A PETROGRAPHIC STUDY OF DEVONIAN SEDIMENTS OF A CLOSED BASIN IN NORTHERN SCOTLAND AND SOUTHERN SHETLAND ISLANDS

By

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CHAPTER I

INTRODUCTION

Statement of Purpose

This thesis describes the petrology and diagenesis of four separate areas in different parts of the Orcadian Basin of North-eastern Scotland and Southern Shetland Islands. Comparison of the four locations revealed how petrology and diagenesis reflect the source rock, the depositional setting, and the relative locations of areas within the basin.

Location of study

During the summer of 1983, R. N. Donovan conducted field work in the areas of Tarbat and Portskerra of North-eastern Scotland, and Melby and Foula of Southern Shetland Islands (Figure 1). Caithness and Orkney contain the most extensive development of the Middle Old Red Sandstone in Scotland. Discontinuous outcrops extend south from Caithness and Orkney predominantly within twenty miles inland of the Moray Firth coastline. Further south along the Great Glen Fault, Middle Old Red Sandstone forms a narrow outcrop between Loch Ness and Loch Lochy. Further east, Middle Old Red Sandstone outliers are located at

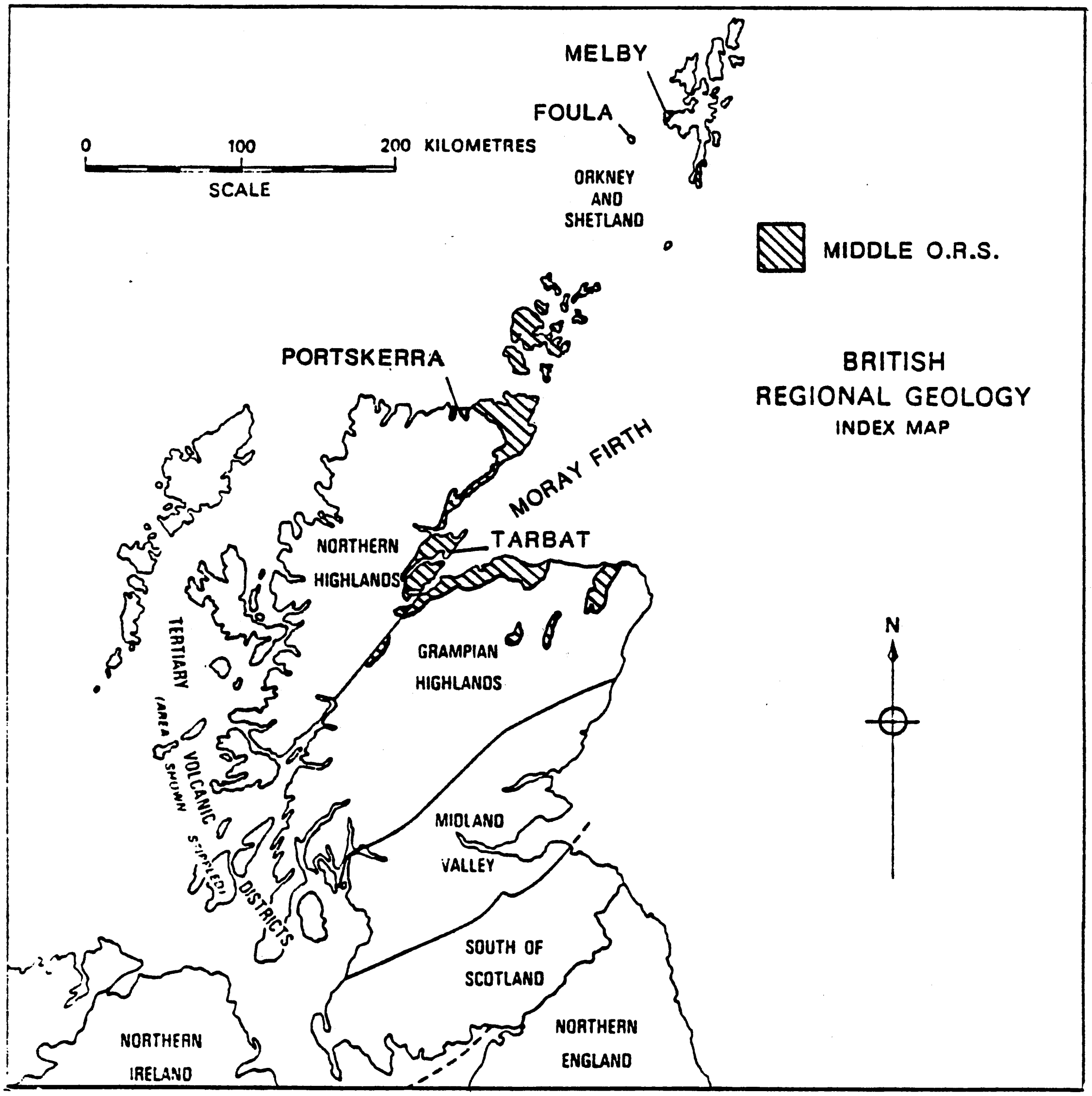


Figure 1. Location Map of Study Areas (after the British Regional Geology Index Map)

Tomintoul and Lumsden. Northeast of the Scottish mainland, Middle Old Red Sandstone facies form small outcrops in the southern half of the Shetland Islands.

In general, these outcrops represent fluvial and lacustrine dominated depositional environments. Middle Old Red Sandstone exposed around the shores of the Inner Moray Firth is predominantly fluvial in origin, and in Orkney and Caithness it is predominantly lacustrine in origin (Donovan, 1984). However, dramatic local variations are common.

Procedure

Fifty-four thin sections from four different areas in the Orcadian Basin were analyzed for petrology and diagenesis. Petrology was used in part to determine a possible source rock type at each location. Then the paragenetic sequences of the four areas were compared to the location of each area within the Basin. Photomicrographs were taken to aid the reader in understanding the petrologic and diagenetic evidence presented in the following chapters.

Background

During Late Silurian and Early Devonian time, formation of the Appalachian Mountains of North America and the Caledonian Mountains of Europe occurred as part of a major orogeny associated with the close of the Iapetus Ocean. The resulting basins started filling with sedimentary deposits that lithified into what is known as the Old Red Sandstone (Anderton et al., 1979).

Two types of depositional basins formed as a result of the orogeny; open basins and closed basins. Open basins, which were bounded in part by the Caledonian Orogenic Belt, were also bounded by the sea. Alluvial plain, fluvial, and shallow marine deposits are characteristic of these basins. Closed basins were within the orogenic belt. As a result of the closed nature of these basins, lacustrine facies commonly filled the basin centers, and alluvial and fluvial facies fringed the basin margins (Donovan, 1975).

The Orcadian Basin of Northern Scotland was a NE/SW trending closed basin that formed within the Caledonian Orogenic Belt. The maximum rate of sediment accumulation was about 8200ft (2500m) per million years for span of ten million years from the beginning of Middle Devonian to Late Devonian times (Figure 2)(Donovan, 1984). Maximum thickness of sediments in the Orcadian Basin is estimated to have been close to 16400ft (5000m).

Allen (1979) used paleomagnetic data to determine the latitudes at which Britain was located during Devonian time. From the Early Devonian to Late Devonian, Britain moved from between 20 and 30 S to between 10 and 20 S (Figure 3). During this time, Britain was dominated by warm to hot, semi-arid to arid climates (Allen, 1979).

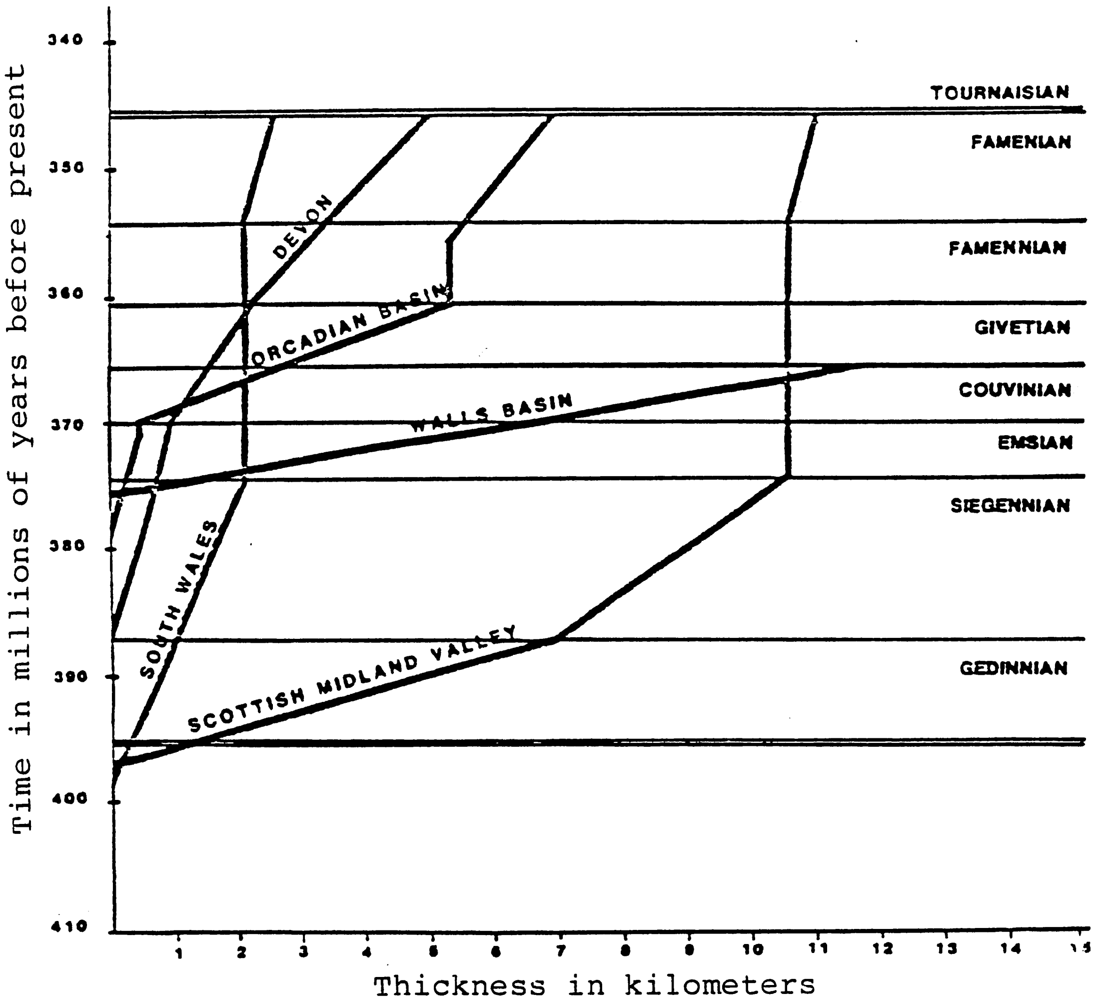


Figure 2. Orcadian Basin Sedimentation Rates and Their Comparison to Other Major British Basin Settings During the Devonian (after Donovan, 1984)

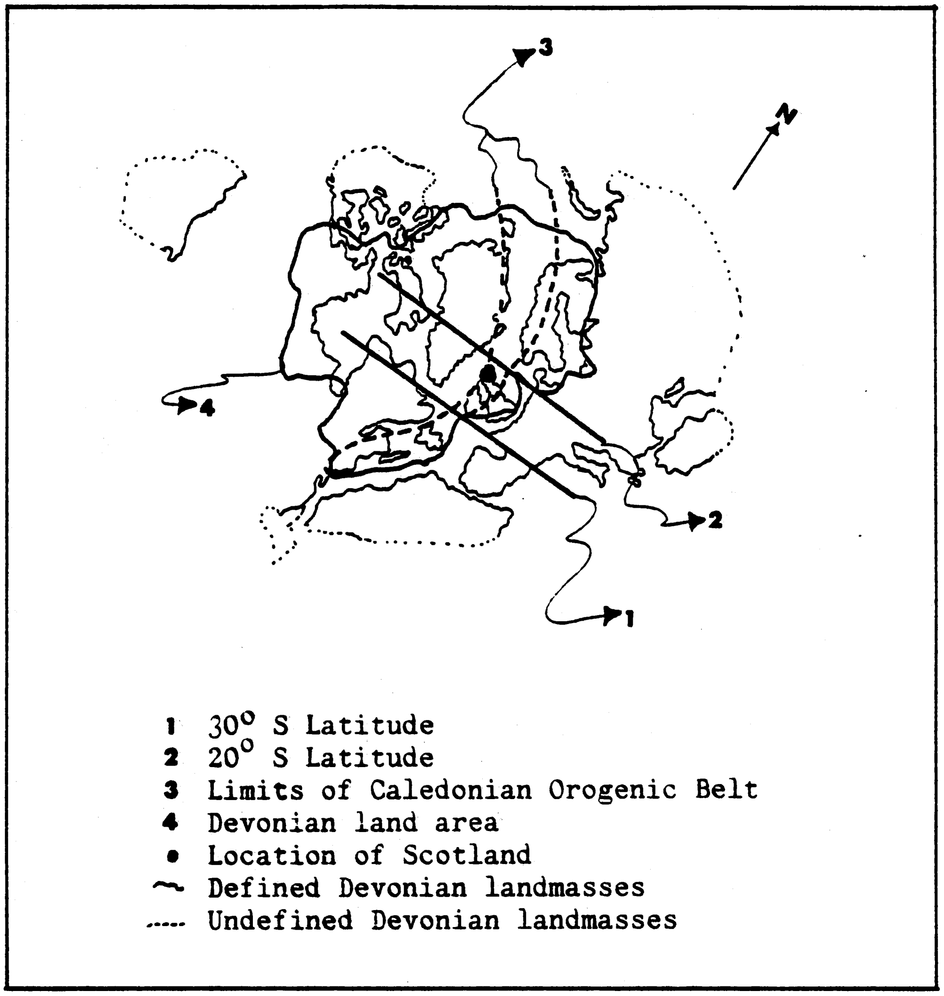


Figure 3. Paleolatitude of Scotland and the Old Red Sandstone During the Early Devonian (after Faller and Briden, 1978)

Local Stratigraphy

The term "Old Red Sandstone" was first applied to Devonian sediments of Britain in 1822 by Conybeare and Phillips. These deposits are of fluvial, aeolian, lacustrine, and marine origin. Murchison (1859) divided The Old Red Sandstone of Scotland into three subdivisions; Lower, Middle, and Upper Old Red Sandstone. Murchison defined the three subdivisions based on geographical location. Geikie (1878) later found that he could correlate each subdivision without regard to its geographic location.

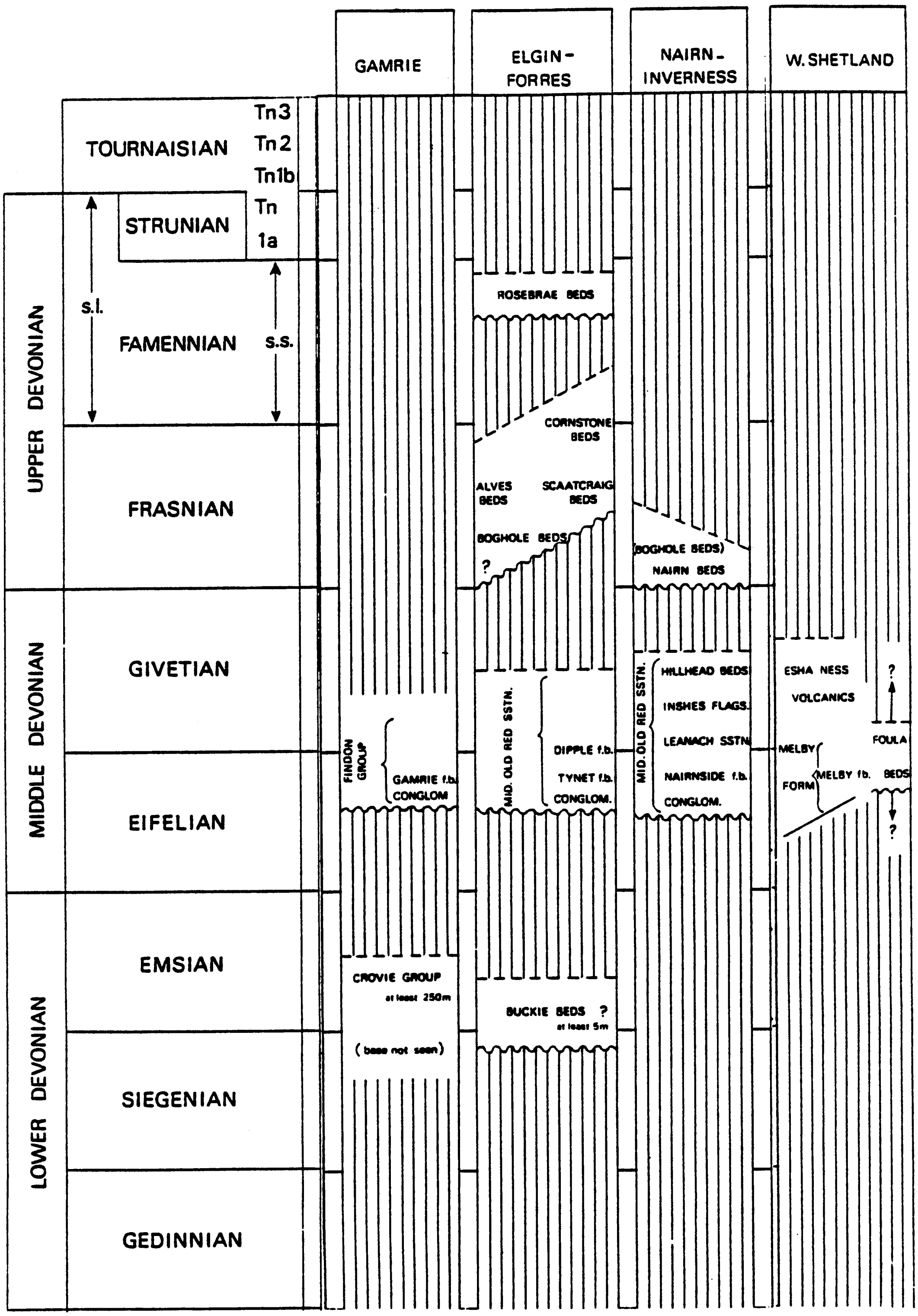
Lower and Upper Old Red Sandstone units are comprised mainly of fluvial deposits. The Middle Old Red Sandstone is predominantly fluvial in the upper part and lacustrine in the lower part. The succession is often incomplete as a result of the relative onlapping and offlapping nature of the three units. The Lower Old Red Sandstone unconformably overlies the Caledonian basement of igneous and metamorphic rocks. In some areas the onlapping nature of the units resulted in Middle and Upper Old Red Sandstone also being uncomformable upon Caledonian basement rock.

Regional Stratigraphy

All three subdivisions of the Old Red Sandstone are within the Orcadian Basin (Table I). Intermittent exposures of Old Red Sandstone occur from Northern Scotland

TABLE I

STRATIGRAPHY OF THE DEVONIAN PERIOD IN NORTHERN SCOTLAND (AFTER WESTOLL, 1977)



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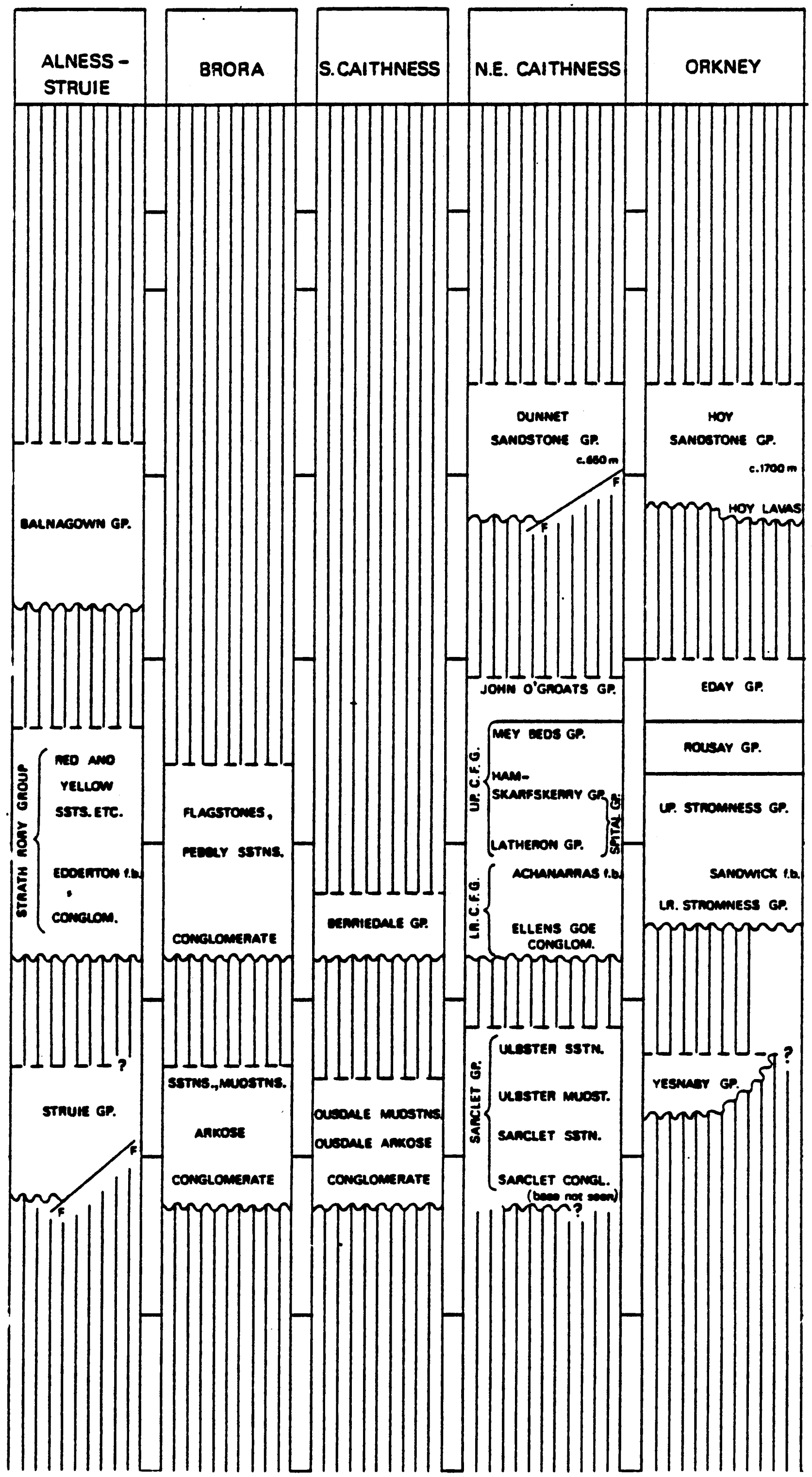

around the Moray Firth area to the southern half of the Shetland Islands. The Middle Old Red Sandstone is the most widely exposed subdivision in the Orcadian Basin (Figure 1).

The lacustrine and fluvial deposits have long been recognized in Scotland (Conybeare and Phillips, 1822; Murchison, 1859; Geikie, 1878; and Crampton and Carruthers, 1914). Sedimentation began with major river systems debouching from the west, south-west, and north-west into the basin, developing flood plains which were covered by small lake systems. Early river systems were most likely subsequent to major structural features. Ridges that may have trended NW/SE in the southern part of the basin could have prevented clastic fluvial sediments from reaching the south-west side of the earliest shallow lake systems (Mykura, 1984). Major faults such as the Great Glen Fault in part maintained or altered the direction to which river systems flowed (Mykura, 1984).

Donovan (1984) approximated the maximum extent of the lake in the Orcadian basin to have covered 50,000km^2. This area includes most of the presently exposed Middle Old Red Sandstone in the basin. At the time of maximum lake transgression, the lake probably covered most of the land within the basin margins (Figure 4). The Achanarras fish horizon is the marker horizon used to estimate the areal extent of the lake waters. This marker was chosen both because of its wide extent and because many fish, such as

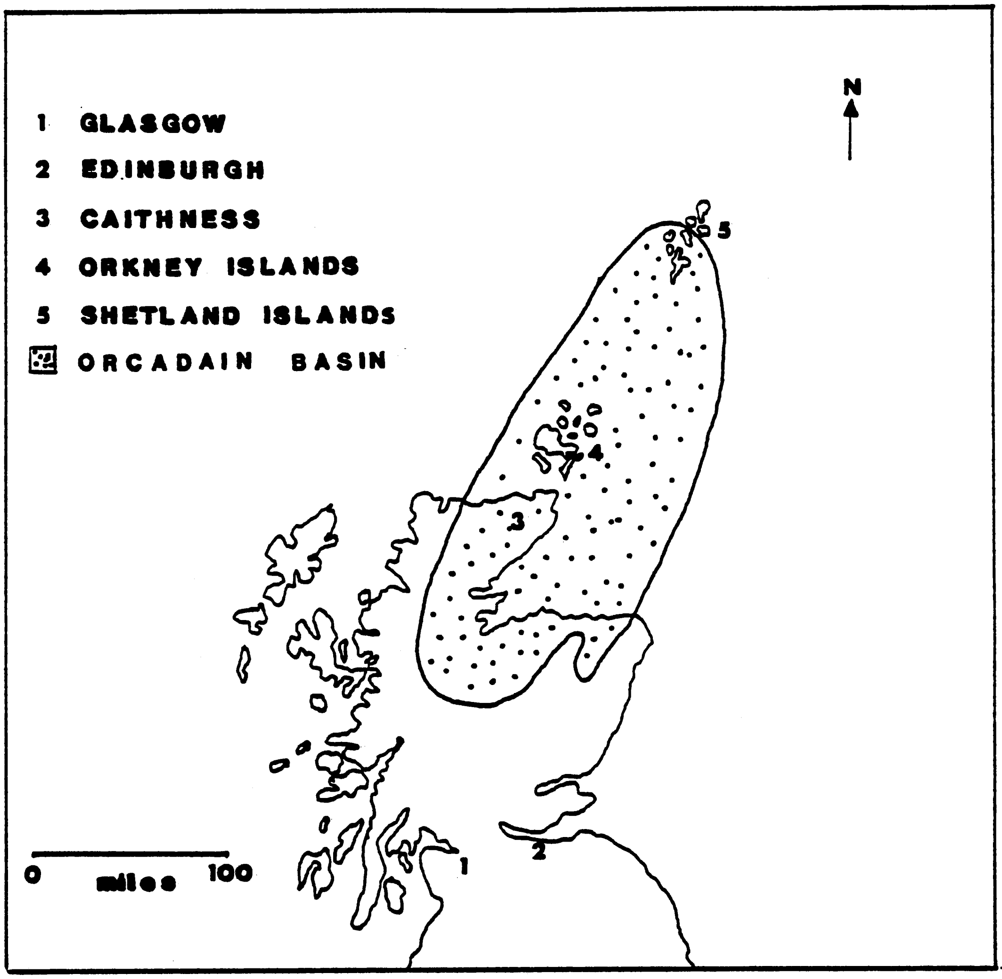

Figure 4. Approximate Limits of the Orcadian Basin in Northern Scotland

the *Palaeospondylus gunni*, are only found within this stratigraphic horizon (Donovan, 1984).

CHAPTER II

PETROLOGY AND DIAGENESIS OF THE OLD RED SANDSTONE OF FOULA

Introduction

Location

Foula is a small island located in the Atlantic Ocean, 14 miles (22km) WSW of Wats Ness of the Shetland Islands (Figure 5). The pear-shaped island consists of 5.3 square miles (13.6km^2) of land with three steep north-facing coastal escarpments and gentle south-facing dip slopes. A west-north-west trending glacially moulded valley, known as The Daal, traverses Foula (Mykura et al., 1976).

General Geology

About 90% of Foula is made of a 6000ft (1800m) thick Devonian (Middle Old Red Sandstone facies) sequence of friable sandstone with subordinate shale and siltstones. Much of the sandstone is cross-bedded showing an east to southeast flow direction. The entire sequence has been folded to form an open, southward plunging syncline.

The sandstone sequence overlies a metamorphic basement that outcrops as a 1/2-mile wide strip extending north to

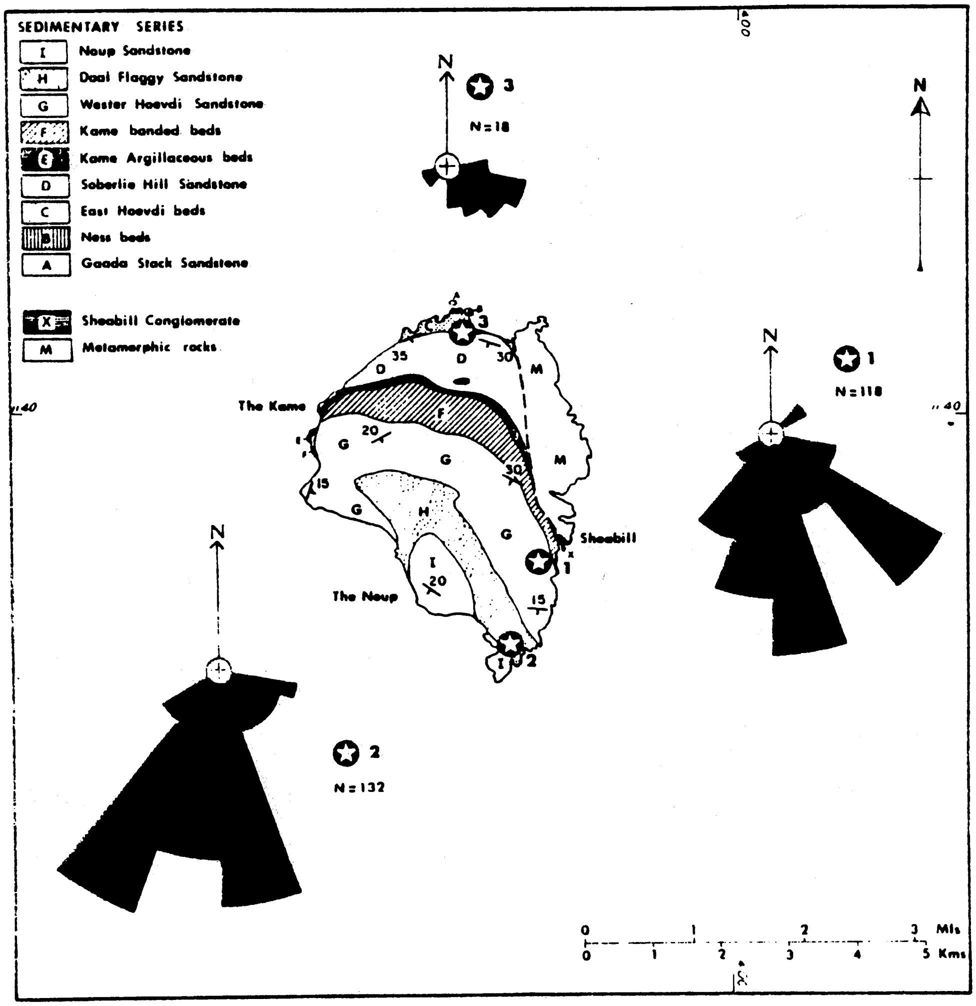

Figure 5. Foula Island of the Shetland Islands
(from Donovan, unpublished)

south along the western edge of Foula. This basement consists mainly of metasediments that are made of alternating bands of garnetiferous quartz′ feldspar-granulite and garnetiferous mica-schist which are cut by microgranite dikes and sills. The contact between the sandstone and the metasediments has been interpreted in the following three ways:

1) As a fault (Mykura and Phemister, 1976)
2) As an unconformity (Donovan, pers. com.)
3) As a shallow fault that becomes an unconformity with depth (Mykura et al., 1976)

Donovan (pers. com.) interpreted the contact as an unconformity because nearest the contact, there are angular cobbles that grade into rounded pebbles within 10ft (3m) up-section. He also found small scale cross-bedding in thin siltstone lenses within the same interval. Other authors have interpreted the coarse breccia at this contact as a fault breccia.

Environment of Deposition

The lower part of the sequence on Foula consists of red, brown, and violet sandstones, siltstones, and mudstones with sand-filled mudcracks indicating a possible meandering stream environment where both channel and flood plain deposits were preserved. Paleocurrents indicate that these rivers probably flowed east to south-east (Mykura, 1976). The middle and upper part of the sequence consists of possible deposits of fast-flowing braided rivers, that may have flowed eastward (Donovan, pers. com.). The similar compositions of sandstones throughout the sequence suggests the likelihood that rivers drained a single source area. The Foula sediments were probably deposited near the northwest margin of the Orcadian Basin (Mykura et al., 1976).

Sedimentary Petrology

Sixteen sandstone samples were collected near the southern and south-eastern shoreline of Foula and four samples near the northern shoreline (Figure 5). The intervals sampled include a section from the unconformity of eastern Foula going up-section approximately 3100ft (950m)(Figure 6).

Textures

The majority of the samples are texturally submature to immature sandstones that consist of very poorly sorted to well sorted grains (Folk, 1974; Pettijohn et al. 1972). The sandstones within 820ft (250m) of the unconformity are generally immature and poorly to very poorly sorted while the sandstones from 820ft to 3100ft (250m to 950m) above the basal contact are generally submature and medium to well sorted. The difference in textural maturity and sorting of the lower and upper sections of the sandstones appears in part to be a result of post-depositional

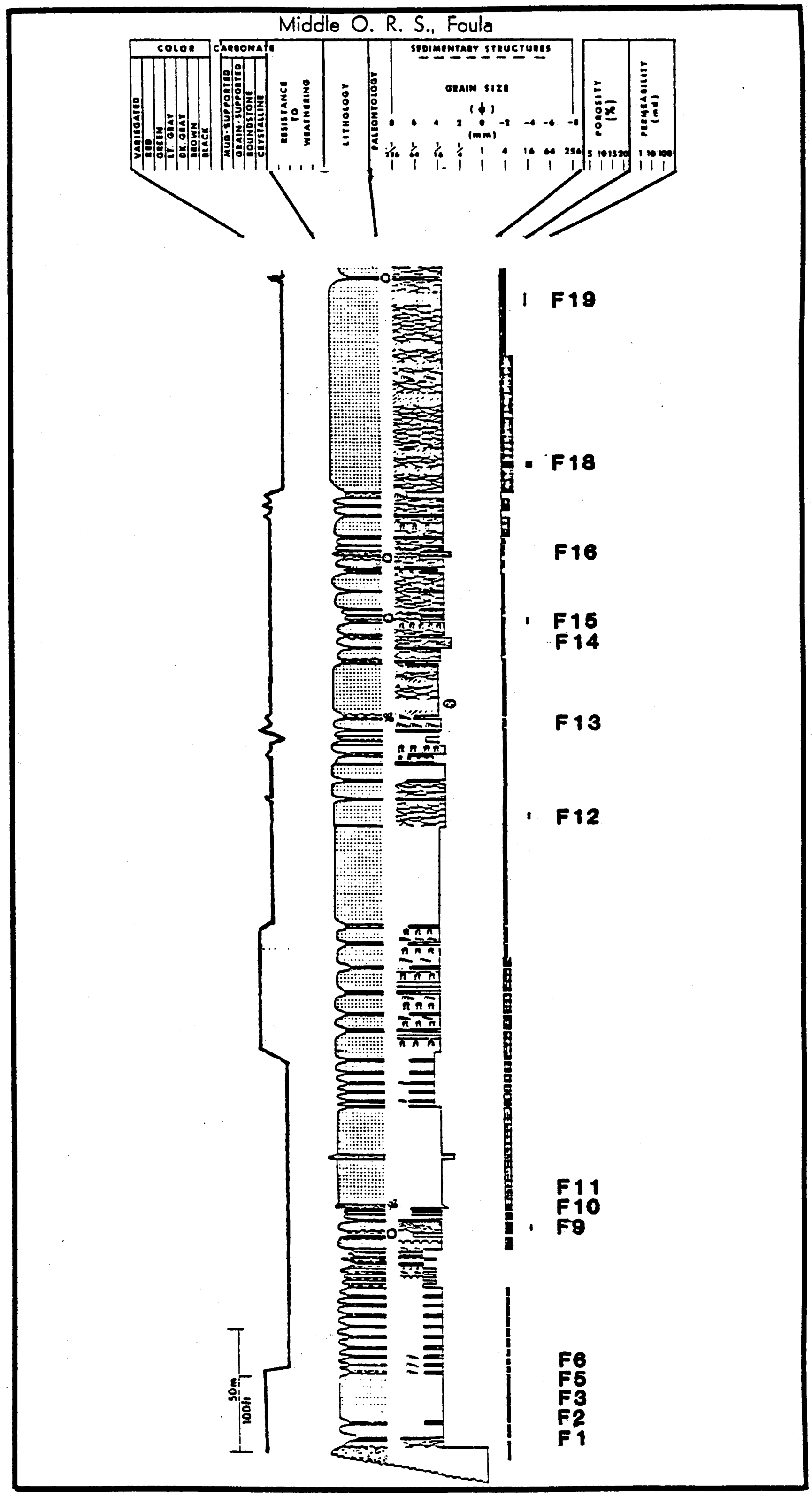

Figure 6. Logged Section from Foula (from Donovan, unpublished)

tectonic stress in addition to factors related to the variation of lithology or depositional environment. Five lines of evidence supporting this idea follow:

1) Fractures and microfaults are common on the lower 1300ft (400m) and less common to absent in the upper samples (Figure 7).

2) A 1300ft (400m) interval of abundant post depositional boehm lamellae, a probable precursor of fracturing, lies just above the fractured and microfaulted section (Figure 8).

3) The number of boehm lamellae in the uppermost 410ft (125m) of section is relatively small compared to that stratigraphically lower (Figure 9).

4) Samples from the lower 1300ft (400m) interval have an average of 22% matrix, two-thirds of which is quartz.

5) The entire sequence is of fluvial origin and the mineralogic composition of the fluvial sandstones is similar (Mykura, 1976).

Most of the samples are medium to fine sandstones with the addition of finer grain size in the poorly to very poorly sorted sandstones. It is possible that some, or maybe all, of the original sandstones were moderately well to well sorted before they were altered tectonically.

Mineralogy

Middle Old Red sandstones primarily are subarkoses, lithic arkoses, and sublitharenites (Figure10). The

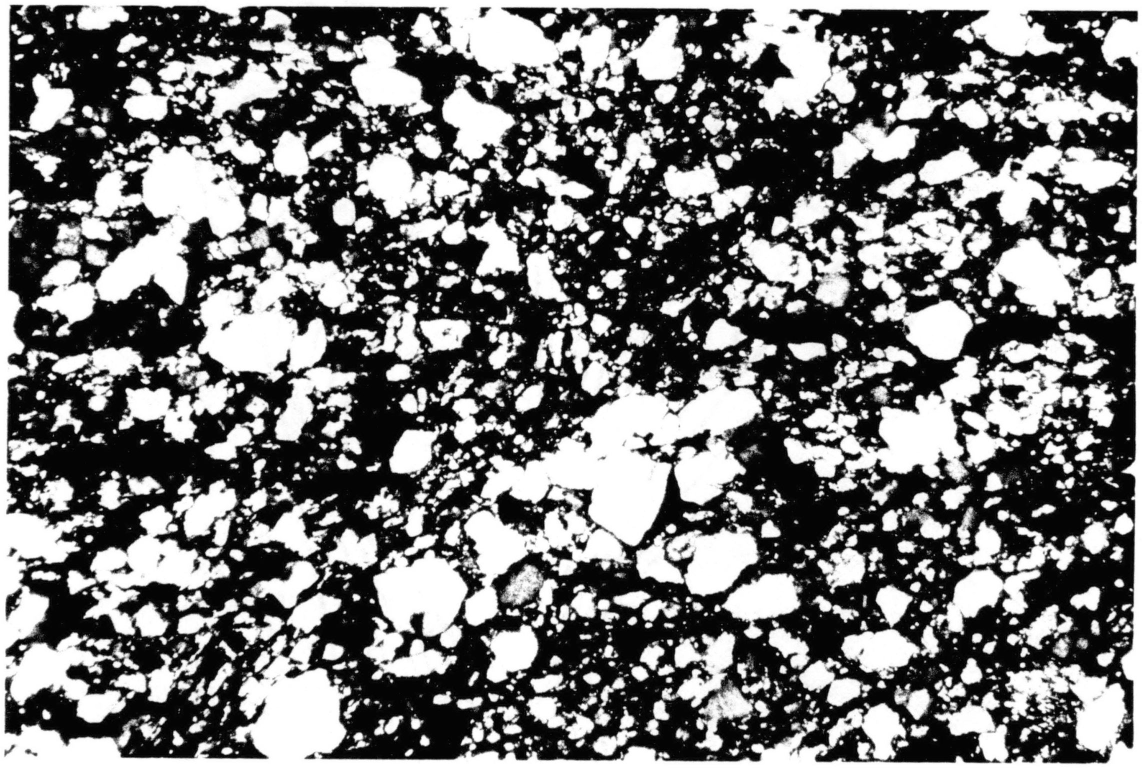

Figure 7. Photomicrograph of a Microfault that Displaced a Fracture (40X, XN)

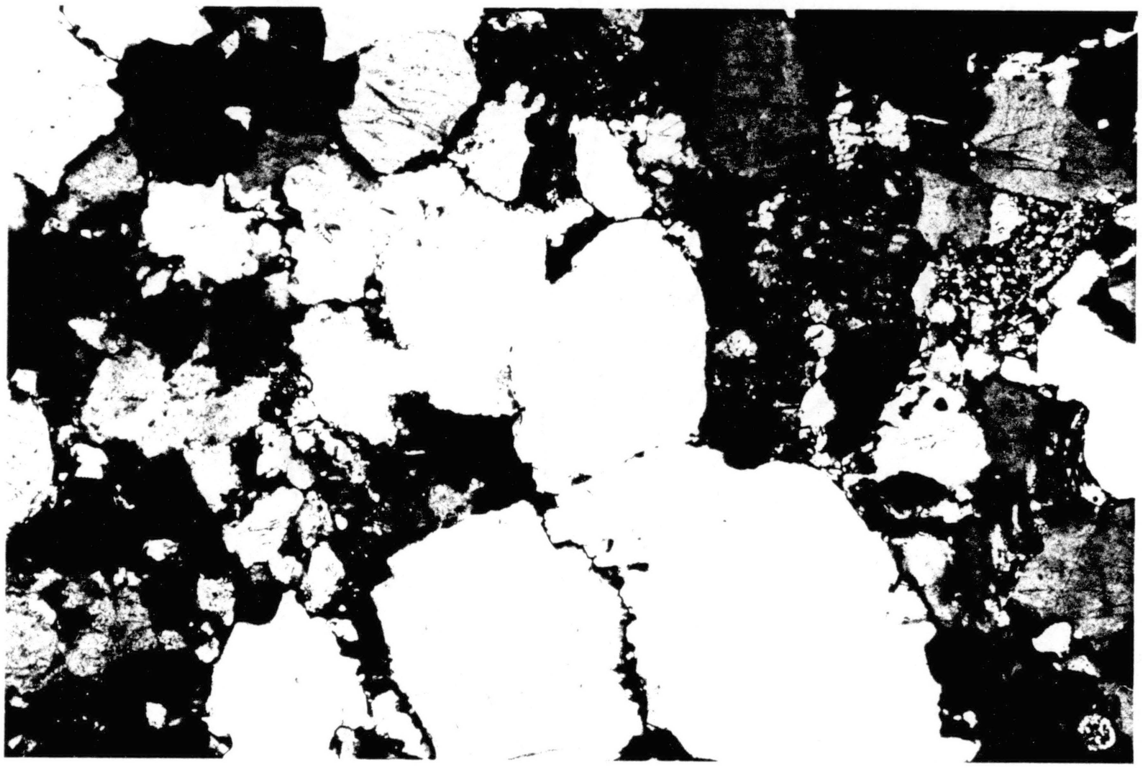

Figure 8. Photomicrograph of Boehm Lamellae from just above the Fractured and Microfaulted Sandstones (100X, XN)

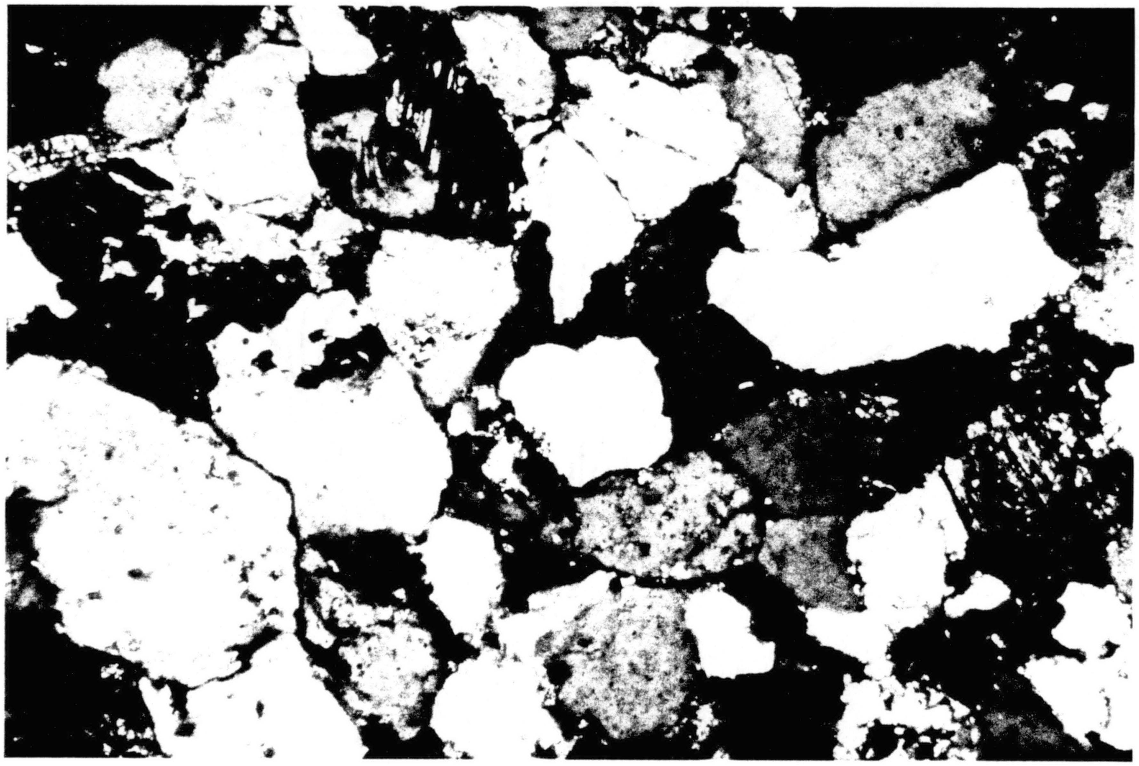

Figure 9. Photomicrograph of Boehm Lamellae in the Uppermost 410ft (125m) of Section (100X, XN)

mineralogy of the detrital grains indicates a metamorphic and igneous source rock.

Quartz. Quartz is the major constituent and on the average it makes up 57 percent of the rock volume. Most grains show slight (less than 5 degrees) to moderate (more than 5 degrees) undulose extinction. The degree of undulosity throughout the samples is constant suggesting that the undulosity is provenance-related rather than a diagenetic fabric. This observation suggests that the majority of the monocrystalline quartz grains may be from a metamorphic source rock (Basu et al., 1975). Close inspection of a quartz-and-feldspar-rich metamorphic pebble shows how it is quite possible to derive several monocrystalline sand size quartz grains from this larger fragment (Figure 11). Four criteria for identifying this fragment as a metamorphic rock fragment follow:

1) Quartz crystals show a preferred crystallographic orientation (Blatt, 1967).

2) Grain size distribution of quartz is bimodal (Blatt, 1967).

3) Intergranular suturing, although not a reliable provenance indicator, suggests a metamorphic source rock (Blatt, 1967).

4) The estimated average undulosity is greater than five degrees (Basu et al., 1975).

Individual quartz crystals in the metamorphic rock fragment are up to .7mm long and .4mm wide. Seven fine

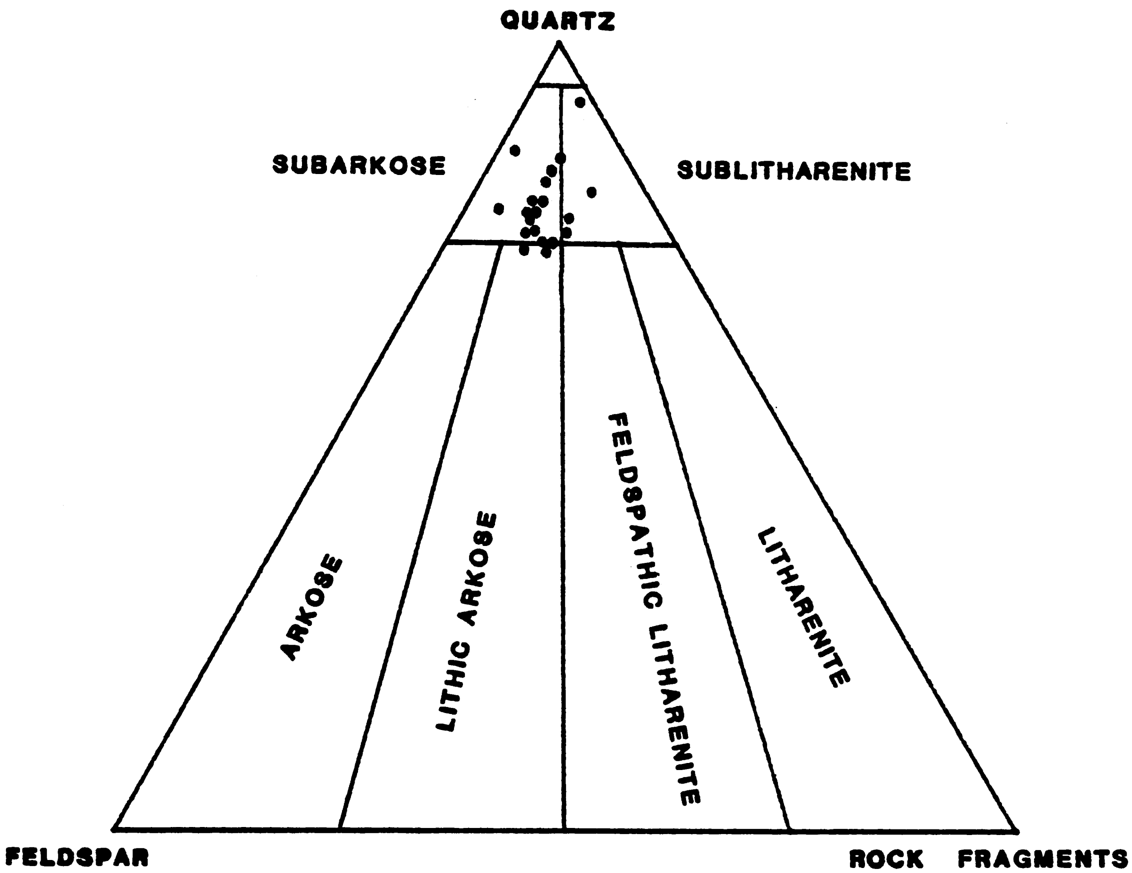

Figure 10. Classification of Sandstones from Foula (Diagram after Folk, 1976)

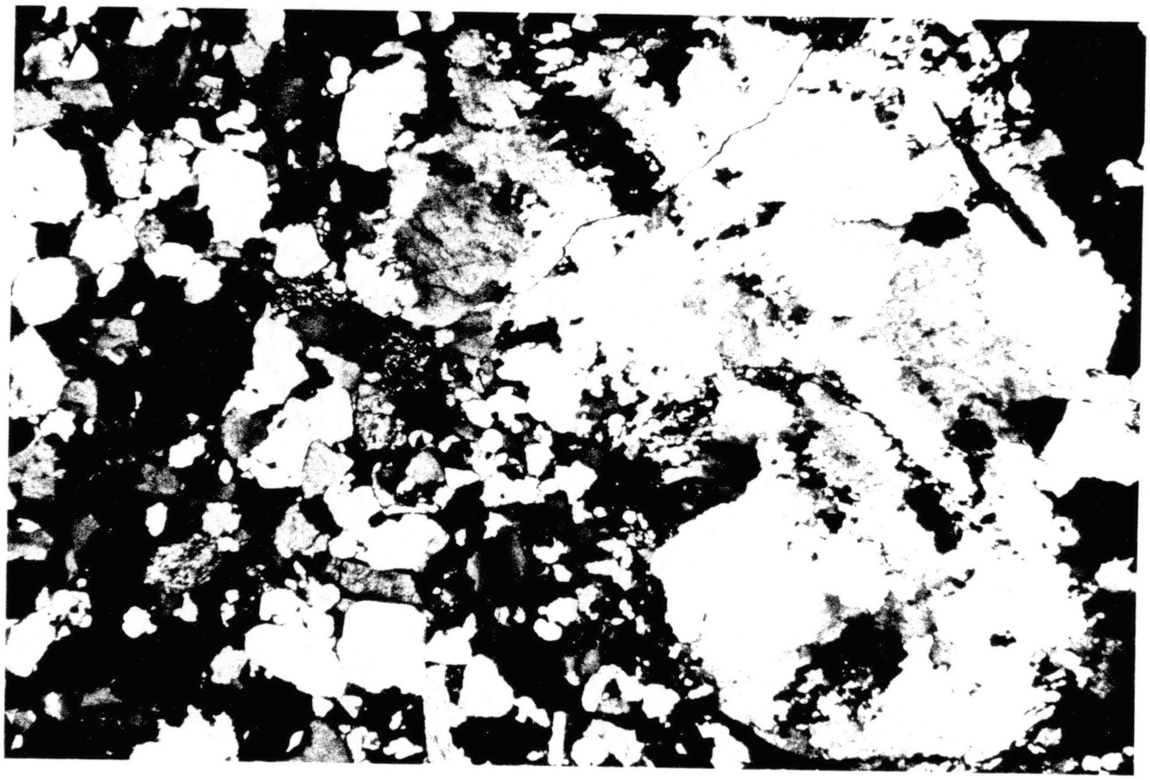

Figure 11. Photomicrograph of a Quartz rich Metamorphic Rock Fragment (40, XN)

Figure 12. Photomicrograph of a Feldspar rich Metamorphic Rock Fragment (40, XN)

grained monocrystalline quartz grains could easily be derived from a crystal that size.

Polycrystalline quartz grains, excluding metaquartzite, make up an average of less than 1 percent of the samples. These grains may be of either igneous or metamorphic origin.

Feldspar. The second major constituent is feldspar which makes up an average of about 9 percent of the total volume of the samples. Of this average, constituents approximately are: orthoclase, 5 percent; microcline, 2 percent; placioclase, 2 percent; and perthite, less than one percent. Close inspection of a quartz and feldspar-rich metamorphic pebble shows how feldspar in the sandstones may be of metamorphic as well as igneous origin (Figure 12). Most of the feldspar grains have been physically and/or chemically altered and they play an important role in revealing the paragenetic sequence of these sandstones.

Rock Fragments. Rock fragments make up an average of 7 percent of the total volume of the samples (6 percent of which is metamorphic rock fragments). Metaquartzite is the most common metamorphic rock fragment; phyllite and gneiss average less than 1 percent. Chert, siltstone, shale, sandstone, and volcanic rock fragments, each average less than 1 percent of the volume of the samples. One sample contains a pebble whose texture suggests that it may have been reworked from an exposed shallow lake deposit during regression of the lake waters (Donovan, pers. comm.).

Other Constituents. Detrital muscovite averages 1 percent of the samples while detrital biotite, chlorite, and hematite are accessory. The original amount of biotite was closer to 3 percent before diagenetic hematisation of many of the biotite flakes took place. Other grains that occur in trace amounts are pyrite, zircon, apatite, garnet, sphene, rutile, blue tourmaline, and glauconite. Detrital matrix averages 9 percent of the samples. The most abundant minerals making up the detrital matrix are quartz, illite, and chlorite.

Four major diagenetic constituents that average from one to 4 percent of each sample include:

1) Quartz as overgrowths

2) Hematite as grain coatings, pore linings, and pseudomorphs of biotite

3) Authigenic illite as grain coatings, pore linings, pore fillings, and grain replacement

4) Authigenic chlorite as pore linings and pore fillings

Five minor diagenetic constituents averaging less than 1 percent of each sample include:

1) Feldspar as overgrowths

2) Calcite as a cement and a replacement mineral

3) Leucoxene as a replacement mineral

4) Chert as fracture fillings

5) Kaolinite as pore fillings and grain replacement

Porosity averages 5 percent of the samples; 2 percent is primary and 3 percent is secondary.

Diagenesis

Thin section analysis has revealed some convincing evidence of the paragenetic sequence. Although minor variations can be detected within a particular sandstone unit or among several units, the "general paragenetic sequence" that has been derived is applicable to all of the samples from Foula (Figure 13). The phrase, "general paragenetic sequence", implies that if two events occurred under different conditions but at the same time, then both events will be represented in the sequence as occurring relatively simultaneously.

The early stages of diagenesis (eogenetic and early mesogenetic) included:

1) Compaction resulting in bending and squeezing of ductile grains, and to a lesser extent, breaking of brittle grains

2) Mechanical infiltration of detrital illite

3) Authigenic illite growth

4) Hematite as grain coatings

5) Hematite as a pseudomorph of biotite

6) Authigenic chlorite growth

7) Quartz overgrowths

8) Feldspar overgrowths

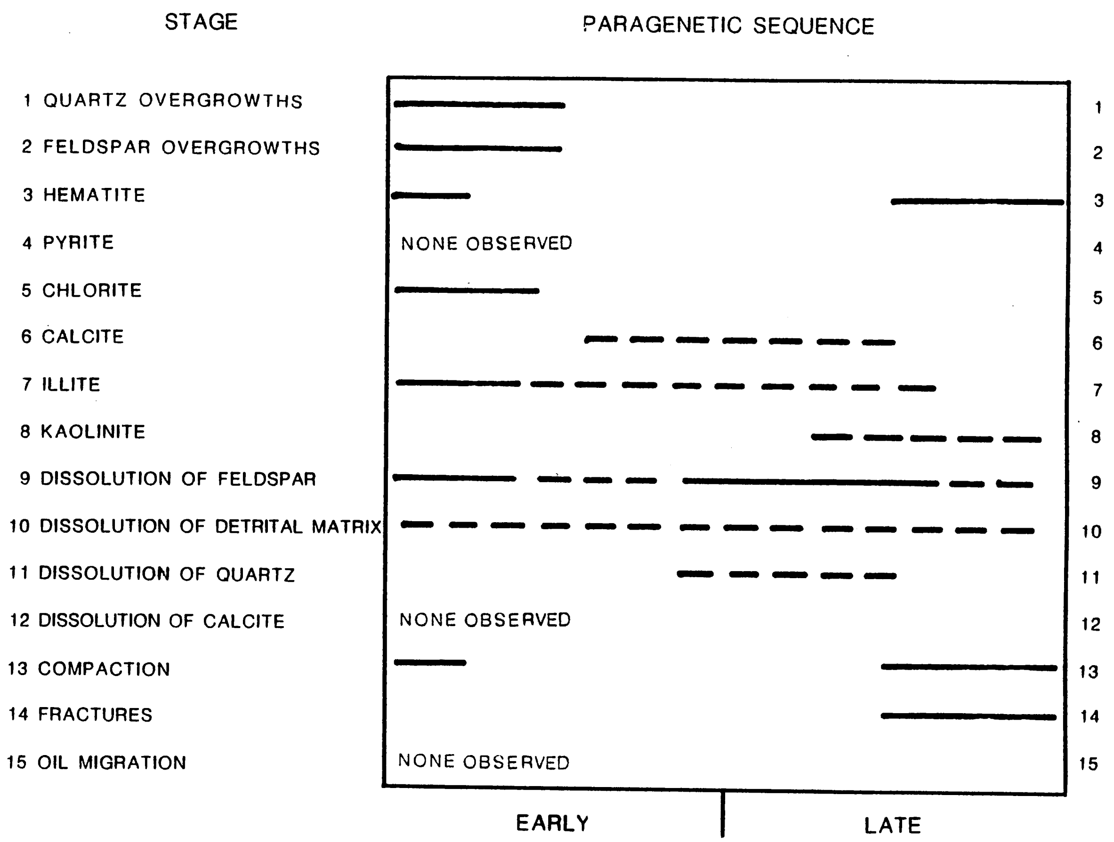

Figure 13. Paragenetic Sequence of Sandstones from Foula

9) Partial dissolution of metastable constituents

10) Precipitation of calcite either as a cement or as a replacement of feldspar, quartz, and metastable constituents

Dust rims of detrital and authigenic illite (some of which are iron stained) suggest that the earliest events involved infiltration of detrital illite into pores, together with partial dissolution of metastable constituents, and precipitation or remobilization of ferric iron with the illite as grain coatings. In one sample the clay coatings appear to have inhibited quartz overgrowths.

The presence of ductile micaceous grains that prevented quartz overgrowths, and of broken feldspars which have been healed by quartz overgrowths, suggests that early compaction predated quartz overgrowths.

Quartz and feldspar overgrowths are two early cements that have an interesting relationship with each other and with the early grain coating minerals. When both authigenic quartz and feldspar have filled the same pore space, the "hacksaw" terminations of the feldspar are usually seen rather than the smooth surface of the quartz (Figure 14). This relationship suggests that the quartz grew up to the "teeth" of the feldspar after the precipitation of the feldspar ceased. In some cases the contact between the quartz and feldspar overgrowths is fairly smooth, possibly indicating competition for pore space (Figure 15). These observations indicate that quartz

Figure 14. Photomicrograph of Feldspar and Quartz Overgrowths (200X, XN)

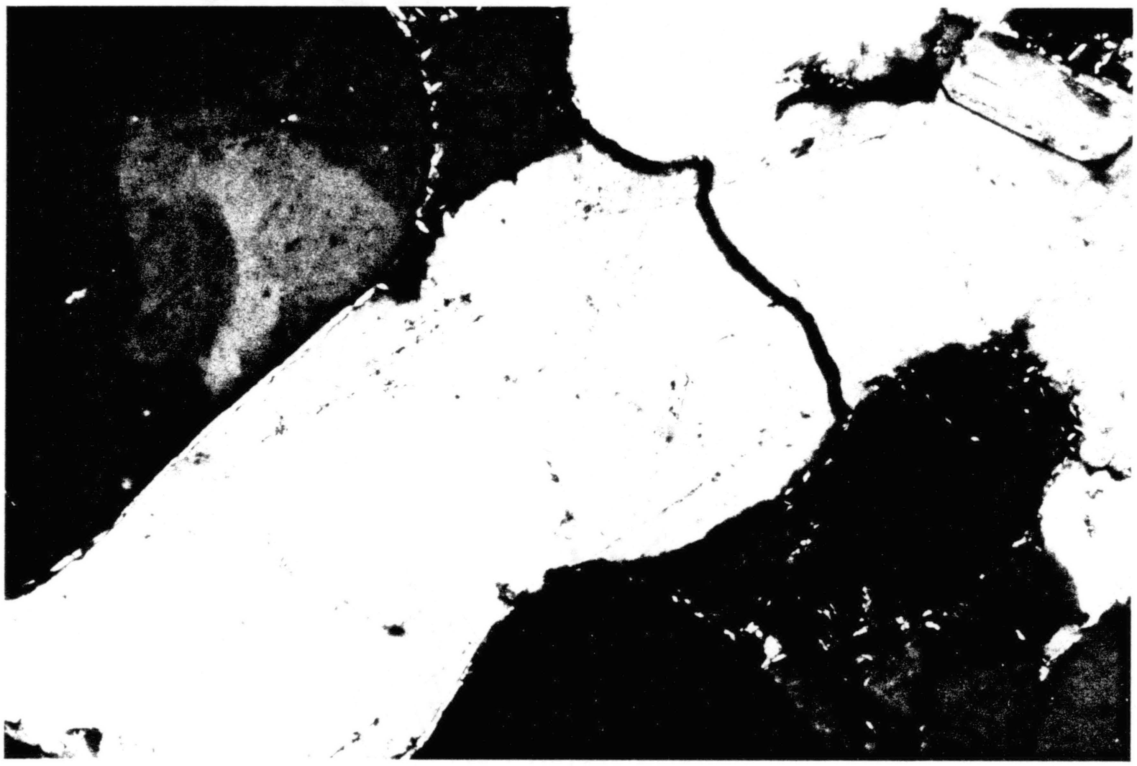

Figure 15. Photomicrograph of Feldspar and Quartz Overgrowths in Competition for Pore Space (200X, XN)

and feldspar may have precipitated more or less contemporaneously.

Feldspar overgrowths seem to have grown slowly enough to reject or exclude much of the "foreign particles" that surrounded the original grain. For example feldspar is seen to have rejected authigenic illite and detrital matrix as it grew (Figures 15 & 16). This is in contrast to the growth style of quartz overgrowths. Whereas Feldspar is seen to have "pushed" authigenic illite against a quartz grain, the quartz grain included authigenic illite in its overgrowth (Figure 15).

Authigenic chlorite is present from a trace up to 1 percent of the volume of the samples examined. It is seen both as partial dust rims on quartz grains and as a precipitate on and in quartz overgrowths (Figure 17). It is probable that chlorite formed as a result of the early dissolution of ferromagnesian minerals. The chlorite may have formed under locally neutral to reducing conditions as a result of a lake transgression.

Early hematite is seen associated with illite as dust rims on quartz and as coatings on other detrital grains. It occurs also as a pseudomorph of biotite. The process of breaking down biotite is controlled by complex variations of conditions during diagenesis (Turner and Archer, 1977). Theoretically, biotite should alter to vermiculite in an acid environment and to vermiculite plus montmorillonite in a neutral to alkaline environment. This relationship helps

Figure 16. Photomicrograph of Feldspar Overgrowth that May Have Displaced Illite as it Grew (400X, XN)

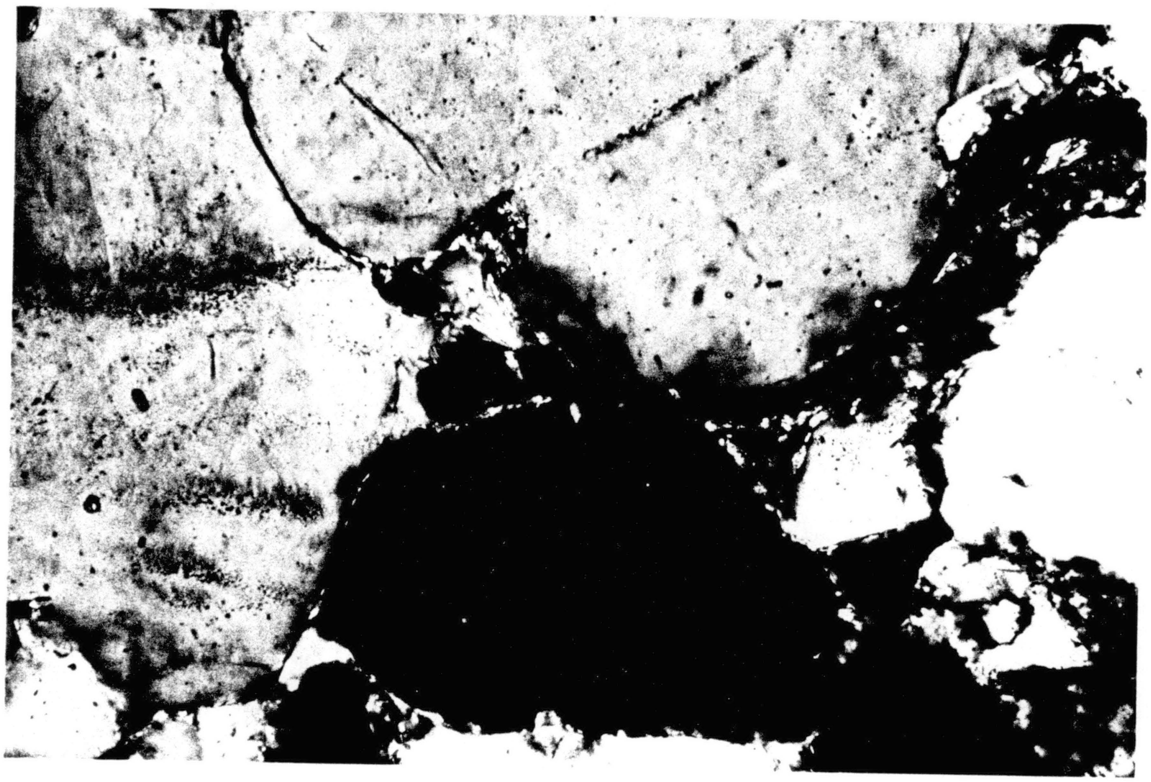

Figure 17. Photomicrograph of Authigenic Chlorite, Hematised Biotite, and Quartz Overgrowths (400X, XN)

to explain the fact that montmorillonite is the most abundant mica clay in calcareous and alkaline soils (McNeal and Sansoterra, 1964). The lack of vermiculite and the abundance of hematite pseudomorphs after biotite in the Foula redbeds suggests that the oxidation of biotite may not have involved vermiculization.

One possible mechanism for oxidation of biotite without vermiculization is the loss of octahedral iron (Farmer et al., 1971):

$$\underset{\text{Biotite (Annite)}}{(SiAlO_{10})Fe_3^{2+}(OH)_2K} + \underset{\text{Oxygen}}{3/4O_2} + \underset{\text{Water}}{1/2H_2O} \rightarrow \underset{\text{Oxidized "Dioctahedral" Biotite}}{(Si_3Al_{10})Fe_2^{3+}(OH)_2K} + \underset{\text{Iron Hydroxide}}{FeO\,OH}$$

During this reaction, $(FeO)^+$ groupings are ejected through hexagonal holes in the silicate sheet probably forming an amorphous iron hydroxide which precipitates in the interlayer spaces (Turner, 1980).

Turner (1980) believed that oxidative decomposition of biotite is an early diagenetic feature of continental alluvium. Even in the earliest stages of weathering, iron shows a tendency to migrate to biotite grain edges where it accumulates as amorphous oxides (Meunier and Velde, 1979). Although the majority of the biotite grains in the Foula sandstones are completely pseudomorphed by hematite, many of the grains are only partially (i.e., circumferentially) replaced. This incomplete pseudomorphing of biotite suggests that oxidizing conditions gave way to reducing conditions before the hematisation process went to completion. During this change, some of the iron was possibly still in the form of amorphous iron hydroxide. The iron from the FeOOH may have been reduced and used in the formation of early chlorite. This sequence of events is suggested where authigenic chlorite has formed in juxtaposition with hematised biotite (Figure 17). Since oxidizing conditions presumably resumed at the telogenetic stage of diagenesis, some late hematite pseudomorphing of biotite may have occurred. The rate of late replacement may have been relatively slow due to the loss of fluid permeability during diagenesis.

Calcite is seen in trace amounts in most of the Foula thin sections. However, in one thin section, calcite cement makes up 7 percent of the rock. This calcite filled most of the pore space and partially replaced quartz, feldspar, and metastable constituents. The fact that the calcite is later than quartz and feldspar overgrowths, illite dust rims, and hematite pseudomorphs after biotite in the thin sections suggests that the calcite was a middle to late phase of early diagenesis.

The late stages of diagenesis (mesogenetic and telogenetic) included:

1) Dissolution of feldspar

2) Growth of authigenic illite

3) Replacement of illite by hematite

4) Growth of authigenic kaolinite

5) Compaction resulting in fractures, microfaults,

grain cataclaysis, and boehm lamellae growth

6) Precipitation of illite in fractures

7) Lining of fractures with hematite

One of the most interesting relationships between a detrital constituent and its diagenetic replacement minerals is found between feldspar, authigenic illite and authigenic hematite. Four of the relationships seen in thin section follow:

1) Authigenic illite has replaced feldspar along cleavage planes in two directions and feldspar has partially dissolved (Figure 18).

2) Authigenic illite with a slight hematite stain is oriented in two directions in a pore space (Figure 19).

3) Authigenic illite and authigenic hematite is oriented in the same two directions in the same pore space (Figure 20).

4) Authigenic hematite is oriented in two directions in a pore space (Figure 21).

There are two working hypotheses as to how the feldspar, authigenic illite, and authigenic hematite relate to one another.

The first hypothesis is that during burial of the sediments, a reducing environment caused iron-rich authigenic illite to partially replace feldspars. This illite replaced the feldspars parallel to the feldspar cleavage of illite seen in thin section. Then the feldspar dissolved away leaving relatively unstable trioctahedral

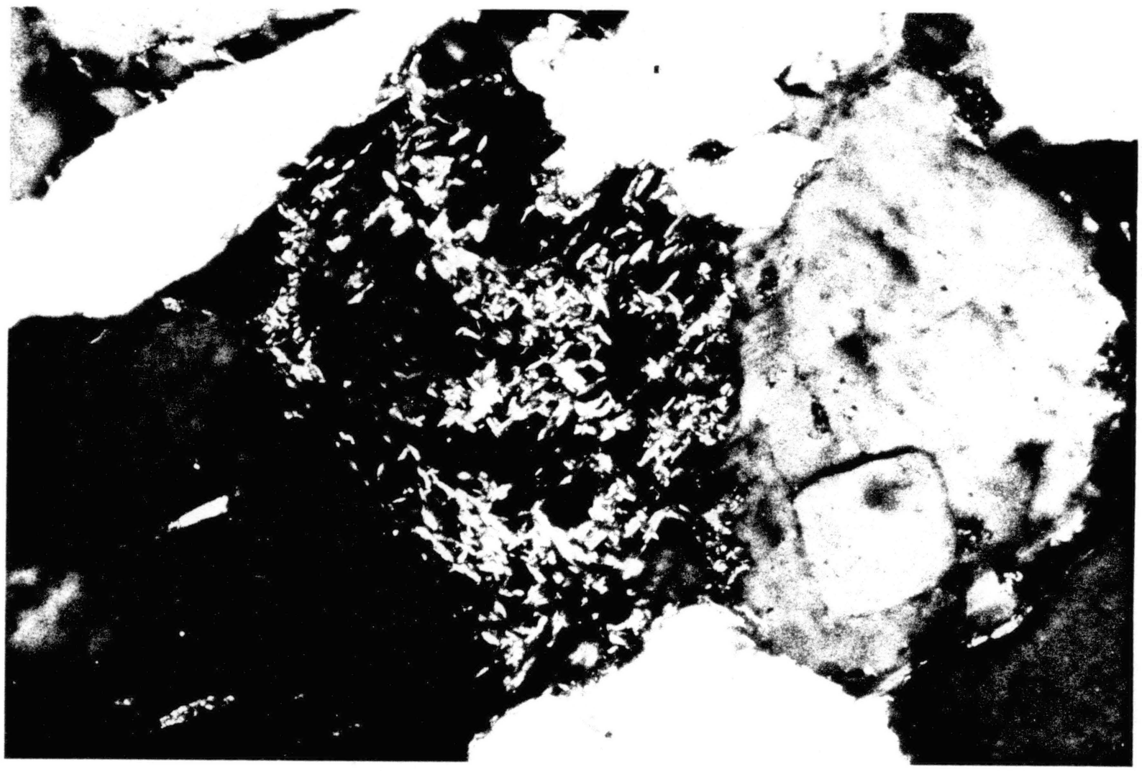

Figure 18. Photomicrograph of Illite in Feldspar (200X, XN)

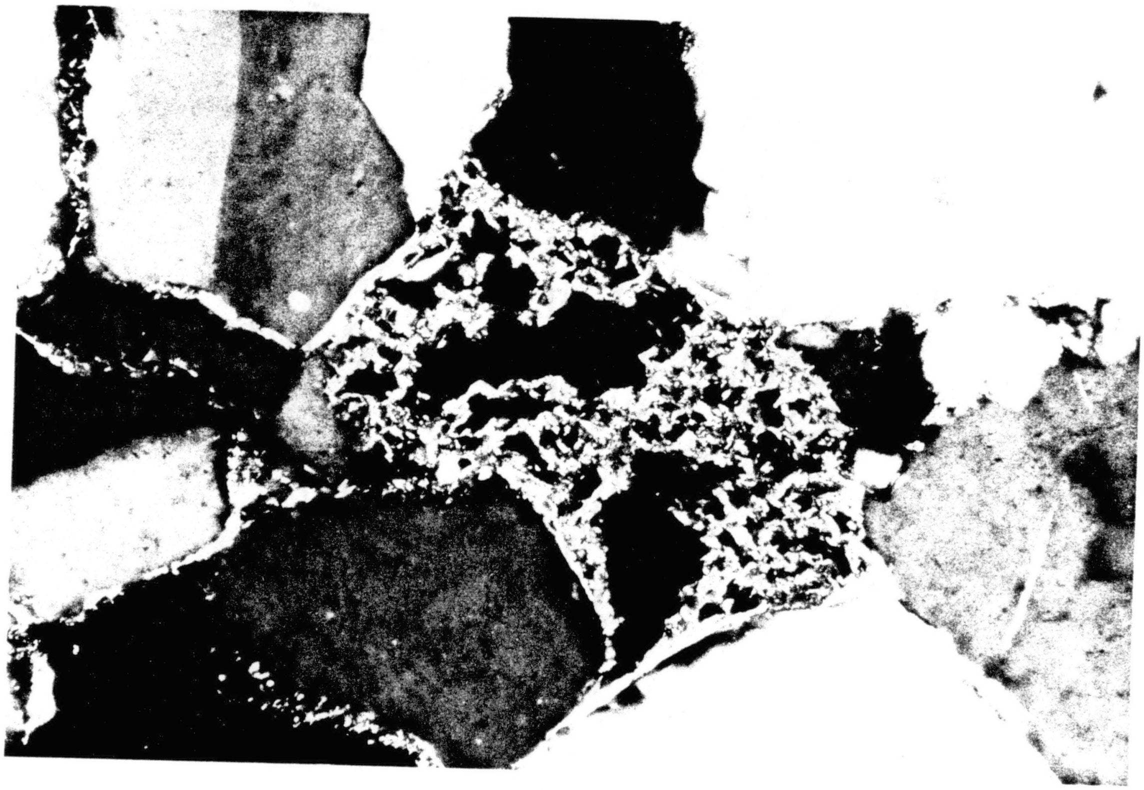

Figure 19. Photomicrograph of Hematite Stained Illite in Feldspar (200X, XN)

Figure 20. Photomicrograph of Hematite and Illite in the Same Pore Space (200X, PPL-top, XN-bottom)

Figure 21. Photomicrograph of Hematite in a Pore Space (200X, PPL)

illite in the pore space. When oxidizing conditions resumed in the telogenetic stage of diagenesis, authigenic hematite began to replace the illite. This hematite precipitated on and replaced the illite, inheriting the criss-cross pattern. Iron present in pore waters and in the authigenic illite probably contributed to the authigenic hematite. Incomplete feldspar illite and illite hematite phases may have resulted from permeability changes that isolated certain pore spaces during diagenesis.

The second hypothesis suggests that some replacement of feldspar by authigenic illite occurred along feldspar cleavage planes during burial. Later, when oxidizing conditions prevailed, hematite replacement occured along feldspar cleavage planes. Then the feldspar dissolved leaving both hematite and illite oriented in a criss-cross pattern in the pore space. Although both hypotheses may apply to the actual events that took place, the author favors the first explanation.

The author favors this explanation because of the nature in which illite and hematite are normally precipitated. Illite commonly replaces feldspars along cleavages planes. Hematite is most often seen as pore linings (i.e., grain coatings). Dissolution of feldspar is not usually confined to cleavage planes, but rather, it creates irregular voids of considerable size. Therefore, if dissolution occurred prior to precipitation of hematite, we would expect hematite to be lining the irregular voids, but not in a geometric pattern.

Kaolinite is a minor authigenic clay that formed in about half of the samples studied. It occurred primarily as a replacement mineral of feldspars and (to a lesser extent) as a pore filling.

Late compressional and tensional stresses resulted in microfaults, fractures, grain cataclaysis, and boehm lamellae. Late authigenic or remobilized hematite is seen lining some of the fractures while an occasional chert-filled fracture indicates a minor silica precipitate. The sandstones nearest the unconformity in eastern Foula have been affected the most by the tectonic events. The textural maturity and sorting of the Foula sandstones increases away from the unconformity suggesting that the greatest amount of stress was near the unconformity.

This stress may have resulted from the folding of the Foula rocks into a gentle syncline. In this case, flexural slip between the sedimentary rocks and the metamorphic basement rock would have tended to push the sandstones over metamorphic basement (Figure 22). Such flexural slip may have occurred along shale beds in the lower part of the sequence. Other flexural slip may have developed minor faulting along parts of the sandstone-metamorphic rock contact. The stress may also have resulted from a more extensive faulting along the sandstone-metamorphic contact in eastern Foula.

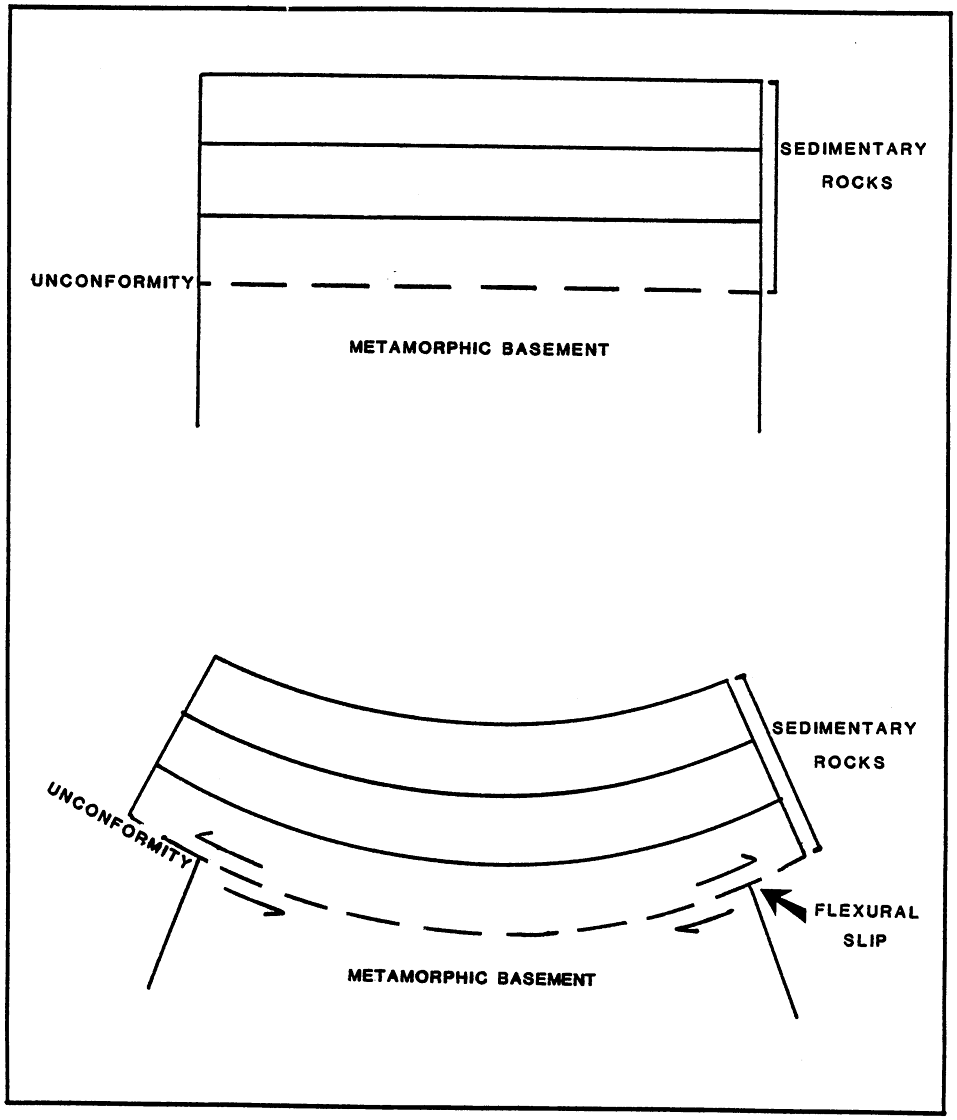

Figure 22. Schematic Diagram of Flexural Slip

Porosity

Seven whole rock samples were measured for porosity and permeability. These measurements together with the estimated thin section porosities are found in Table II (Donovan, pers. comm.). This table gives a rough estimate of what the reservoir qualities would be assuming that the permeability and porosity of each sample is representative of seperate reservoir conditions (Levorsen, 1967).

All twenty-two thin sections were analyzed for porosity evolution. Both primary and secondary porosity are prominent in the samples. Only three samples have greater than 3 percent primary porosity indicating that in most samples the primary porosity was reduced significantly during diagenesis. Compaction and authigenic cements are the major contributers to the loss of primary porosity. However, in one sample at the top of the sequence, 15 percent of the primary intergranular porosity is preserved. It appears that the iron-stained illite grain coatings were effective in inhibiting quartz overgrowths. Such overgrowths grew only where there was a break in the clay coatings (Figure 23). Generally it is clear that only one of several quartz grains adjacent to a pore space had such a break. In some cases, this situation resulted in the overgrowth of this grain filling the entire pore space.

Nine of the samples have greater than 3 percent secondary porosity. The major types of secondary porosity present are fracture porosity, intragranular porosity, and

TABLE II

POROSITY AND PERMEABILITY OF SANDSTONES ON FOULA, WESTERN SHETLAND (AFTER DONOVAN, UNPUBLISHED)

SAMPLE NO.- LOCALITY	PERMEABILITY (Millidarcys) Ka	PERMEABILITY (Millidarcys) Kl	HELIUM POROSITY (Percent)	RESERVOIR QUALITY
EF 9	0.34	0.21	8.8	POOR
EF 12	0.24	0.17	6.0	POOR
EF 15	0.079	0.050	5.0	POOR
EF 18	1.11	0.80	13.6	FAIR
EF 19	0.24	0.15	7.2	POOR
EF 22	74	64	16.0	GOOD
EF 33	0.044	0.020	2.8	POOR

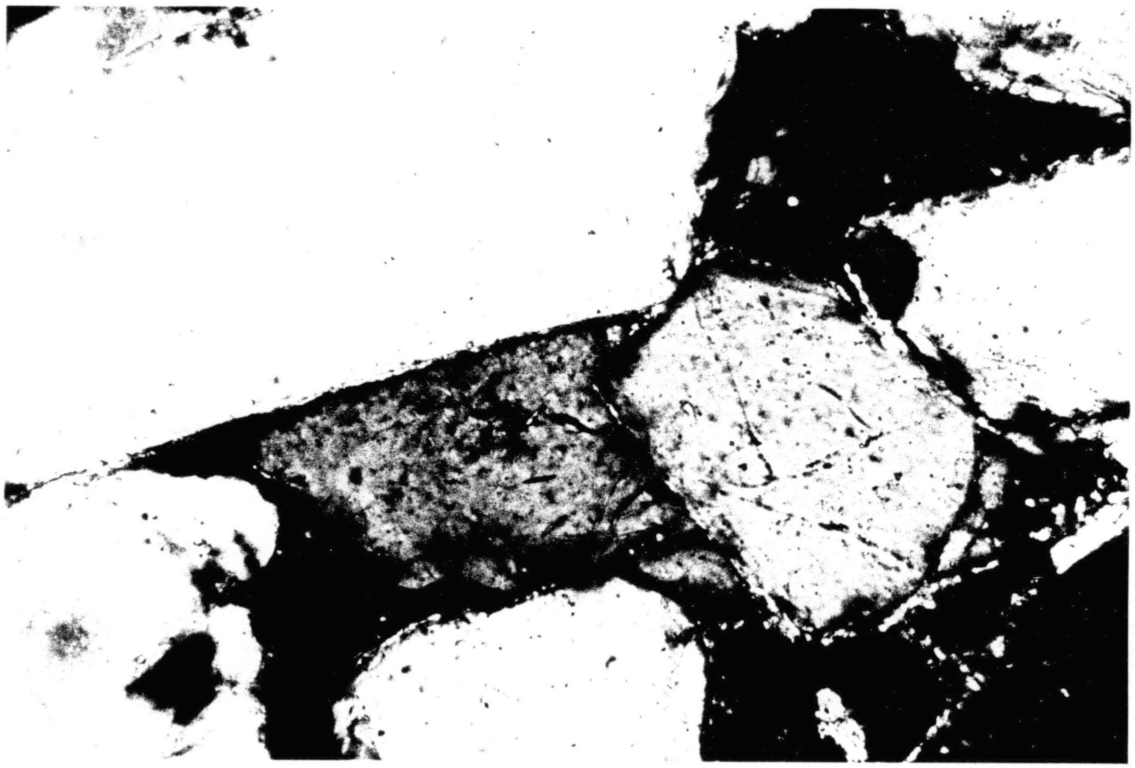

Figure 23. Photomicrograph of Quartz Overgrowth where Clay Coat is Absent (200X, XN)

moldic porosity. The fracture porosity is concentrated in the lower part of the sequence near the sandstone-metamorphic rock contact. Most of the pre-existing porosity was probably destroyed by tectonic events before or during the formation of the fracture porosity. Intragranular and moldic porosity resulted primarily from dissolution of feldspars and other metastable constituents. A few quartz grains also show signs of partial dissolution. Although secondary porosity is more abundant than primary porosity in most samples, secondary porosity does not exceed 10 percent in the samples studied. The occasional preservation of greater than 10 percent primary porosity would be more desirable than the common development of less than 10 percent secondary porosity in consideration of these rocks as oil or gas reservoirs.

Conclusions

The fluvial sandstones of Foula have been affected by their early exposure to oxidizing conditions. These conditions allowed for early hematisation of biotite and early precipitation of hematite from ground waters. The lack of organic material also favored the formation and preservation of hematite in the sediments (Tucker, 1981). Rare transgressions of lake waters may have resulted in temporary reducing conditions for some of the Foula sands during deposition. These sandstones are characterized by relatively abundant chlorite and unaltered biotite.

The Foula sandstones, before dissolution of feldspars and other grains, were probably more arkosic. Hematised biotite present in the samples suggests that the original sediments were biotite-rich. Diagenetic alteration of the feldspar, biotite, and possibly other ferromagnesian minerals may have made the most significant contribution to chemical changes in minerology of the Foula sediments.

The most intense physical alteration of the Foula sandstones occured during the late stages of diagenesis. This alteration, most intense nearest the sandstone-metamorphic rock contact, changed moderately well sorted, submature sandstones into very poorly sorted, immature sandstones. The strain may have resulted from folding and/or faulting.

The porosities preserved in the samples studied include primary and secondary porosity. Although secondary porosity is most common, the highest porosity and permeability was found in a sample where porosity is almost entirely primary.

CHAPTER III

PETROLOGY AND DIAGENESIS OF THE MELBY AREA

Introduction

Mykura (1976) thoroughly described the location, geologic setting, and depositional environment of the Melby Formation. The following three sections are summaries based on his interpretation.

Location

The rocks belonging to the Melby Formation are located in the north-west portion of the Walls Peninsula of the Shetland Islands (Figure 24). This formation outcrops over an area of about one square mile (2.6km) and is separated from the rest of the peninsula by the north-east trending Melby Fault. The samples studied were taken from a north-western coastal exposure between Foglabanks and Humabery. Samples are either stratigraphically below or between the Melby fish beds.

General Geology

The Melby Formation is part of the Middle Old Red Sandstone that outcrops west and north-west of the Melby

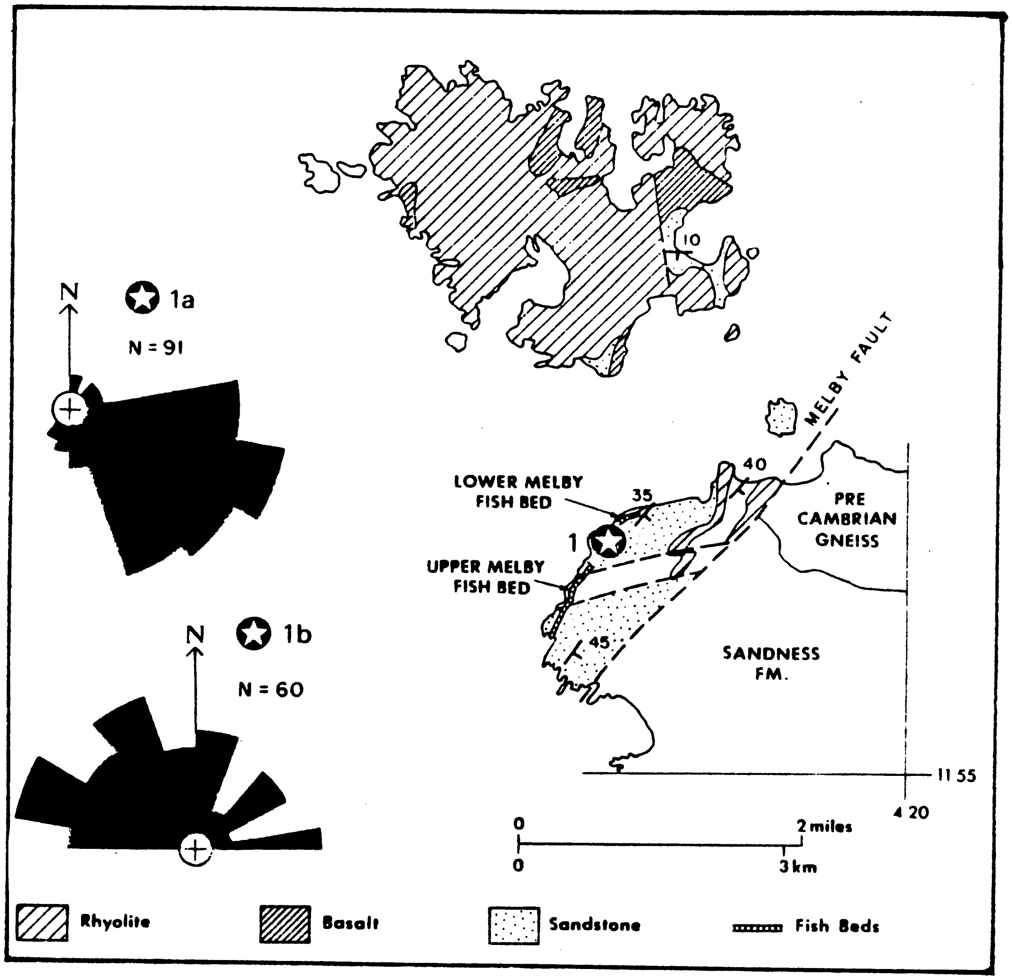

Figure 24. Melby Area of the Walls Peninsula of the Shetland Islands (from Donovan, unpublished)

Fault. It consists of a 2500ft (760m) thick exposure of predominantly fluvial sandstone with two lake fish beds in the lower part of the formation and two groups of rhyolite flows in the upper part. The Melby fish beds have been roughly correlated with the Achanarras horizon of Caithness and the Stromness Beds of Orkney. The two rhyolite groups are thought to be equivalent to the rhyolites of Papa Stour, and the Melby sandstones are thought to be stratigraphically below the Papa Stour volcanics (Finlay, 1930, Knox, 1934).

The Melby Fault separates the Melby Formation from the rest of the Walls Peninsula. The fault is exposed near the southern most portion of the Melby outcrop as a reverse fault which is inclined at 60-70 degrees toward the south-east. However, Mykura (1976) has found evidence which suggests that the Melby Fault is a strike-slip fault with substantial dextral displacement.

Environment of Deposition

Most of the sediments comprising the Melby Formation were laid down by braided rivers. The sandstones below the Upper Melby Fish Bed have mostly planar cross-beds that indicate an east-south-east flow direction. The fish beds in this portion of the formation may have formed as a result of two major lake transgressions. The possible correlation of these fish beds with those of Orkney and Caithness suggests that the fish beds may have been deposited in an extensive though fluctuating lake which filled much of the Orcadian Basin. This interpretation suggests that the deposits found below the Upper Melby Fish Beds were laid down near the north-western margin of the Orcadian Basin.

There are two major differences between the sediments that are stratigraphically below the Melby Fish Beds and those that are stratigraphically higher:

1) The higher beds contain pebbly beds with clasts of lava, siltstone, and coaly plant material. These materials are absent in the lower beds.

2) Cross bedding in the higher beds indicates that sediments were laid down by rivers that flowed west-south-west while cross-bedding in the lower beds indicates that sediments were laid down by rivers that flowed east-south-east.

The change in current direction and material transported may have resulted from a change in topography due to volcanism and associated earth movements.

Sedimentary Petrology

Fifteen sandstone samples were collected between Foglabanks and Humabery near the north-western shorline of the Walls Peninsula. All of the samples were collected either stratigraphically below or between the Melby fish beds.

Textures

The samples are texturally submature to immature sandstones that consist of moderately well to poorly sorted grains (Folk 1974, Pettijohn et al., 1972). All of the immature sandstones consist of grains no larger than very fine sand. The submature sandstones consist of grain sizes ranging from very fine to very coarse sand. The angularity of the grains ranges from angular to rounded with the majority of the grains being subangular to subrounded.

Mineralogy

Middle Old Red Sandstone lithologies are primarily subarkoses, lithic arkoses, and arkoses (Figure 25). The mineralogy of the detrital grains indicates an igneous and metamorphic source rock.

Quartz. Quartz is the major constituent and on the average it makes up 48 percent of the rock volume with 1 percent being polycrystalline. The grains in about half of the samples show mostly straight to slight (less than 5 degrees) undulose extinction while the grains in the other half of the samples show mostly straight to moderate (more than 5 degrees) undulose extinction. Stratigraphically, the samples containing grains of moderate undulosity are interspersed among the other samples. Therefore, the amount of undulosity observed in the grains appears to be a function of source rock variation rather than post-

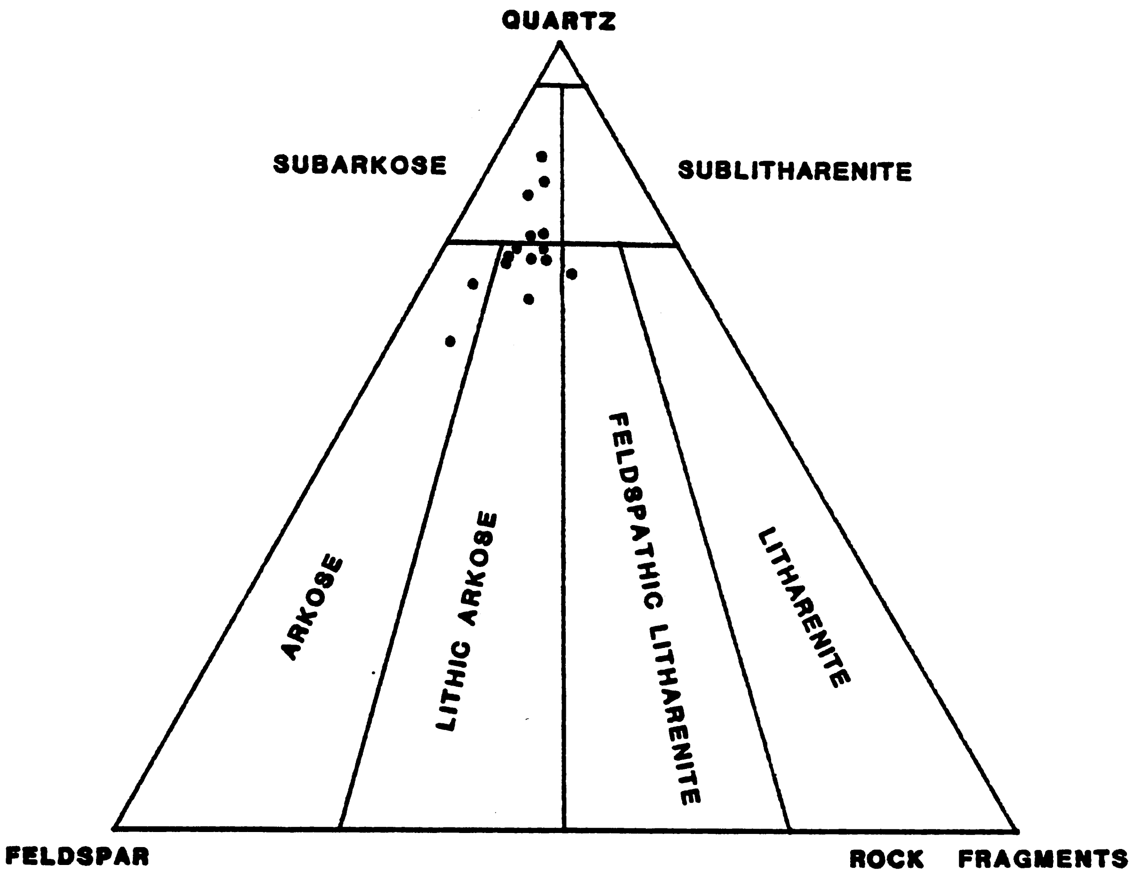

Figure 25. Classification of Sandstones from Melby (Diagram after Folk, 1976)

depositional tectonic activity.

Feldspar. The second major constituent is feldspar which makes up an average of 11 percent of the total volume of the samples (7 percent is orthoclase, 3 percent is plagioclase, and less than 1 percent is microcline and perthite). The grains often appear very dirty in thin section. This dirty appearance may have developed in part during the original crystallization of the grains when inclusions were being incorperated into the crystals. However, the abundance of partial dissolution features and authigenic illite suggests that the diagenetic alteration of the feldspars may be equally responsible for the dirty appearance. Many of the grains have been partially or completely replaced by calcite.

Rock Fragments. Rock fragments average 6 percent of the samples (5 percent are metamorphic). Metaquartzite and gneiss are common metamorphic rock fragments; phyllite is seen in trace amounts. Traces of Chert are seen in most of the samples. Traces of plutonic and volcanic rock fragments are seen in only on sample.

Other Constituents. Grains other than quartz, feldspar, and rock fragments average 6 percent of the samples. Biotite and muscovite average two and 3 percent respectively. The original amount of biotite was closer to 3 percent before diagenetic hematisation of biotite flakes took place. In one thin section detrital hematite makes up

4 percent of the total volume of rock, but on the average it contributes less than 1 percent. The detrital hematite grains occur mainly as subrounded sand grains that appear black under reflected light. Other grains that occur in trace amounts are pyrite, zircon, apatite, rutile, blue tourmaline, chlorite, glauconite, and carbonate ooids. The ooids may have been derived from reworked lake sediments. Detrital matrix, which is composed mainly of illite, chlorite, and quartz, averages 7 percent of the total volume of rock.

Diagenetic constituents average 17 percent of the samples studied. Calcite, the major diagenetic constituent, ranges from 0 to 26 percent and averages 8 percent of the samples. Calcite occurs as a pore-filling and grain-replacing cement. Three other major diagenetic constituents, each averaging from one to 4 percent of each sample include:

1) Quartz as overgrowths

2) Hematite as grain coatings, pore linings, and pseudomorphs of biotite

3) Authigenic illite as grain coatings, pore linings, pore fillings, and grain replacement

Diagenetic constituents averaging less than 1 percent of each sample include:

1) Feldspar as overgrowths

2) Leucoxene as a replacement mineral

3) Authigenic kaolinite as a replacement mineral

4) Authigenic chlorite as radial pore linings

Porosity averages 3 percent of the samples; less than 1 percent is primary and 3 percent is secondary.

Diagenesis

Thin section analysis has revealed some convincing evidence of the paragenetic sequence. Although some variations in paragenesis can be detected within a particular sandstone unit or among several units, the "general paragenetic sequence" that has been derived is applicable to all of the samples from the Melby area (Figure 26). The phrase, "general paragenetic sequence", implies that if two events occurred under different conditions but at the same time, then both events will be represented in the sequence as occurring relatively simultaneously.

The early stages of diagenesis (eogenetic and early mesogenetic) included:

1) Compaction resulting in bending and squeezing of ductile grains

2) Authigenic illite growth

3) Quartz overgrowths

4) Feldspar overgrowths

5) Hematite as grain coatings

6) Hematite formation as pseudomorphs of biotite

7) Authigenic chlorite growth

8) Partial dissolution of metastable constituents,and

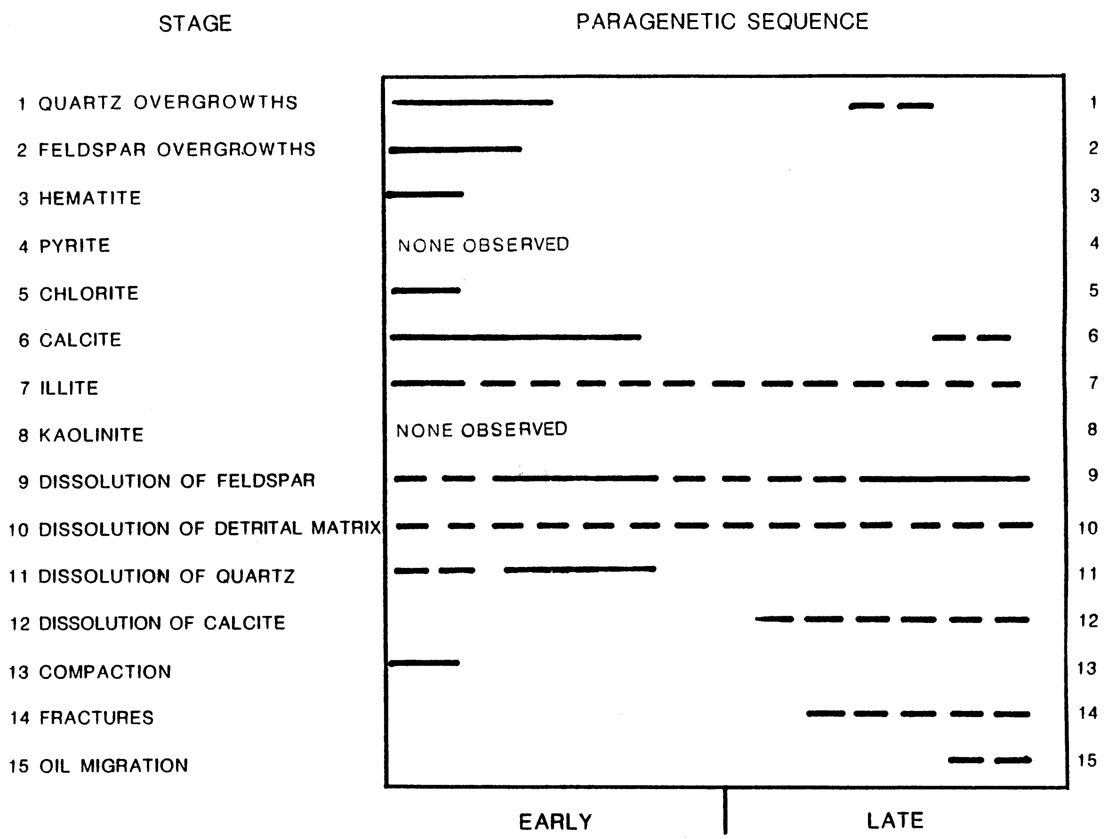

Figure 26. Paragenetic Sequence of Sandstones from Melby

9) Very early calcite cementation resulting in partial dissolution of all other constituents.

Dust rims of authigenic and detrital illite (some of which are iron stained) suggest that one of the earliest events to take place was infiltration of detrital illite into pores. Infiltration occurred together with partial dissolution of metastable constituents and precipitation or remobilization of ferric iron. The early dissolution of metastable constituents may have resulted from compaction.

Syntaxial quartz overgrowths are present in most of the samples. Evidence of quartz overgrowths includes authigenic or detrital clay dust rims and long straight contacts between quartz grains. The absence of dust rims in some samples suggests that the quartz overgrowths were very early. The presence of authigenic clay dust rims suggests that the overgrowths also occurred later.

The relationships among biotite, muscovite, authigenic hematite, and calcite are perhaps the most useful relationships in determining if biotite was a major contributer to authigenic hematite in the samples. These relationships can also be used to help identify which sediments were deposited in areas under the influence of lake waters.

Turner and Archer (1977) studied the Old Red Sandstone in Scotland and found that biotite was a potential source of hematite pigment. The presence of hematite pseudomorphs after biotite in the Melby samples leaves little doubt that some hematite was derived from diagenetic alteration of biotite. The process of hematisation of biotite is discussed in detail in the chapter on Foula (this thesis).

We might ask ourselves, "Does the amount of authigenic hematite found in the samples studied bear any relationship to the original amount of biotite that was present in the sediments?". In order to answer this question, we need a mechanism for estimating the original amount of biotite that was present in each sample. Then we need to make comparisons of the original amount of biotite to the present amount of hematite.

Ten biotite-rich samples (biotite>1%>hematite) were used to plot percent biotite against percent muscovite (which is relatively stable)(Figure 27). The graph shows that there is more or less a one to one relationship between the two micas. This suggests that the original amount of biotite that is or was present in each sample can be estimated from the present amount of muscovite in each sample. Five hematite-rich samples (hematite>1%>biotite) were used to plot percent authigenic hematite against the estimated original percent biotite. The graph shows that the ratio of original percent biotite to percent authigenic hematite is about one to three. This ratio suggests that on the average each percent of biotite may contribute 3 percent authigenic hematite. However, close observation of the graph shows that there is a considerable scatter of the five data points suggesting that the ratio of one to three

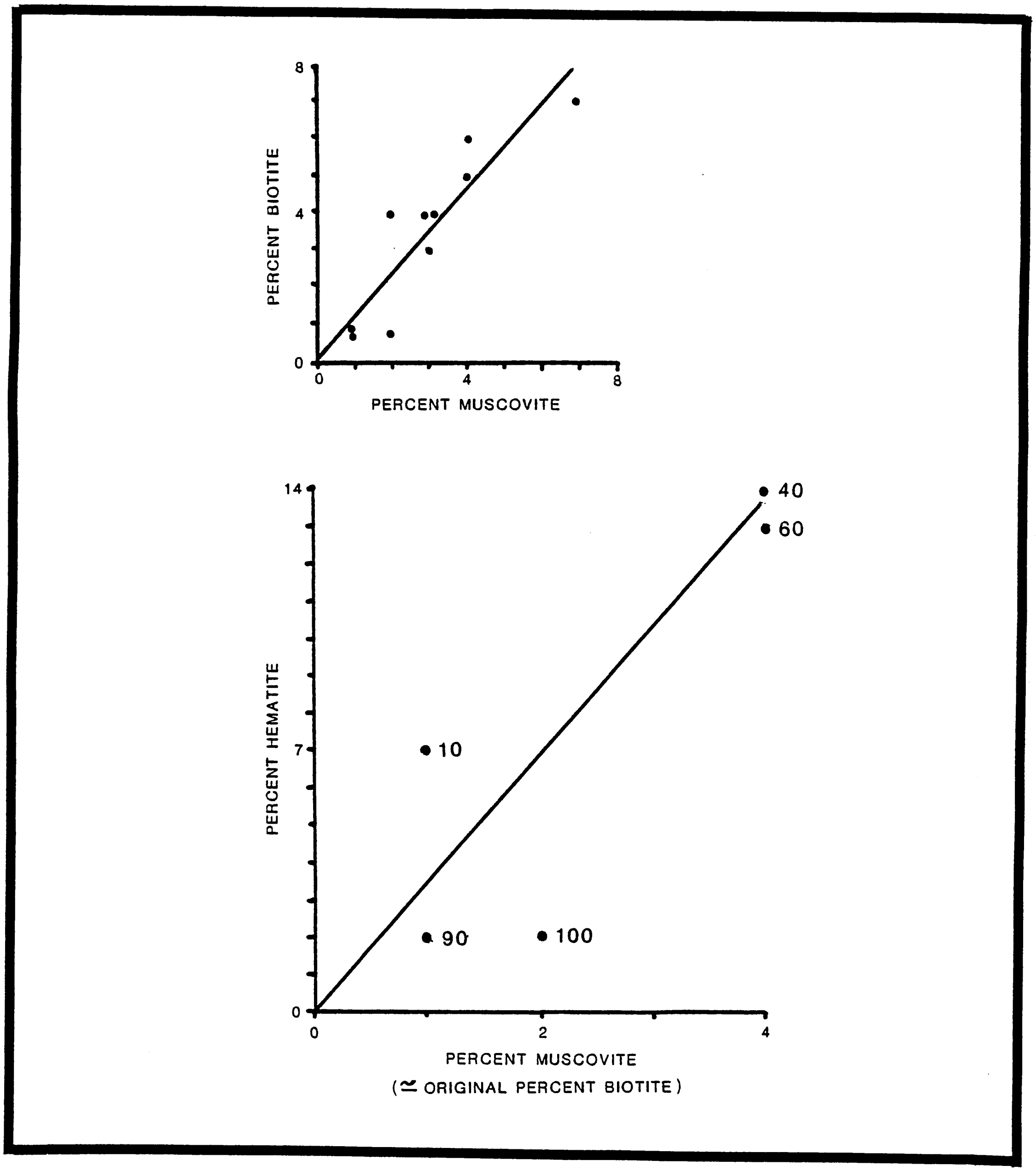

Figure 27. Relationship of Percent Muscovite to Percent Biotite, and of Estimated Percent Original Biotite to Percent Authigenic Hematite (Values Next to Data Points are Approximately Equal to the Percent Authigenic Hematite that Occurs as Pseudomorphs of Biotite)

is only a rough approximation. In samples where hematite pseudomorphs of biotite are dominant, the ratio of biotite to authigenic hematite approaches one to one. In samples where hematite grain coatings are dominant, the ratio of biotite to authigenic hematite approaches one to seven. In general, the two graphs show that in the hematite-rich samples, with an increase in original amount of biotite, there is an increase in amount of authigenic hematite. Therefore, it is quite possible that there is a more or less a direct relationship between the authigenic hematite found in the hematite-rich samples studied and the original amount of biotite that was present.

The hematite grain coatings appear to be one of the earliest diagenetic events to have taken place. In one sample authigenic grain-coating hematite is seen associated with a partially pseudomorphed biotite grain (Figure 28). This relationship suggests that the oxidation of biotite may result in both grain coating and biotite pseudomorphing authigenic hematite. It has been postulated that the occurrence of early grain-coating authigenic hematite is suggestive of a more or less arid continental environment (Folk, 1976). In the Melby area the presence of such hematite in fluvial sandstones may be related to a semi-arid environment.

Calcite appears to have greatly influenced the diagenesis of the samples in which it occurs. Where the original calcite is preserved, its displacive nature

Figure 28. Photomicrograph of Partially Pseudomorphed Biotite Contributing to a Hematite Coating (200X, PPL)

suggests that it is very early. This very early calcite is thought to have been precipitated from ground waters of lacustrine origin. Calcite averages 11 percent in the biotite-rich samples and only 1 percent in the hematite-rich samples. Therefore, calcite may have played an important role in the preservation of biotite.

If lake-related groundwaters were of a reducing character, then the biotite would not be altered to hematite. The early calcite cement would have reduced the porosity and permeability to trace amounts, thus preserving the biotite until dissolution of calcite followed by oxidizing conditions occurred.

Authigenic chlorite is usually present in trace amounts, but in one example it makes up 5 percent of the total rock volume. It precipitated after an incomplete oxidation stage of biotite as evidenced by radial chlorite forming on iron stained grains (Figure 29). Some of the iron from the biotite may have been used in the formation of chlorite under locally neutral to reducing conditions. The chlorite is accompanied by radial authigenic illite. Together, the two clays lined and filled much of the primary pore spaces. Quartz overgrowths formed where breaks in the clay coats occurred (Figure 30).

The late stages of diagenesis (mesogenetic and telogenetic) included:

1) Authigenic illite growth

2) Dissolution of feldspar and detrital matrix

Figure 29. Photomicrograph of Radial Chlorite on Iron Stained Detrital Grains (100X, PPL)

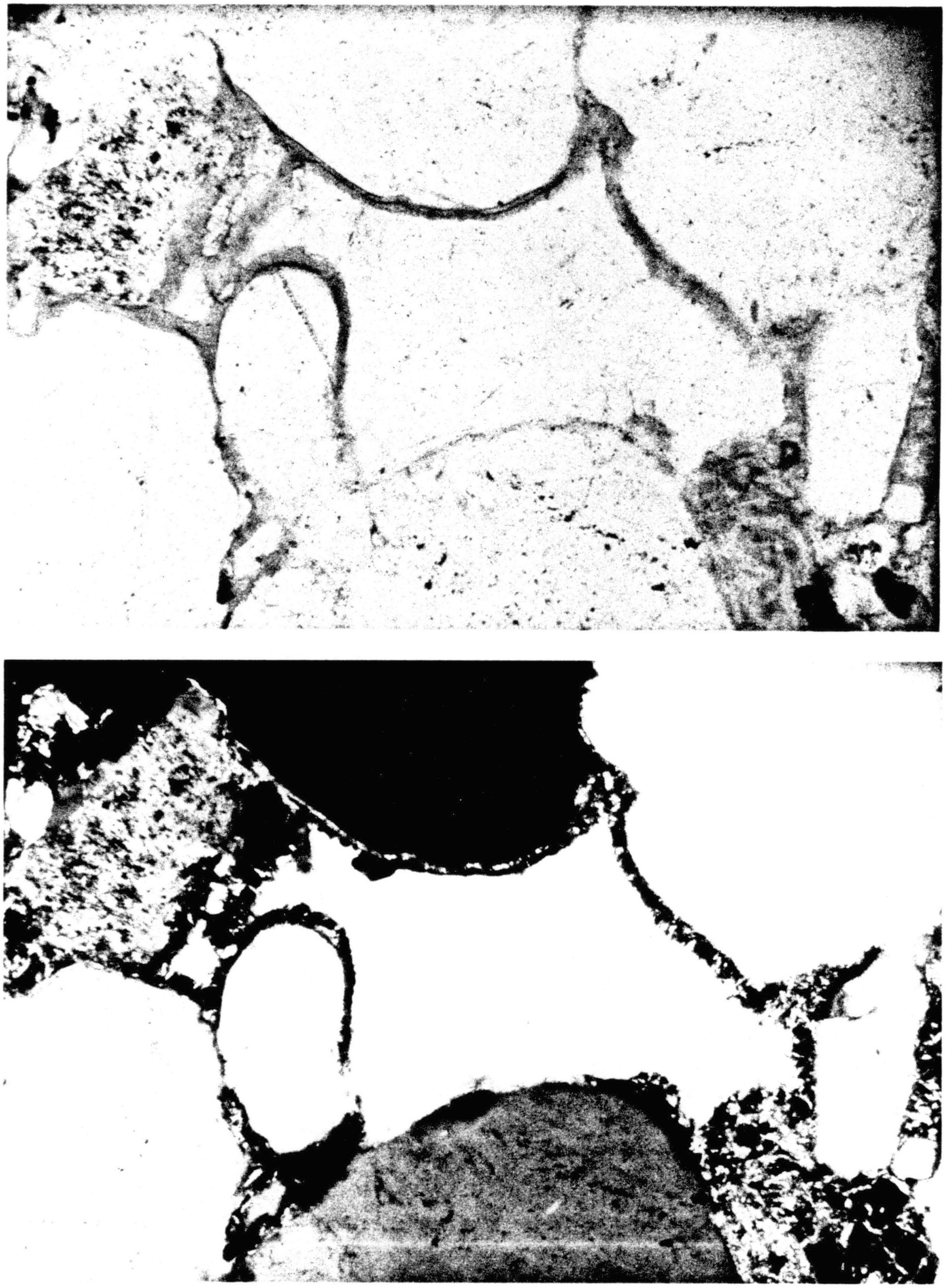

Figure 30. Photomicrograph of Quartz Overgrowth where Break in Clay Coating Occurred (100X, PPL-top, XN-bottom)

3) Dissolution of calcite

4) Fracturing followed by late stage precipitation of quartz and calcite

5) Migration of hydrocarbons

The authigenic illite occurs mainly as a grain replacement mineral of feldspars and detrital matrix. The authigenic illite, being isolated in the feldspar grains and in the detrital matrix without any other evidence of alteration of the two constituents, makes it difficult to classify the illite as being early or late. Therefore, illite may be both early and late, forming whenever conditions are suitable for its growth.

Partial dissolution of calcite is seen in some thin sections resulting in minor secondary porosity. Dissolution of feldspar and detrital matrix are also thought to have contributed in part to the development of secondary porosity.

There is evidence of minor late fracturing followed by precipitation of quartz overgrowths, calcite cement, migration of oil, rejuvenation of the fracture, and partial dissolution of the calcite (Figure 31). Although there is only one occurrence of this type in the samples studied, other fracturing followed by similar diagenetic events may have occurred elsewhere in the Melby area.

Porosity

Five whole rock samples were measured for porosity and

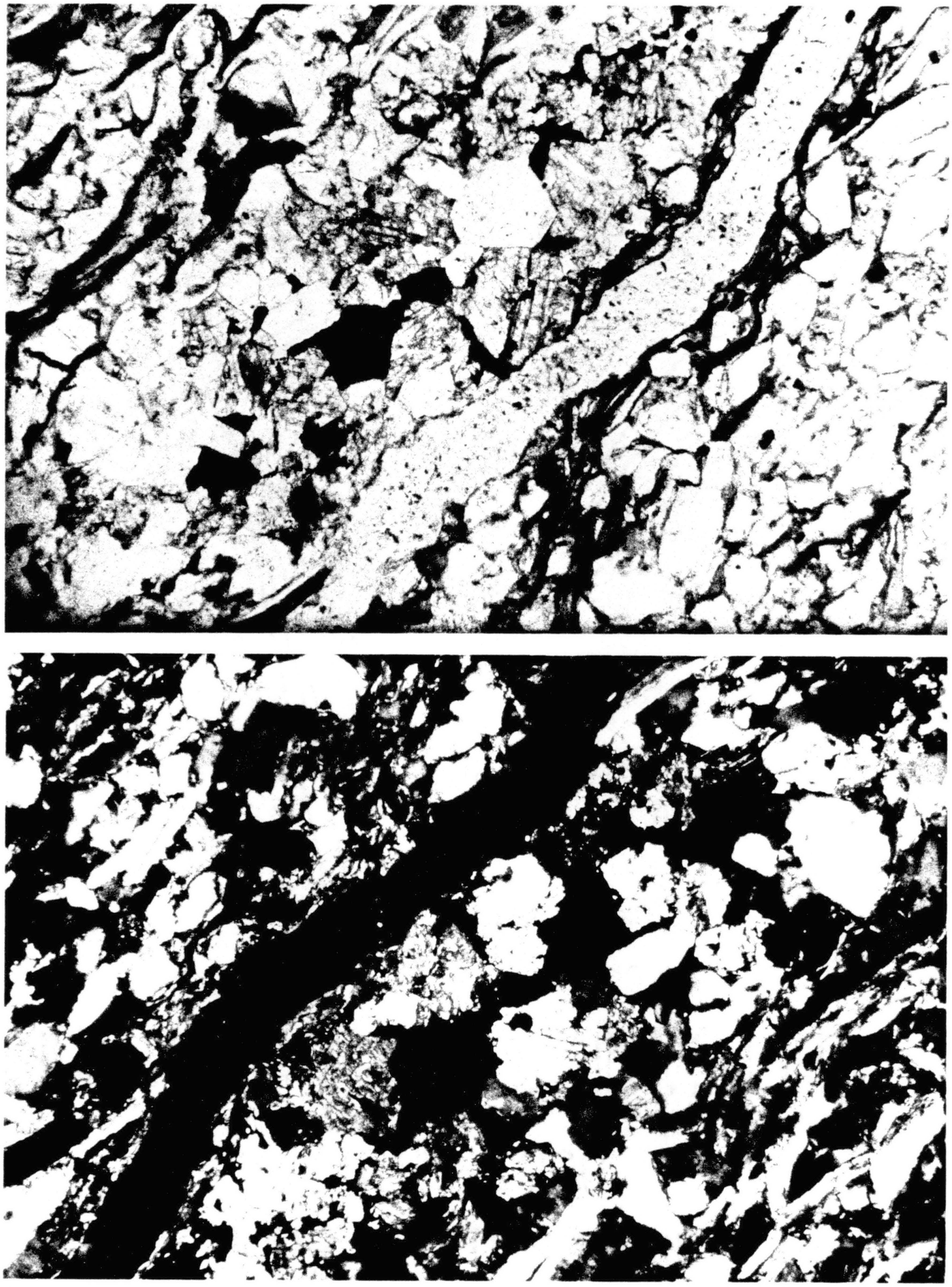

Figure 31. Photomicrograph of Quartz, Calcite, and Residual Hydrocarbons in a Fracture (100X, PPL-top, XN-bottom)

permeability. These measurements together with the estimated thin section porosities are found in Table III (Donovan, pers. comm.). This table gives a rough estimate of what the reservoir qualities would be assuming that the permeability and porosity of each sample is representative of separate reservoir conditions (Levorsen, 1967).

All fifteen thin sections were analysed for porosity evolution. Excluding one sample, the average primary porosity found in thin sections was less than 1 percent. Early calcite cement is the major contributer to the loss of primary porosity in nearly half of the samples studied. Compaction of ductile grains and detrital matrix significantly reduced primary porosity in three samples while another three samples lost much of their primary porosity as a result of quartz overgrowths. On the whole, authigenic clays played a minor role in reducing primary porosity. However, in one sample, radial, pore lining, authigenic chlorite and illite reduced the rock porosity by about 10 percent of the total rock volume. In this sample, clays completely filled many intergranular pore spaces (Figure 32), while quartz overgrowths filled in much of the remaining intergranular porosity. In the sample rich in radial, pore lining, authigenic illite, 9 percent primary porosity was preserved. This 9 percent is more than ten times the average primary porosity preserved in the other fourteen samples. The complete clay coatings preserved the primary porosity by inhibiting quartz overgrowths. Horn

TABLE III

POROSITY AND PERMEABILITY, MELBY SANDSTONES, WESTERN SHETLAND (AFTER DONOVAN, UNPUBLISHED)

SAMPLE NO.-LOCALITY	PERMEABILITY (Millidarcys) Ka	Kl	HELIUM POROSITY (Percent)	RESERVOIR QUALITY
ESH 10	2.1	1.5	10.6	FAIR
ESH 14	0.091	0.050	1.2	POOR
ESH 1	12	10	9.4	GOOD
ESH 7	0.032	0.020	2.2	POOR
ESH 8	1.5	1.0	9.6	FAIR
ESH 9	0.28	0.17	4.4	POOR

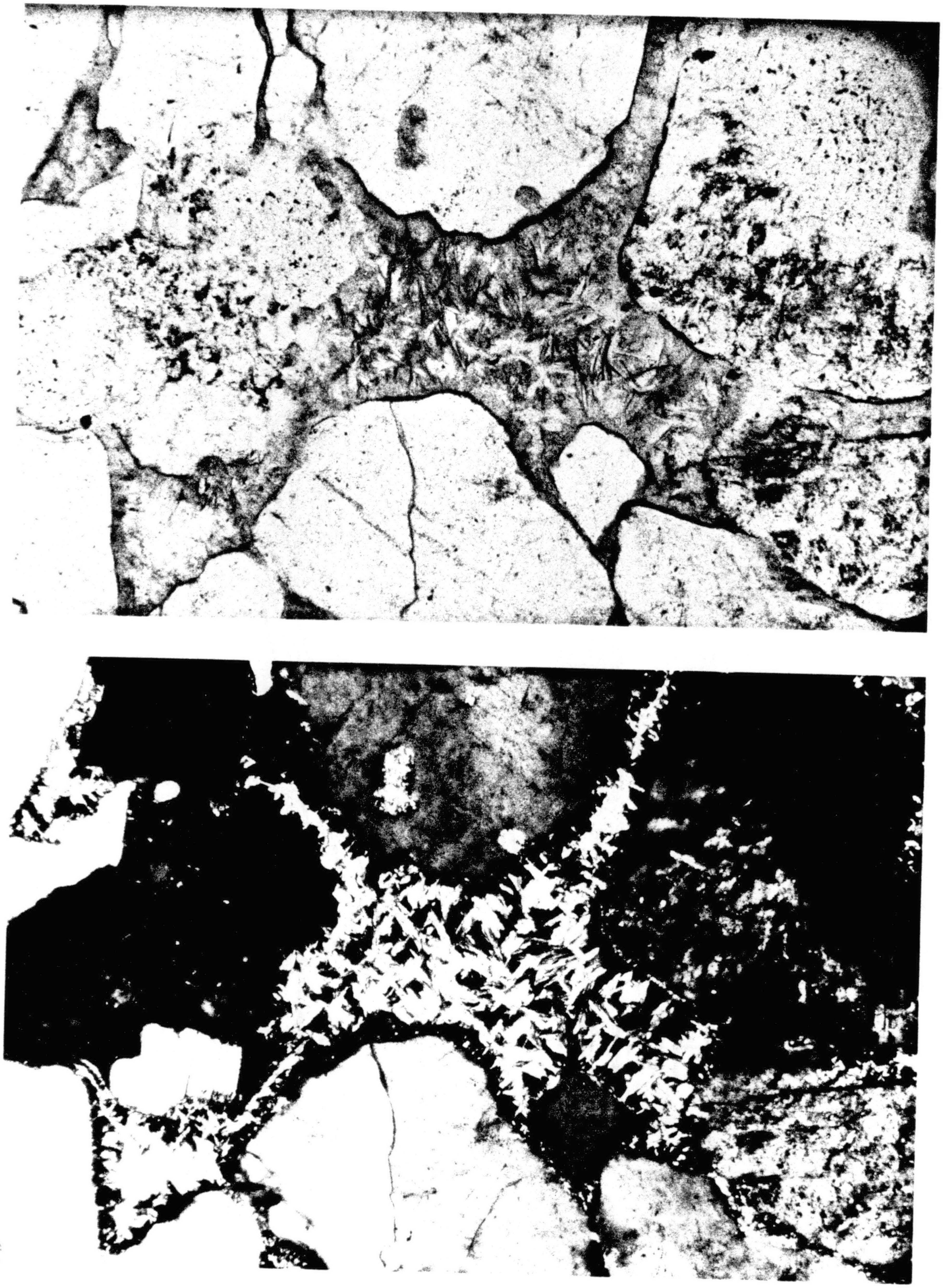

Figure 32. Photomicrograph of Chlorite and Illite Filling a Pore Space (100X, PPL-top, XN-bottom)

(1965), and Tillman and Almon (1979) also noticed the significance of complete clay coatings in the prevention of quartz overgrowths.

The major porosity type is secondary and on the average it makes up 3 percent of the total rock volume of each sample. Only four samples show greater than 5 percent secondary porosity and none show more than 10 percent. Dissolution of feldspars is the major contributer to the development of secondary pore space in the four samples. In the other eleven samples which average 1 percent secondary porosity, partial dissolution of calcite cement is the major contributer.

Conclusions

The sandstone samples studied from the Melby Formation represent primarily ancient braided streams that were frequently transgressed by lake waters. The braided streams flowed east-south-east into the north-west margin of the Orcadian Basin. Diagenetic processes lithified the stream deposits to form subarkosic to lithic arkosic sandstones derived from plutonic and metamorphic source rocks.

Early calcite cement resulting from lake water influences appears to have protected biotite grains from being influenced by oxidizing conditions. In samples where calcite cement is minor, extensive alteration of biotite in oxidizing conditions gave way to authigenic hematite as pseudomorphs of biotite and as grain coatings. The oxidation of biotite is primarily an early diagenetic event thought to be characteristic of stream deposits not influenced by lake waters. In general, it appears that the the amount of biotite present in the original sediments, correlates positively with the amount of authigenic hematite formed.

Primary porosity is dominant in only two of the fifteen thin sections studied. In both cases complete authigenic clay coats around detrital grains were in part responsible for preserving the primary porosity by inhibiting quartz overgrowths. Lack of calcite cement resulting from lake water influences also preserved primary porosity. Secondary porosity developed in part as a result of dissolution of feldspars and to a lesser extent calcite and detrital matrix. Fracture porosity, which is the least common secondary porosity in the samples studied, appears to be associated with hydrocarbon migration.

CHAPTER IV

PETROLOGY AND DIAGENESIS OF TARBAT NESS AREA

Introduction

Location

The Tarbat Peninsula is located in north-eastern Scotland and is bordered to the north-west by the Dornoch Firth and to the south-east by the Moray Firth. The Great Glen Fault strikes north-east and runs parallel to the southern coastline of the Peninsula (Figure 33).

General Geology

The major portions of the Tarbat Peninsula consists of Devonian, Middle and Upper Old Red Sandstone. The north-eastern part of the peninsula is dominated by Upper Old Red Sandstone while the underlying Middle Old Red Sandstone is outcrops in the south-eastern part. These Middle Devonian units, which belong to the Strath Rory Group, consist of 9200ft (2800m) of basal conglomerates and sandstones with interlaminated calcareous shales and thin bedded lake limestones. The basal conglomerates lay unconformably upon Precambrian Moinian basement rock (Ferraro, 1976).

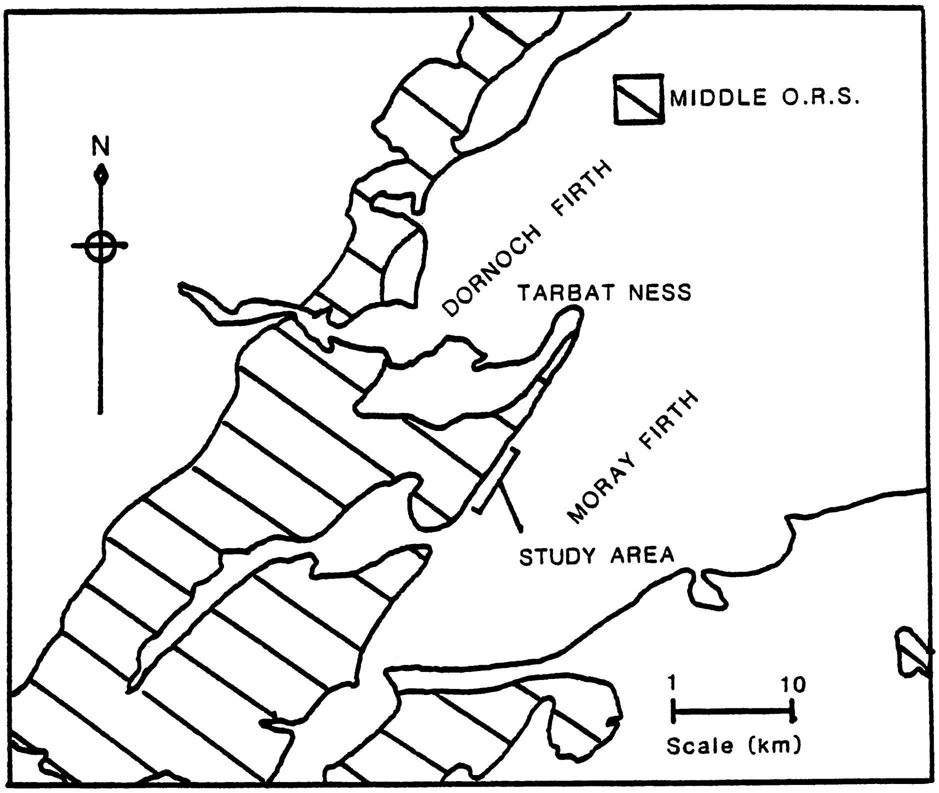

Figure 33. Tarbat Study Area on the Tarbat Peninsula

Environment of Deposition

Sediments that formed the Middle Old Red Sandstone of the Tarbat Peninsula were deposited in both fluvial and lacustrine environments located in the southern margin of the Orcadian Basin. The majority of the sediments were sands deposited by fluvial channels that flowed north into the basin. The source of these sediments was from the Grampian Highlands to the south (Donovan et al., 1976). Temporary lake transgressions are recorded as thin limestones and calcareous shales that are seen interbedded with the fluvial sandstones (Donovan, pers. comm.). The Edderton Fish Bed, an important stratigraphic marker, is located within one of the shale sequences.

Sedimentary Petrology

Thirteen sandstone samples were collected along the southern coast of the Tarbat Peninsula about 6 miles (10km) south of the northern tip of the peninsula (Figure 33). The intervals sampled include a 2100ft (650m) section of primarily fluvial sandstone with some lacustrine limestones and calcareous shales.

Textures

The majority of the samples are texturally submature sandstones with moderately-well to poorly sorted sand grains (Folk 1974, Pettijohn et at. 1972). The grains are generally angular to subangular and grain sizes range from very fine to very coarse sand with about half of the samples containing granules or pebbles. The textures throughout the samples studied are generally constant and any variations found among the samples is not related to their relative position within the 2100ft (650m) section.

Mineralogy

Middle Old Red Sandstone lithologies of Tarbat are primarily subarkoses and lithic arkoses (Figure 34). The mineralogy of the detrital grains indicates an igneous and metamorphic source rock.

Quartz. Quartz is the major constituent and on the average it makes up 47 percent of the rock volume. Most grains show straight to slightly undulose extinction (less than 5 degrees). The lack of moderate undulosity (greater than 5 degrees) may suggest that the majority of the monocrystalline quartz grains are from a plutonic sourcerock (Basu et al., 1975). The observed nonundulose grains of quartz in plutonic rock fragments also suggests a plutonic source rock.

Polycrystalline quartz grains, excluding metaquartzite, make up an average of 2 percent of the samples. These grains may be of either igneous or metamorphic origin.

Feldspar. The second major constituent is feldspar which makes up an average of 12 percent of the total rock

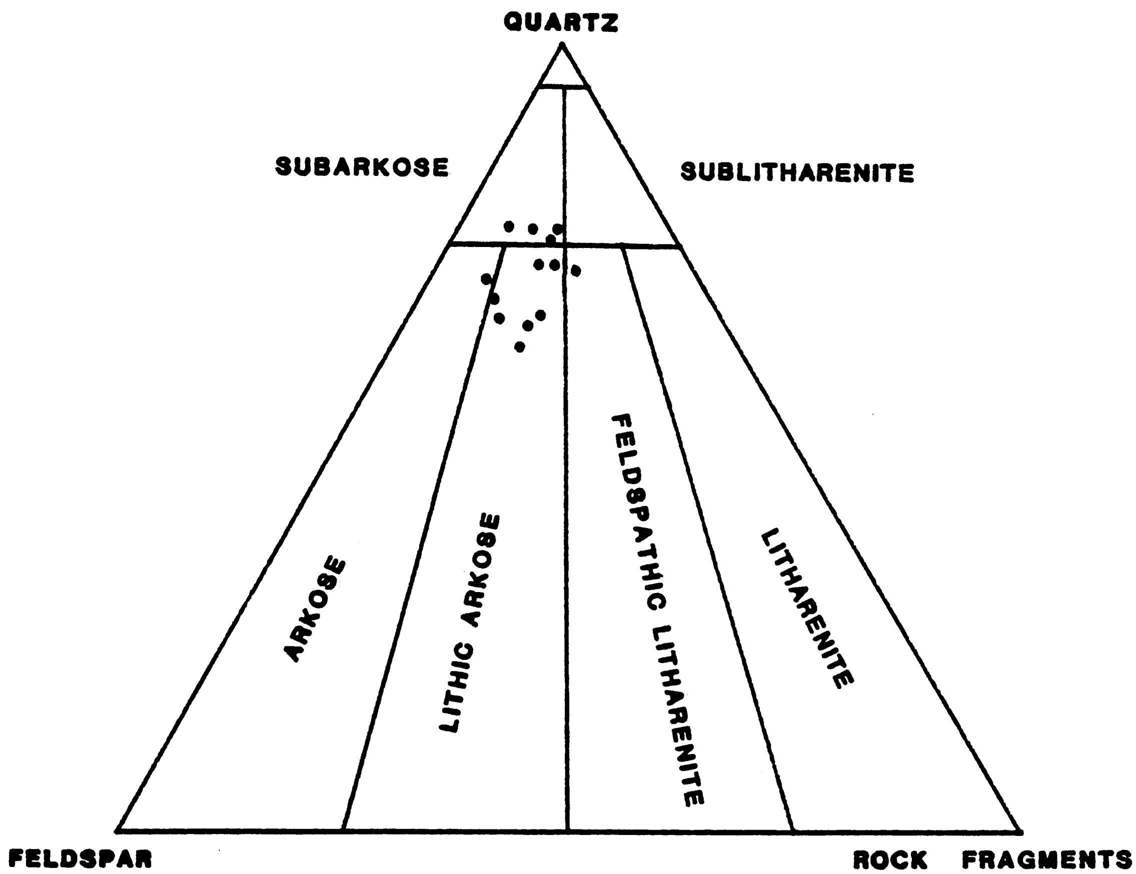

Figure 34. Classification of Sandstones from Tarbat (Diagram after Folk, 1976)

volume of the samples (8 percent is orthoclase, 2 percent is microcline, 2 percent is plagioclase, and less than 1 percent is perthite). Partial dissolution of many of the feldspars suggests that the original sediments were more arkosic.

Rock Fragments. Rock fragments make up an average of 7 percent of the total rock volume of the samples. Of this fraction, 5 percent is metamorphic rock fragments which include metaquartzite, gneiss, and phyllite. Igneous rock fragments, consisting mainly of felsite, make up 2 percent and chert fragments make up 1 percent of the total rock volume of the samples. Collectively, siltstone, carbonate, and plutonic rock fragments make up less than 1 percent of the samples.

Other Constituents. Detrital biotite and muscovite each average 1 percent of the total volume of the samples. Although some of the original biotite flakes have been pseudomorphed by hematite, the majority of the grains is still fresh. Other grains that occur in trace amounts are glauconite, pyrite, hematite, zircon, garnet, rutile, and chlorite. Detrital matrix averages 3 percent of the total rock volume of the samples. The most abundant minerals making up the detrital matrix are illite, chlorite, and quartz.

Diagenetic constituents make up an average of 20 percent of the samples. Thirteen of the 20 percent is calcite that occurs both as a pore filling, displacive cement and as a replacement mineral. Other diagenetic constituents that individually average from 1 to 2 percent include:

1) Quartz as overgrowths

2) Hematite as grain coatings, pore linings, and pseudomorphs of biotite

3) Authigenic kaolinite as pore fillings and as a replacement mineral of feldspar

4) Authigenic illite as grain coatings, pore linings, pore fillings, and grain replacement

Minor diagenetic constituents individually averaging less than 1 percent of the samples include leucoxene as a replacement mineral and authigenic chlorite as pore linings and pore fillings. Thin section porosity averages 8 percent (1 percent is primary and 7 percent is secondary).

Diagenesis

Thin section analysis has revealed some convincing evidence of the paragenetic sequence. Although minor variations can be detected within a particular sandstone unit or among several units, the "general paragenetic sequence" that has been derived is applicable to all of the samples from the Tarbat area (Figure 35). The phrase, "general paragenetic sequence", implies that if two events occurred under different conditions but at the same time then both events will be represented in the sequence as

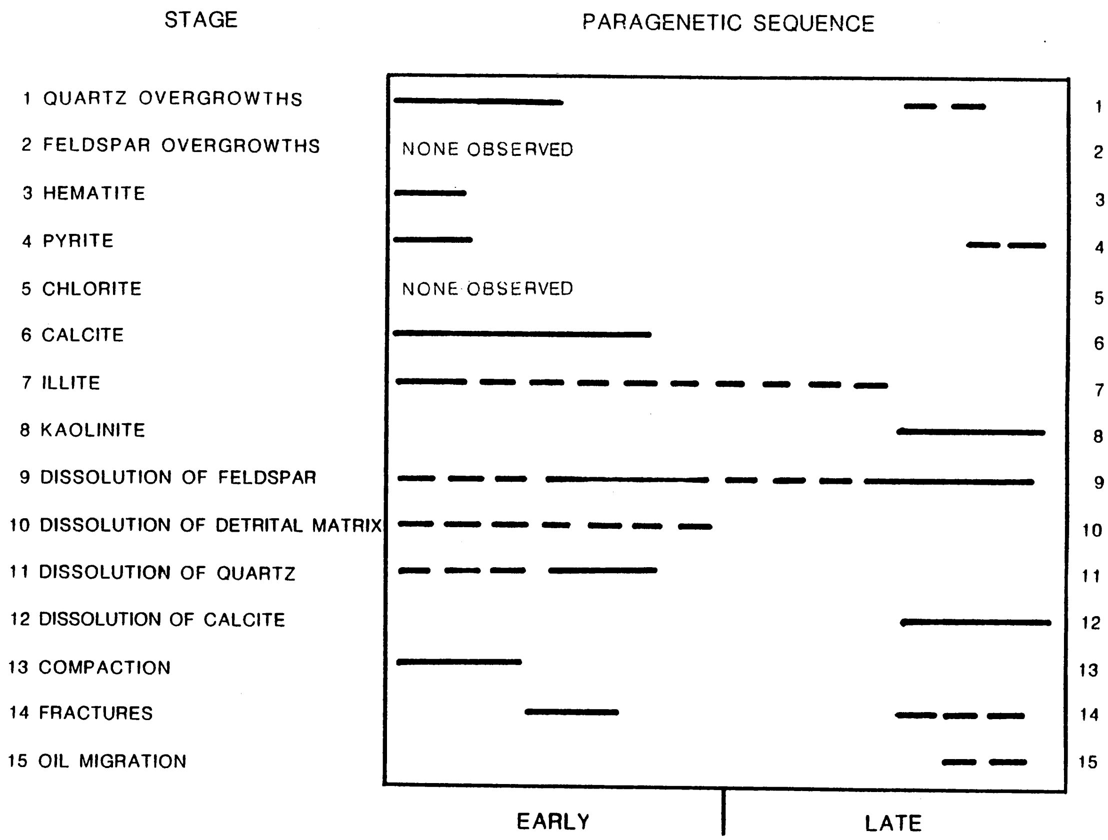

Figure 35. Paragenetic Sequence of Sandstones from Tarbat

occurring relatively simultaneously.

The early stages of diagenesis (eogenetic and early mesogenetic) included:

1) Hematite as grain coatings and grain replacement

2) Compaction of detrital constituents

3) Pyrite as a pore filling cement

4) Partial dissolution of metastable constituents

5) Authigenic illite growth

6) Quartz overgrowths

7) Fractures

8) Calcite as a displacive cement and as a replacement mineral of feldspar, quartz, and metastable constituents

Four of the thirteen samples studied have more than trace amounts of hematite. In these hematite-rich samples, there are only trace amounts of biotite while in the other nine samples there is collectively an average of 2 percent biotite. The authigenic hematite occurs primarily as early grain coatings and secondarily as trace amounts of hematite pseudomorphs after biotite. If we compare the average 2 percent biotite found in the hematite-poor samples to the trace of hematite pseudomorphs found in the hematite rich samples, there appears to be some biotite not accounted for. The lack of biotite or of hematite pseudomorphs after biotite in the hematite rich samples may be explained four ways:

1) The biotite was never present in more than trace amounts.

2) The biotite was present, but it has been almost completely removed from the rock by diagenetic processes.

3) The biotite was present in amounts averaging about 2 percent and it has been diagenetically altered to hematite grain coatings and trace amounts of hematite pseudomorphs after biotite.

4) Reworking and mechanical disintegration of hematised biotites contributed to the hematite grain coatings and traces of hematised biotite.

The first explanation supporting the syndepositional lack of biotite can be argued against from a statistical standpoint. The nine hematite-poor samples averaged 2 percent biotite. Therefore, it is not unreasonable to expect the hematite-rich samples to average 2 percent of eithe biotite or hematite pseudomorphs after biotite. The second explanation, which suggests the diagenetic removal of biotite, can be argued if we look at the timing and condition expected for formation of hematite coatings. The hematite grain coatings appear to be one of the earliest diagenetic events to have taken place. This event is suggestive of more or less an arid continental environment (Folk, 1976). Biotite being exposed to the oxidizing conditions suitable for hematite precipitation would alter as an early diagenetic event (Turner and Archer, 1977). It is unlikely that iron derived from the biotite would be removed from the rock while iron oxide from other sources was being precipitated as grain coatings. The third explanation, which involves diagenetic alteration of biotite to hematite grain coatings and hematite pseudomorphs after biotite raises one question,"Why are there not more hematite pseudomorphs of biotite and less hematite as grain coatings?". During the hematisation of biotite, iron goes through an intermediate stage of diagenesis as an iron hydroxide which precipitates in the interlayer spaces (Turner, 1980). This iron hydroxide, which normally becomes part of the hematite in the pseudomorphs, may be remobilized and precipitated as hematite grain coatings. In the samples studied, hematite pseudomorphs after biotite are found in trace amounts in the hematite-rich samples. This would be expected if most of the iron from the biotite was used as grain coatings. The fourth explanation, involving the mechanical disintegration and reworking of hematised biotites, was invoked by Turner and Archer (1977). In Old Red Sandstone sediments studied by Turner and Archer (1977), presence or absence of hematised biotite flakes bore no relationship to the extent or nature of pigment development. Therefore, the two authors favored the thought that the reworking and mechanical disintegration of hematised biotites is a more important process of hematite grain coat formation.

Compaction resulted in minor bending and squeezing of ductile grains and (to a lesser extent) fracturing of brittle grains. Minor pressure solution of quartz may have occurred as well.

Early pyrite occurs as a minor pore filling cement in one fine grained sandstone sample. Each occurrence covers a diameter of about one millimeter and there are about eight occurrences per square inch. The presence of pyrite, which probably formed under reducing conditions, suggests a possible lacustrine influence in ground waters.

Partial dissolution of feldspar resulted in the development of honeycomb texture. Dissolution of feldspars and other metastable constituents contributed to early authigenic illite growth and formation of secondary porosity. Authigenic illite occurs mainly as a grain replacement mineral. Illite usually replaced the feldspars along cleavage planes while it replaced the other metastable constituents in a random manner.

Minor amounts of silica cement as syntaxial quartz overgrowths are visible in thin sections. The lack of clay dust rims in the majority of the samples studied may have resulted in the underestimation of the actual amount of quartz overgrowths. However, the maximum possible error that may have occurred is relatively insignificant in regard to the results of this study.

Sparry calcite on the average makes up 13 percent of the total rock volume of the samples. This percentage is more than six times greater than the cumulative average of the next most abundant diagenetic constituent and more than twice the cumulative average porosity. Calcite occurs as:

1) A displacive cement resulting in grain fractures

2) A pore filling cement

3) A partial replacive cement of feldspar, rock fragments, and quartz

The early displacive calcite is evidenced by the abundance of sparry calcite cement, the lack of grain to grain contacts, and the presence of calcite-filled tensional fractures (Figure 36). The displacive nature of the calcite resulted from a supersaturated solution in the original sediments. The requirement of supersaturated ground waters was stressed by Weyl (1958), who believed the displacive force exerted by the growing calcite was transmitted through a thin film of fluid. Rothrock (1925) showed that the force exerted by calcite crystallization was enough to fracture quartz. In the Tarbat samples studied, fractures through a calcite-cemented sandstone resulted in quartz and other grains being fractured. These tensional fractures are thought to be a result of displacive calcite growth. The tensional component is evidenced by broken grains matching on either side of the fractures (Figure 36).

Calcite as either a partial or complete pore-filling cement precipitated in all of the samples studied. The amount of original primary porosity filled varies from about 3 to 100 percent. Partial cementation by calcite may be a result of incomplete early calcite cementation or of later partial dissolution of calcite.

Calcite also occurs as a replacement mineral of

Figure 36. Photomicrograph of Calcite Filled Tensional Fractures in Displacive Calcite Cemented Sandstone (40X, XN)

feldspar, rock fragments, and quartz. In some samples, the replacive calcite may have formed during pore-filling calcite growth. However, staining showed that in some cases the replacive calcite is iron-rich and the pore-filling calcite is iron-poor. This relationship suggests that at least two phases of calcite cementation took place. The replacive calcite came later than the pore-filling calcite, but how much later is not certain.

The occurrence of early sparry calcite cement in the Tarbat samples is similar to that seen elsewhere in the Orcadian Basin (Donovan, 1975) and in sandstones associated with numerous modern lakes.

The late stages of diagenesis (mesogenetic and telogenetic) included:

1) Fracturing with precipitation of quartz and calcite
2) Growth of authigenic illite
3) Dissolution of feldspar and calcite
4) Growth of authigenic kaolinite

There is evidence of minor late fracturing followed by precipitation of quartz overgrowths, calcite cement, and migration of oil. Although only one sample contains such fractures, other fracturing followed by similar diagenetic events may have occurred elsewhere in the Tarbat area.

Late replacive calcite cement is speculated to have been able to occur throughout the early part of late burial diagenesis whenever natural to slightly basic conditions were maintained. The incomplete replacement of feldspar by illite suggests that the conditions required for illite to form may have occurred throughout burial diagenesis.

Dissolution of calcite is prominent in some samples and is thought to be related to the maturation of organic matter indicated by trace amounts of residual oil. The maturation process gives off CO_2 which reacts with water to produce carbonic acid. Carbonic acid is responsible for dissolution of carbonates, feldspars, and rock fragments (Al-Shaieb and Shelton, 1981). The dissolution of carbonate cement and feldspars is evidenced by the presence of both calcite and kaolinite (each partially filling intragranular and intergranular pore spaces) and by the presence of remnant feldspar found in the intragranular pores. Kaolinite is a possible product of feldspar dissolution (Al-Shaieb and Shelton, 1981).

Porosity

Thirteen thin sections were analyzed for porosity evolution. Early calcite cement filled most of the primary intergranular pore spaces and prevented the formation of early pore-lining authigenic clays. Five of the thirteen samples studied are still completely cemented by calcite. The other seven samples are only partially cemented, but they are still lacking in pore-lining authigenic clays. These samples are thought to have undergone dissolution of calcite, feldspar, and rock fragments. The dissolution of these materials resulted in the formation of secondary porosity.

The secondary porosity is the major porosity in the samples studied (this includes the intergranular pore spaces that may have once been filled by calcite). Other secondary porosity is seen as partial and complete dissolution of metastable grains. Some of the secondary porosity has been filled with kaolinite creating secondary microporosity (Figure 37). Primary porosity is thought to be minor in the Tarbat area occurring mainly as microporosity.

Conclusions

The fluvial sediments of the Tarbat area were probably deposited in and near lake waters in the Orcadian Basin. The lake water chemistry was responsible for the precipitation of the early to very early calcite cement. The sands that were deposited in the lake environment were characteristically cemented by displacive sparry calcite cement. The biotite in these sands is fresh and hematite grain coatings are absent. Sands that were deposited near lake waters and were subsequently influenced by lake waters were also cemented by sparry calcite. However, early hematite grain coatings and lack of fresh biotite distinguishes these deposits from the lake deposits. Hematite coats may have formed in part as a result of either mechanical destruction of hematised biotite during reworking of sediments or very early chemical destruction

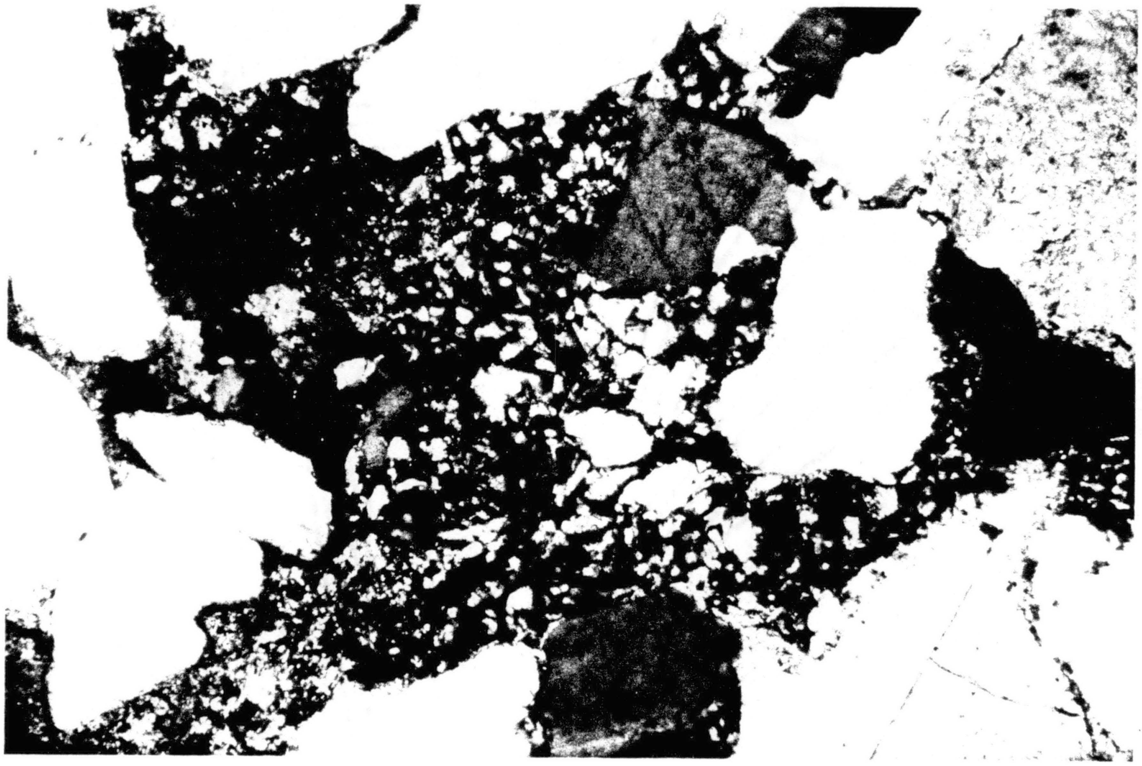

Figure 37. Photomicrograph of Kaolinite in a Pore Space (200X, XN)

of biotite.

Oil migration and maturation of organic materials produced CO_2 which combined with pore fluids to help dissolve calcite, feldspar, and rock fragments (Al-Shaieb and Shelton, 1981). The resulting secondary porosity is the major porosity seen in the samples studied. The abundance of calcite seen in some samples suggests that dissolution was incomplete. It is possible that the undissolved calcite could serve as a barrier of migrating fluids. Therefore, a very thick sequence of sparry calcite-cemented sandstone could serve as a reservoir rock with its own trapping mechanism.

CHAPTER V

PETROLOGY AND DIAGENESIS OF THE PORTSKERRA AREA

Introduction

Location

Portskerra is near the northern coast of Scotland approximately 19 miles (30km) west and 6 miles (10km) south of Dunnet Head, the northernmost point of the Scottish mainland. A thin 30 to 820 foot (10 to 250m) wide strip of Middle Old Red Sandstone outcrops for approximately one mile (1.5km) along the Atlantic coast (Figure 38)(Donovan, pers. comm.).

General Geology

The Middle Old Red Sandstone facies at Portskerra consists of a 245 foot (75m) sequence of breccias, conglomerates, sandstones, and (to a lesser extent) flaggy beds (Figure 39). The lower two-thirds of the sequence is predominantly massive breccias and conglomerates. Near the middle of this lower section, there are some thinly bedded sandstones that contain small scale ripples and cross bedding, plus some thinly bedded flagstones that contain

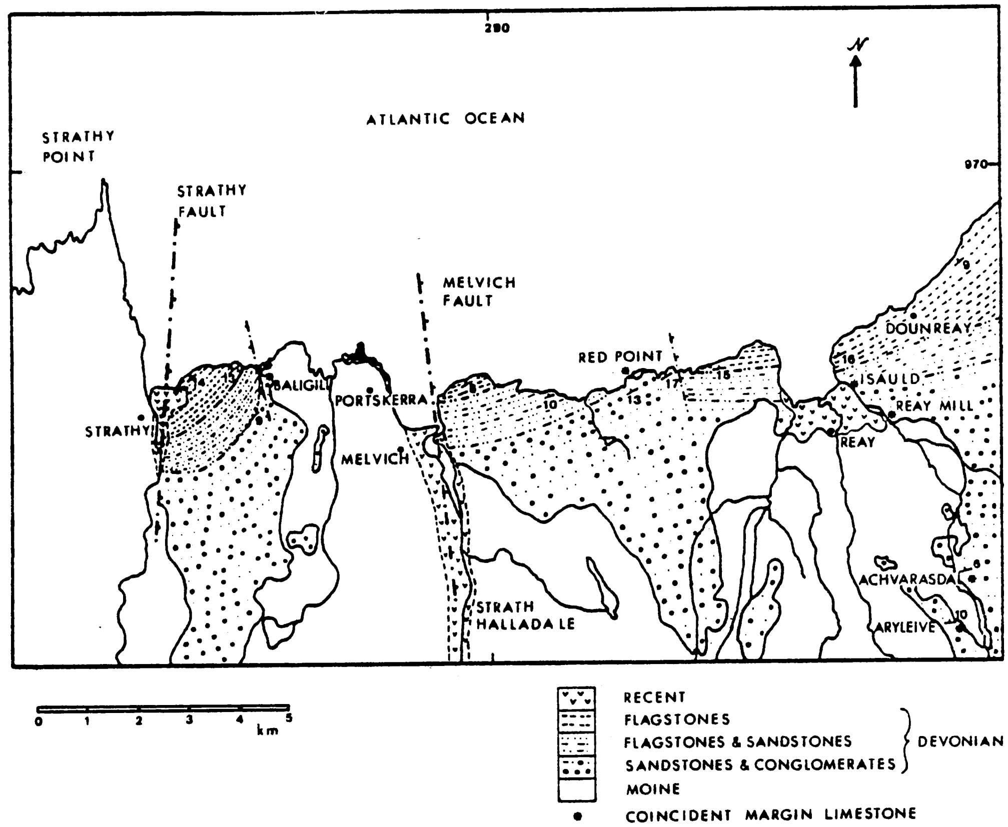

Figure 38. Portskerra Study Area on the Atlantic Coast in Northern Scotland (from Donovan, unpublished)

both subaerial and subaqueous shrinkage cracks. The upper one-third of the sequence is predominantly sandstone in which sedimentary structures that have been preserved include:

1) Medium scale trough cross bedding
2) Small scale cross bedding
3) Dewatering structures
4) Parallel laminations

The Middle Old Red Sandstone sequence unconformably overlies the Precambrian Moinian basement rock. In the Portskerra area the Moinian basement rock is primarily granitic with minor amphibolite facies.

Environment of Deposition

Donovan (unpublished) has described the various depositional environments represented by the sedimentary sequence in the Portskerra area (Figure 39). The paleogeography of the area during Middle Devonian time consisted of ridges and valleys of plutonic and high grade metamorphic rocks. Sediments derived from the highlands to the south filled the valleys and completely covered many of the ridges of the Portskerra area.

The lower 49 feet (15m) of the sequence consists of locally derived talus overlain by massive beds of valley-fill conglomerates derived from the south. Above the conglomerates lies 33 feet (10m) of thinly bedded sandstones, flagstones, limestones, breccias, and

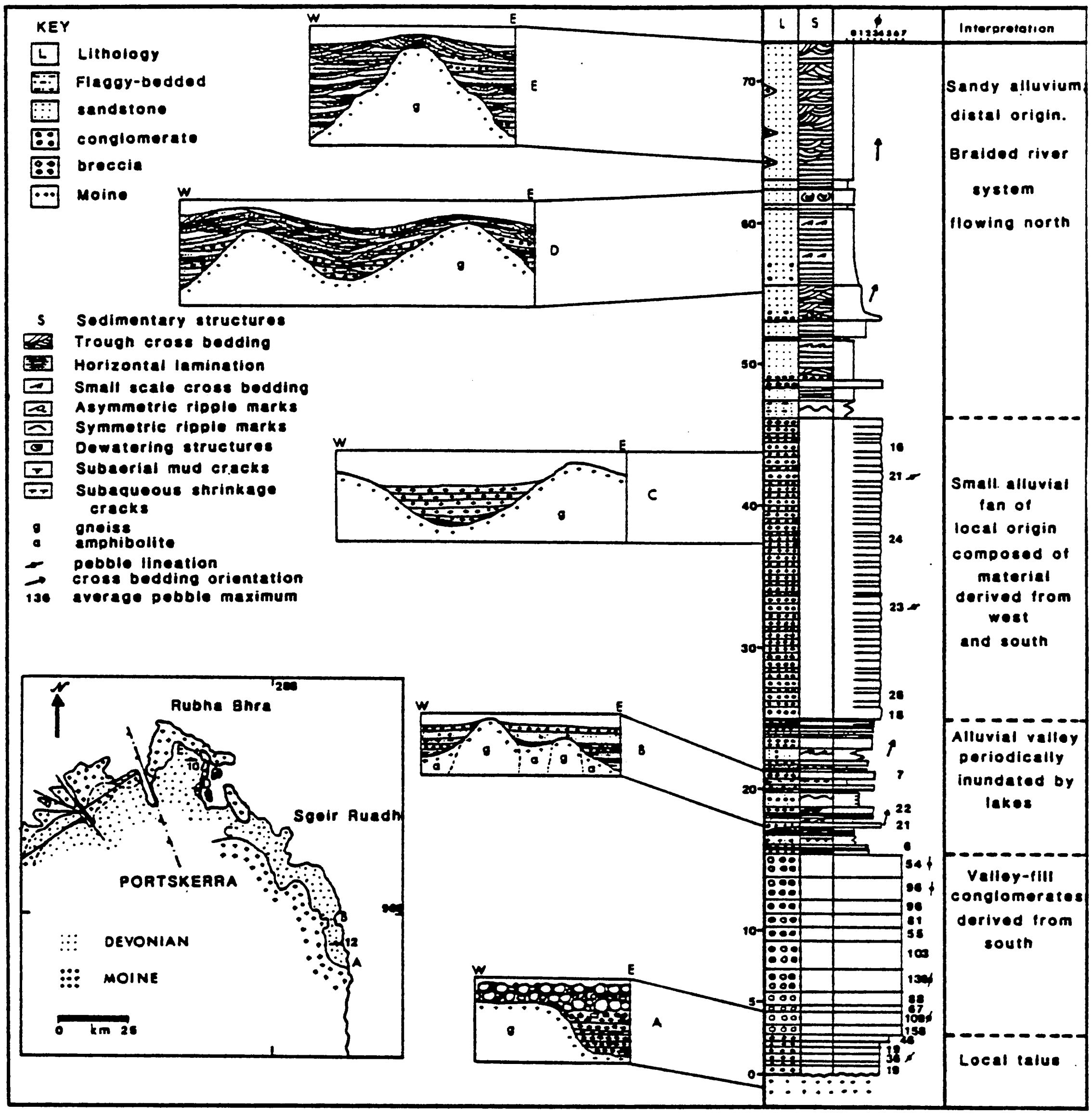

Figure 39. Logged Section from Portskerra (from Donovan, unpublished)

conglomerates. This portion of the sequence which contains subaerial mud cracks, subaqueous shrinkage cracks, and small scale sedimentary structures is thought to represent an alluvial valley that has been periodically transgressed by shallow lakes. The middle part of the sequence consists of 65 feet (20m) of thinly bedded breccia which may represent a small alluvial fan deposit locally derived from the west and south. The upper most 82 feet (25m) of the sequence consists of predominantly sandstone with minor amounts of breccia and conglomerates. This portion of the sequence is thought to represent primarily a braided stream environment where rivers flowed north-northeastward into the Orcadian Basin. The Portskerra sediments were probably deposited in the outer south-west margin of the basin (Donovan, unpublished).

Sedimentary Petrology

Six sandstone samples were collected along the north-eastern coastline of the Portskerra area. The intervals sampled include a 245 foot (75m) section consisting of primarily conglomerates and alluvial breccias in the lower two-thirds of the section and fluvial sandstones in the upper portion.

Textures

The samples are texturally submature sandstones that consist of moderately-well to very poorly sorted grains

(Folk 1974, Pettijohn et al., 1972). The grains are generally angular to subrounded. The angularity of the grains may be slightly overestimated in some samples due to the angular contacts among quartz overgrowths and the absence of dust rims which usually help identify the original grain shapes.

Mineralogy

Middle Old Red Sandstone lithologies are primarily subarkoses and arkoses (Figure 40). The mineralogy of the detrital grains indicates primarily an igneous plutonic and a high grade metamorphic source rock.

Quartz. Quartz is the major constituent and on the average it makes up 53 percent of the rock volume (1 percent is polycrystalline). More than three-fourths of the samples contain quartz grains that have straight to moderate undulose extinction. The average undulosity of each sample is less than five degrees (slight undulosity). Therefore, the major source rock of the quartz grains is thought to be plutonic (Basu et al., 1975). The abundance of larger plutonic rock fragments containing slightly undulose quartz crystals also suggests a plutonic sediment source.

Polycrystalline quartz grains average 1 percent of the samples. The majority of these grains resemble the larger plutonic rock fragments minus feldspars and micas.

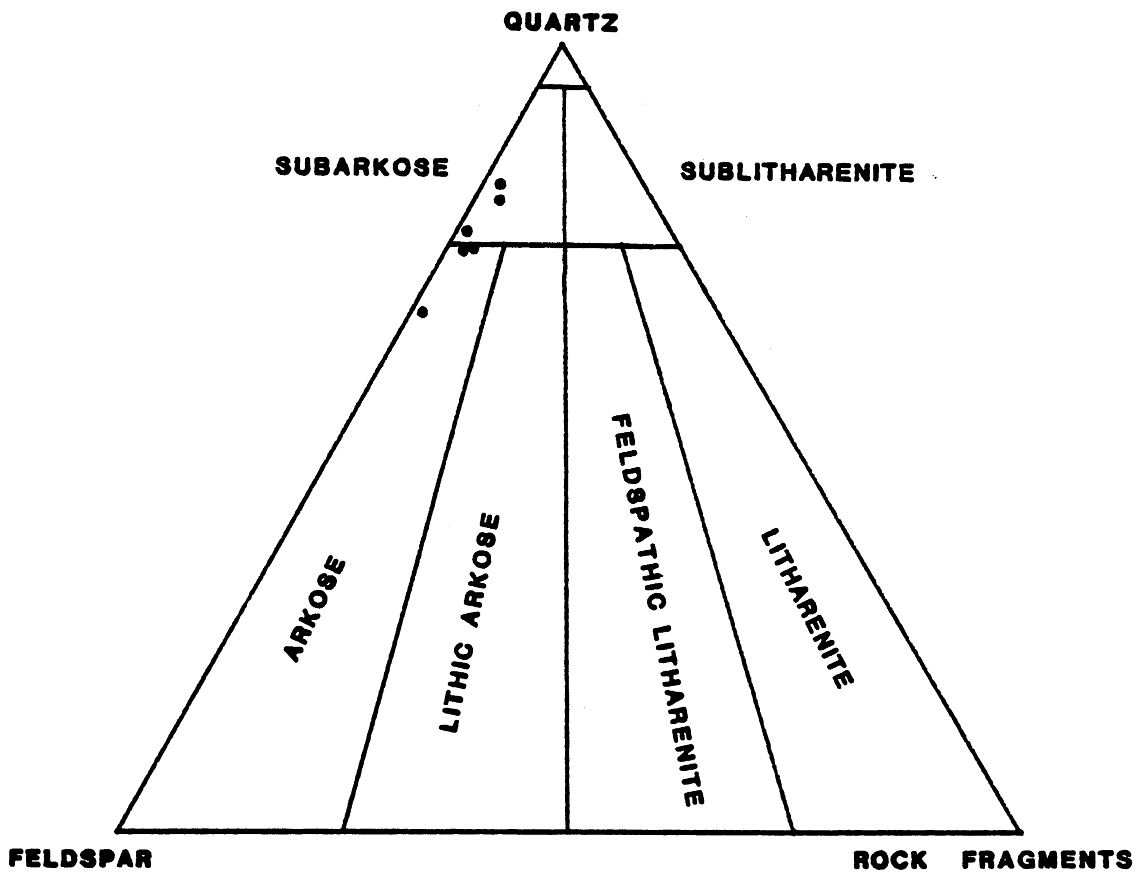

Figure 40. Classification of Sandstones from Portskerra (Diagram after Folk, 1976)

Feldspar. The second major constituent is feldspar which makes up an average of 16 percent of the total volume of the samples (11 percent is orthoclase, 5 percent is plagioclase, and less than 1 percent is microcline and perthite). Many feldspar grains, especially the plagioclase, have been either partially or completely dissolved leaving dissolution voids and moldic porosity. The potassium feldspar grains have usually been partially replaced by illite. Feldspar overgrowths are present on many of the potassium feldspars and more rarely on the plagioclase feldspars. "Hacksaw" terminations are a common feature of these overgrowths.

Rock Fragments. Rock fragments average 2 percent of the samples with plutonic and metamorphic rock fragments making up the major portion. The plutonic rock fragments are usually coarse sand to pebble sized and are granitic in composition. The feldspars within these rock fragments often show dissolution features similar to those of individual sand sized feldspar grains. The metamorphic rock fragments identified in thin section include metaquartzite and phyllite. Large pebbles of amphibolite are common in the conglomerates and they probably represent the major metamorphic rock type that contributed to the sandstones. However, when the amphibolite is broken into sand size particles, the individual stable components and alteration products are identifiable only as independent grains such as feldspar, chlorite, biotite, and apatite.

Chert is seen in trace amounts in four samples, and shale clasts make up 1 percent of one sample.

Other Constituents. Grains other than quartz, feldspar, and rock fragments average 4 percent of the samples. Detrital muscovite averages 2 percent of the samples and detrital biotite averages 1 percent. The original amount of biotite may have been almost 2 percent before hematisation of biotite occurred. Apatite and chlorite individually comprise as much as 1 percent of one sample while on the average they occur in trace amounts. Accessory minerals include hematite, zircon, glauconite, garnet, and rutile. Detrital matrix averages 3 percent of the samples and consists mainly of illite and chlorite.

Five diagenetic constituents that average from one to 5 percent of each sample include:

1) Quartz as overgrowths
2) Chert as pore fillings
3) feldspar as overgrowths and pore fillings
4) Hematite as a grain coating and a replacement mineral of biotite
5) Illite as a replacement mineral of feldspars

Four minor diagenetic constituents that average less than 1 percent include:

1) Calcite as a replacement mineral of feldspar
2) Leucoxene as a replacement mineral
3) Kaolinite as pore fillings
4) Chlorite as a product of recrystallisation of

detrital clays

Porosity averages 8 percent in the samples (8 percent is secondary and less than one percent is primary).

Diagenesis

Thin section analysis has revealed some convincing evidence of the paragenetic sequence. Although minor variations can be detected within a particular sandstone unit or among several units, the "general paragenetic sequence" that has been derived is applicable to all of the samples from the Portskerra area (Figure 41). The phrase, "general paragenetic sequence", implies that if two events occurred under different conditions but at the same time, then both events will be represented in the sequence as occurring relatively simultaneously.

The early stages of diagenesis (eogenetic and mesogenetic) included:

1) Hematite as grain coatings and as a pseudomorph after biotite

2) Compaction resulting in pressure solution of quartz

3) Dissolution of feldspar

4) Dissolution of detrital matrix

5) Precipitation of potassium feldspar overgrowths

6) Precipitation of pore filling potassium feldspar rhombs

7) Precipitation of syntaxial quartz overgrowths

8) Precipitation of replacive calcite

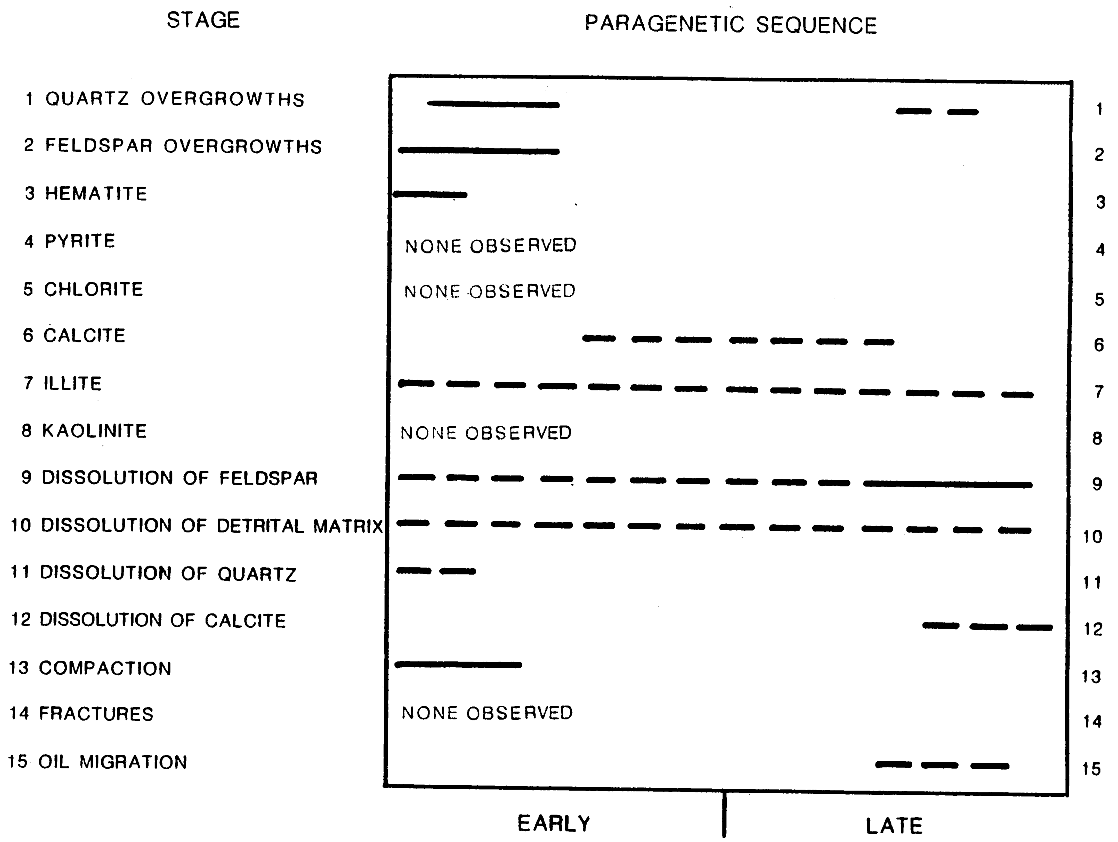

Figure 41. Paragenetic Sequence of Sandstones from Portskerra

9) Authigenic illite growth

One of the earliest events that took place was the formation of authigenic hematite as grain coatings and as pseudomorphs after biotite. Hematite grain coatings are present in only one sample. The grains in this sample are cemented together in part by quartz overgrowths. However, the grains were coated by the authigenic hematite before quartz overgrowths occurred and therefore the original grain shapes can be easily distinguished. Hematite as pseudomorphs after biotite is more common than grain coating hematite. Turner (1980) believed that hematisation of biotite is an early diagenetic event. Details on hematisation of biotite can be found under the heading of "Diagenesis" in the chapter on Foula (this thesis).

The scarcity of ductile grains resulted in a large percentage of quartz grains being adjacent to one another. Overburden and confining pressure applied to contacts between quartz grains caused pressure solution to occur (Figure 42). The dissolved quartz may have later precipitated as syntaxial quartz overgrowths.

Dissolution of feldspars and detrital matrix started very early and continued from time to time throughout the diagenetic history of the samples. Dissolution resulted in voids and moldic pores, many of which were later filled by authigenic minerals and cements. One of the major authigenic minerals that formed early is potassium feldspar. The authigenic feldspar occurs both as

Figure 42. Photomicrograph of Pressure Solution of Quartz (400X, PPL-top, XN-bottom)

overgrowths on orthoclase, microcline, and to a lesser extent plagioclase, and as pore filling rhombohedral crystals (Figure 43). Authigenic potassium feldspar overgrowths were identified by the following five criteria:

1) They were present only around feldspar grains.

2) They displayed first order gray birefringence colors.

3) Characteristic "hacksaw" terminations were common (Turner, 1980).

4) The beckeline test showed that the index of refraction of the feldspar overgrowths was significantly less than quartz. This fact greatly reduces the possibility of the overgrowths being plagioclase feldspar.

5) A biaxial negative optic figure was obtained from an overgrowth further reducing the possibility of the overgrowths being plagioclase feldspar.

Individual rhombohedral crystals of potash feldspar have been incorporated in quartz overgrowths. Aggregates of these rhombohedral crystals have in part filled much of the primary and secondary pore space of two samples. These pore filling aggregates of feldspar look similar to pore filling kaolinite. Therefore, the feldspar aggregates were identified by the following four criteria:

1) No "booklets", which are characteristic of kaolinite, were readily identifiable in any pores or any quartz overgrowths.

2) Rhombohedral shapes were readily identifiable in

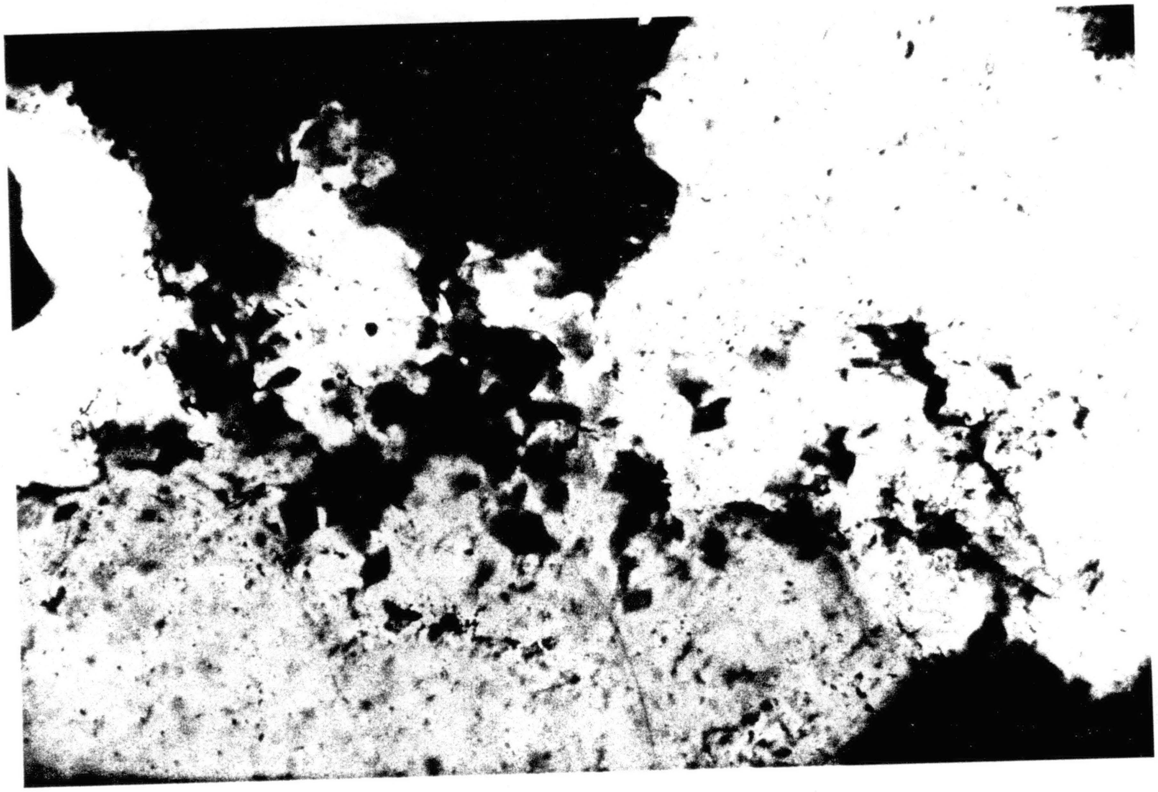

Figure 43. Photomicrograph of Feldspar Rhombs in Pores and in Quartz Overgrowths (200X, XN)

quartz overgrowths and near pore edges. The feldspar rhombs that were not incorporated into the quartz overgrowths were left in the pore space.

3) The beckeline test indicates that quartz has a significantly higher index of refraction than the pore filling aggregate. If reliable, this test alone would eliminate the possibility of kaolinite which has a higher index of refraction than quartz.

4) The aggregates display first order gray birefringence.

Turner (1980) noted that "authigenic potassium feldspar is one of the most commonly occurring diagenetic events in continental red beds" and that "in places, aggregates of feldspar crystals may fill pore spaces or dissolution voids". Waugh (1978) studied authigenic potassium feldspar in British Permo-Triassic sandstones. The authigenic feldspar occurred as feldspar overgrowths and as independent flattened rhombohedral crystals in dissolution voids. By use of X-rays (EDAX) and electron microprobe analysis, Waugh determined that the overgrowths are practially pure potassium feldspar. Therefore, it is not surprising to find authigenic potassium feldspar associated with the Portskerra Old Red Sandstone facies.

Syntaxial quartz overgrowths make up an estimated average of 5 percent of the volume of each sample. In samples where dust rims are absent, overgrowths were identified by:

1) Long grain contacts

2) Absence of porosity between quartz and other grains

3) Irregular quartz crystal shapes

The absence of dust rims suggests that the overgrowths were early. The incorporation of some feldspar rhombs into quartz overgrowths and the "hacksaw" terminations of feldspar overgrowths suggests that precipitation of authigenic feldspar may have occurred both before and during the precipitation of quartz.

Calcite is the only carbonate identified in the samples studied. The calcite occurs in trace amounts of one sample as a replacement mineral of feldspar.

Authigenic illite makes up an average of 2 percent of the samples and it occurs most frequently as a partial replacement mineral along cleavage planes of potassium rich feldspars. The incomplete nature of the replacement suggests that the illite may have formed throughout diagenesis whenever conditions were right.

The late stages of diagenesis (mesogenetic and telogenetic) included:

1) Dissolution of feldspars

2) Dissolution of detrital matrix

3) Authigenic illite growth

4) Precipitation of replacive calcite

5) Oil migration

Dissolution of feldspar and detrital matrix appears to have continued on into the late stages of diagenesis creating abundant secondary moldic porosity. Over 90 percent of the porosity presently within the samples is of this nature. Partial replacement of potassium feldspar by illite may have occurred in a similar manner to that described in the early diagenesis section.

The minor amounts of calcite that were described in the early diagenesis may have continued to precipitate through part of the late stages of diagenesis. Most of the calcite shows signs of dissolution.

One sample contains residual oil. Oil and euhedral quartz overgrowths associated with the oil completely filled most of the secondary porosity. The present secondary porosity is thought to have developed from continued dissolution of feldspars after oil migration.

Porosity

All six thin sections were analyzed for porosity evolution. Early quartz cement in the form of quartz overgrowths filled most of the primary pore space. Preserved primary porosity does not exceed 1 percent in any of the samples.

Secondary porosity is the major porosity in the samples and it occurs mainly as a result of dissolution of feldspars. In two samples, much of the secondary porosity was filled by authigenic potassium feldspar. Continued dissolution of detrital feldspars in these two samples increased the secondary porosity once again. Secondary porosity averaged 8 percent which suggests that the original sandstones were considerably more arkosic.

Conclusions

The Middle Old Red Sandstone rocks of Portskerra unconformably overlie the Precambrian Moine basement rock. The unconformity is highly irregular and it is clear in the field that the Old Red rocks occupy a steep sided valley carved in the older rocks. The abundant breccia and conglomerate facies that are composed of primarily granite and amphiboles suggests that plutonic and high grade metamorphic source rocks were near by. The Moine basement rock is thought to have been part of that sediment source (Donovan, pers. comm.). A small interval of sandstones and flagstones in the lower part of the 245 ft (75m) stratigraphic section of sedimentary rocks have preserved subaerial and subaqueous features that suggest periodic lake transgressions did occur (Donovan, pers. comm.). The rest of the sequence consists of alluvial and fluvial deposits that indicate a north to north-east flow direction. Therefore, the Portskerra area is thought to have been located on the south-western margin of the Orcadian Basin. Both the scarcity of lacustrine influence on the sediments and the irregular nature of the unconformity between the sedimentary rocks and the Moine basement rock suggests that this area is on the outer margin of the basin.

Authigenic hematite occurs as early grain coatings and as pseudomorphs of biotite, but only in minor amounts of each. Authigenic quartz as syntaxial overgrowths was the major contributer to the loss of primary porosity while dissolution of feldspar was the major contributer to the formation of secondary porosity. Authigenic feldspar and residual oil are the main secondary pore fillers. After the occurrance of pore filling events, continued dissolution of feldspars resulted in the averaged 8 percent secondary porosity seen in the samples studied.

CHAPTER VI

FOULA, MELBY, TARBAT, PORTSKERRA: SIMILARITIES AND DIFFERENCES

Introduction

This chapter compares the four areas under study in this thesis. The headings used are similar to those in the previous four chapters so that comparisons can be made easily and in an orderly fashion.

Location

Foula and Melby of the Shetland Islands are presently within 19 miles (30km) of each other (Figure 1). Transcurrent fault movement along several faults in the Shetland Islands and on the Scottish mainland suggests that Foula and Melby may have originally been further apart. Portskerra and Tarbat, which are about 60 miles (95km) apart, are located on the Scottish mainland over 140 miles (225km) from the Shetland Islands. All four areas are thought to be in the Orcadian Basin.

General Geology

Middle Old Red Sandstone sequences from the Tarbat and Portskerra areas unconformably overlie Moinian basement rock. Foula sediments overlie metamorphic basement rock either unconformably or as a fault contact. The Melby area is faulted against Lower Old Red sandstone facies and Precambrian Gneiss. In the three areas that are seen overlying basement rock, it is likely that the underlying basement rock type in part contributed to the sediments of that area.

Environment of Deposition

The samples studied were intentionally selected from sandstone-rich areas thought to be located in the Orcadian Basin. The sandstones represent predominantly fluvial braided stream deposits with minor alluvial and meandering stream deposits. Donovan (unpublished) has proposed a model which can be used to estimate the relative position of each area within the basin (Figure 44). Since the Orcadian Basin is a closed basin, lake level changed constantly with changing climatic conditions. The deepest parts of the basin were almost always under water while the outer most margins were rarely transgressed. It has been suggested that sandstones influenced by lake waters have a different early diagenetic imprint than the sandstones that were never exposed to the lake waters. The presence of "Fish bed horizons" and shallow lacustrine limestones identified in the field by Donovan (unpublished) has been used in this study to verify and semiquantitatively assess the amount of lacustrine influence in each of the four

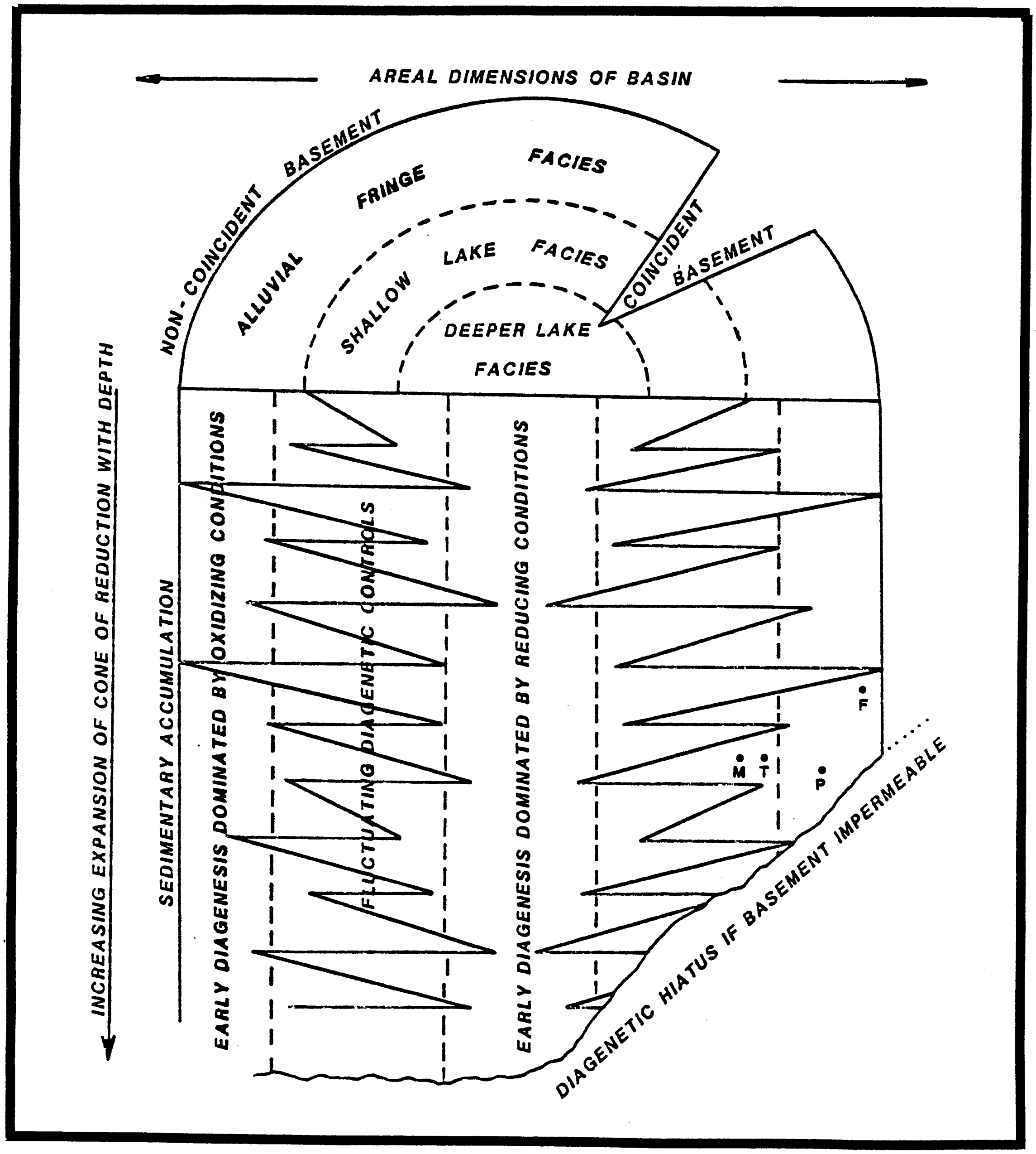

Figure 44. Basin Model Showing Relative Locations of Each Area Within the Orcadian Basin (M= Melby Area, T=Tarbat Area, P=Portskerra Area, F=Foula Area)(after Donovan, unpublished)

areas. The four areas studied have been plotted in their relative positions within the basin margins according to the amount of lacustrine influence that was observed at each location (Figure 44).

The current directions derived from cross-bedding are thought to be in the general direction of the center of the basin. Therefore, because the four areas are thought to be near the margins of the basin, a general outline to the basin can be estimated (Figure 4) (Donovan et al., 1976).

Sedimentary Petrology

Fifty-four thin section of sandstones were analyzed for textures, mineralogy, and diagenesis. Details of the analysis are lodged with R. N. Donovan in the Department of Geology at Oklahoma State University.

Textures

The majority of the samples from each area are submature sandstones with moderately well sorted grains. Foula is the only area where several very poorly sorted samples were found. The abundance of very poorly sorted grains in the Foula samples probably is directly related to postdepositional tectonic events. Both Foula and Melby have about one third of their samples dipping into the immature sandstone category. Immaturity in the Foula samples is again related to postdepositional tectonics while immaturity in the Melby samples is related in part to the very fine grained nature of many samples. In these samples, grains just under half the average grain size of the samples can be classified as detrital matrix.

Most of the grains from the Foula, Tarbat, and Melby areas range from subangular to subrounded. In the Portskerra area, five of the six samples range from angular to subrounded. The angularity in these samples may have been overestimated due to the abundance of quartz overgrowths without dust rims.

Mineralogy

Overall, the primary lithologies of the four areas are subarkoses, sublitharenites, and arkoses (Figure 45). Variations in rock types among the areas is thought to be related in part to variations in source rocks. Various tectonic and diagenetic events have also contributed in part to the variations of lithology; however, these events are thought to have only minor effects. Sandstones of the Melby and Tarbat areas were derived from igneous and (to a lesser extent) metamorphic rocks. These sandstones are primarily lithic arkoses and sublitharenites. Samples from Foula were derived from quartz-rich metamorphic and (to a lesser extent) igneous rocks. These sandstones are primarily subarkoses. Portskerra samples, which were derived from primarily igneous plutonic and (to a lesser extent) high grade metamorphic rocks, are subarkoses and arkoses.

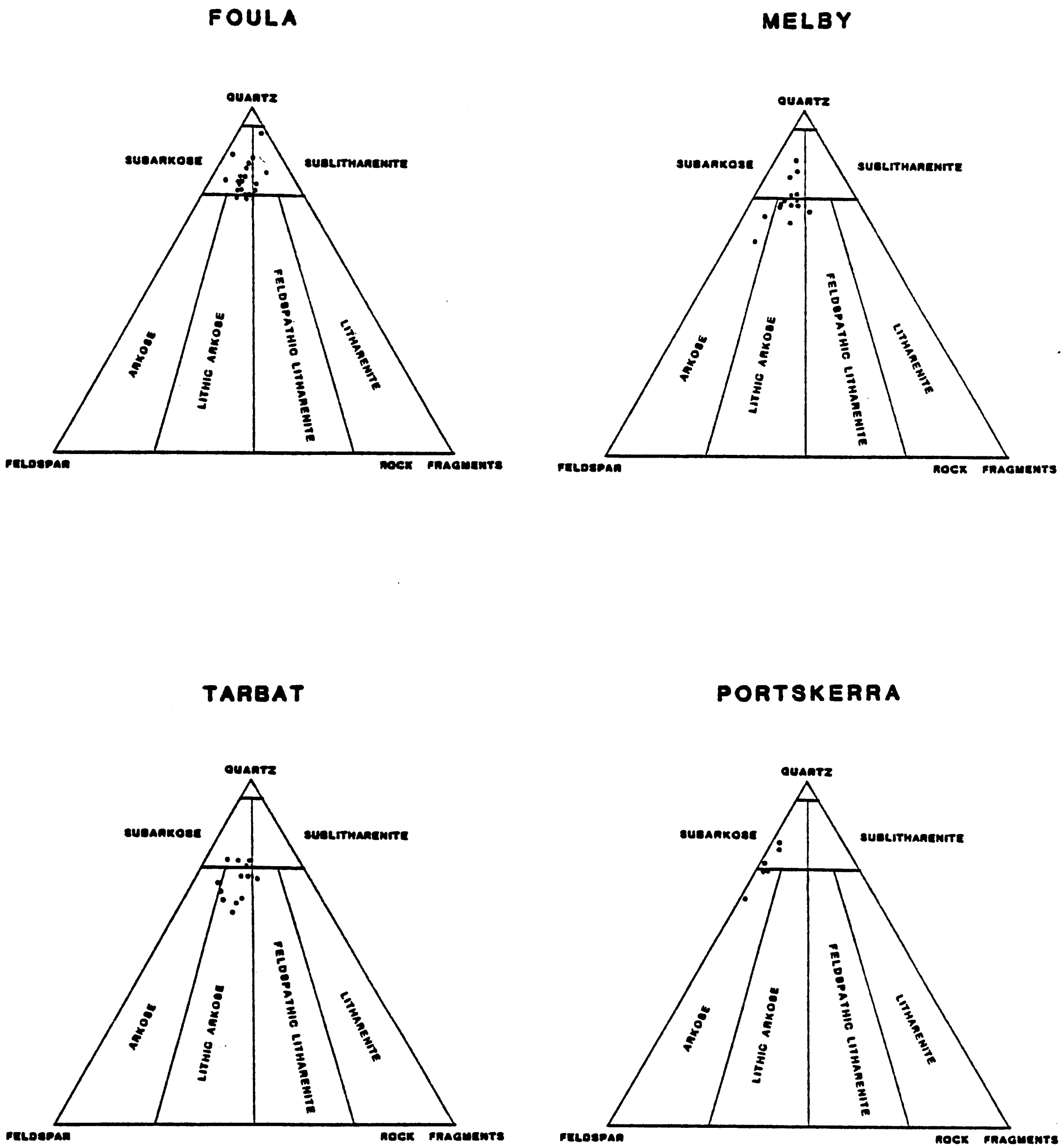

Figure 45. Classification of Sandstones from Foula, Melby, Tarbat, and Portskerra (Diagram after Folk, 1976)

Quartz. Quartz is the major constituent of the areas studied and overall it averages 51 percent of the samples. The quartz grains show straight, slightly undulose (less than 5 degrees), and moderately undulose (greater than 5 degrees) extinction. The average undulosity of the quartz grains was used to help decide if quartz grains were derived from plutonic or metamorphic source rocks (Basu et al., 1975). Quartz grains from all four areas appear to have been derived from both igneous and metamorphic rocks. However, quartz grains from Foula appear to have been derived primarily from metamorphic rocks while quartz grains from the Portskerra area appear to have been derived primarily from igneous plutonic rocks.

Feldspar. Feldspar is the second major constituent of the four areas studied and overall it averages 12 percent of the samples (8 percent is orthoclase, 3 percent is plagioclase, 1 percent is microcline, and less than 1 percent is perthite). Dissolution of feldspar is the major contributor to secondary porosity in each area.

Rock Fragments. Rock fragments average 6 percent of the samples. Whenever fragments are pebble sized or larger, their polycrystalline nature makes them useful indicators of source rock type. Grains smaller than pebble size are often comprised of only a single crystal that by itself is not a useful indicator of source rock type. Pebble sized rock fragments from Foula suggest a primarily metamorphic source rock. Cobbles and pebbles seen in thin sections from Portskerra suggest an igneous plutonic and high-grade metamorphic source rock.

Other Constituents. One of the most significant detrital constituents present in all four areas is biotite which averages 1 percent of the samples. The presence of hematite pseudomorphs after biotite suggests that the original sediments were more biotite-rich. The percentage of biotite that was pseudomorphed by hematite in each sample is related to the original amount of biotite that was present and to the conditions that the biotite grains were exposed to. The significance of these two parameters will be discussed under diagenesis. Muscovite averages 2 percent of the samples and may be used to estimate the original amount of biotite that was present in the samples from the Melby area. Other accessory detrital minerals that occur in one or more of the four study areas include pyrite, hematite, zircon, apatite, garnet, sphene, rutile, blue tourmaline, glauconite, chlorite, and carbonate ooids. Detrital matrix is comprised mainly of illite and chlorite in the Tarbat and Portskerra samples. In the samples from Foula, detrital matrix is comprised mainly of quartz due to tectonic crushing of the sandstones. In the Melby area, quartz is a significant part of the detrital matrix due to the fine grained nature of the samples.

Diagenetic constituents that occur in two or more of the study areas include:

1) Quartz as overgrowths

2) Hematite as grain coatings, pore linings, and pseudomorphs of biotite

3) Authigenic illite as grain coatings, pore linings, pore fillings, and grain replacement

4) Authigenic chlorite as pore linings, pore fillings, and recrystallized detrital clay

5) Authigenic kaolinite as a replacement mineral and as pore fillings

6) Chert as pore and fracture fillings

7) Calcite as a cement and a replacement mineral

8) Leucoxene as a replacement mineral

9) Feldspar as overgrowths and pore fillings

Porosity averages six precent of the samples (1 percent is primary and 5 percent is secondary).

Diagenesis

A "general paragenetic sequence" was derived for samples from each of the four study areas (Figure 46). The charts can be used to compare the relative timing of diagenetic events (but not the mode of occurrence). At first glance charts that show paragenetic sequences might seem to be highly discriminant in interpretation of differences among depositional localities. The following discussion will show that only a few of the diagenetic events are useful for such purposes; however, these lines of evidence are quite valuable.

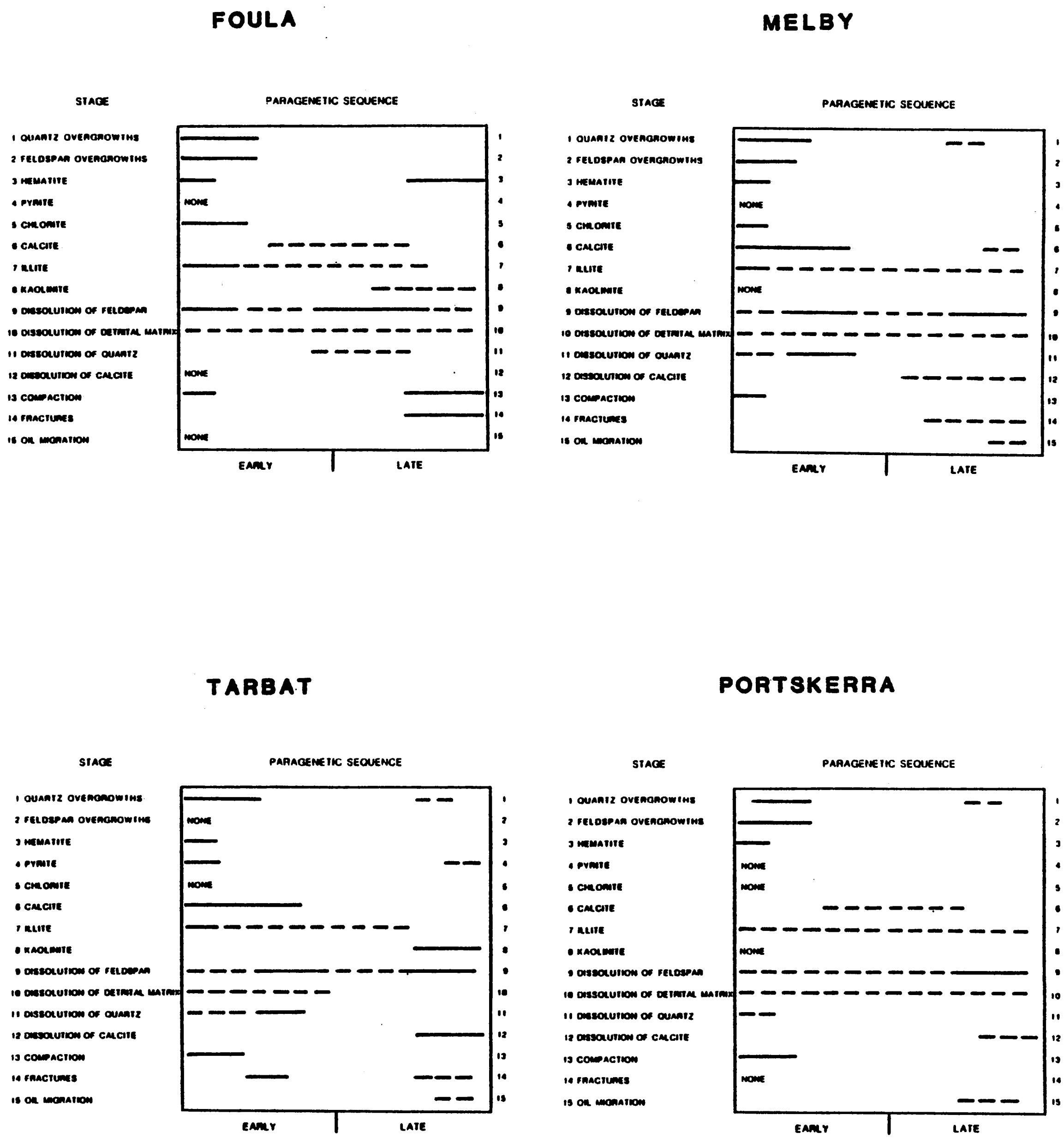

Figure 46. Paragenetic Sequences of Sandstones from Foula, Melby, Tarbat, and Portskerra

One of the objectives in comparing the various diagenetic events among the four areas is to see which events, if any, can be used to differentiate sands that were in contact with water related to lakes from sands that were not influenced by lake waters during early diagenesis. According to the model proposed by Donovan (Page 116, paragraph 1), the Melby and Tarbat areas are much closer to the basin center than the Portskerra and Foula areas. Consequently, it is suggested that the Melby and Tarbat areas were exposed to significantly more lacustrine influences than the Portskerra and Tarbat areas. With this suggestion in mind, this section will concentrate on those diagenetic events which were dominant in or unique to either the fluvial sands that were dominated by a lacustrine environment (Melby and Tarbat) or the fluvial sands that were dominated by a continental environment (Portskerra and Foula).

Compaction to one degree or another was ubiquitous to all four areas. Early compaction resulted in bending and squeezing of ductile grains and (to a lesser extent) breaking of brittle grains. Pressure solution of quartz resulting from compaction is also thought to have been common. Therefore, evidence of early compaction will not be considered to be diagnostic of a particular environment. Fractures and granulation seams which are unique to the Foula area, are quite extensive (Page 16, Paragraph 2). However, late compactional events are not characteristic of a particular depositional environment.

Syntaxial quartz overgrowths averaged four to 5 percent of the samples at each area. Quartz precipitated primarily as an early cement and secondarily as a late fracture filling cement. The time and mode of occurrence of early quartz overgrowths is similar in the samples from the four areas, therefore, the early overgrowths are not diagnostic of a particular depositional environment. In samples from Tarbat and Melby, late syntaxial quartz overgrowths have partially filled in tensional fractures that also contains residual hydrocarbons. In a sample from Portskerra, late syntaxial quartz overgrowths have partially filled pore spaces that also contain residual hydrocarbons. The occurrence of late syntaxial quartz overgrowths in three of the four areas suggests that its occurrence is not diagnostic of a particular depositional environment. However, the presence of oil with the euhedral quartz overgrowths suggests that perhaps the overgrowths are a common by-product of oil migration. Generation of oil may be related to the generation of CO^2 which in turn may be related to dissolution of silica (H^4SiO^4)(Al-shaieb and Shelton, 1981). Some of this dissolved silica may have precipitated along fractures as a result of supersaturation with respect to silica or a decrease in PH or temperature.

Oil migration has occurred in at least three of the four areas (Melby, Tarbat, and Portskerra). In a study of hydrocarbon distribution in the Old Red Sandstone of the Orcadian Basin, Parnell (1983) stated that close spacial association strongly suggests that hydrocarbons were derived from lacustrine laminite facies. Therefore, we might expect the highest concentrations of residual hydrocarbons to be in the samples from the two areas that were dominated by lacustrine influences (Melby and Tarbat). This is the case in the samples from the four areas studied, however, the fact that hydrocarbons have migrated into the Portskerra area suggests that the presence of hydrocarbons alone is not diagnostic of a particular depositional environment.

Fractures are present in four samples from three of the four areas. Stresses thought to be responsible for fracture formation are:

1) Late compressional and tensional stresses associated with faulting and/or folding (Foula)

2) Early tensional stresses associated with the precipitation of displacive calcite cement (Tarbat)

3) Late tensional oil-filled fractures thought to be a result of abnormal pore pressure developed during hydrocarbon generation (Melby and Tarbat)(Momper, 1978, 1980; Meissner, 1980)

Late compressional and tensional stresses that resulted in fracturing and faulting and/or folding were directly related to the tectonic setting of the Foula area and not to the depositional environment (Page 44, paragraph 3).

Oil filled tensional fractures in two calcite cemented samples from the two areas that were dominated by lacustrine influences (Melby and Tarbat) may have formed as a result of abnormally high pressure that could have occurred during hydrocarbon and CO_2 generation (Momper, 1978, 1980, Meissner, 1980). Fractures of this kind would more readily permit migration of hydrocarbons from the source rock to the reservoir (Al-Shaieb and Shelton, 1981). This idea suggests that these fractures indicate a nearby source rock (Al-Shaieb, pers. comm.) which is thought to be lacustrine laminites (Parnell, 1983). Therefore, oil filled tensional fractures in calcite cemented samples may be diagnostic of nearby lacustrine laminite facies.

Early displacive calcite cement caused fracturing in a sample from Tarbat (Page 88, paragraph 1). It is suggested that this type of fracturing is a diagnostic feature of early displacive calcite cement. However, because this type of fracturing is dependent on the early displacive calcite cement, the fracturing can only be related to a particular depositional environment if the calcite cement is also related to that same depositional environment.

Calcite is present in all four areas. It averages 14 percent of the samples from Melby and Tarbat, and less than 1 percent at Foula and Portskerra. Very early displacive calcite is characteristic of the samples from Melby and

Tarbat and is thought to be a diagnostic feature of sands that were diagenetically influenced by lake waters. The displacive nature of the calcite resulted from supersaturated ground waters (Page 88, paragraph 1). The requirement of supersaturated ground waters was stressed by Weyl (1958). Lake waters that were supersaturated with respect to calcite transgressed the fluvial sands and deposited calcite cement. Samples from Melby and Foula have only trace amounts of calcite that may have begun to form during the late part of early diagenesis as a minor cement and replacement mineral. The presence of only trace amounts of calcite together with the absence of any very early displacive calcite may be a diagnostic feature of the locations that were not influenced by lake waters.

Authigenic hematite is present in samples from all four locations. It formed primarily as an early alteration product of biotite. The amount of authigenic hematite seen in thin section depends primarily on:

1) The original amount of biotite that was present in the samples

2) The amount of iron that was redistributed

3) The early environmental conditions that occurred

In the Melby area, a comparison of the estimated original amount of biotite to the existing authigenic hematite showed that with increasing original biotite content, there is an increase in the amount of authigenic hematite formed (Page 62, paragraph 2). The hematite formed in part as pseudomorphs of biotite and/or grain coatings. In thin sections, complete hematite pseudomorphs of biotite appear to occupy approximately the same volume of rock as the original biotite. However, if the iron from the biotite is redistributed as grain coatings, then the hematite appears to occupy a volume several times greater than the original volume of biotite.

To imagine the affect of redistribution of iron on the apparrent volume of iron seen in thin section, imagine how many clear, one foot diameter spheres that could be painted with a gallon of red paint. In thin section, the volume of grain coating hematite could easily be over estimated due to a combination of thin coatings and slanted grain boundaries.

Very early calcite that formed under the influence of lake waters appears to have greatly hindered the oxidation of biotite at the Melby and Tarbat locations (Page 74, paragraph 3). Calcite completely cemented the sandstones, reducing permeability and preventing oxidizing fluids from reaching the biotite. Therefore, the abundance of biotite in calcite cemented sandstones may be indirectly diagnostic of a lacustrine depositional environment and the abundance of early authigenic hematite in calcite poor sandstone may be directly related to a continental depositional environment. Late remobilization of hematite into fractures is unique to samples from Foula, however, this type of situation could presumably have occurred where there were late open fractures, a source of iron, and oxidizing fluids. Therefore, late occurrences of hematite are not diagnostic of a particular depositional environment.

Authigenic potassium feldspar is present in all four areas. It occurs most frequently as early overgrowths on detrital feldspar grains. In samples from Portskerra, independent rhombs of authigenic potassium felspar are present (Page 106, paragraph 3). However, the timing and most common mode of occurrence is similar among the four areas suggesting that the occurrence is not characteristic of a particular depositional environment.

Authigenic chlorite occurs primarily as an early radial pore lining clay in samples from Foula and Melby. Because the two locations represent different environments of deposition and the timing and mode of occurrence of chlorite are similar in each, the presence or absence of early authigenic chlorite is not diagnostic of a particular depositional environment.

Authigenic illite is present in every sample from all four areas. Illite is most commonly seen as a replacement mineral of feldspars along cleavage planes and as a pore lining clay. Illite dust rims suggest that some illite growth was early, while the incomplete nature of illite replacement of feldspar suggests that illite growth may have occurred at any time during diagenesis whenever conditions were right. Therefore, the similarity in timing and mode of occurrence of authigenic illite suggests that illite growth is not a diagnostic feature of a particular depositional environment.

Authigenic pyrite occurs as a minor pore filling cement in only one sample, which is from the Tarbat area (Page 87, paragraph 1). The rest of the sample is cemented by calcite. The presence of early pyrite cement, which probably formed under reducing conditions, and early calcite cement suggests a possible lacustrine influence. However, the scarcity of authigenic pyrite in any of the other samples and the fact that pyrite is also frequently associated with oil migration (which occurred in at least three of the locations) suggests that precipitation of authigenic pyrite is not a diagnostic feature of a particular depositional environment.

Kaolinite was identified only in samples from Tarbat (a lacustrine-dominated depositional environment) and Foula (a fluvially-dominated depositional environment). Kaolinite averages less than 1 percent in the samples from Foula and almost 2 percent in the samples from Tarbat. Kaolinite is thought to have occurred in part as a result of dissolution of feldspars (Al-Shaieb and Shelton, 1981) during late stages of diagenesis under slightly acidic conditions. Because the kaolinite occurred in two areas (each representing a different depositional environment) kaolinite is not thought to be diagnostic of a particular depositional environment.

Evidence of dissolution of feldspar and detrital matrix is a common feature of samples in all four areas. Illite along feldspar cleavage planes, remnant feldspar grains in moldic pores, kaolinite in moldic pores, and calcite replacement of feldspar suggest that feldspar dissolution has occurred. Remnant detrital matrix in irregular pores suggest dissolution of detrital matrix has occurred also. Illite dust rims and moldic pores that are partially filled with early cements suggest that dissolution of feldspars and detrital matrix began early, The incomplete nature of the dissolution suggests that dissolution may have occurred throughout diagenesis whenever conditions were right. Because these dissolution features are relatively similar in time and mode of occurrence in each area, dissolution of feldspars and detrital matrix is not diagnostic of a particular depositional environment.

Dissolution of quartz occurred in all four areas. In the Melby and Tarbat areas, dissolution of quartz is thought to have occurred early during the formation of displacive calcite. The degree of dissolution of quartz in these samples is thought to be minor because of the relatively smooth boundaries between many of the quartz grains and the calcite cement. Dissolution of quartz in the samples from Foula is also similarly related to precipitation of calcite cement. However, in this case the cement is later in occurrence than in the samples from the

Melby and Tarbat locations. Minor pressure solution occurred early in the samples from the Portskerra area. Although timing and mode of occurrence of quartz dissolution varies among the four areas, the amount of detectable dissolution is so slight that no attempt will be made to identify dissolution of quartz as a diagnostic feature of a particular depositional environment.

Minor dissolution of calcite occurred in each of the three areas where calcite precipitation had occurred. Dissolution of calcite is identified mainly by irregular calcite crystal edges adjacent to pore spaces. Dissolution is thought to be a late diagenetic event that occurred in part as a result of near surface conditions that would allow neutral to slightly acidic rain waters to affect the ground water chemistry. Therefore, dissolution of calcite is not a diagnostic feature of a particular depositional environment.

Porosity

All of the thin section were analysed for porosity evolution. The major loss of primary porosity in samples from Tarbat and Melby was due to early calcite cement, and in samples from Portskerra and Foula it was due to compaction and early quartz cement. Therefore, the timing of the loss of primary porosity is similar among the four locations (but the mode of occurrence was different between the lacustrine influenced areas and the continental influenced areas). We might conclude that the mode of occurrence of primary porosity loss is diagnostic of a particular depositional environment, but what we would really be saying is that early calcite cement is diagnostic of a particular depositional environment, a conclusion that has already been established. Early clay coats have prevented loss of primary porosity in samples from Foula and Tarbat. Therefore, early clay coats are not unique to a particular depositional environment. The major porosity in the samples is secondary. Secondary porosity occurs primarily as a result of dissolution of feldspar and (to a lesser extent) calcite. The timing and mode of occurrence are relatively similar. Therefore, secondary porosity is not a unique feature of either depositional environment.

Conclusions

Each of the four study areas (Melby, Tarbat, Foula, and Portskerra) are located somewhere near the outer margins of a closed lake basin, the Orcadian Basin. The relative location of each area with respect to the center and outer margins of the basin was estimated using a model by Donovan (Page 116, paragraph 1). In each, sandstones were deposited in a (braided) fluvial environment. However, Foula and Portskerra were influenced by predominantly fluvially-related ground waters of continental origin during and shortly after deposition. On the other hand, Melby and Tarbat were influenced predominantly by waters of lacustrine origin shortly after deposition.

Most textures are generally similar in samples from the four locations. The sandstones are most often submature with moderately well sorted grains. Variation in texture at Foula was due to a distinctive tectonic setting, and at Melby it was due to the fine grained nature of the sandstones. Mineralogy of the samples from the four locations suggests that sediments were supplied from at least three different source areas:

1) Melby and Tarbat were supplied by predominantly igneous and metamorphic source rocks.

2) Foula was supplied by predominantly metamorphic source rocks.

3) Portskerra was supplied by predominantly plutonic igneous source rocks.

Thin sections were analyzed at each location to determine the diagenetic events that took place and to determine which, if any, were related to early environmental conditions that were dominant at each area. It turns out that early displacive calcite is the most diagnostic feature of areas that were dominated by lacustrine influences shortly after deposition (Melby and Tarbat), and extensive early oxidation of biotite is most diagnostic of areas not influenced by lake waters (Foula and Portskerra). Four features that may have been indirectly related to samples from Melby and Tarbat include:

1) Residual hydrocarbons generated from lacustrine laminites

2) Tensional oil filled fractures related to over pressuring as a result of hydrocarbon generation

3) Calcite filled fractures caused by precipitation of displacive calcite

4) Abundance of preserved biotite

Nine authigenic minerals and paragenetic events that are not diagnostic of a particular depositional environment include:

1) Quartz overgrowths

2) Late hematite

3) Feldspar overgrowths

4) Chlorite

5) Illite

6) Pyrite

7) Kaolinite

8) Compaction

9) Dissolution of detrital constituents

Although early hematite and calcite precipitation are the only diagenetic events directly useful to descriminate among depositonal localities, these lines of evidence are quite valuable for such purposes.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Fluvial and alluvial sands were being deposited in a closed lake basin, the Orcadian Basin, during Middle Devonian time. Lake water level constantly changed both annually and on a longer term basis (c 20,000 year) (Donovan, 1980), and fluvial channels draining into the basin were often transgressed by the lake waters. It is surmised that lake waters transgressed outer basin fluvial deposits less frequently than the fluvial deposits nearer the basin center.

Sandstone samples were studied from four areas of the basin to determine their petrology and diagenesis. The four locations were then compared to determine how these two parameters related to various depositional conditions. The following conclusions were made:

1) Donovan's (unpublished) model was used to determine the relative positions of each area within the Orcadian Basin. Tarbat and Melby are located about two thirds of the way from the basin center toward the outer basin margin. Foula and Portskerra are located about four fifths of the way from the basin center toward the basins outer margin. The frequency of limestone beds present in outcrop

and the abundance of early calcite cement in thin sections were used to predict how each area might fit into the model.

2) Sedimentary Petrology of the samples suggests that there were at least three different source areas; each contributed sediment to one or more of the four study areas. Melby and Tarbat were sourced by primarily igneous and metamorphic rocks. Foula was sourced by primarily metamorphic rocks. Portskerra was sourced by primarily plutonic igneous rocks.

3) Early displacive calcite, which is present in samples from Tarbat and Melby, is diagnostic of sands that were affected by a lacustrine influence during early diagenesis.

4) Oxidation of biotite is inhibited as a result of early calcite cementation in samples from Tarbat and Melby.

5) Extensive oxidation of biotite is diagnostic of sands that were not influenced by lake waters during early diagenesis.

6) Iron derived from early post-depositional oxidation of biotite was redistributed in part as grain coatings.

7) Tectonic activity near the unconformable sediment-metamorphic basement contact on Foula Island was responsible for decreasing the maturity and sorting of sandstones. Sandstones nearest the unconformity are generally immature and poorly to very poorly sorted. These sandstones grade into submature, moderately-well to well

sorted sandstones away from the unconformity.

8) In the Foula area, samples studied are submature to immature, very poorly sorted to well sorted, angular to subrounded, medium to fine grained, subarkoses to lithic arkoses to sublitharenites.

9) Detrital constituents identified in samples from Foula are monocrystalline and polycrystalline quartz, feldspars, metamorphic rock fragments, volcanic rock fragments, siltstone fragments, sandstone fragments, shale fragments, chert, detrital matrix, muscovite, biotite, hematite, glauconite, pyrite, zircon, apatite, garnet, sphene, rutile, blue tourmaline, and chlorite.

10) Authigenic constituents identified in samples from Foula are hematite, quartz overgrowths, illite, chlorite, kaolinite, feldspar overgrowths, calcite, leucoxene, and chert.

11) In the Portskerra area, samples studied are submature, moderately-well to very poorly sorted, angular to subrounded, fine to coarse grained, subarkoses to arkoses.

12) Detrital constituents identified in samples from Portskerra are monocrystalline and polycrystalline quartz, feldspars, plutonic rock fragments, metamorphic rock fragments, chert, volcanic rock fragments, shale fragments, muscovite, biotite, chlorite, apatite, hematite, zircon, garnet, rutile, glauconite, pyrite, and detrital matrix.

13) Authigenic constituents identified in samples from

Portskerra are quartz overgrowths, feldspar overgrowths and rhombs, hematite, illite, kaolinite, chlorite, leucoxene, and calcite.

14) In the Melby area, samples studied are submature to immature, moderately well to poorly sorted, angular to rounded, very fine to coarse grained, subarkoses to lithic arkoses to arkoses.

15) Detrital constituents identified in samples from Melby are monocrystalline and polycrystalline quartz, feldspars, metamorphic rock fragments, chert, carbonate ooids, plutonic rock fragments, volcanic rock fragments, granopheres, muscovite, biotite, hematite, zircon, garnet, chlorite, rutile, pyrite, apatite, blue tourmaline, glauconite, and detrital matrix.

16) Authigenic constituents identified in samples from Melby are calcite, quartz overgrowths, hematite, illite, chlorite, kaolinite, feldspar, and leucoxene.

17) In the Tarbat area, samples studied are submature, moderately-well to poorly sorted, angular to subangular, very fine to very coarse grained , subarkoses to lithic arkoses.

18) Detrital constituents identified in samples from Tarbat are monocrystalline and polycrystalline quartz, feldspars, metamorphic rock fragments, volcanic rock fragments, chert, siltstone fragments, plutonic rock fragments, sandstone fragments, carbonate rock fragments, biotite, muscovite, hematite, zircon, garnet, rutile,

chlorite, pyrite, glauconite, and detrital matrix.

19) Authigenic constituents identified in the samples from Portskerra are calcite, quartz overgrowths, illite, kaolinite, chlorite, hematite, and leucoxene.

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