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KIMMERIDGIAN AND VOLGIAN FAULT-MARGIN SEDIMENTATION IN THE NORTHERN NORTH SEA AREA.

A thesis submitted for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT.

The Upper Jurassic sediments of the East Coast of Sutherland and the South Brae Oilfield were deposited during the late Jurassic taphrogenic episode in which there was rapid subsidence in the grabens and uplift of the adjacent areas. The initiation of coarse-grained sedimentation in the grabens was directly related to an increase in subsidence rates.

At Sutherland the most sand-rich sequences were deposited during the cymodoce zone of the Kimmeridgian, immediately after the increase in subsidence rates. Depositional environments varied from a relatively shallow water and sand-rich submarine slope during the early Kimmeridgian to a deeper water sediment starved submarine slope during the early Volgian.

The sediments of the South Brae Oilfield were deposited in the channelised part of a submarine fan system which was sourced from a point which lay to the west of the 16/7a-8 well and to the southwest of the 16/7a-12 well. The South Brae sequences are part of a much larger complex which was composed of at least seven different submarine fan systems. Sediment entry points occurred along the western margin of the South Viking Graben from the T-Block in the south to East Brae in the north and each of these fed a submarine fan system. The reservoir sequences will tend to be vertically stacked and spatially restricted in proximal areas and will become less stacked and less restricted distally.

Stratigraphically trapped "Brae-like" plays probably exist at the margins of many North Atlantic Continental Shelf grabens. The eastern margins of the Vøring and Træna Basins have especially high prospectivity.

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CONTENTS.

Chapter 1

Introduction

1.A SCOPE

This thesis discusses the sedimentology of Kimmeridgian and Volgian sediments which were deposited adjacent to two major syn-sedimentary, basin-bounding, fault systems in the northern North Sea area. The two principal areas of study are the Sutherland coast near Helmsdale and the South Brae Oilfield. The marginal deposits of the Inner Moray Firth Basin are exposed on the Sutherland coast adjacent to the Helmsdale Fault and the sediments of the extensively cored South Brae Oilfield were deposited adjacent to the western margin of the South Viking Graben (Fig. 1.1). Data from these two areas plus regional stratigraphic data is used to produce a sedimentary and tectonic model which should assist in locating and extracting hydrocarbons from Kimmeridgian and Volgian fault margin reservoirs in the northern North Sea and North Atlantic Continental Shelf area.

The thesis topic was proposed by Dr. A.J. Parsley at Britoil (formerly B.N.O.C.) who appreciated the importance of correctly identifying depositional environments in the Brae Oilfields and possible existence of "Brae-like" plays elsewhere in the North Atlantic Continental Shelf and North Sea.

The principal aims of this research were;

1. To deduce the environment of deposition and distribution of facies adjacent to the Helmsdale Fault and in the South Brae Oilfield.
2. To construct an environmental model for South Brae which would assist in reservoir modelling and the extraction of hydrocarbons from the field.
3. To use the results of the studies on the Helmsdale and South Brae sequences as an aid to the production of hydrocarbons from fields which were deposited in similar environmental and tectonic settings, eg. North/

Brae and the T-Block fields (Fig. 1.1).

4. To synthesize a regional environmental model for Kimmeridgian and Volgian fault-margin sedimentation by integrating regional stratigraphy with data from Sutherland and South Brae. The model should help to locate similar oilfields in the northern North Sea and North Atlantic Continental Shelf.

REGIONAL SETTING

The Jurassic hydrocarbon-bearing sediments of the northern North Sea area were mostly deposited in fault bounded basins. The complex graben system (Fig. 1.1) was the result of the superimposition of the effects of tensional stresses, related to the opening of the Atlantic Ocean, on existing Caledonian and Pre-Caledonian structural elements. The Mesozoic basins were generally bounded by large scale normal faults, some of which have listric profiles (Gibbs, 1984). Although the major movement was normal there is evidence for strike-slip movements along some graben bounding faults (Hay, 1978, McQuillin et al, 1982, Fagerland, 1983). The Helmsdale Fault, which bounds the Inner Moray Firth Basin (Fig. 1.1) also shows evidence of limited strike-slip movement during the Mesozoic (section 2.C).

During the Caledonian orogeny the northern North Sea was folded and deformed into a mountain range that began to subside during the Devonian (Glennie, 1984). The sedimentology of the Upper Palaeozoic sediments is not well known but, in general, Devonian to Permian deposition took place under continental conditions in fluvial and lacustrine environments. An approximate E-W tensional regime was initiated in the early Carboniferous (Haszeldine, 1984) or the early Permian (Glennie, 1984) and the late Palaeozoic and Mesozoic sedimentation was primarily controlled by differential fault related subsidence. Continental conditions continued through the Trias before marine conditions were established in the early Jurassic (Lias), after the Rhaetian to Hettanginian eustatic rise in sea-level (Hallam, 1975), and Liassic sedimentation mostly took place in a shallow epicontinental sea.

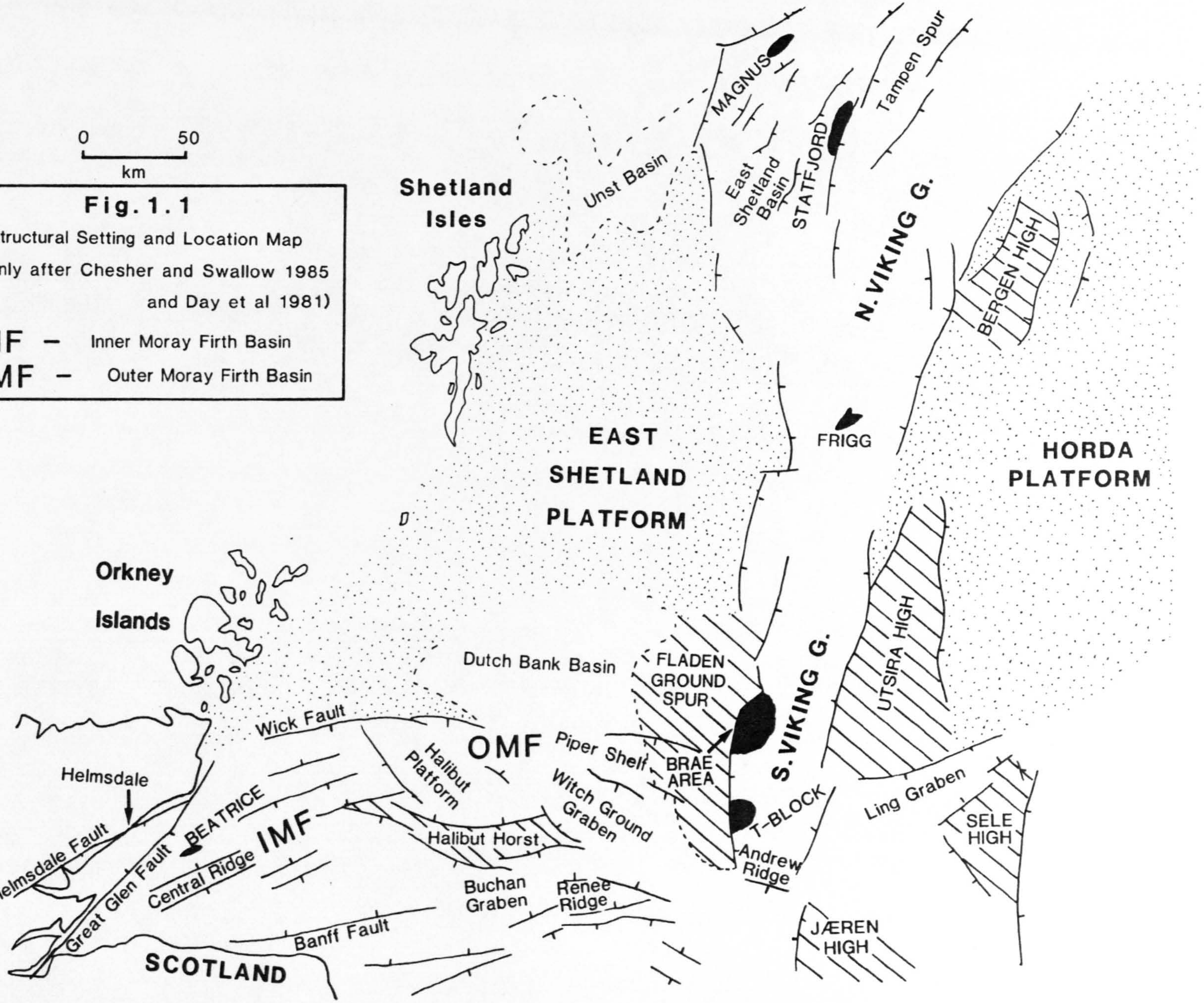


Fig. 1. 1

Structural Setting and Location Map (Mainly after Chesher and Swallow 1985 and Day et al 1981)

IMF – Inner Moray Firth Basin

OMF – Outer Moray Firth Basin

Uplift occurred towards the end of the Lias, after the Central North Atlantic had split during the Pliensbachian, and led to the erosion of much of the Liassic strata. Subsidence resumed during the Bajocian to Bathonian and deltaic sediments, which form the excellent reservoirs of the Brent Group (Deegan and Skull, 1977), were deposited in essentially symmetrical grabens. At this time up to 1km of alkalic basalts were erupted in the eastern part of the Outer Moray Firth (Howitt, 1975, Dixon, Fitton and Frost, 1981). The transition from the Bathonian to Callovian to Oxfordian is a transgressive phase and during the late Jurassic most of northwest Europe and the North Atlantic area was covered by an epicontinental sea with relatively limited land areas (Hallam and Sellwood, 1976).

Subsidence rates increased slightly during the Oxfordian and then dramatically during a major period of rifting which began in the late Oxfordian and early Kimmeridgian (Hallam, 1975) penecontemporaneously with the upwards transition from the poorly-radioactive Heather Formation shales to the highly radioactive Kimmeridge Clay Formation shales (Deegan and Skull, 1977). During this period of rifting many of the basins became clearly asymmetrical, many of the small-scale intrabasinal faults ceased to move and subsidence mostly took place along a few large basin margin faults. Approximately at this time salt diapirism began on a large-scale in the southern North Sea (Hallam, 1975) and volcanism occurred in the West of Scotland and in the North Viking Graben (Knox, 1977). In the northern North Sea, during this major rifting phase, coarse-grained material was shed from the upthrown sides of the graben margin faults and deposited as potential reservoir rocks within the grabens, eg. the Brae and T-Block Oilfields (Fig. 1.1). This thesis is primarily concerned with the distribution and the environment of deposition of that coarse-grained material. Taphrogenic tectonism continued into the middle/

Cretaceous before an essentially epeirogenic phase of subsidence during the late Cretaceous and Tertiary.

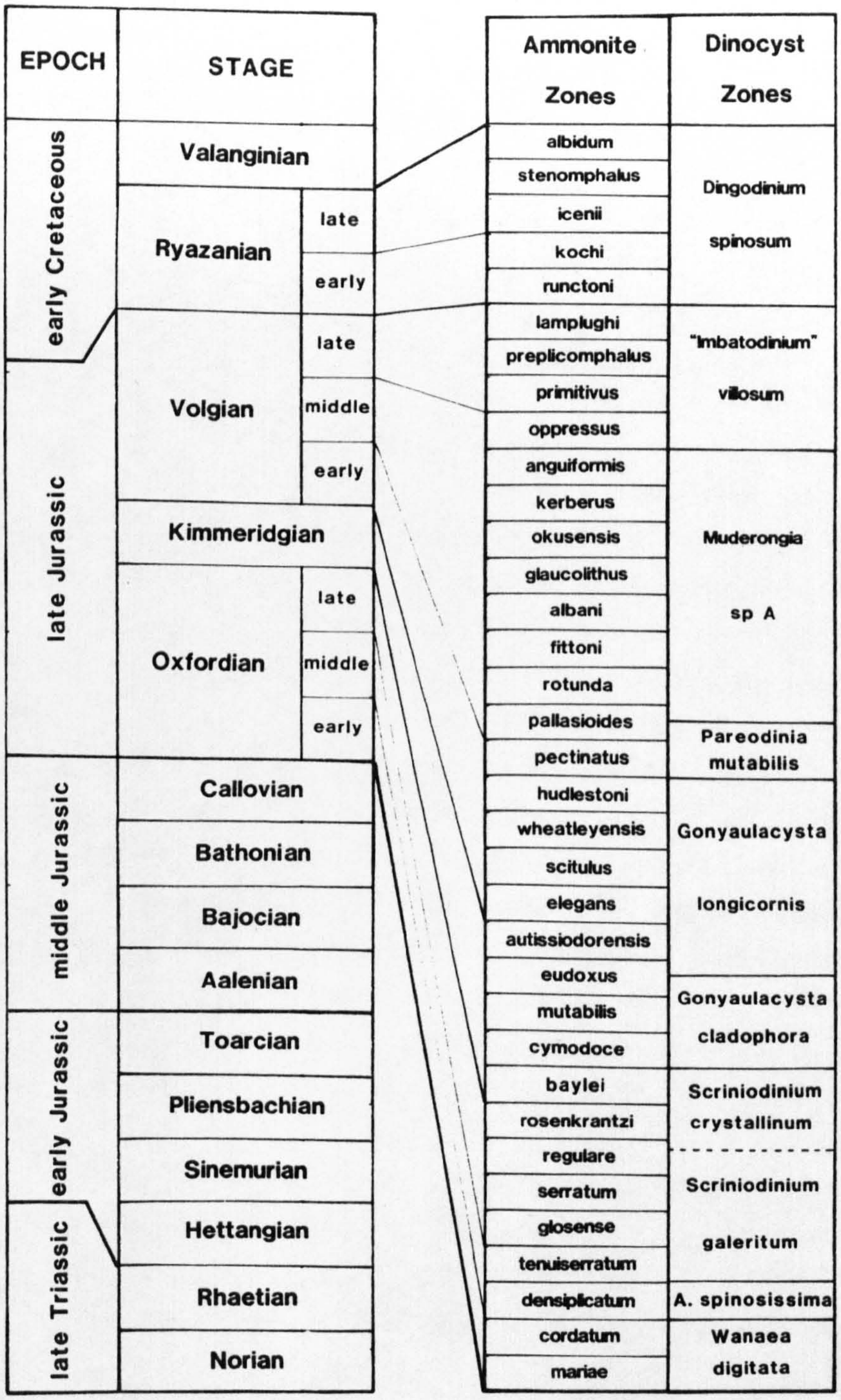
During the Jurassic the climate was more equable than at present and there is no evidence for ice-ages. The tropical and subtropical zones were wider than today and temperate conditions characterised the polar regions (Hallam, 1975). The land areas were mostly well vegetated, especially with gymnosperms but also with ferns, and rich floras are known from palaeolatitudes of 75°N and 63°S (Ager, 1975). Jurassic carbonates are rare in the northern North Sea as the northerly limit for carbonate deposition and coral reef growth was generally in England or France. The allochthonous coral blocks in the Kimmeridgian and Volgian near Helmsdale (section 2B) are the most northerly examples of reef building corals from the Jurassic of Europe (Arkell, 1933). In the late Jurassic the northern North Sea was between 30° and 40° north of the equator (Ager, 1975). The Jurassic seas reached their maximum extent during the late Oxfordian and the high sea-level stands continued through the Kimmeridgian before an eustatic drop in sea-level towards the end of the Jurassic (Hallam, 1975).

(i) Stratigraphy

In late Jurassic times some ammonite families were geographically restricted and this has led to confusion over stage boundaries and nomenclature, with different areas of north-west Europe having different stratigraphic schemes. The fauna which lived in the northern part of the Northern Hemisphere was significantly different from that of the rest of the world and Arkell (1956) termed the northern area the "Boreal Realm" and the southern area the "Tethyan Realm." The chronostratigraphy used in this thesis is Boreal as in late Jurassic times the northern North Sea was in the northern part of the Northern Hemisphere (between 30° and 40°N) (Ager, 1975). The scheme followed (Fig. 1.2) is based on Harland et al (1982, Chart 2.10) and Brown (1984, Table 6.1) and is the one used by most oil companies operating in the northern North Sea. It uses the Boreal "Volgian" as the uppermost Jurassic stage and "Ryazanian" as the basal Cretaceous stage and it places the base of the Kimmeridgian at the Pictonia baylei zone and the base of the Volgian at the Pectinatites elegans zone. The Callovian is included with the middle Jurassic. It is noteworthy that this stratigraphy differs from that of the London Geological Society (Cope et al, 1980).

The lithostratigraphy broadly follows that of Deegan and Skull (1977). However, as a large amount of data has been collected since 1977, a revision is now overdue and the lithostratigraphy is presently under review at the Hydrocarbons Unit of the B.G.S. in Edinburgh. Deviations from the Deegan and Skull nomenclature will be dealt with in the relevant sections. In the Deegan and Skull scheme the Upper Jurassic is represented by the Humber Group, the Kimmeridgian and Volgian belonging predominantly to the/

Fig. 1.2. Biostratigraphical nomenclature



Kimmeridge Clay Formation. The dark, laminated, organic rich shales of this formation range in age from late Oxfordian to Ryazanian.

(ii) Mass Movement Processes

Mass movements are the movements of sediment under the influence of gravity. A review of the literature shows that there is considerable confusion in the application of terms used to describe mass movement phenomena. In this thesis the terminology broadly follows that of Nardin et al (1979) and Lowe (1979, 1982) in which movements are initially defined by deducing the likely mechanical behaviour of the sediment during transportation (Fig. 1.3) from the textures of the resultant strata. This avoids some of the pitfalls incurred when defining sediment gravity flows by inferring sediment support mechanisms (Middleton and Hampton, 1973, 1976) eg. the lack of knowledge of sediment support mechanisms in present day sediment gravity flows, the probability of several support mechanisms acting on the same grains and the probability of different support mechanisms, in the same flow, acting on different size populations of grains. An extreme example of the confusion surrounding support mechanisms is in the use of grain-flow sensu Bagnold (1954). This mechanism has been proposed as a process which can transport and deposit massive thick bedded sands in a deep water environment, however, the theory of Bagnold (1954, 1955, 1956) shows that grain-flows can only flow on slopes of at least 18° and they should deposit thin inversely graded sandstones.

There are three major catagories of mass movement processes that can transport cobbles and boulders over intermediate or long distances (more than tens of metres); rockfalls, debris flows and turbidity currents (Fig. 1.3). Liquefied

Fig. 1.3. Terminology of mass transport processes

Mechanical Behaviour	Mass Transport Processes			Transport (Support) Mechanisms		Typical Sedimentary Structures and Textures
Elastic	Rock Fall			Free fall,rolling or sliding of individual blocks or clasts.		Disorganised gravels with very tightly packed framework supported clasts.
	Slide		Sheet Slide	Failure along discrete shear planes with little rotation.		Essentially undeformed beds adjacent to shear planes or faults.
			Rotational Slide	Failure along discrete shear planes accompanied by rotation		
Plastic Limit			Slump	Failure along many closely spaced shear planes.		Folded and contorted bedding.
Plastic (Bingham)	Sediment Gravity Flow	Debris Flow	Cohesive Debris Flow	Partial support from yield strength.	Yield strength principally from matrix cohesion.	Gravels with disorganised fabrics matrix supported clasts and muddy matrices. Largest clasts towards top.
			Friction Debris Flow		Yield strength principally from matrix friction.	Gravels with framework or matrix supported clasts and sandy matrices. Inversely graded bases and a-axes aligned parallel to flow.
Liquid Limit			Liquefied Flow	Partial support by upwards escaping pore fluid.		Dewatering structures,convolute bedding and homogenized sediment.
Fluid (Newtonian)		Fluidal Flow	Fluidized Flow	Full support by upwards escaping pore fluid.		
			Turbidity Current	Support by fluid turbulence.		Graded beds with possible Bouma series structures. Possible inverse grading at base.

and fluidized flows occur during the early and late stages of transportation and are unlikely to transport sediment for more than a few metres (Lowe, 1976). In the classification outlined in (Fig. 1.3) debris flows are defined as bodies of sediment that have plastic properties during transportation, ie. a yield stress and a constant viscosity (Lowe, 1979). They are subdivided into cohesive debris flows and friction debris flows. The term friction debris flow has been substituted for the term grain-flow in the Lowe (1979) classification as this term will lead to confusion with grain flows sensu Bagnold (1954) in which the grains are entirely supported by dispersive pressure. Johnson (1970) developed a rheological model for debris flow that had the form $y = mx + c$, where,

y = shear stress
m = viscosity
x = velocity gradient
c = yield strength,

The yield strength is composed of two major components; (i) cohesion and (ii) the internal normal stress times the angle of internal friction. In the classification of (Fig. 1.3) debris flows in which the yield strength is primarily due to cohesion are termed "cohesive debris flows" and those in which the yield strength is primarily due to friction are termed "friction debris flows."

In reality there is a continuum between rockfall, debris flow and turbidity flow and considerable overlap between the processes. Also, many mass movements that initiate as rockfalls will become debris flows and ultimately turbidity-currents.

Rockfalls will only transport clasts on slopes which are steeper than the angle of internal friction (angle of repose) of the sediment. In general they will, therefore, only transport boulders and gravel on steep slopes but may also transport sediment for relatively short distances across gentle slopes due to/

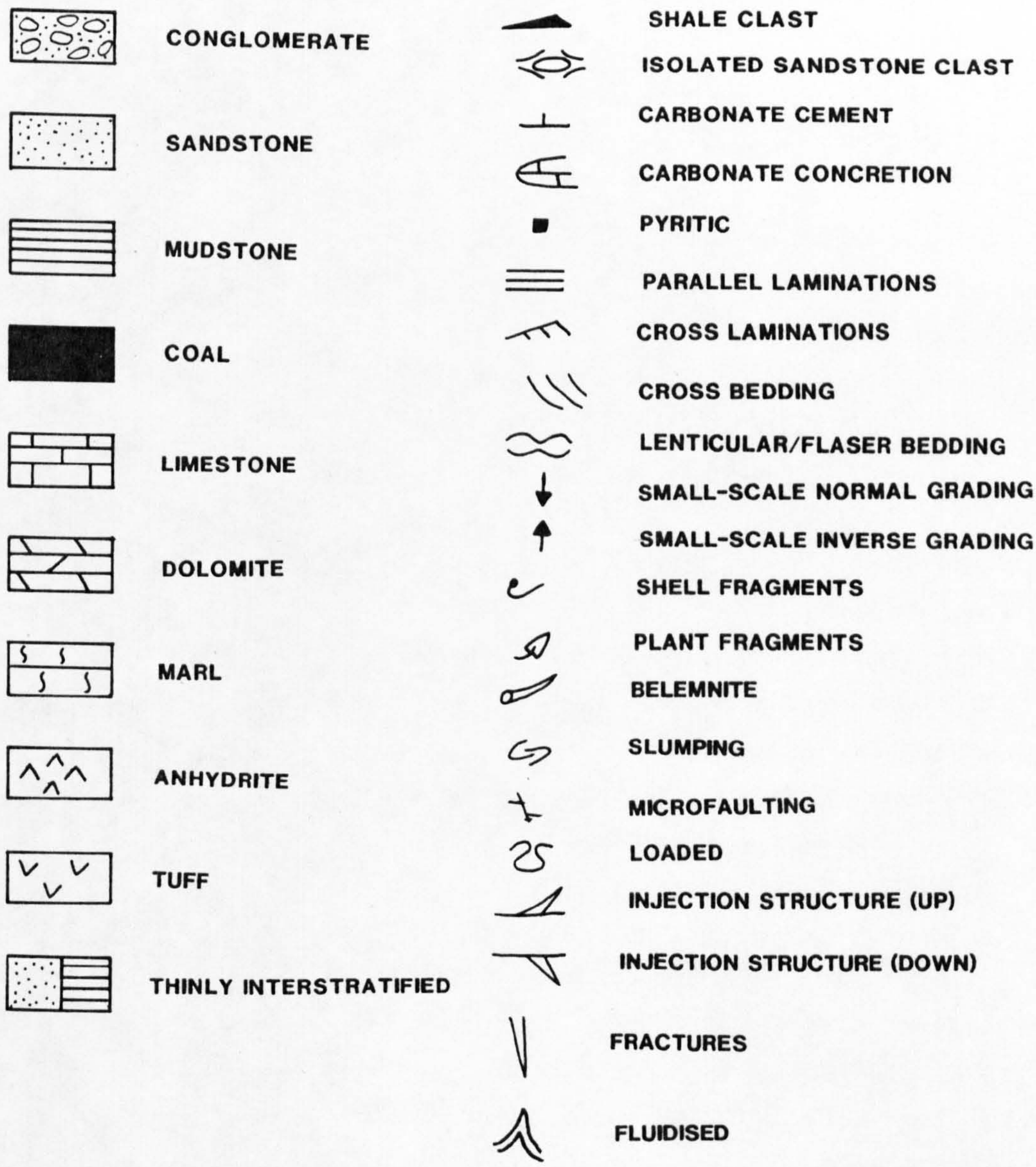
momentum. The clasts are primarily supported by collisions and shearing with other clasts. Debris flows have a finer grained matrix which is important in supporting the boulders and gravel during transportation because of various factors including matrix strength, excess pore pressures (Pierson, 1981) and buoyancy. In turbidity currents the clasts are primarily maintained by turbulent eddies in the flow. There is considerable overlap between debris flow and turbidity flow and the clasts in debris flows can be partially maintained by minor turbulence and the basal parts of turbidity currents, where the grain concentration and shear are highest, are often friction debris flows (Lowe, 1979).

Rockfall deposits can generally be differentiated from debris flow deposits by lack of matrix, very tight packing and chaotic clast fabrics. Debris flows generally have significant percentages of matrix and clasts that are matrix supported or framework supported in point contact. There is often organisation of clast fabrics eg. clast orientated subparallel to bedding, a-axes aligned parallel to flow, basal inversely graded layers and largest clasts concentrated towards bed tops (Fig. 1.3). Turbidites can generally be differentiated from debris flow deposits as turbidity currents tend to deposit graded beds. Both debris flows and turbidity currents can transport sediment over large distances on gentle slopes.

(iii) Sedimentary Structures and Textures

The grain-size terminology of the sedimentary rocks follows that of the Udden-Wentworth scale (Blatt, Middleton and Murray 1982, table 3-3). The key to the symbols used in the logs and diagrams, unless otherwise stated, are shown in (Fig. 1.4).

Fig.1.4 SYMBOLS KEY



1.D FACIES ANALYSIS.

As the environmental interpretations of this thesis are based on facies analyses (chapters 2 and 3), in this section I discuss certain aspects of such analyses. There is generally a loss of resolution and objectivity at each of the stages of a facies analysis. The following discussion is primarily concerned with minimizing the loss of objectivity at the stage of subdividing the sequence into facies. Other "philosophical" aspects of the facies analysis approach to environmental interpretation, such as the need for classification, are not discussed in this section and have not been studied in detail during work for this thesis.

Anderton (1985) reviews clastic facies models and facies. On page 40 he emphasises the importance of objectively subdividing a sequence into facies.

> "... with a given set of criteria every sedimentologist should produce the same classification for the same set of rocks. However, numerous sets of criteria may work equally well on the same rock sequence. A lot of facies schemes come to grief because of the use of inconsistent multiple criteria for distinguishing between facies."

An example of inconsistent multiple criteria is; if facies I is defined as "thin-bedded sandstones", facies II as "graded sandstones" and facies III as "cross-laminated sandstones". This classification will be satisfactory if all the graded sandstones in the study area are medium or thick-bedded and all the cross-laminated sandstones are non-graded etc. However, how does one objectively classify a 7cm thick graded sandstone with a cross-laminated top? The answer is that one cannot! Instead the classification scheme should use a single criterion or multiple criteria arranged in a workable hierarchy,ie, the facies are initially defined by grain-size and subsequently subdivided by bed-thickness, then by internal structures and so on. The first level in most hierarchies will be grain-size or lithology. The objective is to erect a set of definitions that will subdivide all the rock under study into a series of facies such that every rock unit can be classified and that no rock unit can be included in more than one facies. However, the use of inconsistent multiple criteria is presently commonplace and this introduces vast subjectivity into many analyses and subsequent environmental interpretations. In chapters 2 and 3 I have arranged the criteria for defining facies in a workable hierarchy in order to minimise the subjective element of the analyses at that stage.

Where classification schemes for subdividing rock sequences include ratios, eg. sandstone:shale or breccia:shale, a scale must be included in the definition. Also, where ratios are used, facies boundaries are often gradational and can be difficult to locate accurately. Where this problem occurs in this study (chapters 2 and 3) the boundary is generally placed at a prominent bedding plane, at a deformed horizon or arbitrarily placed between sequences.

Chapter 2

The Sedimentology and Structure of the Kimmeridgian and Volgian of East Sutherland

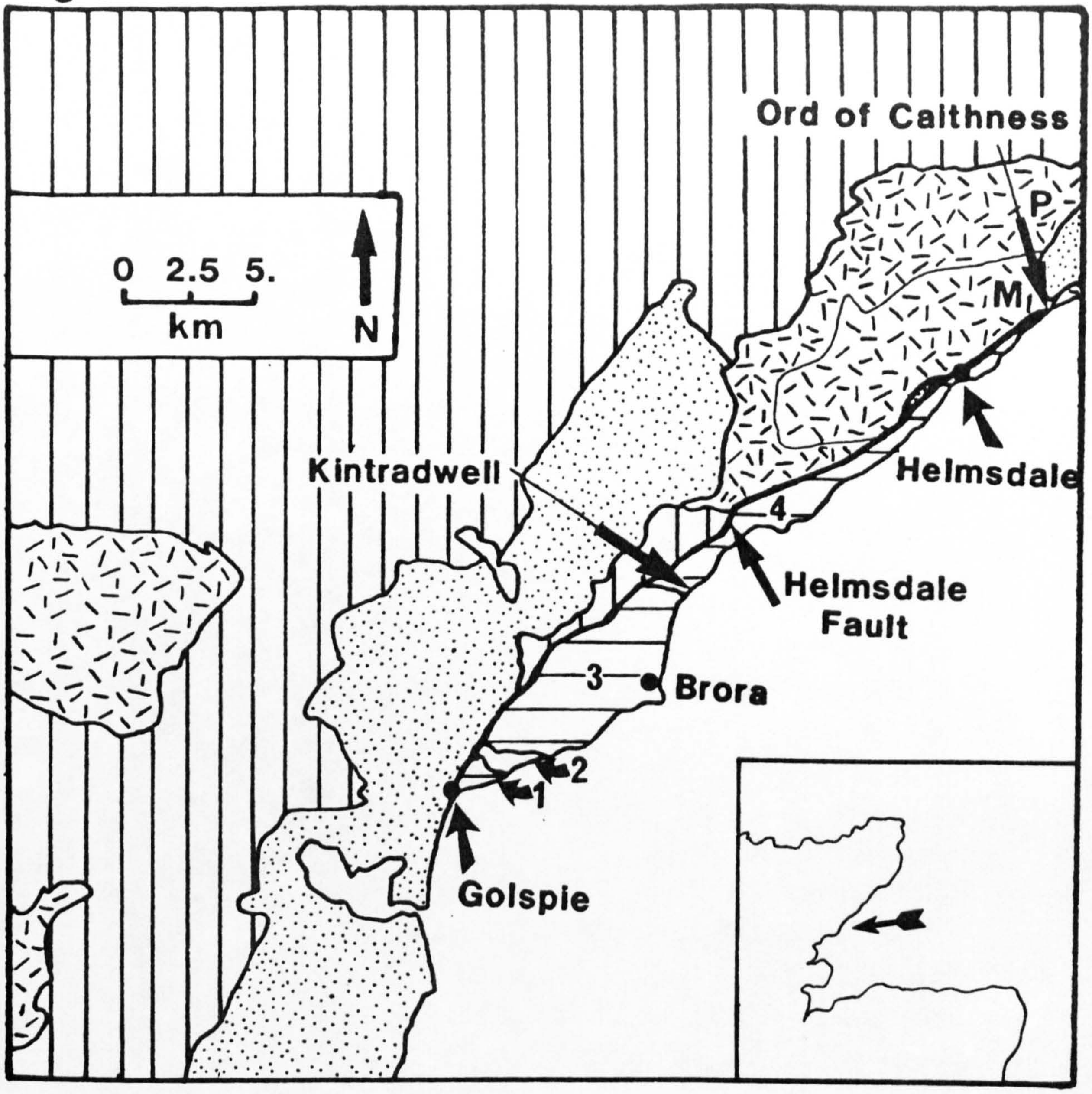
2.A INTRODUCTION

(i) The Mesozoic of East Sutherland

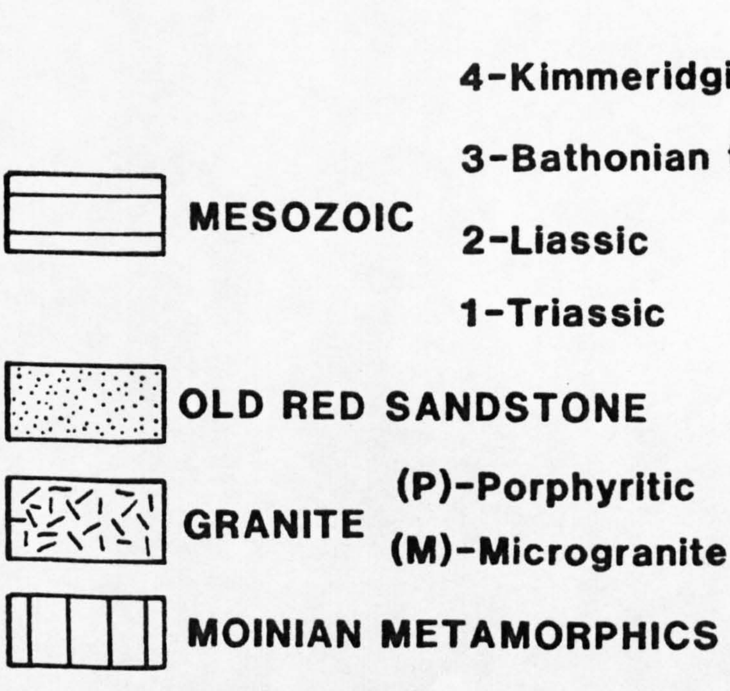
The Kimmeridgian and Volgian of the study area are exposed on the East coast of Sutherland between Kintradwell and the Ord of Caithness (Fig. 2.1). They form the upper part of a Mesozoic sequence which is bounded by the Moray Firth to the East and is downfaulted against the Old Red Sandstone, the Helmsdale Granite and the Moinian schists and granulites which lie to the west. The coastal strip, which generally youngs to the northeast, ranges in age from Triassic near Golspie to middle Volgian near the Ord of Caithness (Fig. 2.1) (Lam and Porter, 1977, Riley, 1980). It has been visited by geologists from most of the oil companies which are operating in the North Sea as it contains the best exposed and most complete Jurassic sequences on the East coast of Scotland adjacent to the North Sea. As the depositional trends of the East Sutherland sequences reflect those of the oil producing areas of the northern North Sea, a study of the Kimmeridgian and Volgian in this fault-bounded basin margin setting should provide a useful insight into similar possible oil producing sequences.

Sedimentological and stratigraphical reviews of the Mesozoic have been produced by Neves and Selley (1975) and Lam and Porter (1977). The Bathonian has been studied in detail by Hurst (1981), the Callovian and Oxfordian by Sykes (1975) and the Kimmeridgian and Volgian by Bailey and Weir (1932), Crowell (1961), Linsley (1972), Brookfield (1976), Riley (1980) and Pickering (1984). A stratigraphic column has been produced by integrating data from the above references with data from the present study and a lithostratigraphy has been erected for the Kimmeridgian and Volgian which complies with the stratigraphic hierarchy of the older parts of the sequence (Fig. 2.2) (section 2.A (iii)).

Fig.(2.1)



Ord of Caithness
0 2.5 5.
km
N
P
M
Kintradwell
Helmsdale
4
Helmsdale
Fault
3
Brora
2
1
Golspie



4-Kimmeridgian and Volgian
3-Bathonian to Oxfordian
MESOZOIC
2-Liassic
1-Triassic
OLD RED SANDSTONE
(P)-Porphyritic
GRANITE
(M)-Microgranite
MOINIAN METAMORPHICS

(ii) <u>The Inner Moray Firth Basin</u>

The Inner Moray Firth Basin is bounded by the Helmsdale Fault to the northwest, the Wick Fault to the north, the Banff Fault to the south and the Outer Moray Firth Basin to the east (Fig. 1.1). Gravity modelling suggests that, in contrast to the other northern North Sea basins, there is little thinning of the crust under the Inner Moray Firth Basin (Donato and Tully, 1981). The boundary between the Inner and Outer Moray Firth Basins is taken by McQuillen et al (1982) as the 0 mGal Bouger anomaly gravity contour of Donato and Tully (1981). The Buchan and Witchground Grabens of the Outer Moray Firth (Fig. 1.1) are underlain by thinned continental crust (Donato and Tully, 1981),and Christie and Sclater (1980) proposed an extensional origin, using the McKenzie (1978) model, for those grabens. They proposed a stretching factor (β) of approximately 2 during the late Jurassic and early Cretaceous which implies stretching of 60 Km in a north - south direction. However, one would expect the Inner Moray Firth to be stretched by approximately the same order as the two basins are adjacent (Fig. 1.1) and the stretching was presumably related to a regional tensional regime. The variable thickness of the Palaeozoic layer in the Christie and Sclater refraction profile implies that the crust was heterogeneous before the late Jurassic stretching event and a Palaeozoic basin probably existed in the Outer Moray Firth area (Smyth, Skuce and Donato, 1980). Although the McKenzie (1978) crustal attenuation model may explain some of the thinning of the crust under the North Sea basins, the different crustal thicknesses are better explained by inheritance from Palaeozoic deformation episodes.

The main control on Mesozoic sedimentation in the Inner Moray Firth Basin was large-scale normal faulting and during the Jurassic the basin was composed of a series/

of intrabasinal grabens and horsts (Fig. 1.1) (Chesher and Lawson, 1983). During the late Jurassic the two major intrabasinal grabens were tilted northwestwards; one towards the Great Glen Fault and the other towards the Helmsdale Fault. To the southeast of the Great Glen Fault was a horst structure (Fig. 1.1) (Chesher and Bacon, 1975). This basement high was probably controlled by the relative bouyancy of an underlying granite (Dinitropoulos and Donato, 1981). Minor Mesozoic strike-slip movements partially controlled the geometry and subsidence history of some basins (McQuillin et al, 1982).

The Mesozoic basin was broadly coincident with the Orcadian Basin that existed during Old Red Sandstone times. Although Carboniferous rocks are not encountered in the Inner Moray Firth, the presence of Carboniferous spores in the Kimmeridgian of Sutherland (Lam and Porter, 1977) and Lower Carboniferous sequences in the Claymore and Piper Oilfields of the Outer Moray Firth (Deegan and Skull, 1977, Maher, 1981) suggests that Lower Carboniferous may have been deposited in the basin but has subsequently been eroded.

Mesozoic marine deposition began towards the base of the Jurassic after continental deposition during the Permian and Triassic (Linsley et al, 1980, Chesher and Lawson, 1983). The late Lias is a regressive phase which led to the deposition of fluvio-deltaic sediments during the Bajocian and Bathonian. The shallow water sand-bar reservoirs of the Beatrice Oilfield were deposited during the Callovian after the return to marine conditions at the end of the Bathonian (Linsley et al, 1980). During the early and middle Jurassic many small-scale faults controlled deposition but during the Oxfordian and Kimmeridgian subsidence rates were dramatically increased and the faulting became concentrated along a few large-scale faults (Chesher and Lawson, 1983). This resulted in the deposition of very thick Oxfordian to Volgian sequences.

Thickness variations suggest that subsidence rates increased from the Oxfordian to the early Kimmeridgian. In the 11/30-1 well of the Beatrice Oilfield the Kimmeridgian and Volgian is more than 700 m thick (Fig. 5.2) and the Kimmeridgian to middle Volgian of East Sutherland is approximately 630 m thick (Fig. 2.2)*. There was a minor period of uplift at the end of the Jurassic and Lower Cretaceous marine sands and shales disconformably overlie the Upper Jurassic in the Beatrice Oilfield (Linsley et al, 1980). Upper Cretaceous and Tertiary sediments are thin or absent over most of the Inner Moray Firth due to uplift of the area at the end of the Cretaceous (Chesher and Lawson, 1983).

(iii) Stratigraphy

A stratigraphy for the Kimmeridgian and Volgian has been erected using both ammonites (Bailey and Weir, 1932, Linsley, 1972, Brookfield, 1976) and palynomorphs (Lam and Porter, 1977, Riley, 1980). Nigel Hooker at Britoil has carried out palynological analyses on selected samples, the data from which agrees with the stratigraphy of the earlier workers. The sequence is folded and deformed and the palaeontology agrees with younging directions taken from structural data (Fig. 2.3)*. The ammonite zone boundaries (Fig. 2.3)*, which were drawn using both palaeontological and strucural data, are accurate in shore sections but interpretitive in inland areas as few stream section samples have been used for dating purposes.

The oldest dated sequences are a sandstone rich sequence, which is best exposed near Loth, and a shale rich sequence which is exposed on the foreshore at Kintradwell (Fig. 2.3). Bailey and Weir (1932), Linsley (1972) and Lam and Porter (1977) have assigned a <u>cymodoce</u> zone (Fig. 1.2) to the shales at Kintradwell. Brookfield (1976)/

* In Pocket at Back

and Linsley (1972) identified an ammonite assemblage in sandstones from the Allt-na-Cuile as cymodoce zone. The relationship between the Loth sandstones and the shale rich sequence exposed at Kintradwell is not exposed and Neves and Selley (1975) have the sandstones underlying the shales whereas Lam and Porter (1977) and Pickering (1984) have the Kintradwell shales underlying the Loth sandstones. Although there is a gap in exposure of about 1 km between the two sequences, both palaeontological and structural evidence suggests that they are approximate lateral equivalents with a syncline between them (Fig. 2.3). Sandstones, similar to those exposed near Loth, are exposed on the foreshore to the northwest of the Midgarty Burn (Fig. 2.3). They are dated as cymodoce or mutabilis zone by Bailey and Weir (1932) and as older than eudoxus zone by Lam and Porter (1977) and are probable lateral equivalents to the sandstones exposed at Loth.

The Loth sandstone rich unit and the Kintradwell shale rich unit are formally grouped together as a new formation termed "the Loth Formation" which is cymodoce and probably partially mutabilis zone in age (Fig. 2.2) and the Loth and Kintradwell units aquire member status. The Loth Sandstone Member, as measured at Lothbeg Point, is 120 m thick and includes the Allt-na-Cuile sandstones of Neves and Selley (1975) and Pickering (1984) and the cymodoce and mutabilis zone breccias and boulder beds exposed adjacent to the Helmsdale Fault (Fig. 2.3).

The oldest beds in the study area, which are exposed on the foreshore between the Loth River and the Allt-na-Cuile (Fig. 2.3), are not dated, but as they underlie the Loth sandstones they must be cymodoce zone or older (Fig. 2.2). They comprise a sequence of bioturbated mudstones and sandstones (Fig. 2.6) which were probably deposited in a relatively stable, well oxygenated shelf environment similar to that of the Callovian and Oxfordian strata/

exposed to the southwest near Brora (Fig. 2.2)* (Sykes, 1975). These bioturbated mudstones contrast with the finely laminated mudstones exposed at Kintradwell and at younger horizons, and probably represent the last of the Jurassic shallow or marginal marine deposits which persisted from the Lias through to the Kimmeridgian (Fig. 2.2)*.

The Loth Formation is overlain by variable sequences of boulder beds, breccias, sandstones and laminated mudstones which are assigned formation status as "The Helmsdale Boulder Bed Formation." On the foreshore to the northwest of Midgarty Burn (Fig. 2.3)* the upwards transition from the Loth Sandstone Member to the Helmsdale Boulder Bed Formation is relatively sharp and is marked by the incoming of several breccias and boulder beds (Fig. 2.34). The upwards transition from the Kintradwell Shale Member to the Helmsdale Boulder Bed Formation is not exposed but is likely to be gradational as both sequences contain similar facies (section 2.B).

The Helmsdale Boulder Bed Formation ranges from the mutabilis zone of the Kimmeridgian to the middle Volgian and encompasses two members which are lateral equivalents; the Dun Glas Member and the Portgower Member (Fig. 2.2)*. The Dun Glas Member comprises a sequence of compound breccias and boulder beds and occurs adjacent to the Helmsdale Fault. The Portgower Member comprises variable sequences of boulder beds, sandstones and shales which generally occur to the southeast of the Dun Glas Member boulder beds and were deposited relatively distal to the Helmsdale Fault.

The Helmsdale Boulder Beds Formation is approximately 500 m thick. An almost continuous section from Midgarty, where the Helmsdale Boulder Beds overlie the Loth Formation, to the southwest of Helmsdale harbour (Fig. 2.3)* is approximately 340 m thick and ranges from the Kimmeridgian mutabilis zone to the Volgian wheatlyensis zone. A section/

* In Pocket at Back

from the northeast of Helmsdale harbour to Sron a Chrochair (Fig. 2.3) ranges from the wheatlyensis to the pectinatus zone and is approximately 110 m thick. The middle Volgian strata that occur to the northeast of Sron a Chrochair are complexly folded and the strike of the beds mostly follows the shoreline. However, approximately 50 m of strata are exposed between the South Allt Briste and the Ord of Caithness (Fig. 2.3). The youngest strata in the study area, which are exposed on the foreshore near the North Allt Briste, have been dated as middle Volgian albani zone (Fig. 1.2) by Riley (1980).

(iv) Past Work

Since the excellent work of Bailey and Weir (1932) the environment of deposition of the Helmsdale Boulder Bed Formation and the Kintradwell Shale Member of the Loth Formation (Fig. 2.2) has been interpreted as a fault controlled submarine slope (Crowell, 1961, Linsley, 1972, Neves and Selley, 1975, Pickering, 1984). Interpretation of sedimentary structures implied that sand and gravel were transported onto the slope from the northwest to the southeast and analysis of syn-sedimentary folds and faults by Crowell (1961) and Pickering (1983, 1984) showed that the slope dipped towards the southeast. The Helmsdale Fault is thought to have separated the slope from a shallow water shelf area to the northwest. Shell debris and sand were washed from the shelf area onto the slope where it mixed with boulders and cobbles shed from the fault scarp.

These interpretations are corroborated by this study which was carried out in an attempt to establish the time and spatial variations of facies on the fault controlled submarine slope. The previous studies assume that the various facies were developed penecontemporaneously and at a set distance from the Helmsdale Fault, whereas this/

analysis demonstrates that the facies vary through time and with increasing distance from the fault. The Loth Sandstone Member of the Loth Formation was interpreted as a submarine slope grain-flow deposit by Neves and Selley (1975) and as a submarine channel deposit by Pickering (1984). This study broadly corroborates the later interpretation.

(v) The "Loth-Helmsdale Strip" of Old Red Sandstone

Judd (1873) and Bailey and Weir (1932) described a strip of Middle Old Red Sandstone sediments which are exposed on the upthrown side of the Helmsdale Fault between Loth and Helmsdale (Fig. 2.3). Subsequent authors have accepted this interpretation. In this study the only mappable unit of Old Red Sandstone is exposed in the Allt-Garbh and streams to the northeast (Fig. 2.3, 2.32). This unit is mainly composed of typical Caithness Flagstone lithologies (Fig. 2.39a) (Mykura 1983) and fish fragments have been collected from the Allt-Garbh sequences (Judd, 1873). Other thin slices of probable Old Red Sandstone are exposed in, or close to the Helmsdale Fault Zone (Fig. 2.3) and are mostly vertically bedded. These sequences do not constitute a mappable unit. Much of the "Loth-Helmsdale Strip" is composed of a compound sequence of Jurassic breccias, eg. in the Loth Burn (Fig. 2.3) most of what has been mapped as Old Red Sandstone by Judd is composed of a chaotic mass of sandstone boulders in a muddy sandstone matrix that is almost certainly Jurassic in age (section 2.B (i)). However, a thin unit of purple and grey sandstones is exposed under the old road bridge adjacent to the fault. For further descriptions of probable Old Red Sandstone sediments in the Helmsdale Fault Zone see section 2.C (iv) .

2.B FACIES ANALYSIS

(i) Methodology

This analysis places emphasis on integrating sedimentological and structural data with the published biostratigraphical information in an attempt to establish the probable 3-dimensional distribution of rock types. Exposures were studied in shoreline areas, stream gullies, railway cuttings, raised beach cliffs and road cuttings. The inland exposures can only be visited in the spring as by the end of June the undergrowth is too dense to allow detailed examination of outcrops. At each outcrop lithologies and sedimentary textures were studied and the dips and strikes of beds were measured to allow the integration of younging directions with the known biostratigraphy. At many outcrops vertical logs were measured at various scales and 2 or 3 dimensional sketches were drawn. Aerial photographs were useful for mapping the Helmsdale Fault Zone in the northeast of the study area and shear structures in the Helmsdale Granite (Fig. 2.3). They were not useful for mapping the distribution of facies associations.

(ii) Facies

The facies classification and the typical features of the individual subfacies are shown in figure (2.4).

a)/

Fig. 2.4. Table of facies characteristics

			Grain-Size	Bed Thick-ness	Sedimentary Structures and Textures	Bed Boundaries	Fossils	Interpreted Depositional Processes
Shales	Laminated Mudstone	1A	Silt	2-5 mm	Parallel laminations	Gradational or sharp	ammonites, belemnites, bivalves, brachs plant fragments	Settling from suspension
	Bioturbated Mudstone	1B	Silt	2 mm to 5 cm	Parallel laminations, single vertical and horizontal burrows, ? ophiomorpha-type burrows	Gradational or sharp	Same as 1 A	Settling from suspension and infaunal churning
Single Sandstones	Thin Bedded	2A	Fine sand	5 mm to 10 cm	Grading, non grading, flute and groove marks, parallel and cross-laminations, minor wavy laminations and bioturbation	Bases: sharp Tops: sharp or graditional	Broken bivalves ammonites etc plant fragments	Mainly deposition from turbidity - currents, also some later tractional reworking plus minor wave reworking
	Medium to Thick Bedded	2B	Fine to medium sand	10-8 cm	Grading, flute and groove marks, parallel and cross-laminations, minor wavy bedding	Sharp Bases and Tops	Same as 2 A	Deposition from turbidity-currents plus minor wave reworking
Compound Sandstones	Thin Bedded	3A	Fine sand	1-10 cm	Non-graded parallel laminated sandstone with minor cross-laminations and abundant bioturbation	Graditional or sharp	Ammonites, bivalves etc (often decalcified) plant fragments	Relatively low energy traction currents and infaunal churning
	Medium to Thick Bedded	3B	Medium to coarse sand	10-200 cm	Graded beds with erosional bases and rare parallel and subparallel lamination	Sharp	Plant fragments plus rare ammonites, bivalves etc	Turbidity - currents
X-Bedded Sandstones	Trough Cross-Bedded	4A	Fine sand	10-80 cm	High and low-angle trough cross-bed, abundant bioturbation	Sharp or graditional	Plant fragments plus rare decalcified ammonites, bivalves etc	Traction currents and infaunal churning
	Bar-Form	4B	Fine sand	10 cm to 3 m +	Low angle inclined bar-form surfaces	Sharp or graditional	Plant fragments	Channelised traction - currents
Breccias Jurassic Clasts	Sandstone Matrix	5A	Pebble to boulder clasts	10 cm to 7 m	Framework and matrix supported clasts, e-axis perpendicular to bedding, rare grading plus largest clasts towards tops of beds.	Sharp	Abundant shell and plant fragments	Rockfall, debris flow, turbidity, current
Breccias Jurassic Clasts	Mudstone Matrix	5B	Pebble to boulder clasts	10 cm to 2,5 m	Mainly framework supported, randomly oriented and distributed clasts	Sharp	Plant fragments	Rockfall and debris flow
Breccias Devonian Clasts	Sandstone Matrix	5C	Pebble to boulder clasts	15 cm to 4 m	Framework and matrix supported clasts, e- axis perpendicular to bedding, a-axis alignment, rare grading plus largest clasts towards tops of beds	Sharp	Abundant shell and plant fragments	Rockfall, debris flow, turbidity - current
Breccias Devonian Clasts	Mudstone Matrix	5D	Pebble to boulder clasts	5 cm to 10 m	Mainly framework supported, randomly oriented and distributed clasts	Sharp	Plant fragments	Rockfall and debris flow

a) Facies 1 Shales

This facies comprises any mudstone bed or laminae plus bioturbated mudstone and sandstone units that are more than 50% mudstone. Ammonites, belemnites, bivalves, brachiopods and fossil plant fragments are common and microfossils include abundant spores, pollen and microplankton (Lam and Porter, 1977). The facies encompasses two subfacies.

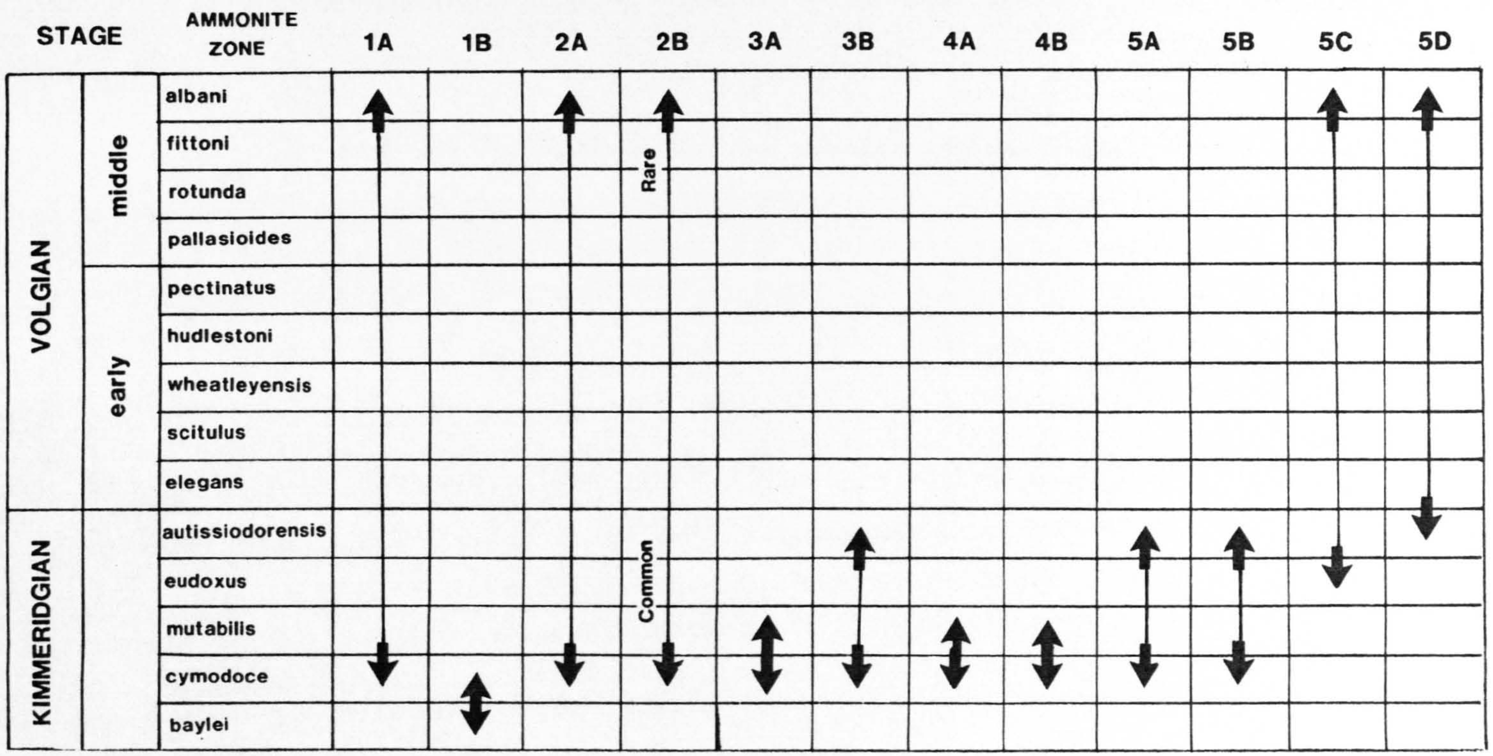
Subfacies 1A - Laminated Mudstone

This subfacies occurs in most sequences and ranges in age from the cymodoce zone near the base of the Kimmeridgian to the middle Volgian (Fig. 2.5) and comprises a black to dark grey, laminated, organic mudstone (Fig. 2.6a). The laminations, which are mostly 2-5 mm thick, are caused by subtle grain-size differences. Thin sections show that the facies commonly contains 10-20% organic material which is composed of fossil plant fragments, fusain, red organic material and amorphous black organic matter. The kerogen residues contain both humic and sapropelic components in varying proportions (Nigel Hooker pers. comm., Tyson, 1984). At some localities, eg. Crakaig Links and Sron Rhuba na Gaothe (Fig. 2.3) a calcite cemented variety of this subfacies weathers proud from the non-calcite cemented shales. This cement is probably concretionary as it occurs as lensoid units which form mounds 1-2 m high and 10-20 m wide on the foreshore (Fig. 2.6b). Incipient cone-in-cone structures are also present in some of these units.

This subfacies is very similar to the Kimmeridge Clay Formation (Deegan and Skull, 1977) shales which are typical of the Kimmeridgian and Volgian of northwest Europe. The shales accumulated in a low energy marine environment where suspension settling of mud was the ambient sedimentation. The abundance of fossil plant/

Fig.(2.5)

The Approximate Stratigraphic Distribution of Subfacies



fragments, spores and pollen testifies to significant terrestrial input and a nearby land area. The lack of bioturbation and the preservation of sapropelic kerogen suggests poorly oxygenated conditions at the sediment-water interface and the mixed humic/sapropelic residues are typical of basin margin Upper Jurassic shales (Barnard and Cooper, 1981). The filter feeding epifauna of bivalves and brachiopods shows that the water column just above the sediment-water interface was, at least sometimes, oxygenated.

Subfacies 1B - Bioturbated Mudstone

This subfacies includes any mudstone, or mudstone and sandstone unit which is more than 50% mudstone, which shows evidence of bioturbation. It is restricted to the oldest parts of the sequence in the Kimmeridgian cymodoce and baylei zones (Fig. 2.5) and is best exposed on the foreshore between the Allt-na-Cuile and the Loth River (Fig. 2.3) where the sediments are extensively burrowed. The bioturbation mostly comprises isolated vertical or sub-vertical sandstone pillars up to 5 cm in diameter enclosed in mudstone which is rich in fossil plant fragments (Fig. 2.6c). There are also some subhorizontal burrows and the kerogen residues are predominantly humic (Nigel Hooker pers. comm.).

The bioturbation contrasts with the well preserved fine laminations of the subfacies 1A mudstones and implies different environmental conditions during the deposition of subfacies 1B. The bioturbation suggests that deposition was in a relatively well oxygenated environment and that the sediment supported an active infauna. The general lack of sapropelic kerogen residues is also consistent with deposition in a well oxygenated environment.

Fig. (2.6) <u>Facies 1</u>

a) View of subfacies 1A, black laminated mudstone. Note pinch and swell of subfacies 2A sandstone beside hammer head (Hammer 40 cm long). Lothbeg Point. NC. 961 096.

b) Light coloured calcite cemented subfacies 1A mudstone weathering proud from the non calcite cemented mudstones. Meter stick for scale. Foreshore at Crakaig Links. NC. 964100.

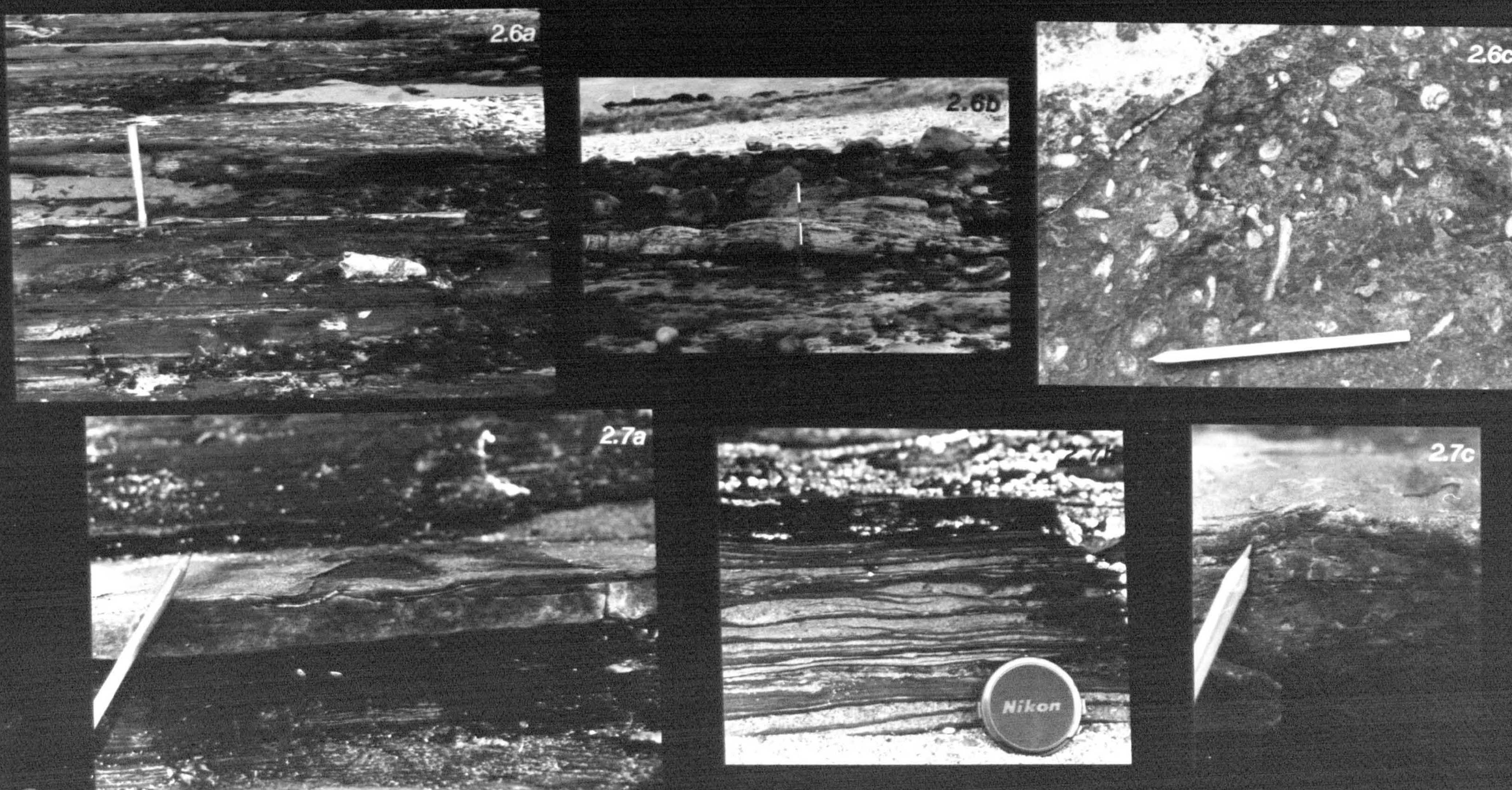
c) Bedding plane view of subfacies 1B, bioturbated mudstone. Foreshore between the Allt-na-Cuile and the Loth River. Pencil for scale. NC. 946095.

Fig. (2.7) <u>Subfacies 2A</u>

a) 4 cm thick T_{bc} Turbidite. Pencil for scale. Lothbeg Point. NC. 961096.

b) Isolated sand lenses. Some cross-lamination, erosional bases and graded beds. Foreshore at Kintradwell. NC. 921072.

c) ? Wave ripple. Pencil for scale. NC. 926074.


2.6a
2.6b
2.6c
2.7a
2.7b
2.7c
Nikon

b) Facies 2 Single Sandstones

This facies encompasses a wide array of sandstones. It comprises single beds that are usually interbedded with shales and includes amalgamated sandstones of up to three beds. The sedimentary features of the component sandstones which form the amalgamated units are the same as those of the single beds. Single cross-bedded sandstones are included in this subfacies but any amalgamated units of cross-bedded sandstones are included in facies 4. The grain-size is most commonly fine sand but can vary from very fine to pebbly sand. Disarticulated and broken fossil shell fragments including bivalves, brachiopods, echinoids, ammonites and belemnites are common in some beds but absent in others. Fossil plant fragments are present in most beds. Some sandstones have been cemented by quartz overgrowths and others by poikilitic calcite. The facies is composed of two subfacies.

Subfacies 2A - Thin-bedded single sandstones

This subfacies comprises sandstones in which the maximum thickness of the bed is less than 10 cm, and is composed of a wide array of sandstone types that can be graded or non-graded. Many of the graded sandstones have erosional bases and some beds have flute marks and shale "rip-up" clasts. The tops of most beds are sharp. Fossil shell fragments are concentrated towards the bases of some beds, whereas fossil plant fragments tend to be preferentially concentrated towards the tops of beds. Some of the graded beds are structureless throughout and others are cross-laminated or parallel laminated. In many beds there is a preferential vertical sequence of structures consisting of a structureless unit at the base overlain by a parallel laminated and then a cross laminated unit (Fig. 2.7a), which indicates deposition from a decelerating current. Although most of the graded/

sandstones are laterally continuous and sheetlike, some pinch and swell across the outcrop (Fig. 2.6a).

The non-graded sandstones can also be structureless, parallel-laminated, or cross-laminated but preferential sequences of structures are not developed. Most of the bed bases and tops are sharp and some bases are erosional. Trough cross laminations are particularly common in the non-graded sandstones and some possible wave ripple forms are developed in some cymodoce zone sandstones (Fig. 2.7c and Fig. 3 of Pickering, 1984). In general, the non-graded sandstones are less shelly than the graded ones.

Subfacies 2B - Medium and thick bedded single sandstones

This subfacies comprises sandstones in which the maximum bed thickness is greater than 10 cm. Some of the beds are non-graded but most are normally graded (Fig. 2.8a). The bases are often erosional and fluted (Fig. 2.8b), the tops are often sharp and rippled (Fig. 2.8c) and the tops of some beds are convoluted. Waning-flow sequences of structures are well developed (Fig. 2.8d) and an upwards increase in the percentage of mudstone laminae is common. Some cymodoce zone beds show probable wave-formed or hummocky cross-bedding (Fig. 2.8e) and one bed exposed near Kintradwell Point showed unusual climbing dune-like structures near its base. Bioturbation was also present in a few cymodoce zone sandstones on the foreshore at Kintradwell (Fig. 2.8f).

Both subfacies represent relatively high energy depositional events in a low energy environment. The disarticulated and broken nature of the shell fragments within essentially siliciclastic rocks and the relative scarcity of similar fauna in the interbedded shales implies that both the shells and the sands were transported to the site of deposition from a shelf with a rich marine fauna (Bailey and Weir, 1932, Pickering, 1984). The common grading, waning-flow structures and erosional,/

Fig. (2.8) <u>Subfacies 2B</u>

a) 30 cm thick graded sandstone. The Gartymore Burn. ND. 013138.

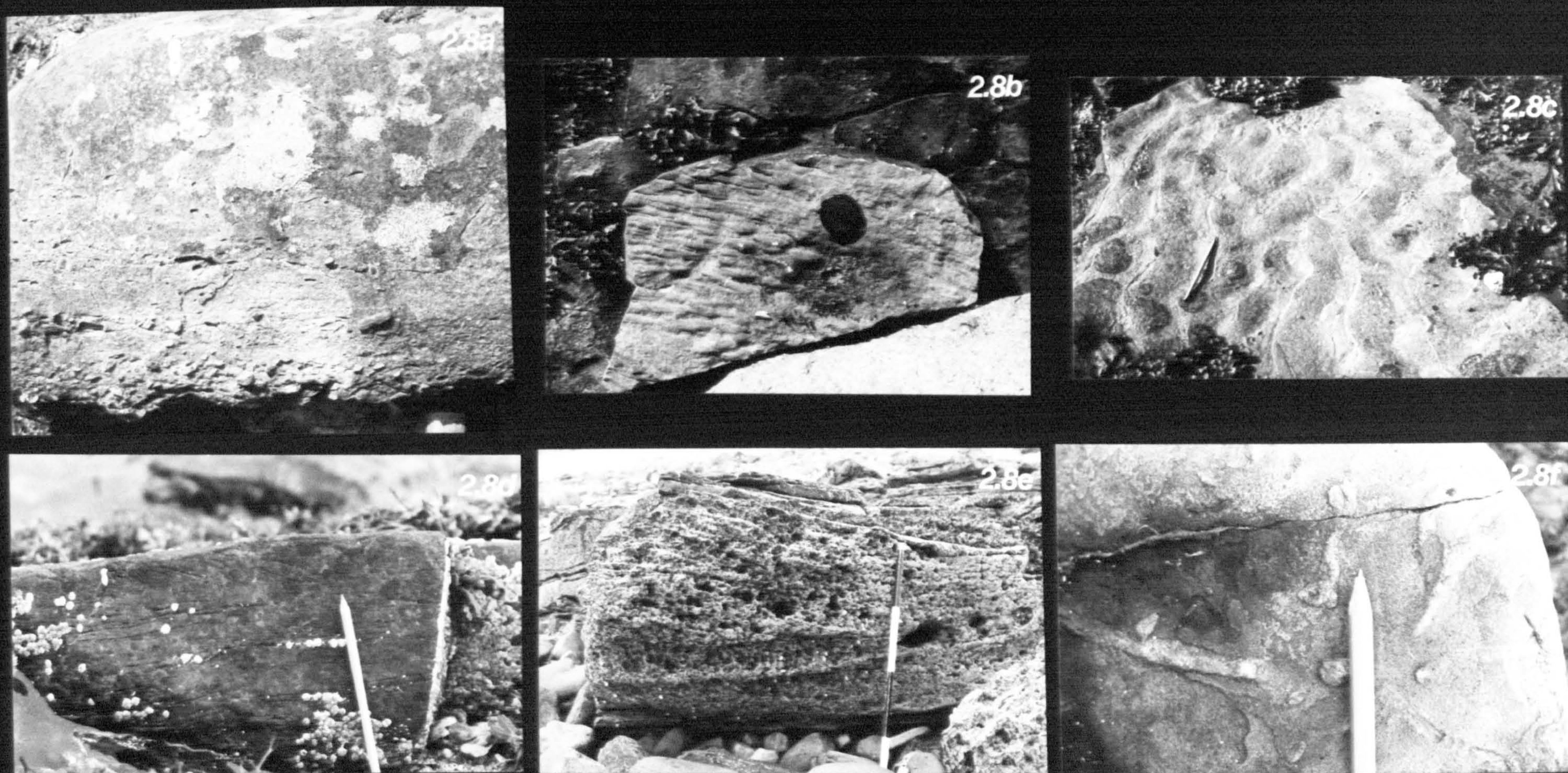
b) Flute structures on base of sandstone. Lens cap for scale. Foreshore at Crakaig Links. NC. 965100.

c) Asymmetrical ripples on the top of a sandstone. Flow from bottom right to top left. Pencil for scale. Foreshore at Crakaig Links. NC. 965100.

d) Parallel laminated unit overlain by cross laminated unit. T_{bc} Turbidite. Pencil for scale. Foreshore at Kintradwell. NC. 926074.

e) Irregular? wave-formed bedding. Meter stick for scale. Foreshore at Kintradwell. NC. 928076.

f) Horizontal burrows on the top of a sandstone. Pencil for scale. Foreshore at Kintradwell. NC. 926074.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2.8d
2.8e
2.8f

fluted bases suggests that most of the sands were transported by turbidity-currents. The abundance of trough-cross laminations and the lack of shell fragments suggests that the non-graded sands were reworked after deposition. Probable wave formed structures are rare and are only present in some cymodoce zone sandstones on the foreshore at Kintradwell. This indicates that in cymodoce zone times the basin was within the storm wave-base whereas after the cymodoce zone it was below the storm wave-base. The bioturbation also suggests that in cymodoce zone times the bottom conditions were more oxic.

c) Facies 3 Compound Sandstones

This facies comprises units consisting of four or more compound or amalgamated sandstone beds which contain less than 10% interstratified mudstone, but does not include cross-bedded or bar-form compound sandstones which are included in facies 4. The grain-size varies from very fine to pebbly sand but is most commonly medium or fine sand. Fossil plant fragments are common, as are decalcified bivalve and ammonite shell casts and fossil bivalves and brachiopods. The facies is composed of two subfacies.

Subfacies 3A - Thin-bedded compound sandstones

This subfacies comprises compound sandstones in which the average thickness of the constituent sandstones, when measured at the thickest point of the individual sandstones, is less than 10 cm. The sandstones units can be up to 4 m thick and are best exposed in the proximity of the Allt-na-Cuile where they are associated with subfacies 3B and facies 4 and 5. The subfacies is most commonly developed in cymodoce and eudoxus zone sequences (Fig. 2.5). Bioturbation is common and mostly takes the form of single vertical burrows(Fig.2.9a) although some "Y" shaped burrows (Fig. 2.9b) may be ophiomorpha-type trace fossils. In some sequences the constituent sandstones are graded but in most sequences they are non-graded. These sandstones are mostly parallel laminated or structureless (Fig. 2.9c) and some beds are cross laminated. Both the bases and tops of beds can be sharp or diffuse and the parallel laminations are the result of concentrations of fossil plant material or grain-size variences. The sandstones are mostly well sorted, friable and poorly cemented by quartz overgrowths. The quartz cement is often variable and almost nodular and as a consequence it is difficult to study the sedimentary structures and textures.

Fig. (2.9) <u>Subfacies 3A</u>

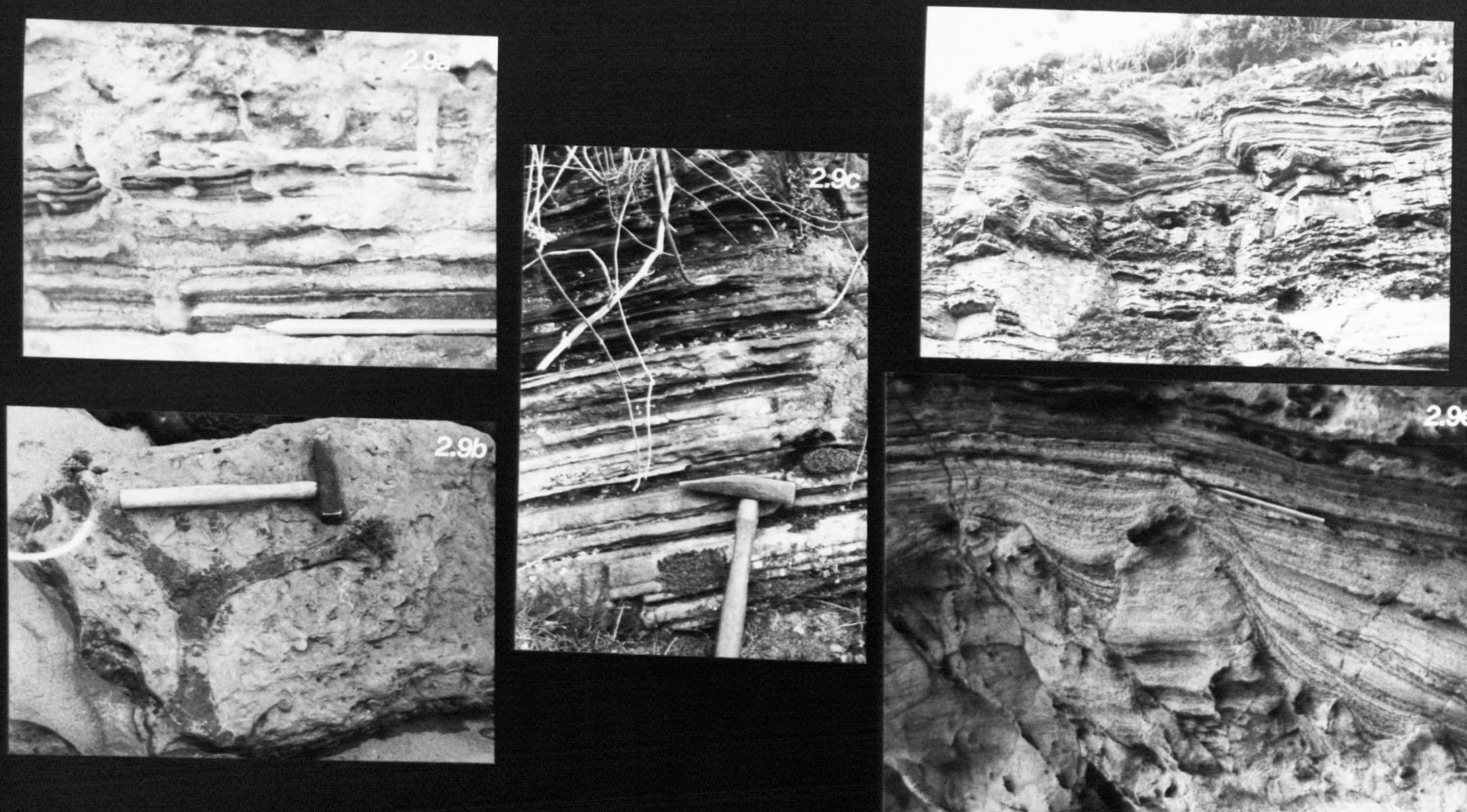
a) Vertical burrows. Pencil for scale. Railway cutting between the Allt-Choll and the Allt-na-Cuile. NC. 939092.

b) Bedding plane view of large ? ophiomorpha-type burrow. Hammer 40 cm. Foreshore to the east of the Allt-na-Cuile. NC. 942092.

c) Typical view of subfacies 3A. Hammer 40 cm. Stream to the east of Allt-Choll. NC. 938092.

d) Top part of the photograph shows thin-bedded sandstones filling a channel. Exposure height 5 m. Railway cutting to the east of the Allt-na-Cuile. NC. 941093. See also Fig. (2.26a).

e) Subfacies 3A overlying subfacies 5A. Note the thickening of sandstones into the depressions between clasts and the lack of scour. Pencil for scale. Small stream to the north-east of the Allt-Choll. NC. 938092.


2.9a
2.9c
2.9b
2.9e

Some of the subfacies 3A sequences were deposited in channels (Fig. 2.9d) and other sequences have sharp or diffuse flat lying bases. Where it overlies facies 5 breccias, subfacies 3A is often ponded into depressions between clasts with no evidence of scour around the clasts (Fig. 2.9e).

The friable nature and the variable cementation of this subfacies plus the lack of well preserved sedimentary structures makes the interpretation of the processes of deposition difficult. However, the lack of grading, the diffuse bedding, the abundant parallel laminations and the lack of scouring between breccia clasts in suggestive of deposition from relatively low energy flows. The abundant bioturbation is consistent with relatively slow deposition rates. Much of this subfacies may have been deposited from relatively weak traction currents.

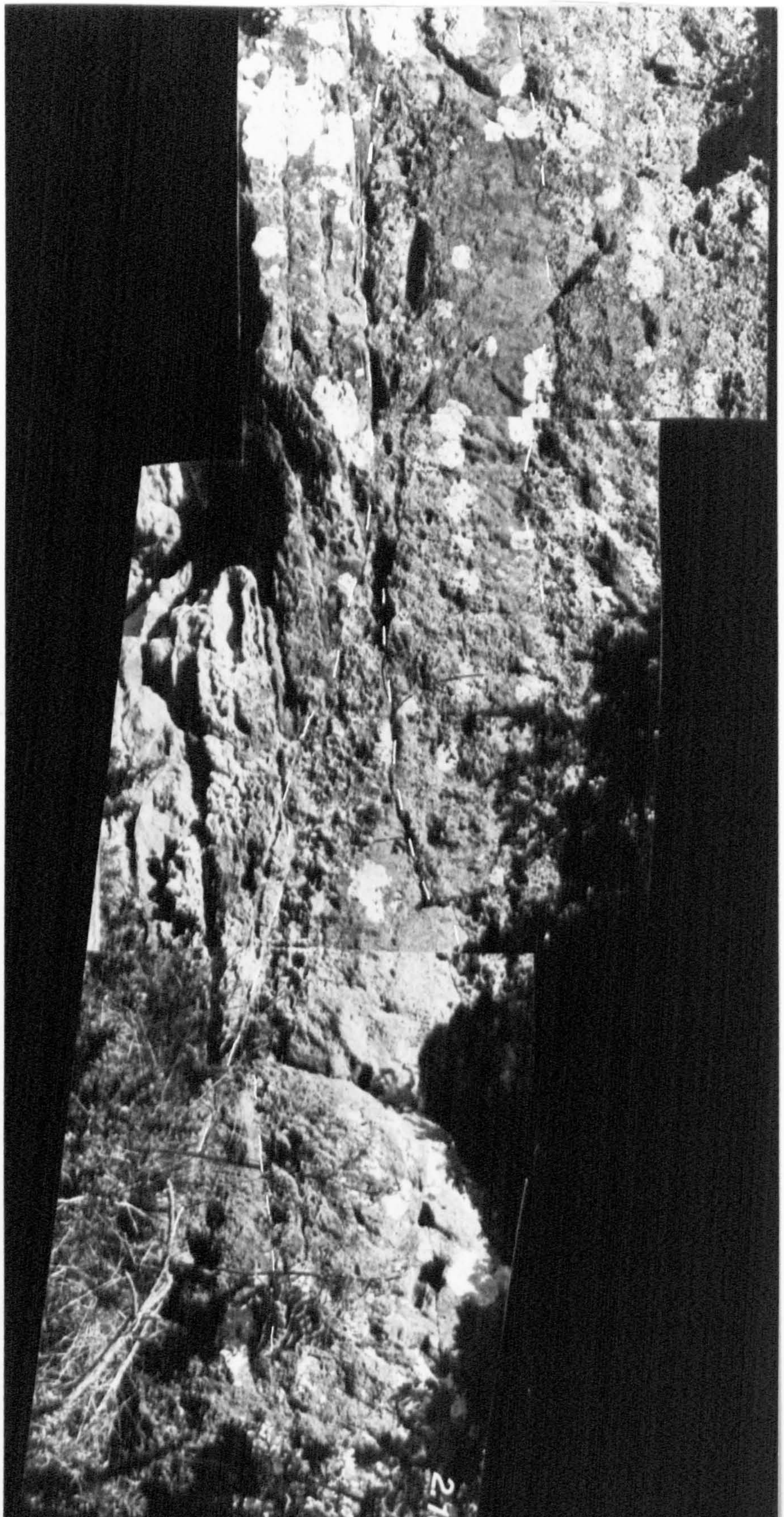
Subfacies 3B - Medium to thick-bedded compound sandstones

This subfacies comprises compound sandstones in which the average thickness of the constituent sandstones, when the thickness is measured at their thickest point, is greater than 10 cm. The units can be up to 6 m thick and are best exposed near the Allt-na-Cuile and Lothbeg Point but are also exposed at various localities along the foreshore eg. Kintradwell, Crakaig and Westgarty (Fig. 2.3). This subfacies is predominantly restricted to Kimmeridgian sequences and is most common in the cymodoce and mutabilis zones (Fig. 2.5). Bioturbation is rare even where the subfacies is closely associated with subfacies 3A. The component sandstone beds are up to 2 m thick and often thin laterally across the outcrop. Some of the beds are poorly graded or non-graded but most of the beds show well developed normal grading (Fig. 2.10a). Bed bases are sharp and often erosional (Fig. 2.10b) and small-scale scour features are locally common (Fig. 2.10c). Fossil/

Fig. (2.10a) Subfacies 3B in a channel

Note the onlapping of graded sandstones onto the channel margin which is composed of subfacies 3A sandstones, and the lateral amalgamation of sandstones. Also note the intraformational breccia at left side of photograph. Hammer 40 cm. Railway cutting between the Allt-Choll and the Allt-na-Cuile. NC. 939092.

2.10a


2.10a

plant fragments tend to be preferentially concentrated towards the tops of beds whereas decalcified shell casts and fossil shell fragments tend to be concentrated towards bed bases. Most of the beds are structureless throughout but parallel and subparallel laminations are locally well developed (Fig. 2.10c,d), and possible soft sediment dewatering structures are found towards the tops of some beds (Fig. 2.10e). Most of the sandstones are clean well sorted quartz arenites which have been cemented by quartz overgrowths or poikilitic calcite.

At some well exposed localities this is clearly a channel fill subfacies but at other localities the evidence for channel deposition is equivocal. Some of the compound sandstone units have basal intraformational breccias and the component sandstones onlap onto an inclined erosion surface, implying deposition within a channel (Fig. 2.10a). Other probable channel fill compound units are lensoid but do not have an exposed basal erosion surface. The constituent sandstone beds thin towards the channel margins and some thin-bedded channel margin sandstones are slumped and contorted. In some compound sandstone units the constituent beds become thinner towards the top of the unit (Fig. 2.10f). Inferred palaeochannel dimensions vary from 1 m to at least 10 m deep and 10 m to at least 65 m wide with width:depth ratios of greater than 10. In the well exposed thick, compound sandstone sequences at Lothbeg Point the evidence for channel deposition is equivocal as some sandstone units are lensoid but others are more laterally continuous and sheet-like. The lack of well developed structures makes the Lothbeg sequences particularly difficult to interpret.

The graded sandstones were probably deposited from turbidity currents and in the terminology of Bouma (1962) they are mostly T_a turbidites with some T_{ab} and T_b units. They were probably deposited from relatively immature, high density turbidity-currents (Lowe, 1982) and are typical of/

Fig. (2.10b - f) <u>Subfacies 3B</u>

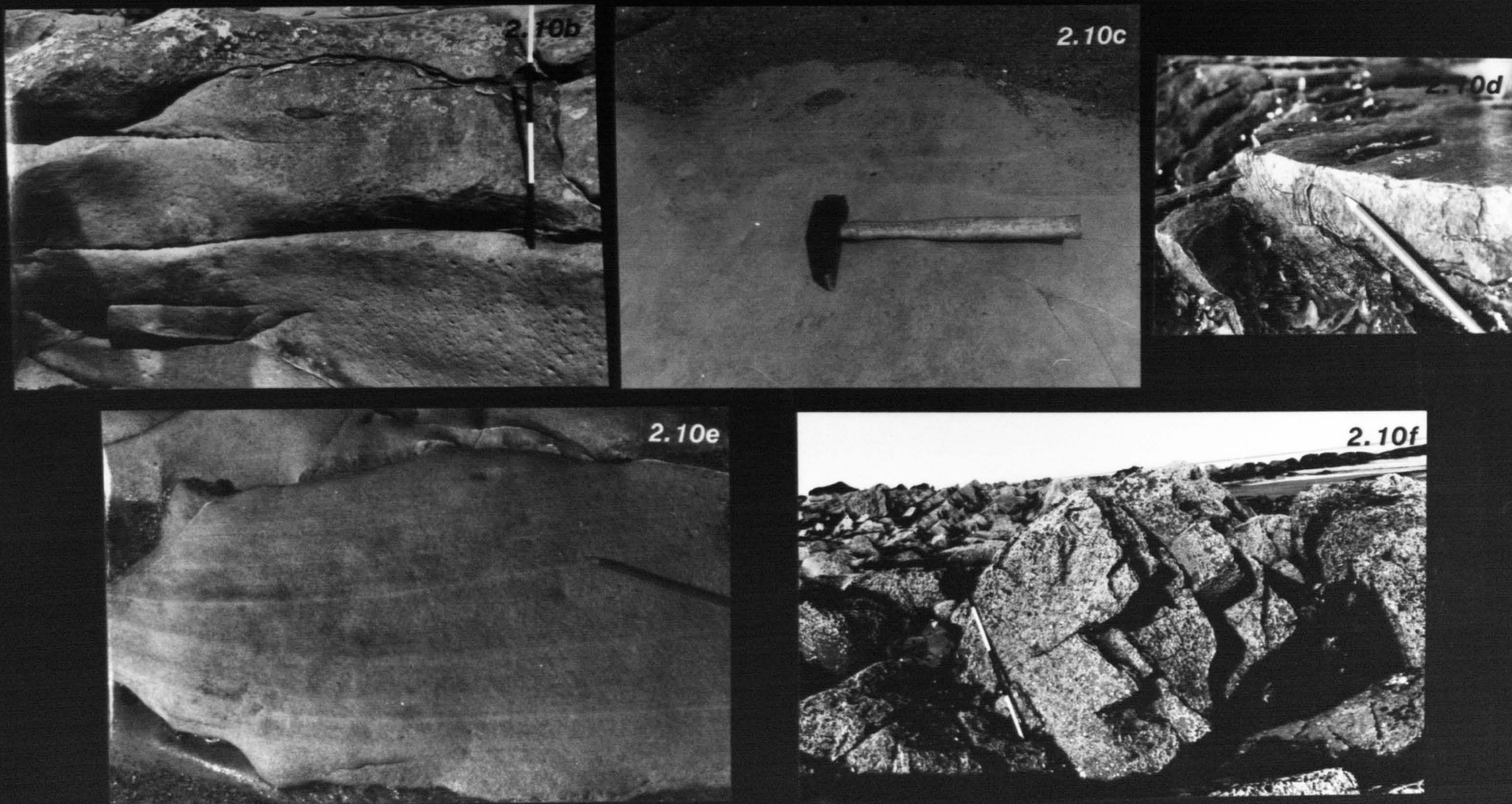
b) Amalgamated, non-graded or poorly graded sandstones. Note erosion surface plus lateral termination of amalgamation surface. Meter stick for scale. Lothbeg Point. NC. 960096.

c) Oblique/bedding plane view of amalgamated sandstones. Note the scoured base and the non-parallel laminations. Hammer 40 cm. Lothbeg Point. NC. 959096.

d) Top of a sandstone showing contorted bedding overlain by a thin massive unit. ? Fluidization or slump feature. Lothbeg Point. NC. 961096.

e) Oblique/bedding plane view of non-parallel laminations. ? cross-bedding. Pencil for scale. Lothbeg Point. NC. 961096.

f) Thick bedding, graded sandstone overlain by thinner bedded sandstone. Meter stick for scale. Foreshore at Kintradwell. NC. 926074.


2.10b
2.10c
2.10d
2.10e
2.10f

of turbidites deposited in submarine channels (Walker, 1978). The thinning-upwards sequences, the slumped, thin-bedded channel margin sediments and the possible fluidization structures are also typical of deposition in submarine channels. The lack of bioturbation in this subfacies when compared with subfacies 3A and facies 4 is probably the consequence of high deposition rates.

d) Facies 4

Cross-bedded and bar-form compound sandstones

This facies comprises any compound sandstone unit of two or more beds that are cross-bedded or in a bar-form. Single cross-bedded sandstones are included in Facies 2. It is only developed in cymodoce and mutabilis zone sequences (Fig. 2.5) and is best exposed in the gorge of the Allt-na-Cuile and the surrounding area (Fig. 2.3). The grain-size is predominantly fine and very-fine sand. Simple vertical burrows are common and some fossil plant fragments and decalcified shell casts are preserved. The rocks are friable and are cemented by quartz overgrowths. The facies encompasses two principal subfacies.

Subfacies 4A - Trough cross-bedded sandstones

This subfacies comprises sandstones that are trough cross-bedded and is best exposed in various railcuttings and raised beaches between the Allt-Choll and the Allt-na-Cuile. An underestimation of the importance of this subfacies by previous authors (Pickering, 1984; Linsley, 1972; Lee, 1925) is the result of the poor definition and preservation of the cross-beds at outcrop which is probably due to the clean, well sorted and friable nature of the sandstones and to an unusual mottled cementation. Detailed analysis of this subfacies is difficult because of the poor definition of the cross-beds and at most outcrops the problems of tracing set and coset boundaries are intractable (Fig. 2.11a, b). Average set thickness is approximately 25 cm and the thickest set is 80 cm (Fig. 2.11c). Most cosets are poorly defined but can be composed of up to 3 sets and can be over 1 m in thickness. Some foresets have superimposed cross-laminations. Low angle trough cross-bedded sets, in which the foresets in current/

Fig. (2.11) Facies 4

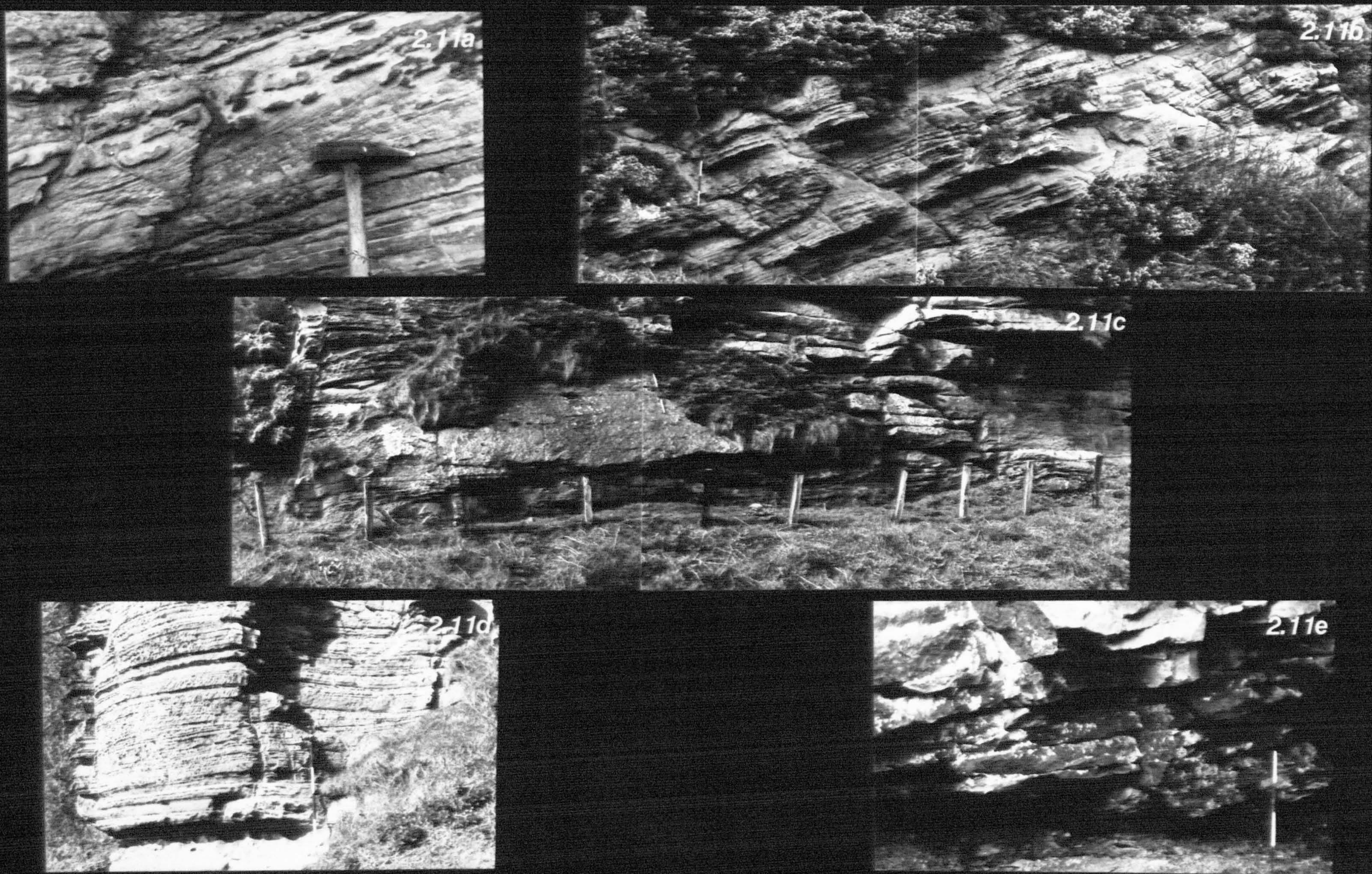
a) Close-up of subfacies 4A trough-cross bedding. Note the mottled weathering of the sandstone. Hammer 30 cm. Railway cutting between the Allt-Choll and the Allt-na-Cuile. NC. 939092.

b) View of exposure primarily composed of subfacies 4A with some subfacies 3A. Note difficulty in tracing out sets and cosets. Meter stick for scale. Railway cutting between the Allt-Choll and the Allt-na-Cuile. NC. 939092.

c) Base of exposure composed of large troughs viewed normal to current direction. The troughs are cut off by the overlying erosion surface. Meter stick for scale. Railway cutting to the north-east of the Allt-na-Cuile. NC. 941093. See also Fig. (2.26a).

d) Low angle trough sets plus subfacies 3A. Meter stick for scale. Railway cutting to the north-east of the Allt-na-Cuile. NC. 941093. See also Fig. (2.26a).

e) Medium-bedded (?bar-form) sandstones onlapping onto a flat lying ? erosion surface. Note the wedging of the sandstones. Meter stick for scale. The gorge of the Allt-na-Cuile. NC. 940094.


2.11a
2.11b
2.11c
2.11d
2.11e

parallel section dip at angles of less than 15°, are developed at some localities (Fig. 2.11d). The sets are often interstratified with subfacies 3A compound sandstones and in poor exposures can be difficult to differentiate from that subfacies. Some of the units were deposited in channels (Fig. 2.26) and other sequences overlie subfacies 3B sandstones which were deposited in channels.

The trough cross-beds are interpreted as the product of migrating 3-dimensional dune forms and they indicate significant tractional transportation of the sediment.

Subfacies 4B - Bar-form compound sandstones

This subfacies comprises compound sandstones which are in the form of a bar and are composed of inclined surfaces which onlap onto a relatively flat erosion surface or the top of a flat lying sandstone unit (Fig. 2.11e). It is best exposed in cliff sections in the gorge of the Allt-na-Cuile. The bars are composed of friable beds of massive sandstone which are between 10 and 50 cm thick and can be sub-parallel sided or lensoid. There are rare hints of possible cross-bedding within the sandstones but the general lack of sedimentary structures prevents any detailed analysis and the bars could have been accreted laterally or in a downcurrent direction. The bars are further evidence for the importance of tractional movement of sediment.

e) Facies 5 Breccias

This facies comprises beds with cobble or boulder size clasts and is spectacularly exposed on the foreshore from Kintradwell to the Ord of Caithness.

Clast Types

Many of the clasts are relatively anonymous sandstones which are similar throughout the sequence but certain "key" clast types are restricted to breccias of specific ages (Fig. 2.12). Six principal key clast types are recognised. Type I is a friable orange to buff, porous quartzose sandstone which may contain bivalve shell casts, carbonaceous partings, clay pellets and round quartz granules, and may be cross-laminated (Fig. 2.13a). It is cemented by quartz overgrowths, shows minor pressure solution and abundant kaolinite (Fig. 2.14a). It is best exposed in breccias of the *cymodoce* and possibly *mutabilis* zones (Fig. 2.12), in the Allt-Choll, the Allt-na-Cuile and the Loth Burn (Fig. 2.3). Clast type II is a dark grey to light grey calcite cemented quartzose sandstone that can contain round quartz granules, clay pellets and bivalve fragments. It is similar to type I except for the coarse poikilitic calcite cement (Fig. 2.14b), and is best exposed in *cymodoce* zone breccias (Fig. 2.12) on the foreshore at Kintradwell. Type III clasts are clean, white to pink, moderately friable, cross-bedded sandstones (Fig. 2.13b) which commonly have deformed foreset bedding, fluidization structures and interbeds of light blue or green mudstones. The sandstone shows moderate pressure solution and has a reddish carbonate mineral filling pore spaces. The clasts are best exposed in *mutabilis* to *autissiodorensis* zone breccias on the foreshore at West Garty and Crakaig links (Fig. 2.3). Type IV clasts are flagstones (Fig. 2.13c) that contain desiccation cracks, syneresis cracks, small-scale/

Fig.(2.12)

The Approximate Stratigraphic Distribution of Clast Types

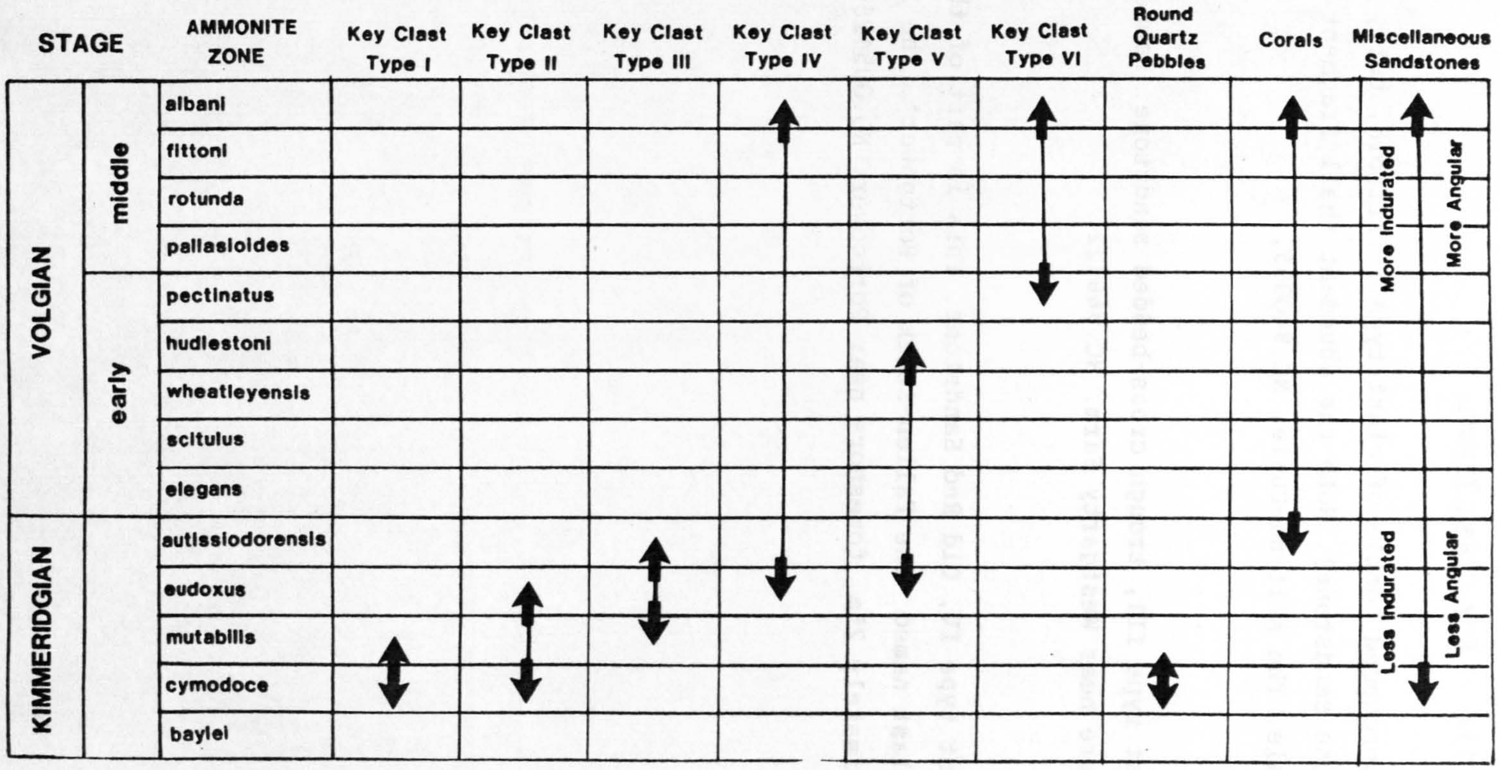


Fig (2.13) <u>Key Clast Types.</u>

a) A subrounded cobble of clast type I (friable, buff, porous, quartzose sandstone). Note the abundant shell fragment casts. Pencil for scale. The Allt-na-Cuile. NC.940095.

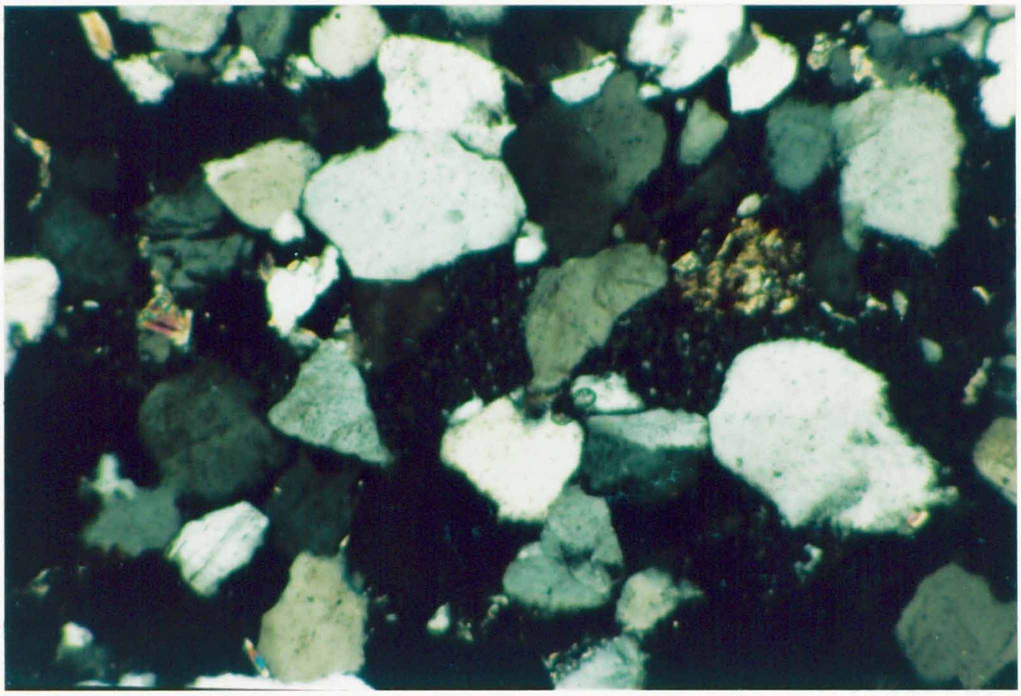
b) Clast type III, trough cross-bedded sandstone. Hammer 40cm. Foreshore near Westgarty Farm. NC.966122.

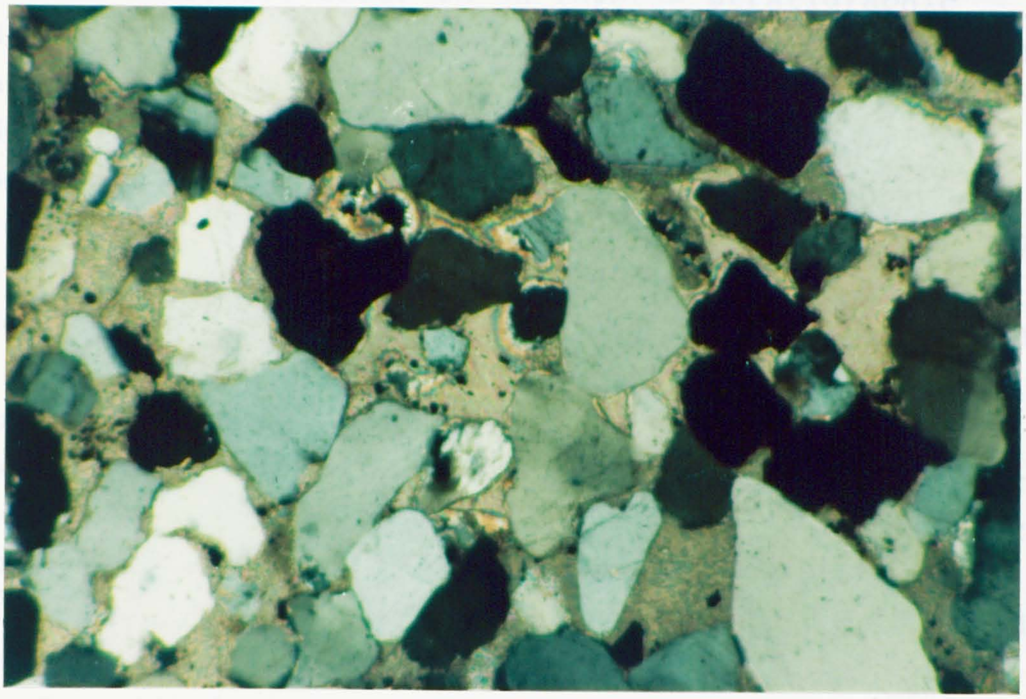
c) Clast type IV, Old Red Sandstone. This is part of the giant 30m long clast named "the Fallen-Stack of Portgower". The field of view is approximately 25m. foreshore near Portgower. ND.005128.

Fig. (2.14) Photomicrographs of Key Clast Types.

a) Key clast type I. Note the abundant kaolinite and the simple concavo-convex boundaries between quartz grains. Field of view 1.6mm.

b) Key clast type II. Note the abundance of quartz grains and the poikilitic calcite cement. Field of view 1.6mm.





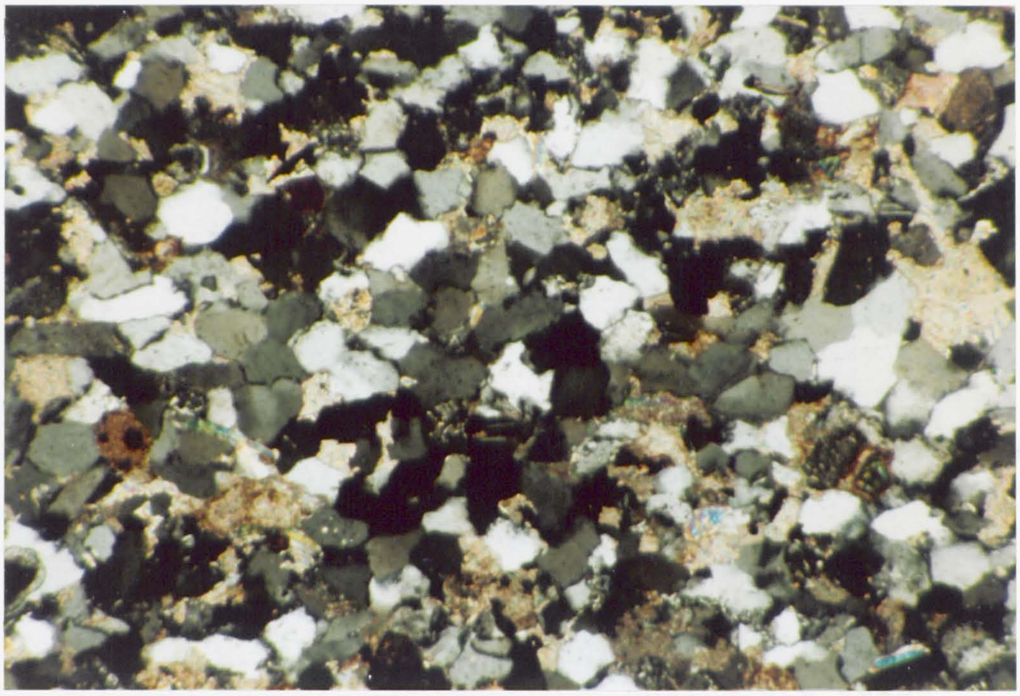
fluidization structures and Devonian fish fragments (Miller, 1854). They show evidence of deeper burial and a more complex diagenetic history than type I clasts and many of the quartz grain boundaries are complexly sutured (Fig. 2.14c). The flagstone clasts occur in breccias which range in age from the eudoxus zone of the Kimmeridgian through into the middle Volgian (Fig. 2.12) and are best exposed at Portgower, Sron Rhuba na Gaothe and various localities to the northeast of Helmsdale. The giant "fallen stack of Portgower" (Fig. 2.13c) is a type IV clast. Clast type V is a light grey marlstone (Fig. 2.14d) that is often associated with flagstone clasts. It is best exposed on the foreshore at Portgower and occurs in breccias which range from the Kimmeridgian eudoxus zone into the early Volgian (Fig. 2.12). Key clast type VI is a red mudstone that occurs in breccias of early and middle Volgian age to the northeast of Helmsdale (Fig. 2.12).

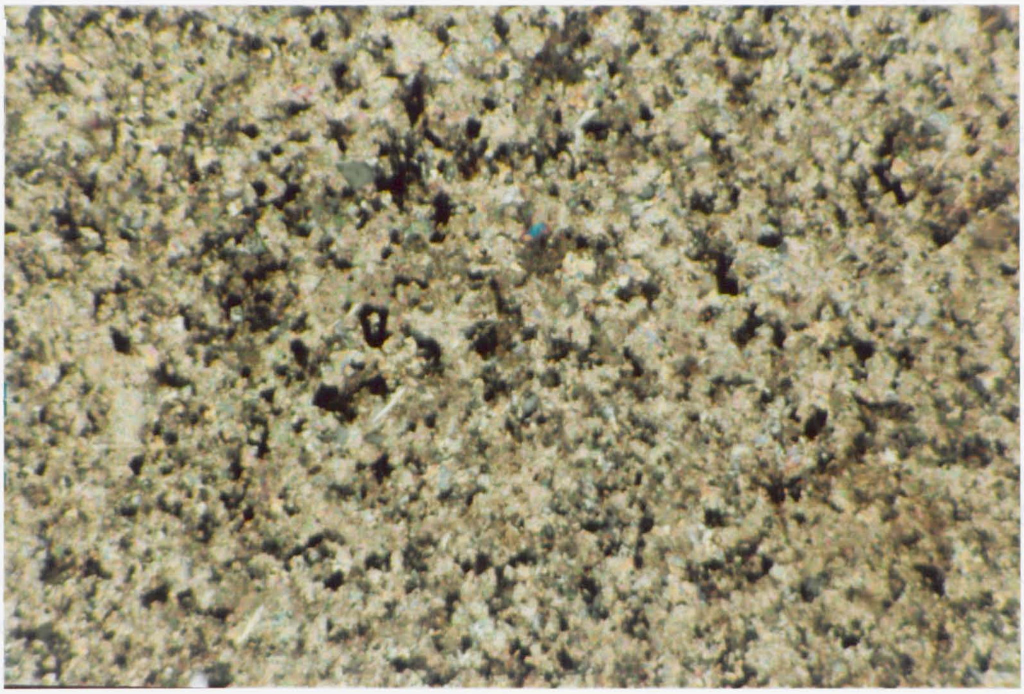
The clast types reflect the composition and age of rock being eroded at the time of deposition of the breccias and will therefore occur in an inverse stratigraphic order, ie, the oldest breccias will contain the youngest clast types and the youngest breccias will contain the oldest clast types. The presence of Devonian fish fragments in type IV clasts clearly indicates that they were derived from Devonian strata. The flagstone clasts are very similar to the Caithness flagstones of the Middle Old Red Sandstone which are spectacularly exposed in the sea-cliffs of Caithness to the northeast of Helmsdale (Mykura, 1983). Type V and VI clasts were also probably derived from Devonian strata as they occur in equivalent breccias to the type IV clasts and similar lithologies are developed in the Old Red Sandstone of the North of Scotland (Mykura, 1983). Clast types I and II are present in the oldest breccias (Fig. 2.12) and are therefore likely to have been derived from the youngest strata. The presence of fossil shell and plant fragments,/

Fig. (2.14)cont. <u>Photomicrographs of Key Clast Types.</u>

c) Key Clast Type IV (ORS Flagstone). Note the moderately sutured quartz grain boundaries. Field of view 1.6mm.

d) Key Clast Type V (marlstone). Field of view 1.6mm.





plus the simple mineralogies suggests that these clast types were probably derived from Jurassic strata. Type III clasts occur in breccias that are of intermediate age between those that contain Devonian and those that contain Jurassic clasts (Fig. 2.12). They are relatively friable and the quartz grain boundaries are more sutured than in type I but less sutured than in type IV (Fig. 2.14). Bailey and Weir (1932) point out that type III clasts are non fossiliferous and assume that they were derived from Devonian rocks. However, similar trough cross-bedded sandstones with contorted foresets are developed in the Callovian Clynelish Quarry Sandstone at Brora (Fig. 2.2) (Sykes, 1975). In general it is difficult to determine a precise age for the type III clasts.

Rounded quartz pebbles and granules are well developed in cymodoce and mutabilis zone breccias (Fig. 2.12) where they are associated with type I and II clasts. They were probably derived from Jurassic conglomerates. In general the relatively anonymous sandstones associated with the key clast types become more indurated and angular upwards in the sequence (Fig. 2.12) and the older breccias tend to contain lighter coloured sandstone clasts than the younger breccias. Many of the sandstone clasts associated with the Devonian derived key clast types have haematite rims around the quartz grains

The breccias are divided into four subfacies based on clast type and matrix composition (Fig. 2.4). Subfacies 5C and 5D contain probable Devonian derived clasts (types IV, V and VI) and subfacies 5A and 5B contain probable Jurassic derived clasts and clasts of uncertain origin (types I, II and III). Subfacies 5A and 5C have sandstone matrices whereas 5B and 5D have mudstone matrices. Subfacies 5A often has the appearance of an intraformational breccia (Fig. 2.15a), whereas the clasts in subfacies 5C are clearly extraformational (Fig. 2.16a).

Subfacies 5A

This subfacies comprises breccias which have sandstone matrices and contain probable Jurassic derived clasts. It is best exposed in the Allt-Choll and on the foreshore at Crakaig links and West Garty. It ranges from the cymodoce to the autissiodorensis zone (Fig. 2.5).

Bed thickness varies from thin 10 cm thick cobble beds to giant 7 m thick boulder beds. The thicker beds are generally sheet-like whereas the thinner beds tend to be laterally discontinuous. Both the bases and tops of beds are sharp and the bases of many beds are erosional. Some clasts have long axes of up to 15 m but most are less than 3 m long. In general, the thicker beds contain larger and poorer sorted clasts than the thinner beds. Most clasts are subangular but some of the very friable clasts are subrounded. Subequidimensional is the most common shape but some clasts are raft like and have short c-axes. In most beds the clasts are randomly orientated or have their c-axes oriented normal to bedding. Matrix supported clasts are slightly more common than framework supported ones and in most beds the clasts are randomly distributed. In some of the thinner beds clasts can be preferentially concentrated towards the tops or bases of the beds or can be concentrated at various levels within a bed. Many of the thinner pebble and cobble breccias are graded.

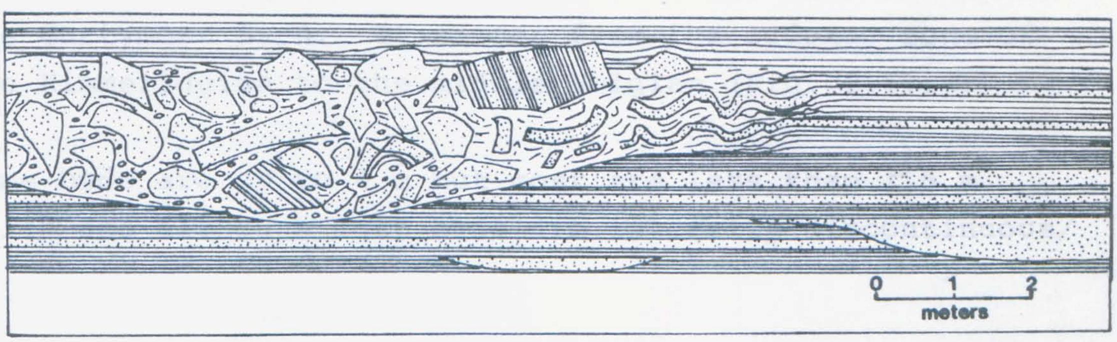
In most beds the matrix is a porous, friable, light grey or buff medium-grained sandstone (Fig. 2.15a) but the thinner cobble beds can have a calcite cemented sandstone matrix. Round quartz granules and pebbles and broken fossil shell and plant fragments are locally common.

Fig. (2.15) <u>Subfacies 5A and 5B</u>

a) Boulder bed of subfacies 5A. Note that the breccia looks intraformational, and the presence of type III clasts. Hammer is 40 cm long. Foreshore at Crakaig Links. NC. 970101.

b) Cobble breccias of subfacies 5A and 5B. Note the matrix supported clasts in both breccias. Hammer is 40 cm long. Foreshore at Kintradwell. NC. 926074.

c) Sketch of a subfacies 5B breccia. Note the probable intraformational clasts and the contorted bedding and clasts at the periphery of the bed. The breccia may have been formed by the widespread failure and slumping of the slope sediment. Foreshore at Kintradwell. NC. 926074.


0 1 2
meters

Subfacies 5B

This subfacies comprises breccias which have mudstone matrices and contain probable Jurassic derived clasts. It is best exposed on the foreshore at Kintradwell and is also exposed on the foreshores at Crakaig links and West Garty and ranges from the cymodoce to the autissiodorensis zone (Fig. 2.5)

Most beds are laterally discontinuous and thicknesses vary from 10 cm to 2.5 m. Some beds merge laterally with contorted and slumped horizons and some clasts are deformed and probably intraformational (Fig. 2.15c). This implies a genetic link between failure of the sedimentary pile and the formation of some of the breccias. The bases and tops of beds are mostly sharp and the bases of most beds are erosive. A majority of clasts are subequidimensional, subangular, and less than 1 m in diameter. They are mostly randomly oriented and distributed and the packing is generally tight. Most clasts are framework supported except in the thinner cobble beds which generally contain matrix supported clasts (Fig. 2.15b). The mudstone matrices are black, organic-rich with abundant sand grains, round quartz granules and pebbles and fossil shell and plant fragments.

Subfacies 5C

This subfacies comprises breccias which have sandstone matrices and contain clasts which were derived from probable Devonian sequences. This is the most common of the breccia subfacies and is well exposed at many localities along the foreshore and in the Allt-Garbh and the Gartymore Burn. It ranges from the eudoxus zone of the Kimmeridgian to the middle Volgian (Fig. 2.5).

Some beds are up to 4 m but most are less than 1.5 m thick and although most beds are laterally discontinuous/

some of the thicker ones are sheet-like. Both the tops and bases of the beds are sharp and the bases of most beds are erosional. The basal parts of some beds are mud rich. Some of the clasts are up to 8 m in diameter but most are less than 1 m, angular and subequidimensional. Packing is variable and the tightly packed framework supported beds have less well organised clast fabrics than the more loosely packed matrix supported ones (Fig. 2.16a, b). In some of the tightly packed breccias clast fabrics are chaotic but in most beds the c-axes of many clasts are perpendicular to bedding (Fig. 2.16a) and in some beds there is a subparallel alignment of a-axes. In many beds the larger clasts are preferentially concentrated towards the tops but in other beds the clasts are randomly distributed or concentrated towards the base or middle and a normal grading of clasts is locally common. The larger clasts can also be preferentially concentrated towards the thickest parts of the bed and a lateral grading towards the thinner parts of the beds is developed. In most beds the matrix is a poorly sorted shelly sandstone which is calcite cemented in foreshore exposures but non calcitic in stream exposures. Thin graded matrix-rich zones cap many of the breccias (Fig. 2.16c). The shells are mostly broken and include fragments of bivalves, brachiopods, gastropods, echinoids, corals and belemnites which can be oriented sub-parallel to the a-axes of the clasts. Fossil plant fragments are locally common.

Subfacies 5D

This subfacies comprises breccias which have mudstone matrices and contain probable Devonian derived clasts. It ranges from the Kimmeridgian <u>autissiodorensis</u> zone to the middle Volgian (Fig. 2.5) and is best exposed on the foreshore between Portgower and Helmsdale and near Navidale.

Fig. (2.16) <u>Subfacies 5C</u>

a) Thin calcite cemented breccia with matrix supported clasts. Crude basal inversely graded layer plus largest clasts towards the top of the bed. Most c-axes are normal to bedding. Hammer 40 cm. Navidale Bay. ND. 042160.

b) Tightly packed framework supported breccia. Angular clasts and disorganised clast fabric. Pencil for scale. Foreshore between Portgower and Helmsdale. ND. 017139.

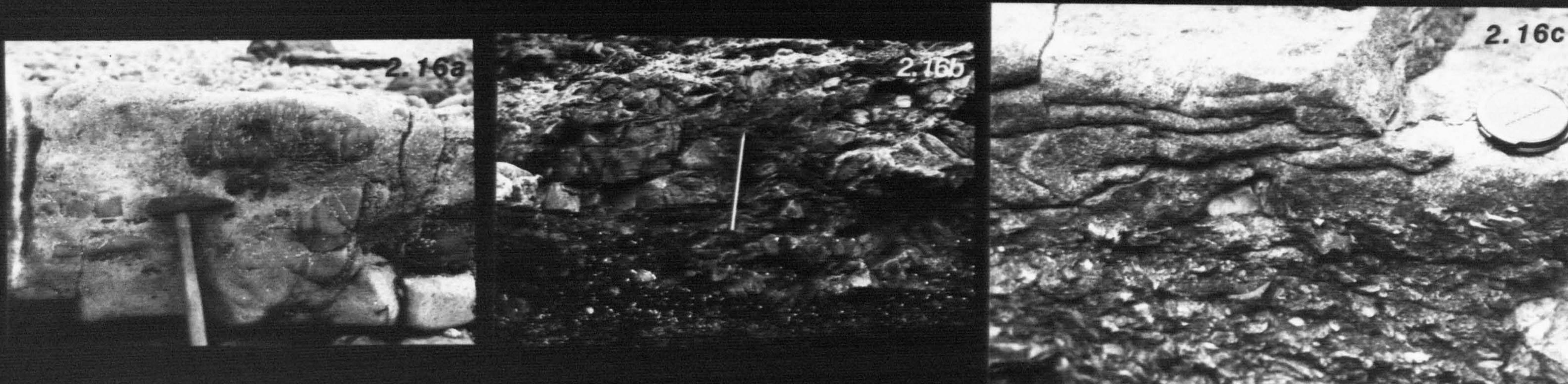
c) Graded, gritty top to breccia. Gartymore Burn. ND. 013137.

Fig. (2.17a-c) <u>Subfacies 5D</u>

a) View of part of the "fallen-stack" breccia. Large ORS flagstone clast at base of breccia erosively overlying mudstone. Meter stick for scale. Foreshore at Portgower. ND. 005128.

b) Erosive base to breccia. Meter stick for scale. To the east of Navidale Bay. ND. 042160.

c) Amalgamated breccia with subrounded cobbles and angular boulders. Meter stick for scale. Foreshore to the south of Navidale Bay. ND. 042159.


2.16a
2.16b
2.16c


2.17a
2.17b
2.17c

The beds can be anything from a few centimetres to 10 m thick and laterally discontinuous or sheetlike. The bases of most beds are erosional and the tops are sharp (Fig. 2.17a, b). This subfacies contains most of the giant clasts for which the Helmsdale sequence is famous, including to 30 m long misnamed "fallen-stack of Portgower" (Fig. 2.13c) and one of 18 m diameter to the northeast of Navidale Bay. However, most of the clasts are less than 2 m in diameter, angular and subequidimensional. Rare beds can contain common rounded or subrounded cobble clasts (Fig. 2.17c). The packing is invariably tight or very tight and the clasts are framework supported (Fig. 2.17e). Clast fabrics are generally disorganised but in some beds the largest clasts are concentrated towards the top of the bed and where the bed is thickest (Fig. 2.17d). This subfacies includes isolated clasts which are entirely surrounded by mudstone. These clasts can occur singly or in beds one clast thick (Fig. 2.17 f). The matrix is a similar lithology to facies 1A and is a dark mudstone or sandy mudstone in which fossil shell and plant fragments are locally common. In some beds there are slightly contorted sandy laminations in the mudstone matrix (Fig. 2.17g).

Fig. (2.17d-g) <u>Subfacies 5D</u>

d) Erosively based, lensoid breccia. Note the tight packing and the large boulders at the top of the bed and where the bed is thickest. Meter stick for scale. Foreshore between Portgower and Helmsdale. ND. 018140.

e) Typical tightly packed subfacies 5D breccia. Meter stick for scale. Foreshore to the north-east of Helmsdale. ND. 032151.

f) Angular cobbles in mudstone. Pencil for scale. Foreshore between Portgower and Helmsdale. ND. 121146.

g) Faint sandstone laminations in the mudstone matrix of a breccia. Hammer is 40 cm. Foreshore between Portgower and Helmsdale. ND. 010134.


2.17d

2.17e

2.17f

2.17g

Interpretation

As pointed out by Bailey and Weir (1932) the shell fragments in the matrix of the sandy breccias are clearly allochthonous and were probably derived, along with the sand, from a relatively shallow water shelf area on the upthrown side of the Helmsdale Fault. The angularity of most of the boulders demonstrates that they were not derived from the shallow water area and the giant dimensions suggests that they did not travel very far. The most likely source of the clasts was therefore the scarp of the Helmsdale Fault that separated a relatively deep water environment on the downthrown side of the fault from the shelf area on the upthrown side (Bailey and Weir, 1932). The occurrence of rare subrounded clasts (Fig. 2.17c) suggests that the upper part of the fault-scarp was sometimes eroded in relatively shallow water and some of the clasts probably rolled around a shelf area before being deposited in deeper water.

The shelf derived sand and shells were probably washed over the fault scarp and mixed with the boulders on the downthrown side before being transported basinward and deposited as subfacies 5A and 5C. The mudstone matrices are similar to subfacies 1A mudstones and were probably derived from the deeper water area on the downthrown side of the fault. In subfacies 5B and 5D the clasts probably mixed with the mud during transportation.

The textures of the breccias show a continuum from very tightly packed and disorganised to loosely packed and graded and were therefore probably transported by a number of different processes transitional from rockfall to debris flow to turbidity flow (section 1C (ii)).

The tightly packed, disorganised breccias and the isolated clasts were probably transported by rockfall mechanisms in which the boulders and gravel rolled or slid down a steep slope (Fig. 1.3). The isolated clasts tumbled down a submarine slope as individuals, whereas the thicker breccias formed when large masses of sediment became unstable and slid basinward. The contorted sandstone laminations in the matrix of some subfacies 5D breccias (Fig. 2.17g) shows that the matrix was not mixed and homogenised during transportation, instead it probably acted as a lubricant to the sliding of the blocks. The giant clasts of subfacies 5D were probably transported in this way. The more organised breccias of subfacies 5B and 5D which have the largest clasts rafted on the tops of beds (Fig. 2.17d) may be cohesive debris flow deposits (Fig. 1.3) or may have been transported by a process transitional between rockfall and debris flow. The relatively matrix rich and well organised breccias of subfacies 5C and 5A with c-axes normal to bedding and subparallel alignment of a-axes and shell fragments are probably friction debris flow deposits (Fig. 1.3) and the commonly graded finer grained and matrix rich breccias were probably transported by turbidity currents or a process transitional between debris flow and turbidity flow (section 1C (ii)).

Fossil Log and Coral Clasts

Fossil logs and corals occur as exotic clasts in the breccias or as isolated clasts in the mudstones. The two fossil logs were found in shale rich sequences on the foreshores at Kintradwell and Portgower. One is uncompacted (Fig. 2.18a) while the other has been compacted to about half its original diameter. Both were calcified during early diagenesis and both the bark (Fig. 2.18b) and the cell structure of the wood have been exceedingly well preserved. They are unusual in being present in a marine mudstone and clearly testify to a relatively nearby vegetated land area.

Rounded or subrounded coral clasts are present in strata of autissiodorensis age and younger (Fig. 2.18c). They are mostly species of Isastrea which is a Scleractinian reef-building coral and they are evidence for "the most northerly station of reef building corals in the Jurassic of Europe" (Arkell, 1933). The corals probably lived in the shallow water shelf area on the upthrown side of the fault (Bailey and Weir, 1932). The rounding of the clasts suggests that the corals were rolled around the shelf area for some time before being washed over the fault into the deeper water environment, and the lack of corals in beds older than autissiodorensis zone implies that in those times the shelf area was a hostile environment not suitable to the growth of coral reefs.

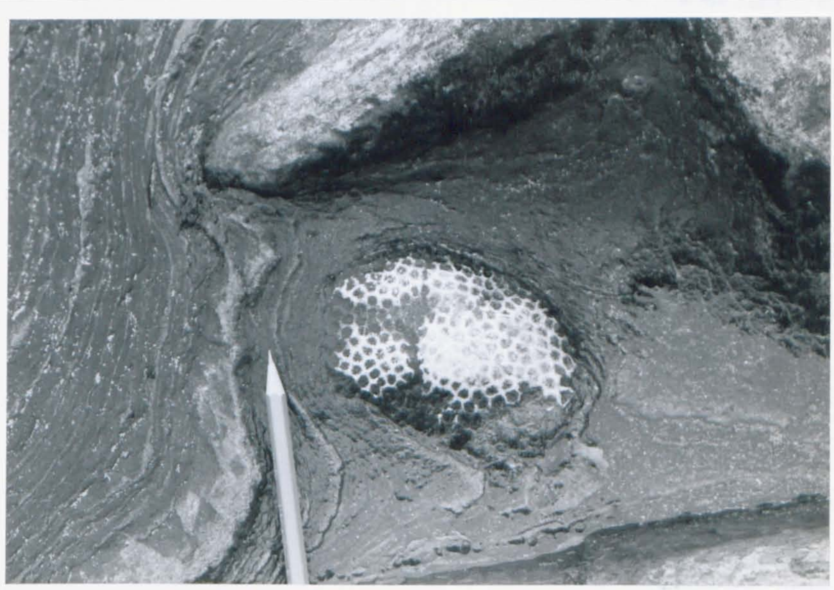
Fig. (2.18) Fossil Log and Coral Clasts.

a) A view of an uncompacted calcified log. The cell structure is exceedingly well preserved. Note the concentric rings - the tree was approximately 30 years old when it died. This specimen is unusual as it was found in a slumped marine shale sequence at Kintradwell. The long diameter is 15cm.

b) A view of the same log to illustrate the excellent preservation of the bark.

c) A rounded Isastrea coral clast. As the clast is enclosed in mudstone it must have been transported by rolling down a steep slope before being deposited on a muddy substrate. Foreshore between Gartymore and Helmsdale. ND.121146.


0 1 2 3
cm



(iii) Facies Associations

For defining the associations facies 1 and subfacies 2A are grouped together as "mudstones", subfacies 2B, facies 3 and 4 as "sandstones", and facies 5 is "breccias." The three groups are plotted at the apices of a triangular diagram and the associations are defined as any rock unit of 10 m thickness which contains specific percentages of the constituent end members (Fig. 2.19). In this way any measured section of 10 m thickness can be objectively defined as a facies association. The relatively large scale of 10 m was chosen for two reasons;

a) to highlight the broad time and space distribution of facies rather than small-scale facies changes and

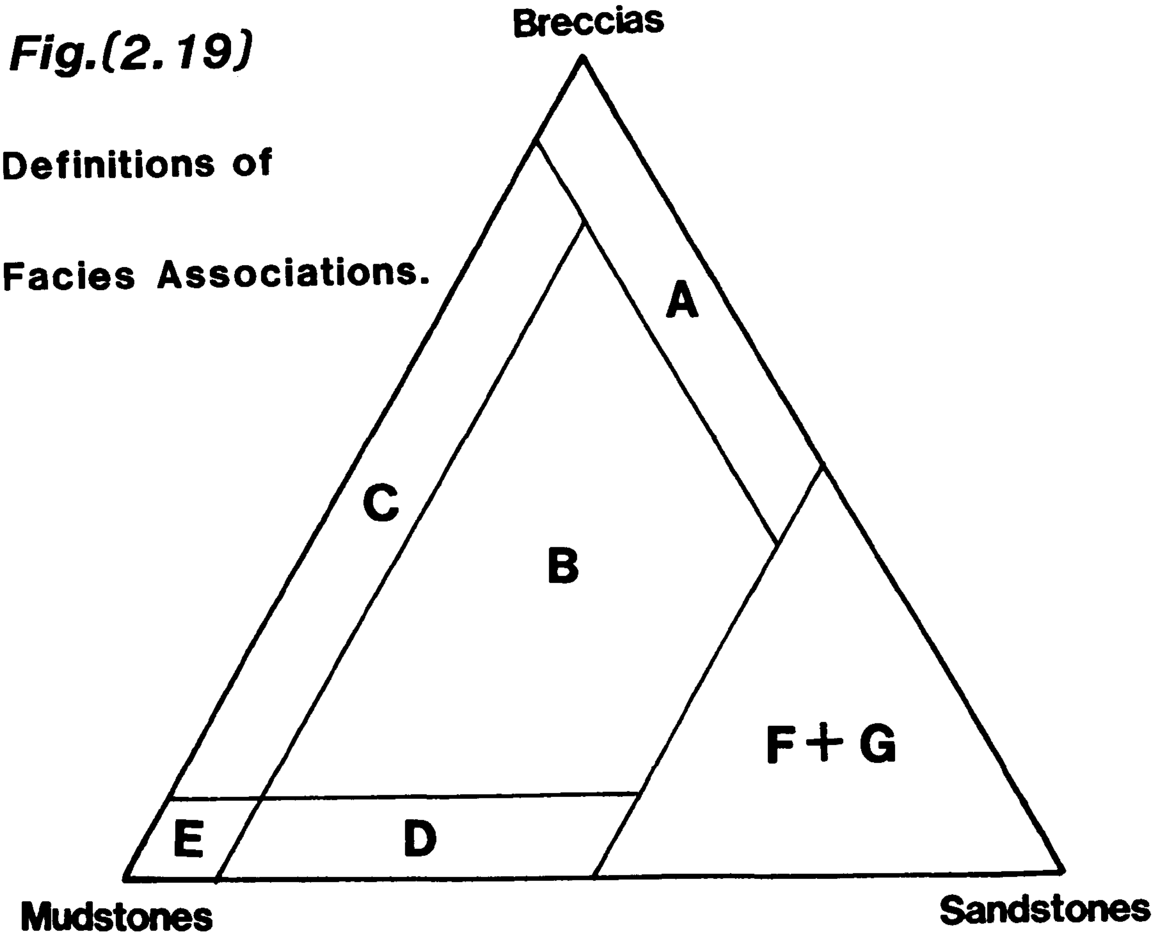
b) because of the thick bedding of many of the facies.

Where exposure is limited and the section exposed is less than 10 m thick care must be taken in assigning sequences to facies associations. An isolated exposure of a 2 m thick breccia could represent part of an association A, B or C sequence and therefore cannot be placed objectively in an association. However, a 5 m exposure composed of subequal proportions of breccias, sandstones and mudstones can be placed relatively safely in association B. The typical percentages of the individual subfacies which are found in each association are shown in (Fig. 2.20). The boundaries between associations are generally taken at a prominent facies change, a prominent bedding plane, a prominent deformed horizon or at a disconformity.

Fig.(2.19)

Definitions of

Facies Associations.



Constituent Lithologies

Facies Associations	Breccias	Sandstones	Mudstones
A	> 40%	< 50%	< 10%
B	> 10%	10–50%	> 10%
C	> 10%	< 10%	> 10%
D	< 10%	10–50%	> 40%
E	< 10%	< 10%	> 80%
F	< 50%	> 50%	< 50%
G	< 50%	> 50%	< 50%

a) Association A

Breccia Association

This association is defined as any rock unit of 10 m thickness that is composed of more than 40% breccias, less than 50% sandstones and less than 10% mudstones (Fig. 2.19). At most exposures it comprises a sequence of compound breccias with minor amounts of other facies (Fig. 2.20). It is best exposed in the Allt Choll, the Garbh Allt and at Dun Glas and is developed in a narrow band of country, less than 400 m wide, immediately to the southeast of the Helmsdale Fault (Fig. 2.3). The association is bounded by the Helmsdale Fault to the northwest and is interstratified and gradational with associations B, C and E to the southeast. It is locally interstratified with associations F and G (Fig. 2.3).

The breccia association includes two subassociations which are differentiated by the composition of the constituent clasts; subassociation AJ includes breccias which contain probable Jurassic-derived clasts (Key clast types I, II and III) and subassociation AD includes breccias which contain probable Devonian-derived clasts (Key clast types IV, V and VI) (Fig. 2.20). Subassociation AJ is usually of Kimmeridgian age (Fig. 2.21) and is best exposed in the southwestern part of the study area in the Allt Choll and the Loth Burn. However, there is also an isolated exposure of this subassociation to the northeast of Navidale between the Sput Burn and the north Allt Briste (Fig. 2.3). It occurs adjacent to the Helmsdale Fault, dips at 70 to the southeast (Fig. 2.41d) and is associated with association F compound sandstones which are similar to those exposed in the proximity of Lothbeg Point and Crakaig Farm. The stratigraphic occurrence of this exposure is anomalous as it is associated with Middle Volgian breccias which contain clasts of Devonian affinity, whereas the other exposures of subassociations AJ are in/

Fig.(2.20) **Typical Facies in each Association.**

ASSOCIATIONS \ FACIES			Shales		Single Sandstones		Compound Sandstones		X-Bedded Sandstones		Breccias			
											Jurassic Clasts		Devonian Clasts	
			Laminated Mudstone	Bio-turbated Mudstone	Thin Bedded	Med. to Thick Bedded	Thin Bedded	Med. to Thick Bedded	Trough Cross-Bedded	Bar-Form	Sst. Matrix	Mudst. Matrix	Sst. Matrix	Mudst. Matrix
			1A	1B	2A	2B	3A	3B	4A	4B	5A	5B	5C	5D
BRECCIA	with Jurassic Clasts	AJ	Rare		Minor	MAJOR	Minor	Minor	Minor	Rare	DOM	Minor		
	with Devonian Clasts	AD	Minor		Minor	Minor	Rare	Rare					DOM	MAJOR
BRECCIA/ SANDSTONE/ SHALE	with Jurassic Clasts	BJ	MAJOR		MAJOR	MAJOR	Minor	MAJOR	Rare		MAJOR	Minor		
	with Devonian Clasts	BD	MAJOR		MAJOR	MAJOR	Minor	Minor					MAJOR	Minor
BRECCIA/ SHALE	with Jurassic Clasts	CJ	DOM		Minor	Minor	Rare	Minor			MAJOR	MAJOR		
	with Devonian Clasts	CD	DOM		Minor	Minor	Rare	Rare					MAJOR	MAJOR
SANDSTONE/SHALE		D	DOM	Minor	MAJOR	MAJOR	Minor	MAJOR			Minor	Minor		
SHALE		E	DOM	Rare	Minor	Rare					Rare	Rare	Rare	Minor
COMPOUND SANDSTONE		F	MAJOR	Rare	MAJOR	MAJOR	Minor	DOM	Minor		Minor			
CROSS-BEDDED SANDSTONE		G	Minor	Rare	Minor	Minor	MAJOR	MAJOR	MAJOR	Minor	Minor			

DOM $>$ 50%

MAJOR 10-50%

MINOR 5-10%

RARE $<$ 5%

Fig.(2.21)

The Approximate Stratigraphic Distribution of Facies Associations and Subassociations

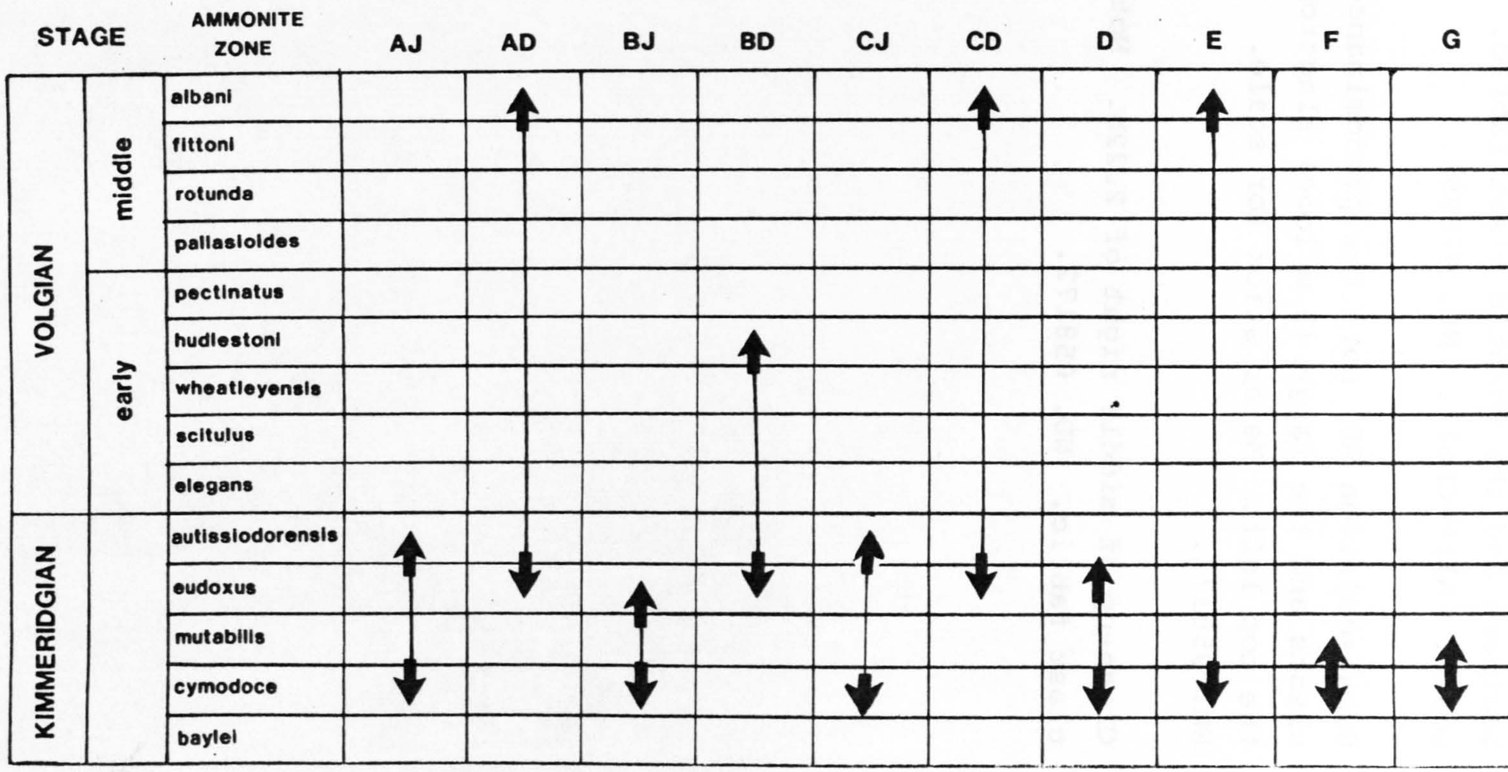


Fig. (2.22) <u>Association A</u>

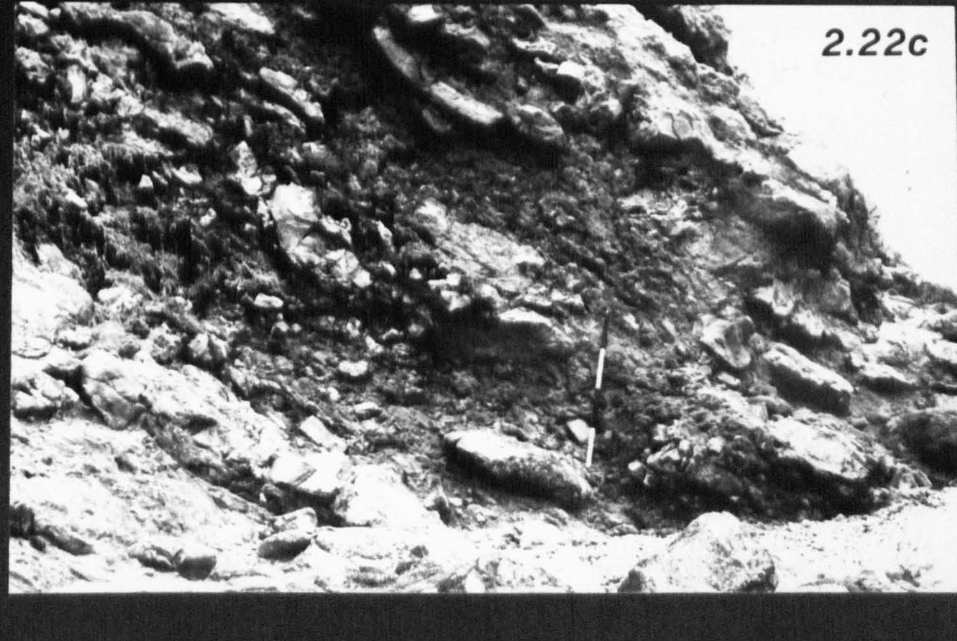
a) Subassociation AJ, note both subrounded and subangular boulders and the chaotic clast fabric. Meter stick for scale. Allt-Choll. NC. 936091.

b) Subassociation AD, note the predominance of angular clasts and the large (3 m long) flagstone clast towards the top left. Meter stick for scale. Dun Glas. ND. 058172.

c) Close-up of middle right of 2.22b. Note the chaotic clast fabric. ND. 058172.


2.22a


2.22b


2.22c

the Kimmeridgian autissiodorensis zone or older. The occurrence of this exposure is an enigma that doesn't comply with the overall model. It may be structurally controlled, fault-bounded unit that has been caught-up in the Helmsdale Fault (section 2.C). Subassociation AD ranges in age from the Kimmeridgian eudoxus zone up into the middle Volgian (Fig. 2.21) and is best exposed in the northeastern part of the study area in the Garbh Allt, the Gartymore Burn and at Dun Glas.

The sedimentary features and textures of the sub-associations are similar except that the AJ breccias tend to be more matrix rich and contain more rounded clasts than the AD breccias. Also the matrix of the AJ breccias is cleaner, better sorted and less shelly than the AD breccias and, therefore, has superior reservoir properties.

At most localities the association is a thick sequence of compound breccias with indistinct bedding surfaces (Fig. 2.22). The individual beds tend to be thick and the average bed thickness in some sequences is greater than 2.5 m. The clasts are generally large, often averaging over 1 m in diameter, angular, randomly oriented and distributed, and tightly packed in disorganised beds (Fig. 2.23a). Bedding surfaces between amalgamated breccias are mostly irregular, discontinuous and indistinct, and often dip steeply to the southeast (Fig. 2.22b). Contorted rafts of shale and thin bedded sandstone occur in some beds. The matrix of most beds is a moderately clean medium to coarse-grained sandstone but in some beds it is an argillaceous sandstone. Breccias with mudstone matrices are rare, broken fossil shell fragments, especially bivalves, and fossil plant fragments are common. The minor amounts of other facies are mostly developed as thin discontinuous lenses between the compound breccias but in some sequences compound sandstones form more continuous units and comprise more than 25% of the sequence.

Fig. (2.23)

a) Subassociation AD, note the angularity of the boulders, the very tight packing and the chaotic clast fabric. Photograph is 4 m high. Garbh Allt. ND. 012138.

b) Breccias and sandstones filling a channel. Meter stick for scale. Foreshore between Portgower and Helmsdale. ND. 010134.

c) Close-up of channel margin. Hammer is 40 cm.


2.23a


2.23b


2.23c

b) Association B

Breccia/Sandstone/Shale Association

This association is defined an any rock unit of 10 m thickness that is composed of more than 10% breccias, between 10% and 50% sandstones and more than 10% mudstones (Fig. 2.19). In some sequences mudstone is dominant, eg. on the foreshore at Portgower in the proximity of the "fallen-stack", and the association comprises a sequence of shales with varying amounts of interbedded breccias and sandstones. At other localities breccias and sandstones are dominant, eg. on the foreshore at Westgarty, and the association comprises a sequence of breccias and sandstones with interbedded shales (Fig. 2.24a). The association is mainly interstratified with associations C, E and F and lies to the southeast of association A sequences (Fig. 2.3). Two subassociations are recognised on the basis of the clast composition of the constituent breccias; subassociation BJ includes breccias which contain probable Jurassic derived clasts (Key clast types I, II and III), and subassociation BD includes breccias which contain probable Devonian derived clasts (Key clast types IV, V and VI). BJ is Kimmeridgian cymodoce to eudoxus zone in age (Fig. 2.21) and is best exposed on the foreshore at Westgarty. BD is Kimmeridgian to Volgian hudlestoni zone (Fig. 2.21) in age and is best exposed on the foreshore at Portgower. In general, association B is most common in the Kimmeridgian mutabilis and eudoxus zones and it becomes less common upwards through the Kimmeridgian and the Volgian.

The breccias tend to be thinner bedded, have a smaller average clast size, are more matrix rich and better organised than the association A breccias. Many of the breccias show non random orientation and distribution of clasts, eg. subparallel alignment of a-axes and preferential concentration of the largest clasts towards the tops of beds. Most of the beds are less than 2 m thick and most/

clasts are less than 1.5 m in diameter. Packing density is variable and both matrix and framework supported clasts are common. Some breccias have a mudstone matrix but most have a sandstone matrix that is often very rich in fossil shell fragments. Most beds are lensoid but some are laterally continuous and sheet-like. Most breccias occur as compound amalgamated units, but some occur as single beds. The sandstones, which are mostly graded, can occur as compound units or as single beds and the shales are the typical black to dark grey laminated organic mudstones of subfacies 1A which are often contorted, eroded and loaded by the overlying breccias and sandstones.

Subassociation BJ is generally more sandstone rich than subassociation BD. Compound sandstones are common in BJ (Fig. 2.24a) whereas most of the sandstones in BD sequences occur as single beds. The BJ breccia clasts tend to be less tightly packed and matrices tend to be less shelly than the BD breccias. Many of the BJ breccias have porous matrices whereas, most of the BD breccias have tight calcite cemented matrices.

The association can occur as a laterally continuous sheet-like unit interstratified with other associations or as a laterally discontinuous lensoid unit enclosed in other associations. Many of the lensoid units were deposited in channels and the constituent beds onlap onto a basal erosion surface (Fig. 2.23b,c). Internal scouring is common in the channel sequences and many of the beds thin and fine towards the channel margins so that the channel axes are breccia rich and the channel margins are sand and shale rich.

Fig. (2.24)

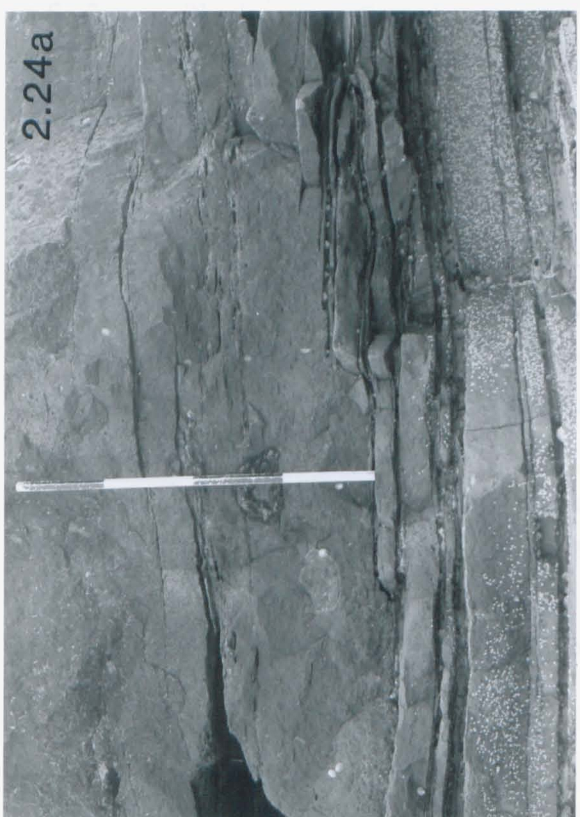
a) Subassociation BJ. This exposure is primarily composed of subfacies 3B and 5A and is typical of the mud-poor units of association B. Note the matrix supported clasts and the erosive bases. Meter stick for scale. Foreshore near Westgarty Farm. NC. 996121.

b) Association D. This figure shows a 3 m thick, lensoid unit of sandstone which is enclosed in a shale rich sequence. The sandstones are primarily subfacies 3B. Meter stick for scale. Foreshore at Crakaig Links. NC. 964100.

Fig. (2.25) <u>Association F</u>

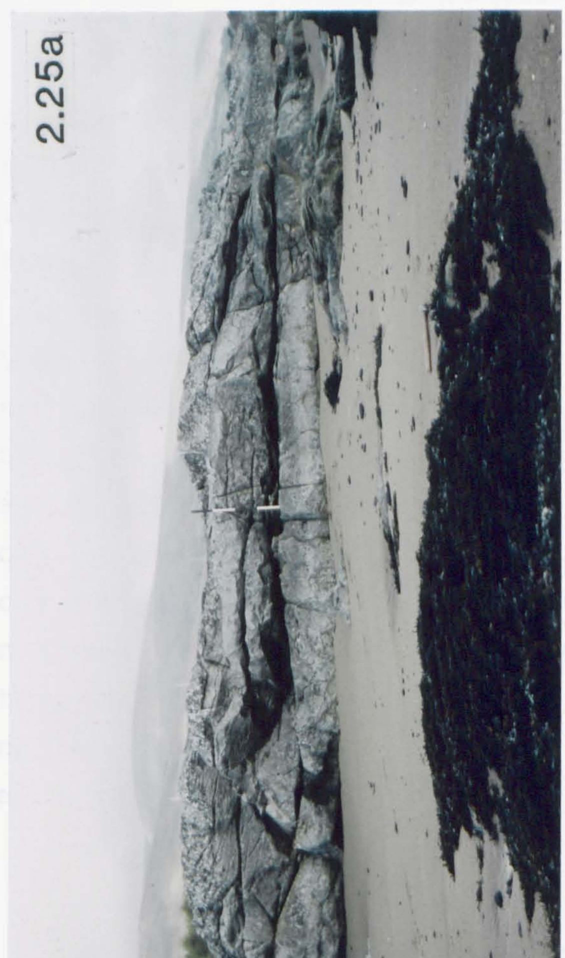
a) This exposure is part of a thick sequence of compound sandstones and is primarily composed of subfacies 3B. Note the amalgamation of beds and the erosive bases. Meter stick for scale. Lothbeg Point. NC. 960096.

b) Anomalous steeply inclined erosion surface/? channel margin. Lothbeg Point. NC. 960096.

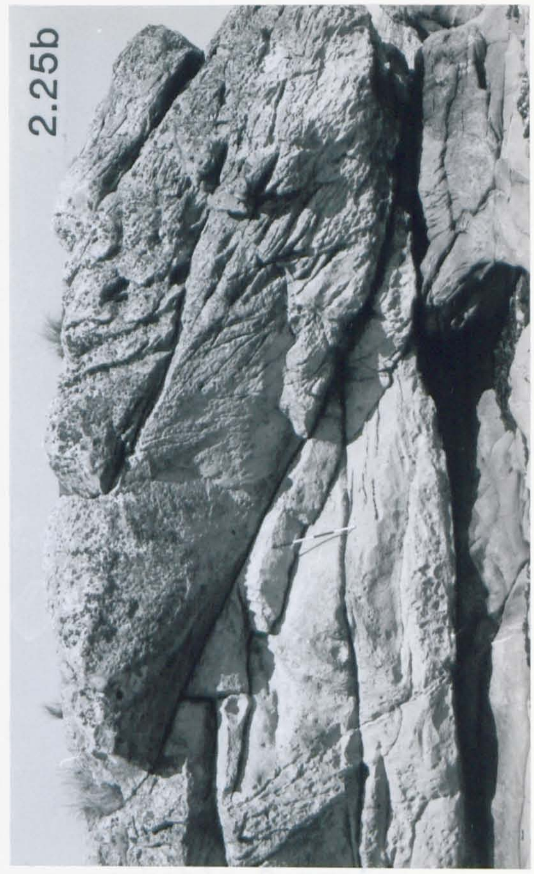


2.24a

2.24b



2.25a



2.25b

c) Association C

Breccia/Shale Association

This association is defined as any rock unit of 10 m thickness that is composed of more than 10% breccias, less than 10% sandstones and more than 10% mudstones (Fig. 2.19). It mostly comprises a sequence of black shales with varying amounts, usually less than 40% of interbedded breccias (Fig. 2.20) and is well exposed at many localities along the foreshore, eg. Gartymore and Navidale. The association mainly occurs as a sheet-like unit interstratified with associations B and E and lies to the southeast of association A and B sequences (Fig. 2.3). Two subassociations are recognised on the basis of the clast types in the constituent breccias; subassociation CJ includes breccias which contain probable Jurassic derived clasts (Key clast types I, II and II) and subassociation CD includes breccias which contain probable Devonian derived clasts (Key clast types IV, V and VI). CD, which is the more common subassociation, is Kimmeridgian eudoxus zone and younger (Fig. 2.21) and is well exposed at many localities along the foreshore to the northeast of Sron Rhuba na Gaothe. CJ is exposed at Kintradwell and Crakaig Links and is Kimmeridgian cymodoce to autissiodorensis zone in age (Fig. 2.21).

The breccias are generally more laterally continuous (Fig. 2.24c) and the clasts are tighter packed than the association B breccias. Many of the breccias have mudstone matrices whereas most association B breccias have sandstone matrices. The breccias can occur as single beds or amalgamated units of up to 4 beds in which the amalgamation surfaces are often discontinuous and indistinct. Some of the breccias with mudstone matrices contain very large clasts including the misnamed "fallen-stack". The shales are the typical mudstones of subfacies 1 A.

d) Association D

Sandstone/Shale Association

This association is defined as any rock unit of 10 m thickness that is composed of less than 10% breccias, between 10% and 50% sandstones and more than 40% mudstone (Fig. 2.19). It mainly comprises a sequence of shales with varying amounts of single and compound sandstones and minor amounts of breccias (Fig. 2.20).

It is best exposed on the foreshore at Kintradwell and is also exposed on the foreshore to the north of Lothbeg Point and to the west of Crakaig Links (Fig. 2.3). The association is predominantly interstratified with associations E and F and subassociation CJ and is best developed in the Kimmeridgian _cymodoce_ zone but also ranges through the Kimmeridgian into the _eudoxus_ or _autissiodorensis_ zones (Fig. 2.21).

The thicker breccias tend to have mudstone matrices, whereas the thinner ones generally have sandstone matrices. They contain probable Jurassic derived clasts (Key clast types II and III) and rounded quartz granules and pebbles are very common. The sandstones are typical subfacies 2.B and facies 3 and the shales can be either subfacies 1.A or 1.B mudstones. The association occurs as both laterally continuous sheet-like units and as lensoid units interstratified and gradational with associations E and F (Fig. 2.24b) and it also encloses some lensoid associations F units.

e) Association E

Shale Association

This association is defined as any rock unit of 10 m thickness that is composed of less than 10% breccias, less than 10% sandstones and greater than 80% mudstones (Fig. 2.19). It mostly comprises a thick sequence of shales with minor interbedded breccias and sandstones (Fig. 2.20) and is well exposed at many localities along the foreshore (Fig. 2.28d) where it is interstratified with associations B, C, D and F. It is the most common association and is well developed throughout the Kimmeridgian and Volgian (Fig. 2.21). In general it is more common at younger than older stratigraphic horizons.

f) Association F

Compound Sandstone Association

This association is defined as any rock unit of 10 m thickness that is composed of more than 50% sandstone of which less than 10% is facies 4 cross-bedded or bar-form sandstone (Fig. 2.19). At most exposures it comprises a sequence of compound sandstones with minor interstratified shales, single sandstones and breccias (Fig. 2.20). It is best exposed at Lothbeg Point and is also well exposed on the foreshore at Kintradwell, in the area around the Loth River between Crakaig Farm and the Allt-na-Cuile, on the foreshore to the northeast of the Midgarty Burn and in a raised beach to the northeast of the Sput Burn (Fig. 2.3). The exposures, excluding the Sput Burn locality, are cymodoce or mutabilis zone in age (Fig. 2.21). The Sput Burn exposure is associated with subassociation AJ sequences and is probably an anomalous structurally controlled, fault-bounded unit (section 2.C). Most sequences are interstratified and gradational with associations D and E. Association F can occur as a sheet-like unit between other associations or as a lensoid pod enclosed in other associations. Association F sequences lie to the southeast of association A sequences and although its relationship to association G is not exposed, field evidence and palaeontology suggests that associations F and G are partial lateral equivalents.

The sequences are predominantly composed of subfacies 3B compound sandstones that can occur as lensoid units or more laterally continuous sheet-like units. The component sandstones are often mutually erosive which produces an amalgamated/lensoid bedding style which is common in this association (Fig. 2.25a). Some of the component sandstones display a well developed normal grading but others are poorly graded or non graded. This lack of grading is perhaps due to erosion of the finer tops of the sandstone.

A steeply dipping erosion surface, which is probably a palaeochannel margin, is exposed at Lothbeg Point (Fig. 2.25b) and is atypical of this association. Most inferred channel margins are gently dipping, implying deposition in shallow, wide channels. The sandstones are medium to coarse-grained and are generally coarser near to association A sequences and the Helmsdale Fault, and finer to the southeast. Most of the sandstones are quartz cemented, well sorted, friable, very porous and, if preserved at depths in the North Sea, would make excellent reservoir rocks. The breccias contain friable sandstone clasts which were probably derived from Jurassic rocks. They are usually graded and sometimes form the basal part of a fining-upwards sandstone sequence. They are most commonly developed close to the association A sequences. The shales are predominantly facies 1.A but some units are facies 1.B and show minor bioturbation.

g) Association G

Cross-bedded Sandstone Association

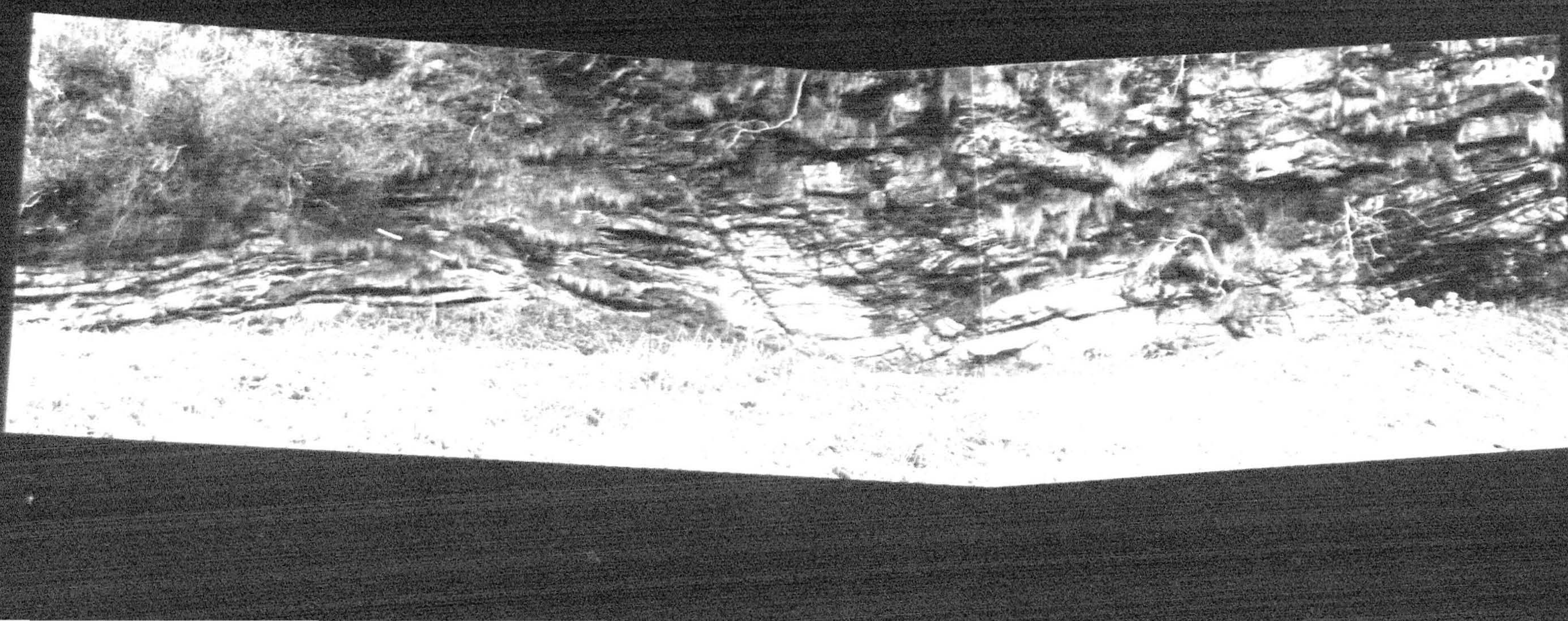
This association is defined as any rock unit of 10 m thickness that is composed of more than 50% sandstone of which more than 10% is facies 4 cross-bedded and bar-form compound sandstones (Fig. 2.19). It mostly comprises a complex sequence of interstratified compound sandstones, cross-bedded sandstones and breccias (Fig. 2.20). It is only exposed in various railway cuttings and streams in the region of the Allt-na-Cuile and the Allt-Choll and is Kimmeridgian cymodoce to mutabilis zone in age (Fig. 2.21). It overlies bioturbated shales and sands of associations E and D and lies to the southeast of, and interfingers with, association A sequences (Fig. 2.3). It is a partial lateral equivalent to association F sequences and is also probably laterally equivalent to the association D and F and subassociation CJ sequences at Kintradwell (Fig. 2.3). At extensive exposures it can be seen that the various cross-bedded sandstones, compound sandstones and breccias were predominantly deposited in broad relatively shallow channels. The best exposure of this association, an 8 m high railway cutting cliff 30 m to the east of Allt-na-Cuile, illustrates many of the features of this association. The exposure is approximately 35 m wide and is composed of five units each of which are bounded by gently dipping erosion surfaces (Fig. 2.26a). At many other localities inclined channel margin surfaces are well exposed (Fig. 2.26b). Another important exposure of this association occurs in a small stream to the northeast of the Allt Choll where two 2 m thick breccias are interstratified with cross-bedded and compound sandstones (Fig. 2.27a). Large single blocks of sandstone which have loaded into and deformed the underlying beds are also well exposed at this locality. Subsequent sedimentation was influenced by the topographic expression of these boulders and the overlying thin bedded and cross-bedded sandstones/

Fig. (2.26) <u>Association G</u>

a) Facies 3, 4 and 5 deposited between 4 erosion surfaces. Meter stick for scale. Railway cutting to the north east of the Allt-na-Cuile. NC. 941093.

b) Facies 3 and 4 deposited in a large channel. The other channel margin is exposed about 40 m to the right (E). Meter stick for scale. 100 m to the west of the Allt-na-Cuile. NC. 940092.


2.26a

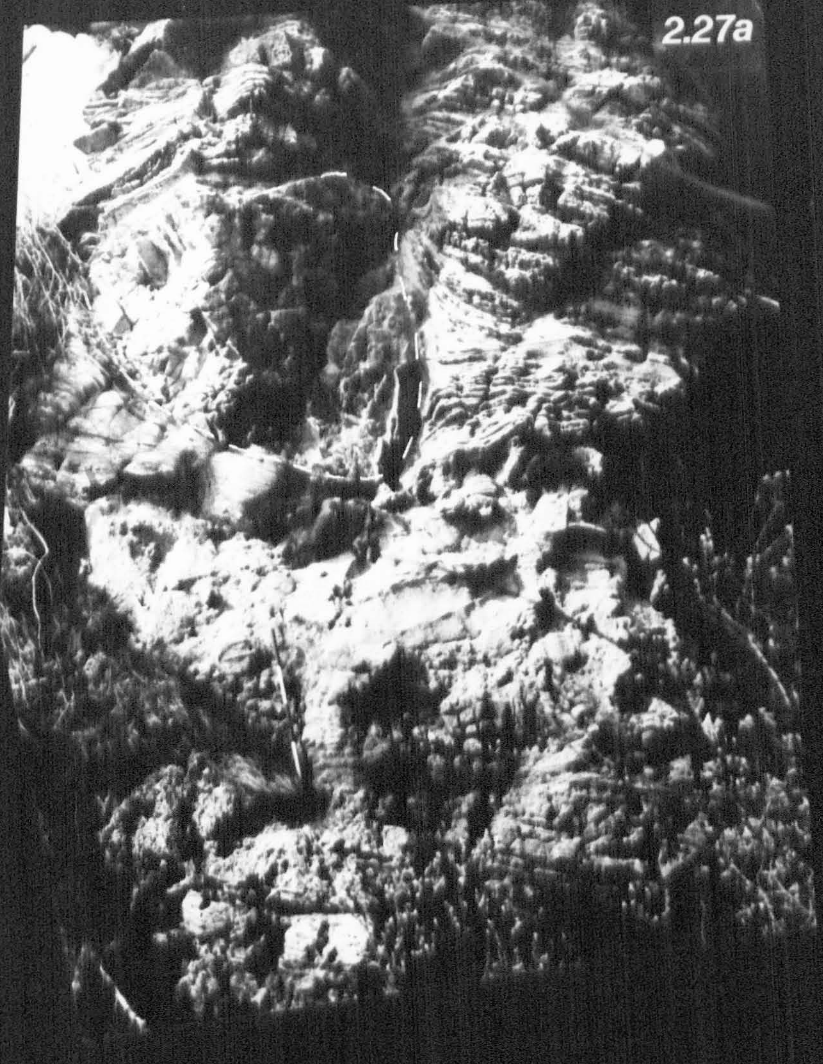


thin towards them and are ponded between them (Fig. 2.9e). In general the various sandstones and breccias are randomly interbedded. However, at some exposures there is a preferential sequence of erosion surface, overlain by medium bedded graded sandstones which are then overlain by cross bedded sandstones which are often extensively bioturbated.

Fig. (2.27) Association G

a) Complex interstratification of subfacies 3A, 4A and 5A. Note the large isolated boulders which have loaded into the underlying sediment and formed topographic features which have controlled the subsequent sedimentation. (see also Fig. 2.9a). Meter stick for scale. Small river to the east of the Allt-Choll. NC. 938092.

b) Angular sandstone clasts in subfacies 5A breccia. Hammer is 40 cm long. Small river to the east of the Allt-Choll. NC. 938092.


2.27a


2.27b

(iv) Syn-sedimentary Deformation

The deformation described in this section affects discrete units of strata less than 20 m thick and is therefore considered to have occurred penecontemporaneously with sedimentation. The syn-sedimentary deformation, which is common throughout the sequence but is best developed in cymodoce zone strata on the foreshore at Kintradwell, includes faults, folds, disconformities and sandstone dykes.

a) Normal Faults

Pickering (1983) describes several types of faulting from the Kintradwell sequences and relates them to various processes including; earthquake shock waves, oversteepening of the sedimentary pile, overburden pressures and hydraulic fracturing. Small-scale (1-30 cm throw) normal faults are ubiquitous in the shale rich sequences (Fig. 2.28a). As normals to the fault planes plot randomly on a stereonet (Fig. 2.28f) it is probable that they are only of very local significance and are related to local conditions and processes. Many of them underlie breccias that have loaded into the sediment. Some of the small-scale faults are therefore probably related to local overburden pressure as described by Pickering (1983). Larger scale normal faults are exposed in some river and raised beach cliffs (Fig. 2.28b). Most have listric profiles and normals to the fault planes plot towards the west and northwest on a lower projection stereonet (Fig. 2.28g). The larger scale faults are, thus, probably related to failure of the sedimentary pile on the east to southeast dipping slope established by earlier workers (Crowell, 1961; Pickering, 1984).

b) Intraformational Disconformities

Disconformities are common in many of the shale rich sequences. The angles of discordance can vary from a few degrees to 45° (Fig. 2.28c). Where high dips are encountered they are invariably towards the northwest and/

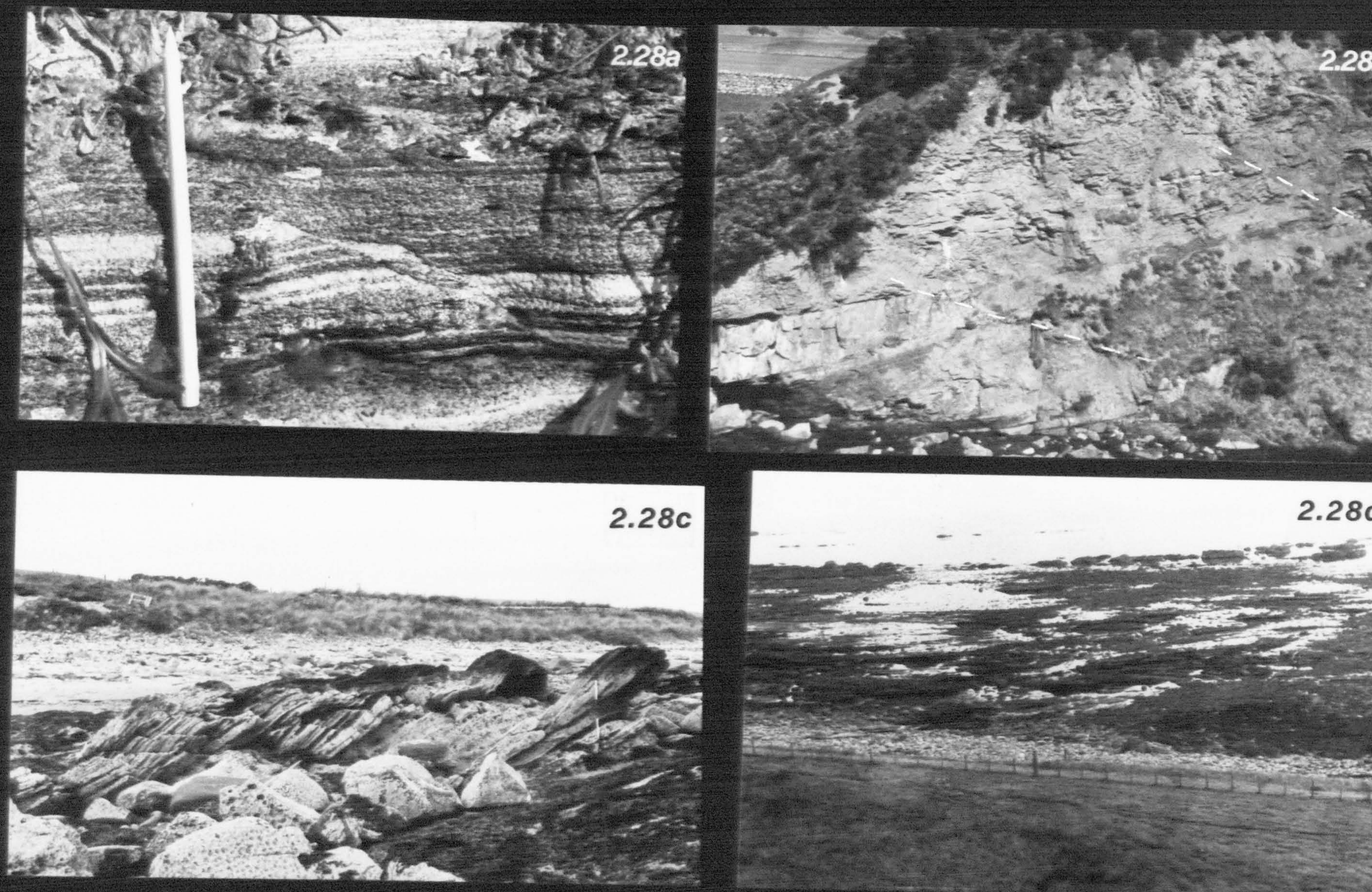
Fig. (2.28a-d) <u>Syn-sedimentary Deformation</u>

a) Small-scale normal faults. Pencil for scale. Lothbeg Point. NC. 961096.

b) Large-scale listric normal faults. The sandstone at the bottom left of the outcrop is 2.5 m thick. The Loth River. NC. 952099.

c) Disconformable unit of strata with anomalously high dips, the enclosing strata are relatively flat lying, ? product of rotational sliding. Foreshore at Kintradwell. NC. 926074.

d) Several disconformable units of association E shales. The person at the right of the photograph is 2 m. Foreshore between Helmsdale and Navidale. ND. 038155.


2.28a
2.28b
2.28c
2.28d

could be related to rotational movements on curved shear surfaces. The northwest dips are again consistent with failure on a southeast dipping slope. Some of the disconformities are draped by the overlying shaley sediment. They are similar to features described by Laird (1968) and Dott and Bird (1979) and may represent the filling of slump scars. Large scale disconformities with relatively low angles of discordance (Fig. 2.28d) may reflect large scale slumping on the slope and may be the result of tilting of the sediment during movements on the Helmsdale Fault. At some well exposed disconformities on the foreshore at Kintradwell, silty beds onlap onto a subhorizontal discontinuity (Fig. 2.28e) and therefore have the appearance of cross-bedding. There is no evidence of deformation above or below the sharp decollment surface which may be the flat lying basal part of a listric fault.

c) Folding

Soft sediment folding is very common at Kintradwell but rarer throughout the rest of the sequence. Some nappe like folds have inverted lower limbs (Fig. 2.29a,b). The sense of overturning of these folds plot between 020° and 225° on a stereonet and therefore broadly corroborate the existence of a southeast dipping slope. However, with most folds it is difficult to interpret the sense of movement as they are highly contorted, complex structures which are often associated with reverse faults and thrusts that usually dip in several different directions at each outcrop. The nappe-like folds were probably formed by failure of the slope during fault-controlled oversteepening of the sedimentary pile. The 200° spread in the senses of overturning implies that much of the movement was towards local topographic lows; eg. channels or minor faults trending normal to the major basin bounding fault, rather than directly down the east or southeast dipping slope. The complexly contorted strata are also probably related to simple downslope failure of the sediment pile but, along/

Fig. (2.28e) Syn-sedimentary Deformation

This exposure is of a disconformity in which the overlying silty shales apparently onlap onto a subhorizontal discontinuity. The decollement surface may be the flat lying basal part of a listric fault. Hammer is 40 cm long. Foreshore at Kintradwell. NC. 926074.

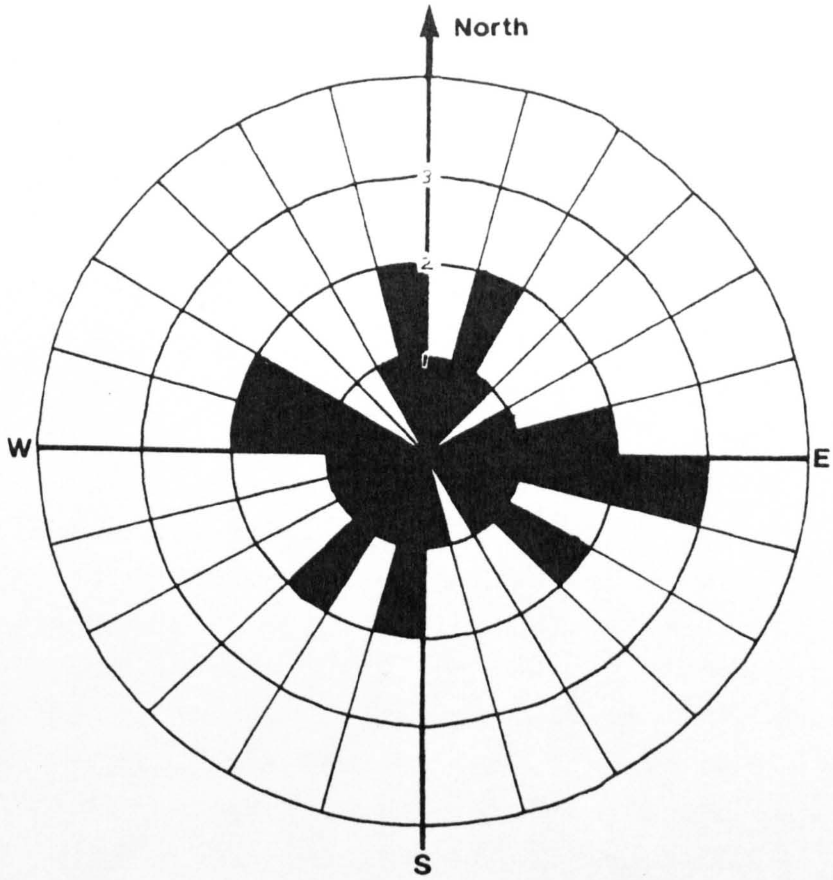

2.28e

Fig. (2.28)cont <u>Rose Diagrams of Syn-Sedimentary Fault Data.</u>

f) Normals to small-scale (1-30cm throw) faults.

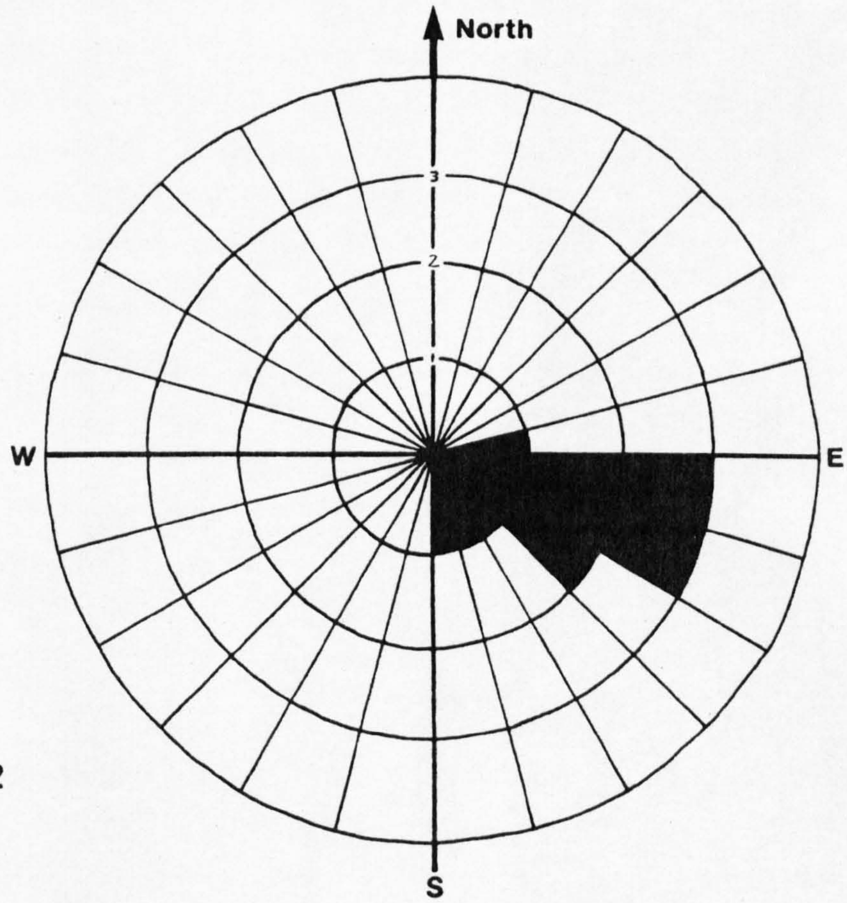
g) Normals to larger-scale faults.

Fig. 2.28.f



n = 30

Fig. 2.28.g



n = 12

with the reverse faults and thrusts, they may also be related to the compressional stresses generated in the basal parts of slides.

d) Sandstone dykes

Sandstone dykes occur sporadically throughout the succession, the largest of which is 70 cm across (Fig. 2.29c) and is known as the Kintradwell sandstone dyke (Bailey and Weir 1932). Most are clean, calcite-cemented, medium-grained, quartzose sandstones but some are coarse grained and contain shale and fossil plant fragments (Fig. 2.29d). Bailey and Weir (1932) ascribe the origin of the dykes to submarine fissuring and infilling from above but Pickering (1984) contests this hypothesis and states that "the dykes are clearly intrusive into overlying strata from below." Some of the dykes are clearly injected along fault planes but the origin of most of them is uncertain and most of the exposed sections are subhorizontal and normal to the probable direction of emplacement. The few exposed vertical sections show that some dykes protrude from the bases of sandstones whereas others have been injected upwards. They are manifestations of the general instability of the basin margin slope and probably represent both sediment fluidization initiated by earthquakes (Pickering, 1984) and the filling of submarine fissures (Bailey and Weir, 1932).

e) Complex brittle deformation

Some units of thinly bedded sandstone and shale, which lie between units of similar strata which are undeformed, have the appearance of intraformational breccias (Fig. 2.29e). Some sort of catastrophic failure of the sedimentary pile probably produced these textures which are similar to those associated with rockfall deposits (section 1.C(ii)).

f) Summary

The abundance of syn-sedimentary deformation features indicates that the basin margin slope was highly unstable during the Kimmeridgian and Volgian and the concentration/

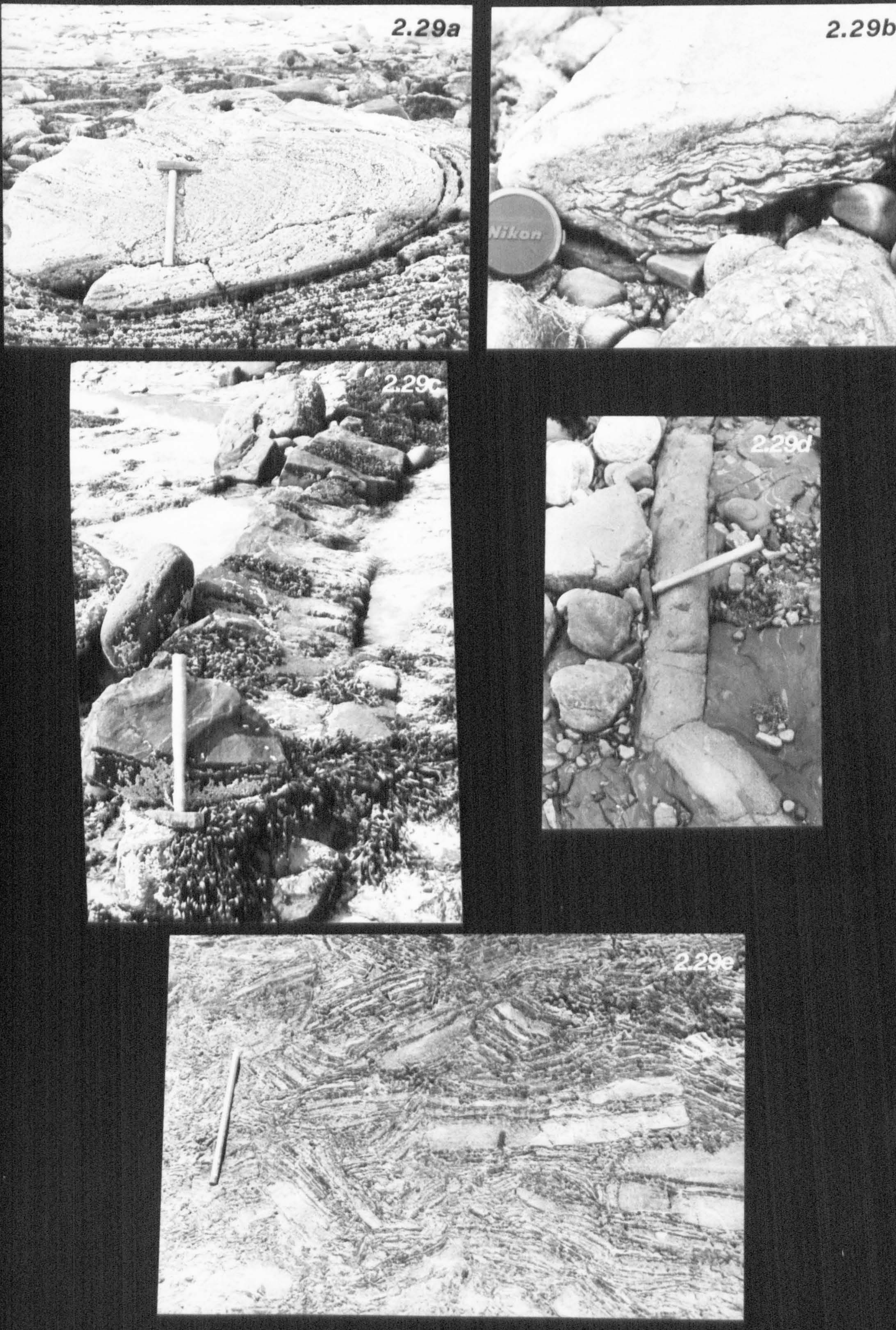
Fig. (2.29) Syn-sedimentary Deformation

a) and
b) Nappe like folds with inverted lower limbs. Hammer is 40 cm long. Foreshore at Kintradwell. NC. 926074.

c) The "Kintradwell dyke." Hammer is 40 cm long. Foreshore at Kintradwell. NC. 926074.

d) Coarse-grained sandstone dyke containing shale and plant fragments. Hammer is 40 cm long. Foreshore between Helmsdale and Navidale. ND. 038155.

e) Intraformational breccia due to complex brittle deformation. Pencil for scale. Road cut to the east of the Gartymore Burn. ND. 014138.


2.29a
2.29b
Nikon
2.29c
2.29d
2.29e

of deformation in the Kintradwell sequences suggests that the slope was most unstable during the cymodoce zone. Direction indicators confirm the interpretation of earlier workers that the slope dipped towards the southeast approximately normal to the Helmsdale Fault.

(v) Palaeocurrents

In general, palaeocurrent data is sparse and only 130 measurements were taken. The results of the data collected agrees with the conclusions of Crowell (1961) who, from 76 readings, concluded that both the sandstones and the breccias were emplaced from the northwest to the southeast on a southeast dipping slope. Most readings have not been corrected for structure as most dips are less than 20°. However, the cross-bedding readings taken in the region of the Allt-na-Cuile (Fig. 2.3) have been corrected for structure in an attempt at more detailed palaeoenvironmental reconstructions for that area.

The following were the most common palaeocurrent and palaeoflow indicators; cross-laminations (Fig. 2.7a), cross-bedding (Fig. 2.11), flute and groove marks (Fig. 2.8b), parting lineation, asymmetrically folded strata beneath breccias and sandstones (Fig. 2.31a,b) and a-axis alignment of clasts and shell fragments (Fig. 2.31c). The most accurate readings were taken from the tops of beds where bedding surfaces were exposed (Fig. 2.8c). Cross-lamination and cross-bedding readings were also estimated from 2-dimensional exposures which were perpendicular to bedding (Fig. 2.8d). Measurements of asymmetrical folds were also taken from 2-dimensional outcrops (Fig. 2.31a).

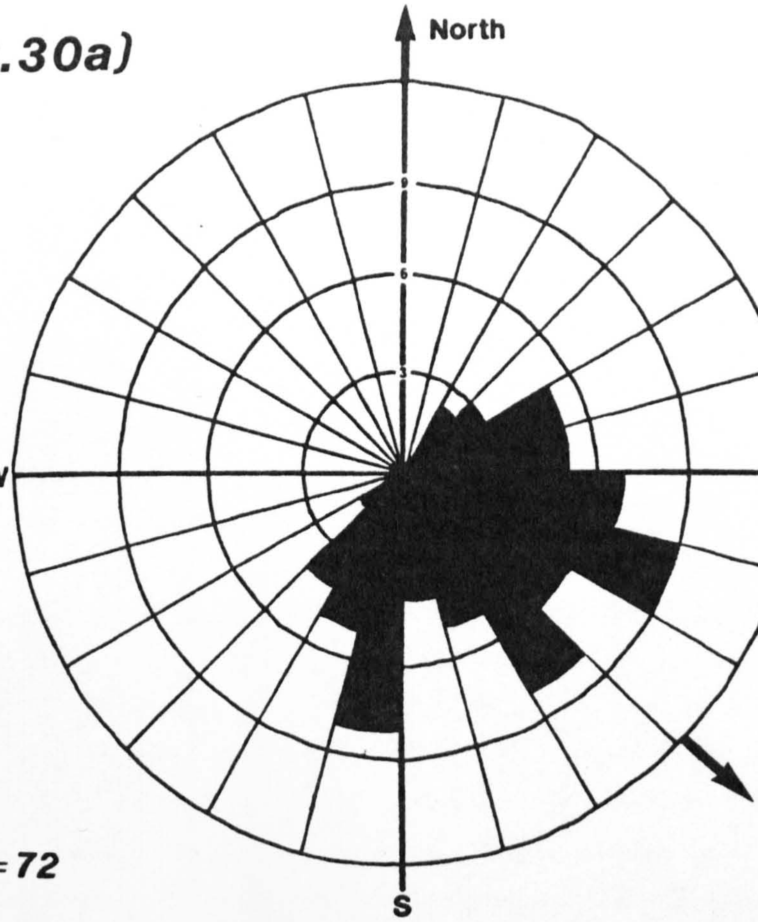
Sub-parallel alignment of clast a-axes was the most common sense of flow indicator observed in the breccias. In recent years it has been noted that during debris flow/

Fig. (2.30) Rose Diagrams of Palaeocurrent Data

a) Indicators which give direction of emplacement, eg. cross-lamination, cross-bedding, flute marks and asymmetrically folded strata beneath breccias and sandstones.

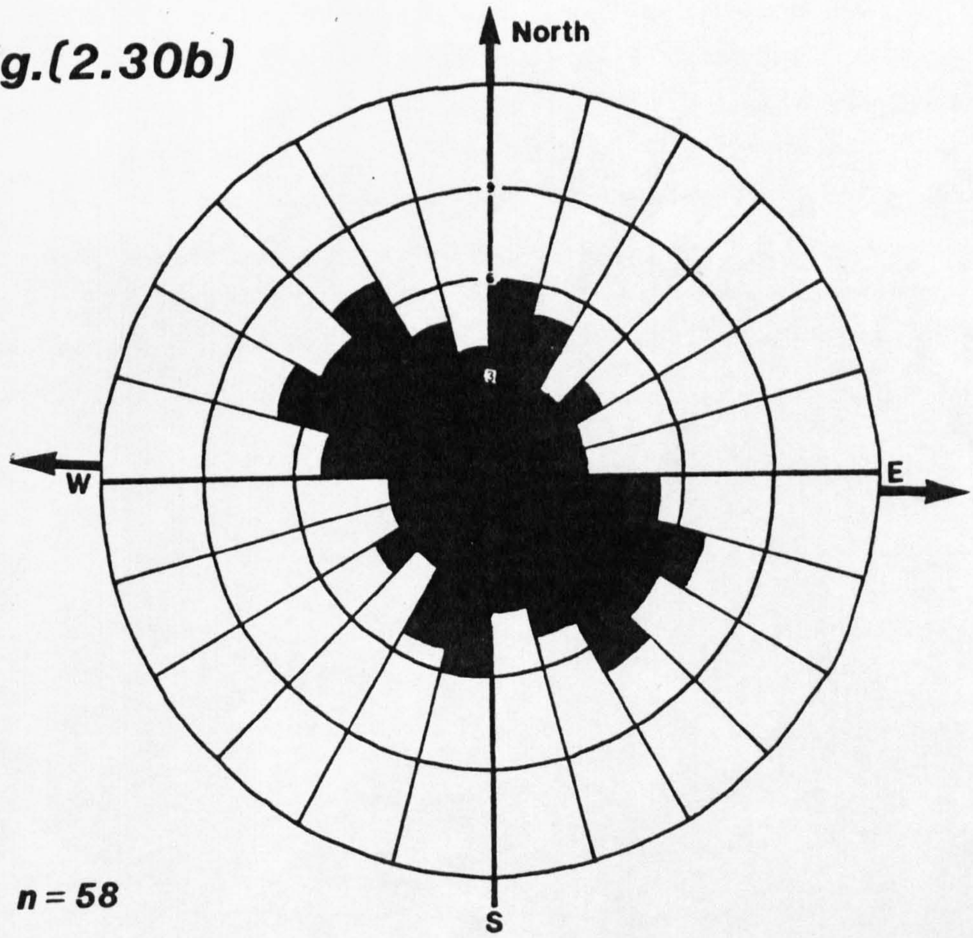
b) Indicators which only give sense of emplacement, eg. a-axis alignment of clasts and shell fragments, parting lineation and groove marks.

Fig.(2.30a)



n = 72

Fig.(2.30b)



n = 58

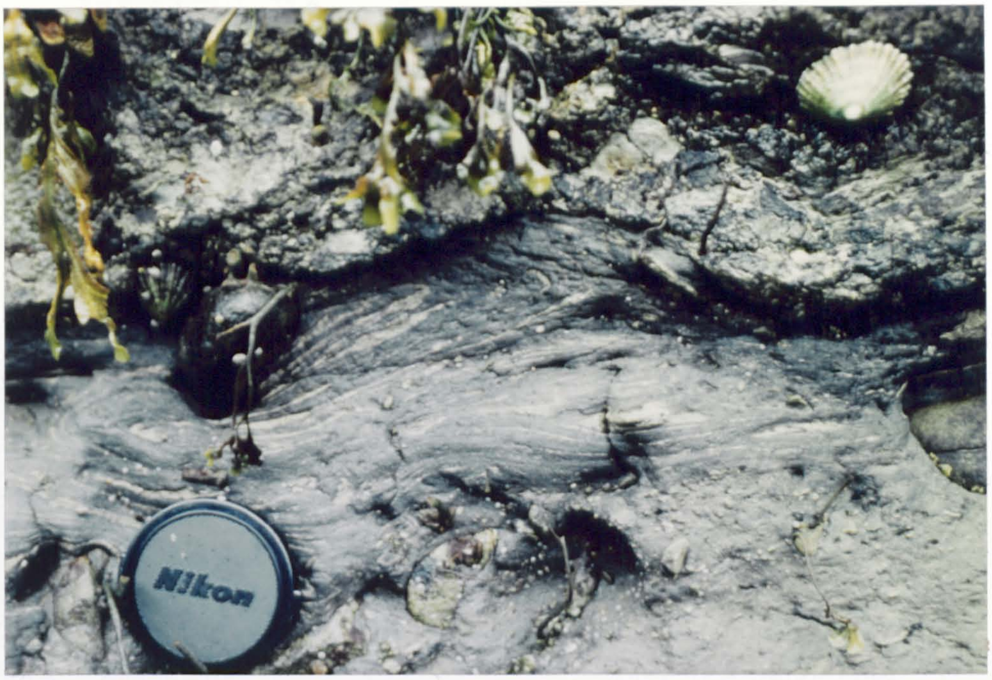
clasts are aligned with the smallest cross sectional area perpendicular to the direction of flow and a-axes parallel to flow (Rees, 1968). This observation has proved to be very useful in basin analysis where sequences are dominated by debris flow deposits (Surlyk, 1978; Walker, 1977). In the Helmsdale sequences sub-parallel alignment was observed in many of the relatively matrix rich breccias of subfacies 5.A and 5.C. Elongate shell fragments, eg. belemnites and echinoid spines, were also found to parallel the a-axes. In facies 2 the shell fragments were also found to have subparallel alignment (Fig. 2.31c) which was parallel to grooves in the bases of some sandstones.

The structures have been divided into two major groups; those which give direction and those which only give sense of movement (Fig. 2.30). Both groups of data show a fairly wide spread of readings but corroborate Crowell's results and show that sand and gravel were mostly emplaced from the northwest. No differences were noted between the directions measured from different types of structure and in general most locations had similar spreads of palaeocurrent readings. The subfacies 4.A trough-cross bedded sandstones (Fig. 2.11) exposed in the Allt-na-Cuile area again showed flow predominantly to the southeast and the facies 4.B bar form sandstones tended to onlap towards the west or northwest. If laterally accreted this would suggest flow to the south or southwest or to the north or northeast. However, the measurements were too few to allow reconstruction of palaeochannel trends.

Fig. (2.31) Palaeocurrent Indicators.

a) Asymmetrically folded mudstone underlying a breccia.

b) Alignment of shell fragments on the top of a sandstone.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(vi) Depositional Environment

a) Introduction

In this section the various depositional environments during the Kimmeridgian and Volgian at the western margin of the Inner Moray Firth Basin are inferred from the data presented above.

The coarseness and angularity of the clasts, the tight packing and disorganised nature of the breccias and its occurrence adjacent to a syn-sedimentary fault suggests that much of association A is a fossil submarine fault-scarp scree. The tight packing and the disorganised nature of the breccias is probably indicative of deposition by rolling or sliding rather than deposition from a debris flow in which some organisation of the clast fabric would be expected (section 1.C). The coarseness and the angularity of the clasts are consistent with relatively short transport distances. Johns (1978) and Surlyk (1978) interpret tightly packed and disorganised breccias as submarine fault-scarp scree deposits but examples of similar sequences in the literature are rare. The most commonly described fossil submarine talus slopes are those associated with forereefs and the textures associated with these deposits are very similar to those of association A breccias (Cook, 1972; MacIllreath, 1977; Enos and Moore, 1983). The stratigraphic distribution of the subfacies (Fig. 2.5) suggests that the fault-scarp evolved from being entirely composed of Jurassic strata during the cymodoce and mutabilis zones to being composed of both Jurassic and Devonian strata during the eudoxus and autissiodorensis zones and during the Volgian it was entirely composed of Devonian strata. The "fallen-stack" of Portgower is a 30 m long clast of Old Red Sandstone Flagstones (Fig. 2.13c). The bedding dips at 75 to the south and is approximately normal to the long axis of the clast. In the Old Red Sandstone exposed throughout the northeast of Scotland bedding is generally subhorizontal/

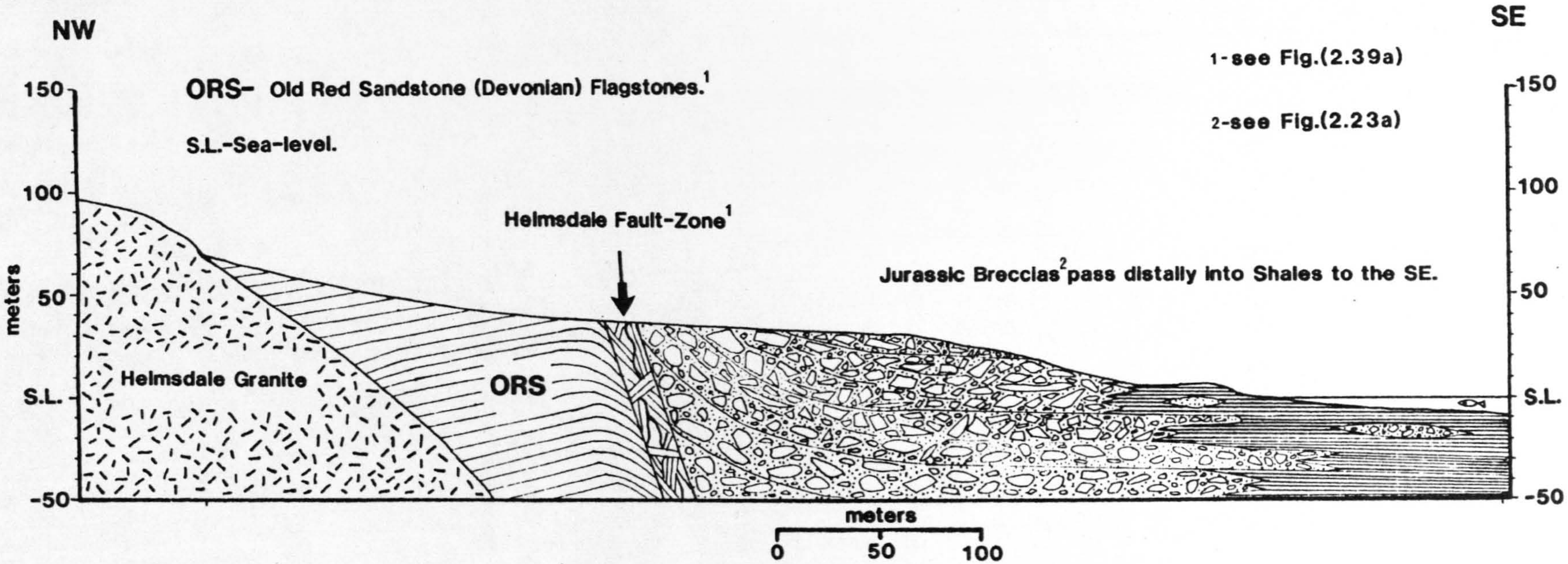
(Mykura, 1983). As it can be assumed that during the Jurassic, the Old Red Sandstone was subhorizontally bedded, the fault-scarp therefore reached a height of at least 30 m during the Kimmeridgian and Volgian.

The other associations occur to the southeast (basinwards) of association A and were probably deposited on or at the base of a submarine slope which was adjacent to a fault-scarp talus slope. In associations B, C, D and E the background sedimentation was the suspension settling of mud (subfacies 1.A) in a poorly oxygenated environment whereas the breccias and sandstones were generally deposited by frequent catastrophic events. The textures of the breccias of the muddy slope associations (B, C, D and E) tend to have more ordered clast fabrics than those of the talus slope association (A). Some of the muddy slope breccias are very tightly packed, have chaotic clast fabrics and were probably deposited after rolling and sliding down a steep slope, but others, which have aligned a-axes, c-axes normal to bedding, grading of clasts and largest clasts on top were probably deposited from debris flows and turbidity currents (section 2.B(i)). There is therefore a spatial distribution from rockfall near the fault to a mixture of debris flow, turbidity-current and rockfall on the muddy slope farther away from the fault. Failure of the talus slope pile during seismic events related to movements on the Helmsdale Fault probably initiated rock-slides or avalanches that evolved into the debris flows and turbidity-currents that transported the gravel and boulders across the muddy slope. The rockfall deposits probably die out rapidly to the southeast whereas the debris flows and turbidity-currents may have transported the coarse material for some distance to the southeast. However, the lack of gravel in boreholes to the east (Linsley et al, 1980; Chesher and Lawson, 1983) suggests that the gravel and boulders were not transported for long distances. Mapping shows that, in general, the breccias become fewer with increasing/

distance from the fault (Figs. 2.3 and 2.32). Movements on the boundary fault also probably caused the oversteepening of the slope sequences which resulted in the widespread soft-sediment deformation by folding and faulting.

As association A generally contains little sandstone it is unlikely that the currents that transported the sand onto the slope were initiated on the fault-scarp talus slope. Instead most of the turbidity-currents were probably initiated in the relatively shallow water shelf area to the northwest on the upthrown side of the fault (Bailey and Weir, 1932) during storms or seismic events. Channels cut across the slope tended to preferentially concentrate the transportation of sand and gravel to produce sandstone and breccia rich lenses in the more mud rich sequences (Fig. 2.23b). In cymodoce and mutabilis zone times the slope was very sand rich when compared with later Kimmeridgian and Volgian times. Some of the turbidity-currents that transported the sands of associations F and D may have been initiated during failure of the more sand rich fault-scarp talus slope that existed in the early Kimmeridgian. The sands were then deposited in channels or as sheetlike bodies on the slope. Association G is restricted both stratigraphically (Fig. 2.21) and spatially (Fig. 2.3). The presence of marine fossils and angular sandstone clasts (Fig. 2.27b) plus the lack of evidence of wave reworking suggests that this association was deposited in a marine environment below wave-base. If the environment was above wave-base one would expect more rounding of the clasts and some wave-reworked laminations or bedding. Deposition was predominantly in shallow shifting channels. The compound graded sandstones were deposited from turbidity-currents and the bioturbated, thin-bedded, non-graded and cross-bedded sandstones were deposited from traction currents when the rate of sand input was relatively low. Rock avalanches occasionally transported large boulders and deposited them in the channels. The environment envisaged for this association is a large/

Fig.(2.32) **Cross-Section B-B.** see Fig.(2.3)



submarine valley with smaller shifting channels on the valley floor in which traction currents reworked sand during periods of low input. The width of the valley probably approximately corresponds with the width of outcrop of association G which is 750 m. In some modern submarine valleys the traction currents flow both up and down the valley and the reversals are related to tidal cycles (Shepard et al, 1979), but in other valleys the reversals do not have a tidal periodicity. During storms the currents generally become unidirectional down the canyon and increase in velocity.

During major storms turbidity-currents are often initiated at the canyon head (Shepard et al, 1979) which then deposits graded sands in channels within the valley. The boulders may have been derived from the fault-scarp analagous to the facies association A breccias but others were probably derived from the collapse of the valley wall as similar talus deposits are common in submarine valleys (Shepard and Dill, 1966).

The interpretation by Pickering (1984) that the Kimmeridgian and Volgian sediments of East Sutherland were deposited on a fault controlled submarine slope is therefore corroborated by this study which demonstrates that a mud rich submarine slope cut by channels lay to the southeast of a fault-scarp talus slope. However, this study also demonstrates that the environments changed through time after the initiation of major faulting and basin subsidence.

b) Stratigraphic Evolution

The stratigraphic evolution of the western margin of the Inner Moray Firth Basin during the Kimmeridgian and Volgian is outlined in this section.

From the Lias to the Callovian faulting controlled sedimentation to some extent (Sykes, 1975), but the relative thinness of the sequences in East Sutherland/

(Fig. 2.2) and in the 11/30-1 well of the Beatrice oilfield (Fig. 5.2) demonstrates that overall subsidence rates were low. The relatively thick Oxfordian sequence in the 11/30-1 well implies that subsidence rates then increased. However, the great thicknesses of the Kimmeridgian and Volgian in East Sutherland (Fig. 2.2) and 11/30-1 (Fig. 5.2) sequences shows that the major faulting and basin subsidence took place during the Kimmeridgian and Volgian. The East Sutherland sequences are shallow or marginal marine from the Lias up to the baylei zone of the Kimmeridgian (Fig. 2.2). The youngest shallow water sediments are composed of (facies 1.B) bioturbated mudstones and sandstones (Fig. 2.6c) and are exposed on the foreshore between the Allt na Cuile and the Loth Burn where they underlie the Loth Formation (Fig. 2.3). They represent the top of the stable shelf sedimentation sequence and from the cymodoce zone upwards sedimentation took place on a relatively unstable submarine slope. The initiation of major basin margin faulting and subsidence was therefore probably in the baylei or cymodoce zones of the Kimmeridgian. This major faulting episode was contemporaneous with the upwards transition from relatively oxygenated bottom conditions (facies 1.B) to the poorly oxygenated bottom conditions (facies 1.A) which are characteristic of the Kimmeridge Clay Formation of northwest Europe (Deegan and Skull, 1977). The deposition and preservation of these organic-rich laminated mudstones which act as the source rocks for most of the North Sea oil was thus probably, in some way, related to major faulting episodes and basin deepening (Hallam, 1975).

After the initiation of faulting the proportions of the facies (Fig. 2.5) and facies associations (Fig. 2.21) changed through the Kimmeridgian and Volgian. In the cymodoce and mutabilis zones four co-existing sedimentary environments are recognised;

1. Fault-scarp talus slope; 2. Submarine valley;
3. Sandy Submarine slope; 4. Muddy submarine slope

(Fig. 2.33). Association AJ represents the relatively sandy talus slope environment and association G the/

submarine valley environment. The sandy slope environment is predominantly represented by association F and is well exposed in the Loth area and on the foreshore to the northeast of the Midgarty Burn (Fig. 2.3). The muddy slope is well exposed on the foreshore at Kintradwell and is predominantly represented by associations D and CJ.

In the cymodoce zone the muddy slope sediments, as exposed on the foreshore at Kintradwell, are more complexly folded and faulted than the other sequences, demonstrating the more frequent failure of the sedimentary pile. The rate of failure of slope sediments is related to the gradient of the slope and the deposition rate. As the cymodoce zone marks the initiation of rapid basin subsidence it is likely that the frequent failure is related to oversteepening of the sedimentary pile during movements on the Helmsdale Fault.

The Kintradwell sequences are also the only ones to show evidence of limited wave reworking. This is further evidence that the major basin deepening was initiated in the baylei or cymodoce zones. During the cymodoce zone the basin was still relatively shallow and was subjected to limited wave influences. The basin then subsided rapidly and by the mutabilis zone was entirely below wave base in relatively deep water. The sandy slope was probably deposited offshore from a major source of sand, eg. a river or a delta, whereas the muddy slope was comparatively starved of sediment and may have been deposited in the lee of a submarine canyon which tended to funnel sand transported by longshore drift from the shelf, producing a relatively muddy shelf and slope on the downcurrent side (Fig. 2.33a). Similar situations exist adjacent to many Californian Borderland submarine canyons (Haner and Gorsline, 1978). The relatively shell rich breccias and sandstones exposed at Kintradwell imply that the shelf to the northwest of the muddy slope supported a filter feeding epifaunal community, whereas the comparative lack/

of shells in the sandy slope sediments suggests that the source area for sediment was hostile to filter feeding fauna.

In the eudoxus zone only two major environmental subdivisions are recognised; a talus slope and a relatively muddy slope basinward of the talus slope (Fig. 2.33b). Subassociations AJ and AD represent the talus slope environment. The basin was therefore bounded by a fault-scarp which was composed of both Jurassic and Devonian strata. The basin now received less sand than in the earlier Kimmeridgian and the relatively muddy slope comprised associations B, C, D and E. The decrease in sand content was probably related to both the more indurated nature of the fault-scarp and a decrease in sand supply from the shelf which was probably the result of an increase in distance between the fault-scarp (shelf margin) and the shoreline (Fig. 2.33). This increase in shelf width may have been related to erosion and retreat of the land area, a marine transgression or to minor subsidence on the upthrown side of the fault.

In the autissiodorensis zone talus slope and muddy slope environments are still recognised. During this zone all the Jurassic was eroded from the upthrown side of the fault and the fault-scarp was entirely composed of Devonian strata.

The talus slope environment was composed of subassociation AD (Fig. 2.33). The muddy slope became even less sandy and mostly comprised associations C and E with minor B. Similar environments and facies associations are recognised throughout the early and middle Volgian. The decrease in sand content was probably due to a decrease in input from the shelf and the less sandy nature of the shelf area is corroborated by the occurrence of coral clasts in breccias of the autissiodorensis zone or younger (Fig. 2.12). In the earlier Kimmeridgian, the shelf was probably too sandy an environment for corals/

but as the sand content of the shelf decreased it became an excellent environment for the growth of coral reefs.

The schematic sequence of basin margin environments after the major increase in faulting and subsidence rates during the baylei or cymodoce zones is shown in (Fig. 2.33). The environments varied from a complicated sand-rich slope in the cymodoce zone to a less sand-rich slope in the eudoxus zone to a comparatively sediment starved basin-margin slope in the autissiodorensis zone and the Volgian (Fig. 2.34).

Fig.2.33 THE TEMPORAL VARIATION IN ENVIRONMENTS DURING THE KIMMERIDGIAN AND VOLGIAN.

a) CYMODOCE ZONE

b) EUDOXUS ZONE

c) AUTISSIODORENSIS ZONE TO MIDDLE VOLGIAN

Fig. 2.33a

cymodoce zone

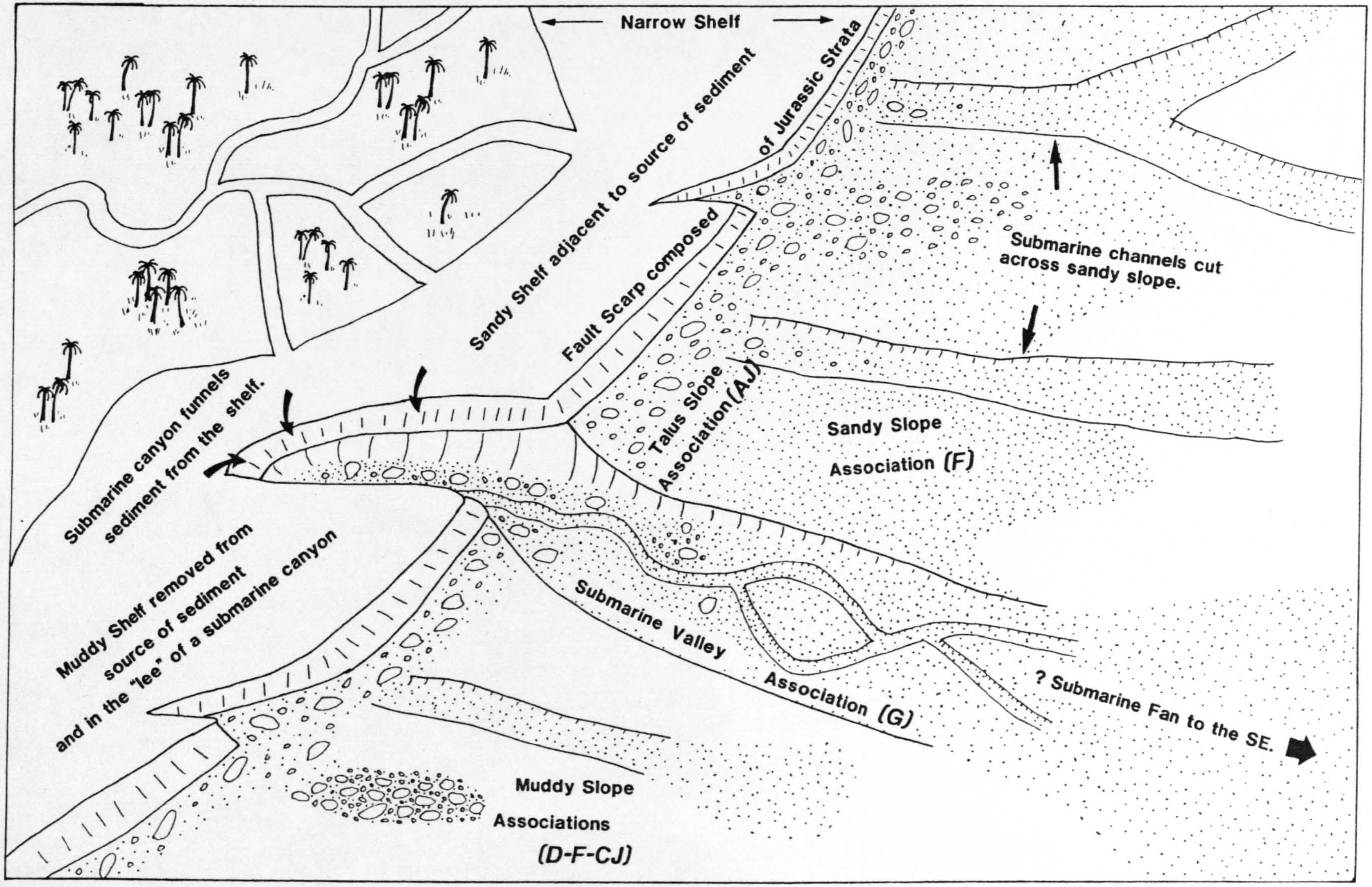


Fig. 2.33b

eudoxus zone

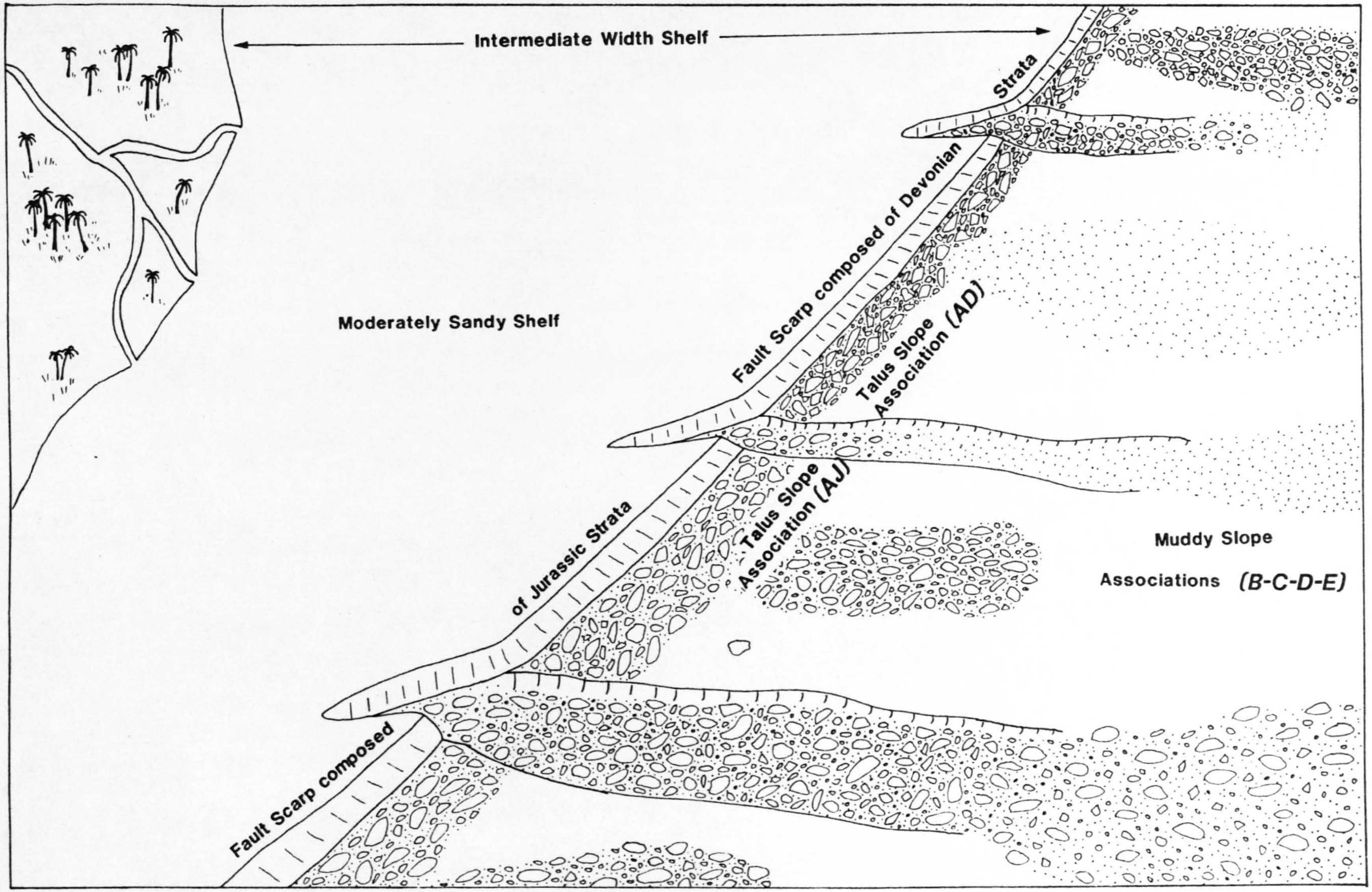


Fig. 2.33c

autissiodorensis zone to middle Volgian

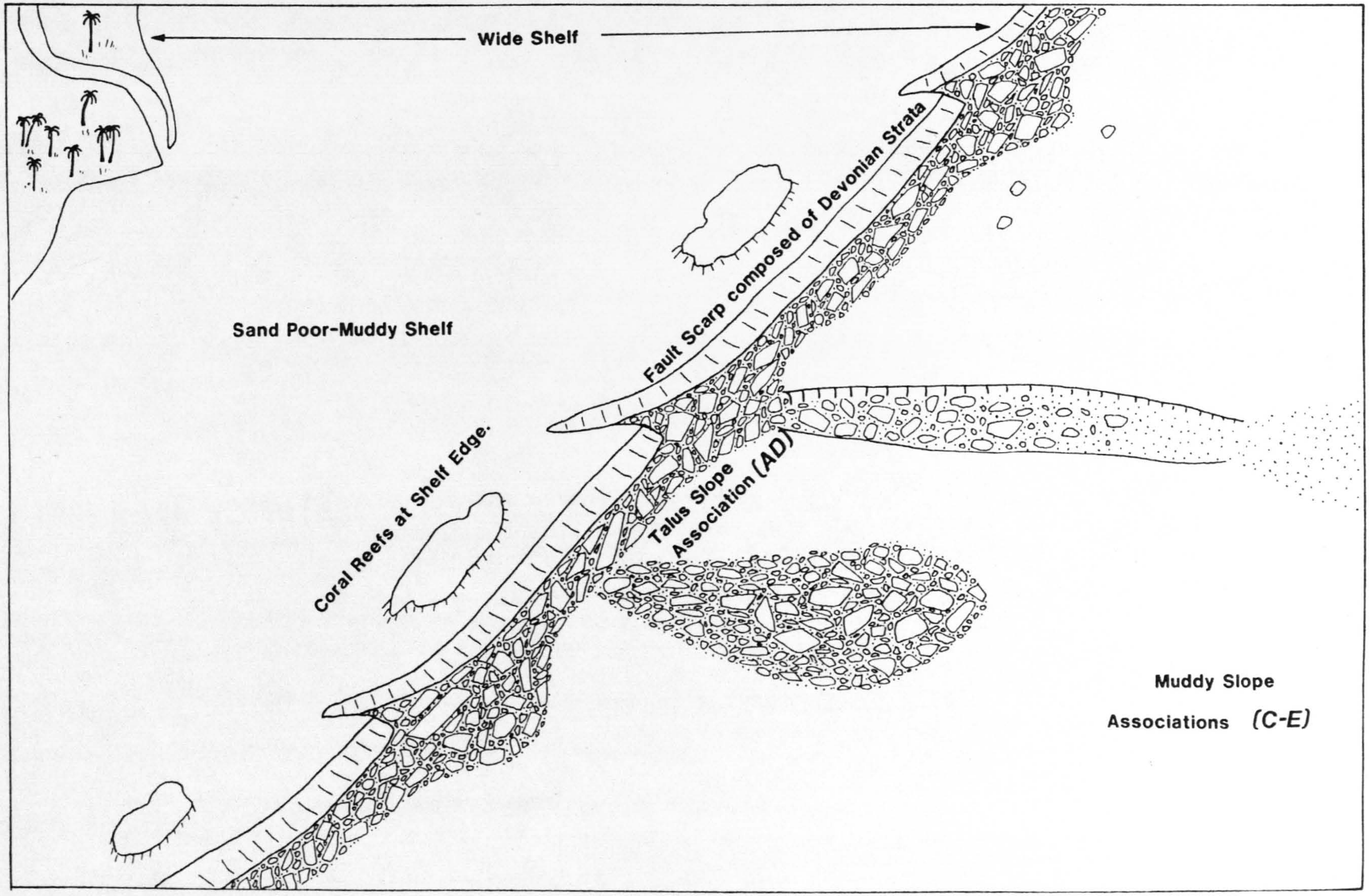
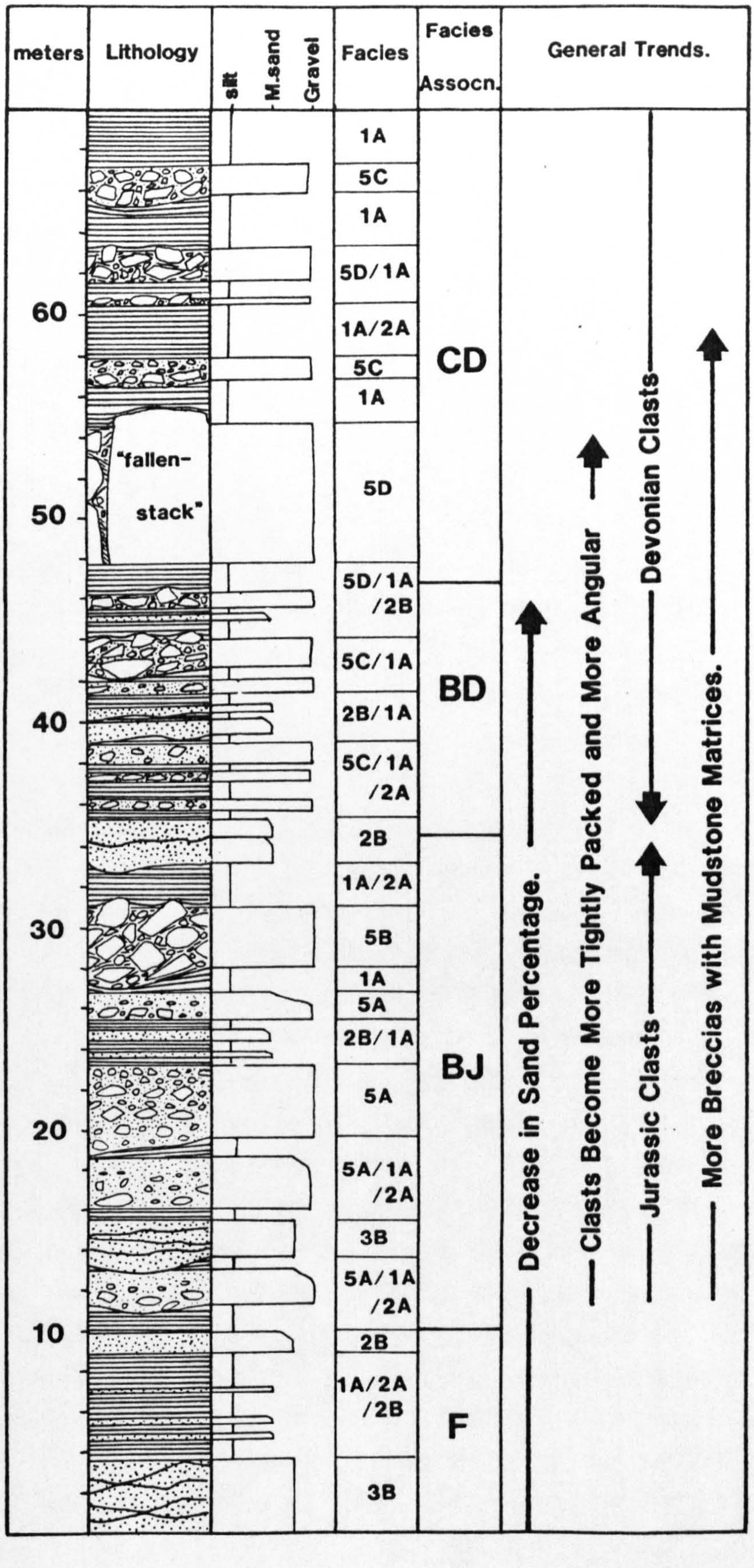


Fig.(2.34)

Stratigraphic Column of Section A-A. see Fig.(2.3)



2.C THE HELMSDALE FAULT AND FAULT ZONE

(i) Introduction

Although the Helmsdale Fault is the only exposed Jurassic basin-margin fault in the northern North Sea area, it has received little attention in the recent past and the best descriptions of the fault and adjacent strata are by Judd (1873). As faulting was important in controlling sedimentation in the hydrocarbon rich Jurassic basins the lack of oil industry interest in the Helmsdale Fault is surprising.

The fault and fault zone are well exposed in the gullies of streams that drain the Helmsdale Granite and in raised beach cliffs to the north-east of Helmsdale. They are also exposed to the south-west of the study area near Brora (Judd, 1873). Although it is best exposed between the Ord of Caithness and Golspie (Fig. 2.1) probable continuations of the fault can be followed south-westwards to the west of Dingwall where it downfaults Devonian against Moinian. To the North of the Ord it disappears under the Moray Firth and may continue northwards onto Shetland as the Walls Boundary Fault. The Helmsdale Fault is one of the north-east - south-west trending system which parallels the Great Glen Fault and was probably formed during the lower Palaeozoic contemporaneous with the Great Glen Fault. The outcrop pattern of the porphyritic and non porphyritic parts of the Helmsdale Granite (Fig. 2.1) suggests that the Helmsdale Fault cuts the granite in two and implies that the granite may have been emplaced up a proto-fault which has been reactivated as the Helmsdale Fault. As the granite is one of the post-tectonic Siluian to Devonian "newer granites" the Helmsdale Fault was probably in existence by at least basal Devonian times. During the Jurassic the Helmsdale Fault was the major fault at the western margin of the/

Inner Moray Firth Basin (Fig. 1.1) and as the thickness of Jurassic in the East Sutherland (Fig. 2.2) sequence and in the 11/30-1 well of the Beatrice Oilfield (Fig. 5.2) is over 1 km the Jurassic throw of the fault was at least that value.

As with most faults, at outcrop, the Helmsdale Fault is not a simple single fault. It is a shear zone which in some places is up to 75 m wide (Fig. 2.3). Movements along the fault led to the fracturing and folding of the adjacent lithologies.

(ii) Folding

In the north-east part of the study area, where the fault runs close to the foreshore exposures, the Jurassic strata are folded into "S" like folds and the direction of fold closures implies some post middle Volgian sinistral strike slip movement on the fault (Figs. 2.35; 2.36). Crowell (1961) recognised some possible crenulation cleavage associated with this folding in the shales near Navidale Bay. A major synclinal feature runs approximately ENE - SSW from Sron Rhuba na Gaothe to Loth. The strata to the north of the syncline dip to the south-east away from the fault and the strata to the south dip to the north-west towards the fault (Fig. 2.3). This situation is typical of fault margin sequences and the south-east dips are due to drag on the fault during later movements and the north west dips are due to the tilted asymmetrical nature of the Upper Jurassic Inner Moray Firth Basin (section 2.A). The general lack of dips to the south east in the Allt-Choll and Allt-na-Cuile area is anomalous and may in some way be related to the pronounced change in direction of the fault where it crosses the Loth River (Fig. 2.3).

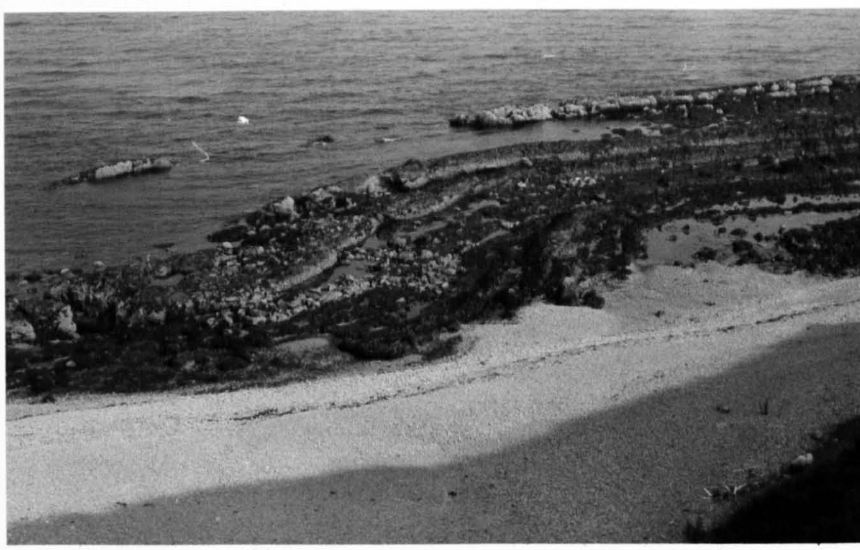
Fig. (2.35) <u>Tectonic Folding</u>

a) View of fold marked "X" in Fig. (2.36), looking to the north-east along the coast. Foreshore is approximately 40 m wide.

b) View of fold marked "Y" in Fig. (2.36), looking seawards to the south-east. Foreshore is approximately 25 m wide.

Fig. (2.36) <u>Schematic Diagram of Folding to the north east of Navidale</u>

The sense of fold closure implies some post middle Volgian strike-slip movements on the fault.



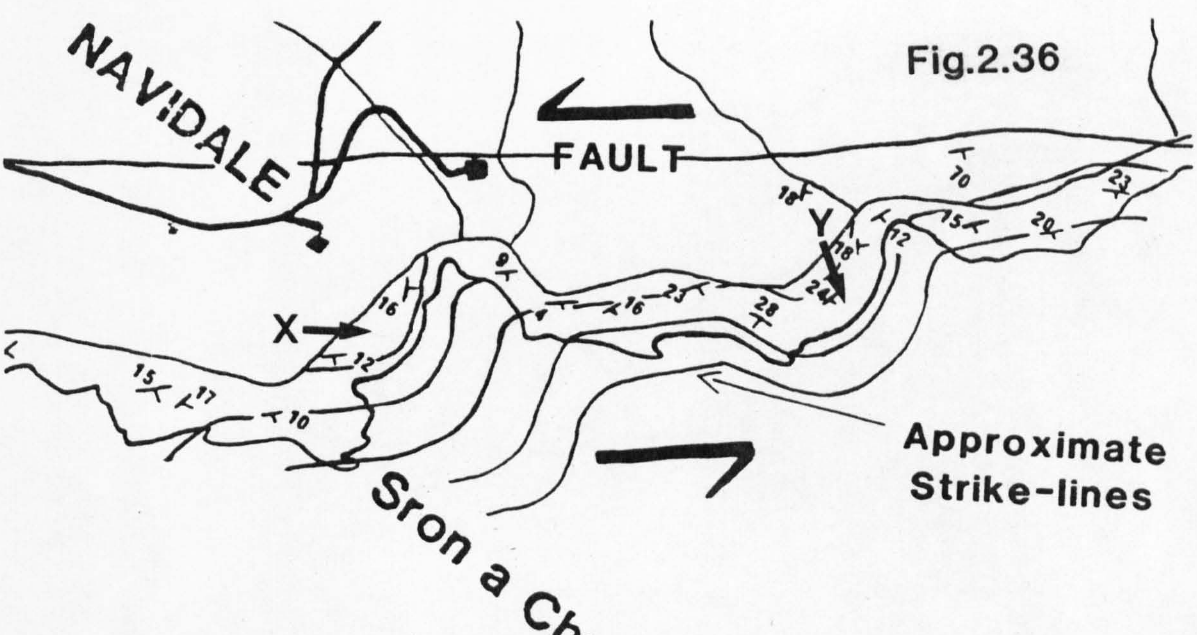

NAVIDALE
FAULT
X
Y
Approximate Strike-lines
Sron a Chrochair

Fig.2.36

(iii) Fracturing

Fracturing occurs in lithologies both to the north-west and south-east of the fault zone. To the south-west the Jurassic strata, within 250 m of the fault, are often cut by sub-vertical calcite filled fractures which are approximately parallel to the Helmsdale Fault (Fig. 2.37a, b). The calcite is a coarse dog-tooth spar. The fractures cut across and are clearly later than, and unrelated to the folds. As they are parallel to the fault they are probably related to a period of tensional faulting. To the north-west of the faults the Helmsdale Granite is extensively fractured in a zone up to 200 m wide and the fractures are again filled with coarse dog-tooth spar (Fig. 2.37c). Aerial photographs show lineaments which offset outcrops of granite and are approximately parallel to the fault (Fig. 2.3). They occur up to 500 m from the fault and are probably the result of shearing of the granite. To the north-east of Helmsdale the microgranite is hetrogeneous and zones of sandstone-like lithologies composed of angular fragments of quartz, feldspar and granite are in vertical contact with the microgranite (Fig. 2.37d and 2.38a). These zones probably reflect shearing within the granite.

In the Westgarty Burn and on the foreshore to the north-east of the north Allt Briste (Fig. 2.3) dark vienlets up to 4 cm across cut the fault-zone sediments. These vienlets contain hydrocarbon minerals (Parnell, 1983) and some sulphides (Fig. 2.38b).

(iv) The Fault Zone

The Helmsdale Fault-zone is up to 75 m wide and is composed of a variety of lithologies that are sub-vertically interstratified.

The best exposed sequence normal to the fault occurs in the Garbh-Allt (Fig. 2.32) where Middle Old Red Sandstone/

Fig. (2.37) <u>Fracturing</u>

a) A breccia cut by a fracture filled with coarse grained calcite. Marker pen is 10 cm long. Foreshore to the south of Navidale Bay. ND. 042159.

b) A breccia cut by subparallel fractures which are filled with coarse grained calcite. Meter stick for scale. Foreshore to the east of Navidale. ND. 044160.

c) Highly fractured Helmsdale Granite cut by a 40 cm wide fracture which is filled with coarse grained calcite. Meter stick for scale. Granite cliffs between Dun Glas and the Ord of Caithness. ND. 061174.

d) Vertical surface in the Helmsdale Granite. To the left of the meter stick is "normal" microgranite, to the right is a badly weathered sandy granite, which may represent a shear zone (see Fig. 2.38a). N. Allt Briste. ND. 052171.

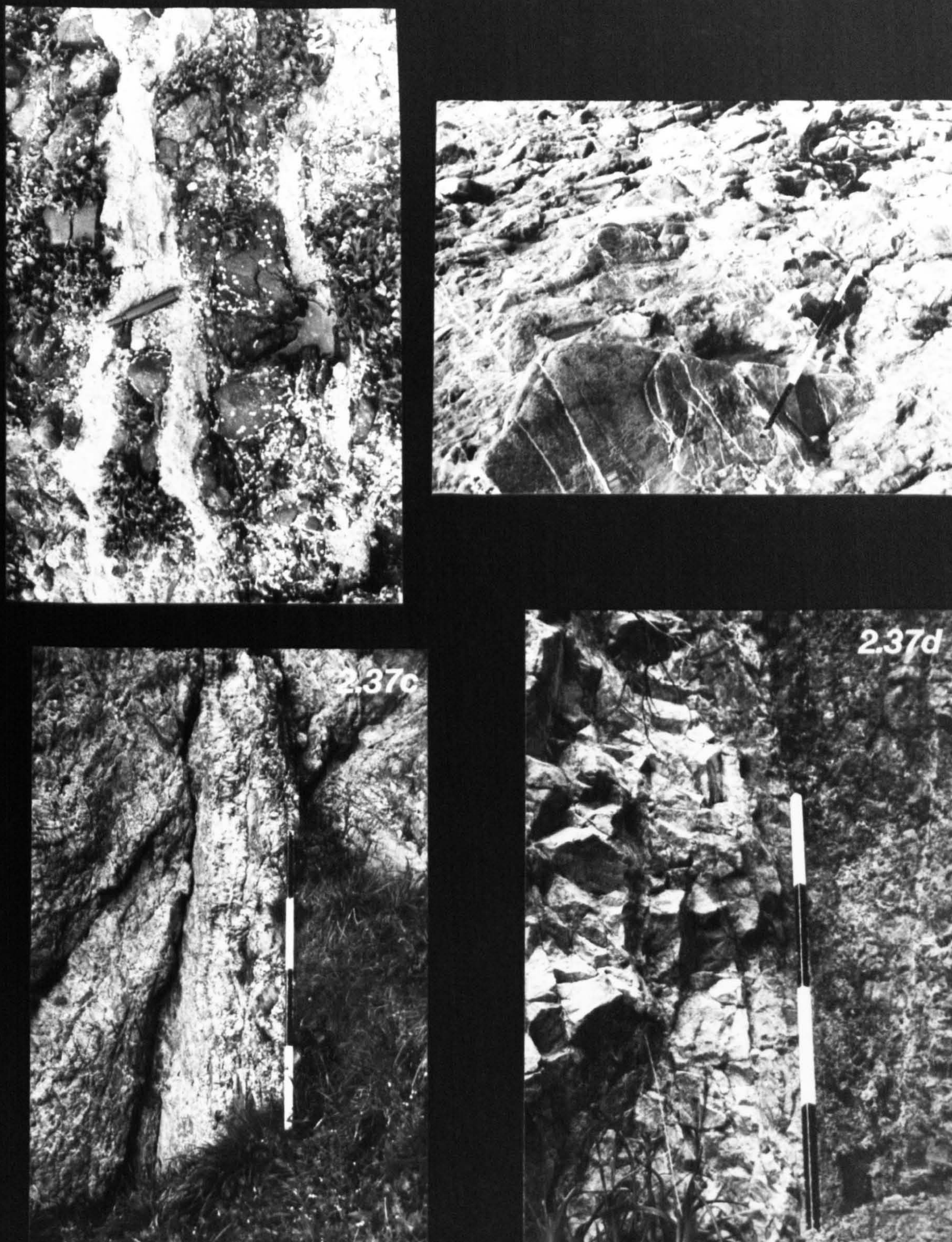
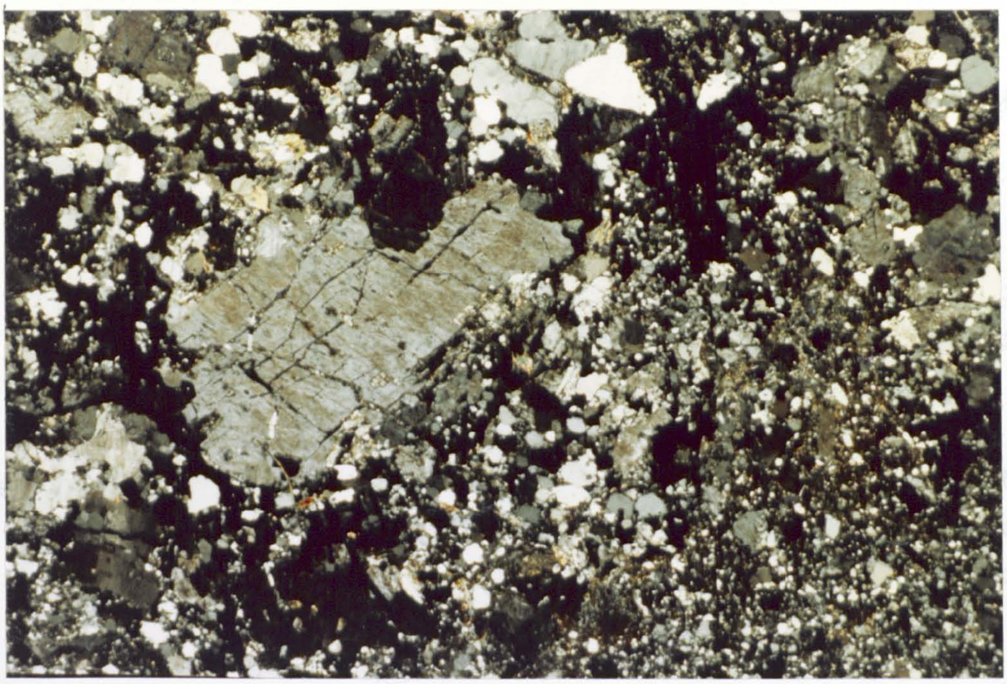

2.37c
2.37d

Fig. (2.38) Photomicrographs of Some Fault Zone Lithologies.

a) Thin-section of the "granite" to the right of the meter stick in Fig.2.37d. The small, equidimensional quartz grains with relatively straight crystal faces are reminiscent of metamorphic quartzes and may reflect shearing of the granite. Field of view 8mm.

b) Pyritic veinlet in fault zone sandstone to the northeast of the North Allt Briste. Field of view 8mm.



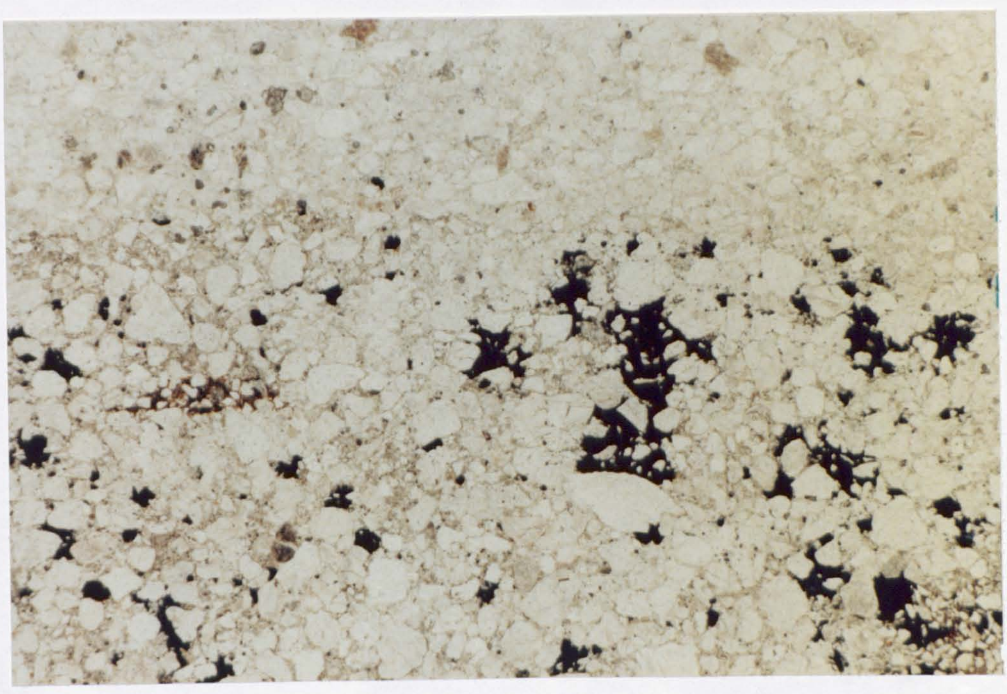
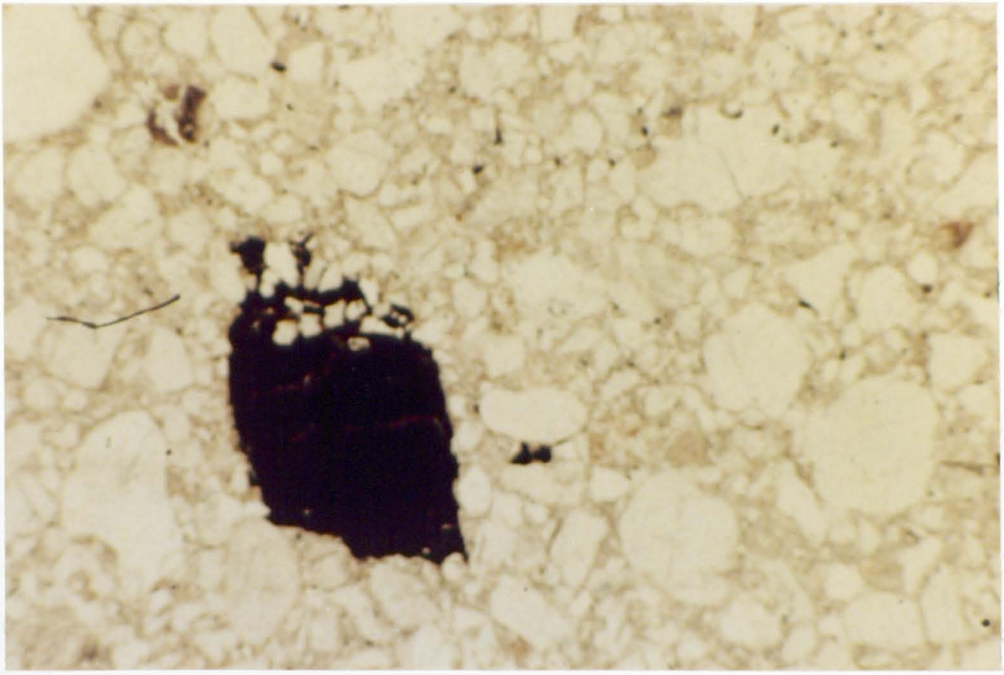
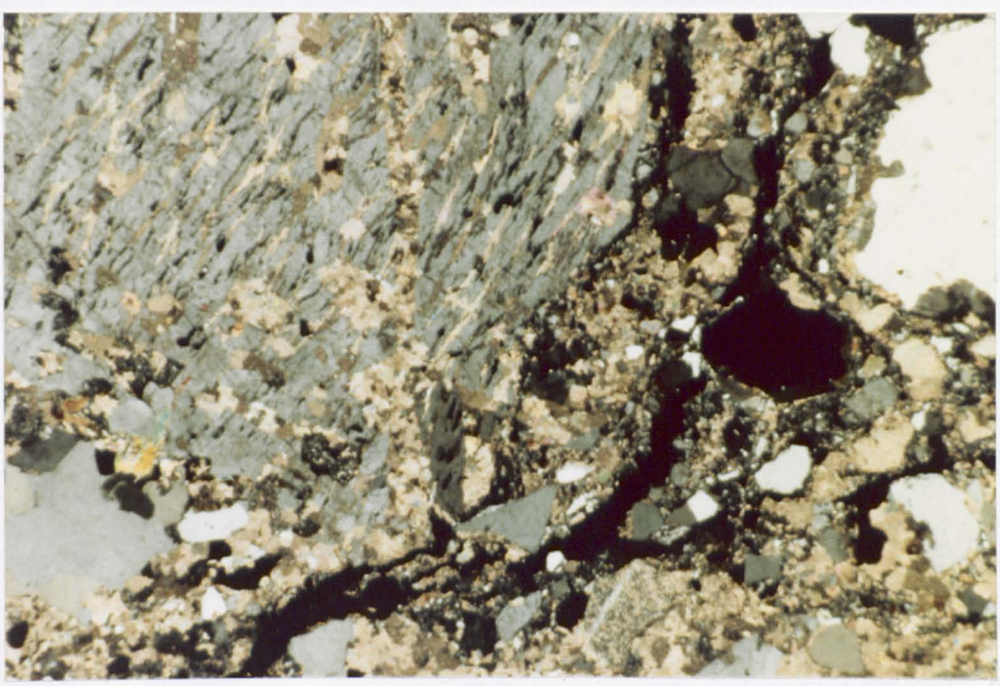


Fig. (2.38)cont Photomicrographs of Fault-Zone Lithologies in the Westgarty Burn. (see Fig.2.39b).

c) Coal fragment in the relatively mature sandstone illustrated towards the left of Fig.2.39b. Field of view 4mm.

d) A relatively immature "granitic" sandstone illustrated to the right of Fig.2.39b. Note the large feldspar and and the alteration by calcite. Field of view 8mm.





flagstones on approaching the fault change dip from 20°to the north to 80°to the south before dipping into a shear zone of mixed lithologies (Fig. 2.39a). For 50 m downstream some probable Old Red Sandstone strata are poorly exposed and have variable dips before Jurassic breccias dipping at 55°to the south are encountered. The dip of these breccias then decreases downstream away from the fault.

Probable Old Red Sandstone purple and grey sandstones are exposed adjacent to the fault in the Loth and Westgarty Burns. These sandstones contain variable amounts of angular feldspar and granite rock fragments. At these exposures there is a complex subvertical interstratification of sandstones and a granitic material which is composed of angular fragments of granite which have been partially replaced by calcite (Fig. 2.38c). These granitic rocks may be highly fractured granite or may be very immature sandstones. Bailey and Weir (1932) interpreted this apparent interstratification as an unconformity with the sandstones filling erosional hollows on top of a granite. In view of the complex shearing discussed earlier and the abundance of calcite filled fractures they could also be shear slices. In the Westgarty Burn an additional complication arises as the very immature granitic sandstones (Fig. 2.38c) are vertically interbedded with relatively mature quartzose sandstones containing coal fragments (Figs. 2.38d and 2.39b). The cause of this interbedding is difficult to resolve unless the sandstones were derived from two completely different source areas. They could also have been faulted or sheared into their present position but the bedding planes are very sharp and there is no evidence of slickensides.

To the north-east of Helmsdale probable Devonian conglomerates and grey sandstones occur adjacent to the Granite (Fig. 2.40). The conglomerates are composed of angular to rounded clasts of granite in a granitic sandstone matrix (Fig. 2.41a, b) and are similar to many basal Old Red Sandstone conglomerates found in the North of Scotland/

Fig. (2.39)

a) Old Red Sandstone Flagstones in the Allt Garbh. The dip of the beds increases towards the right (south east) of the outcrop until they become subvertical and highly sheared in the Helmsdale Fault Zone. Outcrop is about 4 m high. ND. 011139.

b) Fault-zone lithologies in the Westgarty Burn. This exposure shows a very sharp contact (? vertical bedding-plane) between a very immature granitic sandstone on the right and a relatively mature, coal bearing sandstone on the left (see Fig. 2.38c and d). Pencil for scale. NC. 989123.


2.39a


2.39b

(Mykura, 1983). In the Ord Burn (Fig. 2.3), directly to the south-east of the Helmsdale Granite, there is a zone composed of granitic material and sandstones which are vertically interstratified (Figs. 2.40 and 2.41c). The granitic material again may be a sheared granite or may be a very immature sandstone. An anomalous sequence of associations AJ and F has also apparently been caught up in the fault zone (section 2.B(iii)), (Fig. 2.41d).

The Helmsdale Fault-zone contains a complex variety of lithologies and it would be necessary to carry out further work, especially a petrographic analysis, to resolve some of the problems outlined above.

(v) Summary

The Helmsdale Fault is not a simple normal fault. An analysis of the folding and fracturing of the lithologies adjacent to the fault suggests that there was a post middle Volgian phase of movement that had a left lateral strike-slip component. This was followed by an essentially tensional phase which lead to the formation of fractures which were subsequently filled by coarse-grained calcite. In general, the fault and adjacent strata contain many interesting geological features, the significance of which have not been fully resolved in this thesis. Further work should prove to be rewarding.

Fig.(2.40) Cross-Section C-C. see Fig.(2.3)

2-see Fig.(2.41a,b)

1-see Fig.(2.41c)

S.L.-Sea-level

3-see Fig.(2.22b)

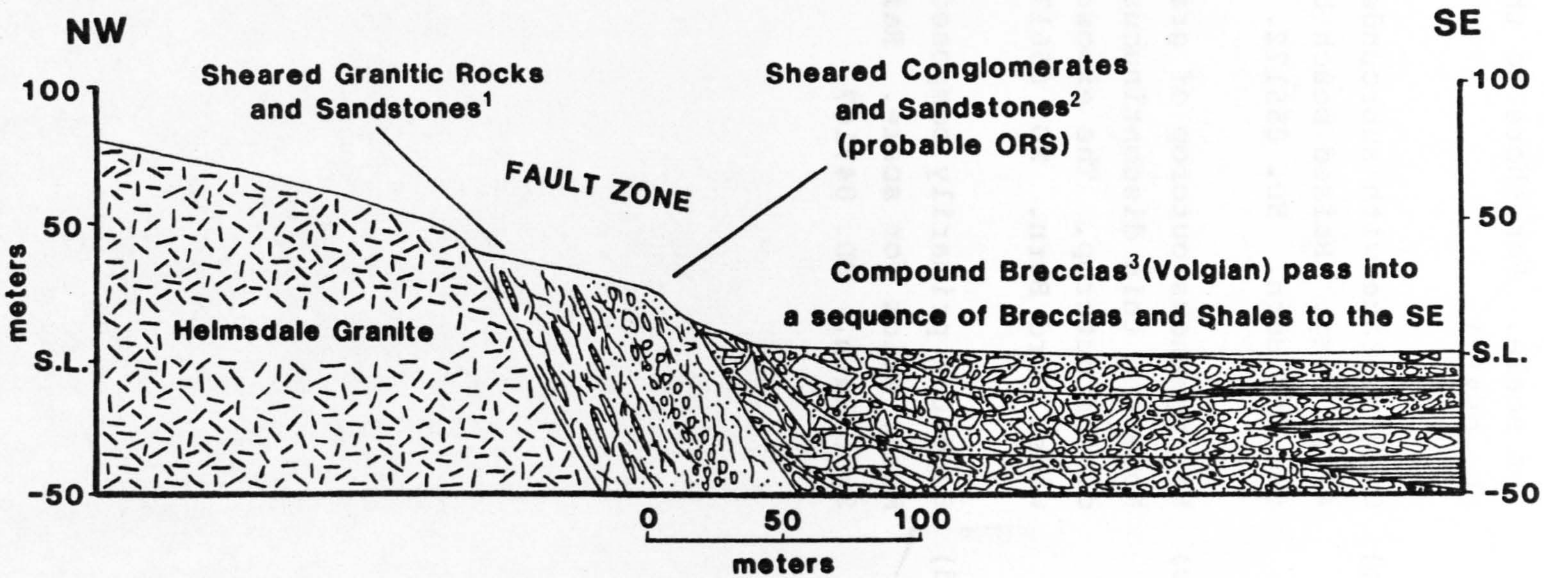


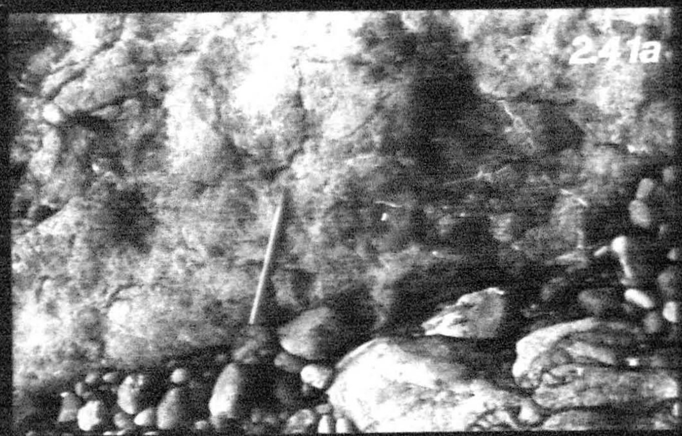
Fig. (2.41) Fault-zone lithologies

a) Fractured breccia/conglomerate which is composed of granite clasts in a granitic sandstone matrix. Pencil for scale. Foreshore to the east of the N. Allt Briste. ND. 052171.

b) Conglomerate with subrounded granite clasts. Hammer is 40 cm long. Raised beach between the N. Allt Briste and the Ord Burn. ND. 055172.

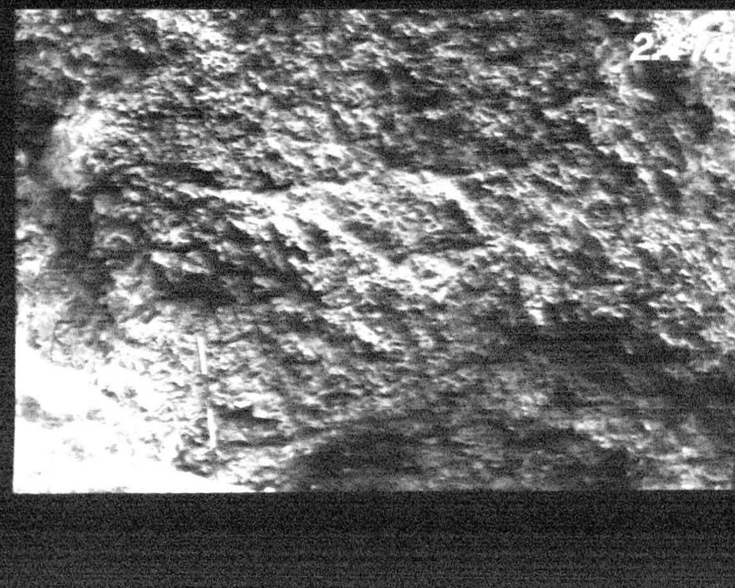
c) Hetrogeneous outcrop of granitic rocks and sandstones. Note the thin discontinuous sandstone bed at the base of the outcrop. The exposure is approximately 12 m wide. Ord Burn. ND. 056173.

d) Exposure primarily composed of subassociation AJ. Meter stick for scale. Raised beach to the east of the Sput Burn. ND. 047167.


241a


241b


241c



2.D SUMMARY AND CONCLUSIONS

Liassic to Oxfordian deposition at the western margin of the Inner Moray Firth Basin generally took place in shallow or marginal marine environments. Fault related subsidence rates dramatically increased during the baylei or cymodoce zones of the Kimmeridgian and subsequent sediments were mostly deposited on a submarine slope which was below storm wave-base. A talus slope environment occurred adjacent to the Helmsdale Fault, which marked the western margin of the basin, and a relatively muddy slope environment occurred to the south-east of the talus slope. Turbidity-currents, debris flows and rockfalls transported sand, gravel and boulders across the muddy slope.

The most sand rich sequences occur in the cymodoce zone of the Kimmeridgian, immediately after the initiation of increased subsidence rates, and the sand content of the sequence decreases upwards through the Kimmeridgian until, in the Volgian, the Inner Moray Firth Basin was relatively starved of sand.

In the Helmsdale sequences the upwards passage from relatively oxygenated bottom conditions (Heather Formation of Deegan and Skull, 1977) to relatively anoxic bottom conditions (Kimmeridge Clay Formation) appears to be related to a major rifting phase, increased subsidence rates and basin deepening rather than to an eustatic sea-level rise as proposed by Rawson and Riley (1982, p. 2636). The end Kimmeridgian (Vail and Todd, 1981) and the end early Volgian (Rawson and Riley, 1982) regressions are not observed at the western margin of the Inner Moray Firth Basin. If sea-level fell, the shelf area which existed on the upthrown side of the Helmsdale Fault, should have become very shallow or even emergent. This would cause large influxes of sand into the basin. As these sand influxes/

are not observed at Helmsdale either;

a) the bold statement of Rawson and Riley (1982, p. 2628 that "......, the effects of eustatic sea-level changes were never completely masked by local tectonics."

is incorrect or

b) the middle Volgian age (Riley, 1980) is incorrect.

Chapter 3

The Sedimentology of the South Brae Oilfield

INTRODUCTION

The South Brae Oilfield is located at the western margin of the South Viking Graben adjacent to the Fladen Ground Spur (Fig. 1.1). The Kimmeridgian and Volgian reservoirs were deposited during an intense period of tectonic activity. Differential movements along the western bounding fault system of the South Viking Graben led to uplift and erosion of the Fladen Ground Spur to the west and deposition of conglomerates and sandstones as potential reservoir rocks in the graben to the east.

The oilfield was discovered in 1977 when the 16/7a-8 well, which was drilled near the crest of a seismically defined top Jurassic structural high, struck an oil bearing sequence of conglomerates, sandstones and mudstones which flowed at rates of up to 7812 barrels of oil per day (BOPD) from a 5/4" choke. During 1978 four more exploration wells were drilled (16/7a-10, 11, 12 and 13) which confirmed the discovery. Production drilling began in 1983 and by the summer of 1984 seven additional wells had been drilled.

The development plan for the field was based on the geological model described by Harms et al (1981) in which the principal reservoirs were deposited in shallow braided streams on a series of alluvial fans that prograded eastwards into the South Viking Graben Sea. Stow, Bishop and Mills (1982) disagreed with this model and proposed that the reservoirs were deposited in a small fault controlled submarine fan. In a discussion of the Stow et al paper, Harms and McMichael (1983) and Stow (1983) restated their original models. As the two models are incompatable and predict different reservoir geometries it was desirable to carry out a facies analysis to try to elucidate the environment of deposition of the South Brae reservoirs. An understanding of the environment of deposition should assist in defining reservoir geometries and hence optimise/

the development of the field.

(i) The South Viking Graben

The South Viking Graben is an approximately N-S oriented trough which is bounded by a southerly extension of the East Shetland Platform, the Fladen Ground Spur, to the west and the Utsira High to the east (Fig. 1.1). In the vicinity of the Brae oilfields it is approximately 45 km wide. The southerly margin is taken as the Andrew Ridge (Fig. 1.1) (Hamar et al 1980) and to the north it widens as it gradationally passes into the North Viking Graben.

It is generally thought that the graben was in existence by at least early Permian times (Glennie 1984). The oldest strata encountered in the Brae wells are of Kimmeridgian age. Therefore, the pre-Kimmeridgian stratigraphy is largely based on data from the T-Block (16/17) wells. The very deep 16/17-6 well, on the Toni structure (Fig. 4.1), illustrates the stratigraphy of the area (Fig. 3.1). The base of the sequence comprises red sandstones and minor shales of the Lower Permian Auk Formation which are overlain by buff dolomites of the Zechstein Halibut Bank Formation. The Middle Jurassic unconformably overlies a shale rich sequence which is assigned to the Triassic Smith Bank Formation. The Bajocian/Bathonian to Oxfordian sequence predominantly comprises sandstones, shales and coals which were deposited in marginal marine and fluvial environments. Conditions changed during the middle or late Oxfordian and the remainder of the Jurassic comprises sequences of conglomerates, sandstones and shales which were deposited in relatively deep water marine environments (Brown 1984). The late Volgian and Ryazanian comprises a typical sequence of Kimmeridge Clay Formation Shales.

Both well and seismic data (Chesher and Swallow 1985, Hamar et al 1980) show that middle Jurassic sediments

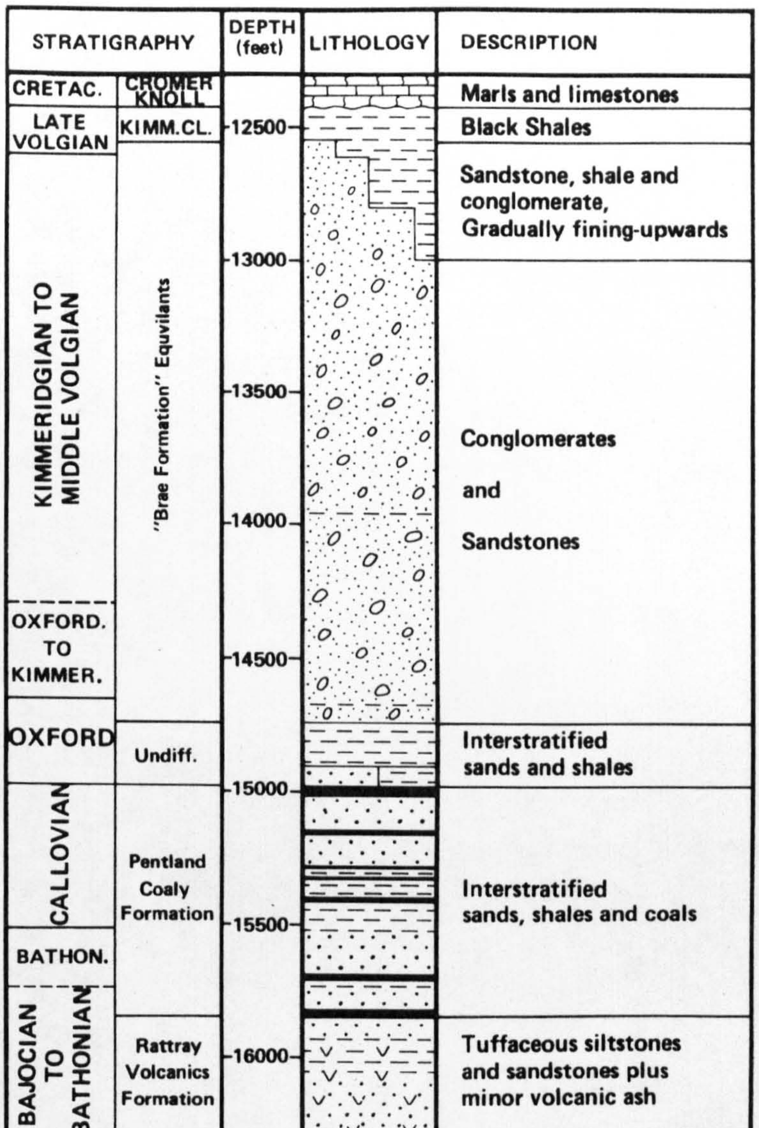


Fig.3.1.

South Viking Graben Stratigraphy, as illustrated by the 16/17 – 6 well.

were deposited in a broadly symmetrical graben, whereas during the late Jurassic subsidence was highly asymmetrial and most of the differential movements took place along the western margin of the basin (Fig. 3.2). Movements along the western margin were not uniform and "scissors-like" displacements took place, with the greatest late Jurassic throw, of approximately 2 km, in the region of the Brae Oilfields (Fig. 3.2a). The throw gradually diminishes to the south to 1 km or less in the T-Block (Fig. 3.2) and only minor displacements occurred in the 16/22 block. During the latest Jurassic and early Cretaceous there were movements along westerly dipping antithetic faults (Fig. 3.2) (Gibbs 1984) and the Lower Cretaceous is a relatively thin sequence. Thick Upper Cretaceous and Tertiary sequences were deposited during the epirogenic period of subsidence.

(ii) Stratigraphy

The biostratigraphical, micropalaeontolgical, and palynological data used in this study is based on the Robertson Research report numbers 2156, 2357, 2383, 2388 and 2397 which were written during 1977 and 1978, plus data from samples analysed at the Stratigraphical Laboratory of Britoil in Glasgow. Four of the wells were terminated, below the hydrocarbon-water contact, in sediments of Kimmeridgian age and the other well (16/7a-12) was terminated in basement of unknown age. The reservoir sequences are Kimmeridgian Gonyaulacysta cladophora to middle Volgain Muderongia sp.A zone (Fig. 1.2) in age. A Kimmeridge Clay sequence, which ranges from the middle Volgian Imbatodinium villosum to the Ryazanian Dingodinium spinosum zone (Fig. 1.2) in age, overlies the reservoir sequences. The sequences were dated using miospores and dinocysts which tend to be rather poorly preserved due to physical degradation and diagenetic alteration. Therefore, the stratigraphic control on sequences is relatively poor and precise correlations between wells are uncertain./

Fig.3.2 E-W CROSS-SECTIONS ACROSS THE SOUTH VIKING GRABEN.

(For location of sections see Fig.4.1)

Note the thickening of Upper Jurassic towards the East and North.

Based on Chesher and Swallow (1985).

The dashes represent areas with poor seismic reflections.

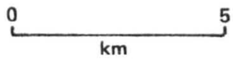


Fig. 3.2.a

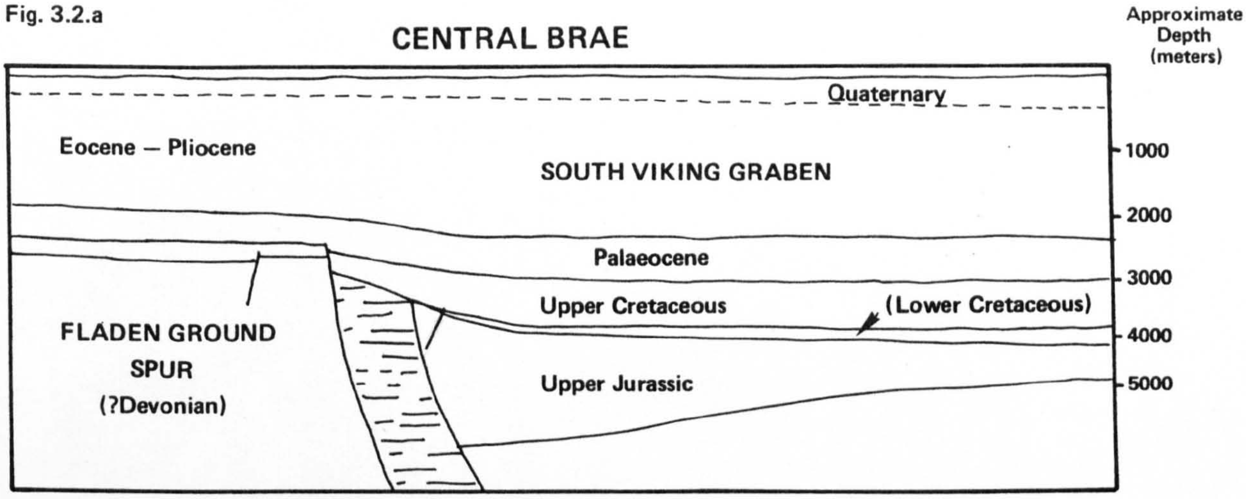


Fig. 3.2.b

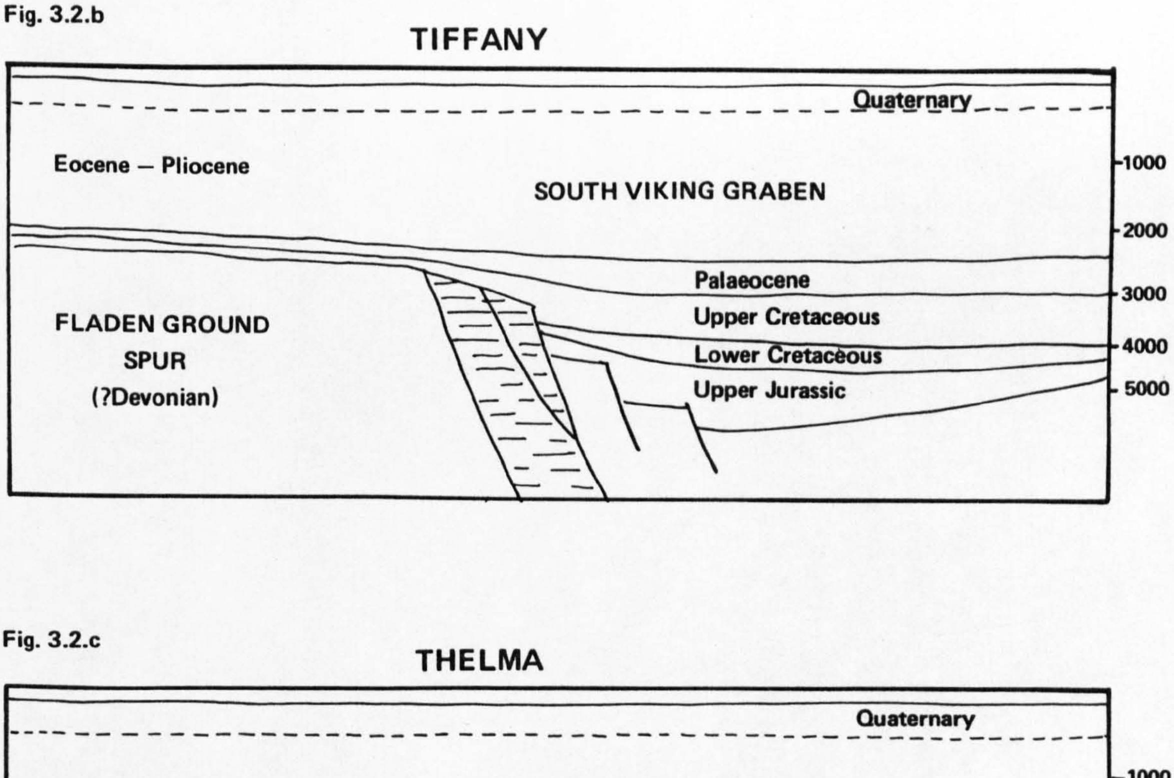
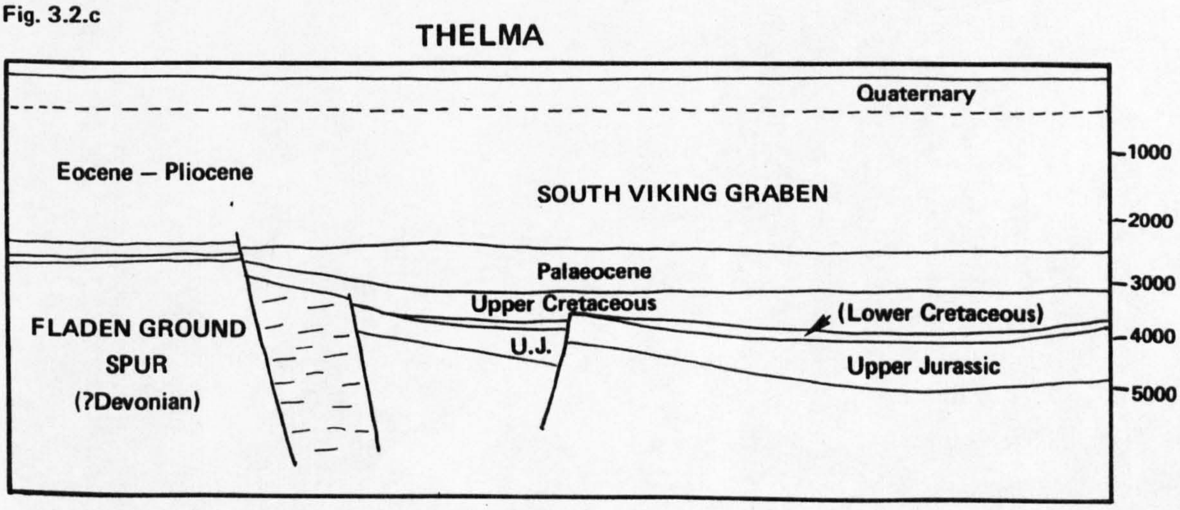


Fig. 3.2.c



(iii) Structure

A structure contour map of the 16/7a block showing depths to the reflector at the top of the Kimmeridge Clay Formation (Fig. 3.3) indicates 3 highs; a) in the vicinity of the 16/7-1 well (North Brae), b) a broad area including 16/7-3 and 16/7a-6 (Central Brae) and c) in the vicinity of 16/7a-8 (South Brae). Although the reflector is generally very complex to the west of an approximate N-S line running through 16/7-3 and 16/7a-8, it shows a latest Jurassic antithetic graben adjacent to the basin margin.

An E-W cross-section through South Brae (Fig. 3.4) shows the top Kimmeridge Clay reflector dipping gently to the east. However, changes in Cretaceous and Tertiary velocities and thicknesses away from the basin-margin may change the dip of the reflector. South Brae is mostly stratigraphically trapped against impermeable basement (? ORS) to the west and by the overlying Kimmeridge Clay. A "rollover" anticline (Gibbs 1984), which lies immediately to the east of the antithetic graben, provides limited structural trapping. Attempts at detailed mapping of the intra-late Jurassic reflectors have only had limited success.

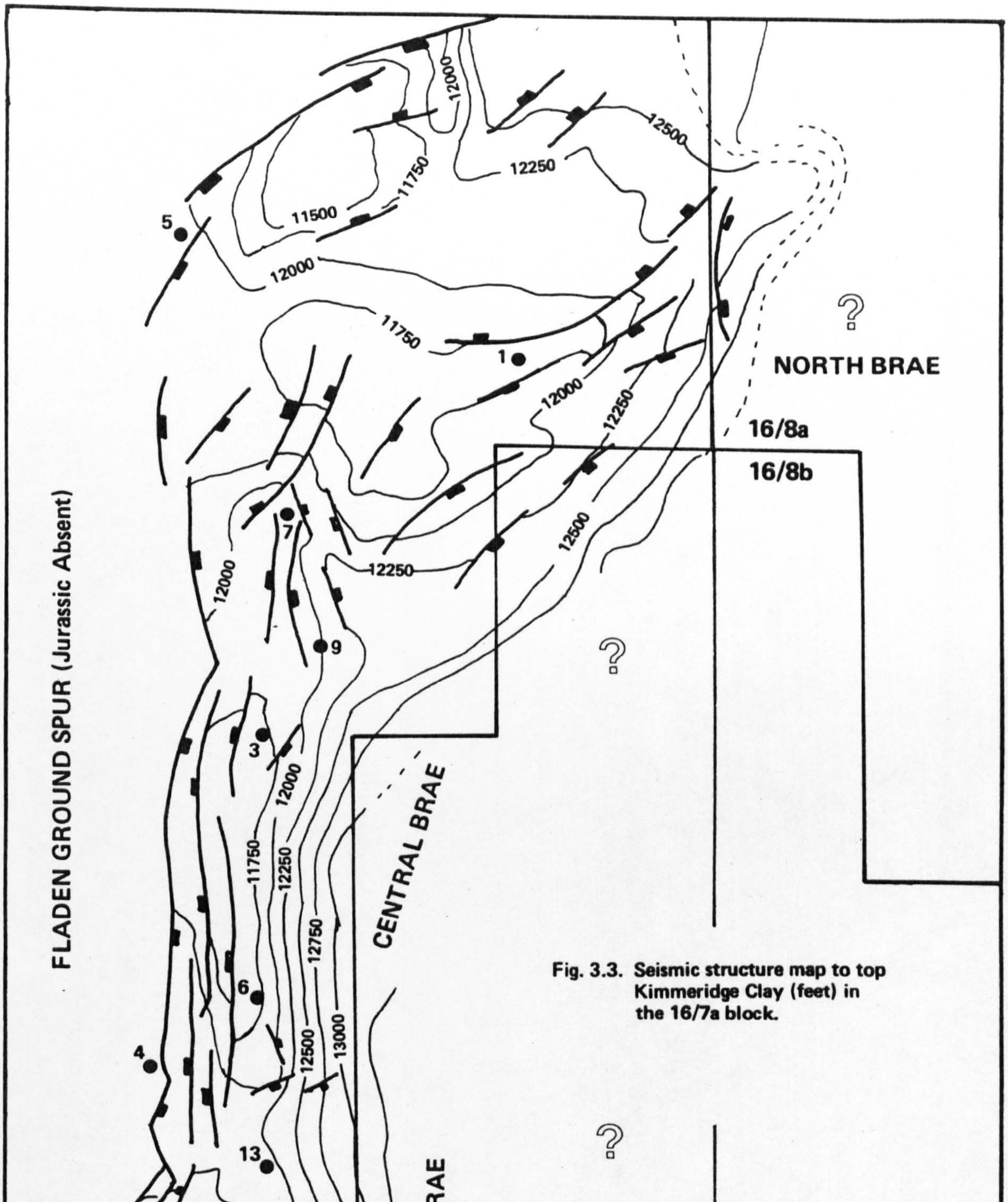
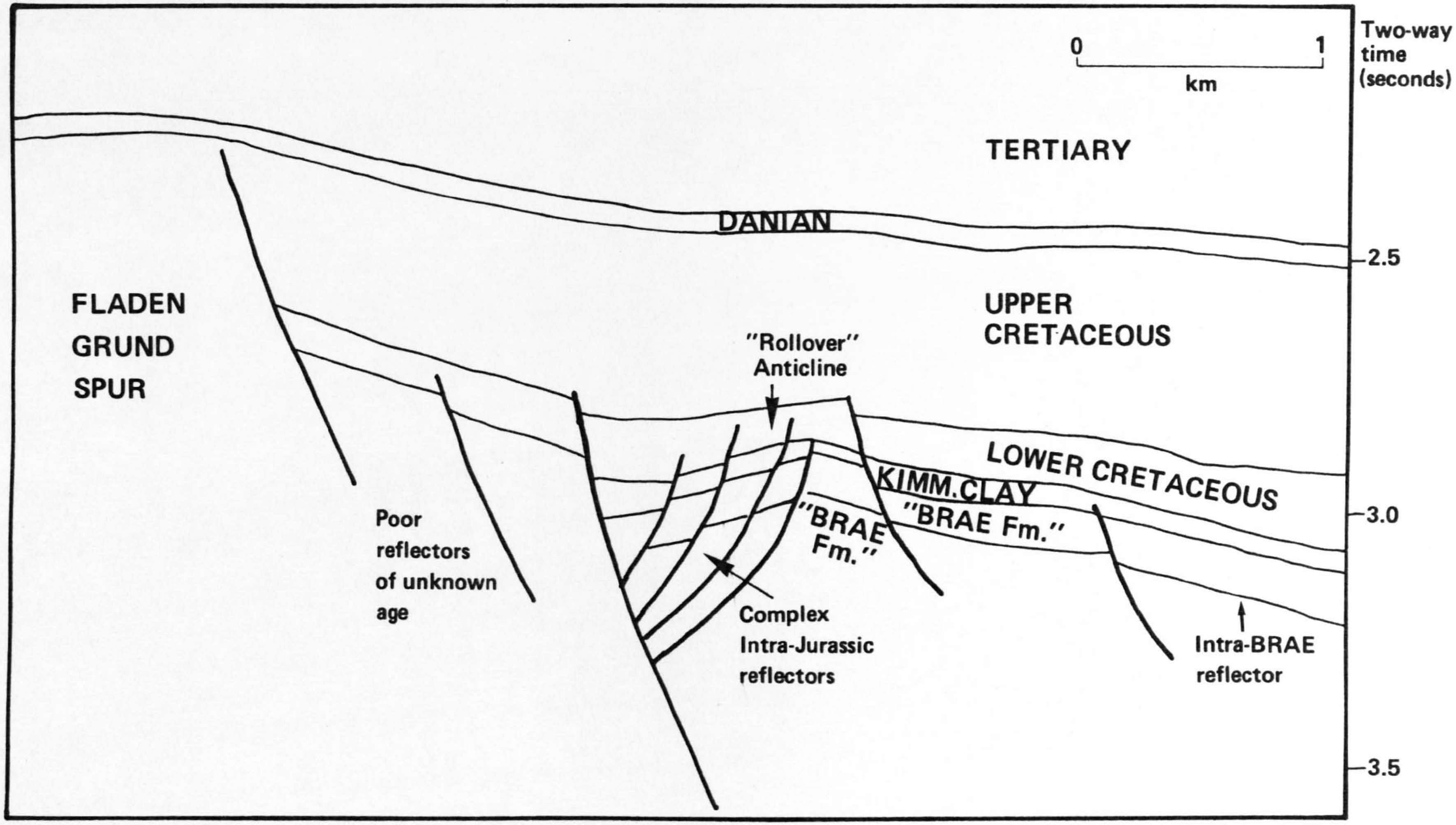


Fig. 3.3. Seismic structure map to top Kimmeridge Clay (feet) in the 16/7a block.

Fig. 3.4. W – E Cross-section through S.Brae.



3.B FACIES ANALYSIS

The analysis was based on a study of core material, core photographs, wireline logs and biostratigraphic reports from the five exploration wells which were drilled during 1977 and 1978. The model should be reviewed and refined in the light of data obtained from subsequent drilling in the 16/7a, 16/7b and 16/8b blocks. The primary purpose of the analysis was to deduce the general environment of deposition and to differentiate between the Stow et al (1982) and the Harms et al (1981) models.

(i) Facies

The lithologies in the South Brae oilfield have been divided into five facies (Fig. 3.5) which have been identified in the uncored intervals by the use of a combination of gamma, neutron, density and dipmeter logs (Figs. 3.14 and 3.15). None of the individual facies are diagnostic of either fan delta or submarine fan environments of deposition. The facies were defined in order to emphasise the variations in depositional energy in time and space as those variations should be different in submarine fan and fan-delta environments. Facies 1 to 5 are gradational and are arranged in order of decreasing depositional energy from facies 1 "conglomerates and breccias" representing the highest depositional energy to facies 5 "mudstones with less that 25% sandstone" representing the lowest energy of deposition.

As some of the facies are defined using sandstone/shale ratios, a minimum thickness for a facies unit must be defined (section 1.D). A thickness of one meter was chosen in order to highlight medium or large-scale rather than small-scale facies variations.

The features of the facies are tabulated in (Fig./

Fig.3.5 South Brae Facies Characteristics

		% of Jurassic	Grain-size	Bed Thick-ness	Sedimentary Structures and Textures	Bed Boundaries	Res. Props.	Fossils and Kerogen	Interpreted Depositional Processes
Breccias and Conglomerates	Facies 1a CONGLOMERATES	19 %	Clasts: 2-150 cm Matrix: medium to coarse sand	5 cm to 5 m (av.50 cm)	Framework and matrix supported clasts, graded and non-graded beds, erosive bases. C-axes perpendicular to bedding. Rare thin basal inversely graded zones.	Bases: Sharp Tops: Sharp or gradaional.	Porosity: typically 10% Permeability: typically 100 md	Common miospores, Microplankton - absent or rare, Kerogen - humic.	Friction debris flows and high density turbidity - currents.
Breccias and Conglomerates	Facies 1b BRECCIAS WITH MUDSTONE MATRICES	0.5 %	Pebble to Boulder Clasts	10 cm to 3 m	Framework supported, randomly oriented and distributed clasts, some erosive bases.	Sharp bases and tops.	Very poor	No analyses, ? microplankton and sapropellic kerogen	Rockfalls plus ? debris flows.
Breccias and Conglomerates	Facies 1c BRECCIAS WITH ARGILL/SST MATRICES	2 %	Mainly Cobble and Boulder Clasts.	Up to 10 m (av. 2 m)	Framework supported, randomly oriented and distributed clasts.	Generally diffuse bases and tops.	Poor	Bivalve and plant fragments ? humic kerogen	Rockfalls.
Facies 2 SANDSTONES W < 5 % INTERSTRATIFIED MUDSTONE		15 %	Very-fine to pebble sand (av.medium)	? cm to 2 m	Commonly graded and structureless beds, also parallel laminations and erosive bases.	Sharp bases and sharp or grad. tops.	Porosity: typically 15% Permeability: typically 500 md	Same as 1a	Relatively high density, immature turbidity - currents.
Facies 3 SANDSTONES W 5 - 25 % INTERSTRAT. MUDSTONE		17 %	Very-fine to medium sand (av.fine)	5 mm to 25 cm (av 4 cm)	Graded and non-graded beds, common cross and parallel laminations.	Generally sharp bases and tops.	Very variable poor vertical K. Porosity 10% Horizontal K 100 md.	Common plant fragment miospores > microplankton humic kerogen	Turbidity - current with tractional reworking.
Facies 4 SANDSTONES W 25 - 75 % INTERSTRAT. MUDSTONE		21 %	Silt plus very-fine to medium sand (av.fine)	Up to 15 cm but mostly 2 mm to 3 cm	Sandstones: Graded and non-graded beds common cross and parallel lamination erosional bases plus? flute/groove marks. Mudstones: Parallel lamination.	Bases: Sharp Tops: Sharp or gradational	Very Poor	Belemnites plus plant fragments, miospores, microplankton. Humic plus sapropellic kerogen.	Suspension settling of mud plus turbidity - currents.
Facies 5 MUDSTONE W < 25 % INTERSTRATIFIED SANDSTONE		26 %	Silt plus very-fine to medium sand (av.fine)	2 mm to 10 cm	Sandstones: Graded and non-graded beds, erosional bases and parallel lamination. Mudstones : Parallel laminations plus rare grading.	Sharp bases and sharp or gradational tops		Same as 4	Suspension settling of mud plus turbidity-currents.

3.5).

a) Facies 1 Conglomerates and Breccias

This facies includes any bed with cobble or boulder size clasts and comprises a variety of conglomerate and breccia types that have been divided into three subfacies.

Subfacies 1a Conglomerates

This subfacies comprises beds in which more than 25% of the clasts are rounded or subrounded. It is the most common subfacies and is well developed in the 16/7a-8, 10, 11 and 13 well sequences.

Bed thickness varies from a few centimeters to 5m, with most beds being 50cm to 1m thick. The bases of beds are invariably sharp and often erosive (Fig. 3.6), whereas the tops can be sharp or gradational into a graded sandstone (Fig. 3.6b, c). Clast size varies from 2 cm to 150 cm. The larger clasts are mostly subangular or subrounded, but most of the smaller ones are rounded or subrounded (Fig. 3.6). Many beds contain two populations of clasts; one of large angular clasts and one of small rounded ones (Fig. 3.6). The clasts are predominantly medium or fine-grained subarkoses with rarer siltstones, quartzose schists and dolomites. Rounded quartz and quartzite clasts are common but are mostly less than 5cm in diameter. Subequidimensional and discoid are the most common shapes of clasts. Some beds show subparallel alignment of clasts to bedding but imbrication was not observed. The packing is variable and the clasts can be framework or matrix supported (Fig. 3.6).

The matrix is mostly a medium grained sand but in some beds it is a very coarse sand or granule gravel. The beds can be graded (Fig. 3.6c) or non-graded (Fig. 3.6a). Often an upward decrease in clast size is concomitant with increasing matrix/

Fig.3.6a <u>Relatively thick-bedded, non to poorly graded conglomerates, Facies 1a, 16/7a-8.</u>

Core diameter approx. 5"

Probable bed boundaries occur at; 12807'3",
812'5",
815'7",
819'7",
822'6".

Note: the relatively tightly packed clasts; the relatively angular sandstone cobbles and boulders, and rounded quartz and quartzite pebbles.


12804.4"
12807.1"
12809.4½
12812.9"
12815
12817.8"
12820.3"
PRESERVED SAMPLE
HALIBURTON SAMPLE
12809.4½
12807.1'
PAN OCEAN 16/7A-8
5625-C CORE #15
12812.9"
12815'
12820.3"

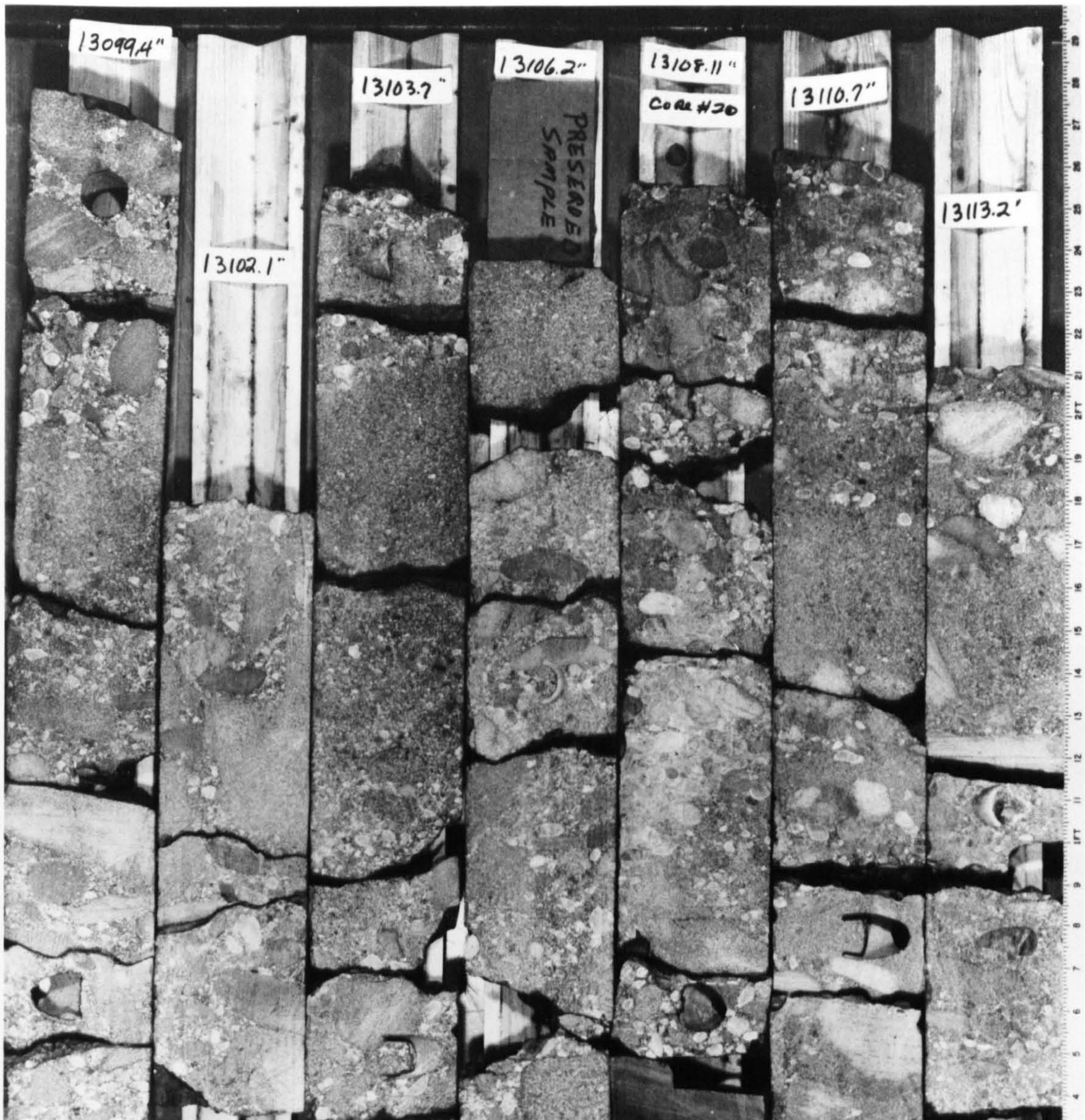
Fig.3.6b Normally-Graded Conglomerates, Facies 1a, 16/7a-8.

Core diameter approx. 5"

Bed Boundaries occur at; 13103'11",
106'0",
?111'1",
111'4",
?113'5".

Note: a) The siltstone clast at 13110'7"

b) The steeply inclined (erosion) surface at 13106'



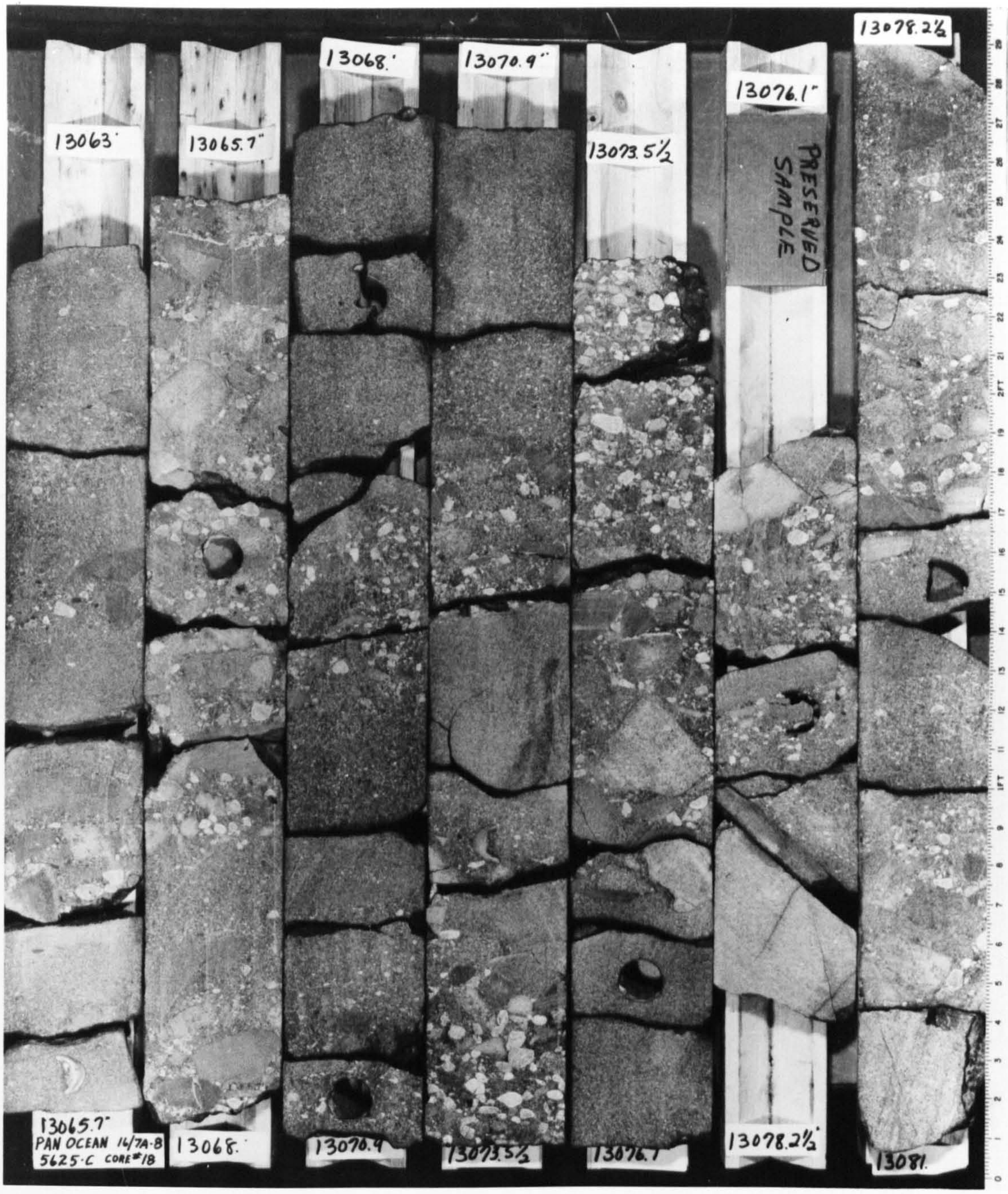
13099.4"
13102.1"
13103.7"
13106.2"
PRESERVED SAMPLE
13108.11"
CORE #20
13110.7"
13113.2'
13102.1"
13103.7"
PAN OCEAN 16/7A-8
5625-C CORE #19
13106.2
13108.11"
PAN OCEAN 16/7A-8
5625-C CORE #20
13110.7"
13113.2"
13114.11"

Fig.3.6c <u>Normally-Graded Conglomerates and Pebbly Sandstones, Facies 1a, 16/7a-8.</u>

Core diameter approx. 5"

Bed bases occur at; 13067'3",
068'0",
069'6",
← 070'9"
072'1",
075'6",
?078'2",
079'8".

Note the extremely well developed normal-grading and the lack of structures in the sandstone-rich units, plus the abundance of rounded quartz and quartzite pebbles.



13063'
13065.7"
13068.'
13070.9"
13073.5½
13076.1"
PRESERVED SAMPLE
13078.2½
13065.7"
PAN OCEAN 16/7A-8
5625·C CORE#18
13068.'
13070.9
13073.5½
13076.1
13078.2½
13081.

proportion and in most graded beds both the clasts and matrix are graded (Fig. 3.6b, c). Some beds have a thin basal inversely graded zone and rare beds have the largest clasts towards the top. Fossil plant and charcoal fragments are locally common, sometimes occurring as discontinuous partings at the tops of beds. Miospores are common and include both coastal, pteridophytic, and hinterland, gymnospermitic, dwelling forms. Permo-Triassic spores are present in some beds. Kerogen residues are mainly humic; both inertinite and vitrinite are present. Marine microplankton, inluding chlorophycean algae, dinocysts and microforaminifera test linings, although rare, are present in some beds.

The presence of rare dolomite clasts and Permo-Triassic spores suggests that the conglomerates were probably at least partially derived from Permo-Triassic rocks. This is corroborated by the presence of common dolomite and anhydrite clasts in the Kimmeridgian and Volgian of the T-Block fields to the south (chapter 4). The marine fossils, though rare, imply that deposition was in a marine environment, whereas the abundant humic kerogen and miospores testify to a nearby land area. The presence of both coastal and hinterland miospores tentatively suggests derivation from a deltaic environment. Overall, the fossils tentatively suggest that much of subfacies 1a was derived from the erosion of Permo-Triassic rocks, the debris from which then passed through alluvial and deltaic systems prior to deposition in a marine environment.

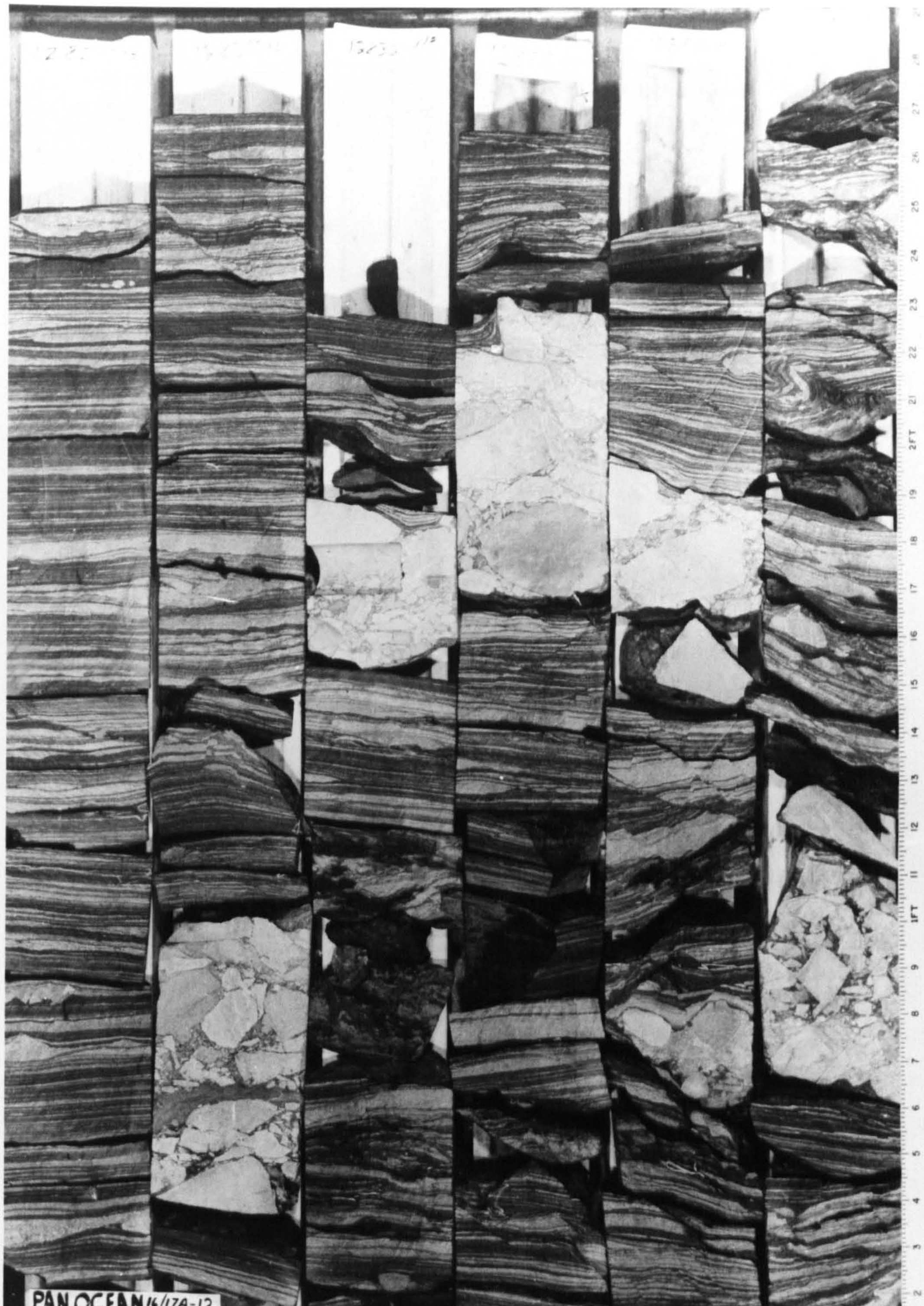
Subfacies 1b   Breccias with mudstone matrices

This subfacies is only developed between 12850' and 12830' in the 16/7a-12 well (Fig. 3.16d) where it is interstratified with facies 4 and 5. Bed thicknesses vary from a few centimeters to 1m. Both the bases and tops of beds are sharp (Fig./

Fig.3.7. Interstratified Facies 1b Breccias and Facies 4 Mudstones and Sandstones, 16/7a-12.

Core diameter approx. 5"

Note: the mudstone matrices; the predominance of angular clasts; the lack of clast fabric organisation; the lack of rounded quartz and quartzite pebbles (in contrast to Fig.3.6); and the abundance of slumping and microfaulting in the fine grained sequences.



PAN OCEAN 16/17A-12
5784-C

3.7) and the bases are erosional in some cases. Clasts vary in size from millimeters to 20cm and they are mainly angular or subangular fine-grained grey subarkoses which are mostly subequidimensional. Unlike subfacies 1a there are no rounded quartz or quartzite clasts. The orientation of clasts is random in most beds, as is the distribution of clasts within beds. The clasts are framework supported and the packing is usually very tight (Fig.3.7). The matrix is similar to the interstratified facies 5 mudstones and in some beds there are sandstone laminations in the muddy matrix.

Subfacies 1c Tightly packed breccias with argillaceous sandstone matrices

This subfacies is mostly restricted to between 13010' and 12850' in the 16/7a-12 well (Fig. 3.16d). It also occurs below 13010' but it is highly fractured and deformed. Bed contacts are diffuse and are picked out by discontinuous shaley laminations, fossil plant partings or charcoal partings which are usually highly contorted. Some beds are 10m thick and most beds are over 2m thick. Clasts are up to 40cm in size and again are mostly fine grained subarkoses with rare shales and dolomites. Rounded quartz and quartzite pebbles are noticably absent. The very large dimensions of some of the clasts make it difficult to study textures in core slices. In most beds the clasts are randomly orientated and distributed and most clasts are angular or subangular. Packing is mostly tight and the clasts are framework supported (Fig. 3.8a). The matrix is an argillaceous fine to medium-grained sandstone that is locally rich in fossil plant material and is locally pyritic. Broken bivalve fragments are locally common (Fig. 3.8b) which implies that the subfacies was deposited in a marine environment. /

Fig.3.8.a <u>Facies 1c Tightly Packed Breccia, 16/7a-12.</u>

Core diameter approx. 5"

Note: the extremely tightly packed clasts; the angularity of the clasts; the lack of rounded quartz and quartzite pebbles; and the argillaceous sandstone matrix.

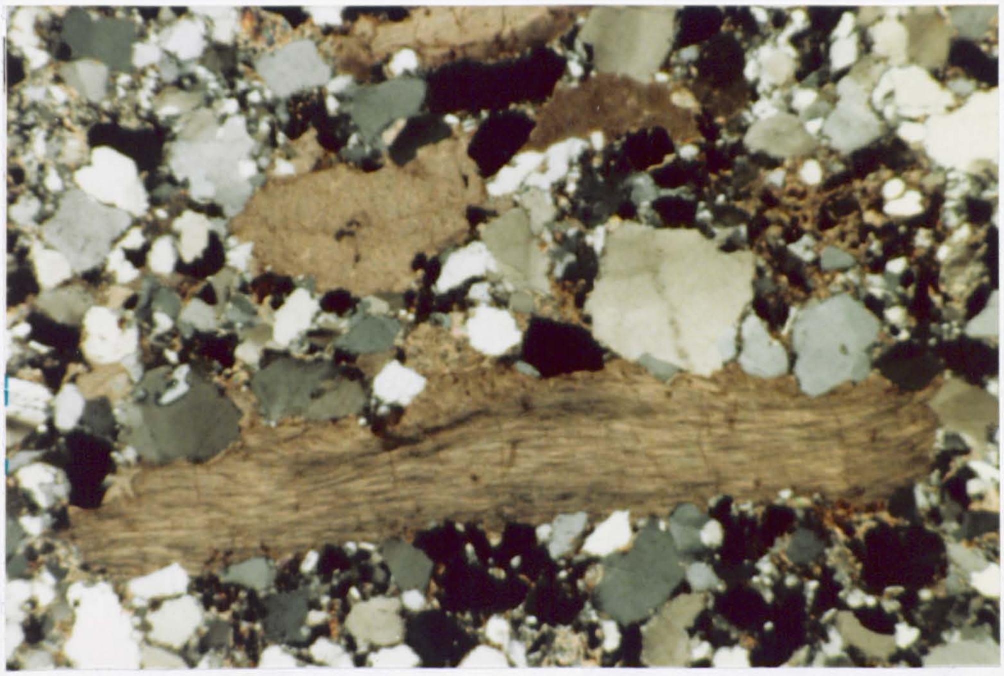
Fig.3.8b <u>Shell Fragments in the Matrix of a Facies 1c Breccia.</u>

Field of view - 4.8mm.

The large fibrous fragment may have been derived from an "oyster".

Note the lack of porosity.


PAN OCEAN 16/17A-12



b) Facies 2 Sandstones with <5% interstratified mudstone

This facies comprises any sandstone unit at least 1m thick that contains no more than 5% of mudstone interbeds. It is mainly composed of graded, medium-grained, medium-bedded sandstones (Fig. 3.9). The bed thickness varies from 2cm to 2m, the average being approximately 30cm (Fig. 3.9). The beds have sharp bases, many of which are erosional (Fig. 3.9). Some beds contain shale "rip-up" fragments (Fig. 3.19).

Tops are mostly sharp or can be gradational into a mudstone. The grain-size varies from pebbly to very fine sand, the average being medium sand. Most of the beds are normally graded (Fig. 3.9). Many of the beds have parallel laminations which are most commonly developed towards the tops of beds and usually overlie a structureless unit. The laminations are mostly caused by subtle grain-size differences and in some beds by concentrations of fossil plant and charcoal fragments. Other beds are structureless throughout. Trough cross-laminations occur in some of the sandstones. They are developed towards the tops of beds as single sets which are mostly less than 3cm thick. The sets often overlie parallel laminated units.

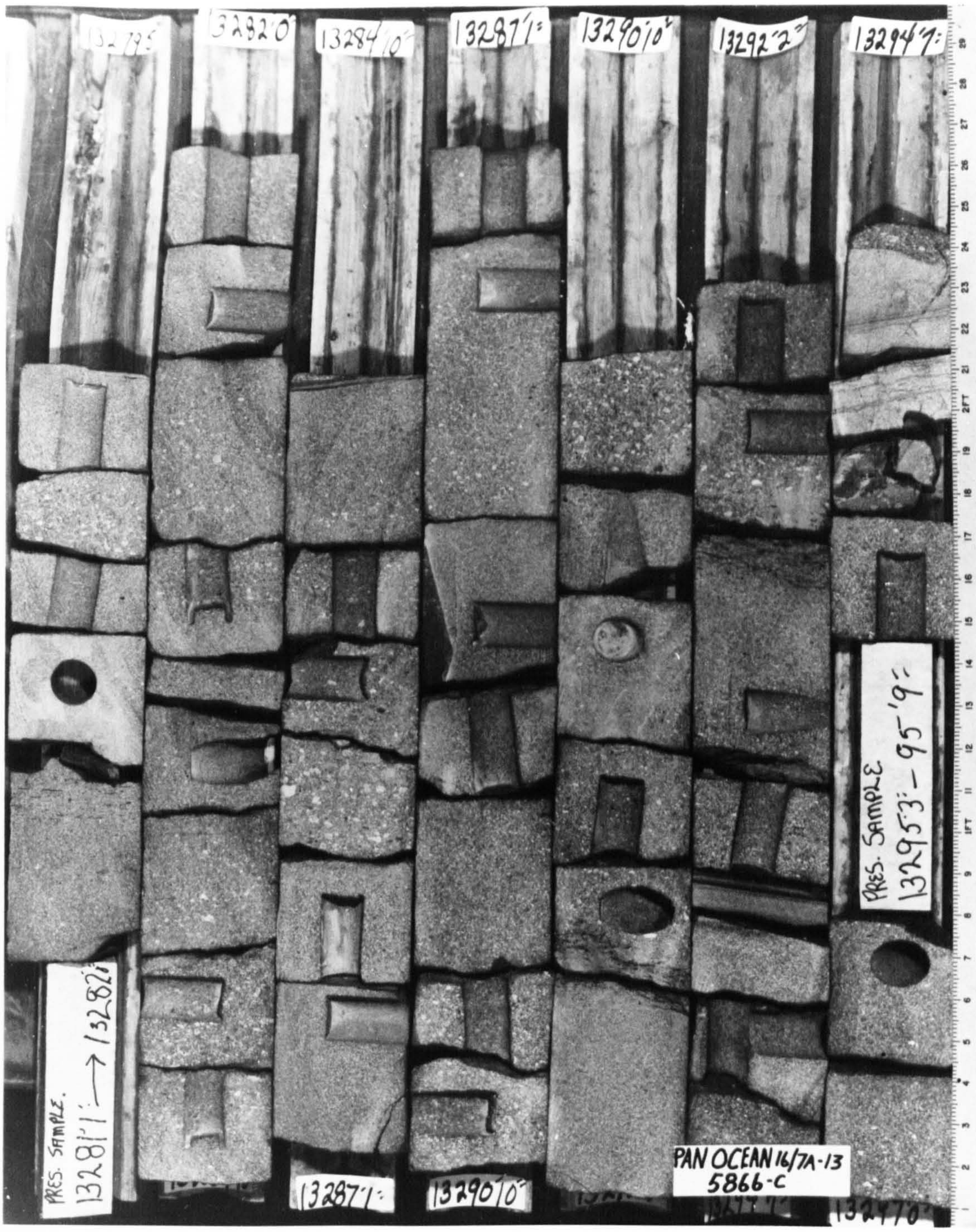
The rare mudstones that occur as partings and laminations towards the tops of the sandstones are usually rich in fossil plant and charcoal fragments. In a few beds the mudstone partings may form low angle cross beds as they can be oriented at angles of up to 15° to each other. Mudstone fragments elongate parallel to bedding are concentrated towards the tops of some beds. They are superficially similar to shale "rip-up" clasts but many were /

Fig.3.9 <u>Normally-Graded (Massive) Sandstones, Facies 2, 16/7a-13.</u>

Core diameter approx. 5"

Note: the concentrations of granules towards the bed bases and plant fragments towards the bed tops; and the well preserved erosional base at 13291'9".

Bed bases at approx : 13279'10",
280'4",
283'3",
284'10",
286'4",
288'1",
291'1",
291'9",
292'9",
293'7".


13282'0"
13284'10"
13287'1"
13290'10"
13292'2"
13294'7"
PRES. SAMPLE
13281'1" → 13282'3"
PRES. SAMPLE
13295'3" - 95'9"
13287'1"
13290'10"
PAN OCEAN 16/7A-13
5866-C

clearly broken "in situ" as adjacent fragments can often be matched and pipe-like features are preserved between some fragments. The fragmentation was probably the result of fluidization or possibly burrowing. As in facies 1, humic kerogen residues and miospores are common whereas microplankton are rare.

c) Facies 3 <u>Sandstones with between 5 and 25% interstratified mudstone</u>

This facies comprises any interstratified sandstone and mudstone unit of at least 1m thickness that is between 95% and 75% sandstone and 5% and 25% mudstone. It is mainly composed of thin-bedded, fine-grained parallel and cross-laminated sandstones (Fig. 3.10).

The sandstones generally differ from those of facies 2 in being thinner bedded, finer grained and having more abundant parallel and cross laminations and less well developed normal grading. The sandstone beds are mostly between 0.5 and 25cm thick, the average thickness being approximatley 3cm. The beds have sharp bases, some of which are erosional. Bed tops are also sharp. The grain-size varies from medium to very fine sand, the average being fine sand. Some of the beds are structureless but most beds contain horizontal and/or trough-cross laminations. The horizontal laminations, which are 2-10mm thick, are caused by grain size variations and concentrations of fossil plant material. The cross-laminated sets can be up to 15cm thick but are mostly between 0.5 and 2.5 cm thick. They can occur as single sets or as cosets of two to four sets. Fading ripples (Stow and Shanmugam 1980), in which cross lamination set thickness decreases in a downcurrent direction, occurs in a few beds. Climbing ripples are present in a few beds but set bounding surfaces are subhorizontal /

Fig.3.10a <u>Facies 3 Interbedded Sandstone and Mudstone.</u>

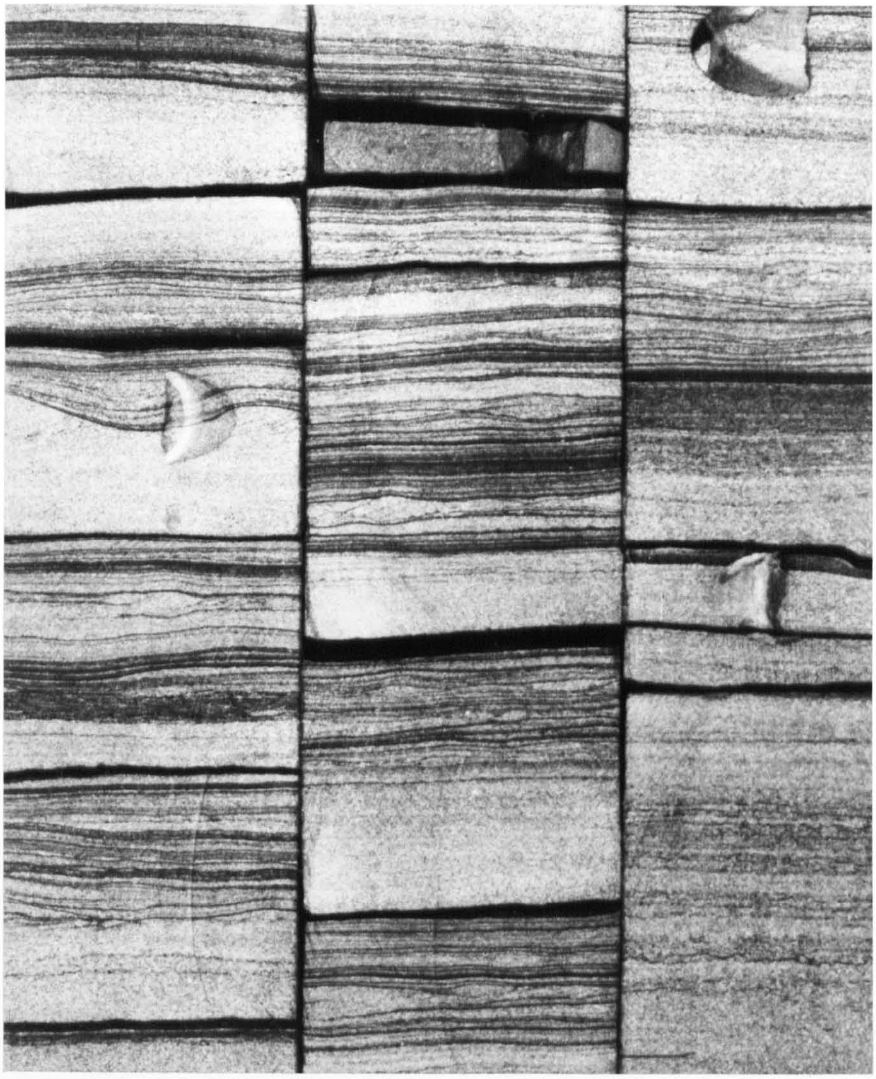
Core diameter approx. 5"

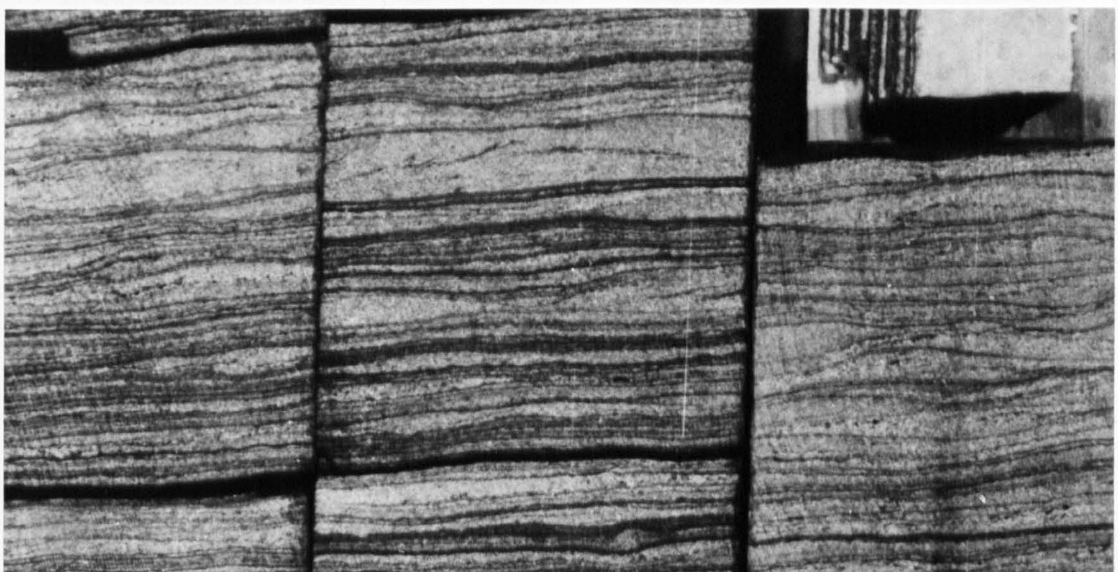
Note: the graded, parallel laminated bed (bottom centre); and the graded, parallel and cross-laminated bed (middle left) ? Tbc turbidite.

Fig.3.10b <u>Facies 3 Interstratified Sandstone and Mudstone.</u>

Core diameter approx. 5"

Note the irregularity of bedding and the abundance of cross-laminations.





in most cases. Fossil plant material is often concentrated along foresets, which mostly dip at between 15 and 20°. In some beds successive ripple sets are out of phase, ie, the troughs overlie the crests and vice versa. These beds have an irregular "wavy" appearance but unequivocal evidence of wave reworking, eg, bundled and chevron upbuilding (De Raaf et al 1977) was not recognised.

More than 50% of the sandstones are graded. Beds with well developed cross-laminations tend to be less well graded than the structureless or horizontally laminated beds. Many of the beds show waning flow sequences of structures with cross-laminations overlying structureless or horizontally laminated units, or horizontal laminations overlying structureless units (Harms and Fahnstock 1965). "Laminar grading", in which there is a gradual upwards decrease in sandstone lamina thickness concomitant with an increase in the proportion of mudstone laminae (Kelling and Woolands 1969), occurs in some units up to 15cm thick.

The mudstones are black, organic and occur as partings and laminae, with sharp bases and tops, between the sandstones. In many laminae more than 25% of the rock is composed of fossil plant fragments plus other organic material. The kerogen residues are predominantly humic and miospores are more abundant than microplankton.

The lower sandstone : mudstone ratio, the finer grain-size and the thinner bedding of the sandstones all imply that facies 3 was deposited in a lower energy environment than facies 2. The graded sandstones, the waning-flow sequences of structures, the fading ripples and the laminar grading are suggestive of deposition from decel erating currents. The poorly graded and the non-graded cross-laminated sandstones underwent substantial tractional reworking/

prior to final deposition. The presence of microplankton, although rare, implies deposition in a marine environment and the abundance of plant fragments and humic kerogen is indicative of a relatively nearby vegetated land area.

d) Facies 4 Sandstone with between 25 and 75% interstratified mudstone

This facies comprises any sandstone and mudstone unit at least 1m thick that is between 25% and 75% sandstone and 25% and 75% mudstone. It is mainly composed of thin-bedded sandstone and mudstone in subequal proportions and is informally known as the "tiger-stripe" facies (Fig. 3.11).

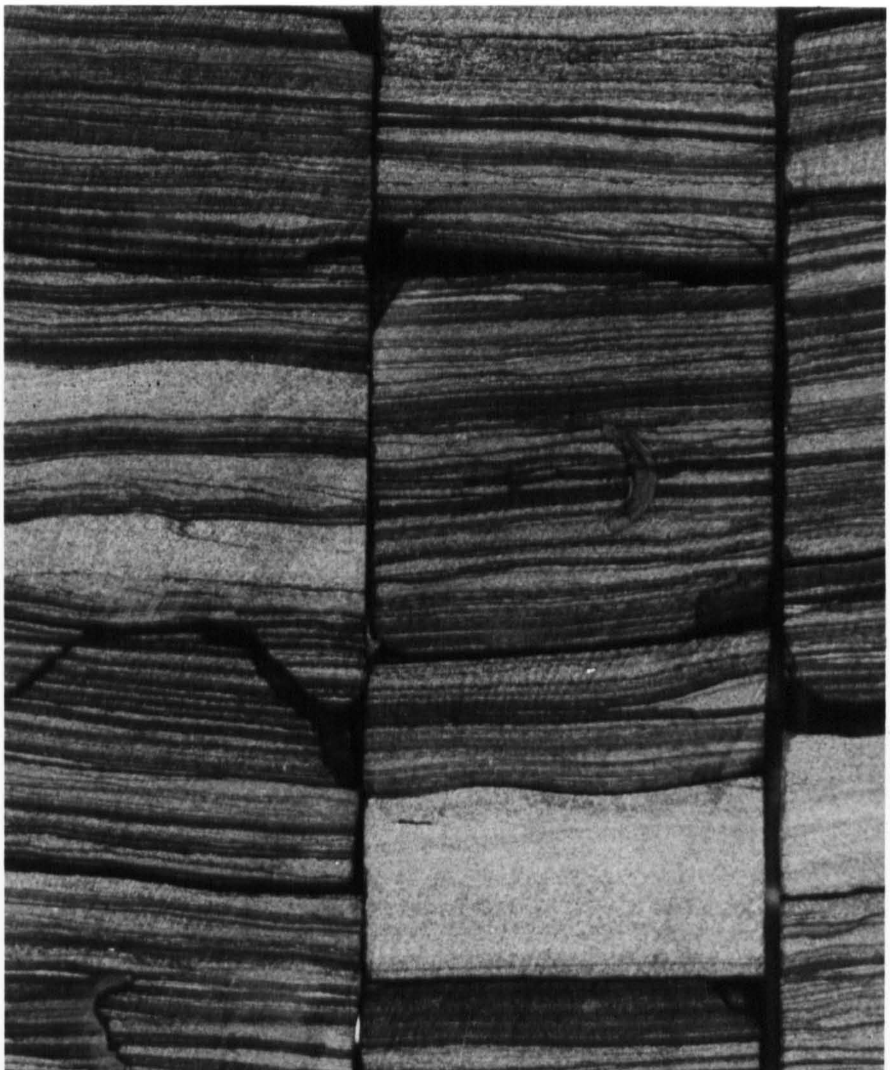
The sandstones are generally similar to those of facies 3 but tend to be thinner bedded. Beds can be up to 15cm thick but are mostly between 0.2 and 3cm thick. They have sharp bases which are often erosional and sometimes loaded into the underlying mudstone. Flute-like structures are preserved on the bases of some sandstones. Bed tops are mostly sharp but can also be gradational into a mudstone. The average grain-size is fine sand.

Horizontal and trough cross-laminations are again the main structures in the sandstones and are similar to those developed in facies 3. The trough cross-laminations mostly occur in single sets. Many of the sandstones are graded. The thicker and the more poorly sorted sandstones tend to be better graded than the thin well-sorted ones. The beds can be structureless throughout, horizontally-laminated throughout, cross-laminated throughout, or be composed of a combination of structureless, horizontally-laminated and cross-laminated units. Again a waning-flow sequence of structures is often developed with cross-laminations overlying parallel /

Fig.3.11 Facies 4 Interstratified sandstones and mudstones, "tiger-stripes".

Core diameter approx. 5"

Note the graded, parallel and cross-laminated sandstone, ? Tab or Tabc turbidite.



laminations overlying a structureless unit (Fig. 3.11).

As in facies 3, the mudstones are black and organic rich. They are often laminated, the laminations being caused by grain-size differences. Some of the mudstones are graded from coarse silt at the base to fine silt towards the top, but most of them are non-graded. The kerogen residues include both humic and sapropellic material and the microfossils include both miospores and microplankton. Belemnites were the only macrofossils observed.

The lower sandstone : mudstone ratio and the thinner beds of sandstone suggests that facies 4 was deposited in a lower energy environment than facies 3. Decreased humic : sapropellic kerogen residue and miospore : microplankton ratios in facies 4 implies more marine influence and decreased terrestrial input compared with facies 3. Most of the sandstones were probably deposited from decel erating currents, as were the graded siltstones. The non-graded mudstone was probably deposited from suspension and the abundance of plant fragments and humic kerogen implies that it is hemipelagic. The presence of sapropelic kerogen suggests deposition in an oxygen depleted environment.

e) Facies 5 <u>Mudstone with less than 25% interstratified sandstone</u>

This facies comprises any mudstone and sandstone unit of 1m thickness that is less than 25% sandstone. It is mainly composed of black mudstone with thin interbeds of sandstone which are generally thinner than those of facies 4 and occur as millimeter scale lamination or as beds up to 10cm thick (Fig. 3.12). The thin laminae can be graded or non-graded and the thicker beds are mostly graded with sharp erosional bases, which may be loaded, and sharp/

Fig.3.12 <u>Facies 5 Laminated Mudstones and thin interbedded sandstones.</u>

Core diameter approx. 5"

Note the dark coloured (organic), laminated mudstones (typical Kimmeridge Clay Formation) and the graded sandstone with a thin set of cross-laminations on top - ? Tac turbidite.

or gradational tops. Waning-flow sequences of structures are again common (Fig. 3.12) but cross-laminae are less common than in facies 3 and 4.

The mudstones are similar to those of facies 4 except that they have lower humic : sapropel kerogen residue and miospore : microplankton ratios. Pyrite balls up to 2 cm in diameter, sometimes nucleated around a fossil plant fragment, are locally common.

Facies 5 is a typical lithology of the Upper Jurassic Kimmeridge Clay Formation (Deegan and Skull 1977) of the U.K. and N.W. Europe which is a black organic rich radioactive shale. The lower sandstone : mudstone ratio and the thinner bedding of the sandstones implies that facies 5 was deposited in a lower energy environment than facies 4. Deposition of mud from suspension was the ambient sedimentation while rare turbidity-currents deposited the thin sandstones. The preservation of abundant sapropelic kerogen debris shows that the sediment-water interface was oxygen depleted and probably anoxic (Demaison and Moore 1980).

(ii) Syn-sedimentary Deformation

Features indicative of syn-sedimentary deformation are common in the fine association sequences and are especially common in the 16/7a-12 well (Fig. 3.16d). The deformation affects discrete packages of beds and comprises both elastic and plastic failure of the sedimentary pile (Fig. 1.3). It includes microfaulting (Fig. 3.13a), chaotic mixes of sand and mud (Fig. 3.22), microfolding (Fig. 3.13b) and units of strata with anomalously high dips which probably reflect rotational movements along curved shear planes (Fig. 3.13b). All these features testify to unstable /

Fig.3.13a <u>Abundant Microfaulting in Thinly Interbedded Sandstones and Mudstones</u>

Core diameter approx. 5"

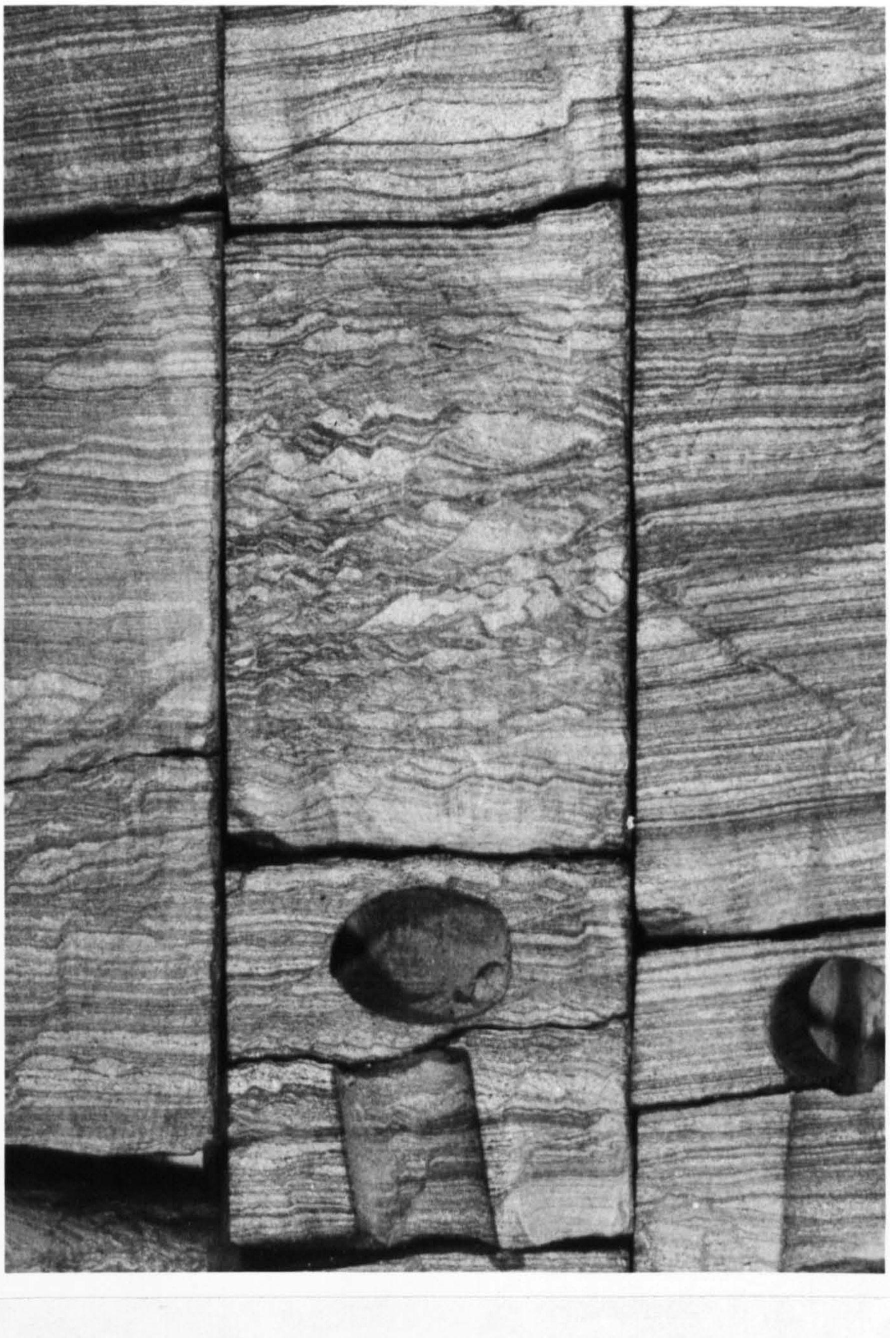


Fig.3.13b <u>Highly Deformed (Slumped) Mudstone-Rich Sequence.</u>

Core diameter approx. 5"


12665'1"
12667'8"
12669'8"
12671'10"
12674'9"
12677'1"
12679'9"
PRES. SAMPLE. 12670'7" – 71'2"
PRES. SAMPLE. 12680'5"
PAN OCEAN 16/7A-13
5866-C
12667'8"
12669'8"
12671'10"
12674'9"
12677'1"
12679'9"
12682'7"

slope conditions during sedimentation.

(iii) Wireline Logs

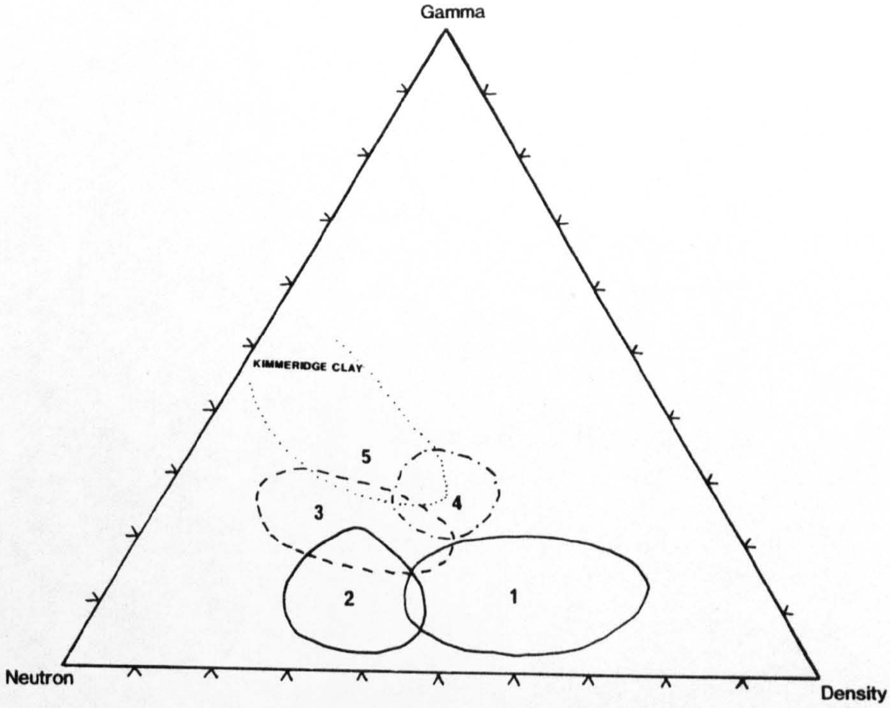
The facies were relatively easily identified in the uncored intervals using a combination of gamma ray, density and neutron logs. The dipmeter also provided a useful check on the initial interpretation as specific patterns from the Schlumberger Cluster program are characteristic of the various facies. Typical log values for the five facies, in the cored intervals, are shown in figure (3.14) and typical cluster dipmeter responses are shown in figure (3.15).

Fig.3.14a Typical Wireline Log Values for the Major Facies

(EXCLUDING GAS ZONE)

FACIES	GAMMA(API UNITS)	DENSITY (gm/cm)	NEUTRON (LST POROSITY)
1a	20-55	2.475-2.5	7.5-13.5
2	15-40	2.4-2.425	9-13.5
3	40-80	2.375-2.475	11.5-13.5
4	65-120	2.475-2.525	12-21
5	95-180	2.4-2.55	15-25

Fig.3.14b Ratio Plot of Gamma vs Neutron vs Density



The plot is made by standardising the observed wireline log measurements to max = 100 and min = 0, followed by standardising the sum of the three "values" to equal 100.

In this example: gamma 200 API = 100 and 0 API = 0
density 2.35 gm/cm^3 = 0 and 2.6 = 100
neutron 0% = 0 and 25% = 100

If the wireline log values were gamma - 20
density - 2.4
neutron - 10.5

- the standardised values would be gamma - 10
density - 20
neutron - 42

- which as percentages are: gamma 14%
density 28%
neutron 58%

This plots at the left edge of the facies 2 field.

The plot is essentially a ratio plot which illustrates the three ratios - gamma:neutron, gamma:density and density:neutron.

It was based on 42 core calibrated measurements and it provides a fairly good descrimination betweeen the 5 facies.

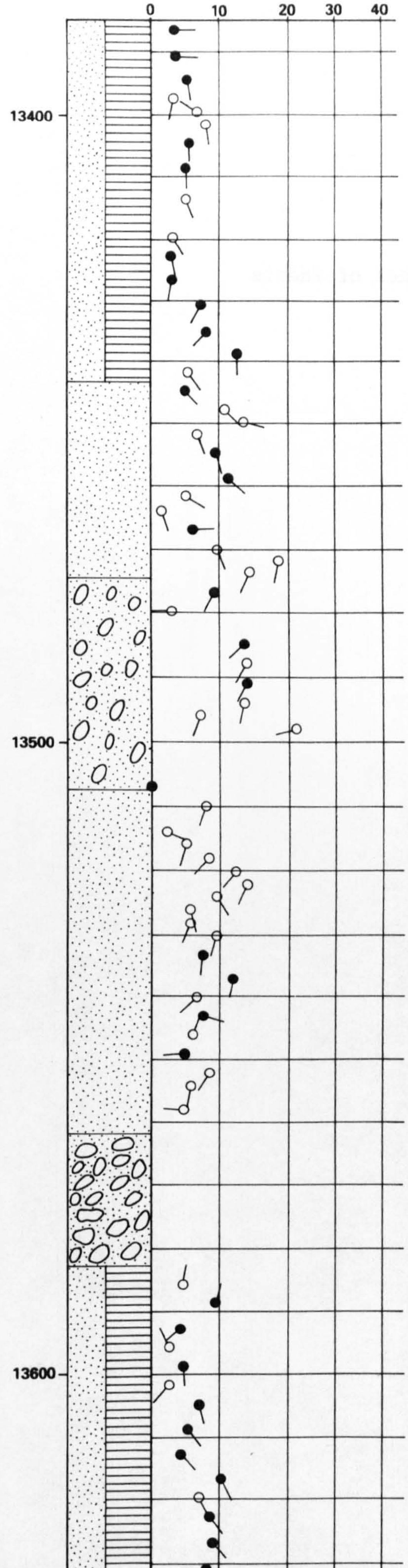


Fig. 3.15.

16/7a – 8 well, Computed dips from the Schlumberger Cluster Program (4x2x35). Note the wider spread of readings in the sand and conglomerate rich sequences and the abcence of dip readings in the lower conglomerate

3.C. FACIES ARRANGEMENT AND DISTRIBUTION

(i) Introduction

Most detailed environmental interpretations must be based on the study of the arrangement and distribution of facies rather than on the study of individual facies in isolation (Reading 1978 p.4). In cored sequences a sedimentologist only has a one-dimensional view of a three-dimensional system and it is vital that he appreciates the importance of Walthers Law which basically states that, only facies that exist beside each other in space can occur in contact in a vertical sequence. An important qualifier to this statement is that the "Law" only applies to successions without major breaks. In oil wells the first step must be to study the grouping and the vertical sequences of facies.

(ii) Vertical Facies Sequences

The 16/7a-8, 10, 11 and 13 contain similar facies and were therefore probably deposited in relatively similar environments (Fig. 3.16)*. The 16/7a-12 well, however, contains two subfacies that are unique to that well (Fig. 3.16d), suggesting that at least part of that sequence was deposited under different conditions.

A facies transition frequency matrix (Davies 1977), which shows the frequency of vertical transitions between facies, has been established for the Jurassic sequences in the 16/7a-8, 10, 11 and 13 wells (Fig. 3.17). The matrix suggests the existence of two facies associations; the frequent transitions between facies 1, 2 and 3 indicates the existence of a course association composed of these facies and the frequent transitions between facies 3, 4 and 5 suggests the existence of a fine association composed /

* In Pocket at Back

Fig. 3.17. Facies transition matrix.

TO

FROM	FACIES	1	2	3	4	5	TOTAL
	1		30	4	1	0	35
	2	17		19	10	4	50
	3	6	6		13	4	29
	4	6	9	5		9	29
	5	5	3	1	4		13
	TOTAL	34	48	29	28	17	156

COARSE ASSOCIATION

ASSOCIATION TRANSITIONS

FINE ASSOCIATION

ASSOCIATION TRANSITIONS

Total fining-upwards transitions 94

Total coarsening-upwards transitions 62

of these facies. A visual study of the logs (Fig. 3.16) corroborates this subdivision. There is an overlap between the associations as facies 3 occurs in both of them. Facies 3 is included in the coarse association where it is interstratified with facies 1 and 2 and is included in the fine association where it is interstratified with facies 4 and 5. Where it occurs between associations it is partly included in each association and the boundary between associations is taken at a prominent slumped or deformed horizon, a major bedding surface, a discontinuity or, if these are all absent, is taken at the middle of the facies 3 unit.

a) Coarse Association Sequences.

The coarse association is often a fining-upwards sequence, eg. 16/7a-13, 13010' - 12955', (Fig. 3.16e) and 16/7a-11, 12770' - 12680' (Fig. 3.16c). Sequences dominated by facies 1 usually pass up into facies 2 dominated sequences which then can pass up into either facies 3 or 4 sequences (Fig. 3.20). The facies transitions can be sharp or gradational. Shale "rip-up" clasts are present towards the base of some of the fining-upward sequences (Fig. 3.19).

The association can also be composed of multiple fining-upwards sequences eg 16/7a-13, 13450' - 13070', and 16/7a-10, 13615' - 13470'. In some multiple fining-upwards sequences each successive fining-upwards sequence is coarser and thicker than the preceeding one, eg. 16/7a-8, 12420' - 13350', and 16/7a-10, 13245' - 13120' (Fig. 3.20). This forms a poorly developed coarsening-upwards megasequence which is internally composed of fining-upwards sequences. Examples of simple coarsening-upwards sequences in the coarse association are rare and thin, eg. 16/7a-8, 12710' - 12680', and 16/7a-11, 13330' - 13310'. In these sequences the contacts between facies are always sharp and often erosional. In some coarse association sequences the facies are randomly interbedded,/

Fig.3.19 Sharp Upwards transition from a Fine Association to a Coarse Association Sequence.

Core diameter approx. 5"

Note the abundance of shale "rip-up" clasts at the base of the coarse association sequence and the lack of coarsening-upwards in the fine association sequence.

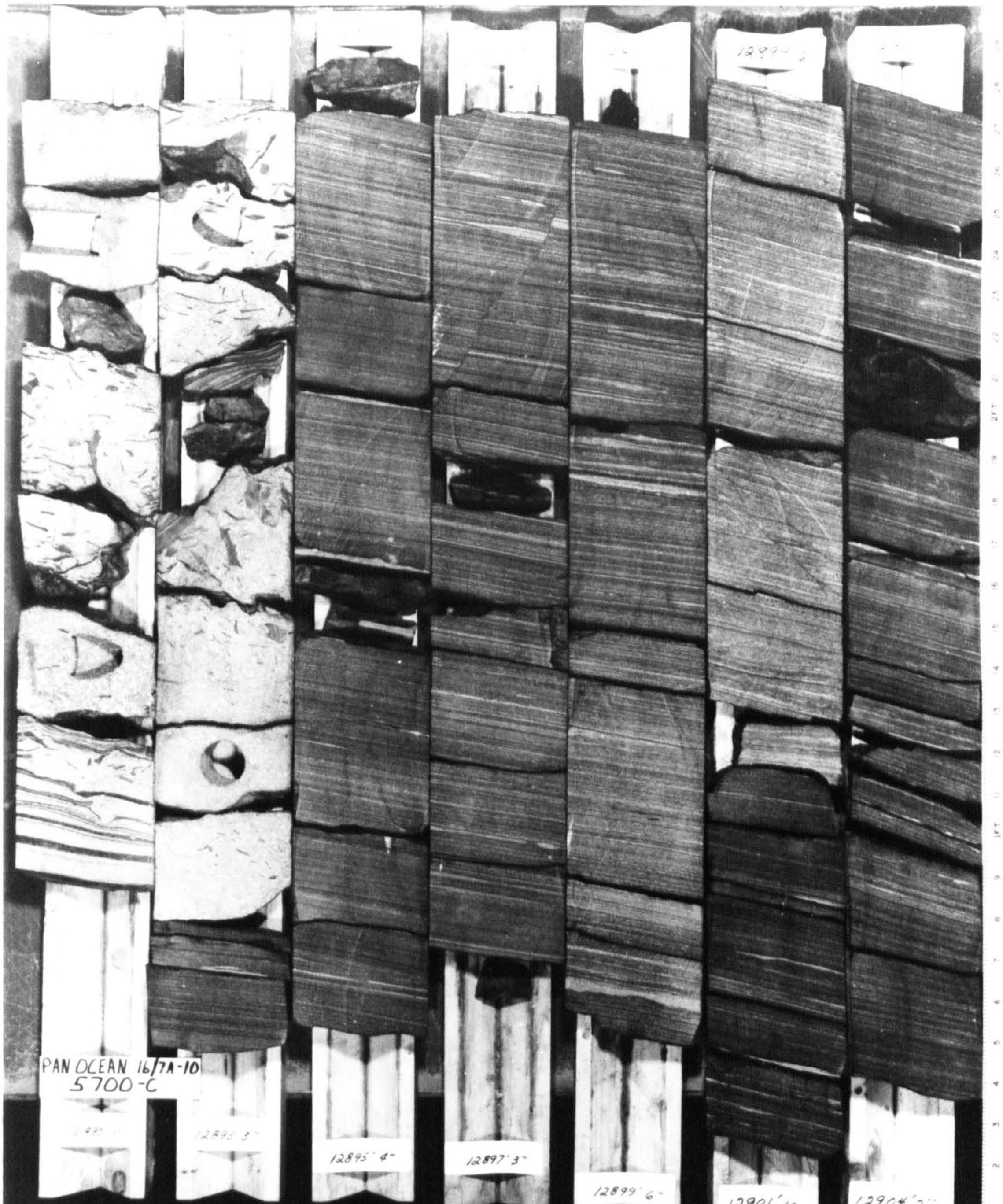
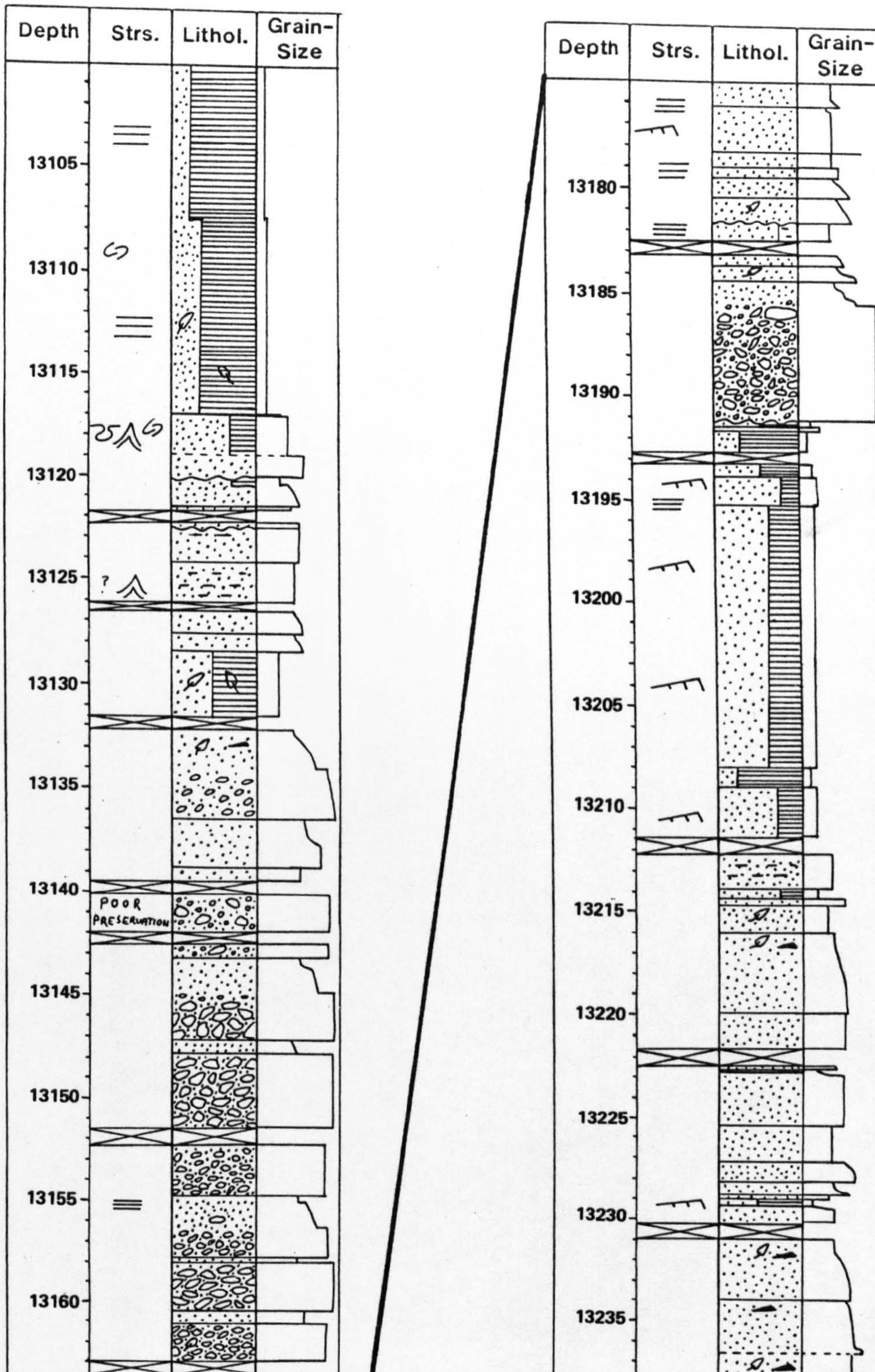

PAN OCEAN 16/7A-10
5700-C
12895' 4"
12897' 3"
12899' 6"
12901' 10
12904' 2"

Fig. 3.20. 16/7a — 10, A coarsening - upwards sequence composed of three (stacked) fining - upwards sequences.



eg. 16/7a-8, 13200' - 12960'. Coarse association sequences tend to be thicker at deeper horizons and thinner towards the top of the Jurassic (Fig. 3.16).

The dominance of fining-upwards sequences in the coarse association is verified by the transition matrix which shows that fining-upwards transitions are more common than coarsening-upwards transitions (Fig. 3.17). Most of the coarsening-upwards transitions are the result of random interstratification of facies within the association and the contacts between coarsening-up transitions are mostly sharp and erosional.

b) Fine Assocation Sequences

The facies transitions in the fine association are mostly gradational. The transition matrix again shows that fining-upwards transitions are slightly more common than coarsening upwards transitions (Fig. 3.17). Fining-upwards sequences are well developed towards the base of some fine association sequences, eg. 16/7a-8, 12350' - 12330', 16/7a-10, 13575' - 13555' (Fig. 3.16). Small-scale coarsening-upwards sequences are developed towards the tops of some fine association sequences where they underly a coarse association sequence, eg. 16/7a-13, 13020' - 13010' (Fig. 3.21). The thickest and best developed coarsening-upwards sequence does not underly a well developed coarse association sequence 16/7a-13, 12780' - 12730' (Fig. 3.16c). This sequence passes gradationally upwards from facies 5 to 4 and then to a mixture of facies 3 and 2 which is in turn sharply overlain by facies 5.

c) Transitions between Associations

Where a coarse association passes upwards into a fine association the contact is often gradational, eg. 16/7a-11, 12700' - 12680' (Fig. 3.16c). The top of the coarse association sequences is nearly always facies 2 or 3 and rarely facies 1. Where /

Fig.3.21 Coarsening-upwards Fine Association Sequence Underlying a Coarse Association Sequence, 16/7a-13.

Core diameter approx. 5"

Note the abrupt transition between the associations and the abundant cross-laminations in the fine association. Also note the lack of evidence for wave reworking in the fine association.


13008'7"
13011'4"
13018'0"
13020'7"
PRES. SAMPLE
13011'11" - 13012'10"
13011'4"
13020'7"
13022'9"
13022'9"
13025'3"
13027'6"
PAN OCEAN 16/7A-13
5866-C
13025'3"
13027'6"
13029'8"

facies 3 is at the top of a coarse association sequence the boundary between associations is often marked by contorted and deformed bedding, eg. 16/7a-10, 13120' (Fig. 3.22).

Where a fine association sequence is overlain by a coarse association the contact is usally sharp, eg. 16/7a-8, 12420' (Fig. 3.16a) but can also be gradational, eg. 16/7a-11, 13320' (Fig. 3.16c). Facies 1 or 2 of the coarse association usually erosively overlie facies 4 and 5 of the fine association, eg. 16/7a-11, 12770' (Fig. 3.16c). In some cases the fine association coarsens up into facies 3 or 4 which is then erosively overlain by facies 1 or 2, eg. 16/7a-13, 13010' (Fig. 3.16e).

d) General Points

The transition matrix (Fig. 3.17) shows that both the fine and coarse associations more often fine-up than coarsen-up and a visual inspection of the logs verifies this. However, attempts to quantify the trends using statistics were unsuccessful because of the high level of "background noise" in the matrix. The high numbers of transitions within the associations acted as the "noise". Nevertheless the 5 Brae sequences generally fine-up rather than coarsen-up and the fining-upwards sequences are best developed at deeper horizons and in the 16/7a-8 well.

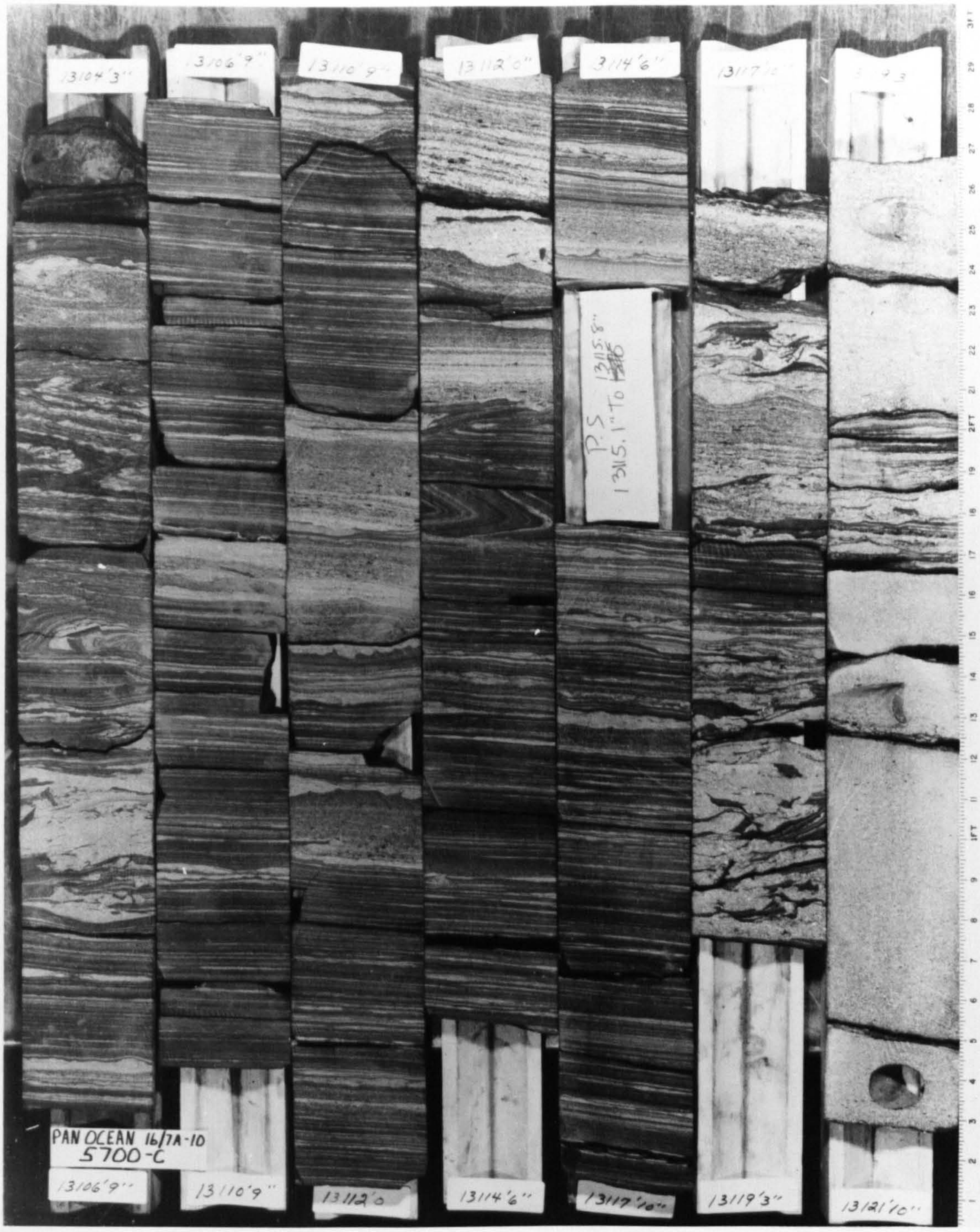
e) 16/7a-12

The 16/7a-12 sequence differs from the other exploration well sequences in containing subfacies 1b and 1c and not containing subfacies 1a and facies 2.

The sequence begins with altered, crushed and fractured breccias and sandstones between 13469' and 13009' (Fig. 3.23). Green alteration, subvertical calcite and mudstone fracture fills and slickensides are common. Two main rock types are recognised; one is a brecciated quartzose sandstone and the other/

Fig.3.22 Deformed Bedding at the upwards Transition from a Coarse to a Fine Association Sequence, 16/7a-10.

Core diameter approx. 5"



13104'3"
13106'9"
13110'9"
13112'0"
13114'6"
13117'10"
P.S.
13115.1" TO
PAN OCEAN 16/7A-10
5700-C
13106'9"
13110'9"
13112'0
13114'6"
13117'10"
13119'3"
13121'10"

is a brecciated tightly packed breccia which was similar to facies 1c before being crushed and fractured. Between 13009' and 12852' is a sequence of tightly packed facies 1c breccias (Fig. 3.8) which are similar to the rocks below except that they are only rarely crushed and fractured. At 12852' the facies 1c breccias are sharply overlain by a sequence of facies 1b breccias and facies 5 mudstones (Fig. 3.7) in which the breccias become less frequent upwards (Fig. 3.24). The passage of facies 1c breccias to a mixture of facies 1b breccias and facies 4 mudstones to facies 4 mudstones is a crude "fining-upwards" sequence. Above this, the sequence is dominated by facies 3, 4 and 5 which are generally more slumped and contorted than in the other wells. Most of the contacts between facies 3, 4 and 5 are gradational. There is an overall coarsening upwards trend from 12600' to 12470' and between 12470' and 12450' there is a fining upwards sequence which has a sharp base (Fig. 3.16d).

f) Basin-Fill

The Kimmeridgian and Volgian basin fill in all the wells comprises a large-scale fining-upwards sequence as there is an overall upwards decrease in coarse : fine association ratios (Fig. 3.16).

(iii) Spatial Distribution of Facies

The spatial distribution of facies cannot be accurately defined by the five exploration wells. The 16/7a-12 well is the most westerly (Fig. 3.3) and the unique development of facies suggests that at least part of the sequence was deposited in a different environment to that of the other wells. The occurrence of similar facies and facies arrangements in the 16/7a-8, 10, 11 and 13 wells suggests that the sequences were deposited in broadly similar environments. The highest coarse association : fine association ratio and facies 1 : 2 ratio (Fig. 3.25) occurs in 16/7a-8 which/

Fig.3.23 Highly Fractured Sandstones and ? Breccias, 16/7a-12.

Core diameter approx. 5"

Note the abundance of subvertical fractures and the dark (muddy) material filling the fractures.


PAN OCEAN
5784-C
13160'3"
13162'10"
13165'9"
13167'10"
13169'11"
13172'1"
13174'5"

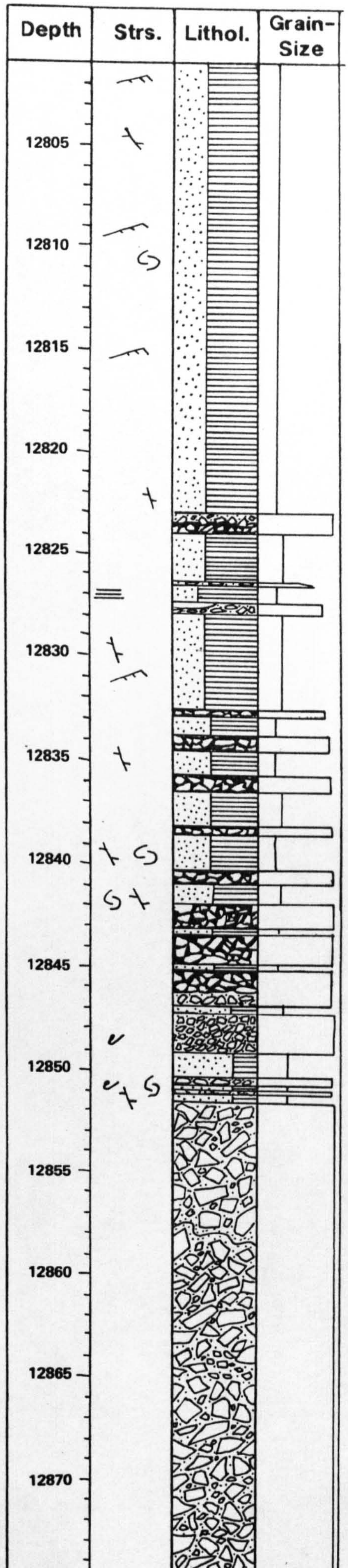


Fig. 3.24. Transition zone from breccia dominated to mud dominated sequences.

16/7a-12

is, therefore, probably the most "proximal" well. The 16/7a-10, 11 and 13 wells contain similar coarse : fine association ratios and are probably relatively "distal" with respect to 16/7a-8. Coarsening-upwards fine association sequences are very poorly developed where associated with thick facies 1 dominated coarse association sequences in 16/7a-8 and are best developed in the relatively fine-grained 16/7a-13 well (Fig. 3.16e).

It is very difficult to correlate sequences between wells with any degree of confidence. The only obvious correlation is of the facies 2 and 3 dominated sequences which occur towards the top of the 16/7a-8 and 10 wells (Fig. 3.16). These sequences have no obvious equivilents in the other wells.

Fig. 3.25.a

Coarse : Fine association ratios

16/7a – 8	**3 : 1**
16/7a – 10	**0• 74 : 1**
16/7a – 11	**0• 46 : 1**
16/7a – 13	**0• 68 : 1**

Fig. 3.25.b

Facies 1 : Facies 2 ratios

16/7a – 8	**2 : 1**
16/7a – 10	**0• 26 : 1**
16/7a – 11	**1 • 2 : 1**
16/7a – 13	**0• 36 : 1**

3.D. INTERPRETATION

(i) Introduction

The occurrence of, graded and non-graded conglomerate beds with erosive bases, structureless or parallel laminated graded sandstones with erosive bases, fining-upwards sequences with sharp bases and sharp or gradational tops, rare marine microplankton, plus the interstratification of sandstone and conglomerate sequences with marine mudstone rich sequences, and the lack of obvious correlation between wells suggests that the coarse association sequences were predominantly deposited in submarine channels that were probably part of a submarine fan complex. The lack of structures and textures associated with shallow water environments suggests that the channels occurred below wave-base.

The common occurrence of soft sediment deformation plus the other sedimentary features of the fine association are consistent with deposition in a submarine slope environment. As it is interstratified with, and sometimes gradational with, the coarse association, it was probably predominantly deposited in the interchannel areas of a submarine fan complex. The environment of the 16/7a-12 well will be dealt with later.

As the "submarine fan model" is in a period of flux (Normark, Mutti and Bouma 1984) I will present a brief review of this depositional environment in order to highlight aspects that can be useful to predicting and modelling reservoir distributions in "submarine-fan" systems. Ricci-Lucchi (1984 p3) explained that:

> "The starting point is to regard the fan as a three-dimensional object, and more precisely as a sand-rich body interposed between muddy and sand-poor deposits (the /

slope and basin-plain), and fed by gravity
flows through a channel or a system of
channels heading in a nearshore point source.
Implicit in this definition is the fact that
a fan is emplaced below wave-base and near
the base of gravity processes, at a break
in slope that promotes deposition of coarse materials."

This is a relatively simple and useful definition of a "submarine fan"" which will be used during this discussion.

The generally accepted "submarine-fan" models were formulated during the seventies. The models of Mutti and Ricci-Lucchi (1972) and Walker (1978) outline similar arrangements and distributions of facies. There are differences in detail but mostly in terminology. The Mutti and Ricci-Lucchi model is mainly based on the study of the Tertiary fan systems of the northern Apennines and the Walker model is based on the study of fossil submarine fans in North America and the U.K. plus data from Normark (1970, 1978) on the present day submarine fans of the Californian borderlands.

Both models place the sand rich "fan" environment between two mud rich environments, the slope and the basin-plain. The slope occurs between a shallow water area and the deeper water environment of the fan. It is generally dominated by mud-rich sequences which are commonly slumped and contorted. The basin-plain occurs distal and adjacent to the active fan and often covers the inactive parts of the fan system. A typical sequence is dominated by mudstone with some laterally continuous sandstone beds.

The active part of the "fan" system is divided into two principal groups of environments; a) a channelised area which is developed in relatively "proximal" regions adjacent to the slope and entry point for sediments, and b) a non-channelled area composed of lobes of sediment that occur between the termini of the channels and the /

basin plain (Fig 3.26). These lobes are probably partially analagous to the mouth bars which develop in fluvially dominated deltas. The fan system is fed by a point source or by a series of point sources. Both Mutti and Ricci-Lucchi (1972) and Walker (1978) subdivided the channelised area into an inner part comprising one or two deeply incised channels that rarely shifted position and an outer part containing shallower channels that tended to avulse and switch frequently. This subdivision has subsequently been largely dropped as many ancient systems do not have inner areas with deeply incised stable channels (Mutti 1977, Link and Nilsen 1980) and it is often difficult to differentiate the two subenvironments. However, it is generally recognised that the channels become shallower down the fan and the shallower channels tend to avulse and switch more frequently than the deeper, more incised channels. In both models the channel sequences tend to develop thinning and fining upwards sequences and the fills are largely composed of sands and gravels with little mudstone. The sandstones generally show features indicative of deposition from relatively dense, immature turbidity-currents (Lowe 1982) and the beds are mainly Ta or Tab turbidites in the terminology of Bouma (1962). There is also a general fining of channel fills across the fan and there is a positive correlation between channel depth and maximum grain-size.

The lobes are almost entirely depositional features with limited scouring at the base of some sandstones. Both models note that the lobe sequences tended to coarsen and thicken upwards. However, recent work (Walker 1984) has shown that these sequences are highly variable and are not as well developed as the channel fill fining-upwards sequences. The component sandstones of the lobes tend to be finer grained than those of the channels and they tend to display better developed Bouma sequences.

In Summary, figure (3.26) illustrates the basic features /

that seem to be present in most well developed modern and ancient fan systems. Therefore, despite the pessimism shown by Normark et al (1984) the following features of submarine fans can be useful to predicting and modelling the distribution of hydrocarbon bearing sediments (see Section 3.F.).

(i) Most submarine fan systems are bounded by two mud rich areas; the slope and the basin-plain. Therefore, the stratigraphic trapping of such systems during either retrogressive or transgressive episodes, is very likely.

(ii) The systems are fed by a point source or a series of point sources. The identification of these points must be one of the first steps to correctly identify reservoir distributions.

(iii) There is an overall fining of sediment from the point source through the channel and lobe areas to the basin plain. This fining occurs in both proximal-distal and axial-radial senses.

(iv) There should be good lateral communication of reservoirs from distal areas towards the point source.

(v) Lateral reservoir continuity, in an axial-radial sense, should increase from proximal to distal areas.

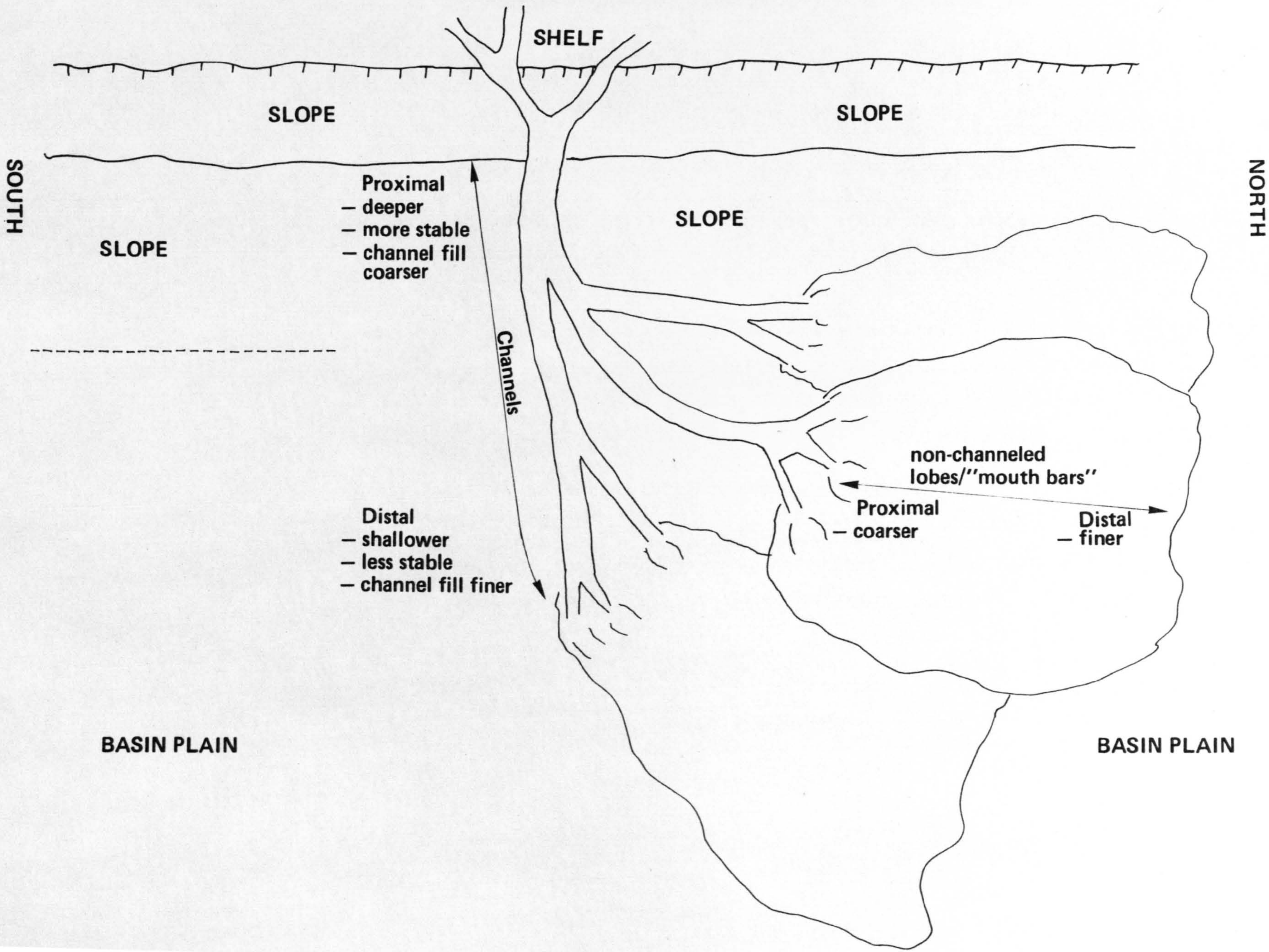
(vi) Vertical connections between reservoir units will become poorer distally.

These general predictions can be made with varying degrees of confidence in different systems. However, with the "state of the art" today more detailed predictions must be treated with extreme caution.

Recently, emphasis has switched to the external controls on submarine fan systems (Ricci-Lucchi 1984). These will/

Fig.3.26 A sketch illustrating the features which are generally present in ancient and modern submarine fan systems.

In a structurally unconfined fan system an overall "fan" or "cone" shape is maintained by switching of the proximal channel system to take advantage of increased gradients and topography in a manner analagous to fluvially dominated delta systems. In this figure the fan has built out towards the north. The next phase of fan building would probably be towards the south or east and the fan system would then rapidly prograde over the relatively low lying basin plain.


SHELF
SLOPE
SLOPE
SOUTH
NORTH
Proximal
– deeper
– more stable
– channel fill coarser
SLOPE
SLOPE
Channels
non-channeled lobes/"mouth bars"
Proximal
– coarser
Distal
– finer
Distal
– shallower
– less stable
– channel fill finer
BASIN PLAIN
BASIN PLAIN

be briefly dealt with later, after South Brae has been compared to the basic submarine fan model which was developed during the seventies.

(ii) The Coarse Association

The various graded, non-graded, framework and matrix supported conglomerates of subfacies la (Fig. 3.6) are very similar to conglomerates deposited in fossil submarine channels (Walker 1975, 1978, Gokcen and Kelling 1983, Cazzola et al 1981, Rochleau and Lajoie 1974, Hendry 1978). Conglomeratic sequences are mostly restricted to the channel systems of submarine fans (Walker 1978, Mutti and Ricci-Lucchi 1972). The scarcity of marine fossils is attributed to a direct fluvial or deltaic source for the sediment, a suggestion supported by the occurrence of abundant fossil plant fragments and miospores. Mutti and Ricci-Lucchi (1972) noted that discontinuous plant rich partings were common in submarine fan channel sediments. The structureless graded sandstones (Fig 3.9) and the graded beds with parallel laminated divisions are typical of beds deposited in fossil submarine channels (Link and Nilsen 1980, Piper et al 1978, Walker 1978, Gokcen and Kelling 1983). In the terminology of Bouma (1962) they are mostly Ta or Tab turbidites. The thin-bedded sandstones of facies 3 (Fig. 3.10) are less typical of submarine channel deposition than facies 1 and 2. However, facies 3 has features similar to facies E of Mutti and Ricci-Lucchi (1972) which is commonly associated with thicker bedded and coarser grained channel sequences. Jacka et al (1968) noted that, in the the Permian Delaware Mountain Group, thin current rippled and laminated sandstones were deposited in fossil submarine channels when they were relatively sediment starved, and in the California Borderland submarine fans, Nelson et al (1978) pointed out that, thin-bedded rippled sands were commonly deposited in the channels during the Holocene when the high sea-level stands led to the relative starvation of the channels. Facies 3 was deposited in a lower energy environment than/

facies 2 and 1 and where closely associated with these facies, the thin-bedded sandstones were probably deposited from relatively small turbidity-current events in comparatively sediment starved submarine channels.

The coarse association fining-upwards sequences (Figs. 3.16 and 3.20)) are very similar to those deposited in the channelised parts of ancient submarine fan systems (Walker 1978, Pickering 1982, Carter 1979, Gokcen and Kelling 1983). In the laterally continuous exposures of the northern Apennines, Ricci-Lucchi (1975) noted that in 80% of the 39 measured channel fills the sequence thinned and fined upwards. In South Brae the coarse association fining-upwards sequences are mostly between 5 and 30m thick (Fig. 3.16). This compares well with inferred depths in ancient (Ricci-Lucchi 1975, Piper et al 1978, Carter 1979) and modern (Normark 1978, Normark, Piper and Hess 1978) submarine channels. Most of the channels described in the literature were filled by vertical accretion, they have a cut and fill geometry in cross-section and there is a progressive onlap of beds onto the channel walls. The resultant sand and conglomerate body is lensoid and has a convex base and a relatively flat top. Some channels are, however, filled by laterally accreted sediments (Hein and Walker 1982) and the resultant sand body has a relatively wide lateral extent and is parallel sided.

The fining-upwards of the vertically accreted fills is thought to be the result of gradual abandonment after partial plugging of the channel by a large flow. The fining-upwards of the laterally accreted fills simply reflects increasing distance from the channel axis in a manner analogous to fluvial point bar sequences.

The single fining-upwards coarse association sequences (Fig. 3.16) are probably the result of the filling of a single channel and the multiple fining-upwards sequences are stacked compound channel sequences. The multiple /

fining-upward sequences in which the succeeding sequences are coarser and finer than the prece ding ones (Fig. 3.20) are probably progradational features that reflect the progradation of a channel system. In the terminology of Mutti and Ricci-Lucchi (1972) they are the result of the progradation of a midfan distributary channel system and in the terminology of Walker(1978) they are the result of the progradation of the channelised part of a suprafan lobe. The coarsening-upwards sequences with erosional contacts between facies groups are also interpreted as progradational channel units and the coarse association sequences with random facies transitions are probably the result of complex channeling and erosion.

(iii) <u>The Fine Association</u>

Taken in isolation, the individual facies could be interpreted as fluvially dominated delta front deposits (section 3.E). However, the scarcity of well developed coarsening-upwards sequences plus the interstratification and gradational relationships with the coarse association, suggests that the fine association was deposited adjacent or distal to submarine channel systems and it represents the relatively inactive parts of a submarine fan system.

The thin graded sandstones with sharp or erosional bases are interpreted as tubidites. The abundance of cross-laminations in the facies 3 beds suggests substantial tractional reworking after initial deposition. The beds are unlikely to be contourites (Stow and Lovell 1979) as they were deposited in a deep restricted basin (Hallam and Sellwood 1975) in which there was very poor water circulation. Also, they are not exceptionally well sorted and they contain plant fragments which would have been winnowed away if the sands were subjected to long term reworking by contour currents. Rather, the reworking was probably carried out by the tail of the turbidity-current that intitally deposited the sand. The non-graded or /

poorly graded sands are also interpreted as turbidites. This interpretation is largely based on their context. The poorly developed grading or lack of grading may be attributed to many factors, eg. (i) deposition from relatively immature turbidity currents in which there was a poor segregation of grain-sizes within the flow, (ii) substantial reworking by the turbidity-current tail and (iii) the input of well sorted sand to the flow.

"Thick-bedded and coarse-grained deposits have generally received more attention than thin-bedded and fine grained deposits in the studies of ancient turbidite basins." Mutti (1977 p108). As a result there are few criteria for using thin-bedded turbidites in environmental analyses. However, the irregularity of bedding, the dominance of cross-statification and the sharp tops to many of the sandstones is generally indicative of deposition in a "proximal" rather than "distal" or basin-plain environments (Nelson et al 1975). This suggestion is substantiated by the abundance of soft-sediment deformation features and the interstratification of the fine association with channel deposits.

The fining-upwards fine association sequences that occur directly above fining-upwards coarse association sequences can be interpreted as the result of continued gradual abandonment of the coarse association channel system. The sequences may also be due to the gradual lateral migration of the channel system and the fining-upwards again simply represents increasing distance from the channel axis. Therefore, the facies 3 sequences would have been deposited in a proximal overbank or levee environment and facies 5 would have been deposited in a distal overbank environment. Pickering (1982) noted in the late Pre-Cambrian Kongsfjord Formation of northern Norway, a similar arrangement of overbank facies; the levee facies was predominantly composed of cross-laminated sandstones and the sandstone : shale ratio gradually decreased with increasing distance /

from the channel. He also noted a palaeocurrent divergence of up to 90° from the channel trends.

The coarsening-upwards fine association sequences, especially those that are erosively truncated by coarse association sequences, probably reflect increasing proximity to the channel system and can be interpreted in terms of either progradation or lateral migration of the channel system.

Although they display similar sandstone : shale ratios and occur in the correct stratigraphic position, underlying the coarse association, the coarsening-upwards fine association sequences are not similar to the "classical" outer-fan lobe coarsening-upwards sequences of Ricci-Lucchi (1975), Mutti and Ricci-Lucchi (1972) and Walker (1978). These sequences are mainly composed of thicker, parallel sided, well graded sandstones that generally display well developed Bouma sequences. The fine association sequences are also thinner than typical "outer-fan lobe" sequences. Mutti (1977) described sequences similar to those of South Brae. They were coarsening-upwards sequences that are generally flaser or lenticular bedded. The sandstones show evidence of substantial tractional reworking. These sequences were thought to have been deposited in a "channel-mouth-bar" environment. According to Mutti this environment occurred between the ends of the channels and the outer-fan lobes in a zone which was bypassed by most of the coarser-grained sediment. However, the existence of such a zone is highly controversial (Walker 1980 p1103). In general, the coarsening-upwards fine association sequences can be interpreted as small-scale "bar" or "lobe" deposits which occurred close to the terminations of the channels.

An alternative explanation is that they were deposited adjacent to the submarine channels in levee and interchannel environments (Pickering 1982) and that the coarsening upwards is due to increasing proximity to the channel /

during lateral migration.

It is significant that the best developed coarsening-upwards sequence, which occurs in the 16/7a-13 well between 12780' and 12730' (Fig. 3.16e), is not overlain by a coarse association sequence. The relative thinness of the other coarsening-upwards sequences is probably due to erosion by the overlying channel (Fig. 3.21), with the result that only the basal parts of the sequences are preserved. The thick sequence in 16/7a-13 (Fig. 3.16e) has a relatively sharp top into facies 5, which probably reflects rapid abandonment or switching of the channel system that supplied the "lobe", "bar" or "levee" environments.

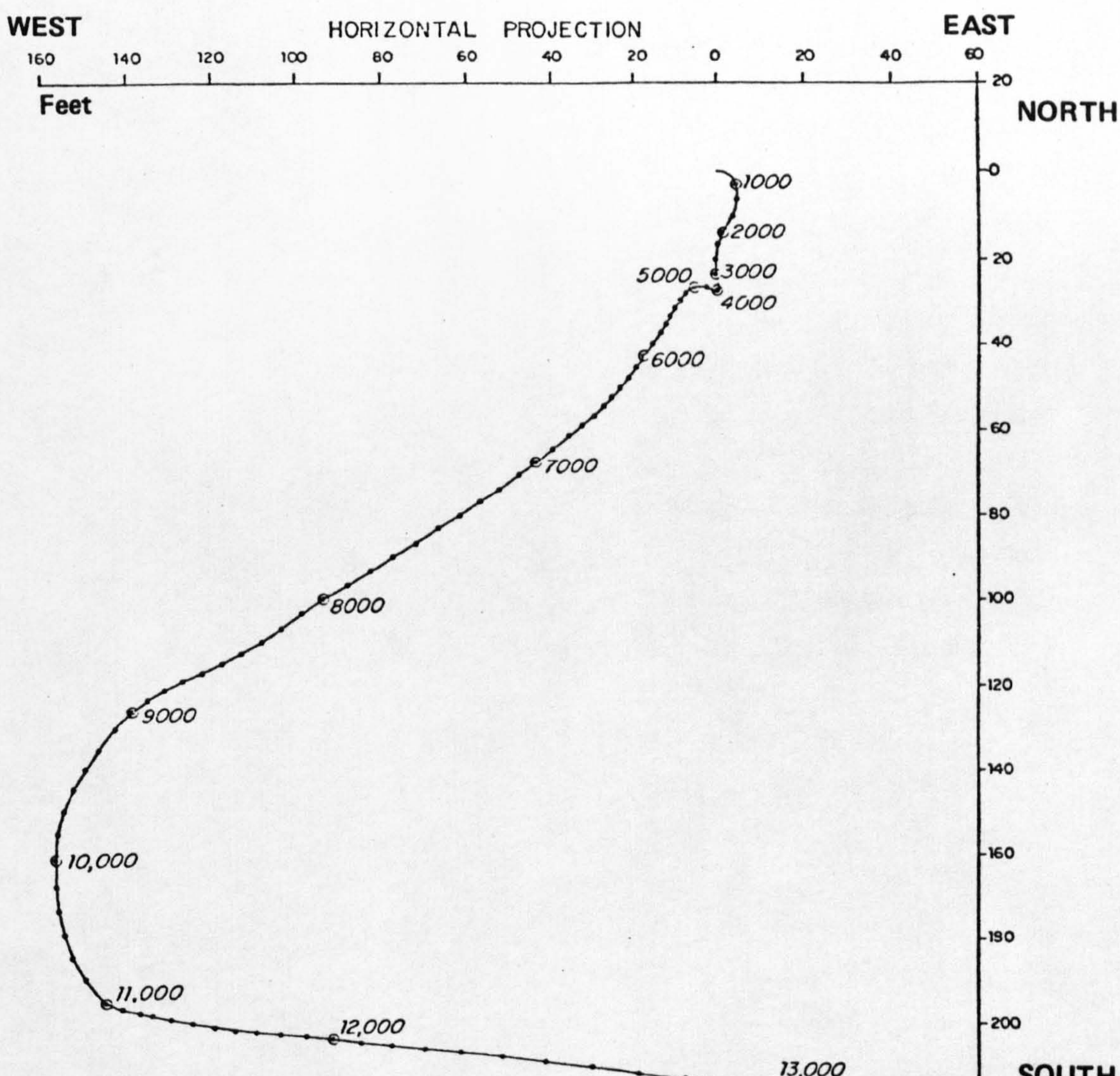
In general, the predominance of gradational facies transitions in the fine association suggests that there are few major environmental changes. In the fining and coarsening-upwards sequences and in those sequences in which there is no systematic trend, the variability in sandstone : shale ratios probably primarily reflects proximity to active channel systems. Other factors, eg. "sandiness" of the channel system are also probably significant.

(iv) <u>The 16/7-12 Well</u>

The unique occurrence of subfacies 1b and 1c and the absence of subfacies 1a and facies 2 suggests that the environment of depostion of, at least part of, the 16/7a-12 well differs from that of the other exploration wells.

The crushed and fractured breccias which occur between 13480' and 13009' (Fig. 3.23) are thought to lie within a fault-zone. As the well drift map (Fig. 3.27) shows that below 13009', the well was drilled at approximately 80° to the E, the thickness of the sequence is probably due to the well being drilled subparallel to an easterly dipping fault-zone./

Fig. 3.27. 16/7a – 12, Well drift map



The very-tight packing, the apparent lack of fabric organisation and the angularity of the clasts (Fig. 3.8a) suggests that the breccias which occur between 13009' and 12852' were transported by rolling and sliding down a steep slope (section 1.C). As the breccias occur directly above a shear-zone and are fossiliferous (Fig. 3.8b), this sequence is probably a fossil submarine fault-scarp scree deposit in which angular clasts of sandstone were eroded from the fault-scarp and deposited on the downthrown side of the fault as a talus slope. Similar lithologies are described by Surlyk (1978) from the Jurassic/Cretaceous Wollaston Foreland Group of East Greenland. Seismic shocks were probably instrumental in initiating the rockfalls (Johns 1978) and the broken shell fragments and sand in the matrix were probably derived from a shelf area on the upthrown side of the fault. As the shells are relatively thick (Fig. 3.8b) they are probably fragments of shallow water fauna which are notably absent from the mudstones of S. Brae. This implies that the shell fragments are allochthonous and the fault separated a relatively shallow water area from a relatively deep-water area. Therefore, it is likely to be a basin-margin fault. This scenario is very similar to that adjacent to the Helmsdale Fault at the western margin of the Inner Moray Firth Basin (chapter 2). The fracturing of the breccias below 13009' can be attributed to later movements on the basin margin faults and to slight adjustments in position.

The entire sequence above 13000' can be simply interpreted using Walthers Law. The facies 1c breccias which lie above the fault zone were deposited adjacent to the fault-scarp. The upwards transition from facies 1c breccias to a mixture of facies 1b breccias and facies 4 mudstones and the further transition into a sequence domination by facies 4 mudstones is a "fining-upwards" sequence that can be interpreted in terms of increasing distance from the fault-scarp (Fig. 3.24). The chaotic /

fabrics, tight packing and the angularity of the clasts suggests that subfacies 1b was transported by rockfall processes (section 1.C). The breccias, therefore, reflect avalanching of gravels across a relatively muddy slope. The gravel was probably derived from the talus slope (subfacies 1c) and the clasts were transported basinwards when parts of the slope became unstable. The initiation of these rockfalls, again, was probably due to movements on the nearby fault. The contorted and faulted facies 5 mudstones were deposited further from the fault-scarp in an area where few rock-fall avalanches reached. This spatial distribution of facies is very similar to that developed in the Kimmeridgian and Volgian sediments adjacent to the Helmsdale Fault (Fig. 2.32).

The sequence above 12700' also reflects increasing distance from the fault-scarp. The overall increase in sandstone percentage above 12650' is probably the result of the transition from the submarine slope, which received little sand from the shelf, to the interchannel areas of a submarine fan system in which the thin sandstones beds were deposited from turbidity-currents that overtopped their channels and flowed across the interchannel areas (Nelson et al 1978). The facies development above 12650' is very similar to that of the "fine association" of the other exploration wells. The sharp based facies 3 unit above 12473' (Fig. 3.16d) may be a submarine crevasse-type channel fill sequence. The common contorted, slumped and faulted beds testify to frequent oversteepening of the sedimentary pile and failure due to seismic shocks.

(v) Basin-Fill

The overall fining-upwards basin-fill in the 16/7a-12 well can be largely explained in terms of increasing distance from the basin-margin fault scarp. However, this cannot entirely explain the fining-upwards in the other wells as the environmental belts in the submarine fan system/

are much wider than at the basin margin. If increasing distance from the basin margin was the only reason for the fining I would expect only slight differences between deeper and shallower horizons. The fining-upwards fill must be partially the result of gradually diminishing coarse-grained sediment supply to the basin. South Brae is, therefore, a retrograde submarine fan system (Ricci-Lucchi 1975). These systems are commonly associated with active faulting and basin deepening episodes (Ricci-Lucchi 1975, Cazzola et al 1981, Surlyk 1978). Data from the T. Block oilfields (Fig. 3.1 and chapter 4) suggests that the South Viking Graben submarine fan systems were probably initiated in the late Oxfordian during a major phase of faulting and basin deepening. During the Kimmeridgian the South Brae system was probably large and extended far out into the South Viking Graben, whereas during the late Volgian the Graben was relatively starved of coarse-grained sediment and the submarine fan system was small. The facies 2 and 3 dominated sequences towards the top of the 16/7a-8 and 16/7a-10 wells were probably deposited in sediment starved channels (p.175). The fining-upwards may be analogous to that of the Wollaston Foreland Group of East Greenland (Surlyk 1978) in which the gradually diminishing coarse-grained sediment supply was due to erosion and retreat of the borderlands. A major eustatic control is rejected as the Volgian is not strongly transgressive (Vail and Todd 1981, Rawson and Riley 1982).

(vi) Spatial Distribution of Facies

The analysis suggests that much of the 16/7a-12 well was deposited on a basin-margin slope which existed between a shallow water area to the west and a deeper water area to the east. The principal South Brae reservoirs were deposited in this deeper water area. The complex seismically defined NNW trending discontinuities which occur close to the 16/7a-12 well (Fig. 3.3) probably reflect the basin-margin fault system./

The dominance of fining-upwards coarse association sequences in the 16/7a-8, 10, 11 and 13 wells suggests that the major reservoirs were deposited in the channelised part of a submarine fan system (Fig. 3.29). The highest coarse : fine association and facies 1 : 2 ratios (Fig. 3.25) implies that the 16/7a-8 well was the most proximal and that a major entry point for sediment lay somewhere to the west of that well. The high coarse : fine association ratio may indicate that the entry point was relatively fixed throughout the Kimmeridgian and Volgian and the distribution of active channels plus the position of the entry point may have been partially structurally controlled (section 3.D [vii]). The general fining plus the decrease in the thickness of coarse association sequences from 16/7a-8 to 16/7a-10, 11 and 13 suggests that there was a general fining of channel sediments and the depths of channels decreased across the fan system from the entry point to the relatively "distal" areas. This is typical for most submarine fan systems (Mutti and Ricci-Lucchi 1972, Walker 1978).

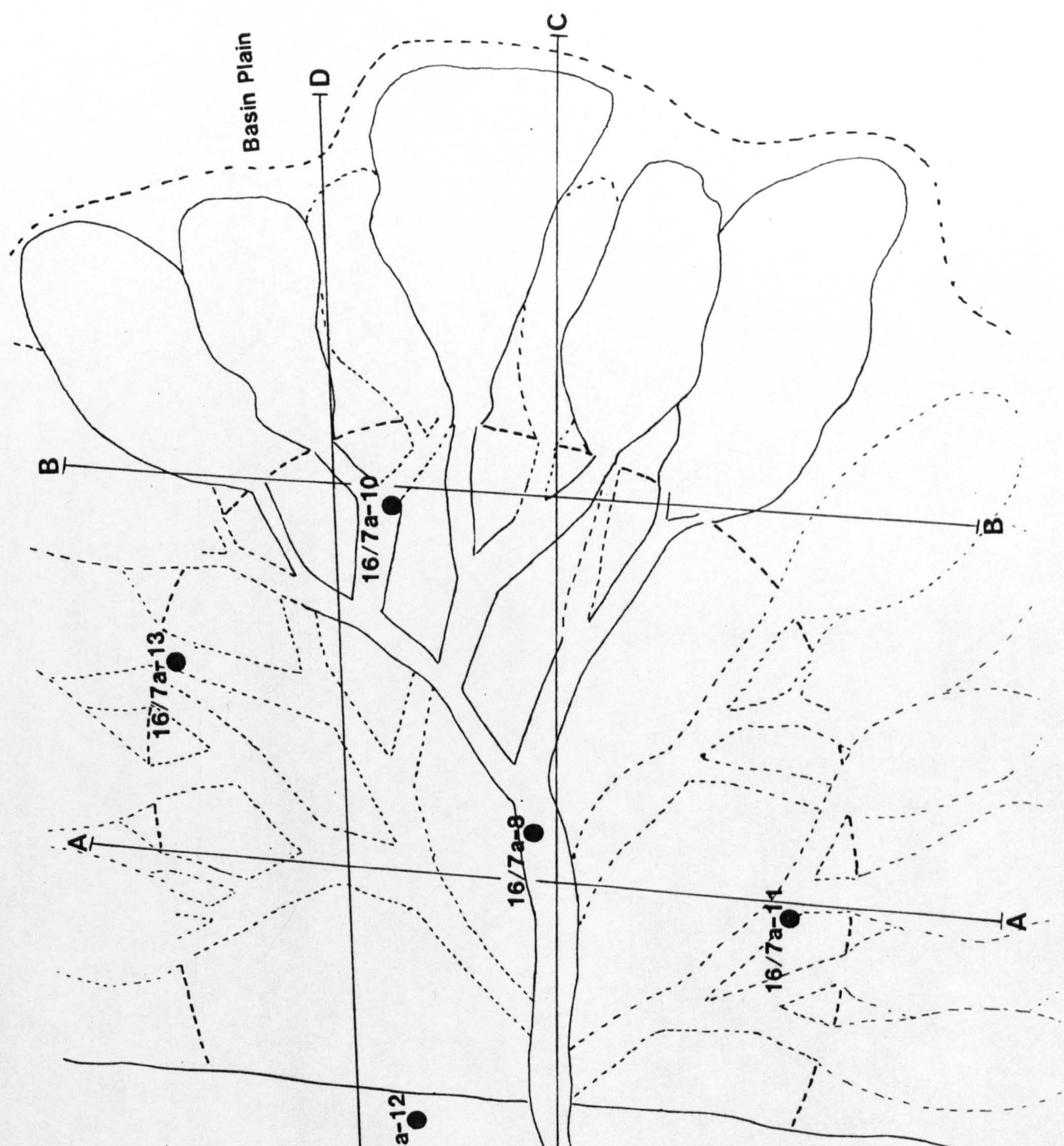
The general lack of coarsening-upwards fine association sequences in 16/7a-8 is probably due to erosion of the sequences during progradation or lateral migration of the deeply incised, relatively proximal channels. The shallower, less incised channels did not completely erode the underlying bar or interchannel sediments and some coarsening-upwards sequences were preserved in the more distal areas.

The relatively high facies 1 : 2 ratio and the relatively low coarse : fine association ratio (Fig. 3.25) tentatively suggests that the 16/7a-11 well was in a relatively "proximal" position that was frequently removed from the area of active deposition. This also suggests a possible structural control on the proximal channel system./

Fig.3.29 A DEPOSITIONAL MODEL FOR SOUTH BRAE (see text for details)

The reservoirs were deposited in the channelised part of a submarine fan system which was fed from a point to the west of 16/7a-8 and the southwest of 16/7a-12.

see Fig. 3.32 for schematic cross-sections.


Basin Plain
D
C
B
A
16/7a-10
16/7a-13
16/7a-8
16/7a-14
16/7a-12
SLOPE
SHELF

The lack of obvious correlations between wells is not surprising as the reservoirs were deposited in laterally confined channels or channel systems. The additional data from production wells should assist possible radial correlations. A very high density of wells would be needed to accurately correlate in an axial-lateral sense. However, it may be possible to correlate between large-scale, tectonically or eustatically controlled, cycles (section 3.D [vii]).

(vii) External Controls on Fan Systems

The above interpretation of the South Brae system assumes that the major controls on the distribution of facies were the internal dynamics of the depositional system. In this section I will briefly review, what are considered to be, the three major external factors; basin structure, sea-level changes, and sediment input type, which influence the distribution of sand and conglomerate bodies. The data available to this study do not allow detailed identification of the effect of external factors.

a) Structural Control

Both the Walker (1978) and Mutti and Ricci-Lucchi (1972) models assume no intrabasinal tectonic control on the distribution of facies and that the sediment body approximates a cone shape around the sediment entry point. This assumption may be valid for large continental slope and oceanic fan systems. However, the distribution of facies in all intracratonic submarine fan systems is strongly controlled by the underlying structure of the basin, syn-sedimentary tectonics, and overall basin geometry.

The channel and lobe systems, which are the potential reservoirs, are often located on the downthrown sides of syn-sedimentary faults or between intrabasinal highs (Cazzola et al 1981). For example, in the Lower Eocene Frigg gasfield in the North Sea, the main reservoirs follow the trends of deep seated/

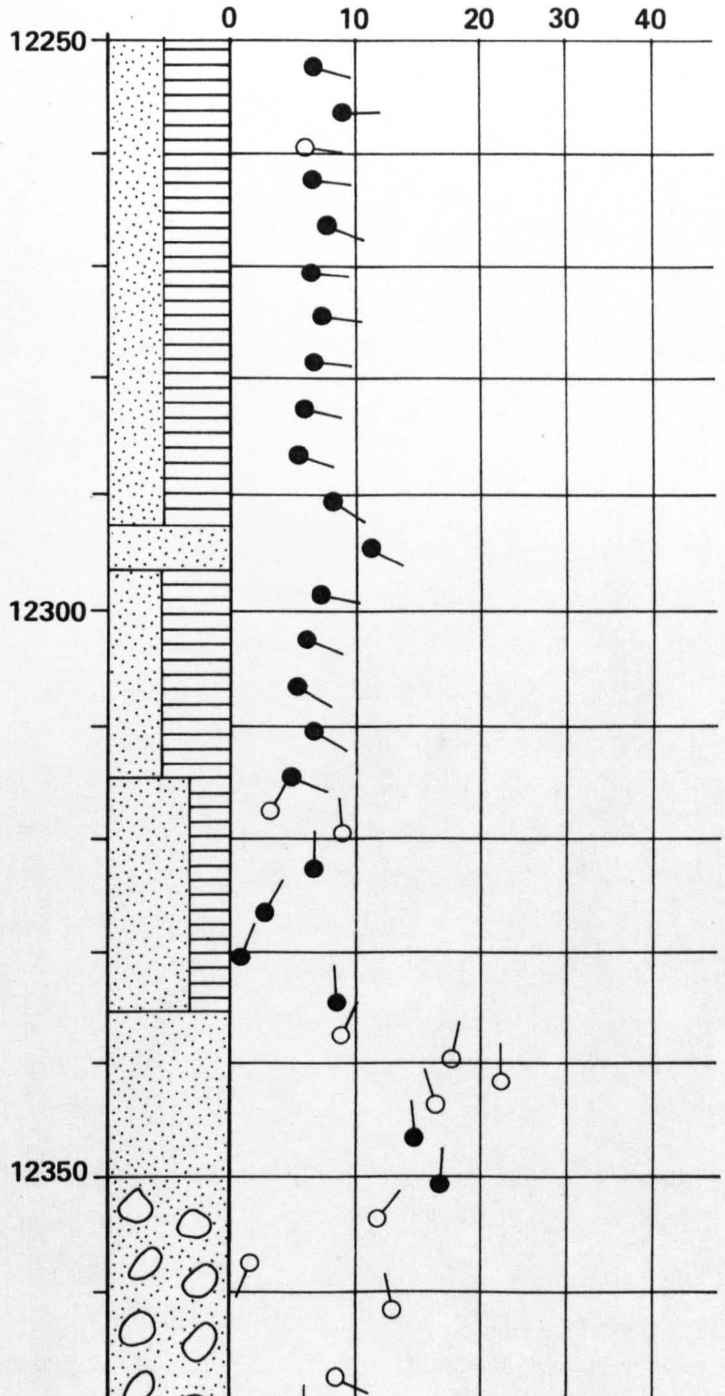
structural elements and the main feeder channel follows a deep faulted zone which parallels Caledonian structures (Heritier et al 1981). As the Frigg field is relatively shallow (2000m) the extent of the reservoirs can be mapped accurately using seismic data.

The identification of tect onically controlled channel and lobe trends will be one of the most important factors in optimising the development of the South Brae oilfield and the Upper Jurassic of the South Viking Graben in general. The poor resolution of the available seismic data and the lack of well control make it impossible to identify channel or lobe trends in this study. However, the 16/7a-8 well has a very high coarse : fine association ratio (Fig. 3.25) which implies that the South Brae channel system was located near to that well during most of the early and middle Volgian. This apparent stability suggests that there was some structural control on the position of the channel system.

During the development of the field it will be very important to carry out further seismic data processing and interpretation, possibly including 3-D seismic analysis and vertical seismic profiles. Also, detailed sedimentological analysis including the production of detailed isopach maps may help to delineate areas where there is a preferential development of good reservoir facies.

A final point that may be worth further investigation is the use of the dipmeter tool in delineating channel trends. Channel fill sequences can show upward decreasing dip patterns with the dip azimuth normal to the channel axis (Selley 1979). In the 16/7a-8 well between 13540' and 12510', and between 12350' and 12320' upwards decreasing dip patterns with northerly azimuths tentatively suggest E-W trending channels (Fig. 3.30). However, the dipmeter response is generally relatively poor in the conglomerate and sandstone channel fill/

Fig. 3.30. Poorly developed "decreasing-upwards" dip pattern between 12350 and 12330 feet in the 16/7a – 8 well. (Dips computed from the Schlumberger Cluster Program 4x2x35)



sequences (Fig. 3.15). Therefore, it may be worth investigating the effect of channel loading of the underlying mudstone. A detailed dipmeter study incorporating both exploration and production wells may be able to define preferred channel trends and therefore, outline possible structural trends.

Overall basin shape will also strongly influence the distribution of reservoirs. Subsidence in the Upper Jurrassic South Viking Graben was highly asymmetrical (Chesher and Swallow 1985) with the major throw along the western bounding fault system (section 3.A). If subsidence rates were higher than sedimentation rates this would produce an asymmetrical basin with a steep easterly dipping slope in the west and a more gentle westerly dipping slope in the east. This scenario occurred in the Upper Jurassic/Lower Cretaceous Wollaston Foreland Group of East Greenland (Surlyk 1978) where the gently sloping dip-slope helped to restrict the coarse grained submarine-fan sediments close to the most active basin margin fault. Also, asymmetrical half-grabens have similar geometries to foredeep or "piggy-back" basins which occur in thrust belts. In these basins longitudinal dispersal of sediment is very common. If subsidence rates outstripped sedimentation rates and an asymmetrical geometry was produced, axial dispersal of sediment may have been important in the Upper Jurassic South Viking Graben. Therefore, outlining of the overall basin geometry will be important to optimising the development of S. Brae and the South Viking Graben in general.

Tectonic movements in the hinterland may have also exerted a control on the sedimentation in S. Brae. Surlyk (1978) noted that the Wollaston Foreland Group of East Greenland was composed of large scale fining-upwards cycles which were related to differential movements in the hinterland. Large-scale faulting /

led to unstable gradients and the erosion of large quantities of sediment which was transported into the basin. Subsequent erosion and retreat of the hinterland during relatively stable periods caused the fining-upwards megacycles. Data from the production wells may allow the delineation of tectonically controlled cycles. The identification of these cycles is important as the mudstone rich top of each cycle will be widespread and is likely to act as a vertical permeability barrier.

b) Sea-level Changes

Minor sea-level changes will be reflected in submarine fan systems. In general, a relative sea-level rise will lead to the deposition of finer grained sediment and a relative sea-level fall will lead to the deposition of coarser grained sediment. As with tectonically induced cycles, sea-level induced cycles should be widespread and will be correlatable between wells. The five exploration wells do not outline any obvious small-scale sea-level or tectonically controlled cycles. However, data from the additional production wells may allow the delineation of such cycles which will be separated by laterally persistent shales which may act as pressure barriers.

North Sea eustatic sea-level curves have received much attention in the literature recently. Vail and Todd (1981) and Rawson and Riley (1982) suggest that the sedimentary modelling of individual oilfields can be in part predicted by a consideration of regional or eustatic sea-level changes. However, the most recently produced sea-level curve for the late Jurassic (Rawson and Riley 1982, Fig. 2) fails to predict the sedimentary characteristics of South Brae and the South Viking Graben in general. The curve highlights two major phases during the late Jurassic; a strongly transgressive phase from the Oxfordian to the end of the early Volgian and a strongly regressive phase from the beginning of the middle Volgian through/

to the early Cretaceous. Therefore, the initiation of late Jurassic coarse clastic deposition in the South Viking Graben, during the Oxfordian (Fig. 3.1) was not related to eustatic changes as sea-level apparently rose during this period (Rawson and Riley 1982). This should have resulted in a decrease in coarse clastic deposition in the graben. Also, there is little evidence for the middle Volgian regressive period. The basin-fill of South Brae tends to fine-upwards during the middle and late Volgian, whereas, a strongly regressive phase should have resulted in a dramatic increase in the quantity of coarse clastic sediments being transported into the basin.

The general palaeogeographic setting of the late Jurassic was one of deep, relatively narrow basins flanked by shallow water or emergent areas (Hallam and Sellwood 1975). In this setting slight variations of sea-level would have dramatic effects on sedimentation. The implication of the middle Volgian regression (Rawson and Riley 1982) is that large quantities of coarse clastic sediments would be transported into the various basins. This is clearly of great importance to exploration geologists as the coarse-grained sediments would form potential reservoirs which were enclosed by Kimmeridge Clay Formation (Deegan and Skull 1977) shales. The resultant play would be very attractive as the Kimmeridge shales would both supply the hydrocarbons and act as a cap rock. However, the results of the studies on S. Brae (chapter 3), and Helmsdale (Chapter 2) suggests that the evidences for, or the consequences of, a widespread reduction in sea-level during the middle Volgian are not as clear cut as implied by Rawson and Riley (1982).

c) Sediment Input Type

Based on the type of sediment input Mutti (1979) divided submarine fan systems into two basic categories, i) high efficiency fans composed of a mixture of /

muddy and sandy sediment and ii) low efficiency fans predominantly composed of sand and gravel. This subdivision is controversial. High efficiency systems tend to produce large fans with well developed outer fan lobes, whereas low efficiency systems tend to produce aerially restricted fans with poorly developed outer fan lobes. Although the South Brae Oilfield contains large amounts of coarse-grained sediment, it also contains relatively mud-rich sequences (Fig. 3.16). Therefore, the relatively dense, immature turbidity currents which deposited much of the facies 1 and 2 sequences may have evolved into less dense, more mature currents down the fan and subsequently deposited sands in outer fan lobe environments. Thus, a consideration of the sediment input type does not preclude the development of non-channel ised reservoir units distal to the channelised sequences described in this study.

3.E. FAN DELTA MODEL

Harms et al (1981) proposed that a system of coalescing fan deltas represented the best depositional model to account for the facies distribution and major sedimentary features of South Brae and during the summer of 1984 this model was being used by the operator to assist the production of oil from the field. The facies analysis described above suggests that the environment of deposition was entirely marine and below wave-base, and thus contradicts the fan delta model. Therefore, the model currently in use by the operator is likely to produce misleading predictions of the distribution of reservoirs and permeability barriers.

Fan deltas are alluvial fans that prograde into a body of water from an adjacent highland (McGowan 1970). They are often associated with syn-sedimentary tectonics. Wescott and Ethridge (1980) recognised two major catagories of fan delta; a) those that prograde directly onto submarine slopes and b) those deposited on the margins of marine shelves. Harms et al (1981) imply that South Brae was deposited in a type a) environment which is termed a "Yallahs type" fan delta by Wescott and Ethridge (1980). There are several well described "Yallahs type" fan deltas in the literature (Wescott and Ethridge 1983, 1980; Flores 1975; Pollard and Steel (1983); Harbaugh and Dickinson 1981; Stanley 1980; Stanley and Surdam 1978; Howell and Link 1979; Handford and Dutton 1980; Link and Osborne 1978). The basic "Yallahs type" fan delta is composed of three principal environmental zones (Wescott and Ethridge 1983), a) subaerial, b) coastal, c) submarine. The subaerial part of the delta is mainly composed of conglomerates and sandstones deposited in alluvial fan or braided stream environments, plus minor mudstone which was deposited in interchannel environments. The coastal transition zone is often the most important /

zone in recognising ancient fan deltas. As most fan deltas are fluvially dominated, the coastal transition zone can be thin and difficult to recognise. However, most fan deltas have thin zones of wave or tidally reworked sediments which directly underlie the subaerial part of the fan. These thin zones are usually preserved because the shallow braided channels of the subaerial part of the deltas do not incise deeply into the delta front. The submarine part of the delta includes the delta front and the delta slope and possible base of slope submarine fans. The slopes become finer grained away from the shoreline and the sequences coarsen upwards during delta progradation. As fan deltas are usually fluvially dominated, mouth bar sequences are common. Some fan delta fronts are flysch-like (Flores 1975.)

The conglomerates and sandstones of South Brae are interpreted by Harms et al (1981) as delta topset beds deposited by streams on the fan surfaces and the interlaminated sandstones and mudstones are interpreted as delta foreset and bottomset strata deposited in the adjacent sea. In the facies analysis described above the coarse association would approximately correspond to the subaerial part of the delta and the fine association would approximately correspond to the submarine part.

The lack of imbrication and cross-bedding suggests that the conglomerates were not deposited in braided stream channels. Rather, the presence of both matrix and framework supported clasts and graded and non-graded beds are suggestive of deposition in very shallow ephemeral streams during flash flood events (Nilsen 1984). Harms and McMichael (1983) overlook the fact that many of the sandstones are graded and have textures that suggest depostion from a decellerating current. Although individual beds could be interpreted as flash flood deposits, thick composite units of flash flood conglomerates and sandstones /

have not been recorded from vegetated temperate or humid region alluvial fans. The occurrence of rare marine fossils is also difficult to resolve with an alluvial fan environment of deposition. The Harms and McMichael (1983) explanation that the marine fossils "could be accounted for as occupying the extreme delta shoreline or the next transgressive phase of marine flooding" is tenuous as there is no evidence for shoreline deposits or wave reworking in the conglomerates and sandstones and the fossils occur sporadically in the coarse association sequences.

Many of the interlaminated mudstones and sandstones of the fine association have features very similar to many delta front or slope sequences. However, the delta fronts and slopes that are preserved in the stratigraphic record are mostly large-scale coarsening-upwards sequences that were deposited during delta progradation, whereas the fine association of South Brae is more often a large-scale fining-upwards sequence, and coarsening-upwards sequences are thin and only developed in the more easterly (distal) wells, eg 16/7a-13. A final reason for rejecting the fan delta model is the lack of a coastal transition zone.

In conclusion, some of the individual features of the South Brae strata are consistent with a fan delta environment of deposition. However, the following points are important inconsistencies;

(i) The poor development of fine association coarsening-upwards sequences.

(ii) The lack of evidence for wave or tidal reworking of the sediments directly underlying the conglomerate sequences.

(iii) The presence of marine fossils in the conglomerates and sandstones. /

(iv) The presence of thick sequences of graded sandstones.

3.F. <u>RESERVOIR DISTRIBUTION</u>

The typical reservoir properties of each of the facies are shown in Figure (3.5). The reservoirs are mostly restricted to the coarse association sequences. Both primary intergranular and secondary dissolution porosity occur in the sandstones and conglomerates (Fig. 3.31a). The secondary porosity is predominantly the result of dissolution of feldspars and micas. The clasts of the conglomerates generally show poor porosity and permeability and the areas with good reservoir characteristics are mostly restricted to the matrix of the beds. The abundance of plant rich laminations in facies 3 drastically reduces the vertical permeability in that facies. The relatively clean sands of facies 2 sequences have the best poro-perm properties. Occasional calcite cemented zones occur at deeper horizons. These concretions are between a few cm and a few meters thick (Fig. 3.31b).

This study suggests that the South Brae reservoirs were deposited on the channelised part of a submarine fan system which was sourced from a point to the west of 16/7a-8 and to the SSW of the 16/7a-12 well (Fig. 3.29,). External controls on fan growth cannot be predicted from the data available to this study. However, several basic predictions concerning reservoir distribution can be made. The cross-sections of Figure (3.32) illustrate a schematic first estimation of possible reservoir distribution. The model should clearly be refined and modified when data from production drilling in 16/7a and exploration drilling in the 16/7b and 16/8a blocks is available.

The following predictions can be made;

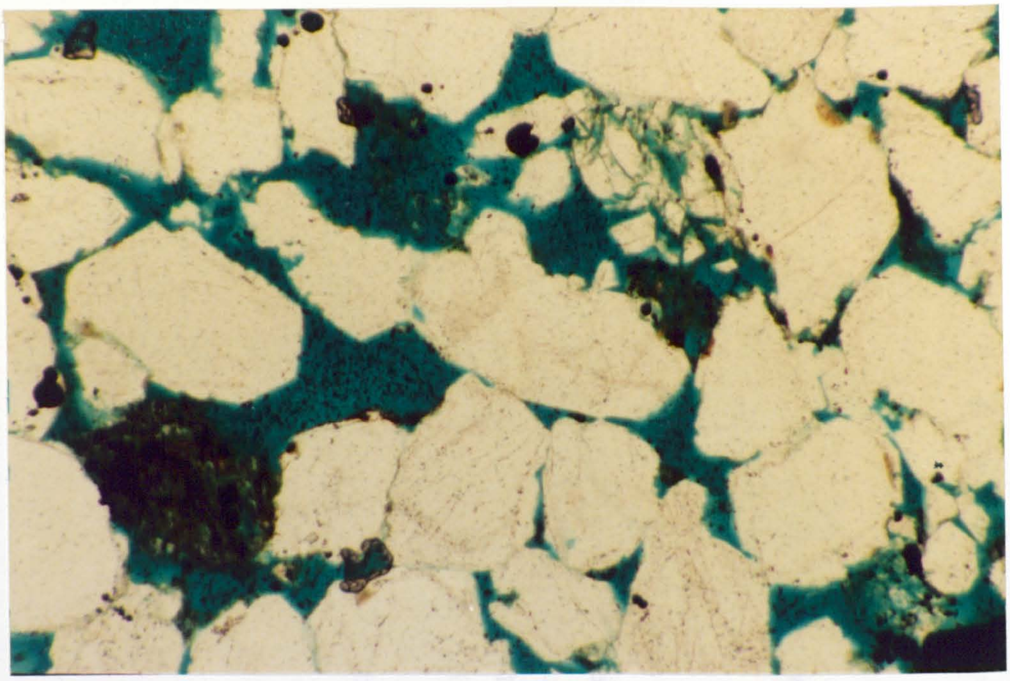
(i) <u>There will be poor reservoir development to the west of the NNE - SSW trending seismic discontinuities which run close to the 16/7a-12 well./</u>

Fig.3.31a <u>Thin-Section of Porous Sandstone.</u>

Field of view 1.6mm.

Note: the partially dissolved feldspar and the enlarged pores (secondary porosity); and the presence of some primary intergranular porosity.

Fig.3.31b <u>Patchy Concretionary Calcite in Porous Sandstone-Rich Sequence.</u>



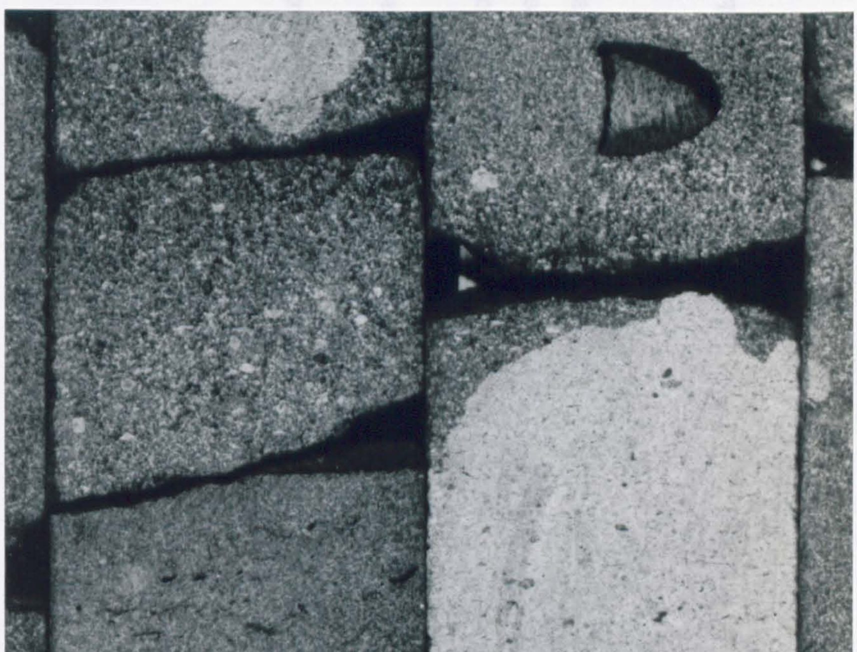
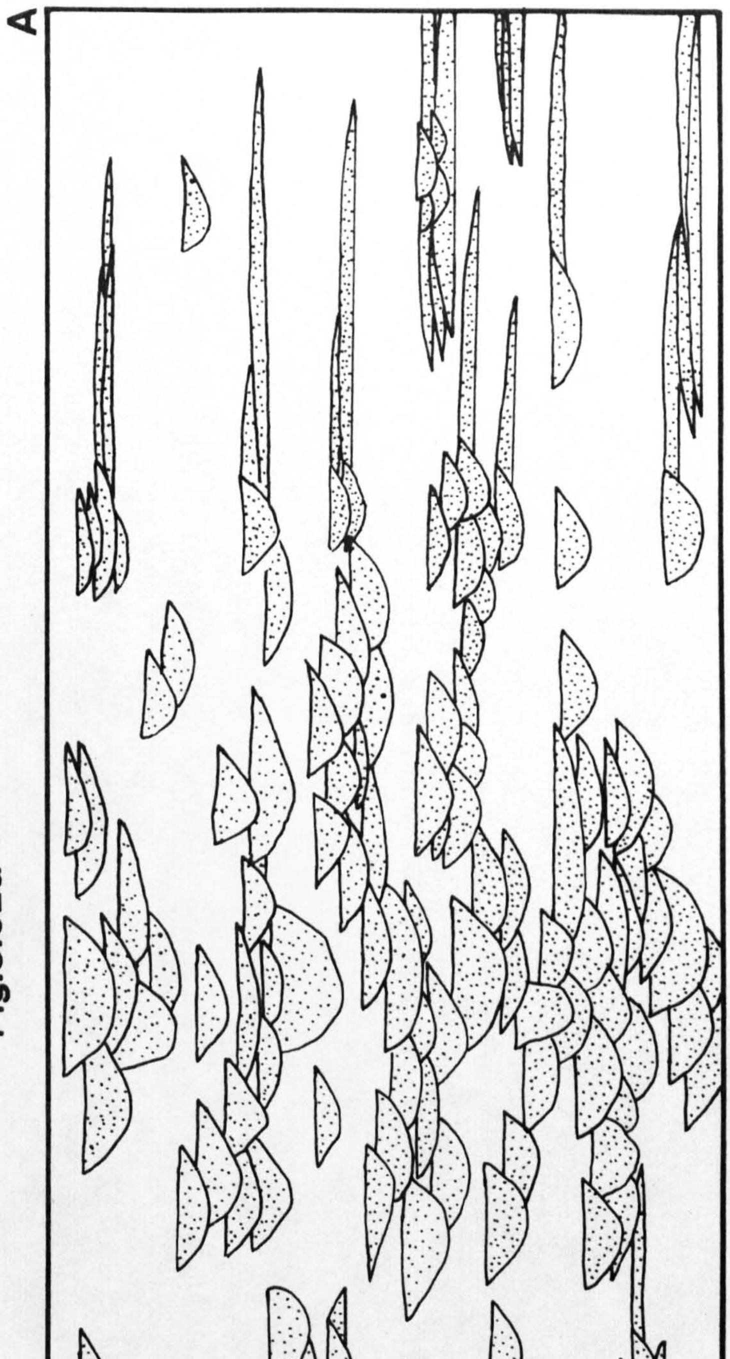


Fig.3.32 SCHEMATIC CROSS-SECTIONS OF THE SUBMARINE FAN SYSTEM DEPICTED IN FIG.3.29.

These cross-sections (2-D slices of a 3-D system) were drawn in an attempt to illustrate the types of reservoir geometry which would be expected from a structurally unconfined submarine fan system which was fed from a point to the west of 16/7a-8 and the southwest of 16/7a-12. (see text for details)

- Vertical scale greatly exaggerated.

Fig.3.32a



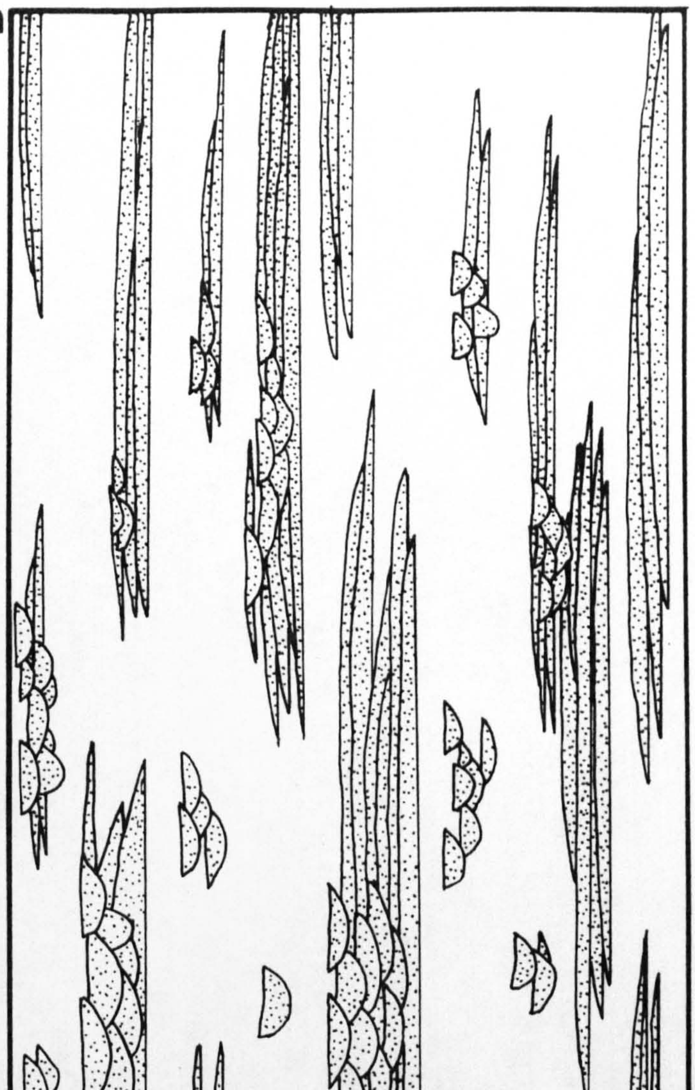


Fig.3.32b

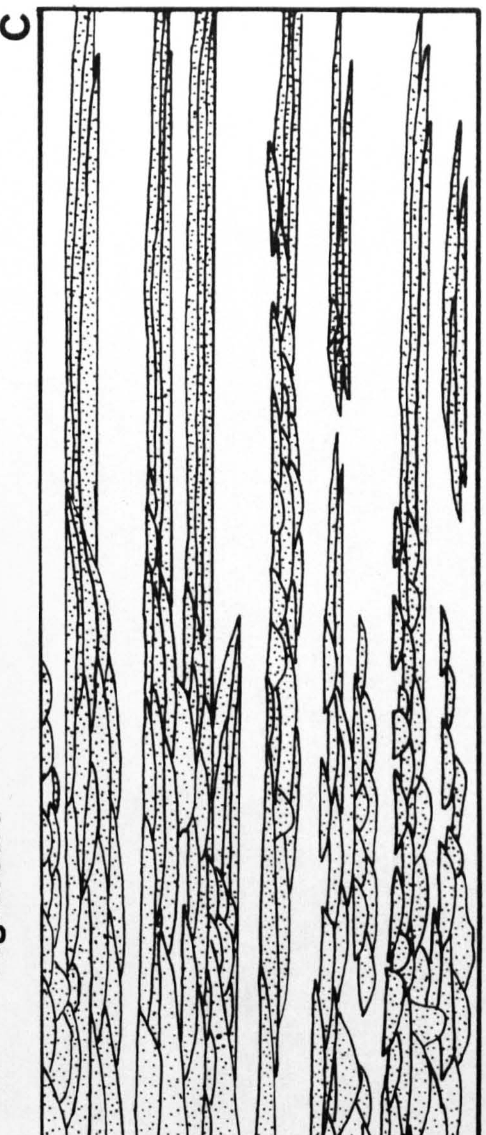
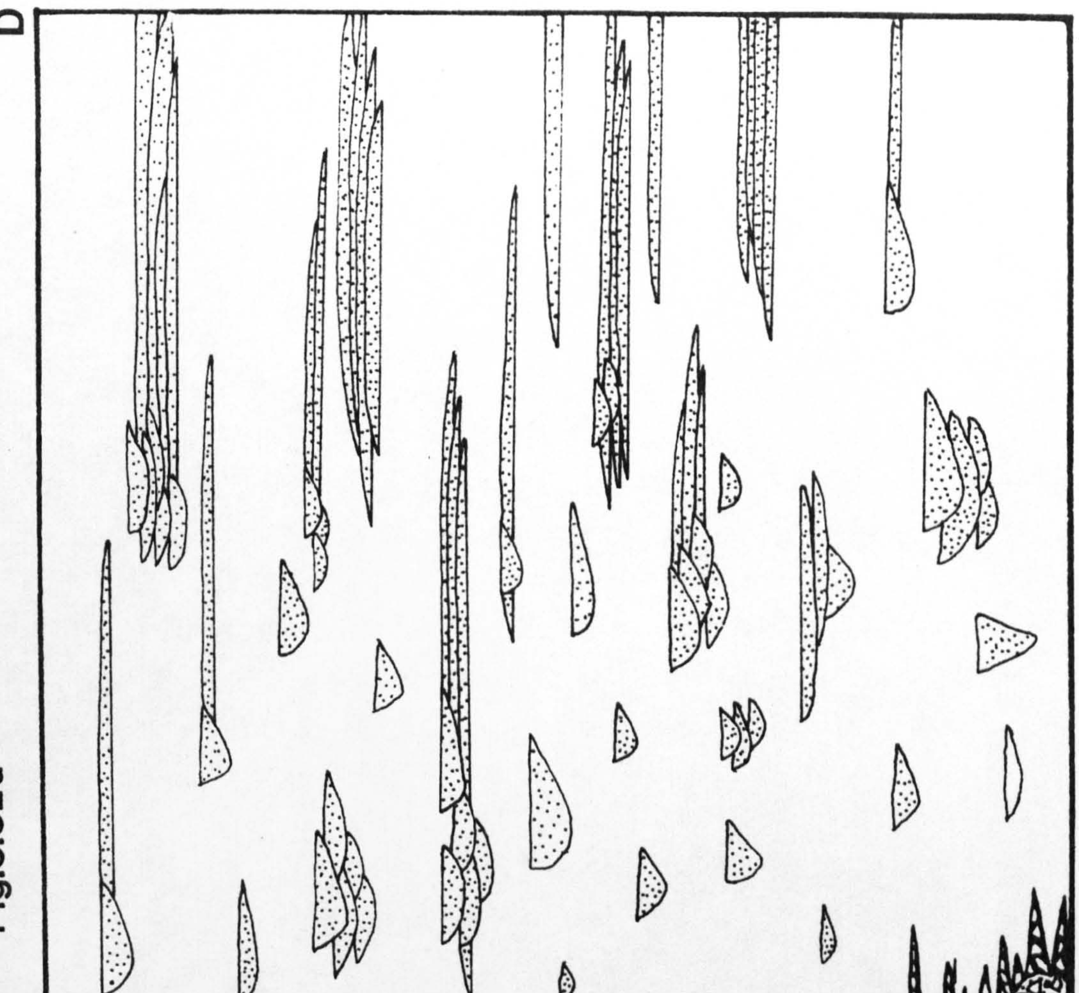


Fig.3.32c

Fig.3.32d


D
D
Fault Scarp Talus
Basin Margin Fault Zone
Basement
(probable Old Red Sandstone)

The 16/7a-12 well was predominantly deposited in a submarine slope environment near the base of a fault scarp which probably marked the western margin of the basin. The seismic discontinuities probably reflect the basin margin faults.

(ii) Both channel and lobe reservoir rocks will be developed distally to the 16/7a-10, 11 and 13 wells.
The 16/7a-10, 11 and 13 wells contain some fining-upwards coarse association sequences that are greater than 10m thick. These sequences were deposited in submarine channels of at least 10m depth. As channels tend to gradually decrease in depth, rather than abruptly terminate, there should be channel sequences, less thick than in the 16/7a-10, 11 and 13 wells, distal to those wells. Outer fan lobe sequences should occur at the termination of the channels. These sequences are usually sand rich and can form potential reservoirs (Casnedi 1983, Carmen and Young 1981, Hsu 1977).

(iii) The thickness of reservoir sequences will decrease from proximal to distal areas.

(iv) There will be a general decrease in reservoir quality from distal to proximal channel areas.
Channel sequences in proximal areas have relatively high facies 1 : 2 ratios (Fig. 3.25b) whereas those in distal areas have low facies 1 : 2 ratios and contain little conglomerate. In most coarse-grained submarine fans there is a gradual decrease in conglomerate : sandstone ratios from proximal to distal channel areas. As facies 2 has the better poro-perm characteristics (Fig. 3.5) there should be a gradual decrease in reservoir quality from distal channel areas, with low facies 1 : 2 ratios, to proximal channel areas with high facies 1 : 2 ratios.

(v) Vertical communication between reservoir units may decrease towards the more distal areas. /

During the building of a structurally unconfined fan system the area of active deposition occasionally switches, thus maintaining the fan shape of the system. After the switching occurs the lobate or sublinear body of channel and outer-fan lobe sediments (Fig. 3.26) will be blanketed by a mud rich sequence that was deposited on the now inactive part of the fan. Over a long period of time, during which the active part of the fan has switched position several times, the fan system will be composed of lensiod bodies of sandstone and conglomerate with intervening mudstone sequences (Walker 1978, Fig. 18). Mapping of the areal distribution of each of the channel/lobe building-block couplets (Fig. 3.26) is a very important step in attempting to predict the behaviour of the reservoir during production (Sarg and Skjold 1982, De'Ath and Schuyleman 1981, Carmen and Young 1981). The mudstone blanket may act as a widespread pressure barrier between units (Kessler et al 1980). However, in proximal areas the incision of relatively deep channels tends to cut through the mudstone blankets and there should be relatively good communication between units. In more distal areas, where deposition is in shallow channels or as sediment lobes, the mudstone blanket is more likely to persist as a barrier to vertical fluid flow.

(vi) The lateral persistence of reservoir units may increase in distal areas (Fig. 3.26).

(vii) There may be mudstone rich sequences to the north and south of the entry point and the proximal channel system.

The high coarse : fine association ratio suggests that the proximal channel system was maintained close to the 16/7a-8 well during much of Kimmeridgian and Volgian. As proximal channel systems are relatively laterally impersistent, (Fig. 3.26) areas to the north and south of 16/7a-8 are likely to be relatively mudstone rich./

(viii) <u>There should be good sublinear communication from the distal areas at the base of the structure towards the entry point near the top of the structure.</u> The basic channel-lobe building blocks of submarine fan systems are sublinear features which radiate from the entry point. It is generally considered that most channel and lobe systems are continuous features that are attached to each other (see Walker 1980 p1103). Therefore, sublinear reservoir zones should occur in a radial pattern centred on the entry point to the west of 16/7a-8 and the hydrocarbons should flow relatively easily from the distal areas at lower structural levels to the more proximal areas at higher structural levels (Fig. 3.3). However, the horizontal permeability will decrease towards the top of the structure as facies 1 : 2 ratios increase.

The occurrence of relatively high permeability zones (facies 2 sequences) and the radial reservoir pattern may lead to early water production problems (Craig 1980). However, the facies 2 sequences often occur towards the middle or the top of reservoir zones. This may reduce early breakthrough problems and help to maintain a relatively vertical oil/water front within the reservoir zones (Craig 1980).

(ix) <u>As South Brae is a retrograde submarine fan system, the reservoirs probably became more areally restricted from the Kimmeridgian to the early Volgian to the middle Volgian.</u>

The points outlined above generally assume little structural control on sedimentation. As all submarine fans that are deposited in intracratonic basins are structurally controlled to some extent it is imperative to attempt to recognise the structural control as early as possible in order to optimise the development of/

South Brae and the other South Viking Graben hydrocarbon accumulations. Syn-sedimentary faulting and intrabasinal structural highs tend to preferentially concentrate the good reservoir facies so that areas of the fan system will have a better development of reservoirs and other areas will have a poorer development than predicted by the model outlined above.

SUMMARY AND CONCLUSIONS

This study suggests that the South Brae reservoirs were predominantly deposited in the channelised part of a submarine fan system which was, for the most part, sourced from a point to the west of 16/7a-8 and to the SSW of 16/7a-12. Thus, the fan delta model currently in use by the operator is incorrect and is likely to produce misleading predictions of reservoir distribution.

The 16/7a-12 well was deposited on a submarine fault-controlled basin margin slope and there will be little reservoir development to the west of a NNE - SSW trending line running through that well. The reservoirs in the 16/7a-8 well were deposited in relatively "proximal" submarine channels and those in the 16/7a-10, 11 and 13 wells were deposited in relatively "distal" submarine channels.

The submarine fan environment of deposition first proposed by Stow et al (1982) is generally corroborated by this study. However, the model outlined above differs from the Stow et al model in two respects;

a) The Stow et al model suggests that South Brae has a linear source whereas, this present study surmises a point source.

b) Only the proximal (channelised) part of a submarine fan is recognised in the model outlined above whereas, the Stow et al model suggests that both channel (proximal) and lobe (distal) sequences have been drilled.

The study suggests that "distal" channel and outer fan lobe sequences may be developed in the 16/7b block, and perhaps the 16/8b block (Chapter 4). These sediments will be in communication with the South Brae reservoirs in the 16/7a block. It is essential to determine the /

extent of the reservoirs before the injector wells are drilled.

Chapter 4

The Upper Jurassic Submarine Fan System of the South Viking Graben

4.A INTRODUCTION

This chapter places South Brae in context with the other Upper Jurassic oilfields of the South Viking Graben (Fig. 4.1) During 1984 there was great interest in this area and many successful wells were drilled (see Oil and Gas Journal and Noroil). The recoverable reserves from the Brae, Miller and T-Block fields are now estimated to lie between 750 and 2000 million barrels of oil and oil equivalent gas and condensate. The B.G.S. at Edinburgh has, so far, released data on 24 wells from this area (Fig. 4.2) and the interpretations of this chapter are largely based on core and log data from these wells. Reports on the recently drilled wells have appeared in the oil industry journals (Oil and Gas Journal, Noroil, etc) and the limited data from these reports forms a minor part of this chapter.

Most of the available data originates from two principal areas; the Brae/Miller complex (blocks 16/7 and 16/8) and the T-Block complex (the 16/17 block) (Fig. 4.1). These two areas will be dealt with separately before the overall sedimentary model is presented.

Fig.4.1 SOUTH VIKING GRABEN LOCATION MAP
(mainly after Chesher and Swallow 1985).

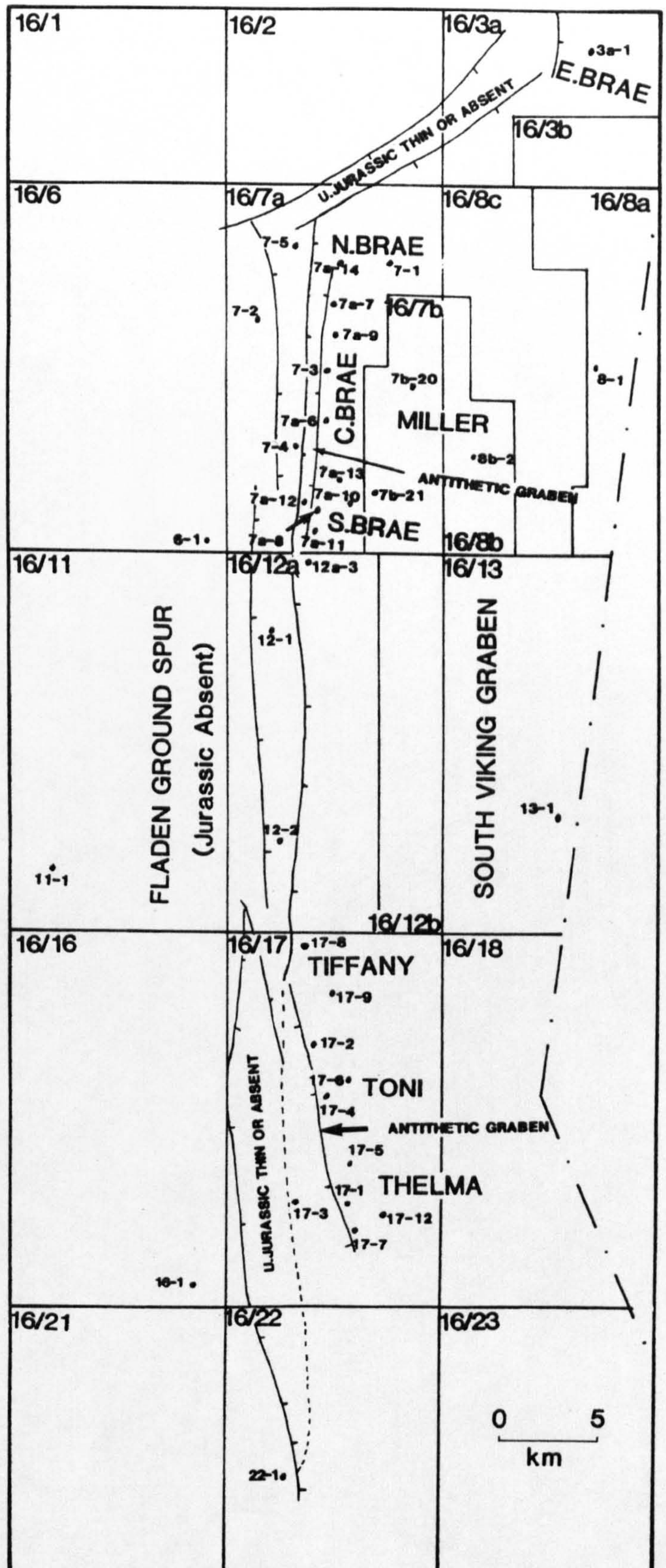


Fig. 4.2. List of South Viking Graben wells which have been released for general study by the B.G.S. Up to and including the 15th release (Feb. 1985).

WELL	OWNING * COMPANY	AREA
16/7 – 1	Pan Ocean	North Brae
16/7 – 2	Pan Ocean	West Brae
16/7 – 3	Pan Ocean	Central Brae
16/7a – 4A	Pan Ocean	Central/South Brae
16/7a – 5	Pan Ocean	North Brae
16/7a – 6	Pan Ocean	Central Brae
16/7a – 7	Pan Ocean	Central Brae
16/7a – 8	Pan Ocean	South Brae
16/7a – 9	Pan Ocean	Central Brae
16/7a – 10	Pan Ocean	South Brae
16/7a – 11	Pan Ocean	South Brae
16/7a – 12	Pan Ocean	South Brae
16/7a – 13	Pan Ocean	South Brae
16/8 – 1	Shell	——
16/12 – 1	Placid	——
16/13 – 1	Deminex	——
16/17 – 1	Phillips	Thelma
16/17 – 2A	Phillips	——
16/17 – 3	Phillips	——
16/17 – 4	Phillips	Toni
16/17 – 5	Phillips	Toni
16/17 – 6	Phillips	Toni
16/17 – 7	Phillips	Toni/Tiffany
16/17 – 8A	Phillips	Tiffany

* At the time of drilling

4.B. THE BRAE/MILLER COMPLEX

The Brae/Miller complex comprises South Brae, Central Brae and Miller (Fig. 4.1). The extents of the individual fields are disputed by the participating companies. However, "this area could prove to be the first major oilfield to be found in the North Sea for some time." (Noroil, September 1984 p75). The total recoverable reserves for the area could be as high as 1000 million barrels of oil plus significant quantities of gas. North Brae and East Brae (Fig. 4.1) are gas condensate fields which have different hydrocarbon/water contacts from Central Brae. These fields will be briefly dealt with in section 4D.

Data from 4 Central Brae wells has been released for general study by the B.G.S. (Fig. 4.2). Two wells (16/7-3 and 16/7a-6) contain coarse-grained sequences, whereas 16/7a-7 and 16/7a-9 predominantly comprise fine-grained sequences (Fig. 4.3)*. The facies that occur in the Central Brae sequences (Fig. 4.4) are generally similar to those of South Brae (Fig. 3.5). However, there are some important differences as follows;

a) Different clast types. The rounded quartz and quartzite pebbles which are abundant in the S.Brae sequences (Fig. 3.6) are absent in the C.Brae sequences. Also, angular pebbles and cobbles of sandstone and siltstone are abundant in C.Brae but do not occur in S.Brae. In general, the C.Brae clasts are more angular than those of S.Brae. As a result the subfacies la "conglomerates" of S.Brae (Fig. 3.5) do not occur in C.Brae. Instead, the major coarse-grained facies is subfacies la "breccias with sandstone matrices" (Fig. 4.4) ✓

* In Pocket at Back

Fig.4.4 Central Brae Facies Characteristics

		% of Jur-assic	Grain-size	Bed Thick-ness	Sedimentary Structures and Textures	Bed Bound-aries	Res. Props.	Fossils and Kerogen	Interpreted Depositional Processes
Breccias and Conglomerates	**Facies 1a** BRECCIAS WITH SANDSTONE MATRICES		Pebble to Boulder Clasts	10 cm to 5 m (av. 1m)	Mainly framework, but also matrix supported clasts, c-axes commonly normal to bedding. Non-graded and graded beds. Erosive bases.	Bases: sharp Tops : sharp or gradational	Porosity: mostly 0-10 % Permeability: mostly 0-100 md	Common miospores, Rare microplankton Humic kerogen, Shell fragments.	Friction debris flows and high density turbidity-currents.
	Facies 1b BRECCIAS WITH MUDSTONE MATRICES		Pebble to Boulder Clasts	10 cm to 3 m	Framework supported, randomly oriented and distributed clasts.	Sharp bases and tops.	Very poor.	Miospores + micropl. Humic + sapropellic kerogen, belemnites	Rockfalls plus? cohesive debris flows.
	Facies 1c BRECCIAS WITH ARGILL/SST MATRICES		Mainly Cobble and Boulder Clasts	50 cm to 2 m	Framework supported, randomly oriented and distributed clasts.	Sharp or diffuse bases and tops.	Poor.	Common miospores, Humic kerogen, Shell fragments.	Rockfalls.
	Facies 2 SANDSTONES WITH < 5 % INTERSTRAT MUDSTONE		Medium to pebble sand	5 cm to 2 m	Graded and non-graded, structureless beds, also parallel laminations and erosive bases.	Bases: sharp Tops : sharp or gradiational.	Porosity mostly 5-15 % Permeability mostly 50-250 md.	Same as 1a.	Relatively high density, immature turbidity-currents.
	Facies 3 SANDSTONES WITH 5 - 25 % INTERSTRAT MUDSTONE		Very-fine to coarse sand (av.fine)	1-10 cm	Graded and non-graded beds, abundant cross and parallel laminations	Generally sharp bases and tops.	Poor vertical K. Horizontal K- 50-250 md Porosity: mostly 5-10 %	Miospores>micro-plankton humic kerogen plant and shell fragments.	Turbidity-currents with tractional reworking.
	Facies 4 SANDSTONES WITH 25 - 75 % INTERSTRAT MUDSTONE		Silt plus very-fine to medium sand	0.5-5 cm	Sandstones: parallel and cross-laminations graded and non-graded beds, erosive bases. Mudstones : parallel laminations.	Bases: sharp Tops : sharp or gradational.	Very poor.	Miospores plus microplankton, humic and sapro-pellic kerogen. Ssts: shell and plant fragments Mdsts: belemnites ammonites and fish fragments.	Suspension settling of mud plus turbidity - currents.
	Facies 5 MUDSTONE WITH < 25 % INTERSTRAT SST		Silt plus very fine to medium sand	0.2 to 5 cm	Same as 4.	Same as 4			Suspension settling of mud plus turbidity - currents.

b) The common occurrence of bivalve fragments in the matrix of subfacies 1a and in the sandstones of facies 2, 3, 4 and 5 of C.Brae. The fragments are relatively thick and often curved and were probably derived from relatively shallow water oysters. These shallow water derived fragments contrast with the deep water fauna, of belemnites, ammonites and fish fragments, which occur in the mudstones.

c) More abundant calcite cement in C.Brae. This cement mostly occurs as concretionary zones from a few centimeters to 5m thick. In places, these zones comprise more than 50% of the sequence and, therefore, considerably reduce the net pay. Also, patchy calcite cement occurs sporadically and reduces the reservoir properties of the Central Brae sequences.

d) The occurrence of glauconite in Central Brae. Glauconite occurs in minor quantities throughout the Central Brae sequences (Stow et al 1982), but is absent from South Brae.

e) The occurrence of sandstone crack fills in Central Brae. These crack fills are mostly 1-5 mm wide and up to 5 cm long. They are ptygmatically folded due to the differential compaction of the mud and sand and they mostly protrude from the bases of thin sandstone beds. They usually occur singly and in bedding parallel sections they are relatively straight. They are probably sandstone dykes or syneresis crack fills.

As with South Brae, Central Brae can be broadly divided into a coarse and a fine association. The subfacies 1b "breccias with mudstone matrices" (fig. 4.4) are included with the fine association as they occur as interbeds in mudstone rich sequences. Although/

the lithologies of South and Central Brae are generally similar, the relative abundance and distribution of facies is considerably different. The following are the most important differences;

a) The occurrence of very thick coarse association and very thick fine association sequences in Central Brae. In the South Brae wells, except 16/7a-12, there is an interstratification of the coarse and fine association on a scale of tens to a few hundred feet (Fig. 3.16). In contrast, the Central Brae sequences tend to be dominated by either coarse or fine association with little interstratification between the two. The 16/7-3 well is predominantly composed of an 800' thick coarse association sequence (Fig. 4.3a) and the 16/7a-7 and 16/7a-9 wells are almost entirely composed of fine association sequences (Fig. 4.3). The 16/7a-6 well most closely resembles the South Brae sequences as there is some interstratification of coarse and fine associations in that well.

b) The poor development of coarse association fining-upwards sequences in Central Brae. The 16/7-3 and 16/7a-6 wells contain some coarse association fining-upwards sequences (Fig. 4.3) but they are not as well developed as those of South Brae (Fig. 3.16).

c) More abundant subfacies 1b "breccias with mudstone matrices" in Central Brae. In South Brae, breccias with mudstone matrices only occur between 12850' and 12825' in the 16/7a-12 well (Fig. 3.7), whereas, this facies is common in Central Brae and occurs throughout 16/7a-7 and 16/7a-9 and towards the top of 16/7-3 (Fig. 4.3).

Central Brae was initially thought to have been deposited in a fan delta environment, in which the coarse association represented the topsets and the/

fine association represented the foresets and bottomsets of the delta front. This interpretation was largely based on the presence of supposed wave-formed structures in the thin sandstones of facies 3 and 4. However, it is notoriously difficult to differentiate wave and current formed cross-laminations in two-dimensions, and although some of the features of the facies 3 and 4 sandstones are similar to those interpreted as wave formed by de Raaf et al (1977), they can also be interpreted in terms of deposition from fluctuating unidirectional currents. Structures which are strongly suggestive of wave reworking such as bundled and chevron upbuilding (de Raaf et al 1977), do not occur in the Central Brae sequences. Also, large charcoal and plant fragments occur along many of the foresets and many of the sandstones are relatively poorly sorted. These features suggest that the thin-bedded sandstones of facies 3 and 4 were not subjected to prolonged wave reworking. Therefore, at best, the evidence for wave reworking is equivocal, if not, negative.

The occurrence of glauconite and shell fragments of shallow water origin in the breccias and sandstones, and the presence of a deep water fauna of ammonites, belemnites and fish fragments in the mudstones is the typical scenario for a submarine fan environment of deposition in which the coarse-grained material passed through a shallow water environment before being redeposited in deeper water. The presence of sequences of graded sandstones and breccia beds with fossiliferous mudstone matrices is also typical of deposition in a marine environment below wave-base.

The Central Brae sequences were probably deposited in the very proximal part of a submarine fan complex. The occurrence of very thick coarse-grained sequences and very thick fine-grained sequences is typical/

of the most proximal "inner" parts of submarine fan systems (Mutti and Ricci-Lucchi 1972, Walker 1978). The coarse-grained sequences were deposited in relatively deep channels that rarely shifted position and the thick mudstone sequences were deposited in proximal interchannel and slope environments (Fig. 3.26). The poorer development of coarse association fining-upward sequences also suggests that Central Brae was deposited in more proximal channels than South Brae (Mutti and Ricci-Lucchi 1972, Walker 1978) and tightly packed breccias with mudstone matrices are typical of slope and proximal interchannel areas of some submarine fans (Nelson 1984). The different clast composition of the Central Brae breccias suggests that they were derived from a different source to that of South Brae. The presence of glauconite and more abundant shell fragments suggests that the shelf area to the west of Central Brae was wider than that to the west of South Brae (Stow et al 1982). From the data available to this study it is impossible to tell whether 16/7-3 and 16/7a-6 were part of the same channel system or were two separate systems fed by different feeder channels.

The interpretation of Central Brae as the very proximal part of a submarine fan system suggests that the Upper Jurassic oil bearing sediments of the 16/7b and, probably, 16/8b blocks were transported through 16/7a before being deposited in more "distal" submarine fan environments. Also, the more proximal nature of Central Brae suggests that a "South Brae type" of system may have been deposited to the East of the 16/7a part of C. Brae. The submarine fan system is probably more sand rich to the east and as a result the more easterly sequences are likely to have better poro-perm characteristics (Fig. 4.4). Noroil (December 1984 p56) states that "Previous bullish assessments of a definite link between Miller/

and Central or South Brae have yet to be proven". However, the results of this study suggests that Central Brae and, at least part of, Miller are probably parts of the same submarine fan complex and, if the area is developed, pressure testing will corroborate the "bullish assessments".

4.C. THE T-BLOCK SUBMARINE FANS

The coarse-grained Upper Jurassic clastics of the 16/17 block have been interpreted as proximal submarine fan sequences (Brown 1984). The reservoirs occur in three different structures (Tiffany, Toni, Thelma, Fig. 4.1) which have different hydrocarbon/water contacts and the sediments were probably deposited in three separate submarine fan systems. Conglomerate and sandstone rich sequences occur in the 16/17-8 (Tiffany), 16/17-4, 16/17-6 (Toni) and 16/17-1 (Thelma) wells. These sequences were probably deposited in relatively proximal submarine channels. The 16/17-5 well contains a thick sandstone rich sequence which was probably deposited in relatively distal submarine channels. The 16/17-7 well is essentially non-reservoir and predominantly comprises mudstones and breccias which were deposited in a submarine slope or proximal interchannel environment similar to that of the 16/7a-7,9 and 12 wells (Figs, 4.3 and 3.16).

Although the block contains large quantities of oil, a final decision has not been made on the viability of exploitation and the extent of the various reservoirs is still being actively evaluated 8 years after oil bearing Upper Jurassic sediments were discovered in the 16/17-1 well. This is primarily the consequence of the complexities of the reservoir sequences. Recently the "dryish" 16/17-14 well confirmed the southerly limit of the T-Block reservoirs and one test in the successful 16/17-15 well flowed at 7500 BOPD through a 56/64 inch choke. The northerly limit of the reservoirs has not been delineated and one test in the 16/12-5 well flowed at 4116 BOPD through a 13/16 inch choke. This suggests that much of Tiffany may lie to the north of the 16/17 block.

4.D. A DEPOSITIONAL MODEL FOR THE UPPER JURASSIC OF THE SOUTH VIKING GRABEN.

In this study I have, so far, discussed five submarine fan systems which accumulated along the western margin of the South Viking Graben (Central Brae, South Brae, Tiffany, Toni and Thelma). The sediment for each system was transported into the basin from a point source or, as in Central Brae, two closely spaced point sources. These "points" were probably submarine canyons which cut through the basin-margin faults from a shallow water area on the upthrown side.

North Brae is a gas condensate accumulation which has a different hydrocarbon/water contact to that of Central Brae. It will enter a production phase later in the decade. The sediment probably entered the basin from a point to the west of the 16/7-1 well. Core was not taken from this well and Stow et al (1982) interpret the wireline logs as suggesting a thick sandstone sequence. However, a comparison with the core calibrated logs from South and Central Brae (Fig. 3.14) suggests that the 16/7-1 well was drilled through thick conglomerate sequences. If this interpretation is corroborated by subsequent coring the North Brae system may prove larger than at presently assumed and it may extend into the blocks to the east.

Successful recent drilling also suggests that the 16/3 block (East Brae) may become another gas condensate development. Therefore, it is likely that, by the end of the century, up to seven Upper Jurassic hydrocarbon accumulations will be developed in the South Viking Graben./

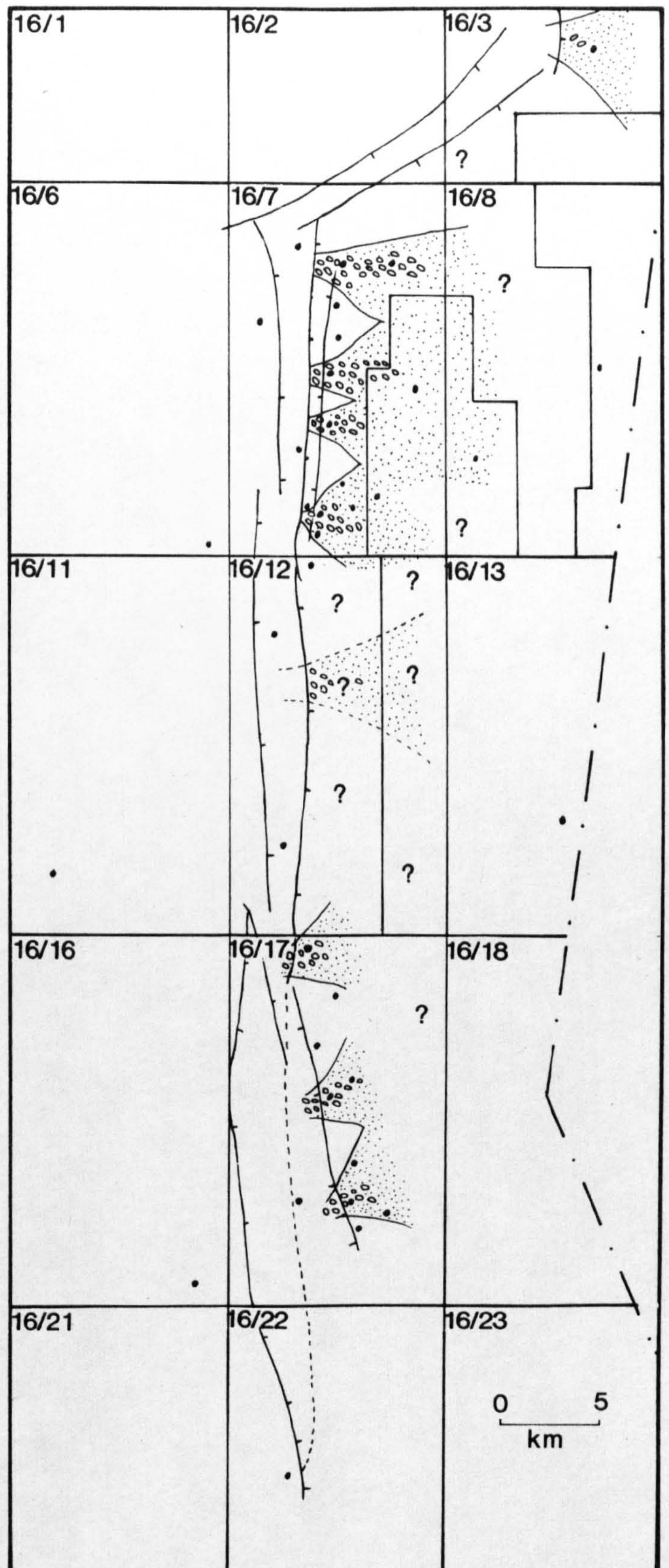
During the late Jurassic there were at least seven or eight entry points for sediment (submarine canyons) along the western margin of the South Viking Graben and each of these canyons fed a submarine fan system. A very basic sedimentary model for the graben can be produced by integrating the submarine fan model depicted in figure 3.26 with the position of the entry points (Fig. 4.5). The sizes of the various systems can be very approximately estimated from the grain-size and sediment thickness characteristics of the known sequences, eg the very thick conglomerate or breccia sequences in the 16/7-1 and 16/7-3 wells suggests that North and Central Brae may be very large systems.

The model depicted in figure 4.5 is, of course, simplistic and highly stylised. Although all intercratonic submarine fan systems are structurely controlled to some extent (section 3.D) the model assumes little intrabasinal structural control on the distribution of sediment. If structure has strongly controlled sedimentation the resultant distribution of potential reservoirs will be very different from that predicted by figure 4.5. However, the model serves as a first estimation of the possible distribution of reservoirs and illustrates the importance of locating the entry points. Additional data from appraisal and production wells may delineate elements of intrabasinal structural control which should be integrated with this basic model.

The model predicts the following:

a) Central Brae was a very large submarine fan complex that extended far out into the South Viking Graben. The Miller field sequences are probably the distal equivalents of the proximal sequences that were cored in the 16/7a part/

Fig.4.5 A Depositional Model for the Upper Jurassic of the South Viking Graben (see text for details and Fig.4.1 for field and well locations)



of Central Brae.

b) Some of the sediment deposited in the Miller area may have been transported through North Brae, which was also a very large submarine fan complex.

c) South Brae was probably not as large a system as North or Central Brae. However, the field will extend into the 16/7b and possibly 16/8b blocks.

d) Other submarine fan systems may be located along the western margin of the South Viking Graben. An obvious area for additional exploration is the 16/12 block. The exploration wells have been drilled close to the basin-margin where mudstone rich sequences are likely to be encountered. Wells drilled farther from the margin would be more useful in evaluating the prospectivity.

Finally, the simplistic model of figure 4.5 illustrates one of the most fundamental principles that is implicit in the submarine fan model, namely that coarse-grained (potential reservoir) sequences tend to be vertically stacked and restricted spatially in proximal areas and become less stacked and less restricted distally. This principle implies that, in general, the exploration or evaluation of submarine fan reservoirs should initially be carried out some distance from the basin margin.

Chapter 5

The Distribution of "Brae-Like" Plays in the Northern North Sea and North Atlantic Continental Shelf Area

5.A INTRODUCTION

During the late Jurassic the tectonic evolution of West and Central Europe became increasingly dominated by the Arctic-North Atlantic rift system (including the northern North Sea) and the North Atlantic area was subjected to intensified regional crustal extension (Zeigler 1981). This tensional regime led to rapid subsidence and thinning of the continental crust under most of the major basins. Many authors, including Christie and Sclater (1980) and Wood and Barton (1983), have related the crustal thinning and subsidence to the lithospheric stretching model of McKenzie (McKenzie 1978, Jarvis and McKenzie 1980). Although some of the crustal thinning can be better explained by inheritance from Palaeozoic deformation episodes and pre-middle Jurassic extentional events (chapter 2),(Smythe et al 1980), the general McKenzie model of block faulting and differential subsidence during rapid extension of the continental lithosphere, followed by widespread regional downwarping during post stretching thermal relaxation explains many of the features of the late Mesozoic and Tertiary evolution of the northern North Sea and North Atlantic Continental Shelf area. The widespread taphrogenic subsidence which occurred during the late Jurassic and early Cretaceous is related to rapid extension of the continental lithosphere according to the McKenzie model and the dominance of post early Cretaceous epierogenic downwarp has been related to the thermal relaxation phase (Jarvis and McKenzie 1980, Wood and Barton 1983).

During this late Jurassic and early Cretaceous episode of crustal extension and related taphrogenic subsidence the basins became asymmetrical and half-graben geometries were produced. The tilting of the fault-blocks was due to the curved (listric) geometry of the basin-margin faults (Gibbs 1984). The sediments deposited in these asymmetrical grabens are easily recognised on seismic lines. The typical profile is one of wedging Upper Jurassic or Lower Cretaceous reflectors overlying the essentially parallel reflectors of the Middle Jurassic and older strata (Fig.5.1). The syn-tectonic wedge of Upper Jurassic or Lower Cretaceous also tends to be much thicker than the underlying sequences. The tilting of the fault-blocks and the concom itant increase in subsidence rates did not occur

FIG.5.1 CROSS-SECTIONS TO ILLUSTRATE THE NON-CONTEMPORANEOUS TIMING OF THE LATE JURASSIC / EARLY CRETACEOUS SUBSIDENCE AND ROTATION EPISODES.

a) E-W cross-section across the North Viking Graben through the Frigg Gasfield (Fig.1.1). Based on Goff (1983) and Heritier et al (1981).

b) NW-SE cross-section through the Statfjord Oilfield, East Shetland Basin (Fig.1.1). Based on Kirk (1980).

c) SW-NE cross-section from the Renee Ridge to the Witch Ground Graben, Outer Moray Firth Basin (Fig.1.1). Based on Chesher and Swallow (1985).

Fig. 5.1.a

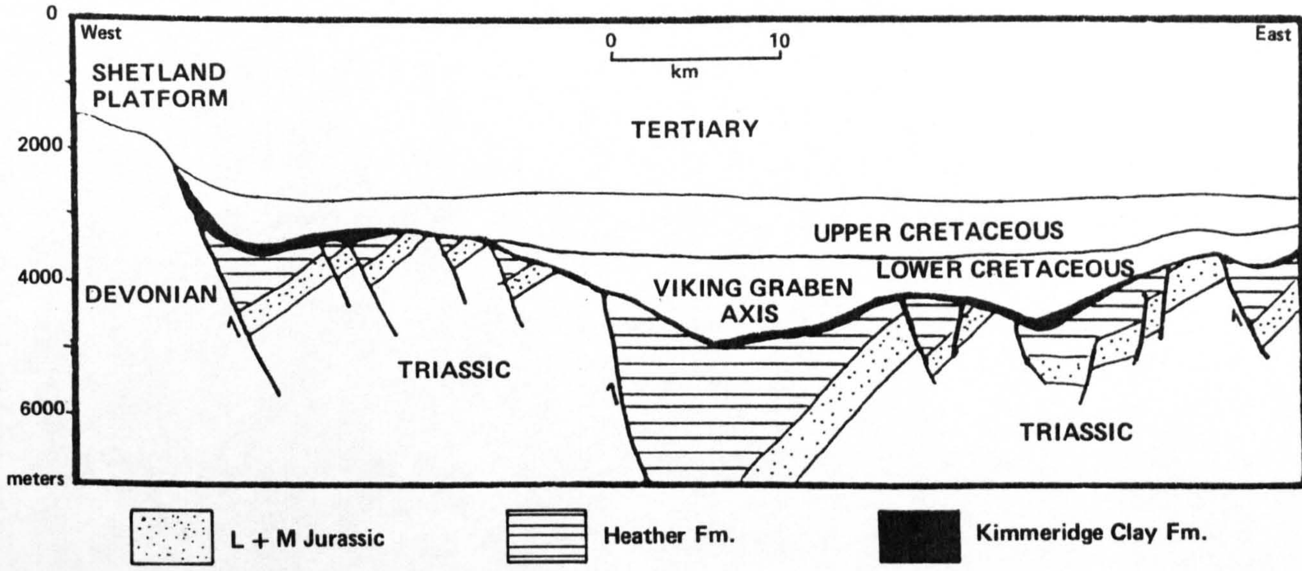


Fig. 5.1.b

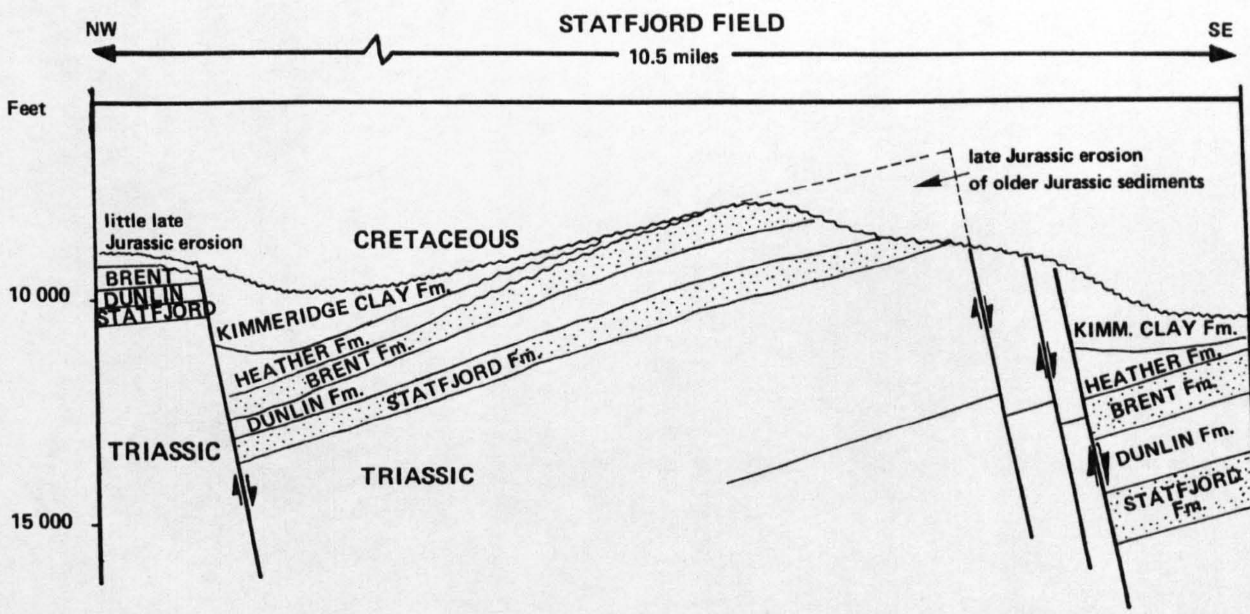
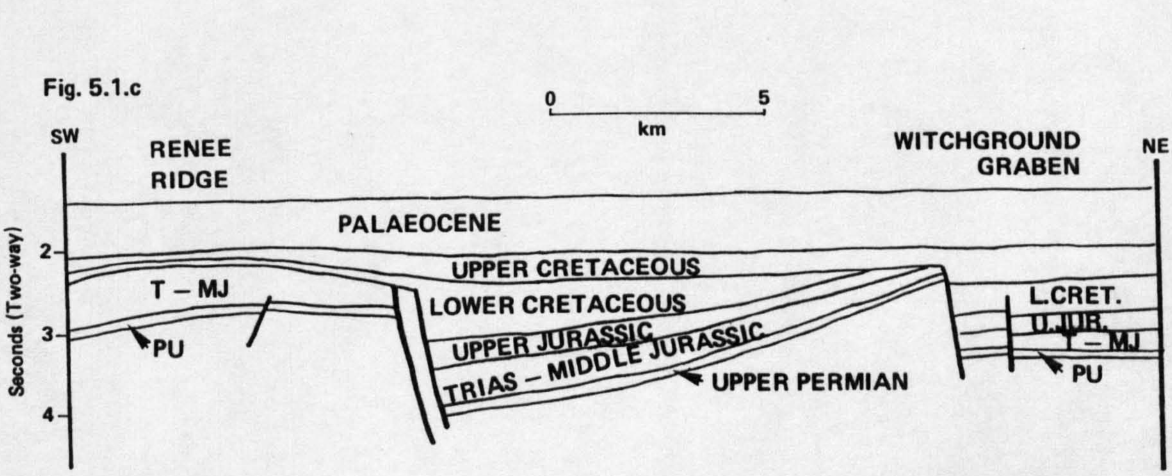


Fig. 5.1.c



contemporaneously from area to area. Rather, the principal faulting episodes occurred in different areas at different times (Fig.5.1).

In this study a "Brae-like" play is considered as a coarse-grained clastic sequence which was deposited during a late Jurassic or early Cretaceous tilting and differential fault-contolled subsidence episode. Sediments were eroded from the upthrown sides of faults and deposited on the downthrown sides in the gradually tilting grabens. At the western margins of the Inner Moray Firth Basin (chapter 2) and the South Viking Graben (chapters 3 and 4) the initiation of coarse-grained deposition was directly related to tilting and differential movements and to an increase in subsidence rates. The South Viking Graben reservoirs are stratigraphically trapped against impermeable (?ORS basement) rocks and Kimmeridge Clay Formation shales form the cap rock. Therefore, the seal is provided by both the basin-margin faults and the overlying mudstones. The structural component to the trap is minor (section 3.A). The "Brae-like" play should, therefore, be fault trapped against impermeable basement rocks and should be capped by Upper Jurassic or Lower Cretaceous shales. These traps would have formed soon after the deposition of the reservoir rocks, before peak oil migration during the Tertiary (Goff 1983).

The following features would initially point to the possible existence of "Brae-like" plays:

1. Wedging Upper Jurassic or Lower Cretaceous seismic reflectors overlying subparallel reflectors of Middle Jurassic or older sequences.
2. Anomalously thick Upper Jurassic or Lower Cretaceous sequences.
3. Evidence of widespread late Jurassic or early Cretaceous erosion on the upthrown side of basin margin faults.

5.B THE NORTHERN NORTH SEA

The late Mesozoic taphrogenic subsidence episodes can be broadly divided into the following three intervals which affected different areas at different times (Fig.5.1):

1. Callovian to Oxfordian. (Heather Formation) During this period high subsidence rates were generally restricted to the principal axis of the North Viking Graben where up to 2.5km of Heather Formation sediments were deposited (Fig.5.1a). Elsewhere in the northern North Sea Callovian to Oxfordian sedimentation rates were relatively low and seismic reflectors are mostly parallel or subparallel (Fig.5.1). In the North Viking Graben the subsidence rates decreased during the Oxfordian and the Kimmeridge Clay Formation is very thin.

2. Oxfordian to Ryazanian. (Kimmeridge Clay Formation) Differential fault-controlled subsidence and the tilting of fault-blocks became more widespread during this period. In the Inner Moray Firth Basin (chapter 2) subsidence rates increased slightly during the Oxfordian then dramatically at the base of the Kimmeridgian (Figs.2.2 and 5.2). Subsidence rates generally remained high through the early Cretaceous. In the Outer Moray Firth Basin subsidence rates were extremely variable from area to area. At some localities the Upper Jurassic is very thin and the enclosing seismic reflectors are parallel or sub-parallel (fig.5.1c). In these areas the overlying Lower Cretaceous is usually relatively thick. However, in other areas the Upper Jurassic is relatively thick and is overlain by thin Lower Cretaceous (Chesher and Swallow 1985). The South Viking Graben was the area of greatest subsidence during this period and up to 2km of Oxfordian to Ryazanian sediments were deposited in the Brae area (Fig.3.2a). There was uplift during the early Cretaceous and the thick Upper Jurassic is overlain by very thin Lower Cretaceous sequences. In the North Viking Graben area the main differential movements occurred in the East Shetland Platform to the west of the main Graben. In this area moderately thick Kimmeridge Clay Formation sediments were deposited during the tilting of the Brent Province fault-blocks. The tilting of these fault-blocks during this period produced the structural traps that now contain the most important hydrocarbon reservoirs of the

northern North Sea (Parsley 1984). The Magnus Sands of the Magnus field (De'Ath and Schuyleman 1981), which lies towards the north of the East Shetland Platform, were deposited within a relatively thick Kimmeridge Clay Formation sequence.

3. Early Cretaceous. (Cromer Knoll Group) Subsidence rates generally remained high in the Inner Moray Firth area (Fig.5.2) and in the Outer Moray Firth the subsidence rates were again variable from area to area (Chesher and Swallow 1985). In some wells thin Lower Cretaceous overlies relatively thick Upper Jurassic. However, in other areas the early Cretaceous was a time of increased subsidence rates and rotation of fault-blocks (Fig.5.1c)(Beach 1984). The Lower Cretaceous is very variable in the North Viking Graben area.

Outwith the South Viking Graben there are several areas where "Brae-like" plays may occur in the northern North Sea area. The studies of chapters 2 and 3 suggest that the most widespread coarse-grained sequences are most likely to occur immediately after the initiation of increased subsidence rates and fault-block tilting as during these periods relatively unconsolidated sediments were rapidly eroded from the upthrown blocks.

In the Outer Moray Firth area there are some thick late Mesozoic syn-tectonic wedges of sediment (Fig.5.1c). When exploring for "Brae-like" plays it is essential to outline areas on the upthrown fault-blocks where deep erosion has occurred. Hancock (1984) mentions a Lower Cretaceous gas-condensate reservoir which lies to the south of the Fladen Ground Spur and Chesher and Swallow (1985) suggest relatively deep late Mesozoic erosion in this area. However, the cross-sections of Chesher and Swallow, and Beach (1984) generally suggest that there was little erosion on the upthrown sides of many of the Outer Moray Firth fault-blocks. These areas will have relatively poor prospectivity.

In the North Viking Graben area the Lower and Middle Jurassic reservoirs of the Brent Province were partially eroded during the late Jurassic rotation of fault-blocks. In most areas the erosion was

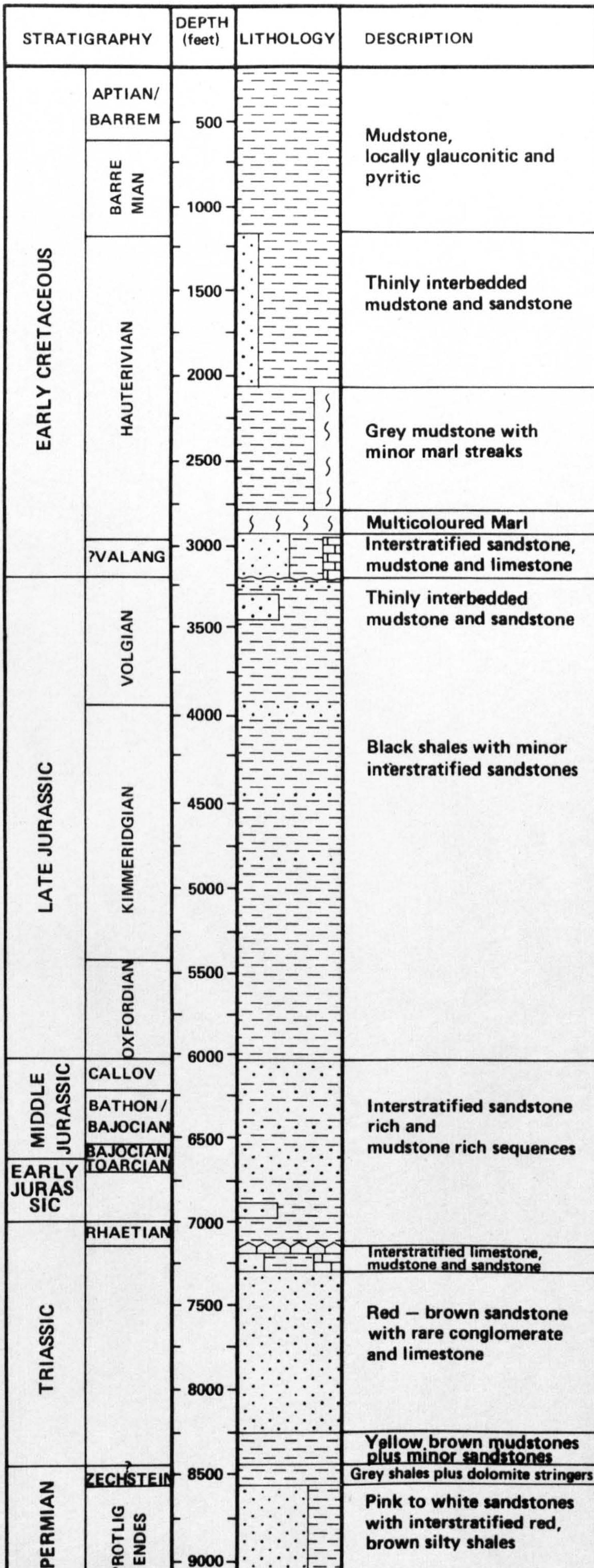


Fig. 5.2.

Stratigraphy of the 11/30 – 1 well (Beatrice Oilfield) minor. However, to the S.E. of the Statfjord field a moderate amount of Brent Group and Statfjord Formation was eroded (Fig.5.1b).The displaced sand may form a small "Brae-like" accumulation on the downthrown side of the rotated Statfjord fault-block. A further study of the North Viking Graben/East Shetland Platform area may highlight areas of moderate to extensive late Jurassic erosion of Brent sands and, therefore, outline the location of possible "Brae-like" accumulations.

5.C MID-NORWAY AND EAST GREENLAND

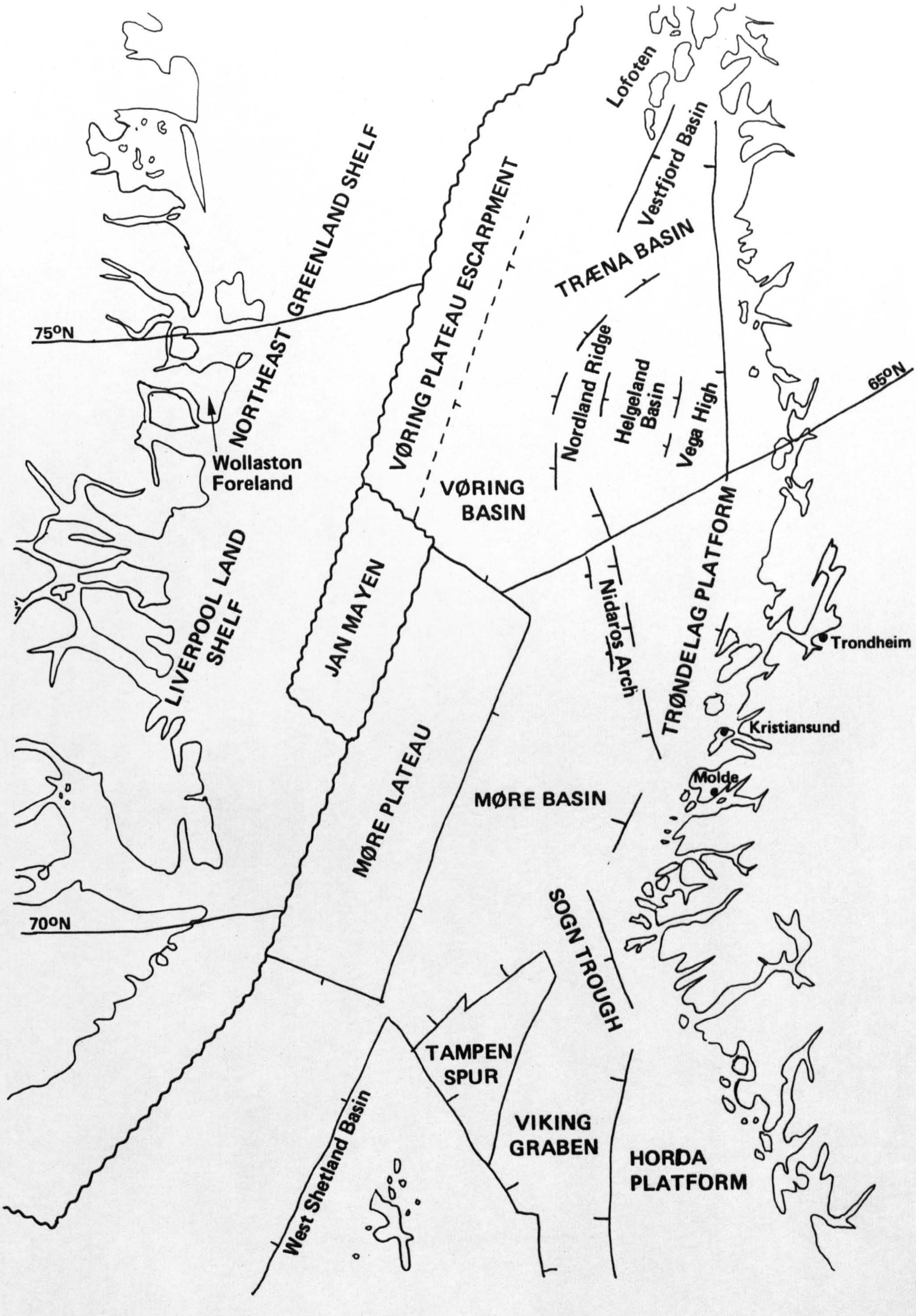
(i) Mid-Norway.

The mid-Norway Continental Shelf and Slope areas are presently the sites of intense exploration activity. Numerous geophysical surveys have been carried out and many wells have been drilled. In general, there is a striking similarity between the Post-Caledonian sedimentary record of the mid-Norway Continental Margin and that of northern U.K. and the northern North Sea (Bukovics et al 1984). The main structural elements of the shelf and slope are shown in figure 5.3.

The principal exploration targets are fluvial and shallow marine sandstones of the Lower and Middle Jurassic which were deposited on the Trondelag Platform (Fig.5.3)(Hollander 1982, Larsen and Skarpness 1984). However, Larsen and Skarpness, and Bukovics et al (1984) also recognise the possibility of Lower Cretaceous "Brae-like" plays at the margins of the Møre, Vøring and Traena Basins.

In an analogous manner to that of the northern North Sea, the mid-Norway Continental Margin area was subjected to a long-term tensional regime which commenced during the Palaeozoic after the Caledonian Orogeny. During the latest Jurassic there was accelerated crustal extension and rifting became concentrated on the more axial parts of the East Greenland-Mid Norway rift system (Bukovics et al 1984) and subsidence rates in the major basins (Fig.5.3) increased dramatically. Much of the Trondelag Platform remained stable during this period, however, its western periphery (the Nidaros Arch and the Nordland Ridge) became updomed and were deeply eroded and peneplained. Figure 5.4 illustrates the level of erosion of part of the Nordland Ridge. The displaced sediment, including Lower and Middle Jurassic sands, was mostly transported to the west into the rapidly subsiding Traena, Vøring and Møre basins (Larsen and Skarpnes 1984, Hamar and Hjelle 1984). Bukovics et al (1984) recognise offlapping Lower Cretaceous reflectors at the eastern margin of the Voring Basin which they interpret as the result of progradational submarine fan systems.

Fig.5.3 A sketch map to illustrate the reconstructed (pre-Tertiary) position of Norway and Greenland plus the major tectonic features of the mid-Norway Continental Shelf and Slope.


NORTHEAST GREENLAND SHELF
VØRING PLATEAU ESCARPMENT
Lofoten
Vestfjord Basin
TRÆNA BASIN
75°N
Nordland Ridge
Helgeland Basin
Vega High
65°N
Wollaston Foreland
VØRING BASIN
LIVERPOOL LAND SHELF
JAN MAYEN
Nidaros Arch
TRØNDELAG PLATFORM
Trondheim
Kristiansund
Molde
MØRE PLATEAU
MØRE BASIN
SOGN TROUGH
70°N
TAMPEN SPUR
West Shetland Basin
VIKING GRABEN
HORDA PLATFORM

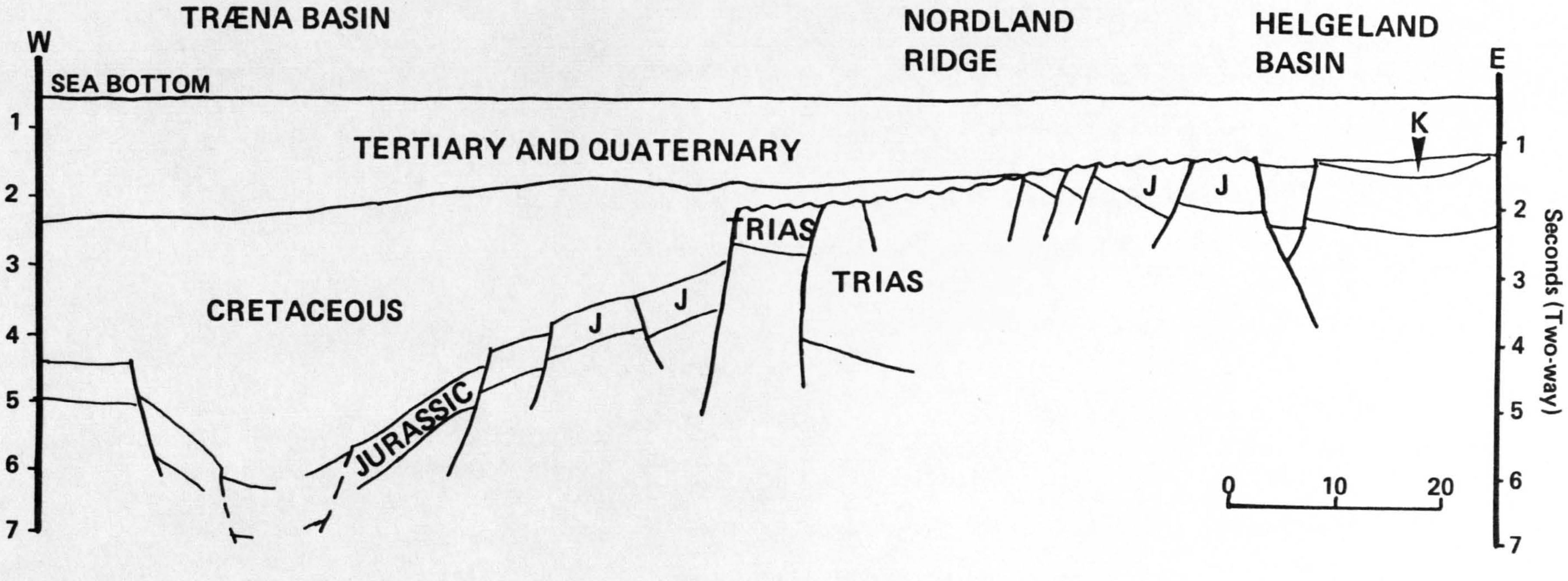


Fig. 5.4. Seismic cross-section illustrating the level of erosion on the Nordland Ridge. Based on Jorgensen and Navrestad (1981) and Bukovics et al (1984).

Larsen and Skarpnes (1984 p231) consider that these Lower Cretaceous sequences are high risk targets "both because of of uncertainty concerning the presence of reservoir rock, and concerning closure.". As large quantities of sediment were eroded from the Nordland Ridge and the Nidaros Arch the uncertainty concerning the presence of reservoir rocks would seem to be minimal. Therefore, the main doubt with these plays must be the problem of seal against the basin-margin faults. Lower Cretaceous shales will form the cap rocks and organic-rich Upper Jurassic and Lower Cretaceous mudstones have generated oil. In conclusion, despite the doubt concerning closure against the basin-margin faults, the hydrocarbon potential of these "Brae-like" plays must be considered excellent.

(ii) East Greenland. To the south of 70 degrees North the distribution of Mesozoic sediments on the East Greenland Shelf is poorly known and the hydrocarbon potential of the area must be considered, at present, poor. Between 70 and 72 degrees North, on the inner part of the Liverpool Land Shelf (Fig.5.3), seismic surveys have outlined deeply buried and rotated fault-blocks which are probably composed of Mesozoic sediments (Larsen 1984). It will be many years before drilling is carried out in this area. However, there is a relatively good chance that "Brae-like" plays will exist. The reconstructed map of figure 5.3 shows that this part of Greenland was very close to mid-Norway and was certainly subjected to the same crustal stresses during the late Mesozoic. Also, the classic study of Surlyk (1978) on the nearby Wollaston Foreland submarine fan system clearly illustrates that there was increased crustal tension during the latest Jurassic and early Cretaceous, and, during the resultant phase of faulting, sand and conglomerate-rich submarine fan systems were deposited in rotating fault-blocks.

5.D WEST OF SCOTLAND AND IRELAND.

During the late Jurassic and early Cretaceous there was large-scale differential subsidence of fault-blocks in many of the basins which occur to the west of Scotland and Ireland (Ridd 1981, Roberts et al 1981, Naylor and Shannon 1982). To the west of the Shetland Isles the most intense phase of differential subsidence probably occurred during the early Cretaceous. At this time there were two major positive areas, the West Shetland Platform and the Rona Ridge, which shed sediment into two rapidly subsiding areas, the West Shetland and Faeroes Basins. The latter locally contains more than 1000m of Lower Cretaceous sand rich sediments (Ridd 1981). To the southwest of Ireland the continental margin was broken into a series of tilted fault-blocks during the late Jurassic and early Cretaceous (Roberts et al 1981). Geophysical surveys of the Porcupine Seabight and Goban Spur areas clearly illustrate half-graben geometries and erosion on the crests of fault-blocks (Roberts et al 1981). Also, late Mesozoic organic rich mudstones occur in many of the basins to the west of Scotland and Ireland (Naylor and Shannon 1982, Ridd 1981). Therefore, provisional studies suggest that the basic components which are necessary for the occurrence of "Brae-like" plays are present in these areas. However, it remains to be seen whether these components occur in the correct combination and the principal doubt, as in mid-Norway, must be the seal against the basin-margin faults.

5.E SUMMARY

The preliminary studies which are described in this chapter suggest that Upper Jurassic and Lower Cretaceous "Brae-like" plays occur in many areas along the Arctic-North Atlantic rift system. One of the principal exploration objectives must be to delineate areas where the upthrown fault-block acts as a seal. Once these areas are outlined, a comparison with the South Viking Graben suggests that, it is probable that the basins will contain several hydrocarbon accumulations.

The lessons of the South Viking Graben (chapters 3 and 4) should prove useful when evaluating these new areas. One of the principal lessons of the South Viking Graben experience is that the presently available seismic technology is not capable of accurately mapping the distribution of reservoirs. Therefore, in areas where stratigraphically trapped "Brae-like" plays are discovered it will be crucial to accurately identify the environment of deposition of the hydrocarbon accumulation and the sedimentology of the area must play a major role in evaluation decisions.

Chapter 6

Summary and Conclusions

During the late Jurassic the northern North Sea and North Atlantic Continental Shelf area were subjected to intensified regional crustal extension which le~~a~~d to rapid subsidence and the thinning of the continental crust under the major grabens. Coarse-grained material was eroded from the upthrown sides of the graben margin faults and redeposited in the rapidly subsiding grabens. The initiation of coarse clastic deposition was contemporaneous with the initiation of increased subsidence rates. However, the principal faulting episodes occurred in different areas at different times. The eustatic sea-level curves which have been produced for the northern North Sea fail to predict the sedimentary characteristics of many of the late Jurassic basin fills.

A study of the marginal deposits of the Inner Moray Firth Basin, which are exposed on the East coast of Sutherland, suggests that there was a major increase in subsidence rates near the base of the Kimmeridgian. The most sand-rich sediments were deposited immediately after the increase in differential subsidence rates and the sequences become less sand-rich upwards through the Kimmeridgian and early Volgian. This "fining-upwards" can be partially related to inverse stratigraphic effects; the early Kimmeridgian sand-rich sequences were derived from the erosion of poorly consolidated Jurassic sequences, whereas the younger sand-poor sequences were derived from the erosion of more lithified older sequences. Erosion and retreat of the sediment source area may have also contributed to the "fining-upwards". The increase in subsidence rates lead to a deepening of the Inner Moray Firth Basin. From the Lias to the *baylei* zone of the Kimmeridgian sediments were deposited in shallow or marginal marine environments. A major deepening episode occurred during the *baylei* and *cymodoce* zones of the Kimmeridgian and by *eudoxus* zone times (Fig.1.2) sedimentation took place below wave-base in a poorly oxygenated environment. Therefore, the upwards transition from the Heather to the Kimmeridge Clay Formation appears to have been partially structurally controlled in this area.

At the western margin of the South Viking Graben subsidence rates increased and the basin deepened during the Oxfordian. The Fladen Ground

Spur to the west was uplifted and deeply eroded and at least seven submarine fan systems transported the displaced sediment across the rapidly subsiding graben. The sediments of the South Brae Oilfield (16/7a block) were deposited in the channelised part of a submarine fan system which was, for the most part, sourced from a point which lay to the west of 16/7a-8 and the southwest of 16/7a-12. The fan system almost certainly extends into the 16/7b and perhaps 16/8b blocks where both channel and outer fan lobe sediments are likely to be encountered. Central and North Brae are large submarine fan systems and the recently discovered reservoirs of the Miller area (16/7b, 16/8b and 16/8a blocks) are probably the distal equivilents of the proximal sequences which have been drilled in the 16/7a block. The Upper Jurassic sequences of the western margin of the South Viking Graben are far more sand and conglomerate rich than those of the western margin of the Inner Moray Firth Basin. This is probably the consequence of differing shelf widths. The distance between the shoreline and the shelf edge, which was marked by the basin margin faults, was probably very small adjacent to the South Viking Graben and coarse-grained fan-deltas probably directly fed the submarine canyons and fans which transported the sediment basinwards. In contrast, the East Sutherland shelf was probably relatively wide and much of the coarse-grained sediment was trapped in this area. Differential movements in the hinterland may also have been a factor which controlled the quantity of coarse-grained sediments entering the basins.

The coarse-grained (potential reservoir) sequences of many submarine fan systems tend to be vertically stacked and spatially restricted in proximal areas and become less stacked and less restricted distally. Therefore, the initial exploration in the South Viking Graben was carried out too close to the basin margin. Further exploration in more distal areas may delineate additional hydrocarbon bearing submarine fan systems.

"Brae-like" plays are likely to be encountered at the margins of other basins in the northern North Sea and North Atlantic Continental Shelf Area e.g. the eastern margins of the Vøring and Træna basins. The following features would initially point to the possible existence of "Brae-like" plays:

1. Wedging Upper Jurassic or Lower Cretaceous seismic reflectors.
2. Anomalously thick Upper Jurassic or Lower Cretaceous sequences.
3. Evidence for widespread late Jurassic or early Cretaceous erosion on the upthrown side of basin-margin faults.

Exploration for these plays should be carried out some kilometers from the basin-margin.

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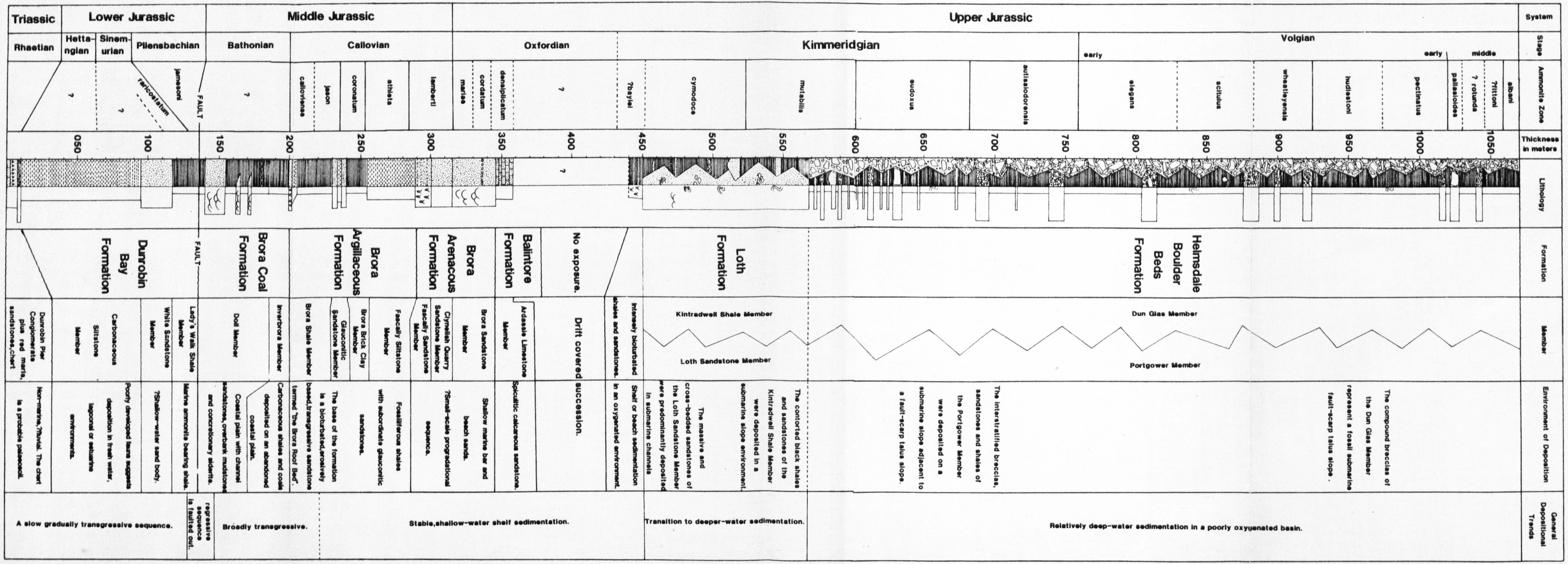


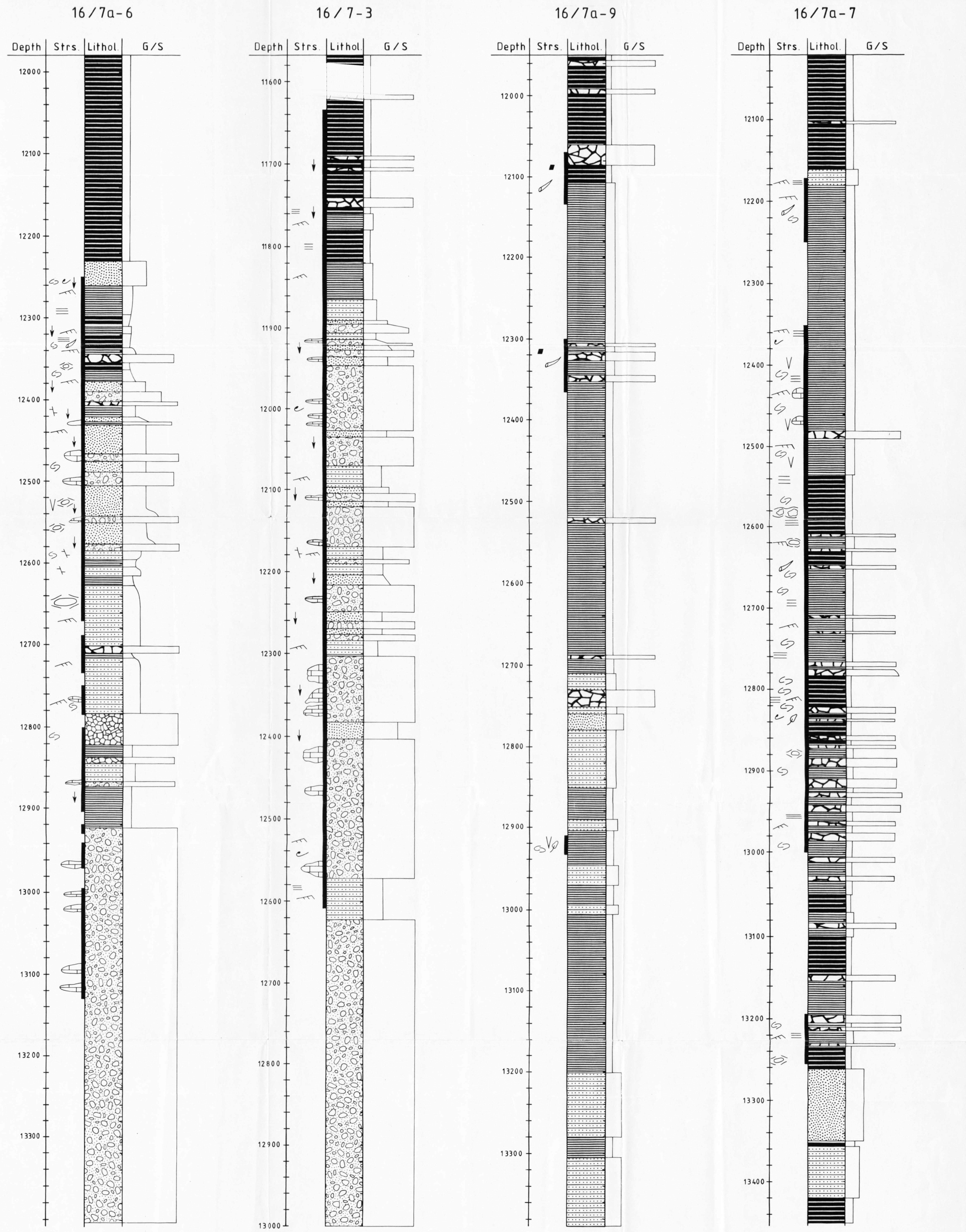
Fig.2.2 Lithostratigraphic Nomenclature of the Mesozoic of East Sutherland.

Fig.2.3 Facies Association and Location Map.

The map shows the interpreted distribution of facies associations (see text for details). In areas where exposure is poor, eg. between Crakaig Farm and Westgarty Burn, the distribution of facies associations was inferred by integrating the known distribution of associations with biostratigraphical and structural data.

The ornament shown in areas of mixed lithologies is schematic and is not meant to imply the orientation of bedding, which is shown by the dip arrows.

Fig. 3.16. FACIES LOGS OF THE SOUTH BRAE EXPLORATION WELLS



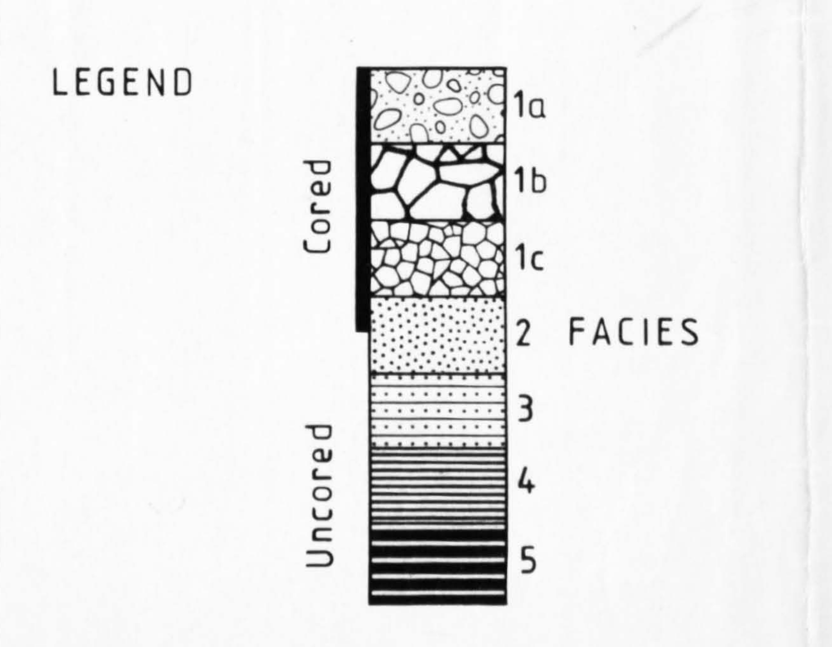


FIG. 4.3. FACIES LOGS OF CENTRAL BRAE EXPLORATION WELLS.