although Vialov (1962) initially recognised these Antarctic forms he was undecided as to their origin. Gevers et al (op cit) express little doubt in interpreting the structures as either surface or shallow annelid feeding burrows. Rolfe (pers comm. 1975) and Pollard (pers comm and 1976) have observed similar surface forms from Lower O.R.S of Dunbartonshire and the Tor Bay breccias in South Down and consider them comparable to those described by Gevers et al (op cit), but created as locomotion or temporary resting traces of amphibians or reptiles.

5.2. (v) Interpretation

Allen (1961) considered several possible modes of origin for the sandstone plugged pipes of the Welsh Borders: (1) A biogenic origin he felt was unlikely because of the large size of the structures, the absence of skeleton remains, and that the structures appeared to be unlike any attributed to organic processes. (2) He rejected the notion of injection of sand and silt lubricated with water because of the shape and interrelationships of plugs and also the lack of associated sand veins and stringers. (3) Allen suggested that "the most consistent explanation" was that rising water initiated tubular ducts in the unconsolidated sediment - choking of the ducts occurring when the velocity of the water fell below the settling velocity of any suspended detritus.

A physical origin for the Old Red Sandstone plugged pipes described here is unlikely because:-

(a) The internal curved bedding is seen to seal the pipe completely and thus would prevent further movement of water.

(b) The pipes and cylinders cut through a wide range of lithologies but their morphology is not controlled by grain size as might be expected if they were formed by moving water.

(c) They are restricted to the upper surfaces of thin sandstones and upper portions of thicker sandstone units.

(d) Pipes may repeatedly coalesce.

(e) Pipes appear to be genetically related to cylinders.

(f) No change of form exists at the end of each pipe.

(g) Cylinders have circumferential silt films and show evidence of slight lateral migration and size adjustment.

(h) The lower terminations of cylinders project downwards into the siltstones below i.e. the cylinders originated from above, and not from below.

(i) Sedimentary structures in clastic sediments attributed to dewatering phenomena are usually folded rather than fragmented such as to allow the release of angular siltstone fragments into any released fluid.

(j) The transport of large siltstone clasts and coarse sand in a restricted pipe would presumably cause a significant rounding of the clasts. In fact the clasts are angular.

(k) The sides of cylinders and pipes are vertical, a phenomenon typical of damp rather than saturated sand. If the structure acted as a conduit for any length of time presumably collapse would occur as the sides became wet. Silt films parallel to the sides of cylinders suggest that the structure has witnessed several stages of development - in none of the examples studied is there any evidence of collapse or winnowing of the sides of the cylinder.

A biogenic mode of origin for the pipes and cylinders is a little easier to support. The lack of variation of size and form of the pipes even in differing lithologies suggests that they may not be produced by a hydrodynamic process which would presumably produce different sized pipes depending on the grain size of the host sediment and water velocity within the pipe. Pipes frequently pass through a variety of grades of sediment along their length, and no change in size or form of the pipes is produced. This suggests that the mechanism producing the pipe was independent of the physical properties of the sediment. A burrowing organism would produce a burrow of fairly consistent dimensions irrespective of the nature of the sediment.

Similarly, a burrowing organism may pack sediment, secretions or excrement into a burrow sealing the tube behind it, and whilst in the process of burrowing or feeding could easily transport silt from the surface into the pipe. The pipes and cylinders are confined to the upper portions of sand units. They do not originate from below but instead from the silts above, suggesting entry from above. In the two examples of cylinders showing a lower termination the sand also projected down into the underlying siltstone. The sand lamellae of the pipes are wedge-shaped, (Plate 5.1) thinner at the base than at the top where the sand may be overturned. This could have resulted if a burrowing organism packed the sand into sheets by 'bulldozing' it along the pipe.

Modern examples of lungfish burrows show clearly the presence of a mucous lining to the 'cocoon', it is conceivable that the vertical silt films recorded in the cylinders from Gamrie are a vestage of such a lining, now only recorded by the presence of entrapped silt.

As previously mentioned, the sediment had undergone at least some desiccation prior to the development of the pipes and cylinders. This fact may add further support to the suggestion that the cylinders are in fact burrows. The sand and silt was clearly in a state of partial or total desiccation over the general period when the structures were produced, and thus could have been produced by organisms trapped in ponded water on the floodplain. This is the environment at present day causing lungfish to aestivate, and although unrecorded, it is possible that the pipe like structures are a record of such an organism attempting to move through partially desiccated silt. From work on Gambian lungfish, Johnels and Svenson (1955) observed that modern lungfish 'awakened' by being placed complete with burrow in a tank of water left their "nests", but returned periodically for protection for up to 6 - 7 hours before resuming a normal free swimming life. If the silt had been totally desiccated the pipes may represent feeding trials initiated during a subsequent flood but this is unlikely to be the case as cylindrical aestivation burrows would not be produced in such a situation. The absence of cylindrical structures on Mousa may also be ascribed to the absence of advanced desiccation if the structures are correctly interpreted as aestivation burrows.

Several cylinders show radiating desiccation cracks and thus suggest that the silt and sand was only partially desiccated (Figure 5.2a). Donovan and Archer (1975) have shown that natural or artificial inhomogeneities in desiccating mud can have a significant control on desiccation crack patterns. Thus it appears quite possible that the silt and sand was actually undergoing desiccation and that the structures described were in fact produced in response to this drying invironment.

5.2.(vi) Discussion and Conclusions

The evidence compiled seems favourable for the interpretation of the cylindrical structures as burrows. The pipe structures present a greater problem in that there is only one record in the literature of similar structures directly attributed to burrowing or feeding organisms.

The majority of pipes are surface forms, occurring on the sand-silt interface and therefore may represent feeding trials rather than burrows. A discussion on the feeding habits of Devonian fish and other large aquatic organisms is beyond the scope of this paper, particularly as the sediments considered are devoid of skeleton fossil remains thus offering no clues as to the identity of a suitable organism. (To date only one fish scale of

Porolepis a mid-water Crossopterygian, has been extracted from the entire Orcadian "Basement Group").

Several of the major groups of fishes in existence could have offered individuals of the required size and bottom feeding habits (Westoll, pers. comm.) but none has been noted to produce feeding structures similar to those described. In the Gamrie outlier no evidence exists of any flora or fauna available in abundance to support a bottom feeding biota. Parrington (1958) suggested that the Anaspids and Heterostracans fed head down, steeply inclined to the bottom, and that the action of the hypocercal tail - elevating the snout during swimming (Kermack, 1943) actually served initially to enable the fish to plough through the bottom sediments in search of prey. Such a mechanism may be a source of structures similar to those described here.

In an attempt to simulate the above feeding process, wet silt covered sediment was prodded at a steep angle by an 8cm wide blunt nosed object. It was found relatively easy to produce surface expressions similar to the pipes described, and also comparable sections of internal bedding. This apparently simple method of producing pipe like structures has several drawbacks.

(a) Such a process cannot easily produce inclined pipes, and many of the horizontal pipes examined at Gamrie do become inclined along their length.

(b) If the cylinders genuinely represent aestivation burrows, and the relationship between cylinders and pipes is not fortuitous, why do other examples of aestivation burrows not show the pipe like trails?

(c) Aestivating Dipnoans are not recognised as feeding by the method described by Parrington.

(d) The organism responsible would be feeding immersed in water and not desiccating sediment as the evidence suggests.

(e) The organism would need a mechanism of moving in a reverse direction. Unfortunately, however there is a complete absence of any surface markings attributable to pectoral fins or tail markings.

On the other hand the suggested mechanism of formation of the pipe structures would strongly favour an origin similar to Beaconites. Gevers et al (op cit) suggest that annelids feeding in the nutrient rich surface sediments ingested and consequently excreted large volumes of sediment. The animals regularly pushed this bulky excrement, the product of rhythmic defecation, backwards to produce the curved pipe filling "as a result of peristaltic motion".

The environmental interpretation, and the timing of development of such structures would favour a similar interpretation, although Pollard (1975) supports Ridgeways (1974) argument that defecation back packing is unlikely due to low organic content and coarse angular nature of the sediment.

In conclusion, Ridgeway (1974), favoured a tetrapod origin for the structures, a mechanism also strongly supported by Pollard (1976) for the Permo-Triassic examples. Rolfe (pers. comm.) favours a comparison with Beaconites for the Old Red Sandstone examples he has observed.

Clearly, due to the age of the sediments concerned, a tetrapod origin is highly unlikely! Many of the features may be explained by comparison with Beaconites, but the strong rejection of this mechanism by Ridgeway (1974) and Pollard (1976) must be considered. The interpretation of the structures as lungfish burrows, although having many drawbacks, may be valid and possibly the pipe structures are analogous to Pollard's (1976) consideration of tetrapod burrows as "...temporary resting or locomotion burrows ......".

Although two possible modes of origin have been considered, the author considers that at the present state of knowledge the problem must largely remain open. Many problems remain, and will do so until further light is thrown onto the complex feeding habits of the available Devonian fauna. With this in mind, new faunal evidence from the many new localities displaying such structures may be forthcoming as even if annelid forms were responsible, chitinous jaws and teeth may have been left in the sediment.

5.3 Small Scale Inclined Burrows (Plate 5.1)

Trace fossils of this nature are uncommon in the area considered, examples being restricted to the Quarryhill Sandstone Formation at Quarryhill near Rhynie. The structures occur at numerous levels within the higher part of the Quarryhill Sandstone Formation, being concentrated in fine sandstones interbedded with siltstones, interpreted as recording a proximal floodplain environment.

The burrows are quite consistent in shape, size and form, ranging in size from 3 to 7mm diameter and 10 to 25mm length. In cross section they are circular to subcircular, maintaining approximately the same diameter down to a gently rounded base. The structures are always sand filled, usually somewhat crowded but rarely in contact, and slightly inclined to the bedding. No examples have been observed to branch. Many of the burrows appear to be smooth walled, and several examples (see Plate 5.1) show features suggesting that the burrow was actively, rather than passively infilled.

The above structures are quite confidently interpreted as burrows and probably worm burrows. They bear a striking resemblance to structures broadly interpreted as Scolithos worm-burrows from the Upper Old Red Sandstone of the Elgin district (Peacock pers. comm. and Peacock et al 1968).

5.4 Small scale Surface Markings

Three forms of surface markings have been recognised, all from within floodplain sediments of the Quarryhill Sandstone Formation at Quarryhill near Rhynie. Briefly these surface forms are:

(i) curved positive relief features

(ii) smooth surface trials

(iii) sharp surface impressions

5.4(i) Positive relief features have been observed in thin sandstones of floodplain origin. Plate 5.2a illustrates the form of these markings, the original sample being an undersurface. A rubber cast (plate 5.2b) shows the true positive form of these features.

The markings are restricted to the surface of the sediment, and are up to 2cm in maximum length. Plate 5.3 illustrates clearly the almost straight to tightly curved shape of the markings, and demonstrates the occurrence of these markings in close proximity to the previously described burrows, and to trails to be described later.

Although difficult to ascertain, no overall preferred orientation of these markings is apparent other than possible association separated in Plate 5.3 and discussed later.

Interpretation poses several problems, the greatest being that the traces are totally positive relief features and not depressions on the bedding surface. This latter point is regarded as significant in excluding crawling organisms and probably also fish tail markings (although the tightness of many of the curves probably would exclude the latter).

Recent discussion with N. Trewin indicates that example of this form are unknown in sediments of the Orcadian Basin, but have been observed in recent sediments, produced by worms in shallow water. Effectively, the worm is partially supported by the water preventing normal locomotion. Instead sideways movement of its body ploughs minor amounts of sediment into small lateral ridges, maximum ridge height corresponding to the maximum sideways displacement of the worm. In the light of this suggestion, a reconsideration of the traces on Plate 5.3 allows the separation of several groups of traces, based on either relative age or size. Plate 5.3 illustrates the result of such a consideration, and adds support to such a proposed origin.

Structures of a similar shape and size have been included by Hantzschel (1975) and ascribed to a type of insect track. Unfortunately, although such an interpretation would be acceptable in the present case, significant differences do exist; the major difference being the positive relief of those structures described here, but also those structures detailed by Hantzschel (op cit) tend in all cases to show complete lines of curved trackes rather than the isolated portions observed in the present example. The strongest support for Trewins' suggestion comes from the identification by Moussa (1970) of Eocene Nematode trails. In his interpretation he draws attention to the significance of water depth, indicating that the effects of surface tension in shallow films of water may either serve to increase the effective weight of the creature (thin films), or in the case of thicker films surface tension is ineffective and the creature is essentially bouyant. Thus Moussa points out that in shallow water films such creatures may indeed produce distinct trails whilst increasing water depth reduces this likelihood.

It may be possible that the Rhynie examples represent a situation where a 'worm like' creature was supported enough by the water film to prevent it causing significant trails to be formed. Instead, its movements were only able to produce lateral displacement features.

As traces of this form have no previous record, interpretation is difficult. The suggestion that the trails have been produced by worms in shallow water seems mechanically feasible, and has at least some support in the close proximity of worm burrows (previously described), and in the trails to be described in the next section which are regarded as being of a 'similar' origin.

On the other hand, a recent experiment involving desiccated 'algal mat' demonstrates a further possible means of production of such surface features without recourse to invertebrate assistance.

Plate 5.4a, b illustrates the results of the total desiccation of a thin algal layer overlying a fine sediment film. Well documented features such as 'micro desiccation polygons' and curled mudflakes developed, but more important, with repeated wetting and drying the curled edges of flakes rolled tightly to produce small curved 'positive relief features' incorporating large amounts of the underlying sediment. It is particularly interesting that these 'accidentally' produced structures show many features closely comparable to those found in the Quarryhill Sandstone.

Plate 5.4a shows clearly the comparable size of these experimentally produced structures, and also concentric curved features (Plate 5.4a B), and circular forms (Plate 5.4a, A). Both of these features are also apparent in the Quarryhill Sandstone example (Plates 5.2 and 5.3).

The structures produced in the laboratory formed in response to the development of a thin layer of green algae in shallow water overlying a layer of coarse siltstone. The algal layer produced abundant gas photosynthetically, causing the development of small floating bubbles or 'blisters'. Evaporation of the water film resulted in sediment being bound to this algal layer, this occurring most abundantly at the edges of bubbles or 'blisters' where the algae was thickest and remained moist longest. These regions of thicker algal material eventually became boundaries to larger desiccation features (see Plate 5.3b B, A) which with advanced desiccation produced curled edges, ultimately producing tightly curled features on the sediment surface (Plate 5.3b c).

Clearly, this mechanism could have produced the randomly oriented, uniform sized positive relief features on a floodplain surface. It would appear that the important factor is not simply the development of a floating algal mat, but the production of gas blisters immediately prior to total evaporation of the water layer.

5.4(ii) Smooth Surface Traces An isolated surface trace preserved as a reddish brown mud film has been observed in sediments adjacent to those containing the traces above. The trace is illustrated in Plate 5.5 and reaches a maximum length of 5cms with a width in the order of 0.5cm. In appearance the trace is very plant like, showing a definate branched appearance. Unfortunately only one example has been recorded, severely restricting a detailed appraisal of the true form of such traces.

Nevertheless, unless the traces are actually of plant origin they compare reasonably with traces described by Hantzschel (1975) and interpreted as collapsed worm burrows (e.g. compare with Chondrites a possible marine anologue.)

5.4(iii) Sharp Surface Impressions A series of sharp, circular, pit like depressions have been recorded adjacent to the previously described examples in floodplain sediments at Quarryhill. Again, restricted evidence prevents a full understanding. The impressions are illustrated in Plate 5.6 The rows can only be traced for approximately 10cms, but clearly consist of two pairs of parallel rows of simple pits approximately 1 to 1.5cms apart, the rows separated by about 4cms.

Many variants of this form of structure have been described and interpreted as invertebrate walking tracks. It is reasonable that such an interpretation be applied here as numerous invertebrate species have been recorded from the Rhynie Cherts occurring in the sediment immediately above the Quarryhill Sandstone Formation. The cherts are known to contain:- Arachnids, Crustacea, Insects and Eurypterids.

Trewin (1976 pers comm) has observed similar tracks in siltstones of the West Harbour Formation at Gamrie and attributes them to a similar origin, possibly an arthropod. At this same locality Trewin has also observed Isopodichnus (see Trewin 1976) a trace fossil of wide distribution in the Orcadian sediments, and interpreted as an arthropod walking trail.

5.5 Mud-lined Vertical Tubes

Small scale structures tentitively interpreted as plant rootlets have been observed both at Gamrie in the West Harbour Formation, and at Rhynie in the Quarryhill Sandstone Formation.

At Gamrie, small scale vertical or steeply inclined smooth walled structures are commonly observed in fine sandstones of the West Harbour Formation, and range in size from 0.4 to 1cm diameter and up to 12cm length. They are always circular to sub-circular in section, and filled with sandstone but lined with reddish mud. At Crovie the structures are smooth walled, whereas in the West Harbour Formation the walls show irregular sharp outwardly protruding 'dimples'. Although often steeply inclined, the structures in the latter locality also show frequent sharp obtuse bends, but never appear branched. The structures in both localities show little change in dimensions over their length, although in the West Harbour Formation lower terminations have not been recorded. At Crovie, a marked thinning leads to a sharp base to the structures. In both localities the structures occur in types of floodplain sediment, and generally appear to postdate the sedimentary unit in which they occur, originating from the upper surfaces of sandstone units overlain by floodplain silts.

At Rhynie, floodplain sediments within the Quarryhill Sandstones sequence contain similar structures, but generally in greater abundance and with larger dimensions (see Plates 5.8, 5.7a).

The Rhynie examples are illustrated in plate 5.8 and clearly occur densely packed, but still always isolate and never cross cutting or branched. The structures extend to considerable depths, up to 60cms, always originating within the floodplain sediments and extending well into the thick underlying sandstones. Plate 5.8 also demonstrates the close relationship between the tube development and Channel development within sandstone units. It would appear from this example that the tube structures developed at times in floodplain sites adjacent to active channels.

Interpretation is again difficult, but, the shape, form and interrelationships seem to preclude an animal origin (e.g. lack of cross cutting relationships), and although details of the habitat of Devonian flora has not been studied in great detail, it may be possible that these mud lined 'tubes' are rootlet horizons.

5.6 Branching Carbonate Filled Tubes (Plate 5.9, 5.10)

In the basal deposits of the Gamrie Outlier at Quarryhead this fourth group of problematical structures is abundantly displayed. As the title implies, the structures are tublar and carbonate filled, but there is little evidence to allow speculation as to their origin, even their description as 'Trace Fossils' must remain uncertain.

The carbonate filled tubes occur in a variety of lithologies at

Quarryhead, ranging from boulder conglomerate to fine sandstone, but excluding finer siltstones which dominate certain vertical and lateral situations.

Two distinct size ranges are developed, the larger forms ranging from 0.5 to 2.8cm diameter being generally circular or oval in section, and up to 45cm in length although more commonly they range between 10 and 25cms. The smaller varieties rarely exceed 0.2cms diameter and range between 0.5 and 4cms in length.

All varieties of tube are observed to branch repeatedly, the larger forms branching often in three dimensions, whilst the smaller forms tend to be restricted to bedding surfaces (this latter feature is difficult to confirm due to the restricted size of development). The nature of this branching tends to be fairly specific in that large and small forms both may show 'Y' or 'T' junctions, but the larger varieties only may show 'Y' branches in any sense of direction. The side branches appear to occur randomly, the side tube always being of a smaller diameter than the main or original tube. The smaller forms typically show multiple change in direction, often acutely, and often in response to obstacles. The larger forms do not show major directional changes, but their cross section is often modified by an obstacle (i.e. flattening often occurs against pebbles).

There is little evidence as to the origin of these structures. Their mechanism of origin is difficult to ascertain as the beginning and ends of such tubes cannot be located with confidence. There is no apparent lining to the tubes, and although the occasional example may show several periods of cement or have an uncemented core, no sediment infilling or floor deposits have been recognised.

The shape and interrelationships of the structures are considered to support a biogenic origin; for example, the relative uniformity of the tube systems and their branching forms combined with the relationships between tubes and obstacles are regarded as features providing more support to a biogenic origin than against.

The distribution of the tubes remains a source of concern, as the coarse sediments and calcrete horizons would seem to be a somewhat hostile environment for any form of life. Plant evolution is certainly not regarded as being adequate to enable colonisation of such environments, whilst at the same time if the structures are considered to be burrows, the environment (including the implied aridity) would appear to fail to provide a food source.

Fursich and Palmer (1975) have described similar structures from Bathonian sediments and interpreted them as crustacean burrows. They also regard a relationship to areas of calcrete developments as being significant in that the system could remain open during vadose cementation. Presumably such burrows may have been more common than is apparent as such cementation would be an ideal guarantee of preservation without which collapse and destruction would be relatively easy. These authors also regard it possible that the burrows were cemented early due to organic material (e.g. mucous lining) serving as a nucleus for calcite precipitation. Furthermore, they do not consider the problems mentioned above because ...."It is difficult to make inferences about the ecology of the animals responsible for the burrows, as their recent counterparts exhibit a wide range of behaviour, particularly with regard to feeding." (Fursich and Palmer op cit).

5.7 Other Examples

Little information has been published on Old Red Sandstone trace fossils in Scotland, Trewin being perhaps the leading worker in this field (see Trewin 1976), *Isopodichnus* has been recorded from many localities in Northern Scotland (Trewin op cit) and although not identified during this study, rare examples have been found in the siltstones of the West Harbour Formation (Trewin pers comm). This record adds further evidence to the invertebrate fauna of the Orcadian Basin, *Isopodichnus* being interpreted by Trewin as an arthropod walking trail.

Trewin has also recognised structures bearing a strong resemblance to those described here as walking trails, from the West Harbour Formation.

5.8 Conclusions

The remarkable scarcity of fossil remains in the majority of the Old Red Sandstone of North East Scotland, in particular the virtual absence of a fossil record in the Lower Red Sandstone sequences, restricts attempts at detailed environmental reconstruction. Attempts have been made in this thesis to evaluate the local paleogeography of the region during Old Red Sandstone times, and it is felt that many of the conclusions reached may have been supported had fossil evidence been available.

A substantial flora has been extracted from the Rhynie Cherts, and also a restricted fauna established - including species of arachnids, crustacea, insects and eurypterids.

A specialised knowledge of these species may allow further detailed interpretation of the trace fossils to be made. At present the value of such traces is still considerable in demonstrating that not only was the Lower Old Red Sandstone less 'barren' than perhaps at first envisaged, but also that many environments generally regarded as arid/semi-arid on sedimentological evidence were in fact capable of supporting a sparse but varied population and of course its' (unrecorded) food source.

CHAPTER 6

THE ORIGIN OF RED BEDS IN THE GAMRIE AND RHYNIE OUTLIERS

6.1 Introduction

The origin of the colour in red beds has been a controversial subject for many years and the problem is far from resolved. Essentially two strong different lines of argument have developed. Krynine (1949) and Van Houten (1961, 1968) argued that erosion of iron oxides from upland red soils (traditionally from warm, moist, tropical or sub tropical climates) resulted in the deposition of potential red rocks, the reddening being completed by the "ageing" of the iron hydroxide to hematite. Such arguments have been supported by many authors, although controversy exists about the exact physico-chemical conditions necessary for the ageing process. (see discussion page 370)

More recently Walker (1967a, 1967b) Walker et al (1967) and Walker and Honea (1969), postulated the derivation of iron oxide (and clay) from the in-situ early diagenetic breakdown of iron-bearing silicate minerals. Walker's argument involves the decomposition of iron silicates into an iron-rich montmorillonitic clay, with a later redistribution of the iron oxides by oxygenated pore waters. No direct climatic implications are involved by this theory. Friend (1966), utilising earlier theories, suggested that sedimentological controls maintained certain Eh-pH conditions and determined whether iron hydroxides were oxidised to hematite (in floodplain areas) or reduced and removed in solution (in channel areas). Friend's hypothesis provided an explanation for the red drab differentiation commonly mentioned in red bed descriptions, but was not concerned with the origin of the pigment.

This chapter is concerned with the origin of the colour of the Devonian red bed sequence exposed in North East Scotland, in an attempt to determine the source of the pigment (transported or authigenic), the conditions of its formation, and any climatic inferences.

6.2 Field Evidence

At Gamrie, red beds dominate the succession, and overall cannot be assigned to a particular range of sediment grade. However, locally in the East and West Harbour Formations, and the rocks at Rhynie, the coarse members of cyclothems are commonly drab, while the fine members are red or brown. At Gamrie many sequences exist with a coarse-fine interrelationship, but only rarely does this equate with colour changes. One such case is where drab sandstone overlies siltstone, then a thin zone of reduction may occur, as noted by Friend (1966).

Many sandstone units at Gamrie, and Rhynie show well-developed intraformational mudflake conglomerates which may consist of red, brown or green mudflakes set in a red or drab sandstone matrix. Red mudflakes are most common in red sandstones while drab sandstones normally contain brown or green mudclasts. Reduction zones are common around the edges of red mudclasts preserved in drab sediments, whilst brown siltclasts may be reddened at the edges when occurring in red sediments. Green mudclasts were only recorded in drab sediments.

In the West Harbour Formation laminated mudstones are common and consist of graded laminae (3 - 6mm thick) of silt fining into clay. The silt portion is drab to brown in colour, while the clay is bright red and frequently opaque in thin section due to the abundance of pigment (see plate 6.1a).

In the New Aberdour Siltstone Formation desiccation of siltstones and mudstones is common. The desiccated surfaces and part of the crack are commonly reddened but preceeding and succeeding sediment is grey in colour.

At Rhynie climbing ripple lamination shows the development of reddening as spots of pigment associated with concentrations of biotite mica on the lee faces of ripple laminae, the host sediment being drab to pink in colour (Plate 6.2). Reduction spots are abundant in the Castle Hill Sandstone Formation at Gamrie. Siltstone and mudstone clasts transected by reduction spots show an absence of intense reddening and biotite flakes similarly transected in red sandstone do not show hematised cleavages (plate 6.1b).

Many of the earliest red-bed sequences at Gamrie and at Rhynie contain abundant calcrete developments (see Chapter 7).

The drab - red, coarse - fine relationship has been noted by Friend (1966) and taken as evidence for the sedimentological control of reddening, i.e. fine-grained sediments deposited on overbank floodplain areas where oxidising conditions probably persisted for a long period in contrast to the reducing environment more typical beneath the water table and in channel sandstone deposits. In addition the oxidation of floodplain sediments would probably continue long enough to complete the ageing of amorphous iron hydroxide to hematite, whilst at the same time breakdown of iron-bearing detrital silicates would be possible. The 'less oxidising' or very mildly reducing channel enrivoment would not be as favourable for such long oxidation, neither would the sandstones be as rich in detrital iron bearing clays. Thus the red - drab grain size relationship in part suggests a diagenetic origin but one partly influenced by sedimentological controls and partly by clay content.

Mudflake conglomerates support the notion of environmental control plus the importance of fine grained clay. The fine detritus, reddened in an overbank environment remains red if oxidising conditions persist, but probably becomes reduced in non-oxidising channel enviroments responsible for non-red sandstones.

Laminated mudstones stress the importance of fine-grained materials in the genesis of red beds. Reddened laminae are frequently only millimetres thick and laterally persistent, they do not correspond to desiccated surfaces. Local Eh - pH controls cannot be invoked (cf. Friend 1966 for Channel and overbank sediments). The evidence supplied by the laminated mud suggests that although lithological/diagenetic controls may decide which sediments become red and remain red, it is the availability of a hematite precurser that decides the nature or ease of reddening, and this precurser may exist within the fine grained portion of the sediment.

The evidence from desiccation cracks at New Aberdour supports the need for suitable environmental conditions in that grey mudstones have the ability to be reddened, but only when oxidising conditions persist.

Reduction spots are regarded as local areas of sediment, perhaps rich in organic matter, where oxidising conditions did not develop; siltstone clasts have thus been reduced, i.e. hematite removed, and biotites have not suffered secondary hematisation.

6.3 Petrographic Evidence

6.3a Location of Pigment

In all cases studies the colour of the red beds is due to a fine particulate pigment which may occupy a variety of textural sites. (plates 6.3a, b)

(a) Most common to all red sediments are particulate grain coatings frequently appearing as finely crystalline (c.2μ) hexagonal red translucent particles. This pigment is conspicuously absent from drab and grey rocks. (Plates 6.4a - 3 and 6.5a - f).

(b) Large irregular patches of hematite up to 0.4mm in length occupy intergrain positions. These are clearly of post-depositional origin. (Plate 6.6)

(c) Large, dense patches of pigment may occupy areas of grain contact or embayments on grain surfaces. (Plate 6.6f)

In most cases particulate grain coatings completely envelop all grains (but in poorly compacted sediments this may be of no significance). However, some grain contacts may show a lack of pigment at the contact point (Plate 6.5) suggesting that the pigment formed post depositionally (a feature noted by Miller and Folk 1955 and Glennie 1970). A post depositional origin is also indicated by continuous pigment lining cavities' created by grain contacts (plate 6.5). Point contacts on the other hand are not always devoid of pigmentation (plate 6.5) and may imply that pigment was available during deposition, or that compaction occurred later than pigmentation. The large patches of pigment also indicate that at least some hematite, or its precursor, originated post-depositionally in that such patches appear to be a replacement of argillaceous matrix (iron-rich clay?) in some cases with gradational margins. Other examples being sharply defined may represent post-depositionally remobilised detritial grains as discussed by Picard (1965). Fine-grained (1μ to 20μ) red translucent hexagonal crystals may occur individually or in small clusters on grain coatings or on biotite and chlorite surfaces and cleavages (plate 6.3a, b) their delicate nature being a clear indication of their post depositional origin. Friend (1966) showed that much of the red pigment of the Catskill red beds consisted of fine grained hexagonal crystals of this type. Waugh (1967) also demonstrated that the pigmenting agent in the Penrith Sandstone was this type of hematite. Dense patches of finely crystalline hematite may also occupy quartz grain embayments and areas of grain contact and are further suggestion of post depositional crystallisation. (plate 6.6f)

The generation of hematite in the distorted cleavages of compacted detrital micas is considered in more detail later, but indicates that at least some of the reddening is post-depositional in origin.

6.3a Textural Relationships

Several stages of cementation can be recognised in the red sandstone of the Gamrie Outlier, the primary cementing agents being authigenic clay associated with calcite and minor amounts of silica cement. A combination of textural evidence from all thin sections studies gives the following sequence:-

(a) Sand grains are coated by hematite pigment or its precursor either pre- or post-depositionally or both.

(b) Quartz overgrowth (plate 6.7a, c,e and 6.8a, b,e)

(c) Minor pigmentation

(d) Pore filling by authigenic kaolinte (plate 6.7a, b,c,d, plate 8d, f and 9b)

(e) Inclusion of pigment and authigenic silica.

(f) Calcite cementation with accompanied local destruction of clay cement. (plate 6.7a, b)

	Reduction Spot	Host Sediment
Fe^{2+}	0.96	0.36
Fe^{3+}	0.26	0.95
Fe^{2+}/Fe^{3+}	3.69	0.38
MgO	0.95	1.10
MnO	0.09	0.05
K_2O	2.35	2.10
CaO	3.7	4.05

Table 6.1 Chemical analyses of a 'Reduction Spot' area in comparison to the host (red) sandstone

Two important points arise:-

1. Some pigment is of post-depositional origin, and
2. Silica overgrowth occurs at an early stage and may be related to generation of kaolinite.

Authigenic kaolinite, the dominant cement, shows good crystal form and frequently envelops 'floating' detrital quartz grains, suggesting that the crystallisation was early and probably pre-compaction. Since pigmentation is largely pre-crystallisation of kaolinite, this indicates an earlier formation for the pigmentation. The crystals form (i.e. "books and worms") suggests that the kaolinite may be the variety dickite, which may originate from potassium feldspar by:-

K feldspar ⟶ Dickite + SiO2 (Smithson and Brown 1954)

Such authigenic dickite is always associated with large volumes of authigenic silica, and is believed to be of very early diagenetic origin (Smithson and Brown op.cit). The occurrence of such authigenic clay is of great interest if it is truly dickite. Harms (1975) notes that dickite is traditionally thought to be a high temperature mineral, but also records authigenic dickite in marine Permian sediments. More recently, Hancock and Taylor

(1978) and Blanche and McD Whitaker (1978) have reported fairly extensive early diagenetic kaolinite cementation in the Brent Formation (Middle Jurassic- North Sea). Calcite in all cases examined appears to be pre-compaction (evidence from floating grains).

The occurrence of reduction spots in sandstones offers some interesting petrographic evidence, both biotites and mudclasts have been recorded transected by reduction spots (plate 6.1b). In such areas, hematisation has not taken place, biotites are fresh and mudclasts if present are drab. Outside the reduction sports hematite genesis is normal. Are reduction spots areas of hematite reduction and dissolution, or are they areas of non-oxidation? Chemical analysis of reduction spots and their host rocks (Table 6.1) suggests that they are 'non-oxidisation' areas as total iron is constant, but ferrous iron predominates. Thus for various reasons, presence of organic matter or whatever, reducing conditions prevailed in such areas whilst oxidation occurred elsewhere. They are not considered areas of post-reddening reduction, and they confirm (hematisation of biotites and mudclasts) that post-depositional hematisation did occur. (As opposed to reduction of hematite post-depositionally).

6.4 Magnetic Evidence

There is some controversy over the interpretation of palaeomagnetic data from the Scottish Old Red Sandstone, (see Donovan, Archer, Turner and Tarling 1976, Turner, Archer, Tarling and Donovan 1977), but it is only recently that an attempt has been made to understand the diagenesis and magnetisation of these sediments (Turner and Archer 1975, 1977).

Palaeomagnetic studies of red beds (Baag and Helsey 1974, Collinson 1974) have shown that in many cases the magnetisation was carried by hematite pigment, and acquired shortly after deposition, because secular variation has been preserved in the magnetic record. They inferred therefore that pigment generation was very early.

Recent magnetic studies of the red sandstone of the Gamrie Outlier (Turner and Archer 1975) concluded that the production of pigment with a stable magnetisation was necessary for the preservation of Devonian pole positions. The preservation of two or more antiparallel directions in the pigment indicated that pigment production must have been continuous during diagenesis to accommodate normal and reversed magnetic periods. Reversals may involve periods of the order of 10,000 years.

Remagnetisation was considered to be a result of long term processes completing the alteration of magnetite to hematite

i.e. magnetite → maghemite → hematite

and demonstrating that red-bed processes continued for a very long time after burial, in this case culminating during Permo-Carboniferous times.

6.5 Detrital Opaque Oxides

Van Houten (1968) demonstrated the importance of the nature of opaque oxide suites in the evaluation of the history of red beds. His work indicated that detrital grains were predominantly magnetite, ilmenite, maghemite and hematite, and the abundance of ilmenite and magnetite were noted to decrease relative to hematite in older red beds. Drab beds showed an overall depletion of the opaque suite due to reduction and dissolution. The implications of Van Houten's conclusions are that diagenetic processes may control the iron minerals present in red beds for a very long period after deposition.

Turner (pers. comm.) has observed that drab sediments (in this case reduction zones) in the Triassic St. Bees Sandstone contain an opaque oxide assemblage dominated by anatase, whereas corresponding red beds are dominated by iron-titanium oxides, principally hematite.

Polished specimens of red and drab sandstones, plus polished separations of heavy mineral suites have been studies in an attempt to identify the iron oxides present and to study their textural relationships.

Polished specimens of red sediments confirm the presence of hematite as grain coatings and a matrix constituent, as well as a direct replacement of phyllosilicates (Plate 6.10, 11). Drab specimens are characteristically lacking in hematite grain coatings and hematite matrix.

Separations of heavy minerals from red beds proved that the opaque iron oxide suite was composed of hematite, magnetite, chromite and leucoxene. Hematite, including hematised magnetite dominated all separations,

	RED			DRAB	
Sample	P.5	G.7	G.25	G.13	G.11
Hematite	15	12	15	13	21
Magnetite	2	0	0	0	0
Chromite	1	0	0	0	0
Leucoxene	6	4	4	7	3
Magnetite-Hematite	76	84	81	80	76

Table 6.2 Modal analyses (100 grains each) of the opaque oxide suite of 3 red and 2 drab sandstones

magnetite and chromite being recorded in only one sample whilst leucoxene formed a minor constituent to all separations (Table 6.2). On average about 80% of hematite grains counted displayed an internal polycrystalline appearance (Plate 6.11 and Table 6.2) i.e. martitisation textures due to the hematisation of magnetite along (111) partings (Thompson 1970, Edwards 1947). Those hematite grains showing no polycrystalline appearance showed varying degrees of secondary alteration in the form of anastomosing corrosion pits and channels (Plate 6.11) similar in all respects to those described and illustrated by Thompson (1970) and Turner (1974). Similar relationships were found to exist between the opaque oxides in both red and drab sediments, the main difference being that the total opaque suite was depleted in drab beds. Magnetite and chromite, being recorded in only one specimen are not significant in the present example, although the common occurrence of leucoxene, an amorphous titanium oxide, suggests the alteration of ilmenite both in red and drab sediments.

Previous studies of red beds have reached similar conclusions namely that the detrital iron oxide suite has largely been altered. (Cf Miller and Folk 1955, Thompson 1970, Van Houten 1968, Turner 1974). Although this conversion process may have been initiated during transport, deposition, and early diagenesis (Van Houten 1968) its activity may have continued for a long time after deposition (Turner 1974). Such a long term oxidisation of magnetite, or periodically rejuvinated oxidation, is a factor recently considered in connection with palaeomagnetic dating of the sediments of the Gamrie outlier (Turner and Archer 1975) and in particular their acquisition of Permo-Carboniferous pole positions.

Turner and Archer (1977) offer some verification of the above results in that measurements of a number of different grain size separations of opaque oxides recorded only hematite Curie points, with no indication of magnitite in any of the samples studied. This largely also confirms Van Houtens' (1968) conclusions.

6.6 Replacement of Iron Silicates

A consideration of conglomerate composition in the sediments of the Gamrie Outlier (see Chapter 4.) allows a prediction of detrital mineralogy to be made, and of the iron bearing silicate minerals, an assemblage of olivine, hornblende, pyroxene, and biotite would be expected. Olivine, hornblende, and pyroxene were not recorded in this study although Mackie (1923) does refer to rare examples of hornblende and pyroxene. Biotite occurs, often in profusion, and with chlorite forms the only iron-bearing silicates detected.

Hematisation of magnetite has been considered by many authors in the past, but recent magnetic experiments (Turner and Archer 1977) have demonstrated a new textural site for hematite, a site which the author considers important in relation to recent models of hematite genesis (Walker 1967).

Olivine, hornblende and pyroxene are notably unstable, and would not be expected to be common in sediments of this age; their absence may support Walkers (1967) contention that in-situ degradation of iron-bearing silicates releases iron and assists in red-bed formation, but unfortunately their absence can also be explained simply in terms of the mineral instability with sediment age (Van Andel 1959).

Biotites and chlorites show several stages of replacement by fine grained, red, translucent often hexagonal-shaped pigment. Detrital grains range from totally fresh, to opaque specimens almost totally replaced by pigment (see Plate 6.12). Initially pigment crystallises on the grain margins before attacking cleavages (Plate 6.12c). Cleavages are first altered in the vicinity of compaction and distortion where cleavages are split (Plate 6.12c and d), or at the ends of flakes where similar splitting occurs. Random crystallisation of pigment occurs first, later replaced by sheets of pigment which ultimately obliterate the whole grain. A sequence of thin-section photographs is presented in Plate 6.12 to illustrate this phenomenon and Figure 6.1 is a schematic reconstruction of the process. The total replacement of phyllosilicate grains is easily recognisable because the original grain outline is preserved, and individual cleavage traces are frequently easily discernable (plate 6.12f). The preservation of distorted cleavages (Plates 6.12d, e), and the initial attack of such sites suggests that alteration took place post-depositionally.

Silicate grains altered in this manner are common throughout the sediments of the study area and the occurrence in any one section of biotites and chlorites with varying degrees of alteration suggests that although alteration appears to be post-depositional, reworking of numerous floodplain sites may have caused the resulting mixture of weathering products. Such a phenomenon was reported by Friend et al. (1963) and Friend (1966) proposed that a mixing of variously-weathered detritus may have been responsible. However this need not imply a derivation from upland red soils.

During the course of this study the nature of the hexagonal crystalline alteration product has received close attention, thin section evidence being complimented by a scanning electron microscope (SEM) study utilising energy dispersive X-ray analysis (EDAX).

A selection of biotite flakes with varying degrees of alteration were carefully split to expose cleavage surfaces (Plate 6.13a).

Relatively unaltered biotites showed a fairly smooth surface. The initial hematite crystallisation (Plate 6.13b, c and 6.14a, b) produces a regular, often coalescing, pseudo-hexagonal relief. The dimensions of these crystals are comparable to those observed in thin section, ranging from 0.25μ to 20μ in unrestricted areas, cleavage traces more commonly being cluttered with 2μ to 5μ crystals. EDAX analysis of these areas (Plates 6.14 and 6.15) demonstrates a progressive iron enrichment, at the expense of silicon, magnesium, and aluminium, when compared with the background. With increasing hematisation, the surface relief increases in intensity without increase in crystal dimensions and this is frequently associated with the separation of pseudo-hexagonal flakes (Plate 6.13 c, d). Plate 6.15 summarises the apparent stages in development, illustrating the separation of flakes (Plate 6.15a), their coalescence (Plate 6.15b), and final pseudomorphing of a biotite (Plate 6.15c).

In an attempt to confirm the composition of these clay sized flakes, EDAX was applied to separations of clay from disaggregated micas made under gravity in a strong magnetic field. The results were inconclusive, numerous specimens were identified as iron oxides were identified as iron oxides, while others of the same size and shape were alumino-silicates. If the pigment was genuinely hematite, it must be concluded that the clay fraction obtained was strongly contaminated by kaolinite (although kaolinite has not been recorded with a red colouration (Robb 1949) and therefore may not be the red hexagonal crystals on all biotites). The presence of kaolinite within the biotite cleavages is not regarded unusual, considering the discovery of other minerals during a study of biotites from the Upper Old Red Sandstone of Caithness, and Silurian red sandstones from the Ringerike Group of Norway in which authigenic albite was found to be present in a cleavage site. (see Plate 9d).

Separations of detrital iron oxide, 'hematised' mica and grain pigment have been studied with reference to their magnetic properties (Turner and Archer 1977), and the conclusions indicate that the magnetic properties of the altered mica were consistent with those of hematite pigment, rather than those of specularite. It appears therefore that hematite crystallisation has occurred in the biotites and chlorites, although EDAX analysis and X-ray diffraction failed to detect this mineral.

Many authors have recognised that iron is liberated during the oxidation of biotite (Wilson 1966, Rice and Williams 1969) and Farmer et al (1971) considered to mechanism of oxidation in detail.

Iron occupies an octahedral site in biotite, but as noted, hematite crystallises in an interlayer cleavage position. Normally the iron is in a ferrous state, but oxidation converts the iron to the ferric state. A reversible loss of protons, and an irreversible loss of octahedral iron is thought to accompany this change, and to compensate for the change in valency (Farmer et al 1971).

$$(Si_3AlO_{10})Fe_3^{2+} + (OH)_2K + \frac{1}{2}O_2 \rightarrow (Si_3AlO_{10})Fe^{2+}Fe_2^{3+} + O_2K + H_2O$$

LOSS OF HYDROXYL PROTONS

$$(Si_3AlO_{10})Fe_3^{2+} + (OH)_2K + \frac{3}{4}O_2 + \frac{1}{2}H_2O \rightarrow (Si_3AlO_{10})Fe_2^{3+}(OH)_2K + FeOH$$

LOSS OF OCTAHEDRAL IRON

The process of electron transfer from octahedral Fe^{2+} is probably mediated through a hydroxyl or oxide ion. Initially the transfer of hydrogen atoms from a OH group to the oxidant takes place while Fe^{2+} ions are coordinated to oxide ions, electrons may transfer directly from oxide ions to oxidant or indirectly through bridging water molecules. In this manner the $(Fe_3{}^{2+}\ Fe^{2+}\ O_2^{2})^{4+}$ grouping is converted to $(Fe_3{}^{2+}\ O_2{}^{2-})^{5+}$ the resultant local concentration of +ve charges being unstable and a $(Fe^{3+}\ O_2{}^{2-})^{+}$ grouping is ejected through hexagonal holes in the silicate sheet into an interlayer (cleavage) space.

Farmer et al (1971) showed that this interlayer oxide was either amorphous iron hydroxide or a crystalline phase of β -FeOOH. Both of these could readily be converted to hematite (α -Fe_2O_3) with continued oxidation.

A number of authors have studied the loss of iron during biotite weathering, Wilson (1966) noted a decrease from 15.5% to 10.5% in weathered mica from well-drained soils. In such sites there is evidence therefore that complexing and reducing agents can extract the ejected Fe^{3+} ions. Rice and Williams (1969) found that iron staining and disintegration of biotite was associated with loss of Fe^{2+} from octahedral layers.

It appears therefore that the process of breakdown of biotite and hematite development without input of iron is understood, x-ray diffractograms of selected biotite flakes, fresh and hematised were compared, and demonstrate an increase in the spacing of the 001 layer (Figure 6.2) corresponding to the loss of Fe^{2+} (i.e. from the 10 Å octahedral layer). In the present case, in all flakes studied, iron has crystallised as hematite, and has not been leached to contribute significantly to the grain pigment. Therefore it must be concluded that although other iron silicates may have contributed to the iron content of the red beds, and biotites may have released iron in other depositional sites, the in situ breakdown of biotite is not solely responsible for redbed genesis in the Gamrie outlier.

In the light of this evidence it would appear that the irregularities recorded in the S.E.M. pictures may represent breakdown of the biotite lattice, and gradual fixing of hematite in interlayer positions. Release of hematite does not occur until the biotite structure has been leached sufficiently to destroy the original lattice, leaving the interlayer hematite, and in ultimate cases hexagonal flakes of kaolinite (see also

Chillingar and Larson 1967).

6.7 Clay Mineralogy

6.7a Introduction

In certain circumstances clay mineralogy has proven to be a valuable tool in the characterisation of environments, source areas, and depositional conditions. The clay mineralogy of the red-bed sequence at Gamrie has been studied with an aim to clarifying the environment in which the sediments were transported and deposited.

Appendix IIoutlines the approach used by the present author to the analysis of separated clay fractions.

Examples of X-ray diffractograms are shown in Figures 6.3 and 6.4, the major clay minerals present in the sediments consisting of the following types:

1. Muscovite Group Minerals
2. Chlorite Group Minerals
3. Kaolinite Group Minerals

These three groups of minerals form the geologically important clays found in both recent and ancient sediments. Expanding clays (e.g. montmorillonite) may often be an addition to certain sediments, and have in fact been isolated by Donovan (1971) from the Sarclet Basement Group south of Wick, and noted by Wilson (1971) to occur in small quantities in Caithness sediments. During the present survey, however, no expanding clays were detected.

Reesman and Keller (1967) noted that one of the most profound effects on clay minerals in a given environment, was the production of mineralogical simplification of the original assemblages. Hence, the restricted assemblage found in the Gamrie sediments may reflect such a simplification.

6.7.b Results

1. Muscovite Group Minerals recorded range from the true muscovite ordered 1M and 2M polymorphs, to the disordered 1Md polymorph (illite). Muscovite was recognised by the 001 basal reflection at 10Å (8.9°2θ) and subsidiary peaks at 17.8° 2θ, 26.7° 2θ. The sharpness of many of the peaks suggests that the muscovite is largely of the 1M or 2M polymorph with good crystal form, a feature supported by the abundant detrital muscovite recorded in thin sections.

Disordered 1Md illite is also abundant, being further support of silicate breakdown during weathering. Thin sections show no evidence of authigenic muscovite, and it is concluded that the ordered 1M or 2M polymorphs recorded are purely of detrital origin, and not due to the recrystallisation of 1Md disordered varieties. The nature of the source area (see Chapter 4), an igneous-metamorphic terrain would also support the primary, first cycle origin of muscovite.

2. Chlorite Group Minerals were distinguished by a 14Å 001 reflection (6.2° 2θ) plus an integral series of reflections at 7Å, 3.5Å etc., for second and third order reflections. The 7Å 002 reflection is complicated by the 7Å 001 kaolinite peak. This problem may be resolved by heating the sample to 560°C during which time the kaolinite structure collapses to X-ray amorphous meta-kaolinite (Carrol 1970).

During the present study an alternative approach was used in the identification of chlorite and kaolinite, based on the 14Å reflection and the slow-scan separation of the 3.54Å chlorite and 3.58Å kaolinite peaks (see Figures 6.3 and 6.4).

The chlorite present notably has suppressed 001, 002, 003 and 005 reflections, with stronger 002 and 004 peaks indicating that the chlorites are iron-rich (Brindley 1961, Carrol 1970), a phenomenon common to other ancient red-bed sequences (Turner 1974). Furthermore the diffractograms suggest a good crystal form to the chlorite, and combine with thin section evidence to suggest that the chlorite may largely be of detrital origin, a feature also expected from source area considerations.

3. Kaolinite Group Minerals have been recognised as mentioned above by the 001 7Å peak, and separated from chlorite by identification of the 3.58Å peak at slow scan speeds. The kaolinite present is generally only abundant in red sediments, in particular red sandstones. The diffractograms show strong sharp peaks, and combine with thin section evidence to confirm a good crystal form to the kaolinite, this time exclusively authigenic in origin.

6.7.c. Relationship of clay mineralogy to colour

Friend (1966) studied the clay mineralogy of the Catskill red-bed facies and found that chlorite, kaolinite, and illite were predominant. Sandstones were noted to be richer in chlorite and kaolinite, whilst siltstones were richer in illite. No relationship between clay mineralogy and rock colour was apparent. Thompson (1970) detected illite and chlorite but no kaolinite in the Juniata and Bald Eagle Formations and recognised that although red and drab sandstones showed a predominance of illite in the red portion, there was no variation in total clay content between red and drab sandstones.

6.7.d. Discussion

Figure 6.5 summarises the results of the present study and demonstrates that:

(i) Illite is present in all sediments, of all grain sizes, but is most abundant in finer grained and redder deposits. (cf. Thompson 1970)

(ii) Kaolinite is present in brown siltstones and red sandstones, the greatest abundance being recorded in the redder coarser deposits. Kaolinite is virtually absent from all mudstones and grey, fine grained siltstones and mudstones.

(iii) Chlorite is most abundant in darker finer grained sediments, and is common in most fine grained rocks, particularly brown siltstones. Chlorite is of low percentage in the reddest deposits, coarse or fine.

It appears that some colour differentiation exists, particularly between chlorite and illite in fine grained rocks, although grain size of the host rock appears to have an important control on the clay mineral assemblage as shown by Figure 6.5 and 6.6. These Figures show that the coarser grained deposits are richer in kaolinite but poor in both chlorite and illite.

Thin-section evidence (page 345) demonstrated that the kaolinite in all cases is authigenic whereas chlorite and particularly illite are detrital. From this evidence it may be pertinent to exclude the kaolinite from the initial consideration and conclude that the clay mineral abundance is essentially related to colour and that illite dominates redder sediments.

Theoretically the weathering products of feldspathic detritus may be potassic clay (illite), smectite, kaolinite or gibbsite, depending largely on the intensity of weathering processes and their duration. In moist tropical soils, or environments where metal cations are freely available, illite and smectite remain in the soil, but with increasing intensity and duration of weathering leaching of metal cations increases allowing sodium and calcium to be stripped from interlayer positions in smectites, and potassium to be removed from similar locations in illite - resulting in kaolinite rich soil profiles. The generation of authigenic kaolinite requires several critical factors - the Si and Al ratio must be low in order that alumina, being more susceptible to flocculation, is relatively enriched. Metal cations must be depleted by extensive leaching, or in the case of ferrous iron, oxidising conditions are necessary for its effective removal in the Fe^{3+} state (Ross 1943). Acid oxidising conditions are therefore favoured (Grim 1953). The timing of this genesis is critical to the present study as the kaolinite-rich sequence in intimately associated with calcrete developments, which as Walker 1967 recorded, belong at the opposite end of the (climatic) spectrum, kaolinite being more common in moist tropical climates compared to the relatively dry semi-arid calcrete environment (Goudie 1973).

Hematite genesis in the Sonoran desert, (Walker 1967) takes place at a pH consistantly above 8. Significantly kaolinite is of minor importance. In contrast, sediments of the Orinico basin, a moist tropical setting, have high kaolinite clay contents (Walker 1967b). Walker concluded that hematite genesis is taking place within the vadose zone, with acid oxidising conditions existing above and below the water table.

Pettijohn et al (1973) considered that kaolinitisation took place from meteoric water "within a few hundred feet of the surface" (also see Millot 1963). Kaolinitisation of the porous sandstones therefore probably occurred during an early diagenetic episode, but not in response to prevailing climatic conditions. Calcrete development occurs virtually syndepositionally, and the high availability of Ca during this period would effectively inhibit kaolinitisation (Grim 1953). The good crystallinity/well-defined shape of the kaolinite suggests its post-depositional origin and indicates that precipitation probably occurred directly from solution (Mankin et al, 1970). The appearance of the kaolinite strongly suggests that many of the "books" and "worms" of clay may be authigenic dickite, which may readily develop from potassium feldspars (Smithson and Brown 1954) whilst liberating substantial amounts of silica, and believed to be of early diagenetic origin (Smithson and Brown op.cit). The sequence of events during cementation indicates that calcite was the last phase to develop, and an overwhelming amount of evidence has been produced in recent years noting the frequent early diagenetic occurrence of calcite in sandstones (Glover 1963, Pettijohn et al, 1973) although Siever (1959) described its occurrence at a later stage than silica overgrowth.

Thus in conclusion - although kaolinite dominates the sandstones, the environmental inferences from such a mineralogy are not valid, since the clay is authigenic and although early diagenetic it formed later than calcrete development. The latter is a more reliable indicator of the paleoclimate.

6.7.e. Significance of Clay Mineralogy

The study of clay mineral suites in sedimentary rocks may allow a relationship to be established between them and environment, source and depositional processes (see Beaven 1966, Neiheissel and Weaver 1967, Porrenga 1967, Weaver 1967). Care must be taken with such interpretations as diagenetic modification may pose great problems; as mentioned, diagenetic simplification of diamorphic clay minerals is probably the most common effect (Reesman and Keller 1967) and is apparent by the simple three fold division of the clay minerals extracted during this study.

Kaolinite is authigenic, its environmental implications are therefore largely invalid, although Aristarain (1970) does record kaolinite development in calcrete profiles. Kaolinite is normally accepted as being the product of weathering of alumino-silicates where metal cations are removed by intensive leaching; wet climates are invoked to facilitate repeated leaching, under oxidising and acid conditions (Grim 1953).

Illite in siltstones would require adequate supply of silica, and an abundance of Ca, Mg, and Fe ions, alkaline conditions would thus be favoured, and leaching could not be extensive as much potassium must be available in solution. Alternate wetting and drying favour illite preservation. Occurrence of illite in floodplain sediments suggests a not-so-well drained site.

6.8 Chemical Analysis of Red Beds

Forty samples of red, drab and brown sediments were analysed by a combination of atomic absorption and colorometric techniques discussed in

Appendix II. The grain size of these sediments was estimated to the nearest Wentworth grade, and the colour noted by comparison with standard charts (Goddard 1951). Analyses, in all cases, were made in duplicate and the results averaged. The samples were separated into three colour groups, red (5R and 10R), brown (5YR and 10YR), and drab (Y, G, N, etc.). The iron contents of these groups are listed in Table 6.3.

	Fe^{2+} %	Fe^{3+} %	Fe_{tot} %	Fe^{2+}/Fe^{3+}
Red	0.4	1.12	3.7	0.36
Brown	1.14	1.3	5.4	0.88
Drab	1.47	0.7	4.8	2.1

Table 6.3 Summary of iron analyses of red, brown and drab Sediments

Total iron is lower in the red beds, but as discussed later this is strongly influenced by grain size. Ferric iron is more abundant in red and brown beds, while ferrous iron is most abundant in drab beds. The influence of grain size upon total iron content is demonstrated in Figure 6.7 where a strong correlation exists (0.8), finer sediments having greater total iron. The effect of this variation can be partially offset by consideration of the 'oxidation ratio' (Fe^{2+} Fe^{3+}); red and brown beds are similar in their low ratio compared to the much higher Fe^{2+}/Fe^{3+} ratio in drab beds. Furthermore the brown and drab beds are similar in grain size yet show little difference in total iron. The latter supports the idea of Fe^{3+} enrichment in red beds without variation in total iron. Figure 6.8 is a sequence of graphs illustrating the relationships between Fe^{2+}/Fe^{3+} and Fe tot. for the three colour groups. Table 6.4 lists the correlation coefficients calculated for these grpahs.

	Red (n=40)	Brown (n=20)	Drab (n=20)
Fe^{3+} v Fe^{2+}	0.44	0.32	-0.85
Fe^{tot} v Fe^{2+}	0.35	0.17	0.19
Fe^{tot} v Fe^{3+}	0.91	0.96	0.94

Table 6.4 Correlation between Ferric, Ferrous and total iron in red, brown and drab Sediments

These results demonstrate that Fe^{3+} represents a high proportion of the total iron in all sediments. The strong negative correlation (- 0.85) between Fe^{2+} and Fe^{3+} in drab beds is due to the primary nature of drab silts, muds and sandstones, and also secondarily reduced drab sediments which still retain a high Fe^{3+} content of specularite. Hence drab sediments tend to be either Fe^{2+} rich or Fe^{3+} rich causing a reciprocal relationship between Fe^{2+} and Fe^{3+}. Graphs of Fe^{2+} and Fe^{3+} against grain size show a moderate negative correlation of Fe^{2+} and grain size (- 0.36) but a strong negative relationship between Fe^{3+} and grain size (- 0.71) indicating that Fe^{3+} is related to finer grained sediment, perhaps directly related to clay.

The results of the chemical analysis have been grouped using the Weighted Pair - group Method with arithmetic averages. The Q-mode dendrogram is shown in Figure 6.9, the R-mode dendrograms have been computed for red and drab rocks and are shown in Figure 6.10. The cluster analysis was carried out using the computer program CLUSTER described by Davis (1973).

The Q-mode dendrogram (Figure 6.9) can be subjectively partitioned into four lithologically and chemically discrete groups.

1. Red sandstones from the Castle Hill Sandstone Formation with Significantly high Fe^{3+} and K_2O but low Fe^{2+} and low CaO.
2. Red Sandstones from the lower portion of the Crovie Group with Higher Fe^{2+} and lower Fe^{3+} therefore less oxidised, MgO and CaO higher but K_2O less.
3. Drab mudstone, high Fe^{tot}, MgO, K_2O, and CaO, highest Fe^{2+}.
4. Red siltstones, highest Fe^{tot}, and highest Fe^{3+}, K_2O, high MgO and CaO.

The significant features of these results are

a) significantly higher Fe^{3+} in red beds.

b) significantly higher Fe^{tot}, in fine beds.

c) significantly higher K_2O and MgO in fine beds.

Overall, fine deposits are enriched in iron and oxides related to clay minerals. It is suggested from this that either iron and thus hematite may have been generated from the breakdown of iron-bearing silicates and clays (cf Walker 1967, Walker, Ribbe and Honea 1967, Walker and Ribbe 1967, Turner and Archer 1975) or iron and hematite may be enriched through oxidation of iron-bearing detrital clays (Walker and Honea 1969).

The R mode dendrogram (Figure 6.10) adds further support to these ideas in that:

1. Red Beds (a) Total iron is related to K_2O, perhaps located in potassic clay. Illite is abundant in red beds, and is known to have the ability to absorb and transport iron.

(b) Ferric-iron is related to MgO, perhaps in the form of chlorite. The general lack of chlorite in red beds detracts from this possibility unless the absence is due to chlorite breakdown. Such breakdown would also assist in causing ferric-iron enrichment.

These relationships may also be connected with biotite breakdown, as EDAX analysis of hematised biotite demonstrated that the hematite carries significant amounts of magnesium, presumably derived from the biotite lattice. (Plates 6.14, 6.15). Ferrous iron is also significantly related to MgO, and again this may imply a link between iron, and either chlorite or biotite.

2. Drab Beds (a) Ferrous and ferric iron are significantly related, and

(b) both are related to MgO and K_2O

(c) total iron is related to both (a) and (b).

It may also be pertinent to consider clay mineralogy in the light of these chemical analyses.

1. The red bed groups are generally enriched in kaolinite, particularly the coarser deposits - these deposits are also notably depleted in K_2O, MgO, CaO.

2. Drab beds lack kaolinite but have higher chlorite and illite - notably K_2O, MgO, CaO are high.

Chemical analysis may be directly related to clay content, OR lack of metal cations in red beds may have assisted kaolinite development, but the enrichment of K, Ca, Mg, may have inhibited kaolinite development in finer beds while at the same time enriching chlorite and illite.

6.9 Summary

Chemical analysis demonstrates ferric-iron enrichment in red beds, which may be due to the introduction of amorphous ferric hydroxides concentrated in muds and silts. This is further supported by fine beds having higher total iron, and fine beds being Fe^{3+} enriched. Drab beds may have been selectively reduced by post depositional reduction and solution (Miller and Folk 1955) or the in-situ oxidation of iron-rich silicates and iron-bearing clays may have occurred (Walker and Honea 1969). The comparison of brown (red) and drab fine-grained sediments suggests that little difference exists in total iron, and therefore selective enrichment in Fe^{3+} is not supported.

Variations in Fe^{2+} and Fe^{3+} support a mechanism of oxidation and/or reduction of the total iron population. Post-depositional reduction and dissolution (Miller and Folk 1955) is not favoured. Support is greatest for Walker and Honea's (1969) hypothesis of post-depositional oxidation, in this case of detrital iron rich clay.

The environment of deposition and subsequent reddening must be considered in order to evaluate the causes of reddening. Sedimentological studies (Chapter 3) suggest that ephemeral conditions prevailed in many of the rivers depositing the sandstones. Calcrete developments verify the arid semiarid nature of the climate where precipitation was exceeded by evapotranspiration. Reddened siltstones and mudstones are abundantly desiccated and mudflakes (resulting from desiccation) are common in sandstones.

Previous discussion suggested that iron may have been introduced into the sediments as iron-rich clays. This would probably correspond to the amorphous iron hydroxide approximating to Fe(OH) considered by Krynine (1949) and Van Houten (1968) to be the hematite precursor. Unfortunately the recognition of such a source of iron is not enough, much argument has taken place as to the ability and conditions under which such an iron hydroxide may 'age' to hematite. Essentially the problem is, can limonite age to hematite, and can it do so in the presence of water?

The genesis of hematite in sediments has been argued principally from two fronts:

(i) that under suitable pH and Eh conditions hematite may form below the water table (Walker 1967), and

(ii) hematite cannot form in the presence of liquid water (i.e. below the water table (Schmalz 1968).

There is little doubt that abundant moisture is essential to the chemical weathering of iron-bearing rock-forming minerals, and although these ferrosilicates may release their iron under anhydrous conditions the rate of release is so low, even by geological standards, as to be negligible. In moist climates iron-rich soils form rapidly on suitable substrates even where temperatures are low throughout the year (Schmalz 1968) - at this stage of hematite genesis high temperatures are unimportant although they would of course accelerate the weathering process. Under moist oxidising conditions the principal iron-rich weathering product is an amorphous ferric oxyhydroxide (approximately ferric hydroxide) which recrystallises very rapidly to goethite ($HFeO_2$). Either of these phases may impart a characteristic yellow, yellow - brown colour to the sediment. Schmalz (1968) argues that the characteristic red pigment hematite may form from these initial weathering products (amorphous ferric hydroxide or goethite) by three possible reactions:-

(1) $2Fe(OH)_3 \rightleftharpoons Fe_2O_3 + 3H_2O$

(2) $2Fe(OH)_3 \rightleftharpoons 2HFeO_2 + 2H_2O \rightleftharpoons Fe_2O_3 + 3H_2O$

(3) $2HFeO_2 \rightleftharpoons Fe_2O_3 + H_2O$

The substantial amounts of water liberated from these reactions lead Schmalz to conclude that the formation of hematite must be considered as the dehydration of the primary weathering products of iron-rich minerals, and also that a dry climate was essential for its formation. Further, Schmalz argued that on thermodynamic grounds amorphous ferric hydroxide would spontaneously recrystallise to geothite plus water at 25°C and 1 atmosphere total pressure.

$$Fe(OH)_3 \rightleftharpoons HFeO_2 + H_2O$$

For this reaction he quotes a Gibbs free energy of - 4.69 K cal/mol., thus indicating that it could take place below the water table. The more critical question, can hematite or goethite be the stable ferric oxide phase under standard conditions (25°C 1 atmos.), Schmalz attempted to answer from thermodynamic data. For the reaction - (3) above Schmalz quoted a Gibbs free energy between 0.2 and +2.2 Kcal/mol (hematite) and concluded from the positive free energy that the reaction (under standard conditions) will move spontaneously to the left, and therefore hematite cannot form stably in the presence of liquid water. Furthermore Schmalz contested Walker's contention that hematite might form below the water table under suitable Eh - pH conditions by re-examining the stability fields of hematite and geothite. That the Eh - pH characteristics of near surface groundwaters generally lie within the "hematite" field of Garrels (1960). Garrels and Christ (1965) and within the "ferric hydroxide" field of Hem and Cropper (1959), Schmalz (1968) claimed such a basis for Walker's (1967) hypothesis is inappropriate on several counts.

(i) Ferric hydroxide is unstable relative to goethite,

(ii) Ferric hydroxide is yellow-brown and not red,

(iii) The hematite field of Garrels and Christ (1965) assumes the presence of pure liquid water (i.e. aH_2O = 1.0) under such conditions hematite is unstable relative to goethite. Garrels (1960) acknowledged that hematite may not be the stable phase but assumed that (op. cit) the hematite stability field in water is essentially the same as goethite. But as

Schmalz (1968) has shown (eq^n 4) the stability relations of hematite and goethite are independant of Eh and pH, and equilibrium at standard temperature and pressure depends only on the aH_2O (water activity) in the system .... a parameter not included in the Eh/pH plot. Thus the stability field "hematite" of Garrels and Christ (1965) and Garrels (1960) represents an approximation of the stability field of goethite - a yellow brown pigment.

In summary Schmalz (1968) defined some possible conditions for formation of red beds.

(i) Sufficient moisture to facilitate rapid deep chemical weathering and the release of iron from parent minerals. Also preferably warm.

(ii) Absence (or reduced activity) of water to promote dehydration of these primary weathering products.

Berner (1968) has produced experimental evidence to indicate that goethite could recrystallise to form hematite plus water and that this could occur in the presence of liquid water. Such contradictions serve to illustrate that with such uncertainty about the variable involved in arguments of this nature - evidence of this nature will at present offer little assistance in interpreting the process of hematite formation.

Walker (1967a, 1967b) investigated the origin of hematite pigmentation in a series of immature arkosic sediments in the region of Baja California. He concluded that the iron oxide pigment in red sandstones was formed by the redistribution of iron outwards from the decomposing grains by oxygenated pore waters during diagenesis, and that climate during deposition of the sandstones may be irrelevant to the formation of the red pigment.

Several lines of evidence from the present work indicate that a variety of processes and factors combine to produce the reddening of the sediments, and to create the red-drab differentiation. As recorded by earlier authors the red colouration is caused by finely-crystalline hematite present as grain coatings and within the clay matrix. The crystal form and textural sites occupied by this hematite clearly indicate that at least some crystallised post-depositionally, although the variety of hematised biotites in many samples suggests that this process of hematisation was probably active in numerous floodplain sites prior to final deposition. Hematisation of phyllosilicates continued long after deposition, and demonstrates the range of time involved in hematite genesis.

Consideration of source area and sediment compositions suggests that breakdown of iron-rich silicates (hornblende and pyroxene) may have been a contributory factor in freeing of Fe from the lattices, but the in-situ breakdown of such minerals as suggested by Walker (1967a, b) and Walker et al (1967) is not evident in the Gamrie Outlier. In fact the study of biotite morphology in red beds in the study area (and others) has demonstrated that although biotite weathering may liberate free iron oxide, the presence of hematite in biotites and chlorites indicates that the phyllosilicates were acting as a 'trap' recipient for iron rather than a source. As hematisation of micas was initiated during transport it is very likely that mechanical disintegration of corroded biotite would liberate substantial quantities of iron into the system, to be dissolved and redistributed, or transported and incorporated in sediments as an iron-rich clay. Micaceous sediments at Rhynie demonstrate that the in situ breakdown of phyllosilicates is possible but the outward migration of iron is very limited in this instance.

Thus, the in situ oxidation and liberation of free iron oxides from detrital iron-bearing silicate grains is possible, not directly by in situ breakdown, but by breakdown within the sedimentary basin with subsequent redistribution of the weathering products. As such, the author believes that this preliminary conclusion supports the concept of Walker (1967a, b), Walker and Honea (1969) although in many respects is may be analogous to Van Houten's and Kry/nine notion of derivation from 'upland' red soils.

The production of red or drab sediments at Gamrie and Rhynie is probably a dangerous argument as the normal red-drab, fine-coarse relationship is only locally developed. The sedimentological control invoked by Friend (1966) and supported by Turner (1974) can be used to explain the red-drab differentiation noted in the present study, although field evidence and petrographic evidence favour an alternative mode of origin. In many examples redness is a function of grain size, so that under suitable conditions the iron present in fine grained sediment is oxidised to produce red beds. This implies that any fine grained sediment has the ability to become reddened, but it is the environmental or diagenetic conditions which trigger the process. Chemical analysis confirms this; red and grey siltstones have comparable total iron contents, but different Fe^{2+} and Fe^{3+} contents suggesting that it is the conversion of Fe^{2+} to Fe^{3+} that controls the reddening. Figure 6.11 is a graph of Fe^{2+} v Fe^{3+} incorporating grain size and colour. The distinguishing line in the present analysis is $Fe^{2+} = Fe^{3+}$, greater Fe^{3+} allows red beds, greater Fe^{2+} - drab beds. This conclusion is irrespective of grain size. Field and petrographic evidence confirms this idea. Sandstones may become reddened, but in the vicinity of reduction spots no hematite pigment is or has been generated. Mud clasts incorporated in reduction spots are drab in the spot but red outside suggesting that the hematite precursor was initially available, and not introduced at a later stage.

It is concluded from the present study that hematite pigment crystallised post-depositionally, and was derived from the oxidation of iron-rich detrital clay derived from an upland area. Breakdown of detrital iron-rich silicates probably also liberated iron, but this cannot be proven in situ in any but one case. Iron may have been attached or incorporated within clays either derived from iron-silicate breakdown in floodplain sites, or from source rock disintegration in the Caledonian Uplands. The ultimate control of reddening was an environmental one, the presence or absence of oxidising conditions decided whether iron hydroxides would 'age' to hematite.

Carroll (1958) recognised that as well as the chemical transport of iron a mechanical method existed as iron may be carried into the depositional basin either incorporated within the clay shructure, or by adhering to the clay surface. The importance of clay minerals in the transport of iron was stressed by her work, iron oxides were recognised as being responsible for the colouration of red soils but, more important, these iron oxides were always associated with clay minerals. Analysis of clay fractions demonstrated that iron was mainly associated with the finest fractions - probably in relation to the very large surface area of finer particles (see also Baver 1956). Most important is Carroll's (op. cit.) note that the iron attached to clay minerals was in an easily removable form.

Analysis quoted by Carroll indicated that as much as 10% ferric oxide may be transported in modern clays. Carroll summed up the importance of clays by noting that they may accumulate ------" a considerable quantity of iron and the mechanism is certainly of geological importance in the movement of iron".

Although a discussion of the physico-chemcal controls of hematite genesis is beyond the scope of the present project it is interesting to note that the combination of evidence, (i.e. implied semi-arid conditions, plus development of calcrete profiles developing before, at, or near the time of hematite genesis) might suggest that hematite crystallisation occurred above the water table, and the subsequent burial beneath the water table probably allowed the early crystallisation of kaolinite directly from meteoric groundwaters.

If such an argument is valid then iron-silicate breakdown and redistribution of liberated iron would probably not be feasable. Hematite would be generated in a relatively dry environment, the lack of water also preventing mobilisation of any iron liberated by disintegration of iron silicates.

CHAPTER 7

CHAPTER 7 - PALEOSOIL HORIZONS IN THE GAMRIE AND RHYNIE OUTLIERS

Introduction

Within the Gamrie and Rhynie Outliers two forms of mineral concentration have been recognised and interpreted as having formed as a result of soil forming processes.

The first and most extensive of these deposits consists of large accumulations of carbonate material within floodplain sediments, and has been interpreted by analogy with modern calcrete or caliche developments in arid and semi-arid environments.

The second form is much less extensive, and occurs in sandstones and conglomeratic sandstones of distal alluvial fan regions, and consists of the concentration of iron and manganese rich minerals. Such concentrations are again considered to be the result of soil forming processes in a manner analogous to the development of 'hardpans'.

PART A - Calcrete Horizons

7.1 Introduction

Carbonate-rich horizons are present within the lowest sediments of the Lower Old Red Sandstone sequences at:

(i) Crovie and Quarryhead,

(ii) New Aberdour Shore and Counter Head,

(iii) Rhynie, in the lower red shales in Corbiestongue,

and in Middle Old Red Sandstone sediments in:

(iv) the upper portion of the Findon Fish Bed.

From the stratigraphy outlined in Chapters 1 and 2, it is clear that such developments are widely distributed both in area and in time. The development and interpretation of such deposits is regarded important due to both the climatic implications, and the time and tectonic stability required for their formation.

7.2 Terminology

In recent years, many studies have been made on both recent and ancient calcretes, and an abundance of terminology has developed. During this study, the terms calcrete and caliche have been used in reference to pedogenic accumulations of carbonate, where calcrete implies an indurated deposit whilst caliche refers to recent 'powdery' deposits (cf. Aristarain, 1970, Lamplugh, 1907, and James, 1972).

Most recent descriptions of calcretes employ, quite reasonably, terminology derived by soil scientists. In keeping with this trend, several soil terms are also used during this study, and the reader is referred to Brewer (1964) and Gile et al (1966) for a full description of these terms.

Unfortunately, the terminology is very much open to misuse, and although Brewer (1964) draws attention to 'a confusion in terminology' over nodule/concretion terminology, the collective term glaebule has still recently found great use in place of the highly specific term "nodule." The term glaebule has therefore been avoided during this discussion, as in all cases the 'glaebules' concerned can be readily indentified as nodules (see Brewer, 1964, p. 258).

7.3 Calcrete Developments in the Gamrie Outlier

7.3(i) Quarryhead/Crovie Type Profile

7.3(i)a Description (see Plates 7.1 to 7.3)

Concentrations of carbonate material commonly occur as irregular beds between 15 and 65 cms thick in which calcite nodules lie unevenly scattered through a groundmass of red-brown siltstone/ mudstone. The nodules are generally knobbly or tuberose in shape and rarely exceed 45 cms in diameter. The nodules are always quite hard and crossed by several stages of calcite veining.

Several stages of nodule development are recognised:

Stage I — The host sediment shows the development of small (5mm to 30 mm) prismatic or columnar peds with a strong vertical element and distinct polygonal or rectangular cross-section.

Stage II — Calcite precipitates both in the matrix of these peds, and also in the voids between the peds developed during Stage I. This produces initial weak nodule developments and occasionally predominant calcite veins. These veins are considered to be the 'crystallaria' of Brewer (1964) and may become so extensive that a pseudo-brecciation fabric develops. Normally, Stage II grades directly into Stage III.

Stage III — With extension of the calcite cementation initiated during Stage II, nodules develop in abundance but rarely exceed 20 mm in diameter. With increasing maturity as increased density of nodule development is apparent, but without notable increase in size.

Stage IV — A marked increase in nodule density is apparent, with the initial prismatic fabric often exerting a strong influence on the site of calcite precipitation. Thus during Stage IV as nodules begin to coalesce, crude pipe-like structures develop.

Stage V Extreme coalescing of nodules, but never to the extent that distinct carbonate sheets develop. Nodules become densely packed, eventually only separated by thin skins or films of host sediment.

7.3(i)b Miscroscopic Description (see plates 7.7, 7.8)

Compositionally, the nodules are always quite simple, the non-detrital component consisting of microcrystalline calcite. Generally, the structureless host sediment (the s-matrix of Brewer, 1964) shows various development of calcite cementation.

During Stage I, cementation is not readily apparent, the host sediment is relatively unconsolidated, and no fretting of detrital grains or exfoliation of mica is apparent.

Stage II cementation shows the replacement and/or displacement of the original host sediment (the s-matrix of Brewer, 1964) by microcrystalline calcite; coarser microcrystalline calcite fills voids between peds (the crystallaria of Brewer, 1964).

Stage III shows intensification of this cement and the true development of a fairly continuous undifferentiated crystic-plasmic-fabric (i.e. a mosaic of microcrystalline calcite). During this stage, detrital grains become widely separated and although exfoliation of detrital quartz grains (as figured by Allen, 1974) is not apparent, exfoliation of detrital mica is a distinct and common feature.

Stage IV shows further expansion of areas of undifferentiated crystic-plasmic-fabric as dense fine mosaics of microcrystalline calcite, with quite numerous small calcite crystallaria. Although nodule size is relatively large, agglomeratic fabric is also recognised (consisting of oval and sub-circular areas of microcrystalline calcite with coarser calcite in between). The crystallaria at this stage show complex relationships suggesting that several generations of crystallisation have occurred, crystallaria frequently show complex cross-cutting relationships, and some of the latest phases show the development of crudely laminated crystallaria (also observed by Allen, 1974).

7.3(i)c Interpretation

The development of the Quarryhead/Crovie type of carbonate is regarded as having been a gradual but complex event. Plates 7.1 to 7.3 show the stages in the development of a mature profile, and many features illustrated are closely comparable to those found in younger calcretes.

The features noted in the previous section are closely comparable to those detailed by several authors. Freytet (1973) described similar calcareous nodules associated with prismatic host-sediment fractures, and noted the occurrence of the more mature 'columnar' type of nodule. Similar nodules and in similar profiles are also noted by Chapman (1974), Reeves (1970), Allen (1974), Goudie (1973), and Steel (1974) and have been interpreted as calcrete. In particular, the observed sequence fits very well into the morphogenetic sequence of Gile et al (1966) which perhaps forms the basis of many recent studies of such deposits. Gile et al (op cit.) outline a four stage development closely comparable to that detailed on page 381 :

Present Study		Gile et al. (1966)	
I	Formation of primary peds		
II	Precipitation of calcite in the s-matrix	I	Thin discontinuous coatings
III	Development of nodules	II	Few to common nodules
IV	Increased density of nodule development	III	Many nodules and internodule fillings
V	Coalescing of nodules	IV	Increasing carbonate impregnation
			Laminar horizon overlying plugged horizon

Table 7.1 Comparison of the stages of carbonate accumulation observed at Crovie and at Quarryhead, with those outlined by Gile et al (1966)

In making this comparison, the major difference is only in the absence of the mature stage IV deposits of Gile, and as discussed later, this is perhaps a stage which would be most likely to be absent (see page 402).

The evidence provided by thin sections strengthens such comparisons. Siesser (1975), Nagtegaal (1969), and Steel (1974) note the characteristic micrite pore-filling of calcrete nodules, and the initial local development of such micrite infilling followed by its extension to a 'continuous crystic-plasmic-fabric' (terminology of Brewer, 1964).was noted by Gile et al (1966) in their definition of the K-horizon (a soil-horizon of carbonate accumulation characterised by such 'continuous crystic-plasmic-fabric', a term shortened by them to K-fabric).

Furthermore, the maturation and development of such a K-fabric is a complex polyphase event as indicated by the numerous phases of cross-cutting crystallaria traversing the basic K-fabric calcite. Similar conclusions were reached by Freytet (1973) and Gile et al (1966) who describe 'crystallaria' and 'stellate voids' as retraction features caused by shrinkage during periodic desiccation of the profile. Similar features have been observed by Chapman (1974), Swineford et al (1958), Reeves (1970), Steel (1974) and Sehgal and Stoops (1972).

Although it was noted earlier that the sequence lacked the mature Stage IV of Gile et al (1966), the presence of laminated crystallaria may be an early form of such a mature stage. Essentially, the mature Stage IV of Gile et al (1966) is characterised by distinct laminar subhorizons at the top of the main carbonate horizon. Such subhorizons are generally accepted to be the result of 'plugging' of the profile by extensive carbonate crystallisation causing a very much reduced permeability. In the present instance, the eventual close 'packing' of the nodules during late stages of development would also reduce permeability and leave retraction fissures as the only route for the downward migration of carbonate laden water. Such conduits would then be in a suitable position to be prime sites for carbonate deposition as laminae or coatings on the walls of the fissures or cracks (see also Flach et al, 1969, and page 386).

Thus in summary the development of the Quarryhead/Crovie type of calcrete is considered to involve:

(i) desiccation of the host-sediment and the production of prismatic peds (see also Freytet, 1973);

(ii) the prismatic peds become the site of localised micritic calcite crystallisation infilling sediment pores (see also Siesser, 1975, Nagtegaal, 1969, and Steel, 1974). Such micrite develops the characteristic K-fabric of Gile et al (1966) first as isolate zones, and then coalescing as nodules grow and begin to merge;

(iii) carbonate development varies in intensity, in all cases some primary s-matrix is retained, but separation of detrital grains occurs by the expansion of the micrite cement. This eventually causes the destruction of the primary fabrics leaving only variable amounts of insepic and asepic plasmic-fabrics (see also Nagtegaal, 1969, Sehgal and Stoops, 1972); and finally,

(iv) desiccation causes retraction fissures in which coarse grained micrite crystallises to form the crystallaria of Brewer (1964) and stellate voids of Freytet (1973) noted earlier. Such void infills appear to post-date the main K-fabric development as crystallaria clearly invade the crystic s-matrix.

The primary fissures forming the prismatic peds probably initially allowed the rapid transfer of water through the host-sediment. Capilliary action would not only elevate pore water above the water table, but would also draw moisture within the peds themselves. Nodule formation would thus initiate from within such peds. Carbonate would continue to accrete towards such centres and eventually produce elongate nodules as prismatic peds became totally calcified (Freytet, 1973, describes a similar mechanism which he calls 'radicular aspiration', and Flach et al, 1969 , offer a similar mechanism of nodule growth whereby nodules are regarded as zones of restricted hydraulic conductivity serving to funnel carbonate saturated solutions to previously uncemented regions).

7.3(ii)a <u>Counter Head/New Aberdour Shore Type Profile</u> (Plates 7.4, 5,6)

The second type of profile recognised in the Gamrie Outlier outcrops exclusively in the New Aberdour Siltstone Formation at Counter Head (and to a lesser extent at New Aberdour Shore itself). The profile developed at Counter Head is a modification of the lowermost portion of the siltstone sequence and the uppermost portion of the Dundarg Castle Sandstone Formation sequence. The complete sequence is illustrated in Fig. 7.1, and is comprised the following carbonate morphological types (letters refer to those in Fig. 7.1):

1. Discontinuous thin-sheets of carbonate interdigitating with thin sandstones and siltstones. Symmetrical-ripples and desiccation cracks are often preserved within such carbonate. This form is only well developed in the lowest portion of the profile

in sediments considered to be marginal to the true Piedmont Floodplain/Playa facies (Fig. 7.1A).

2. Similar discontinuous thin-sheets of carbonate to those above, but with much reduced interbedded clastic material (Fig. 7.1B). This form is restricted to lower portions of the siltstone sequence, and appears to replace the previous type A carbonate in more distal sites where the clastic component is very much reduced.

3. Isolate, often large, reddish-brown to green carbonate nodules occurring along distinct and laterally persistent horizons. Along such horizons nodules occur widely spaced and always separate (Fig. 7.1C).

4. Clustered nodules occur within siltstones in higher and mid portions of the profile and are in all ways comparable (except in size) to the nodules already described from Crovie and Quarryhead. The dimensions of nodules ranges much larger at Counter Head, where individual nodules may reach 15 cm. This form of carbonate is again restricted to fairly persistent horizons, although as illustrated on Fig. 7.1 the intensity of nodule development may vary considerably laterally, and in particular in the vicinity of underlying dense carbonate 'knolls' (Fig. 7.1D, E).

5. Continuous but thin single sheets of red-brown or pale grey-green internally massive fine-grained carbonate occurring in mid and higher parts of the profile within thick, massive, brown siltstones. Frequently, such carbonate developments weather orange (Fig. 7.1F).

6. Single, laterally persistent, thick sheets of fine pale red-brown

or pale grey-green carbonate occurring within finest sediments in the profile, and although laterally persistent they may thicken rapidly to form dense carbonate 'knolls' (Fig.7.1 G).

7. Thick relatively impersistent units of massive fine-grained carbonate. Generally such units are pale-grey to pale-green in colour, but very commonly weather orange, and in particular the uppermost portions of such units frequently weather an intense orange. These thick units may develop as thickenings of the previously mentioned sheets of carbonate (see Fig. 7.1 H, J) or they may develop as isolated 'knolls' of carbonate. Where bedding is distinct in the host sediment, such as in lower parts of the profile where sands and silts interdigitate, the edges of such 'knolls' may interdigitate with the host sediment, elsewhere the units are sharp margined. The developments of 'knolls' of carbonate are frequently repeated along a single horizon, with units up to 70 cm thick repeated along one horizon at distances of approximately 10 m. 'Knolls' of carbonate frequently influence the development of carbonate immediately above, generally reducing the intensity of development in such sites. A common feature of 'knolls' is for the upper portion of dense units to be brecciated and recemented, the resulting breccia weathering the most intense orange (Figs. 7.1 H, J.).

7.3(ii)b Microscopic Description (Plates 7.7 to 7.13)

Of the morphological types of carbonate previously described, majority are relatively simple and in many ways directly reflect the carbonate developments described from Crovie and Quarryhead (page 360). Types C, D, E, F and G are almost identical, being composed of a continuous microcrystalline calcite cement. As with the carbonate at Crovie and Quarryhead the Counter Head varieties show features such as replacement/displacement textures, fretting of detrital quartz grains, and intense exfoliation of detrital biotite flakes. Several Stages of carbonate development are again apparent, but are less distinct than in the previously mentioned examples. The Counter Head varieties show the III, IV and V stages mentioned earlier, but not the early development of prismatic fabrics. Similarly, the Counter Head examples show the development of many phases of crystallaria, although laminated crystallaria have not been observed in type C and E forms. Type C carbonate most commonly shows crystallaria of septarian forms.

Overall, low magnesium carbonate predominates, but iron-rich calcite and ferroan dolomite occur in orange-weathering zones. Most commonly, the ferroan dolomite occurs as a replacement of earlier micritic calcite and shows relatively large rhomb-shaped crystals. Where brecciation has occurred, recementation generally occurs by means of ferroan dolomite.

The most distinctive cementing fabric occurs within types A and B carbonate where the previously detailed continuous 'K-fabric' totally invades the host sediment, but due to the frequent occurrence of sheet-cracks numerous elongate voids occur which have been infilled by sparry calcite, and in places by fibrous ferroan dolomite.

The majority of these cavities show pseudo-concentric, largely substrate parallel patterns defined by inclusions and colour banding within the sparry calcite, and furthermore, frequently show the development of predominantly downward growing, gravity, or dripstone microstalactitic calcite. Such downward growth appears most frequently from protuberances on the roofs of sheet cracks and fenestral voids. More rarely, cavities may show the presence of crudely bedded sediment infills.

The intercrystalline boundaries within the sparry calcite are unrelated to the previously mentioned inclusion patterns, and thus indicate a later origin for the sparry cement. The inclusion patterns vary in extent, being thicker in regions where blocks of s-matrix are in contact, or where cracks penetrate into the s-matrix.

In the upper portions of type A and B carbonate profiles, where orange weathering is distinct, fibrous dolomite may occur as a final infilling to sheet cracks, infilling cavities lined by 'drusy' sparry calcite.

7.3(ii)c Interpretation

The predominance of fine-grained floodplain sediment cemented by a continuous microcrystalline cement showing extensive displacive relationships, exfoliation of detrital micas, plus features such as crystallaria and the accumulation of carbonate as thick laterally extensive often nodular horizons, leads to a general interpretation of the Counter Head profile in a similar manner to the previously described Quarryhead and Crovie profiles. That is, having formed as a result of the epigenetic accumulation of carbonate in the Cca zone of floodplain soils.

Nevertheless, some variations worthy of note do exist, particularly within carbonate forms A and B.

Several generations of cement are apparent within these forms. Firstly, the floodplain sediment appears to have become indurated by microcrystalline calcite forming the distinctive 'k-fabric'. Although largely displacive, this phase of cementation was also accompanied by shrinkage allowing the development of many sheet-cracks and fenestral voids.

A second phase of cementation involves the coating of such voids by the tufa-like microstalactitic cavity lining. The abundant sub-parallel inclusion patterns present in these coatings are comparable to those described by Kendall and Tucker (1973) and considered to represent impurities within former cements, and now recording growth stages in the original cement.

Several lines of evidence combine to suggest that these early stages of cementation took place above the water table:

(i) the development of 'K-fabric' is probably a grain contact cement formed by evaporation of capilliary moisture,

(ii) shrinkage cracks and fenestral cavities were probably open and subject to vadose fluids allowing only the development of the tufa/travertine like cavity linings,

(iii) the presence of sediment infills also strongly supports a vadose origin for this stage of cementation,

(iv) the thickening of the cavity linings in regions where cracks terminate or where large fragments of s-matrix are in close contact is probably a large scale analogy of the meniscus cement commonly referred to as typical of vadose cementation, (Dunham, 1971, James, 1972, Land, 1970).

The final infilling of such cavities by sparry calcite, and the recrystallisation of the earlier cements represents a later diagenetic event, probably related to the transfer of the profile into the phreatic zone of groundwater. Whether such a change occurred due to elevation of the water table or depression of the sediment profile cannot be ascertained. The presence of a late infilling of sparry calcite associated with brecciation and re-crystallisation of earlier cements and ultimately followed by a phase of ferroan dolomite crystallisation, may in some way relate to the ultimate 'plugging' of the profile by the early phreatic cement.

Once the profile became relatively impermeable, any fluid above the main carbonate level would tend to concentrate by evaporation, gradually increasing the Mg/Ca ratio as low magnesium calcite precipitated as drusy sparite. The brecciation noted earlier in more distal situations may also relate to such a pond-ing of subsurface moisture, as the later phase of sparry cement binds the brecciated fragments and causes some recrystallisation of the primary 'K-fabric'. Folk and Land (1975) note that subsequent dilution of high Mg/Ca brines is a feasible mechanism for the precipitation of dolomite, as the dilution by fresh water serves to maintain the high Mg/Ca ratio, but reduces the salinity..

Thus the interpretation of petrographic evidence may be summarised as follows:

1. early cementation of floodplain sediment by the evaporation of capilliary moisture;
2. development of cavity linings as a vadose cement, plus some sediment deposition upon cavity floors;
3. brecciation of earlier cemented floodplain sediment followed by precipitation of phreatic drusy sparry calcite, plus extensive recrystallisation of earlier cements;
4. continued precipitation of drusy sparry calcite as trapped water evaporates. Eventually an elevated Mg/Ca ratio is produced

allowing the precipitation of dolomite largely as a final fibrous cavity infilling, but also as a microcrystalline cement within some breccia horizons.

The major differences between the Counter Head and Quarryhead types of carbonate profile are attributed largely to the facies of the host sediment.

At Quarryhead and Crovie, marginal floodplain environments probably suffered localised intense floods and relatively higher rates of sedimentation being somewhat closer to the base of the alluvial fan. Furthermore such a location would also be well situated to receive moisture travelling down gradient having seeped into the porous fan surface during flood episodes (see also Eugster and Surdam, 1973). These factors would combine to reduce the effect of the Cca pedological zone, by providing:

a) too much sediment;

b) a broad zone of wetting within the soil; and

c) a means of removal of carbonate laden water down slope towards the floodplain s.s.

At Counter Head, in more distal floodplain situations, both the effect of floods and sediment dispersion would be spread over wider areas. The water table would be more stable, and the zone of wetting and drying would probably be more consistent allowing intense carbonate accumulation to occur. The lack of extensive floodplain relief would prevent gradients developing that would allow the migration of sub-surface moisture. Because of these factors, the concentration of carbonate would be more intense, as periods of stability would exist for longer periods, and solutions would be capable of concentration and evaporation to allow the production of dolomite (the distribution of dolomite in the calcretes also tends to support this view in its total restriction to the Counter Head type profile, and in particular, only to portions of this profile considered to represent more distal floodplain sites).

The absence of extensive calcretes from higher portions of the sequence is probably due to such distal sites being wettest, possibly even supporting small impersistent lakes. The environment is somewhat analogous to the situation described by Williams (1970) and already discussed in Chapter 3 (page 214). Williams notes the presence of calcretes in distal-fan marginal floodplain sites, but indicates their absence in the more distal positions ('the chotts') where water is frequently ponded and commonly evaporates to produce extensive salt deposits.

Structures similar to the 'reefs' and 'knolls' of carbonate have been described from many recent caliche profiles; 'pseudo-anticlines' being noted by Price (1975), Jennings and Sweeting (1961), 'buckle-cracks' by Reeves (1970), and 'expansion-structures' by Bretz and Horberg (1949), and Gile et al (1966). Allen (1973b, 1974) also describes antiform structures from calcretes in the British Lower Old Red Sandstone, whilst much literature is available on similar but subtidal and peritidal 'tepee' structures (Smith, 1974, and Assareto et al, 1977).

All of the above cases (except tidal/peritidal) occur within mature caliche/calcrete horizons and have dimensions similar to those described here. In several of the recent examples, and Allen (op cit.) the structures are observed in three dimensions and demonstrate a megapolygon form.

There is general agreement that the genesis of such structures is closely related to the expansion of the host sediment, deep seasonal wetting producing a 'patterned ground', the displaced sediment later replaced and strengthened by carbonate precipitation (Allen, 1973, 1974a). This is vaguely accepted by Jennings and Sweeting (1961) for Australian caliche pseudo-anticlines, but they place more emphasis on high temperature and aridity, whilst Paton (1974) who also considered Australian 'gilgai' and related structures concluded that they probably originated due to differential loading of sediments.

Nevertheless, the weight of support is for a 'displacive/replacive' origin as summarised by Allen (1973). Assereto et al (1977), while considering peritidal tepee antiforms discuss the various mechanisms proposed and conclude that they form by a combination of:

1. desiccation and thermal contraction of the host sediment,
2. enlargement of fractures during wetting phases,
3. further enlargement of fractures by carbonate crystallisation,
4. further enlargement of fractures by hydrolysis of minerals (clays).

In making these suggestions, they also suggest that caliche soil structures are probably a dry end member of a subtidal-peritidal-continental series of structures.

It would seem reasonable that the structures observed at Counter Head are comparable to those noted from the literature, particularly in the comparable size and regular spacing of the Counter Head varieties suggesting that the coastal section may be a cross-section through a polygonal type of patterned ground as detailed by Allen (1973, 1974a,b).

Why carbonate precipitation should be so intense in the anticline regions may also be answered by Allens' (1973, 1974) comparison of the structures with patterned ground or 'gilgai'. Although Allen (op cit.) compares the antiform structures with 'gilgai', Paton (1974) points out that 'gilgai' are in fact the depressions between such structures, the term being an aboriginal one for a water hole. If such a patterned ground were to develop on a floodplain and maintain water for even a short length of time, evaporation would probably be most intense in marginal regions actually in contact with the anticlinal structure. These areas would therefore be expected to witness most intense carbonate precipitation.

Even without continual ponded water, areas above such anticlinal structures would probably be more open and porous, and a pore-moisture gradient would exist between the open anticline region and the less porous 'gilgai' area, allowing further preferential crystallisation of carbonate in the anticlinal regions (see also Stuart and Dixon, 1973, and Aylor and Parlange, 1973, for consideration of the effect of capilliary action on carbonate precipitation).

7.4 Origin of Calcrete

Calcrete and caliche appear as a world-wide feature of many present day arid and semi-arid regions, and similarly, calcretes have been recorded from numerous Pleistocene and Quarternary arid and semi-arid regions and are being frequently described from sediments deeper in the stratigraphic record. Calcretes have been described from the British Old Red Sandstone (Allen, 1974a,b, Burgess, 1961) and the Triassic (Steel, 1974).

Many theories have in the past been offered to explain their origin, and although perhaps no single mechanism has universal application, many have now been disregarded. Theories range from:

1. Chemical and biochemical deposition in surface waters, such as the removal of CO_2 from surrounding water by Charophyte algae to coat stems and reproductive bodies with $CaCO_3$. An increased pH allows the precipitation of $CaCO_3$ on the floor of ponded-water (Davis, 1901, and later reconsidered by Friend and Moody-Stuart, 1970).

2. Deposition by groundwater principally by capilliary-rise and evapotranspiration in the zone of capilliary-rise from a relatively high water table.

3. Deposition within the Cca zone of soils by both evapotranspiration of capilliary water and introduction of $CaCO_3$ laden water from dissolved airborne carbonate-rich dust.

The first hypothesis may be valuable in explaining the formation of some lacustrine marls, but cannot be applied to the present alluvial fan slopes and marginal floodplain environments (in fact carbonate is virtually absent from distal floodplain sites where temporary lacustrine conditions are most common).

Similarly, the second hypothesis has limited application, particularly in accumulating the large amounts of carbonate, and in generating the morphological-genetic sequences already recorded.

Most of the features recorded can be easily accommodated by the third hypothesis, and in fact many of the features detailed have been recorded from present day pedocal soils.

This last hypothesis has been considered in detail by several authors (see Bretz and Horberg, 1949, Brown, 1956, Price, 1958, Gile et al, 1964, 1966, and Ruhe, 1967) who, in general, agree that the most likely source of $CaCO_3$ is from windborne dust and carbonate rich rain-water within the soil. In principal, the mechanism they propose entails the soaking of floodplain soils during wet episodes, and the concentration of $CaCO_3$ by evaporation during subsequent dry periods.

As noted previously, they consider that initial carbonate precipitation occurred interstitially, with the maximum impregnation occurring within the 'zone of most frequent wetting'. Plugging of the profile, they considered, would pond water above the main horizon and further evaporation would produce the laminar horizons common in many recent and ancient calcretes.

That such an interpretation is in essence correct is strongly supported by both chemical analysis and by radiometric dating of the genetic sequences. Aristarain (1970) considered the distribution of major elements in the upper portions of Recent caliche profiles, and concluded from the concentration of Ca, C, O and H_2 that additions of these elements were made from above, resulting in the enrichment of underlying sediments rather than the simple evaporation of capilliary water drawn up from the water table. Similarly, radio-carbon dating has shown that within the morphogenetic sequence outlined by Gile et al (1966) the higher laminae are younger than the underlying nodular developments.

One feature stressed by many descriptions of calcretes is the re-deposition of silica initially put into solution during the elimination of much of the detrital framework of the host sediment. This silica tends to be re-deposited as chert, but to date, no secondary silica in any form has been detected within the sequences at Gamrie.

In summary, the following factors are regarded by most authors as important in controlling calcrete development:

1. time: long enough to allow carbonate accumulation without influence of tectonism or excessive sedimentation;

2. an adequate supply of carbonate to the profile;

3. a surface temperature high enough to maintain evaporation of sub-surface moisture; and

4. sufficient addition of water to carry carbonate down into the sediment, but not too much to cause leaching of such material.

Goudie (1973) has generalised these factors and notes that extreme aridity would prevent soil leaching, mobilisation, and eventual accumulation of calcium carbonate, whilst on the other hand too much moisture would tend to leach out most of the soluble material required for calcrete formation. In general it is considered that thick, mature calcrete developments required suitable semi-arid/arid environments for their formation, although Reeves (1970) indicates that calcretes may still develop in wetter climates, provided that the temperature is high enough to maintain the necessary evaporation rates.

7.5 Significance of the Distribution of Calcrete in the Gamrie and Rhynie Outliers

As already discussed in some detail, calcrete horizons are very restricted in their distribution in these Outliers. The broad distribution is considered of some value in the interpretation of the sedimentary history of the area, in particular, that of the

Gamrie Outlier.

The concentration of calcrete in the lower or fining upward part of the Lower Old Red Sandstone sequence suggests by comparison with recent analogues that the environment was probably semi-arid/ arid, and that floodplain aggradation was also probably quite slow. Furthermore, and surprisingly, although the calcretes develop in sediments quite close to the base of the sequence and therefore belong to the very early history of basin development, tectonic stability is generally considered a prerequisite for calcrete formation, (instability is usually assumed to generate either large amounts of sediments or cause erosion).

As sedimentation continued, more and more distal facies are represented in the profile, and as discussed earlier, the absence of calcrete in such locations is probably not surprising as such distal sites would most likely be the wettest; too wet for extensive carbonate accumulation.

At higher levels, coarser sediment is introduced, and paleocurrent trends indicate that renewed tectonism caused a shift in source area. The renewed activity and advance of alluvial fans is recorded in the absence of calcrete from the coarsening portion of the sequence; the new sedimentation rates were clearly too high for carbonate accumulation.

During the deposition of the Middle Old Red Sandstone conglomerates, calcretes were present within the area, as calcrete nodules have been found as a detrital component in these conglomerates. Further confirmation comes from the calcretisation of the upper portion of the Findon Fish Bed; evidence supporting the view that the semi-arid climate probably did continue well into the Middle

Old Red Sandstone.

7.6 Time of Development

Clearly, throughout the sequences described two events are involved; firstly the deposition of floodplain detritus, and then a phase of progressive soil development. From Chapter 3 it is concluded that deposition of floodplain sediments was a rapid but probably rare event. A further consideration of the rate of development of the calcareous profiles serves to strengthen this view.

Steel (1974) notes that the acceptance of 'cornstone' as an indicator of pedogenesis suggests that floodplain sedimentation was ephemeral, a view supported by numerous recent radiometric datings of Quaternary and Tertiary calcretes (such as those carried out by Gile et al, 1966, Gile and Hawley, 1966, Williams and Polach, 1969, 1971, Williams, 1973). Gile et al (1966) showed that the laminar stage alone (Stage IV) may involve periods of up to 10,000 years per inch of carbonate, and a mature profile may represent up to one million years. Gardiner (1972) by perhaps less quantitative means derived ages of between 400,000 and 2.5 million years. Leeder (1974) has recently summarised much of the available evidence, and he outlines a series of ages which appear to be broadly equivalent to Stages I to IV of Gile et al (1966), i.e:

Stage I	1000 - 4500 years
Stage II	3500 - 7000 years
Stage III	6000 - 10,000 years
Stage IV	10,000+ years

Although Gile and Hawley (1966) managed to relate the time required for calcrete development to the nature of the host rock (essentially higher permeabilities allowed faster development rates), Leeder also considered the importance of floodplain accretion rates. He noted that the Stages I to IV of Gile et al.(1966) probably required progressively lower accretion rates for their development.

As it is considered that the sequences described here are commonly equivalent to Gile et al's stage II and frequently stage III (possibly even bordering on stage IV), a consideration of the time of development confirms that the calcareous soil profile must have been stable for very long periods of time, and as discussed earlier, such a condition would necessitate: (i) a slow accumulation rate on the floodplain surface, (ii) stability of the marginal fan facies, and most significantly (iii) tectonic stability.

7.7 Summary and Conclusions

In summary, the similarity between the morphogenetic sequences derived from the present work and that outlined by Gile et al (1966) is regarded very close, and it is considered that the previously described mechanisms were probably responsible for carbonate accumulation in the sequences described. The variation in type of profile and the diversity of carbonate types developed is largely considered to be influenced by host rock facies.

PART B - Iron/Manganese Concentrations

7.8 Introduction

Within the Dundarg Castle Conglomerate and Pennan Sandstone sequences, an unusual form of sandstone cementation is recognised and consists of extensive grain coatings of an iron oxide, combined with pore fillings of psilomelane and kaolinite. Although not recorded from Recent or ancient hardpans, the present examples are considered primary cements probably formed as 'soil' horizons in an intense oxidising environment.

7.9 Description

Several regions of such cementation occur, rare occurrences have been observed in the Dundarg Castle Conglomerate Formation beneath Dundarg Castle, but the most extensive developments occur within the Pennan Sandstone sequence. Essentially, areas of such cementation consist of deep reddish brown sandstones with distinct almost black parallel zones of psilomelane, commonly in the order of several cms in thickness. Such zones are substrate parallel, and in the Dundarg Castle sequence are cut by erosion surfaces, confirming their primary rather than late diagenetic origin.

In thin section, a distinct paragenesis of mineral development is readily apparent. Within the host sediment, haematite pigmentation occurs on detrital grains as detailed in Chapter 6 for the commonly occurring red beds. In areas where psilomelane occurs, extensive coatings of authigenic silica occur, often showing very distinct euhedral faces (plate 7.14b). Following the period of quartz overgrowth, precipitation of very thick pellicles of iron oxide around grains and infilling small cavities occurred. This iron oxide has a fibrous form, and occurs as botryoidal pore linings. Major cavities and pores are subsequently infilled by a mixture of psilomelane and authigenic kaolinite. It would appear that kaolinite crystallised early during this later phase, as many of the large crystals are expanded and infiltrated by psilomelane.

Many of the quartz grains within these zones show a distinctive fracturing (see plate 7.14,d,e)Plate 7.14 shows the typical form of such fracturing which occurs as sub-parallel flaking of the upper portions of quartz grains, the flaking also being parallel to bedding. The development of this flaking predates the development of both the iron oxide and psilomelane, but as the flakes are infilled by kaolinite, it would appear that the crystallisation of this clay occurred continuously rather than being restricted to locations within the psilomelane. Nevertheless, the most extensive phase of kaolinite crystallisation does appear from the bulk of clay within the psilomelane to have been a relatively late event.

Petrologically, the identification of the major mineral phases proved difficult. As mentioned the iron oxide grain coating shows fibrous form in transmitted light, and frequently shows a botryoidal cavity lining appearance (a feature shown clearly in electron micrographs shown in plate 6.9c). The iron oxide coatings appear deep reddish brown in transmitted light, whereas the psilomelane is opaque. Polished blocks of such cements show that the main cavity infillings (psilomelane) are isotropic and have a mean reflectance of 23.9%, whilst the cavity linings show a reddish brown internal reflection and a mean reflectance of 18%. Psilomelane has a reflectance in the 23 to 25% range, and goethite (a possible cavity lining) has a reflectance in the order of 16 to 18%, whilst haematite, also a possible lining has a much higher reflectance of between 25 and 30%.

The probability that the main cementing agent was psilomelane was first realised from X-ray fluorescence measurements of separated fragments of cement which indicated that the mineral was barium - manganese rich. Measurements of the d-spacing derived from X-ray powder photographs have since confirmed this view, the results are listed in the adjacent table:

Mineral		d-spacing			intensity		
Pyrolusite	MnO_2	3.14	2.41	1.63	100	50	50
Birnessite	$(Na_7Ca_3)Mn_7O_{14}\ 2.8H_2O$	7.27	2.44	1.41	100	70	70
Pyrochroite	$Mn(OH)_2$	4.73	2.45	1.83	100	40	25
Manganite	$Mn_2O_3\ H_2O$	3.40	2.64	2.28	100	60	50
Hydrohausmannite	$(Mn_4Mn)Mn_8O_{16}OH$	4.65	2.50	2.78	100	60	50
Hausmannite	Mn_3O_4	2.48	2.75	-1.57	100	63	50
Psilomelane	$(BaH_2O)_2Mn_5O_{10}$	2.41	2.19	3.48	100	85	60
X-ray powder photograph		2.40	2.19	3.45	100	75	50

Table 7.2 **Comparison of d-spacings for areas of cement presumed to be Psilomelane, with d-spacings for other common manganese rich minerals.**

Identification of the cavity lining mineral proved impossible as relatively pure separations could not be made. Separations of the psilomelane cement were easily achieved as the mineral is unaffected by hydrofluoric acid.

A further study of the cements using an electron microprobe adds further support, indicating that the proposed psilomelane portions have the required proportion of manganese, but the barium content is low (presumably due to the barium content being related to the hydration state of the mineral, ie.$(BaH_2O)_2\ Mn_5O_{10}$). The cavity lining suggested as goethite showed much less total iron than expected, but again goethite is a hydrated mineral and the addition of only 3 or 4 water molecules to the structure would reduce the total iron content to the amount detected during this study.

The results of these analysis are listed in the following table, figures in parenthesis are values derived from theoretical pure minerals, and disregard the influence of hydration.
(see also plate 7.15 for summary)

Sample	Percentage				
	Ba	Mn	Fe	Ti	Mg
Goethite (?)	.6	2.5	47 (70)	.1	.1
Psilomelane	12.7 (23)	44 (46)	.35	.4	.07

Table 7.3 Results of electron microprobe analysis of the two cementing phases. Figures in parenthesis refer to theoretical, pure, mineral species.

It is concluded from the present study that the lower reflecting cavity lining phase may be goethite, but that this cannot be confirmed. The higher reflecting phase is confidently indentified as psilomelane.

7.10 Interpretation

At first, the mineralisation was considered to be secondary accumulation. Several factors combine to suggest that the development is in fact authigenic:

(i) zones of mineral cementation are present in substrate parallel bands;

(ii) such zones are always transected by erosion surfaces; and

(iii) 'sheeted' or 'exfoliated' quartz grains also occur in substrate parallel zones within the cement.

The development of 'sheeted' quartz grains is of interest, and may be analogous to the common presence of shattered pebbles and sheeted bedrock in modern arid and semi-arid regions (Cooke and Warren, 1973, Glennie, 1970, Ollier, 1969), although no details are given of such features on a microscopic scale. In the geological record such phenomena are rare, Tucker (1974) has described exfoliated pebbles and sheeting within the Triassic of South Wales.

Blackwelder (1925, 1933), and Griggs (1936) produced experimental evidence to demonstrate that physical processes alone could not produce such disintegration without the assistance of chemical weathering. Fractured quartzite and flint pebbles described by Bosworth (1922) and Ollier (1963) would on the other hand appear to confirm that insolation alone may be quite effective.

Allen (1974a) records the presence of corroded and exfoliated detrital fragments from Siluro-Devonian limestones he interprets as calcrete, and thus it would seem reasonable to conclude that the present examples probably also formed in a semi-arid environment that was known to exist and was producing calcretes in laterally equivalent situations.

A source of both barium and manganese is as yet unknown, although in North East Scotland barytes veining is not uncommon, and Wallace as early as 1919 noted concentrations of 'low grade' manganese rocks near the Middle Old Red Sandstone unconformity south of Clava near Nairn.

Krauskopf (1957) and later Hem (1972) considered factors relating to the availability of both iron and manganese in sediments. In general their conclusions were that both iron and manganese were relatively insoluble in oxygenated neutral or midly alkaline water (Hem, op. cit.), and that inorganic processes should always concentrate iron from solution before manganese (Krauskopf, op.cit.). Krauskopf also concluded that a suitable mechanism for such a separation and concentration was by the addition of alkali to a solution in contact with atmospheric oxygen.

7.11 Summary and Conclusions

It would therefore be reasonable to conclude that in an area where calcrete horizons are not uncommon, the occurrence of sheeted quartz grains may represent a paleosoil horizon. If such a horizon was in fact witnessing evaporation of groundwater and capilliary water as is common in semi-arid soils, then the increasing alkalinity would provide an ideal mechanism for the separation of an iron oxide first cement followed by the precipitation of psilomelane. This may be even more probable as the microprobe analysis indicates that the early iron oxide cement does in fact have a lot more than trace amounts of both barium and in particular manganese.

BIBLIOGRAPHY

ALLEN, J.R.L. 1960 — Cornstone
Geol. Mag. 97: 43-48

ALLEN, J.R.L. 1961 — Sandstone-plugged pipes in the Lower Old Red Sandstone of Shropshire, England.
Jour. Sediment Petrol. 31: 325-335

ALLEN, J.R.L. 1962(a) — Lower Old Red Sandstone of the southern British Isles: a facies resembling the Alpine Molasse.
Nature V.193,4821, p.1148-1150

ALLEN, J.R.L. 1962(b) — Petrology, origin, and deposition of the highest Lower Old Red Sandstone of Shropshire, England.
Jour. Sediment Petrol. 32: 657-697

ALLEN, J.R.L. 1962(c) — Intraformational Conglomerates and scoured surfaces in the Lower Old Red Sandstone of the Anglo-Welsh Cuvette.
J. Geol. 3, 1-20

ALLEN, J.R.L. 1963 — The classification of cross-stratfied units, with notes on their origin.
Sedimentology 2: 93-114

ALLEN, J.R.L. 1964(a) — Studies in fluviatile sedimentations six cyclotherms from the Lower Old Red Sandstone, Anglo-Welsh Basin.
Sedimentology 3: 163-198

ALLEN, J.R.L. 1964(b) — Primary current lineation in the Lower Old Red Sandstone (Devonian) Anglo-Welsh Basin.
Sedimentology 3: 89-108

ALLEN, J.R.L. 1965(a) — A review of the origin and characteristics of Recent alluvial sediments.
Sedimentology 5, No. 2 (Special Issue) : 89-191

ALLEN, J.R.L. 1965(b) — Fining upward cycles in alluvial successions.
J. Geol. 4, 229-246

ALLEN, J.R.L. 1966 — On bed forms and paleocurrents.
Sedimentology, 6: 153-190

ALLEN, J.R.L. 1968(a) — Current Ripples
North Holland, Amsterdam 433 pp.

ALLEN, J.R.L. 1968(b) On the character and classification of bed forms.
Geologie en Mijnbouw, 47: 173-185

ALLEN, J.R.L. 1970(a) Studies in fluviatile sedimentation: a comparison of fining upwards cyclotherms, with special reference to coarse member composition and interpretation.
Jour. Sediment Petrol., 40: 298-323

ALLEN, J.R.L. 1970(b) A quantitative model of climbing ripples and their cross-laminated deposits.
Sedimentology, 14: 5-26

ALLEN, J.R.L. 1971 Instantaneous sediment deposition rates deduced from climbing ripple cross-lamination.
J. Geol. Soc. London, 127: 553-561

ALLEN, J.R.L. 1973(a) A classification of climbing-ripple cross-lamination.
J. Geol. Soc., 129: 537-541

ALLEN, J.R.L. 1973(b) Compressional Structures (Patterned Ground) in Devonian Pedogenic Limestones
Nature, 243: 84-86

ALLEN, J.R.L. 1974(a) Sedimentology of the Old Red Sandstone (Siluro-Devonian) in the Clee Hills Area, Shropshire, England.
Sed. Geol., 12: 73-167

ALLEN, J.R.L. 1974(b) Studies in fluviatile sedimentation: implications of pedogenic carbonate units, Lower Old Red Sandstone, Anglo-Welsh outcrop.
J. Geol., 9: 181-208

ALLEN, J.R.L. 1974(c) Geomorphology of Siluro Devonian alluvial fans.
Nature, 249/5458, 644-645

ALLEN, J.R.L. AND FRIEND, P.F. 1968 Deposition of the Catskill facies, Appalachian region: with notes on some other Old Red Sandstone Basins.
In: G.Dev. Klein (Ed.), Late Paleozoic and Mesozoic Continental Sedimentation northeastern North America.
Geol. Soc. Sp. Paper, 106: 21-74

ALLEN, J.R.L. AND TARLO, L.B. 1963 The Downtanian and Dittonian facies of the Welsh Borderland.
Geol. Mag. 100: 129-155

ALLMAN, M
AND LAWRENCE, D.F. 1972 — Geological Laboratory Techniques
Blandford: London 335 pp.

ANDEL, TJ. H. VAN 1959 — Reflections on the interpretation of heavy mineral analyses.
Jour. Sediment/Petrol, 29: 153-163

ANDERSON, B. 1961 — The Rufiji Basin, Tanganyika, VII Soils of the Main Irrigable Areas.
FAO Rep. to Government of Tanganyika, 125 pp.

ANDERSON, J.G.C.
AND OWEN, T.R. 1968 — The Structure of the British Isles
Pergainan Press

ANDERSON, T.W.
AND GOODMANN, L.A. 1957 — Statistical inference about Markov Chains.
Annals. Math. Stats., 28: 89-110

ARISTARAIN, L.F. 1970 — Chemical analysis of caliche profiles from the High Plains, New Mexico.
J. Geol. 78: 201-212

ARNBORG, L. 1958 — The lower part of the River Angermanalven
Publ. Geograf. Inst. Univ. Uppsala 1: 181-247

ASHCROFT, W.A.
AND WILSON, C.D.V. 1976 — A geophysical survey of the Turriff basin of Old Red Sandstone, Aberdeenshire.
Jour. Geol. Soc, 132: 27-43

ASHCROFT, W.A.
AND MUNRO, M. 1978 — The Structure of the Eastern part of the Insch Mafic Intrusion, Aberdeenshire.
Scott. J. Geol, 14: 55-81

ASSERETO, R.L.A.M.
AND KENDALL, C.G.St.C. 1977 — Nature, origin and classification of peritidal tepee structures and related breccias.
Sedimentology, 24: 153-210

AUGUSTINUS, P.G.E.F.
AND REIZEBOS, H.T. 1971 — Some sedimentological aspects of the fluvioglacial outwash plain near Soesterberg (The Netherlands).
Geol. Mijnb, 50: 341-348

AYLOR, D.E.
AND PARLANGE, J.Y. 1973 — Vertical infiltration onto layered soil.
Proc. Soil Sci. Soc. An., 37: 673-676

BAAG, C.H.
AND HELSLEY, C.E. 1974 — Evidence for penecontemporaneous magnetisation of the Moenkopi Formation.
J. Geophys. Res, 79: 3308

BARRET, P.J. 1970 — Paleocurrent analysis of the mainly fluviatile Permian and Triassic Beacon Rocks, Beardmore Glacier area, Antarctica.
Jour. Sediment Petrol, 40: 395-411

BOWER, L.D. 1956 — Soil Physics
Wiley: New York

BEAVEN, P. 1966 — Clay Mineralogy and geomorphology in the Carribean Islands.
Clay Miner. Bull., 6: 371

BEERBOWER, J.R. 1964 — Cyclotherms and cyclic depositional mechanisms in alluvial plain sedimentation.
In Merriam (Ed.), Symposium on Cyclic Sedimentation, Vol. I, Kansas Geol Survey, 169, 31-42

BERNARD, H.A. AND MAJOR, C.F. 1963 — Recent meander belt deposits of the Brazos River: an alluvial "sand" model (abstr.)
Bull. Am. Assoc. Petrol. Geol., 47: 350

BERNARD, H.A, LE BLANC, R.J, AND MAJOR, C.F. 1962 — Recent and pleistocene geology of southeast Texas.
Geol. Gulf Coast and Central Texas and Guidebook of Excursion.
Houston Geol. Soc., 175-224

BERNER, R.A. 1968 — Calcium carbonate concretions formed by the decomposition of organic matter.
Science, 159, 195-197

BERNER, R.A. 1969 — Geothite stability and the origin of red beds.
Geochim. Cosmochim, Acta, 33: 267-273

BERNER, R.A. 1971 — Principles of Chemical sedimentology.
McGraw-Hill, 240 pp.

BLACKWELDER, E. 1925 — Exfoliation as a phase of rock weathering.
J. Geol, 33: 793-806

BLACKWELDER, E. 1928 — Mudflow as a geologic agent in semi arid mountains.
Geol.Soc.Am.Bull, 39: p.465-483

BLACKWELDER, E. 1933 — The isolation hypothesis of rock weathering.
Am J. Sci, 26: 97-113

BLANCHE, J.B. AND McD. WHITAKER, J.H. 1978 — Diagenesis of part of the Brent Sand Formation (Middle Jurassic) of the northern North Sea Basin. J. Geol. Soc., 135: 73-82

BLATT, H. 1967(a) — Original characteristics of clastic quartz grains. Jour.Sediment Petrol., 37: 401-424

BLATT, H. 1967(b) — Provenance determinations and recycling of sediments. Jour.Sediment Petrol., 37: 1031-1044

BLATT, H. AND CHRISTIE, J.M. 1963 — Undulatory Extinction in Qtz. of Ign. and Met. rocks, and its significance in provenance studies of sedimentary rocks. Jour.Sediment Petrol., 33: 559-579

BLATT, H. MIDDLETON, G. AND MURRAY, R. 1972 — Origin of sedimentary rocks. Prentice Hall: New Jersey, 634 pp.

BLISSENBACH, E. 1954 — Geology of alluvial fans in semi-arid regions. Geol. Soc. Am. Bull, 65: 175-190

BLUCK, B.J. 1964 — Sedimentation of an alluvial fan in Southern Nevada. Jour.Sediment Petrol, 34: 395-400

BLUCK, B.J. 1965 — The sedimentary history of some Triassic conglomerates in the Vale of Glamorgan, South Wales. Sedimentology, 4: 225-245

BLUCK, B.J. 1967 — Deposition of some Upper Old Red Sandstone conglomerates in the Clyde area: a study in the significance of bedding. Scott. J. Geol., 3: 139-167

BLUCK, B.J. 1971 — Sedimentation in the meandering River Endrick. Scott. J. Geol, 7: 93-138

BOOTHROYD, J.C. 1972 — Coarse-grained sedimentation on a braided outwash fan, North eastern Gulf of Alaska. Massachusetts Univ. Amherst, Coastal Research Center, Tech. rept. 6, 142 pp.

BOOTHROYD, J.C. AND ASHLEY, G.M. 1975 — Process, bar morphology, and sedimentary structures on braided outwash fans, North eastern Gulf of Alaska. In: Av. Jopling and B.C. MacDonald (Eds.) "Glaciofluvial and Glaciolacustrine Sedimentation" Soc.Econ.Paleontol. Mineral. Spec. Publ. 23: 193-222

BOSWORTH, T.O. 1922
Geology of the Tertiary and Quarternary Periods in the North western part of Peru. (MacMillan, London, 1922)

BOTT, M.H.P. 1964
Formation of sedimentary basins by ductile flow of Bostatic origin in the upper mantle.
Nature, 201: 124-9

BOTT, M.H.P. 1965(a)
Formation of oceanic ridges.
Nature, 207: 840

BOTT, M.H.P. 1967(b)
Terrestrial heat flow and Mantle convection.
Geophys. (J.R., 14: 413

BRETZ, J.H.
AND HORBERG, L. 1949
Caliche in south western New Mexico.
J. Geol., 57: 491-511

BREWER, R. 1964
Fabric and Mineral Analysis of Soils
Wiley, New York, 470 pp.

BRICE, J.C. 1964
Channel patterns and terraces of the Loup Rivers of Nebraska.
U.S. Geol. Surv. Prof. Paper., 422-D

BRINDLEY, 1961
Chlorite minerals.
In: G. Brown (Ed.). The X-Ray Identification and Crystal Structures of Clay Minerals.
Mineralogic Soc, London, pp.489-516

BROWN, C.N. 1956
The origin of caliche on the north eastern Llano Estacado, Texas.
J. Geol., 64: 1-15

BROWN, P.G.
MILLER, J.A.
AND GRASTY, R.L. 1968
Isotopic ages of late Caledonian granitic intrusions in the British Isles.
Proc. Yorks. Geol. Soc., 36: 251

BULL, W.B. 1964
Geomorphology of segmented alluvial fans in western Fresno County, California.
U.S. Geol.Surv.Prof. Paper, 352E, 89-129

BURGESS, I.C. 1961
Fossil soils of the Upper Old Red Sandstone of South Ayrshire.
Geol. Soc. Glasgow, Trans., 24: 138-153

CARLSON, K.J. 1968
The skull morphology and Estivation Burrows of the Permian Lungfish, Gnathorhiza Servata.
J. Geol, 76: 641-663

CARROLL, D. 1958 Role of clay minerals in the transportation of iron. Geochim Cosmochim Acta, 14: p1-27

CARROLL, D. 1970 Clay minerals, a guide to their X-ray identification. Geol.Surv.America Spec. Paper, No. 126, 80 pp.

CARROLL, R.L. 1965 Lungfish burrows from the Michegan Coal Basin. Science, N.Y., 148: 963-964

CARVER, R.E. (Ed.) 1971 Procedures in sedimentary petrology. J. Wiley & Sons, Interscience, N.Y.

CHAPMAN, R.W. 1974 Calcareous duricrust in Al-Hasa, Saudi Arabia. Geol.Soc.Am.Bull. 85: 119-130

CHAWNER, W.D. 1935 Alluvial fan flooding, the Montrose, California, flood of 1934. Geog. Rev., 25: 225-263

CHIEN, N. 1961 The braided stream of the lower Yellow River. Scientia Sinica X: 734-754

CHILLINGAR G AND AND LARSON 1967 Diagenesis in Sediments. Developments in Sedimentology : 8 Elsevier : Amsterdam.

CHINNER, G.A. 1966 Distribution of pressure and temperature during Dalradian metamorphism. Q. J. Geol. Soc. Lond, 122: 159-181

CHRISTIE AND DOCKER 1826 Included in Murchsion 1929. Supplementary remarks on the strata of the Oolitic Series. Trans. Geol. Soc. London, Second Series Vol. II, p. 363

COLEMAN, J.M. 1969 Brahmaputra River: Channel processes and sedimentation. Sed. Geol, 3: 129-239

COLEMAN, J.M. AND GAGLIANO, S.M. 1964 Cyclic sedimentation in the Mississippi River deltaic plain. Gulf Coast Assoc. Geol. Soc. Trans., 14: 67-80

COLLINS, A.G. AND DONOVAN, R.N. 1977 The age of the two Old Red Sandstone sequences in Southern Caithness. Scott. J. Geol., 13: 53-58

COLLINSON, D.W. 1968 — An estimate of the haematite content of sediments by magnetic analysis. Earth. Planet, Sci. Letters, 4: 417

COLLINSON, D.W. 1969 — Investigations into the stable remanent magnetization of sediments. Geophys. J, 18: 211

COLLINSON, D.W. 1974 — The role of pigment and specularits in the remanent magnetism of red sandstones. Geophys. J.R. Astron. Soc., 38: 253

COLLINSON, J.D. 1970 — Bedforms of the Tana River, Norway. Geogr. Annlr., 52A, 31-56

COOKE, R.U. AND REEVES, R.W. 1976 — Arroyos and environmental change in the American South-west. Oxford Research Studies in Geography

COOKE, R.H. AND WARREN, A. 1973 — Geomorphology in deserts Batsford, London, 1973

CROFT, W.N. AND GEORGE, E.A. 1959 — Blue-green algae from the Middle Devonian of Rhynie, Aberdeenshire. Bull. Brit. Mus. (N.H.), 3: 339-353

DAVIS, C.A. 1901 — On the natural history of marl. J. Geol, 9: 491-506

DAVIS, J.C. 1973 — Statistics and data analysis in Geology Wiley & Sons Inc, New York, 550 pp.

DAVIS, W.M. 1938 — Sheetfloods and streamfloods Geol. Soc. Am. Bull, 49: 1337-416

DEWEY, J.F. 1969 — The evolution of the Appalachian/Caledonian orogen. Nature, 222: 124-129

DEWEY, J.F. AND PANKHURST, R.J. 1970 — The evolution of the Scottish Caledonides in relation to their isotopic age pattern. Trans. Roy. Soc. Edinb, 68: 361-389

DEWEY, J.F. AND BIRD, J.M. 1971 — Origin and emplacement of ophiolite suite. Appalachian ophiolites in Newfoundland. J. Geophys. Res, 76: 3179

DINELEY, D.L. 1960 — The Old Red Sandstone of Eastern Ekman-fjorden, Vestspitzbergen. Geol. Mag, 97: 18-32

DIONNE, J.C. 1971 — Vertical packing of flat stones Can. Jour. Earth Sci, 8: 1585-1591

DOEGLAS, D.J. 1962 — The structure of sedimentary deposits of braided rocks. Sedimentology, 1: 167-190

DONOVAN, R.N. 1971 — The Geology of the coastal tract near Wick, Caithness. Univ. Newcastle upon Tyne, Ph.D. Thesis (unpubl), 870 pp.

DONOVAN, R.N. 1973 — Basin margin deposits of the Middle Old Red Sandstone at Dirlot, Caithness. Scott. J. Geol., 9: 203-211

DONOVAN, R.N. 1975 — Middle Devonian Limestones developed at the margin of the Orcadian Basin, Caithness. J. Geol. Soc, 131: 489-510

DONOVAN, R.N. AND ARCHER, R. 1975 — Some sedimentological consequences of a fall in the level of Haweswater, Cumbria. Proc. Yorks. Geol. Soc, 40: 547-562

DONOVAN, R.N. ARCHER, R TURNER, P. AND TARLING, D.H. 1976 — Devonian paleogeography of the Orcadian Basin and the Great Glen Fault. Nature, 259: 550-551

DONOVAN, R.N. AND FOSTER, R.J. 1972 — Subaqueous shrinkage cracks from the Caithness Flagstone Series (Middle Devonian) of North East Scotland. Jour. Sediment Petrol, 42: 309-317

DOVETON, J.H. 1971 — An application of Markov Chain analyses to the Ayrshire Coal Measures succession. Scott. J. Geol, 7: 11-27

DUFF, D. 1967 — Cyclic sedimentation in the Permian Coal Measures of New South Wales. J. Geol. Soc. Australia, 14: 293-308

DUFF, D. AND WALTON, E.K. 1962 — A statistical basis for cyclotherms: A quantitative study of the sedimentary succession in the East Pennine Coalfield. Sedimentology, 1: 235-255

DUNGWORTH, G. AND SCHWARTZ, A. 1971 — Kerogen isolates from the Precambrian of South Africa and Australia. Analysis for carbonised micro-organisms and pyrolysis-gas-liquid-chromatography. In: Advanced in Organic Geochemistry 1971 (Eds.) Von Gaertner, HRV, and Wehner H. Pergainon, 1972, 699 pp.

DUNHAM, R.J. 1971 — Meniscus cement.
In: D.P. Bricker (Ed.)
Carbonate Cements
Johns Hopkins Press
Baltimore, p. 297-300

DURY, G.H. 1971 — Hydraulic geometry
In Chorley, R.J. (Ed.)
Introduction to fluvial processes
146-156, London

ECKIS, R. 1928 — Alluvial fan of the Cucamonga district, Southern California.
Jour. Sediment Petrol., 21: 147-150

EDWARDS, A.B. 1947 — Textures of the ore minerals and their significance.
Australian Inst. of Mining and Metallurgy
Melbourne, 166 pp.

EUGSTER, H.P. AND SURDAM, P.C. 1973 — Depositional environment of the Green River Formation of Wyoming: A preliminary report.
Geol. Soc. Am. Bull., 84: 1115-1120

EYNON, G. AND WALKER, R.G. 1974 — Facies relationships in Pleistocene outwash gravels, southern Ontario: a model for bar growth in braided rivers.
Sedimentology, 21: 43-70

FAHNSTOCK, R.K. 1963 — Morphology and hydrology of a glacial stream, White River, Mount Rainer, Washington.
U.S. Geol.Surv.Profess.Pap, 422-A: 1-70

FARMER, V.C. RUSSELL, J.D. McHARDY, NEWMAN, A.C.D. AHLRICHS, J.L. AND RIMSAITE, J.Y.H. 1971 — Evidence for loss of protons and octahedral iron from oxidised biotites and vermiculites.
Min. Mag., 38: 121-137

FEUNEMAN, N.M. 1906 — Floodplains produced without floods.
Geol. Soc. Am. Bull, 38: 89-91

FISHER, R.V. 1971 — Features of coarse-grained, high concentration fluids and their deposits.
Jour. Sediment Petrol., 41: 916-927

FISK, H.N. 1944 — Geological investigation of the alluvial valley of the lower Mississippi River.
Miss. River Comm, Vicksburg, Miss., 78p

FISK, H.N. 1947 — Fine-grained alluvial deposits and their effects on Mississippi River activity. Miss. River Comm, Vicksburg, Miss, 82p

FITCH, F.J. MILLER, J.A AND MITCHELL, J.G. 1970 — A new approach to isotopic dating in orogenic belts. In: Time and Place in Orogeny, London, Geol Soc. pp – ?

FLACH, K.W, NETTLETON, W.G, GILE, L.H. AND CADY, J.G. 1969 — Pedocementation: induration by silic carbonates and sesquioxides in the Quarternary. Soil Sci., 107: 442

FOLK, R.L. 1974 — Petrology of sedimentary rocks. Hemphill Publ. Co., 182 pp.

FOLK, R.L. AND LAND, L.S. 1975 — Mg/Ca Ratio and Salinity: Two controls over crystallization of Dolomite. Bull. Am. Ass. Petrol Geol, 59: 60-68

FOSTER, R.J. 1972 — The Solid Geology of North-East Caithness Univ. Newcastle upon Tyne, Ph.D. Thesis (unpubl), 334 pp.

FRANKS, P.C. 1969 — Nature, origin, and significance of cone in cone structures in the Kiowa Formation (early Cretaceous), North Central Kansas. Jour. Sediment Petrol, 39: 1438-1454

FRASIER, D.E. AND OSANICK, A. 1961 — Point bar deposits, Old River Locksite, Louisiana. Trans. of the Gulf Coast Assoc. of Geol. 11: 121-137

FREYTET, P. 1973 — Petrography and paleo-environment of Continental Carbonate Deposits with particular reference to the Upper Cretaceous and Lower Eocene of Lauguedoc (Southern France). Sed. Geol, 10: 25-60

FRIEND, P.F. 1965 — Fluvial sedimentary structures in the Wood Bay Series (Devonian) of Spitzbergen. Sedimentology, 5: 39-68

FRIEND, P.F. 1966 — Clay fractions and colours of some Devonian Red Beds in the Catskill Mountains. Q. JP. Geol. Soc. London, 122: 273-92

FRIEND, P.F. 1967 — Tectonic implications of sedimentation in Spitzbergen and Midland Scotland. In: Oswald D.H. (Ed.) International Symposium on the Dalradian System. Alberta Soc. Petrol. Geol., 2: 703-710

FRIEND, P.F. AND MOODY STUART, M. 1970 — Carbonate deposition on the river flood-plains of the Wood Bay Formation (Devonian) of Spitzbergen. Geol. Mag., 107: 181-195

FURSICH, F.T. AND PALMER, T.J. 1975 — Open Crustacean burrows associated with hardgrounds in the Jurassic of the Cotswolds, England. Proc. Geol. Assoc., 86: 171-181

FYFE, W.S. 1967 — Stability of the Al_2SiO_5 polymorphs. Chem. Geol, 2: 67-76

GARDINER, R.G. 1972 — Origin of the Mormon Mesa Caliche, Clark County, Nevada. Geol. Soc. Am. Bull, 83: 143-156

GARRELS, R.M. 1960 — Mineral Equilibria at low temperature and pressure. Harper: New York (Harper Geoscience Series)

GARRELS, R.M. AND CHRIST, C.L. 1965 — "Solutions Minerals and Equilibria" 450 pp. Harper & Row, New York.

GEIKIE, A. 1879 — On the Old Red Sandstone of western Europe. Trans. Roy. Soc. Edinb., 28: 345-452

GEOL. SURVEY 1890 — Description of Sheets 86, 96 Mem. Geol. Surv. Scotland

GEORGE, T.N. 1965 — In: The Geology of Scotland (Ed. G. Craig). Oliver and Boyd, p. 1-48

GEVERS, T.W. FRAKES, L.A. EDWARDS, L.N. MARZOLF, J.E. 1971 — Trace-fossils in the Lower Beacon sediments (Devonian), Darwin Mountains Southern Victoria Land, Antarctica. J. Paleontol, 45: 81-94

GILE, L.H. AND HAWLEY, J.W. 1966 — Periodic sedimentation and soil formation on an alluvial fan Piedmont in southern New Mexico. Proc. Soil Sci. Soc. Am, 30: 261-268

GILE, L.H.
PETERSON, F.F.
AND GROSSMANN, R.B. 1965
The K-horizon: a master soil horizon of carbonate accumulation.
Soil Sci, 99: 74-82

GILES, L.H,
PETERSON, F.F.
AND GROSSMANN, R.B. 1966
Morphological and genetic sequences of carbonate accumulation in desert soils.
Soil Sci., 101: 347-360

GLENN, J.L.
AND DAHL, A.E. 1959
Characterisitcs and distribution of some Missouri River deposits.
Proc. Iowa Acad. Sci, 66: 302-311

GLENNIE, K.W. 1970
Desert sedimentary environments
"Developments in sedimentology - 14"
Elsevier, Amsterdam

GODDARD, E.N. 1951
Rock colour chart
Geol. Soc. Am., New York

GOUDIE, A 1972
On the definition of calcrete deposits.
Zeitschrift fur Geomorphologie, 16: 464-468

GOUDIE, A. 1973
Duricrusts in tropical and subtropical landscapes.
The Clavenden Press, Oxford,
Research Studies in Geography, 174 pp.

GRANT
WILSON, J.S.
HINXMAN, L.W. 1890
The Geology of Aberdeenshire (central)
Mem. Geol. Surv. Scotl.

GREENSMITH, J.T.
AND TUCKER, E.V. 1968
Imbrication structure in Essex off-shore shell banks.
Nature, 220: 1115-1116

GREENSMITH, J.T.
AND TUCKER, E.V. 1969
The origin of Holocene shell deposits in the Chenier plain facies of Essex (Great Britain).
Marine Geol, 7: 403-425

GREGORY 1860
Notes of fossiliferous localities of the Old Red Sandstone of the East of Scotland.
The Geologist, Vol. III, p. 146

GRIGGS, D.T. 1936
The factor of fatigue in rock exfoliation.
J. Geol., 44: 781-796

GRIM, R.E. 1953
Clay Mineralogy
McGraw-Hill Book Co. Inc., 384 pp.

GUSTAVSON, T.C. 1974 — Sedimentation on gravel outwash fans, Malospina Glacier Foreland, Alaska. Jour. Sediment Petrol, 44: 374-389

HANCOCK, N.J. AND TAYLOR, A.M. 1978 — Clay mineral diagenesis and oil migration in the Middle Jurassic Brent Sand Formation. J. Geol. Soc., 135: 69-71

HANTZSCHEL, W. 1975 — Trace fossils and problematica In: R.C. Moore (Ed) Treatise on invertebrate paleontology. Geol. Soc. Am, Part W, p W177-W249

HAPP, S.C. RITTENHOUSE, G. AND DOBSON, G.C. 1940 — Some aspects of accelerated stream and valley sedimentation. U.S. Dept. Agr. Techn. Bull, 695: 1-134

HARMS, T.F. 1975 — Lithium in unconsolidated sediments and plants of the Basin and Range Province, Southern California and Nevada. Prof. Paper U.S. Geol. Surv, 918: 23 pp.

HARMS, J.C. AND FAHNSTOCK, R.K. 1965 — Stratification, bed forms, and flow phenomena (with an example from the Rio Grand). In: Middleton G.V. (Ed) "Sedimentary structures and their hydrodynamic interpretation". S.E.P.M. Spec. Publ., 12: 84-115

HARMS, J.C. MACKENZIE, D.B. AND McCUBBIN, D.G. 1963 — Stratification in modern sands of the Red River, Louisiana. J. Geol, 71: 566-580

HARPER, C.T. 1967 — The geological interpretation of potassium-argon ages of metamorphic rocks from the Scottish Caledonides. Scot. Jour. Geol, 3: 46-66

HARPER, C.T. 1967(b) — On the interpretation of potassium-argon ages from Precambrian Shields and Phanerozoic orogens. Earth. Planet Sci. Lett, 3: 128-132

HARRIS, P.M. FARRAR, E. MACINTYRE, R.M. YORK, D. AND MILLER, J.A. 1965 — Potassium-argon age measurements on two Igneous rocks from the Ordovician system of Scotland. Nature, 205: 352-353

HAY
CUNNINGHAM 1843 — Geognostical account of Banffshire
Trans. High. Agric. Soc. Scotland
Vol. XIV, p. 467

HELLEY, E.J. 1969 — Field measurements of the initiation of a large bed particle motion in Blue Creek, near Klamath, California
U.S. Geol. Surv. Prof. Pap, 562-G, 1-19

HEM, J.D. 1972 — Chemical factors that influence the availability of iron and manganese in Aqueous systems.
Geol. Soc. Am. Bull, 83: 443-450

HEM, J.D.
AND CROPPER, W.H. 1959 — Survey of ferrous-ferric chemical equilibria and redox potentials.
U.S. Geol Surv. Water Supply Paper 1459-A, 31p.

HINXMAN, L.W. 1888 — The geology of the country between Huntly and Kildrummie Castle.
Trans. Inverness Sci. Soc. and Field Club, 3: 419

HIRST, S. 1923 — On some arachnid remains from the Old Red Sandstone (Rhynie chert Bed, Aberdeenshire)
Ann. Mag. Nat. Hist., 12: 457-474

HIRST, S.
MAULIK, S. 1926 — On some Arthropod remains from the Rhynie Chert (Old Red Sandstone)
Geol. Mag., 63: 69-71

HJULSTROM, F. 1939 — Transportation of detritus by moving water.
In: P.D. Trask (ed)
Recent Marine Sediments, p. 5-31
Bull. Am. Assoc. Petrol. Geol.

HOOKE, R. LeB 1967 — Processes on arid-region fans
J. Geol., 75: 438-460

HOPPE, G.
AND EKMAN, S.R. 1964 — A note of the alluvial fans of Ladtjoragge, Swedish Lapland.
Geogr. Annlr, 46: 338-342

HORNE, J.
MACKIE, W.
FLETT, J.S.
GORDON, W.T.
HICKLING, G.
KIDSTON, R.
PEACH, B.N.
AND WATSON, D.M.S. 1916 — The plant bearing cherts at Rhynie
British Assoc. Ann. Rept., 1916

HORNE, J. 1916 — Description of sheet 96
Geol. Survey Scotland

HORNE, R.R. AND GARDINER, P.R.R. 1973 — A new trace fossil from non-marine Upper Paleozoic Red Beds in County Wexford and County Kerry, Ireland.
Geologie en Mijnbouw, 52: 125-131

JAHNS, R.H. 1947 — Geologic features of the Connecticut Valley, Massecheusetts, as related to recent floods.
Wat.-Supply Irrig. Pap. Wash. 996

JAMES, N.P. 1972 — Holocene and Pleistocene calcareous crust (caliche), Profiles: criteria for subaerial exposure.
Jour. Sediment Petrol, 42: 817-836

JENNINGS, J.N. AND SWEETING, N.N. 1961 — Caliche pseudo-anticlines in the Fitzroy basin, Western Australia.
Am. J. Sci, 259: 635-639

JOHANSSON, C.E. 1965 — Structural studies of sedimentary deposits.
Geol. Foren Fordhandlinger, 87: 3-61 Stockholm.

JOHNELS, A.G. AND SVENSON, G.S.O. 1954 — On the biology of Protopterus annectens (Owen).
Ark. Zool., 7: 131-164

JOHNS, R.K. 1968 — Investigation of Lakes Torrens and Gairdner.
Geol. Surv. South Austr. Rep. Invest. 31: 90p., Adelaide

JOPLING, A.V. 1964 — Laboratory study of sorting processes related to flow separation.
J. Geol. Res, 16: 3403-3418

JOPLING, A.V. WALKER, R.G. 1968 — Morphology and origin of ripple drift lamination, with examples from the Pleistocene of Massachusetts.
Jour. Sediment Petrol, 38: 971-984

KENDALL, A.C. AND TUCKER, M.E. 1973 — Radiaxial fibrous calcite: a replacement after acicular carbonate.
Sedimentology, 20: 365-389

KENNEDY, W.Q. 1948 — On the significance of thermal structure in the Scottish Highlands.
Geol. Mag., 85: 229-234

KERMACK, K.A. 1943 The functional significance of the hyopcercal tail in Pteraspis. J. Exp. Biol., 20: 23-27

KIDSTON, R.
LANG, W.H. 1917-21 On Old Red Sandstone plants showing structure from the Rhynie Chert-Bed, Aberdeenshire. Parts 1-5, Trans. Roy. Soc. Edinb. Vols. 51 & 52

KRAUSKOPF, K.B. 1957 Separation of manganese from iron in sedimentary processes. Geochimica Cosmochimica Acta, 12: 61-84

KRAUSKOPF, K.B. 1967 Introduction to Geochemistry McGraw Hill, 721 pp.

KREJCI
GRAF, K 1963 Organische Geochemie Naturwiss, Rdsch, 16: 175-186

KRIGSTROM, A. 1962 Geomorphological studies of sandier plains and their braided river in Iceland. Geogr. Annlv, 44: 328-346

KRUMBEIN, W.C. 1967 Fortran IV computer programmes for Markov Chain experiments in geology. Kansas Geol. Survey, Computer Contribution, 13: 38 pp.

KRUMBEIN, W.C.
AND SLOSS, L.L. 1963 Stratigraphy and sedimentation Freeman: San Fransisco, 660 pp.

KRYNINE, P.D. 1949 The origin of red beds Trans. N.Y. Acad. Sci, 2: 60-68

KUENAN, Ph. H. 1966 Experimental turbidite lamination in a circular flume. J. Geol., 74: 523

LALOU, 1957 Studies on bacterial precipitation of carbonates in seawater. Jour. Sediment Petrol, 27: 190-195

LAMPLUGH, G.W. 1902 Calcrete Geol. Mag, 9: 575

LAND, L.S. 1970 Phreatic versus vadose meteroic diagenesis of limestones; evidence from a fossil water table. Sedimentology, 14: 175-185

LANE, E.W. AND CARLSON, E.J. 1954 — Some observations of the effect of particle shape on movement of coarse sediments. Trans. Am. Geophys. Union, 35: 453-462

LARRABEE, E. McM. 1962 — Ephemeral water action preserved in closely dated deposits. Jour. Sediment Petrol, 32: 608-609

LATTMANN, L.H. 1960 — Cross-section of a floodplain in a moist region of moderate relief. Jour. Sediment Petrol., 30: 275-282

LATTMAN, L.H. 1973 — Calcium carbonate cementation of alluvial fans in southern Nevada. Geol. Soc. Am. Bull, 84: 3013-3028

LATTMAN, L.H. AND SIMONBERG, E.M. 1971 — Case hardening of carbonate alluvium and colluvium, Spring Mountains, Nevada. Jour. Sediment Petrol., 41: 274-281

LEEDER, M.R. 1971 — Initiation of the Northumberland Basin. Geol. Mag., 108: 511-516

LEEDER, M.R. 1972 — Upper Old Red Sandstone - Tournasian sedimentology and the initiation and origin of the Northumberland Basin. Univ. of Reading Ph.D. Thesis

LEEDER, M.R. 1975 — Pedogenic carbonates and flood sediment accretion rates: a quantitative model of alluvial arid-zone lithofacies. Geol. Mag, 112: 257-270

LEOPOLD, L.B. AND MILLER, J.P. 1956 — Ephemeral streams - hydraulic factors and their relation to the drainage net. U.S. Geol. Surv. Prof. Pap., 282-A: 1-37

LEOPOLD, L.B. AND WOLMAN, M.G. 1957 — River channel patterns, braided, meandering, and straight. U.S. Geol. Surv. Prof. Pap., 282-B: 39-84

LEOPOLD, L.B. WOLMAN, M.G. AND MILLER, J.P. 1964 — Fluvial processes in geomorphology. San Fransisco: W.H. Freeman and Co. 522 pp.

LORENS, L.B. AND THRONSEN, R.E. 1955 — Geology of the fine-grained alluvial deposits in Sacremento Valley and their relationships to seepage. In: H.O. Banks (Ed.) Seepage Conditions in Sacremento Valley - Rept. Water Proj. Authority Calif., pp. A1-A26

LUGN, A.L. 1927 — An observed origin of some mud pebbles.
Proc. Iowa Acad. Sci., 34: 249-251

LUSTIG, L.K. 1965 — Clastic sedimentation in Deep Springs Valley, California.
Prof. Paper, U.S. Geol. Surv. 352 F: 131-192

MACKIE, W. 1899 — The sands and sandstones of eastern Moray.
Edin. Geol. Soc. Trans, 7: 148-172

MACKIE, W. 1914 — The rock series of Craigbeg and Ord Hill, Rhynie, Aberdeenshire.
Trans. Edin. Geol. Soc., 10: 205

MACKIE, W. 1925 — The principles that regulate the distribution of particles of heavy minerals in sedimentary rocks, as illustrated by the sandstones of the north-east of Scotland.
Trans. Edinb. Geol. Soc., 11: 138-164

MALCOLMSON 1839 — On the relations of the different parts of the Old Red Sandstone.
Proc. Geol. Soc. London, Vol. III, p.141 also Quart. Jour. Geol. Soc., Vol. XV, 1859, p. 336

MANKIN, C.J. 1970 — Introduction to symposium papers on environmental aspects of clay minerals.
Jour. Sediment Petrol., 40: 788

MANSFIELD, G.R. 1938 — Flood deposits of the Ohio River, January-February, 1937 - a study of sedimentation.
Water-Supply Irrig. Pap. Wash., 838: 693-733

MARTINI, I.P. AND OSTLER, J. 1973 — Ostler lenses: possible environmental indicators in fluvial gravels and conglomerates.
Jour. Sediment Petrol., 43: 418-422

MELTON, M.A. 1965 — The geomorphic and Paleoclimatic significance of alluvial deposits in southern Arizona.
J. Geol., 73: 1-38

MELTON, M.A. 1965 — Debris covered hillslopes of the southern Arizona desert - consideration of their stability and sediment contribution.
J. Geol., 73: 715-729

MIALL, A.D. 1970 — Continental marine transition in the Devonian of Prince of Wales Island, North-west Territories. Canadian Jour. of Earth Sciences, 1: 125-144

MIALL, A.D. 1970 — Devonian Alluvial Fans, Prince of Wales Island, Arctic Canada. Jour. Sediment Petrol., 40: 556-571

MIALL, A.D. 1977 — A review of the braided-river depositional environment. Earth Sci. Rev., 13: 1-62

MIDDLETON, G.V. 1970 — Experimental studies related to problems of Flysch sedimentation. In: Flysch sedimentology in N. America. Geol. Ass. Canada, Spec. Paper 7, 253-272

MII, H. 1957 — Peculiar accumulation of drifted shells. Saito Ho-on Kai Mus. Res. Bull, 26: 17-24

MILES, R.S. AND WESTOLL, T.S. 1963 — Two new genera of Coccosteid Arthrodira from the Middle Old Red Sandstone of Scotland, and their stratigraphic distribution. Trans.Roy. Soc. Edinb., 65: 179-210

MILLER, D.N AND FOLK, R.L. 1955 — Occurrence of detrital magnetite and Ilmenite in red sediments; new approach to significance of red beds. Bull. Amer. Assoc. Petrol Geol., 39: 338-345

MILLOT, G. 1970 — Geology of clays. Springer: New York

MOODY-STUART, M. 1966 — High and low sinuosity stream deposits with examples from the Devonian of Spitzbergen. Jour. Sediment Petrol., 36: 1102-1117

MOORBATH, S. 1967 — Recent advances in the application and interpretation of radiometric age data. Earth Sci. Rev., 3: 111-133

MOUSSA, M.T. 1970 — Nematode Fossil Trails from the Green River Dormation (Eocene) in the Uinta Basin, Utah. J. Paleontol, 44: 304

MURCHISON, R.I. 1829 — Supplementary remarks on the strata of the Colitic Series. Trans. Geol. Soc. London, 2nd Ser. Vol. II, p. 363

McALPINE, A. 1978 — The Upper Old Red Sandstone of Orkney, Caithness and neighbouring areas. Univ. Newcastle upon Tyne, Ph.D. Thesis (unpubl.)

McDONALD, B.C. AND BANERJEE, I. 1971 — Sediments and bedforms on a braided outwash plain. Canadian Jour. of E. Sci., 8: 1282-1301

McGOWEN, J.H. AND GARNER, L.E. 1970 — Physiographic features and stratification types of coarse-grained point bars: Modern and Ancient examples. Sedimentology, 14: 77-111

McKEE, E.D. 1938 — Original structures in Colorado River flood deposits of Grand Canyon. Jour. Sediment Petrol., 8: 77-83

McKEE, E.D. 1939 — Some types of bedding in the Colorado River delta. J. Geol., 47: 64-81

McKEE, E.D. 1957 — Primary structures in some recent sediments. Bull. Amer. Assoc. Petrol. Geol., 41: 1707-1747

McKEE, E.D. 1965 — Experiments on ripple lamination. In: Middleton G.V. and Briggs L.I.(eds.) Primary sedimentary structures and their hydrodynamic interpretation. Soc. Econ.Paleontol. Mineral. Sp. Publ. 12: 66-83

McKEE, E.D. 1966 — Significance of climbing ripple structure. Prof. Paper US Geol. Survey, 550 D D94-103

McKEE, E.D. CROSBY, E.J. AND BERRYHILL, H.L. 1967 — Flood deposits, Bijon Creek, Colorado, June, 1965. Jour. Sediment Petrol., 37: 829-851

NAGTEGAAL, P.J.C. 1969 — Microtextures in recent and fossil caliche. Leid. Geol. Meded., 42: 131-142

NEIHEISSEL, J. AND WEAVER, C. 1967 — Transport and deposition of clays in the south-eastern United States. Jour. Sediment Petrol., 37: 1084-1116

NEVIN, C.M. 1946 — Competency of moving water to transport debris. Geol. Soc. Am. Bull., 57: 651-674

OLLIER, C.D. 1963 — Insolation weathering: examples from Central Australia. Am. J. Sci., 261: 376-387

OLLIER, C.D. 1969 — Weathering Olliver and Boyd, Edinburgh

OKADA, H. 1971 — Classification of sandstone: Analysis and proposal. J. Geol., 79: 509-525

ORE, H.T. 1964 — Some criteria for recongition of braided stream deposits. Univ. Wya. Publs. Sci. (Geol.), 3: 1-14

PANKHURST, R.J. 1970 — The geochronology of the basic igneous complexes. Scott. J. Geol., 6: 83-107

PARRINGTON, F.R. 1958 — On the nature of the Anaspida in "studies on fossil vertebrates". Ed. Westoll, T.S. The Athlone Press, London

PATON, T.R. 1974 — Origin and terminology for Gilgai in Australia. Geoderma II: 221-242

PEACOCK, J.D. BERRIDGE, N.G. HARRIS, A.L., AND MAY, F. 1968 — The Geology of the Elgin District. Mem. Geol. Surv. Scotl., Edinburgh

PETTIJOHN, F.J. 1975 — Sedimentary Rocks Harper, 628 pp.

PETTIJOHN, F.J. AND POTTER, P.E. 1964 — Atlas and glossary of primary sedimentary structures. Berlin - Gottingen - Heidelberg - New York: Springer, 370 pp.

PETTIJOHN, F.J. POTTER, P.E. AND SIEVER, R. 1972 — Sand and sandstone Berlin - Heidelberg - New York: Springer, 618 pp.

PICARD, N.D. 1965 — Iron oxides and fine grained rocks of Red Peak and Crow Mountain sandstone members, Chugwater (Triassic) Formation Wyoming.
Jour. Sediment Petrol., 35: 464-479

DANE PICARD, M. AND HIGH, L.R. 1973 — Sedimentary structures of ephemeral streams.
Developments in Sedimentology, Vol. 17, 223 pp., Elsevier.

PITTMAN, E.D. 1963 — Use of zoned plagioclase as an indicator of provenance.
Jour. Sediment Petrol., 33: 380,386

PITTMAN, E.D. 1970 — Plagioclase feldspar as an indicator of provenance in sedimentary rocks.
Jour. Sediment Petrol., 40: 591-598

PLIMMER, R.S. 1974 — The Sedimentology and Stratigraphy of the Middle Old Red Sandstone Rousay Group of the Orkney Islands.
Univ. Newcastle Upon Tyne, Ph.D. Thesis (unpubl.)

POLLARD, J.E. 1976 — A problematical trace fossil from the Tor Bay Breccias of South Devon. Written discussion of paper taken as read.
Proc. Geol. Ass., 87: 105-109

PORRINGA, D.H. 1967 — Clay mineralogy and geochemistry of Recent sediments in tropical areas.
Stolk-Dort, Dordrecht, Netherlands, 145 pp.

POTTER, P.E. AND BLAKELY, R.F. 1968 — Random processes and lithologic transitions.
J. Geol., 76: 154-170

POTTER, P.E. AND PETTIJOHN, F.J. 1973 — Paleocurrents and basin analysis
Academic Press, New York, NY, 296 pp.

POTTER, P.E, PETTIJOHN, F.J. AND SIEVER, R. 1972 — Sand and sandstone.
Springer, Berlin, 608pp.

PRATT, J.B. (Rev.) 1870 — 'Buchan'
Arthur King and Co., Aberdeen

PRESTWICH, 1838 — Observations on the Ichthyolites of Gamrie in Banffshire, and on the accompanying Red Conglomerates and Sandstones.
Proc. Geol. Soc. London, Vol. ii, p. 187

PRESTWICH, 1840 — On the structure of the Neighbourhood of Gamrie, Banffshire.
Trans. Geol. Soc. London, 2nd Ser., Vol. V, p. 139

PRICE, W.A. 1925 — Caliche and pseudo-anticlines
Bull. Ame. Assoc. Petrol Geol., 9: 1009-17

PRICE, W.A. 1933 — Reynosa problem of S. Texas and origin of caliche.
Bull. Amer. Assoc. Petrol Geol., 51: 1939

PRICE, W.A. 1958 — Sedimentology and Quaternary geomorphology of South Texas.
Trans. Gulf. Cst. Assoc. Geol. Soc., 8: 41-75

RAICHLEN, F. AND KENNEDY, J.F. 1965 — The growth of sediment bed-forms from an initially flattened bed.
Internat. Assoc. Hydraulic Res. 11th Internat. Congress, Leningrad
Paper 3.7, 8 p.

RAPP, A. 1963 — The debris slides at Ulvoadal, western Norway. An example of catastrophic slope processes in Scandinavia.
Slopes Comm. Rep., 3: 195-210

RAYNER, D.H. 1963 — The Achanarras Limestone of the Middle Old Red Sandstone, Caithness, Scotland.
Proc. Yorks. Geol. Soc., 34: 117

READ, W.A. 1969 — Analysis and simulation of Namurian sediments in Central Scotland using a Markov-Process model.
Mathematic Geology, 1: 2 9-219

REESMAN, A.L. AND KELLER, W.D. 1967 — Chemical composition of illities
Jour. Sediment Petrol., 37: 592-596

REEVES, C.C. 1970 — Origin, classification, and geological history of caliche on the south-eastern High Plains, Texas and Eastern New Mexico.
J. Geol., 78: 352-362

REINECK, H.E. AND SINGH, I.B. 1975 — Depositional sedimentary environments Springer-Verlag, Berlin, 434 pp.

REINECK, H.E. AND WUNDERLICH, F. 1968 — Classification and origin of flaser and lenticular bedding. Sedimentology, 11: 99-104

RICE, C.M. AND WILLIAMS, J.M. 1969 — A Mossbauer study of biotite weathering. Min. Mag., 37: 210-215

RICHARDSON, J.B. 1965 — Middle Old Red Sandstone spore assemblages from the Orcadian Basin, North-east Scotland. Paleontology, 7: 559-605

RICHARDSON, J.B. 1967 — Some British Lower Devonian spore assemblages and their stratigraphic significance. Rev. Palaeobt. Palynol., 1: 11-29

RIDGEWAY, J.M. 1974 — A problematical trace fossil from the New Red Sandstone of South Devon. Proc. Geol. Ass., 85: 511-517

ROBB, G.L. 1949 — Red bed colouration Jour. Sediment Petrol., 19: 99-103

ROMER, A.S. AND OLSEN, E.C. 1954 — Aestivation in a Permian Lungfish Breviora, 30: 1-8

RUCHIN, L.B. 1958 — Grundzuge der Lithologie Berlin: Akademie-Verlag, 806 pp.

RUHE, R.V. 1967 — Geomorphic surfaces and surficial deposits in southern New Mexico. New Mexico State Bureau of Mines and Mineral Resources, Memoir 18, 66 pp.

RUSSEL, R.J. 1954 — Alluvial morphology of Anatolian rivers. Ann. Ass. Am. Geogr., 49: 363-391

RUST, B.R. 1972(a) — Structure and process in a braided river. Sedimentology, 18: 221-245

RUST, B.R. 1972(b) — Pebble orientation in fluvial sediments. Jour. Sediment Petrol., 42: 384-388

SANDERSON, D.J. AND DONOVAN, R.N. 1974 — The vertical packing of shells and stones on some recent beaches. Jour. Sediment Petrol., 44: 680-688

SCHMALZ, R.F. 1959 — A note on the system Fe_2O_3-H_2O
Jour. Geophys. Res., 64: 575-579

SCHMALZ, R.F. 1968 — Formation of Red Beds in modern and ancient deserts. Discussion.
Geol. Soc. Am. Bull., 79: 277-280

SCHUMM, S.A. 1960(a) — The shape of alluvial channels in relation to sediment type.
U.S. Geol. Surv., Prof. Pap., 352-B: 17-30

SCHUMM, S.A. 1960(b) — The effect of sediment type in the shape and stratification of some modern fluvial deposits.
Am.J. Sci., 258: 177-184

SCHUMM, S.A. 1961 — Effect of sediment characteristics on erosion and deposition in ephemeral stream channels.
Geol.Surv. Prof. Paper., 352-C: 1-70

SCHUMM, S.A. 1963 — Sinuosity of alluvial channels on the Great Plains.
Geol. Soc. Am. Bull., 74: 1089-1100

SCHUMM, S.A. 1968 — River adjustment to altered hydrologic regimen - Murrumbigee River and paleo-channels, Australia.
U.S. Geol. Surv., Prof. Paper, 598: 65 pp.

SCHUMM, S.A. AND LICHTY, R.W. 1963 — Channel widening and floodplain construction along Cimarron River in South Western Kansas.
U.S. Geol. Surv. Profess. Papers 352D: 71-88

SCOURFIELD, D.V. 1926 — On a new type of Crustacean from the Old Red Sandstone (Rhynie chert bed, Aberdeenshire). Lepidocaris rhynieusis gen et sp. nov.
Phil. Trans. R.Soc.B, 214: 153-187

SEDGEWICK AND MURCHISON, R.I. 1835 — The structure and relations of the deposits contained between the Primary Rocks and the Oolitic Series in the North of Scotland.
Trans. Geol. Soc. London, 2nd Series Vol. iii, p. 125

SEHGAL, J.L. AND STOOPS, A. 1972 — Pedogenic calcite accumulation in arid and semi-arid regions of the Indo-Gaugetic alluvial plain of erstwhile Punjab (India) - their morphology and origin.
Geoderma, 8: 59-72

SELLEY, R.C. 1968 — Facies profile and other new methods of graphic data presentation: application in a quantitative study of Libyan Tertiary shoreline deposits. Jour. Sediment Petrol., 38: 363-372

SELLEY, R.C. 1970 — Studies of sequence in sediments using a simple mathematical device. Quart. J. Geol. Soc. London, 125: 557-581

SENGUPTA, S. 1966 — Studies on orientation and imbrication of pebbles with respect to cross-stratification. Jour. Sediment Petrol., 36: 362-369

SHANTZER, E.V. 1951 — Alluvium of river plains in a temperate zone and its significance for understanding the laws governing the structure and formation of alluvial suites. Tr. Inst. Geol. Nauk, Akad. Nauk. S.S.S.R. Geol. Ser., 135: 271 pp.

SHARP, R.P. AND NOBLES, L.H. 1953 — Mudflow of 1941 at Wrightwood, Southern California. Geol. Soc. Am. Bull, 64: 547-560

SHEPARD, F.P. 1956 — Marginal sediments of the Mississippi delta. Bull. Am. Assoc. Petrol. Geol., 40: 2537-2623

SIESSER, W.G. 1975 — Diagenetically formed ooids and intraclasts in South African calcretes. Sedimentology, 20: 539-551

SIEVER, R. 1959 — Petrology and geochemistry of silica cementation in some Pennsylvanian sandstones. In: 'Silica in sediments' Soc. Econ. Paleontologists and Mineralogists, Spec. Publ., 7: 55-79

SIMONS, D.B. AND RICHARDSON, E.V. 1961 — Forms of bed roughness in alluvial channels. Proc. Am. Soc. Civil Eng., J. Hydraulics Div., 87: 87-105

SIMONS, D.B. RICHARDSON, E.V. AND NORDIN, C.F. 1965 — Sedimentary structures generated by flow in alluvial channels. Soc. Econ. Paleontologists Mineralogists Spec. Publ., 12: 34-52

SINGH, I.B. 1972 — On the bedding in the natural levee and the point-bar deposits of the Gomti River, Uttar Pradesh, India. Sediment. Geol., 7: 309-317

SISLER 1962 Microbiology and biochemistry of sediments and overlying water. In: Cloud P.E. (Ed.) Environment of calcium carbonate deposition west of Andros Island, Bahamas. U.S. Geol. Surv. Prof. Paper, 350: 64-69

SMITH, D.B. 1974 Origin of tepees in upper Permian shelf carbonate rocks of Guadalupe Mountains, New Mexico. Bull. Am. Ass. Petrol Geol., 58: 63-70

SMITH, H.W. 1931 Observations on the African Lungfish Protopterus Aethiopieus, and on evolution from water to land environments. Ecology, 12: 164-181

SMITH, N.D. 1970 The braided stream depositions environment: Comparison of the Platte River with some Silurian clastic rocks. Geol. Soc. Am. Bull., 81: 2993-3014

SMITH, N.D. 1971(a) Pseudo-planar stratification produced by very low amplitude sand waves. Jour. Sediment Petrol., 41: 69-73

SMITH, N.D. 1971(b) Transverse bars and braiding in the Lower Platte River, Nebraska. Geol. Soc. Am. Bull., 82: 3407-3420

SMITH, N.D. 1972 Flume experiments on the durability of mud clasts. Jour. Sediment Petrol., 42: 378-383

SMITH, N.D. 1972 Some sedimentological aspects of planar cross-stratification. Jour. Sediment Petrol., 42: 624-634

SMITH, N.D. 1974 Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream. J. Geol., 82: 205-224

SMITHSON, F. AND BROWN, G. 1954 The petrography of diclcitic sandstones in North Wales and Northern England. Geol. Mag., 91: 177-188

SNEED, E.D. AND FOLK, R.L. 1958 Pebbles in the lower Colarado River, Texas, a study in particle morphogenesis. J. Geol., 66: 114-150

SORBY, H.C. 1859 On the structures produced by the currents present during the deposition of stratified rocks. Geologist, 2: 137-147

SORBY, H.C. 1908 On the application of quantitative methods to the study of the structure and history of rocks.
Quart. J. Geol. Soc. Lond., 64: 171-232

STALDER, P.J. 1975 Cementation of Pliocene-Quaternary fluviatile clastic deposits in and along the Oman Mountains.
Geologie en Mijnbouw, 54: 148-156 N

STANLEY, D.J. 1968 Graded bedding - solemarking - greywacke assemblage and related sedimentary structures in some carboniferous flood deposits, eastern Massechusetts.
Spec. Pap. Geol. Soc. Am, 106: 211-239

STEEL, R.J. 1974 Cornstone (fossil caliche) its origin, stratigraphy and sedimentological importance in the New Red Sandstone Western Scotland.
J. Geol., 82: 351-369

STEEL, R.J. 1974 New Red Sandstone floodplain and piedmont sedimentation in the Hebridean Province, Scotland.
Jour. Sediment Petrol., 44: 336-357

STEPHENSON, D. 1972 Middle Old Red Sandstone alluvial fan and talus deposits at Foyers, Inverness-shire.
Scot. J. Geol., 8: 121-127

STOKES, W.L. 1950 Pediment concept applied to Shinarump and similar conglomerates.
Geol. Soc. Am. Bull., 61: 91-8

STOKES, W.L. 1961 Fluvial and eolian sandstone bodies in Colorado Plateau.
In: J.A. Peterson and J.C. Osmond (Ed.) Geometry of sandstone bodies (A symposium)
Bull. Am. Assoc. Petrol. Geol, Tulsa, Okla. pp 151-178

STRAKOV, N.M. 1969 Principles of lithogenesis 3 Vols.
Oliver & Boyd Edinburgh ?

STUART, D.M. AND DIXON, R.M. 1973 Water movement and caliche formation in layered arid and semi-arid soils.
Proc. Soil Sci. Soc. Amer., 37: 323-324

SUNDBORG, A. 1956 The River Klavalven - a study of fluvial processes.
Geogr. Ann., 38: 127-316

SUTTON, J. 1965 — Some recent advances in our understanding of the controls of metamorphism. In: Controls of Metamorphism Edinburgh.

SWINEFORD, A. CONARD, A.B. AND FRYE, J.C. 1958 — Petrology of the Pliocene pisolitic limestone in the Great Plains Bull. Geol. Surv. Kansas, 130: 97-116

SWINEFORD, A. FRYE, J.C. AND LEONARD, A.B. 1956 — Petrography and genesis of the Ogallala 'algae' limestone in Kansas and adjacent states. Jour. Sediment Petrol., 26: 786

SWINEFORD, A. LEONARD, A.B. AND FRYE, J.C. 1958 — Petrology of Pliocene pisolitic limestones in the Great Plains. Bull. Kansas Geol. Surv., 130: 97-116

THOMPSON, A.M. 1970 — Geochemistry of Colour Genesis in Red Bed sequence, Juniata and Bald Eagle Formations, Pennsylvania. Jour. Sediment Petrol., 40: 599-615

TRAQUAIR, R.H. 1896 — The extinct vertebrate fauna of the Moray Firth area. In: J.H. Harvey-Brown & T.E. Buckley (Eds.) Vertebrate fauna of the Moray Firth., Vol. 2, Edinburgh.

TREWYN, N.H. 1976 — Isopodichnus in a trace fossil assemblage from the Old Red Sandstone. Lethaia, 9: 29-37

TUCKER, M.E. 1974 — Exfoliated pebbles and sheeting in the Triassic Nature, 252: 375-376

TURNER, P. 1974 — Origin of red beds in the Ringerik Group (Silurian) of Norway. Sed. Geol., 12: 215-35

TURNER, P. AND ARCHER, R. 1975 — Magnetisation history of Lower Old Red Sandstones from the Gamrie Outlier, Scotland. Earth. Planet. Sci. Lett., 27: 240-250

TURNER, P. AND ARCHER, R. 1977 — The role of biotite in the diagenesis of Devonian Red Beds from Northern Scotland. Sed. Geol., 19: 241-251

TURNER, P. TARLING, D.H. ARCHER, R. AND DONOVAN, R.N. 1976 — The paleomagnetic argument concerning post-Devonian displacement along the Great Glen Fault. Geol. Mag., 113: 365-370

TURNER, F.J. AND VERHOOGEN, J. 1960 — Igneous and metamorphic petrology. McGraw-Hill, 694 pp.

VAN HOUTEN, F.B. 1961 — Ferric oxides in red beds as paleomagnetic data. Jour. Sediment Petrol., 31: 296-300

VAN HOUTEN, F.B. 1964 — Origin of red beds - some unsolved problems: In: Nairn, A.E.M. (Edit) "Problems in palaeoclimatology" Interscience Publishers N.Y. 705pp.

VAN HOUTEN, F.B. 1968 — Iron oxides in red beds Geol. Soc. Am. Bull., 79: 399-416

VARNES, D.J. 1958 — Landslide types and processes. In: Eckel E.B. (Ed.) Landslides and engineering practice. Highway Res. Board, Spec. Rep., 29: 20-47, Washington DC

VAUGHN, P.P. 1964 — Evidence of aestivating lungfish from the Sangre de Cristo Formation, Lower Permian of Northern New Mexico SCI. Contrib. Los. Ang. Co. Mus, 80: 1-8

VIALOV, O.S. 1962 — Problematica of the Beacon Sandstone at Beacon Heights West, Antarctica. N. Zealand Jour. Geol. Geophys. 5: 718-732

WAUGH, B. 1967 — Environmental and diagenetic studies of the Permo-Griassic clastic and carbonate sediments of The Vale of Eden. Unpubl. Ph.D. Thesis, Univ. of Newcastle Upon Tyne, 309 pp.

WALKER, T.R. 1967(a) — Formation of red beds in modern and ancient deserts. Geol. Soc. Am. Bull., 78: 353-368

WALKER, T.R. 1967(b) — Recent sediments in tropical Mexico, a contribution to the origin of red beds. Geol. Soc. Am. Bull., 78: 917-920

WALKER, T.R. AND HONEA, R.M. 1969 — Iron content of modern deposits in the Sonovan Desert: a contribution to the origin of red beds. Geol. Soc. Am. Bull., 80: 535-544

WALKER, T.R. AND RIBBE, P.H. 1967 — Formation of iron-rich authigenic clay by intrastiatal aleration of horn blende in an arid climate: a contribution to the origin of haematite stained matrix in red beds. Geol. Soc. Am. Spec. Paper, 101: Abstr. for 1966, p. 233

WALKER, T.R. RIBBE, P.H. AND HONEA, R.M. 1967 — Geochemistry of horn blende alteration in Pliocene red beds, Baja California, Mexico. Geol. Soc. Am. Bull., 78: 1055-1060

WALLACE, T.D. 1919 — A new locality for manganese Trans. Geol. Soc. Ed., 11: 135-137

WEAVER, C. 1967 — Variability of a river clay suite Jour. Sediment Petrol., 37: 971-974

WEEKS, L.G. 1957 — Origin of carbonate concretions in shales, Magdelena Valley, Columbia. Geol. Soc. Am. Bull., 68: 95-102

WESTOLL, T.S. 1951 — The vertebrate bearing strata of Scotland. Rept. Int. Geol. Cong., 18th Session Gt. Britain, pt. 11, 5-21

WESTOLL, T.S. 1964 — The Old Red Sandstone of N.E. Scotland Advan. Sci. 20 (87), 446 (Summary)

WIEDEMANN, H.V. 1972 — Shell deposits and shell preservation in Quaternary and Tertiary estuarine sediments in Georgia, U.S.A. Sedimentary Geol., 7: 103

WILLIAMS, G.E. 1968 — Formation of large-scale trough cross-stratification in a fluvial environment. Jour. Sediment Petrol., 38: 136-140

WILLIAMS, G.E. 1970 — Piedmont sedimentation and late Quarternary chronology in the Biskra region of the northern Sahara. Z. Geomorph., 10: 40-60

WILLIAMS, G.E. 1973 — Late Quaternary piedmont sedimentation, soil formation and paleoclimate in South Australia. Z. Geomorph., 17: 102-125

WILLIAMS, G.E. AND POLACH, H.A. 1969 — The evaluation of 14C ages for soil carbonate from the arid zone. Earth and Planetary Sci. Letters, 7: 240-242

WILLIAMS, G.E. AND POLACH, H.A. 1971 — Radiocarbon dating of arid-zone calcareous paleosoils. Geol. Soc. Am. Bull., 82: 3069-3086

WILLIAMS, P.F. AND RUST, B.R. 1969 — The sedimentology of a braided river. Jour. Sediment Petrol., 39: 649-679

WILSON, M.J. 1966 — The weathering of biotite in some Aberdeenshire soils. Min. Mag., 35: 1080-1093

WILSON, M.J. 1971 — Clay mineralogy of the Old Red Sandstone (Devonian) of Scotland. Jour. Sediment Petrol., 41: 995-1007

WOLMAN, M.G. 1955 — The natural channel of the Brandywine Creek, Pennsylvania. U.S. Geol. Surv. Prof. Paper, 271, 56p

WOLMAN, M.G. AND BRUSH, L.M. 1961 — Factors controlling the shape and size of stream channels in coarse non-cohesive sands. U.S. Geol. Surv. Prof. Paper, 282G: 183-210

WOLMAN, M.G. AND LEOPOLD, L.B. 1957 — River floodplains: some observations on their formation. U.S. Geol. Surv. Prof. Paper, 282G: 87-109

WOODROW, D.L. AND FLETCHER, F.W. 1968 — Upper Devonian aestivation tube casts. (Abs.) Geol. Soc. America Spec. Paper 121: 383-384

YEAKEL, L.S. 1962 — Tuscarora, Juniata, and Bald Eagle paleocurrents and paleogeography in the Central Appalachians. Bull. Geol. Soc. Am., 73: 1515-1539

ZINGG, G.T. 1935 — Beitrag zur Schotteranalyse Schweitz. Min. u. Pet. Mitt. Bd. 15: 39-140