UNIVERSITY OF SOUTHAMPTON

Kerogen variation in a Devonian half graben system

Reuben Guthrie Speed BSc., MSc.

Doctor of Philosophy

Department of Geology

February 1999

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE
GEOLOGY

Doctor of Philosophy

KEROGEN VARIATION IN A DEVONIAN HALF GRABEN SYSTEM

by Reuben Guthrie Speed

The Middle Devonian Rousay Flagstone Formation of Orkney is a 200m thick lacustrine succession that contains abundant preserved organic matter. It was deposited into a series of half graben formed by the collapse of over-thickened Caledonian crust. The 14 lake cycles that comprise the Rousay Flagstone Formation (RFF) were correlated across Orkney during 6 months of fieldwork. Two of the lake cycles were sampled in detail for geochemical analysis. This work has enabled an understanding of the sedimentary and tectonic processes that controlled the distribution of facies and the quality of source rocks within the Orcadian Basin during this time. The processes and environments present in Orkney during this time may be compared to the Horton Group in Nova Scotia (Hamblin & Rust 1989).

The main finding of this research has been the extent to which the East Scapa Fault (ESF) caused variation in sedimentation. By slowly extending throughout the RFF, the half graben bounding fault caused certain areas of Orkney to experience continued relative uplift.

Two aspects of the structure of the half graben were of greatest influence. Firstly the uplifted footwall of the half graben provided an environment away from the influence of inflowing sediment and oxygen rich turbidity currents. The quiescent environment in this area allowed the greatest amount of laminite facies accumulation. It was found that high TOC (total organic carbon), H/C (hydrogen/carbon ratio) and spore numbers were associated with these areas of enhanced laminite deposition.

The second area was a transfer zone located at the northern splay of the ESF. The zone acted as a linkage zone between the ESF and a half graben to the north. Because of its location between adjacent half graben depocentres, sedimentation was affected by the relative uplift of the area in a manner similar to the uplifted footwall area to the west of the ESF.

The main agents that were detrimental to the formation of source rocks were turbidity currents. These currents originated from the three main areas of alluvial fan input in the basin. Turbidity currents carrying sediment and oxygenated water from these fans would bypass the shallower and more uplifted areas and preferentially deposit in the more distal and downthrown areas. The area immediately to the east of the ESF was the main location to have experienced reduction in kerogen quality (TOC, H/C and spore numbers) because of turbidite deposition.

The preserved organic matter is predominantly composed of amorphous organic matter, making the main kerogen type Type I. About 40% of each Rousay Flagstone Formation lake cycle contains measurable organic matter, on average about 0.8%. The amount of organic matter is controlled by facies type, with laminite facies having the highest average TOC (1.55%) and grey silts having least (0.3%).

Exinite reflectivity and spore colour variation analyses from across Orkney indicate that the thermal maturity of the sediments is within the thermal range of hydrocarbon generation. Additionally the uniform spread of maturity values across Orkney indicates that fault movement was never great enough to cause differential thermal maturity regimes to form across Orkney.

Contents

Contents continued

Contents continued

List of Figures

List of figures continued

List of Tables and Plates

Acknowledgements

This study would not have been possible if not for the previous work of my supervisor John Marshall, and Tim Astin. Both of who inspired me to look a little deeper into Orkney. Thanks for the constant support and encouragement.

During the course of the fieldwork for this project, I met more wonderful people than I thought possible. These kind souls shared tents, hostels, houses, cars, vans, garages, stone circles, food and drink with an over-enthusiastic geologist and didn't complain much. John Brown, geologist of Stromness, thank you for your time and vision.

My stay in the south was made all the warmer by the friendship of Kevin, Nik, Rob, Robin, Gavin, Dom, Lawrence, Big Dan, Leila, Helen, Elena, Sylvia, Nora, Jenny, Rosie and Lynda. Cath, I couldn't have done it without you.

Shir Akbari is gratefully thanked for teaching me how to handle HF, and for processing above and beyond the call of duty. Jack Saxon of Scrabster helped me find the allusive *Asmusia*. Cheers!

I would also like to thank Tony Hewett and Richard Pawlyn for their prompt and pragmatic help as well as access to Kerr McGee's bountiful resources.

Big thanks also to Lawson Brown of Alastair Beach Associates for the breathing space to finish this thesis.

The financial support of a NERC CASE studentship with Kerr McGee Oil Ltd is gratefully acknowledged.

Faim

Si j'ai du goût, ce n'est guère
Que pour la terre et les pierres.
Je déjeune toujours d'air,
De roc, de charbons, de fer.

Mes faims, tournez. Paissez, faims,
        Le pré des sons.
Attirez la gai venin
        Des liserons.

Mangez les cailloux qu'on brise,
Les vieilles pierres d'églises;
Les galets des vieux déluges,
Pains semés dans les vallées grises.

Arthur Rimbaud 1854 -1891.

Dedicated to my Mum.

1.1 Aims

This dissertation reports a field and laboratory based study of the sedimentary facies and preserved organic matter present within the Middle Devonian lacustrine rocks of Orkney.

The main aims of this work are to:

- Establish a basin wide stratigraphy of the Rousay Flagstone Formation, using detailed field measurement and lithostratigraphic correlation.
- Describe the sedimentary and tectonic regime present in Orkney during the time of deposition of the Rousay Flagstone Formation, with particular reference to how these factors affected the quality and distribution of sedimentary organic matter.
- To quantify the hydrocarbon potential of these rocks.

1.2 Introduction

One is doubly blessed when fieldwork in Orkney is undertaken. These islands which lie immediately north of Scotland are one of the most awe inspiring places in which to study geology, and are inhabited by some of the most kind hearted folk one could wish to meet. There are about 20 inhabited islands and numerous, smaller uninhabited ones in the archipelago (Figure 1-1). Most of the 20 000 Orcadians live on the biggest island imaginatively called Mainland and which will be referred to as such throughout this thesis. The general topography is that of gently rolling hills which in Rousay, Westray and West Mainland can exceed heights of 250m. High sea cliffs are developed to the west of many of the islands.

Hence, Orkney is ideally suited for geological study because a significant proportion of its coastline offers excellent exposure, regularly scoured clean by fierce Atlantic storms. In many cases the generally gently dipping strata may be easily followed between outcrops both on the same island and between islands. This means that the 2500 km^2 that the islands occupy, form the ideal setting for the study of the large-scale sedimentary system that comprised this area in Devonian times.

The sedimentary rocks of Orkney are composed mostly of the Orkney Flagstone Group, which is mid Devonian in age. This Group (or its equivalent) extends south to Caithness and north to Shetland (Mykura 1976). It also occurs offshore to the east (Duncan and Buxton 1995) and possibly to the west of Orkney (Coward & Enfield 1987). The area into which these Devonian sediments were deposited is generally referred to as the Orcadian Basin.

These rocks include organic matter rich sediment, which were deposited across the Orcadian Basin, in one or a series of large stratified lakes. The Orkney Flagstone Group's lateral equivalent in the Moray Firth is accepted as the source of all (Bailey et al. 1990) or part of (Duncan & Hamilton 1988) the Beatrice oil field.

It is generally accepted that these sediments were deposited in a semi-arid environment (Donovan 1980, Rogers & Astin 1991) and were associated with a variety of sand-rich continental-type facies. The interplay between the lake and sand rich sediments can be seen to be the result of a periodically changing environment. When the climate was wetter lakes formed, and when it was drier, sand rich sediments were deposited by terminal fans that transported sand onto the dry lake beds by a mixture of processes. Thus the Orkney Flagstone Group can be seen as a series of around 80 wet-to-dry sedimentary cycles formed by climate variation (most recently discussed in Marshall 1996 and Astin 1990). Careful field observation of these lake cycles has allowed parts of the Orkney Flagstone Group to be reconstructed and correlated across Orkney (Astin 1990 and this thesis). This stratigraphic framework has allowed the sedimentary processes in individual lake cycles to be studied in detail.

Using detailed lithostratigraphic correlations and lab based organic matter analysis, a study of the distribution and variation of the kerogen found in individual lake units throughout Orkney provides a valuable insight into the depositional processes that were operating in the ancient lake system. This information about the potential richness of Devonian source rocks in the Orcadian basin will be of use in future hydrocarbon exploration in the area.

1.3 Regional Geology

Stratigraphy / Sedimentation

The majority of Orkney is composed of continental sediments of Early to Mid Devonian age, with rare occurrences of exposed pre-Devonian metamorphic basement in the west of Mainland, and some late-Middle Devonian volcanic rock. The continental sediments were deposited in a gently extending and subsiding basin now generally accepted as being caused by the approximately east-west collapse of over-thickened Caledonian crust (McClay, et al.. 1986).

Of these sediments, perhaps the most interesting are the group of Middle Devonian lacustrine sediments known as the Orkney Flagstone Group, comprised of the Upper and Lower Stromness and Rousay Flagstone Formations (Figure 1-1). These are the deposits of an ancient lake system that extended from the Moray Firth to the Shetland Islands - an original distance of over 500km (Rogers, Marshall & Astin 1989). The Orkney Flagstone Group was deposited in a distal area of this basin and developed a marked cyclicity caused by periodic water level fluctuations in the lake (Donovan 1980). The lake cycles represent changes from wetter to drier environments of deposition suggesting that the lake partially dried up and was replenished frequently. The cycles are mainly in the region of 10 to 20 metres thick. At present a thickness of over 1500m of these sediments are preserved within the Orcadian Basin (Astin 1991) (Figure 1-2).

The flagstone cycles have been interpreted by Rogers & Astin (1991) as consisting of an initial permanent lake deposit, forming the lower part of each cycle and containing laminite and other fine grained sediments (along with fish fauna and stromatolites). This is followed by sediment deposition in an arid, ephemeral lake environment with associated terminal fan deposits (Figure 1-3). The transition between the two depositional styles is thought to have been rapid and caused by cyclic climatic change on the scale of 123,000 years (Astin 1991, Marshall 1996). Hypersalinity and anoxia during the deposition of the lacustrine-type facies has resulted in the widespread preservation of organic matter (Marshall et al. 1985, Parnell 1985).

The Orkney Flagstone Group is divided into three formations (Figure 1-2). The Lower Stromness Flagstone Formation is stratigraphically the lowest and onlaps onto metamorphic basement in west Orkney. Above this is the Upper Stromness Flagstone Formation. These two formations occupy most of west Mainland (Figure 1-1).

The boundary between the Upper and Lower Stromness Flagstone Formations is the Sandwick Fish Bed Cycle (the Orkney lateral equivalent of the Achanarras fish bed of Caithness). This cycle is the unusually thick deposit of a laterally extensive, deep lake, which persisted for longer than usual and contains a diverse and distinctive fauna of fossil fish (Wilson et al. 1935, Trewin 1986, Fannin 1970). Due to the monotonous and repetitive nature of the lake sediments in the Orkney Flagstone Group, basinwide correlation depends heavily on the recognition of this unique and distinctive horizon.

The third formation of the Orkney Flagstone Group and the focus of this thesis is the Rousay Flagstone Formation which is of Eifelian/Givetian age. The Rousay Flagstone Formation is the most widespread unit in Orkney, occurring over most of the northern isles of Orkney, east Mainland, south east Hoy and parts of the southern islands – roughly 1600 km^2 (Figure 1-1). In the past, the Geological Survey used the first occurrence of the fossil branchiopod *Asmussia* (formerly *Estheria*) to place the base of the Rousay Flagstone Formation (Wilson et al. 1935). However, recently a lithostratigraphic framework has been constructed by Astin (1990), which redefines the Orkney Flagstones in terms of correlatable lake cycles (Figure 1-4). In this framework the Rousay Flagstone Formation is defined as occurring between the 25th lake cycle above the Sandwick Fish Bed Cycle and the overlying Eday Group. Astin's work has also reduced the thickness of the Rousay Formation from an estimated 1675 m (Wilson et al. 1935) to around 200 m (Table 1-1). The consequences of Astin's work will be discussed in Chapter 2.

The Eday Group immediately overlies the Rousay Flagstone Formation. It consists three large-scale fluvial and aeolian sandstone units interbedded with 2 units of marl and flagstone. The sandstones are characteristically red or yellow in colour and so provide a visual marker indicating the top of the predominantly blue–grey coloured Rousay Flagstone Formation. The Eday Group is found mainly in Eday, east Mainland, Hoy and South Ronaldsay (Figure 1-1).

General literature on the geology of Orkney (e.g. Wilson et al. 1935, Mykura 1976) regards the Hoy Sandstone as belonging to the Upper Old Red Sandstone, separated by a regional unconformity from the underlying Eday Group. However increasing evidence suggest that only a local unconformity exists between the two units, and that the two are lateral equivalents (Rogers 1987 and Astin unpublished).

Structure and tectonics

The broad structure of Orkney is relatively simple (Figure 1-5). Most of the folds that affect the Devonian sediments are very open and many have a northerly trend. The most noticeable regional folds are the northward plunging Eday Syncline and the West Mainland Anticline, which are responsible for much of the structural variation in Orkney (Figure 1-6). The main faults on Orkney strike north-northeast, south–southwest and east-northeast, west-southwest (Figure 1-5). Both sets of faults are believed to have had two main phases of movement. Firstly the faults extended normally during the deposition of the Devonian sediments and are believed to have controlled sediment distribution (Astin 1985; Enfield & Coward 1987; Astin 1990; Hippler 1993). After this, many of the faults were reactivated prior to the intrusion of a suite of Permian dykes. Slickenside measurements suggest a sinistral, oblique-slip motion to the reactivation (Hippler 1993).

Commercial speculative seismic data acquired immediately to the west of Orkney (Enfield & Coward 1987) has revealed a series of generally northeast trending, east dipping faults (Figure 1-7). These faults were probably first active as extensional faults in the Devonian (Brewer & Smythe 1984) and are thought to be the graben bounding faults delimiting the graben into which the Devonian sediments were deposited (Enfield & Coward 1987). It is thought that faults of similar trend seen on shore, such as the East Scapa Fault (Figure 1-5), are the exhumed remains of other such graben bounding faults (Astin 1990). Note that due to the nature of the outcrop in Orkney (limited onshore or covered in water), the exact trace of many of the faults is uncertain. Different workers in this field have tended to use different estimations of the position of these faults. For example Enfield & Coward (1987) mark the East Scapa Fault as passing to the west of Shapinsay, whereas Astin (1985) has the East Scapa Fault passing through Shapinsay. Additionally Astin (1990) has noted several short unlinked faults along the west coast of Mainland, whereas Enfield & Coward (1989) have amalgamated these faults into a single, east dipping normal fault cutting the entire length of the coast. It is not within the scope of this thesis to argue the placing of these faults, since the alternative position of these faults do not conflict with any of the results of this work. For consistencies sake the structural map of Coward & Enfield (1989) is used throughout this thesis (Figure1-5). Note also that the previously unnamed fault on the west coast of Mainland is referred to in this thesis as the West Mainland Fault.

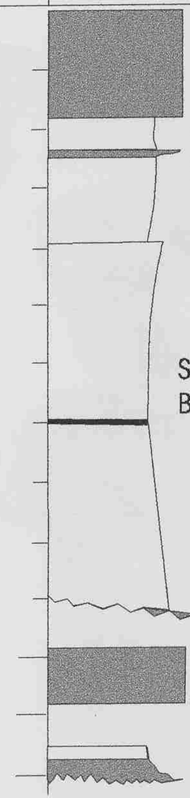
Wilson et. al. (1935)	Fannin (1970)	Fannin (1970) quoted in Mykura (1976)	This thesis and Astin 1990.		
Eday Beds					Eday Group
Rousay Beds 1675m				Sacquoy Sandstone Member 4-17m Rousay Flagstone Fm (~ 14 cycles) approx 200m	Orkney
Upper Stromness Flags 335m Sandwick Fish Bed	Upper Stromness Flags 290m Sandwick Fish Bed 0.5m	Upper Stromness Flags 190m Hoy Cycles 61-79m Sandwick Fish Bed Cycle 55-61m		Upper Stromness Flagstone Fm (24 cycles) 325m Sandwick Fish Bed Cycle 5m	Flagstone
Lower Stromness Flags 1077m	Lower Stromness Flags 350m	Lower Stromness Flags 215-350m		Lower Stromness Flagstone Fm 215-350m	Group
	Yesnaby Sst Group 200m Yesnaby Fm Harra Ebb Fm	Basal Breccia 0-20m			

Table 1-1. Summary of sedimentary thickness revisions - Orkney Flagstone Group. Modified from Astin 1990.

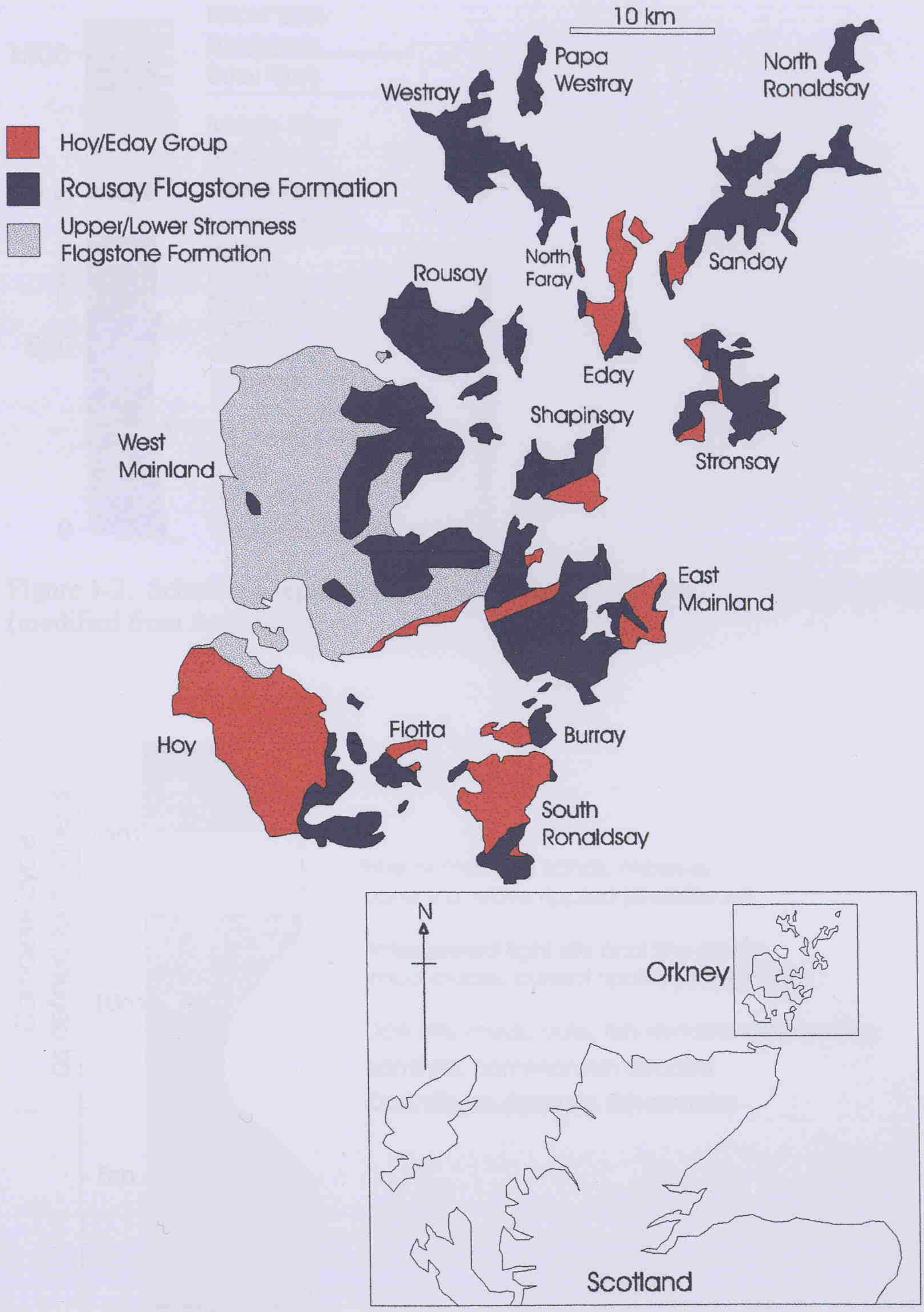


Figure 1-1. Location map of Orkney and simplified Devonian geology.

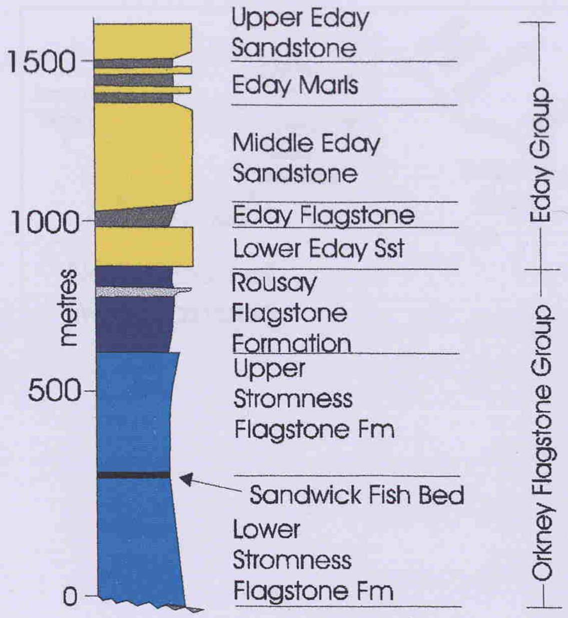


Figure 1-2. Schematic representation of the Middle Devonian stratigraphy of Orkney (modified from Astin 1990).

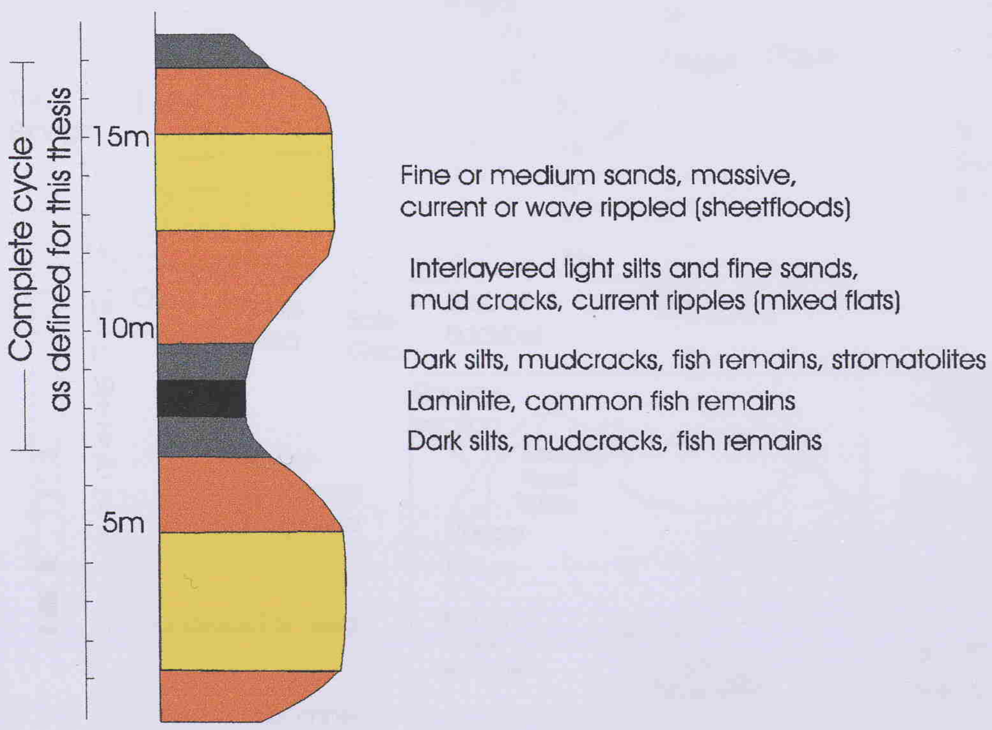


Figure 1-3. Schematic diagram of ~2 Orkney Flagstone Formation cycles, showing the approximate scale of the cycle, and the main lithologies present.

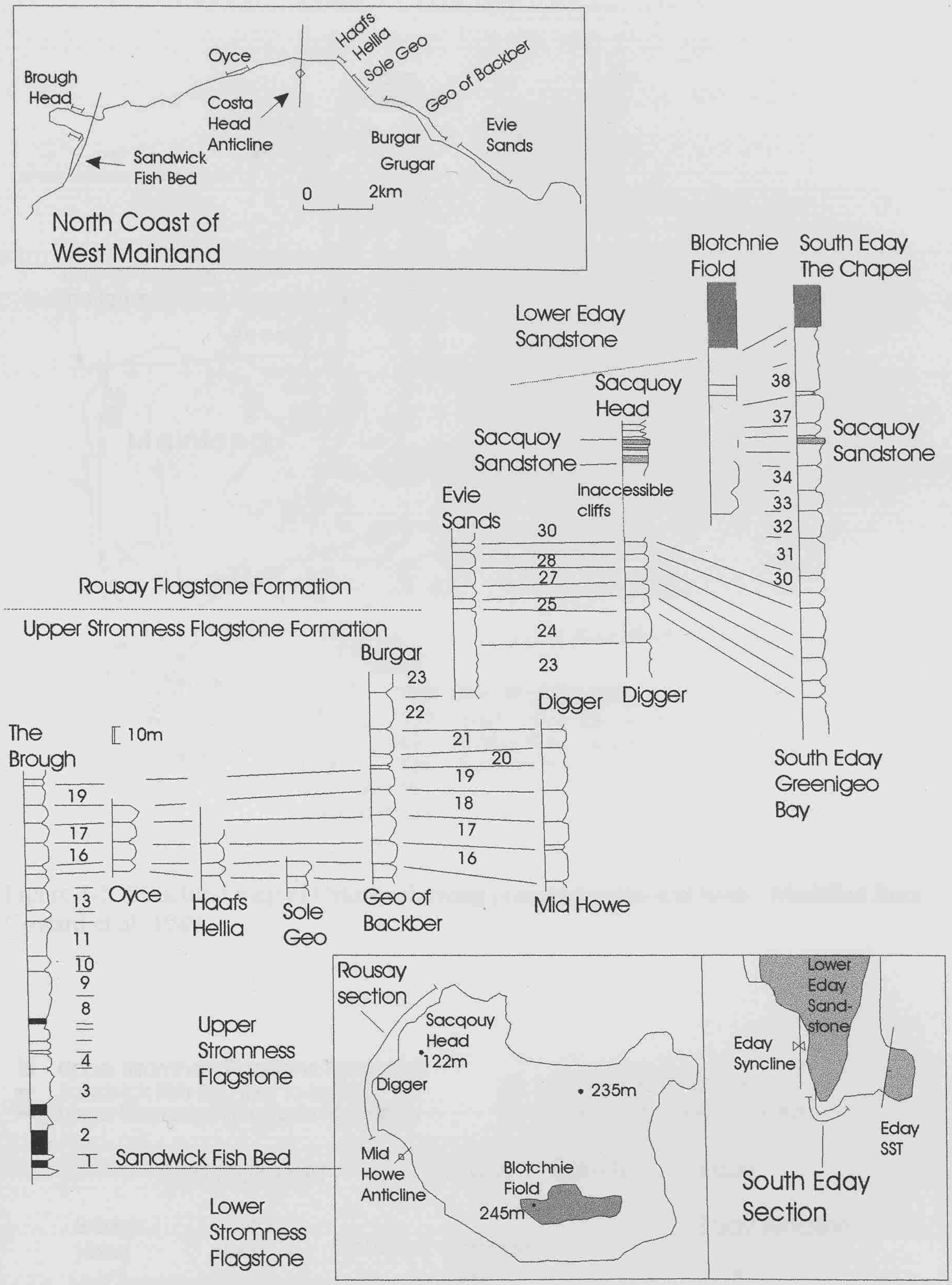


Figure 1-4. The Orkney Flagstone Group stratigraphic framework proposed by Astin (1990).

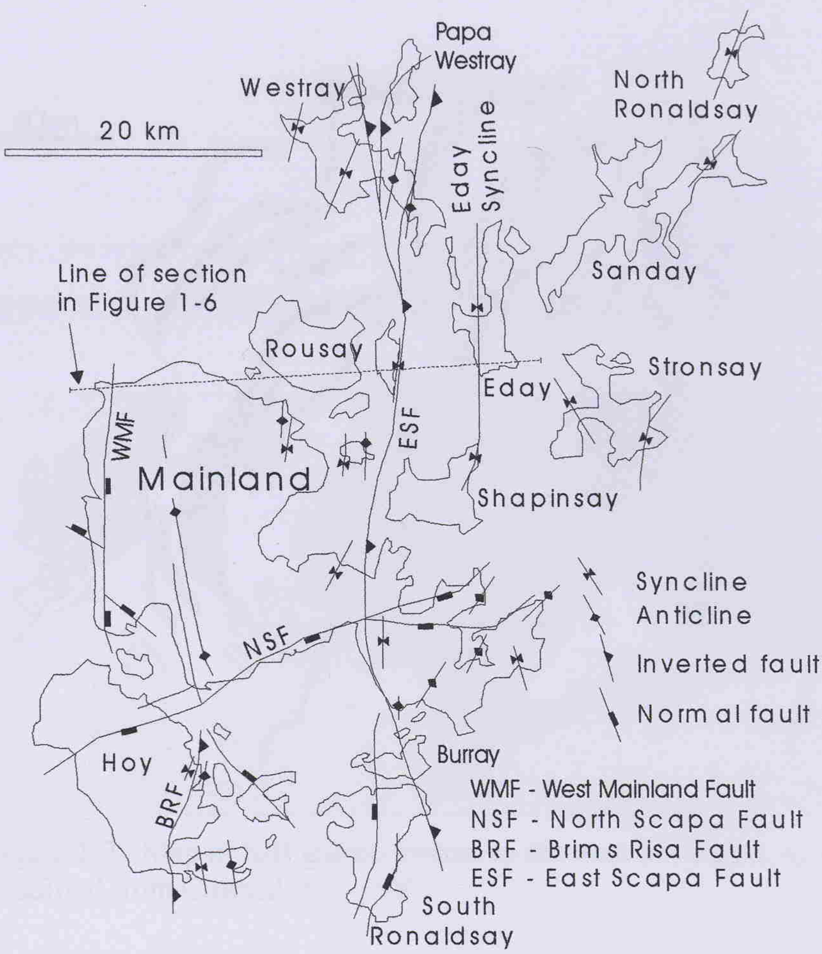


Figure 1-5. Structural map of Orkney showing principal faults and folds. Modified from Coward et al. 1989.

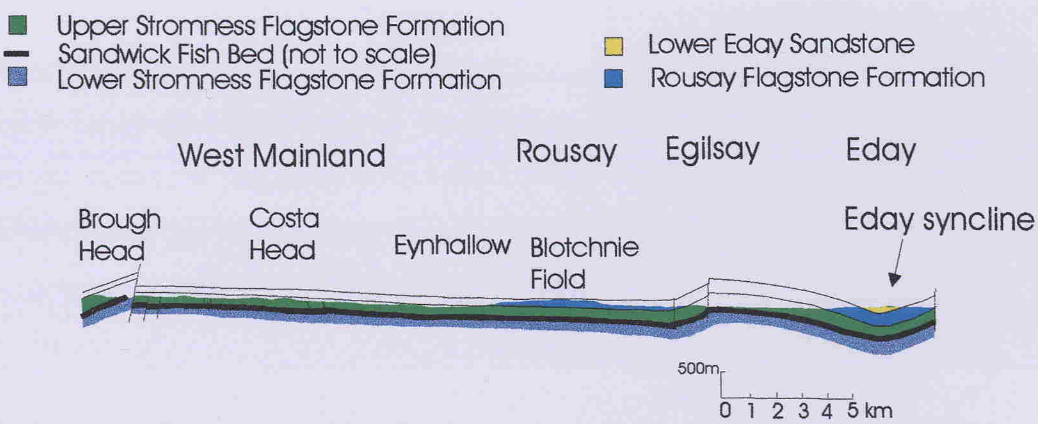


Figure 1-6. West-east cross section of northern Mainland, Rousay and Eday. Modified from Astin 1990. See Figure 1-5 for location of cross section.

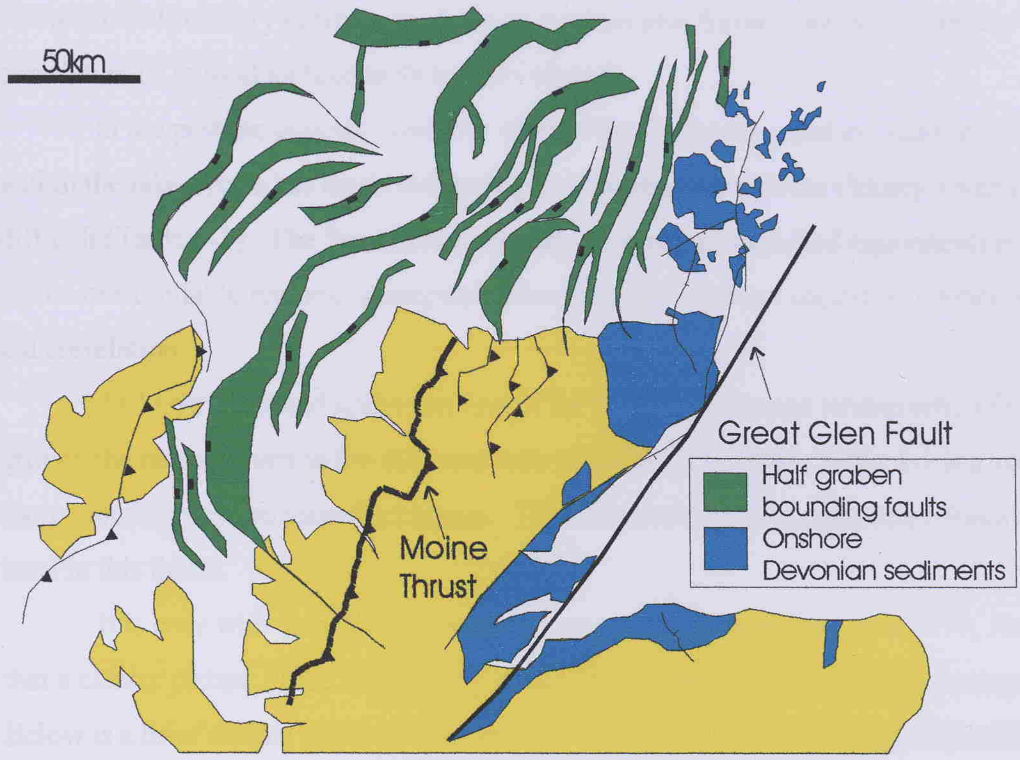


Figure 1-7. Map of half graben system to the west of Orkney, as shown on seismic data. Modified from Coward et al. 1989.

2 A stratigraphic framework

To make possible the study of the sedimentary processes that occurred within the Devonian sedimentary basin, some form of stratigraphic framework was needed to enable the correlation of individual lake units across Orkney.

In the past the general similarity of both the thicknesses and the sediments contained within the lake cycles has made estimating the true thickness of the Orkney Flagstone Group difficult (Table 1-1). The Sandwick Fish Bed (Achanarras Fish Bed equivalent) is thought to be the most reliable regional stratigraphic marker, and has been used in a number of works to aid correlation.

As knowledge and understanding of the Middle Devonian stratigraphy of Orkney has grown, the names given to the different rock units have changed. Table 1-1 is a summary of the various names and their thicknesses. The formation names proposed by Astin (1990) are used in this thesis.

It is only with detailed section measuring and correlation (Fannin 1970, Astin 1990) that a clearer picture of the stratigraphy of the Orkney Flagstone Group has emerged. Below is a brief outline of the development of the present understanding of Orcadian stratigraphy.

2.1 A brief history of the geological study of the Orkney Flagstone Group

J. S. Flett produced the first detailed stratigraphy of Orkney in 1897 where he recognised the Rousay Beds as a separate formation. Following this in 1935, the Geological Survey produced a descriptive memoir of the geology of the islands (Wilson et al. 1935). They estimated about 3100m of Middle Old Red Sandstone lake sediments (Wilson et al. 1935). This thickness was composed of at least 1067m of Lower Stromness Flagstones between the Sandwick Fish Bed and the metamorphic basement. Above this was 335m of Upper Stromness Flagstone and 1700m Rousay Flagstones between the Sandwick Fish Bed and the distinctive sandstone of the Eday Group (Wilson et al. 1935). Their correlation between outcrops was based on the recognition of key species of fossil fish and the branchiopod *Asmusia membranacea*, with little attention being given to lithological variations.

Fannin (1970 and quoted in Mykura 1976) in an unpublished thesis, brought a degree of accuracy to the study of Orcadian stratigraphy. Detailed section measuring in West Orkney allowed correlation between sections of the Stromness Flagstone Formation. He recognised the Sandwick Fish Bed in many more places than the Geological Survey, and thus was able to revise the stratigraphic thickness of the Lower Stromness Flagstones downward from 1087m to 350m. He also proved at least 290m of Upper Stromness Flagstones above the Sandwick Fish Bed. Work on the Rousay Flagstone Formation was outside of the scope of that thesis.

South of Orkney, in Caithness, Donovan et al. (1974) estimated a total of more than 3800m of cyclic Middle Old Red Sandstone lake sediments. This was composed of more than 2300m of the Lower Caithness Flagstone Formation below the Achanarras Fish Bed. This was overlain by at least 1500m of the Upper Caithness Flagstone Group between the Achanarras Fish Bed and the mainly fluvial sediments of the John O'Groats Group. The John O'Groats Group is known to correlate with the Eday Group of Orkney (Flett 1897, House et al. 1977, and Astin 1985). Donovan et al. did not present detailed correlations across the numerous faults that cut the coastal sequence in Caithness. The presence of key fossil fish species and broad lithological variations being used to assign structurally separated sections to specific stratigraphic positions.

Plimmer (in his unpublished 1974 PhD thesis) attempted to define the stratigraphy and sedimentology of what he called the 'Rousay Group'. The main assumption made in this thesis was the estimate for the top and base of the Rousay Group from the Orkney Memoir (Wilson et al. 1935) and hence an estimated 2000m thickness for the unit. Correlation was based mainly on fossil fish occurrence and took little account of fault repetition. In this thesis the 'Rousay Group' was subdivided into three lithostratigraphically defined subgroups. No attempt was made to explain these lithological variations in terms of lateral facies variation rather than vertical facies change.

The most recent attempt at detailed correlation within the Orkney Flagstone Group was by Astin (1990). Careful stratigraphic logging of central and western Orkney, allowed a framework of about 45 lake cycles, to be extended from the Sandwick Fish Bed through the Upper Stromness Flagstone Formation and the Rousay Flagstone Formation to the base of the Eday Group (Figure 1-4).

Astin (1990) used the Sandwick Fish Bed as the key correlative horizon in his stratigraphy. This horizon contains a distinctive fish fauna and has been mapped by various workers (Wilson et al. 1935, Fannin 1970) at several locations in western Mainland. Working up from this horizon, Astin correlated individual lake cycles in the Orkney Flagstone Group across Western Mainland, Rousay and Eday.

The key features used to aid correlation were:

- Patterns of cycle thickness
- The nature of individual fish beds including their overall thickness
- The abundance, size and degree of articulation of fish fossils
- Presence or absence of stromatolites,
- The nature of the ephemeral components of the cycles
- In west Mainland the presence of decollement horizons and in the upper part of the Rousay and Eday sections the position of fluvial sand bodies with distinctive palaeocurrent directions (the Sacquoy Sandstone Member).

From this framework Astin estimated that the Upper Stromness Flagstone Formation was 325m thick, which agrees well with Fannin's (1970) figure of about 290m (Table 1-1). Astin redefined the Rousay Flagstone Formation as lake cycles 25 to 38 above the Sandwick Fish Bed. He defines the base of the Rousay Flagstone Formation as: 'the base of a thick 'fish bed' rich in fossil fish and stromatolites occurring at Scara Taing in Rousay, east of Grugar in N Mainland, and at Greenigeo Bay in south Eday...and starts a sequence of much thinner cycles'(Astin 1990). The correlations presented in Astin's work reduce the thickness of the Rousay Flagstone Formation from 2000m to approximately 200m. Astin's framework is the basis to the correlation panel presented in this thesis (Figure 2-1).

2.2 Note on the use of fossil fish in the stratigraphy of Orkney

The presence of fossil fish, preserved in the lake sediments of Orkney has proven extremely useful in the understanding the stratigraphy of the Orcadian Basin. Fish remains are often found in the deeper water sedimentary facies either as disarticulated collections of scales or as entire carcasses. The earliest workers used differences in the distribution of fish species to correlate between the Old Red Sandstone of Caithness and Orkney (Miller 1849, 1858) and to differentiate the Orkney Flagstone Group into different formations (Murchison 1897). For example two species of fossil fish *Thursius pholidotus* and *Millerosteus minor* occur in only in the Rousay Flagstone Formation (Flett 1898b), not in any older formation.

No attempt was made in this thesis to identify individual fish species. Previous workers (Wilson et al. 1935, Fannin 1970, Marshall 1998 etc) have through use of spores or fish defined with reasonable accuracy, the extent of the formations of the Orkney Flagstone Group. A summary of the fish biostratigraphy for Caithness and Orkney is given in Donovan et al (1974), together with an outline of the inherent uncertainties in establishing the biostratigraphy. Saxon (1975) describes in detail the appearance of the common fossil fish found in the Devonian of the north of Scotland. When fish remains were found during the fieldwork for this thesis, only their abundance and degree of articulation were noted to aid correlation between lake cycles.

2.3 Introducing the present correlation of the Rousay Flagstone Formation.

It was decided to create a stratigraphic framework only for the Rousay Flagstone Formation, rather than for the entire Orkney Flagstone Group. The main reason for this was that the Rousay Flagstone Formation has the largest area of exposure of the three Orkney Flagstone Group formations (Figure 1-1). This allows a more detailed study of lithological variation within a distinct unit, rather than a less rigorous study of several units.

As noted by Astin (1990) the base of the Rousay Flagstone Formation is not immediately obvious in the field. In order to place accurately the base of the Rousay Flagstone Formation, the original field logs used by Astin for the preparation of his 1990 stratigraphy were used to help re-log the parts of his stratigraphy. These were sections that linked the Upper Stromness Flagstone Formation to the Rousay Flagstone Formation (the Evie, Digger and South Eday sections) (Figure 1-4). Having established sections of known stratigraphic position, nearby sections were logged and where possible matched with the known sections. In this way a framework of logged sections of known stratigraphic position was extended across Orkney.

For the purpose of this thesis, as with Astin (1990), the base of the Rousay Flagstone Formation, is defined as the first well developed fish bed (containing fish remains and stromatolites), occurring above an especially thick cycle containing poorly developed lake facies in the Upper Stromness Flagstone Formation. This definition is adequate for the north western part of Orkney, however further south the character of the base of the Rousay Flagstone Formation changes. This is as expected since all of the lake cycles change due to natural variation in facies across the Orcadian Basin.

The Rousay Flagstone Formation contains about 14 first order lake cycles, and ends at the base of the distinctive, yellow Lower Eday Sandstone. The top of the Rousay Flagstone Formation is often heralded by the irregular occurrence of reddened silts and sandstones. This increase in subaerial exposure may signify increased fault movement and uplift (Astin 1990).

Several other lithological features were used to aid correlation. Of great stratigraphic value was a distinctive pebbly sandstone unit called the Sacquoy Sandstone Member (Astin

1990) which occurs close to the top of the Rousay Flagstone Formation. Although distinctly fluvial, the member is not erosive in nature as in no instance does it cut into the underlying dark silts, suggesting that it is not diachronous in nature. The Sacquoy Sandstone occurs in cycle 35 and is most prominent in the northwest of Orkney.

In short sections, or in sections where the top of the Rousay Flagstone Formation was not present, the most important method of stratigraphic correlation was comparing patterns of cycle thickness. This means that when trying to link two locations, the patterns of the relative thicknesses of the cycles were compared rather than the absolute thicknesses of the cycles. In this way more distal areas may be linked with proximal areas even where absolute thicknesses of sediment may be different.

Other features used in the correlation were variations in laminite facies thickness, the nature of the ephemeral-type facies of the lake components, and in the upper part of the Rousay and Eday sections, the position of fluvial sand bodies and palaeocurrent data. The complete Rousay Flagstone Formation correlation chart is presented in Figure 2-1.

2.4 Fieldwork

The detailed logging required for this thesis, took place over two, three month field seasons during the summers of 1996 and 1997. Most of the time in the field was spent making detailed sedimentary logs from wherever there were relatively unfaulted sections of Rousay Flagstone Formation strata. Heavily faulted, brecciated and poorly exposed sections were mostly avoided due to the uncertainty they would have introduced to the correlations. In many cases the locations visited were those selected sections described by Plimmer (1974) in his thesis dealing with the sedimentology and stratigraphy of the Rousay 'Group'. His work was invaluable for locating the best exposures of the Rousay Flagstone Formation.

This thesis investigates sedimentary variation within the Rousay Flagstone Formation. However in some cases strata of the previously unidentified underlying Upper Stromness Flagstone Formation were also measured, as an unavoidable part of the logging procedure. The Upper Stromness Flagstone sections were not studied.

This research studied processes operating on a basin-wide scale. This necessitated the gathering of as much data from as wide an area as possible. Since there was a limited amount of time to gather the information, the thinnest sedimentary unit that was measured was about 5cm thick (apart from thin but notable layers such as stromatolites or decollement surfaces). Details of the different facies types measured in the field, and their environmental interpretations can be found in Chapter 3.

For the purpose of this thesis a base of a lake cycle is defined as where the first visible organic matter rich sediment is seen. The top of the cycle ends immediately before the reappearance of organic matter in the following cycle (Figure 1-3).

In total more than 4.5km of sediment was logged from 49 sections. Detailed information on all of the sections logged is given in Appendix 1. Of these, 19 sections could be confidently included in the stratigraphic framework (Figure 2-1). These sections allowed the correlation of the Rousay Flagstone Formation across most of Orkney. The sections not included in the stratigraphy were either too short or badly faulted to be linked reliably with other areas of Orkney. Table 2-1 lists the locations and other information about the sections used in the stratigraphic framework. Figure 2-2 shows the locations of the section used.

2.5 Points to note from the stratigraphic framework

- Although the Bight of Aith section from Stronsay is shown on the correlation panel (Figure 2-1), no sedimentological or palynological data was used from this section because the amount of faulting and fracturing present in the section made any precise measurements unrealistic. For similar reasons the Skerry of Work section (east Mainland) was also shown on the stratigraphic correlation, but not examined in detail.
- In two cycles, lake conditions did not develop fully. These semi-developed lakes are characterised by the development of lighter silts and the presence of mudcracks rather than by laminites and dark silts. In the correlation panel these semi-developed lakes are denoted 'a, b,' etc and occur in cycles 31 and 35. The poorly developed lakes have limited lateral extent. Lake 31b is only found east of the East Scapa Fault. Lakes 35b and c are found only in the extreme north west of the area. Astin (1990) notes similar partly developed lakes in his stratigraphy.
- In the case of North Ronaldsay, the sections logged did not match with any portion of the stratigraphic framework. It is suspected that the island may be composed of Upper or Lower Stromness Flagstone, rather than Rousay Flagstone Formation.
- Logging certain parts of the stratigraphic framework required the use of climbing equipment. The section of cliff marking the resumption of the Rousay section, and several sections at Halcro Head were logged in this way. Needless to say great care is required when visiting these locations.

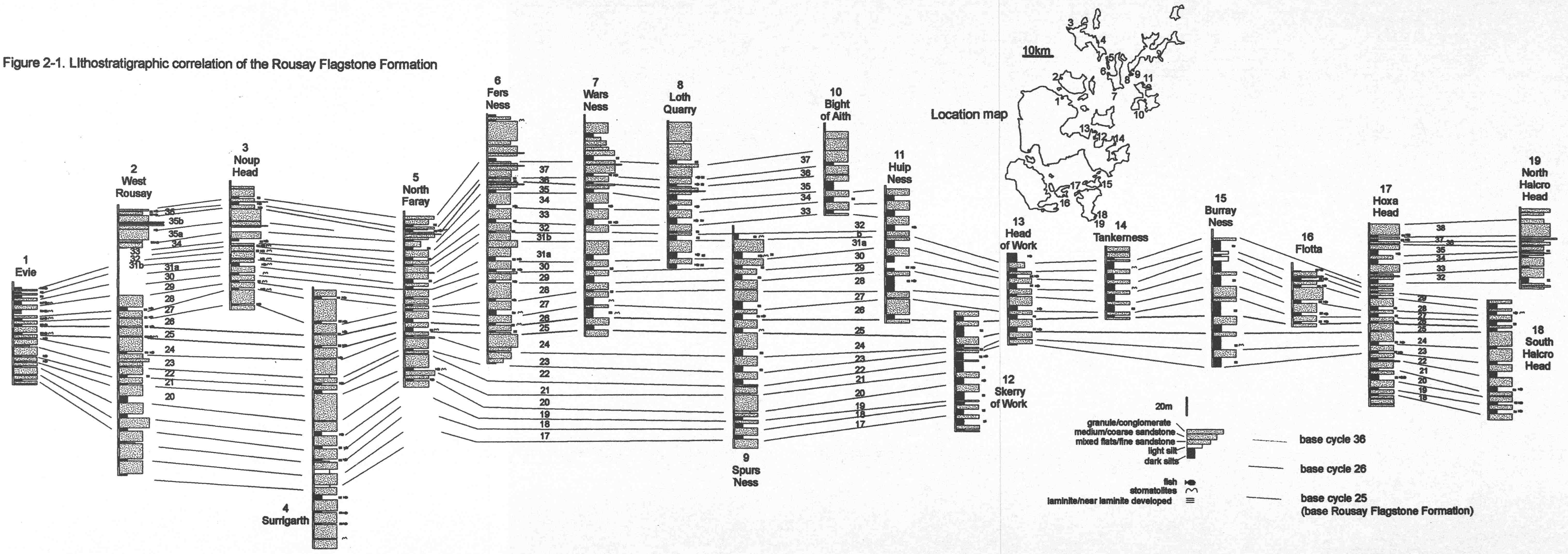
Island	**Section Name**	**Location co-ordinates**	**Outcrop Quality**	**Stratigraphic Position**	**Notes**	**Length of logged section**
West Mainland	Evie	HY355273 - HY364268	Moderate intertidal	1/2 USFF 1/2 RFF		103m
Rousay	Rousay	HY363317 - HY382350	Moderate intertidal & clifftop. Inaccessible 50m section	1/2 USFF 1/2 RFF	Sacquoy present	166m
Westray	Noup	HY408494- HY395501	Good intertidal/ clifftop	Upper RFF	Sacquoy present	128m
	Surrigarth	HY492452- HY497437	Good above HWM	Lower USF Upper RFF		282m
North Faray	North Faray	HY528381- HY531378	Moderate intertidal	Entire RFF Some USFF	Sacquoy present	185m
Eday	Wars Ness	HY557288 - HY549289	Poor intertidal/ good above HWM	Entire RFF	Sacquoy present	217m
	Fers Ness	HY529339 - HY534338	Good narrow intertidal	Entire RFF	Sacquoy present	250m
Sanday	Spur Ness	HY667332	Moderate intertidal	Upper USFF Lower RFF		250m
	Loth Quarry	HY602342 - HY600344	Good quarry and intertidal	Upper RFF LESM	Sacquoy	160m
Stronsay	Huip Ness	(HY648299) - (HY641308)	Intermittent moderate – poorly exposed intertidal	Lower & Middle RFF	Faulted but no section missing	153m
	Bight of Aith	(HY645241) - (HY647239)	Narrow intertidal	Upper RFF LESM	Extreme brecciation and faulting	92 m?

Table 2-1. Location of sections used in the stratigraphic framework. See Figure 2-2 for map.

Island	Section Name	Location Co-ordinates	Outcrop Quality	Stratigraphic position	Notes	Length of logged section
East Mainland	Head of Work	(HY482140) - (HY476411)	Low lying intertidal	Lower RFF		97 m
	Skerry of Work	HY477122 - HY479130	Moderate – poor low intertidal	Lower RFF Upper USFF	Poor exposure, faulted	132m
	Tankerness	HY545088 - HY545097	Poor intertidal and clifftop	RFF	Poorly developed lake and sheetflood facies	130m
Burray	Burray Ness	ND507965- ND497965	Moderate - poor intertidal	RFF?	Very thick laminites	140m
Flotta	Flotta	ND362923 - ND363929	Good- low cliffs and intertidal shoreline	Lower RFF		62m
South Ronaldsay	Hoxa Head	ND406935 - ND415944	Good – moderate intertidal	Entire RFF	Top section obscured by seaweed	200m
	North Halcro Head	ND469861 – ND464863	Poor- cliff base, tidal	Upper RFF	Treacherous access	78m
	South Halcro Head	ND475855	Moderate cliff top	Upper USFF Lower RFF	Logged using climbing gear	130m

Table 2-1 cont. Location of sections used in the stratigraphic framework. See Figure 2-2 for map of locations.

Figure 2-1. Lithostratigraphic correlation of the Rousay Flagstone Formation



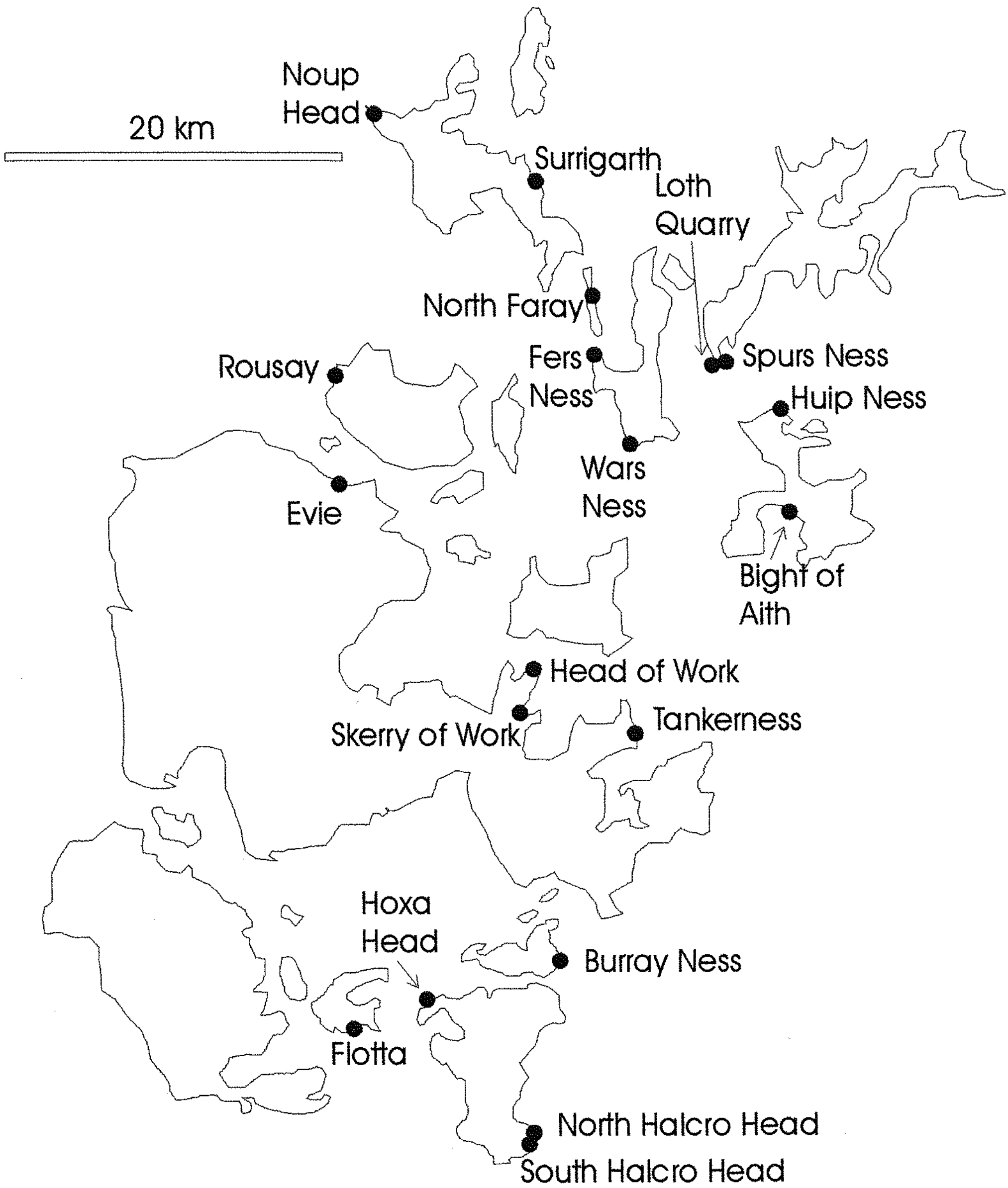


Figure 2-2. Location of the sections used in the lithostratigraphic framework and subsequent lithofacies and kerogen analysis.

3 Sedimentology

This section deals with the description and presentation of the sedimentary data collected for the thesis. The first part of this section describes the different sedimentary rocks of the Rousay Flagstone Formation in Orkney. The information comes from detailed field description, augmented by thin section descriptions and information from existing literature. The second part of this section briefly deals with the various ways in which the facies data was presented and analysed.

3.1 Facies descriptions

During the six months fieldwork spent in Orkney, the same sedimentary facies were seen to occur repeatedly throughout the Orkney Flagstone Group. The following facies definitions represent the level of detail at which rock types were recorded in the field, during the logging procedure. Although they are not as detailed as previous workers (e.g. Rogers & Astin 1991, Astin & Rogers 1991), they are believed to be sufficiently accurate for a basin-scale study. Representative samples of the key facies were taken and thin sections were made for petrographic examination. The clastic samples came from cycle 25 of the Rousay section. Several organic matter containing samples came from cycle 26 of the Flotta and Head of Work sections.

Much has been written on the carbonate mineralogy of the Orcadian basin. Further research into this is outside the scope of a study into kerogen variation, and has been covered adequately by other workers – e.g. Donovan 1975, Trewin 1986, Janaway & Parnell 1989 and Rogers & Astin 1991.

• **Laminite**

Field description:

This rock is composed of parallel, interlaminated dark and light coloured, very fine-grained sediments (Plate 3-3a).

Fish remains of varying degrees of intactness are often present.

Thin section description:

Sample location - cycle 26 Head of Work and Flotta.

These showed well defined sub-millimetre, dark/light laminae (Plate 3-1a and b). Half of the light coloured sediments were laterally continuous bands of angular-subangular, course silt to very fine quartz sand. The rest of the light coloured sediment was micrite, which tends to form in more bulbous layers (Plate 3-1b). The dark laminae are composed of dark silts and bronze coloured organic matter (Plate 3-2a). Generally the light coloured sand bands grade upward into the dark sediments (Plate 3-1a). In the sample from Flotta, the light/dark layers were less well defined than those from the Head of Work.

Environmental interpretation:

The lack of any evidence of wave activity, the fine lamination and the presence of organic matter suggest that this facies represents the sub-wavebase deposits of a permanent lake that was for at least part of the time chemically or thermally stratified.

It is suggested (Donovan 1980) that the dark/light couplets of organic matter and micrite formed when algal blooms increased the lake water pH causing the precipitation of the carbonate. The phytoplankton then died and rained down into the anoxic bottom waters of the lake accumulating as organic carbon on top of the recently precipitated carbonate layer. The clastic material of fine sand/coarse silt grade may be derived from sources such as density flows, wind transport or post-storm sediment re-settling (Rogers & Astin 1991).

• **Near laminite**.

Field description:

This facies is similar to the 'laminite' facies but with less well developed laminae, which may be thicker and sandier than simple laminites. Mud cracks and stromatolites may also be present. Fish remains are common.

Thin section description:

Sample location - cycle 26 Flotta.

The sample is mainly composed of sub-millimetre interlaminated pale and dark brown sediment. Roughly half of the pale laminations are angular/sub-angular coarse silt to medium sand grade quartz with around 5% muscovite also present. The other half of the pale sediment is micrite of a bulbous appearance.

The dark layers are composed of opaque clay, organic matter and less than 10% muscovite.

Environmental interpretation:

The environment of deposition of this facies is very similar to that of the laminite facies, except that several features indicate slightly shallower lacustrine conditions. These include the presence of mud cracks (discussed later), stromatolites and an increase in the quantity and grain size of the quartz sediment.

This facies can be interpreted as being transitional between permanent lake conditions and more ephemeral conditions.

- **Dark silt**

Field Description:

This rock generally appears as massive or poorly laminated, very dark silt.

Fish remains are present. Stromatolites identifiable as thin, pale mounded layers interlaminated with the silts are also common. Ripples in any form are extremely uncommon.

Environmental interpretation:

Two possible interpretations can be made of this facies. The first is that the dark silt is in some cases actually a laminite or near laminite in which the delicate lamination that characterise the facies, has been obscured by poor lighting, vegetation or weathering. This misidentification has certainly occurred before, when localities had been revisited for the collection of samples and it was noticed that facies logged as dark silts were, under closer scrutiny, laminites.

The second interpretation of this facies is indicated by the fact it contains abundant organic matter (shown from TOC analysis), but is not laminated. This suggests that it is a further stage in the incremental change from permanent stratified lake to ephemeral lake conditions see in all the Orcadian lake cycles.

However what definitely can be said about this facies is that it is fine grained, dark in colour, was deposited in sub-wavebase conditions and contains variable amounts of organic matter and is thus akin to the other lacustrine sediments.

• **Sandy dark silt**.

Field description:

This facies appears as a massive or poorly laminated dark silt that commonly contains coarse silt to medium sand grade quartz grains in its matrix or in discrete laminae.

Environmental interpretation:

As with the 'dark silt' facies above, there are two possible interpretations of this facies, either as an incorrectly identified 'near laminite' facies or as a further stage between deep, permanent and ephemeral lake systems.

In either interpretation, the probable mechanisms of sand input could be density flows, wind transport or post-storm sediment re-settling (as discussed in Rogers & Astin 1991).

• **Wick**

Also known as simple flagstone (Rogers & Astin 1991) or Wick type flagstone because it is particularly common and well developed around Wick, in Caithness (pers com T. Astin).

Field description:

This is a common and distinctive facies composed of finely interbedded to coarsely interlaminated muds and siliciclastic silts and fine sands (Plate 3-2b). From every sand layer, lenticular mud cracks pass down into the underlying mud layer and usually no further Plate 3-2b). The lengths of the cracks vary from less than 2cm to over 10cm. The crack infills are usually bulbous in cross section, deformed by post-depositional compaction (Plate 3-2b).

Thin section description:

Sample locations - cycle 25 Rousay and cycle 26 Head of Work.

The mud strata are usually dark blue-grey to brown and 1 to 15 mm thick. They are micaceous clayey silts or silty clays with variable proportions of pyrite, organic matter and carbonate. The calcite ranges from 0 to over 50% of the mud strata. The silt grains contained in the mud are mainly quartz.

The sand strata are composed of coarse silt to fine sand grade, well sorted angular to subangular quartz and are 1 to 20 mm thick. The sand layers also contain around 5-10%

muscovite and 5% calcite clasts. The layers can be parallel or cross-laminated, and are generally laterally persistent.

Mud cracks are common in this facies and are distinctive in thin section (Plate 3-2b). The cracks are filled with sub-angular quartz and are commonly deformed by pre-lithification compaction.

Environmental Interpretation:

1. Mud cracks

The interpretation of this particular facies has been subject to much discussion. Most of this has centred on the origin of the ubiquitous mudcracks seen in this facies. Two schools of thought exist – one of a subaqueous origin of the cracks and another of a subaerial origin. Whether the cracks formed under water or under air is crucial to the understanding of the Orcadian environment in Middle Devonian times, considering that about 30% of the lake sediments in the Orcadian Basin exhibit these cracks (Donovan & Foster 1972).

The mechanism for a subaqueous crack origin is summarised in Donovan & Foster (1972). They suggest that the cracks were formed by clay expansion triggered by salinity changes in an extremely quiescent lacustrine environment.

The other explanation of the mudcracks origin is summarised in Astin & Rogers (1991), discussed in Astin & Rogers (1992) and in Trewin (1992) and in context of the Orcadian Basin in Rogers & Astin (1991). These authors suggest that the mud cracks were formed by a combination of gypsum crystallisation and limited subaerial desiccation (Figure 3-1).

Although both arguments are very persuasive it seems that the subaerial mechanism fits better with the most recent interpretations of how the Orcadian Basin worked during Middle Devonian times. In fact Astin & Rogers (1991) suggest that subaqueously formed cracks, may not be preserved at all in the geological record due to their fragile nature. Smoot (1983) supports this in his re-evaluation of the Wilkins Peak Member of the Green River Formation. Like the Orcadian Basin the Wilkins Peak Member has been used as a type example for the study of 'subaqueously' formed mud cracks. Smoot (1983) refutes this and in his re-assessment suggests a desiccation mechanism for the formation of the mud cracks.

2. General environment of deposition

As summarised in Figure 3-1, this facies was deposited during fluctuating water depths.

It is thought that the mudstone bands formed when mud dropped out of suspension from lakes. The carbonate was precipitated from the lake directly when plankton productivity altered water pH (as with laminites). The absence of intact fish and infrequent lamination suggest a shallow unstratified lake (Rogers & Astin1991).

The sand laminae were probably supplied by wind across emergent desiccating lake floors. The presence of sharp non-erosive bases and tops, lack of overall grading, infrequent flat lamination, and large scale patchiness of the non-reworked sand stratum are all consistent with an origin of wind rippled or aeolian plane bedded low amplitude sand patches (Rogers & Astin 1991).

- **Dark Wick**

This facies type was noted in the field where it was thought that a particularly organic matter rich form of the Wick facies existed. Subsequent Total Organic Carbon (TOC) analysis has shown that most Wick facies sediments contain varying amounts of organic matter. Thus this facies classification has no validity and in reality is no different from the Wick type facies.

- **Mid grey silts**

Field description:

Generally a thinly bedded, wave-rippled sediment with quite variable proportions of silt and sand. Often found associated with organic rich lake sediments. Colour is an intermediate shade of grey between the dark greys of the lake sediments and the lighter greys and blues of the shallower water facies. Desiccation cracks may be present.

Environmental interpretation:

TOC analysis shows that this facies does contain some organic matter. However, the light colour and sedimentary structures are indicative of higher energy deposition. This implies that this facies represents a further transitional stage between a deep water anoxic environment and a shallower water oxygen rich one.

- **Blue silt**

Field description:

Generally observed as massive or rippled beds of light blue or grey-green silts, ranging in thickness from less than 10cm to over 50cm (Plate 3-4b). Desiccation cracks are common.

Environmental interpretation:

These silts were deposited in an oxic, low energy, environment and probably represent the fine fraction of terminal fans (discussed later) (Figure 3-2).

• **Wavy green sands**

Field description:

This facies varies in colour from pale green to grey to pale blue. It is composed predominantly of fine to medium grained sand. Often there is no coherent sedimentary fabric present, but wave ripples may be present. Desiccation cracks may also be present.

Thin section description:

The thin section is composed of 30% fine to medium sub-angular sand in poorly defined layers with 70% fine sandstone and silts inter-layered between. The matrix of the rock is mainly calcite mud.

Environmental interpretation:

The disrupted, wave rippled nature of this facies suggests deposition in an environment where fluvial sands are frequently reworked by wave action. Desiccation cracks also indicate that subaerial exposure had occurred. The combination of fine sands, ripples and desiccation cracks suggests a distal location in the distributary zone of a terminal fan (Figure 3-2).

• **Wavy green silts**

Field Description:

The silts range in colour from pale green to grey to pale blue. Wave ripples that are either well or poorly defined are common. This facies forms beds with thicknesses from 1 cm to 50 cm. Desiccation cracks may be present.

Thin section description:

This sample consists of layers of thinly laminated clay, silts and very fine quartz sand inter-layered with layers of fine-grained sub-angular quartz sand. The inter-layering is frequently disrupted when the sand rich layers seem to have forced themselves up through the silty layers.

Environmental interpretation:

A distal terminal fan type environment is envisaged for this facies (Figure 3-2). However, the presence of a lot of silty material suggests a lower energy depositional environment than that of the wavy green sandstone.

• **Sheet floods.**

Field description:

This facies appears as well defined fine to coarse-grained sand bodies (Plate 3-4c). Internally they appear wave rippled, cross-laminated or structureless. They are laterally persistent and range from less than 10 cm to over 1 m in thickness. Sheetfloods are generally non-erosive in nature and are often interbedded with thin silts.

The sheet flood facies was subdivided into a 'single sheet flood' facies – where one discrete sand unit was contained within a distinct, different facies (Plate 3-4c). And an 'amalgamated sheet flood' facies – where many, less distinct, generally 1-10 cm thick sheetfloods could be seen to be bundled together into a larger sand body (Plate 3-4a).

Thin section description:

The section is composed of 60% angular to very angular, fine-grained quartz (Plate 3-2c), with climbing ripples made visible by thin dark calcite mud drapes forming most of the rest of the section. There is about 5% muscovite present, which lies parallel to bedding. All porosity is filled by calcite cement..

Environmental interpretation:

They are thought to represent the products of flash floods that brought immature sediment rapidly into the basin during times of heavy rainfall. These features are very common in the distal and basinal zones of terminal fans (Kelly & Olsen 1993) (Figure 3-2).

• **Mixed flats**

Field description:

'Mixed flats' is a bulk term for a common occurrence where a variety of facies are thinly interbedded with each other (Plate 3-4b). The individual beds are generally less than 20cm and the facies can be blue silts, green wavy silts and sands or thin sheetfloods. The boundaries between the facies can be either sharp or gradual. Mudcracks may be common.

Environmental interpretation:

This facies represents the complex interplay of sedimentary factors associated with the progradation of a terminal fan into an ephemeral basin (Rogers & Astin 1991).

Detailed field logging has shown a wide range of sand and silt contents in this facies. When roughly averaged from all of the collected field data, about half of this facies is silt dominated and half is sand dominated.

• **Channel sands**

Field description:

These features have a down-cutting, erosive association with the underlying sediments and are often channel shaped when viewed in cross section (Plate 3-4a). They may be composed of fine, medium or coarse sand as well as mud rip-up clasts. Silt layers may be present within the sand body.

Environmental interpretation:

This facies represents confined, distributary river channel sediments, often found in the more proximal parts of terminal fans (Figure 3-2).

Channel sands are not common in the Rousay Flagstone Formation, and are generally restricted to the northern parts of Orkney.

• **Conglomerate**

Field description:

This uncommon facies occurs as a fluvial pebbly sandstone containing clasts of up to 80mm across. The clasts are predominantly sub-rounded and composed mainly of quartzite and psammite, with lesser limestone but can contain significant amounts of feldspar, with rarer limestone and quartz granite. The matrix is composed of fine to coarse quartz sand, showing current and parallel bedding.

Environmental interpretation:

Within the Rousay Flagstone Formation the conglomerate facies is only found towards the base of the Eday Sandstone. Astin (1990) named the pebbly sandstone band found in the 35th cycle above the Sandwick Fish Bed the Sacquoy Sandstone Member. Other pebbly sandstone bodies are found above cycle 35.

Figure 3-3 shows the distribution of the largest clast sizes measured in the Sacquoy Sandstone Member. When combined with palaeocurrent information (Figure 5-24), a point source for these coarse sediments somewhere to the north west of Rousay is implied. This agrees with the findings of Astin (1990), who interprets the Sacquoy Sandstone as alluvial fan sediment sourced from a ridge of Moine schist and Durness limestone that was exposed at the time of deposition. Although the ridge is now submerged, evidence for it can be seen from geophysical data as a ridge of high-density rock a few kilometres to the west of Orkney (McQuillan 1968) (Figure 3-4)

Summary of the environment of deposition of the Rousay Flagstone Formation.

Two distinct phases of sedimentation can be seen in most of the lake cycles. The first phase is characterised by lacustrine conditions in which organic matter was preserved by anoxia and enhanced salinity (Duncan & Hamilton 1988). Estimating the depth of the Devonian lakes has proven problematic due to the lack of palaeo-depth indicators. Using wave fetch estimates, Duncan & Hamilton (1988) were able to estimate the depth to wave base of the Achanarras Fish Bed as 75m for the Caithness and Orkney area. Since the Achanarras horizon is thicker than any other Orkney Flagstone cycle, the water depth indicated will certainly be greater than any of the other, thinner Devonian lake cycles, but it gives an indication of the water depths that were present in the Orcadian basin

The second phase is characterised by increased aridity as indicated by the production of gypsum crystals towards the top of the lacustrine phase (Astin & Rogers 1990). Processes during the more arid phase are related to the action of terminal fans. These features are common in arid basins, and form when sediment-laden streams diminish in size and eventually disappear as a result of evaporation and transmission losses. A model for terminal fans (Kelly & Olsen 1993) suggests a tripartite classification into feeder, distributary and basinal zones (Figure 3-2). Most of the non-lacustrine sediments in each lake cycle can be attributed to sedimentary interplay of processes found mainly in the distributary and basinal zones of terminal fans.

3.2 Note on the comparison of facies types as defined by other workers in the Orcadian basin.

Several authors have defined a series of facies types characteristic of the Middle Devonian age lake sediments found in the north of Scotland. Depending on what the authors were trying to prove, the sediments were described in different ways and on different scales. For example Rogers & Astin (1991) in their detailed work on sediments in Wick defined six facies types. These six facies types compare favourably to the 10 or so facies types defined for this thesis. Not only are the same physical characteristics noted but also the same palaeoenvironmental interpretations are also made.

Alternatively Donovan (1980) assigns four 'lithological associations' to the Caithness Flagstones. These associations A to D, represent the transition from laminite to mixed flats and rely on the subaqueous shrinkage crack model of Donovan and Foster (1972) for much of the palaeoenvironmental interpretation. However although the interpretation of these facies differ from this thesis, the sedimentary features and associations noted are similar.

Finally Astin (1990) is his work correlating the Upper Orkney Flagstone Group, defined only two main facies types – semi-permanent well established lakes and ephemeral lakes. But yet again the sediments described and the palaeoenvironmental interpretations are very similar to those in this work, and in this case more resemble the megafacies classification (below) than the facies classifications above.

3.3 Presentation of sedimentary data

The creation of the lithostratigraphic framework required the collection of much data. The collected sedimentary data have also been used to investigate the sedimentary processes that may have been operating in the Orcadian basin during Middle Devonian times. To aid interpretation much of the data has been presented and manipulated in various ways.

Individual lake profiles

The most detailed presentation of sedimentary and palynological data in this thesis comes in the form of individual lake profile graphs. These graphs show how sedimentary facies, TOC, in most cases spore numbers ('abspore'), and in two cases H/C and O/C ratios vary with height through the organic matter containing, lower part of each lake cycle. Lacustrine processes dominated in the formation of these organic matter rich sediments.

The data were compiled from field and microscopic examination of the rocks collected, point counting of palynomorphs and Elemental Analysis. For the purpose of these lake profile graphs, the facies data was simplified into five organic matter containing **'microfacies'** types – laminite, near laminite, dark silt, Wick and grey silt. They are very similar to the original facies types (described above) except sandy dark silt was grouped with dark silt, and dark Wick was grouped with Wick. These lithotypes were created to reflect increasingly shallow water depths – 'laminite' being the deepest water facies to 'grey silt' being the shallowest. The lake profiles studied were the stratigraphically 'fixed' cycle 26 and cycles 36 locations. These lake profile graphs were used to see if any coherent trends in the general deposition of lake facies, rather than looking for basin wide trends.

Data Maps

The most useful way of presenting much of the data in this thesis is on maps. Data relating to individual lake cycles (cycles 26 and 36) and averaged data relating to the Rousay Flagstone Formation as a whole, have been presented in this way. Although fine detail is necessarily lost when data are averaged, this method has proven extremely effective in highlighting basin wide sedimentological trends across Orkney.

Palaeocurrent maps

In order to chart changes in palaeocurrent direction through the logged Orkney Flagstone Group sections, three maps were plotted showing palaeocurrent trends for the uppermost part of the Upper Stromness Flagstone Formation, the lower half of the Rousay Flagstone Formation and the upper half of the Rousay Flagstone Formation. Palaeocurrent information was measured only from well exposed current ripples, mainly found in sheetflood facies. The palaeocurrent data was plotted on StereoNett version 2.1 as rose diagrams. The rose diagrams, together with the number of measurements taken were plotted on maps of Orkney (Figures 5-28a-c).

Megafacies analysis

Although the facies described in the field can all be assigned to a definite environment of deposition, the variation between the facies often is too slight to be useful in this study of basin wide sediment variation. To simplify the possible environments of deposition, three generalised 'megafacies' are suggested, those of 'lacustrine', 'emergent' and 'fluvial'. The intention of this is to group together the previously defined facies into three groups of similar environments of deposition. The aim of this purely artificial grouping is to enable analysis of gross sedimentation changes spatially and temporally across Orkney. Table 3-1 details how the facies noted in the field correspond to the megafacies scheme.

Definitions

Lacustrine: Permanent water cover, anoxic or dysoxic allowing preservation of organic matter. Stratified or partly stratified water column present.

Emergent: Periodic water cover leading to reduced organic matter preservation, evaporite deposition and desiccation.

Fluvial: High energy, coarser sediments, and highly oxidising environment.

Megafacies	Facies			
Lacustrine	Laminite	Near Laminite	Dark Silt	Sandy dark Silt
Emergent	Mid grey silt	Blue Silt	Mixed flats	Wick/dark Wick
Fluvial	Wavy silt and sands	Sheetfloods	Channels	Conglomerates

Table 3-1. Facies/megafacies definitions

Presentation of megafacies data

The megafacies data were presented both in map and graph form. Of particular interest was a series of graphs was produced to show the relative and actual variation on megafacies on either side of the major east-west and north-south faults found in the basin. For the graphs, megafacies data were averaged from cycles: 24, 25, 26, 27, 28, 29, 30, 32, 34, 36, 37, which represent a wide selection of the best defined and best exposed lake cycles associated with the Rousay Flagstone Formation.

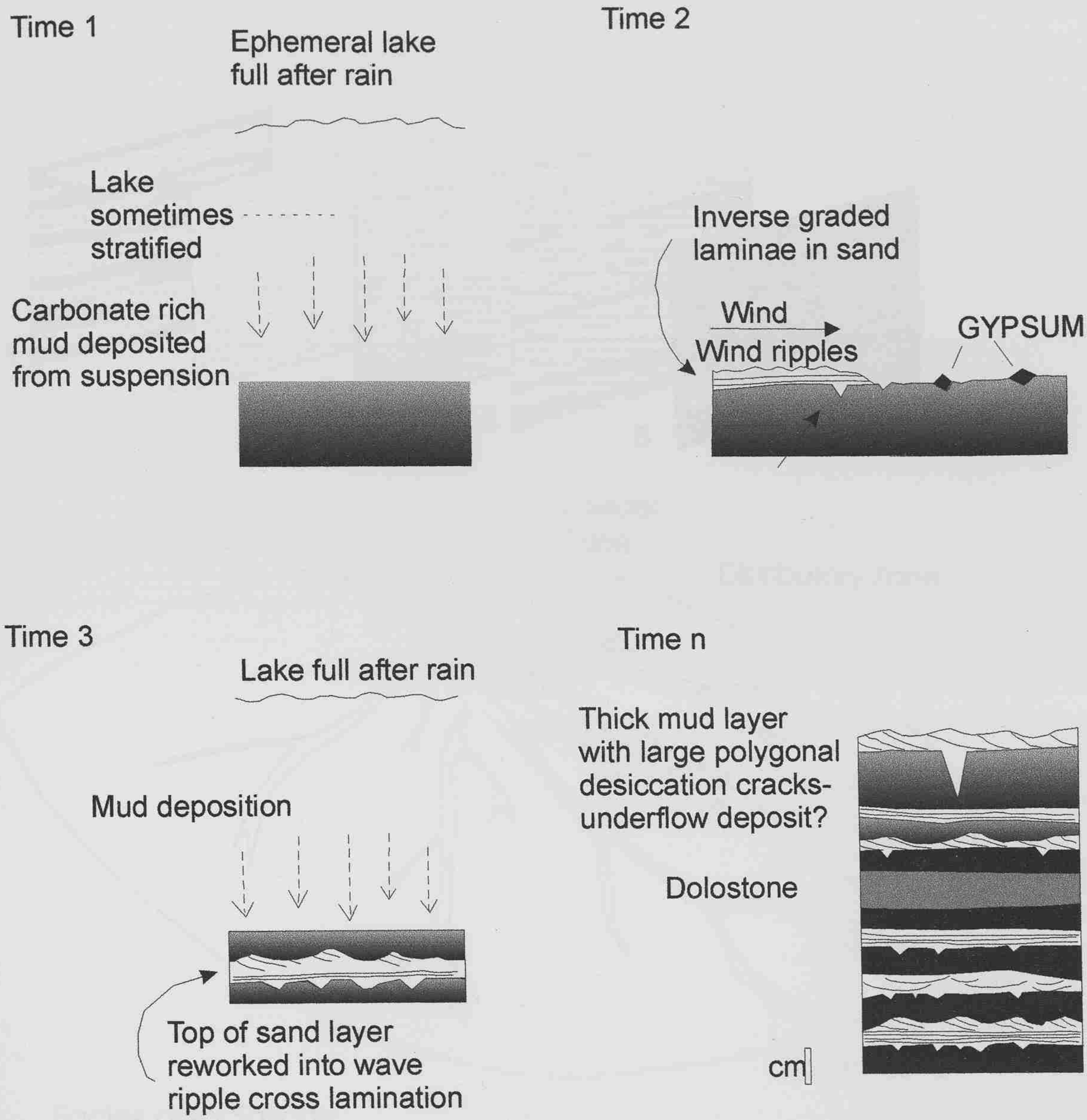
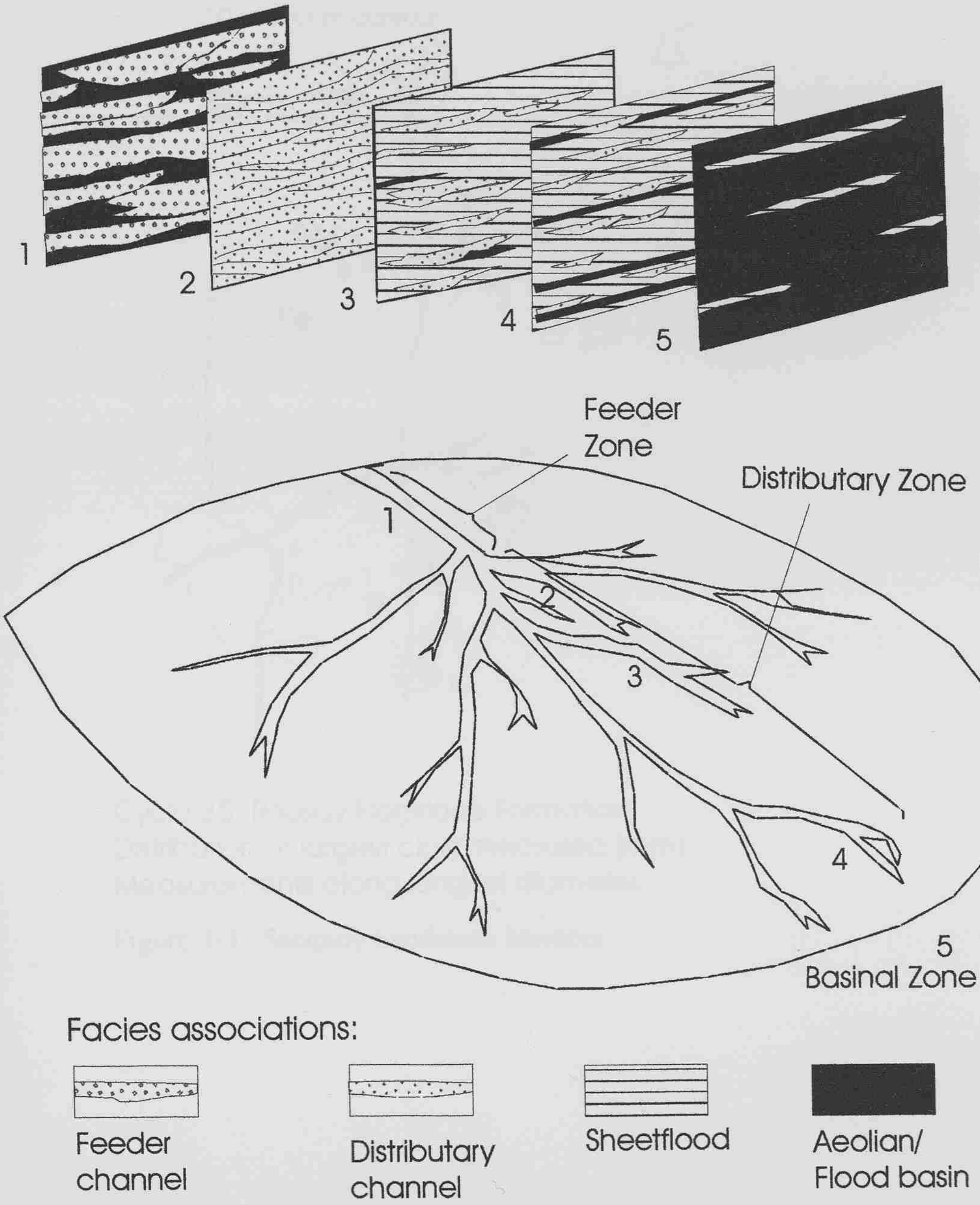
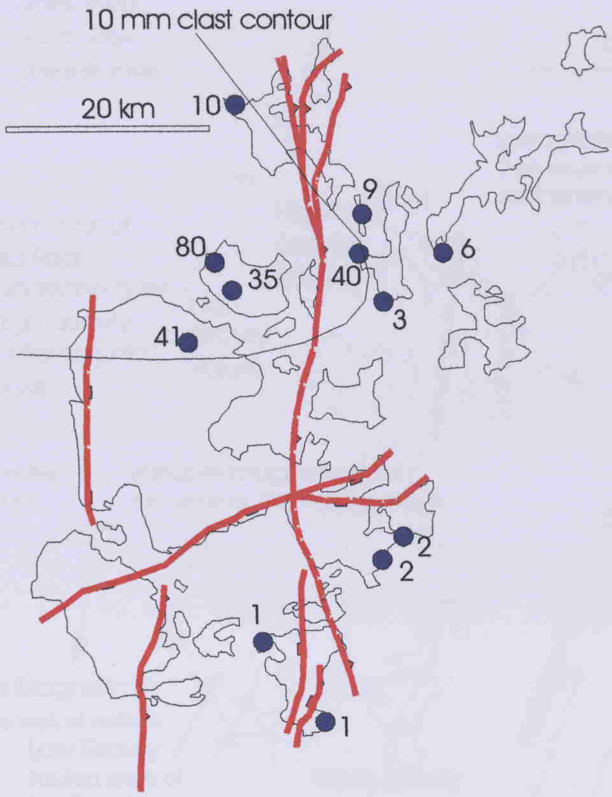


Figure 3-1. Proposed model of Wick facies formation, with especial reference to mud crack formation (Rogers & Astin 1991).



(1=feeder zone, 2=proximal feeder zone, 3=medial feeder zone
4= distal feeder zone 5= basinal zone.)
The maximum downstream extent of individual terminal fans is unlikely to exceed 100km.

Figure 3.2 Facies model for terminal fans (Kelly & Olsen 1993)



Cycle 35, Rousay Flagstone Formation.
Distribution of largest clast measured (mm).
Measurements along longest diameter.

Figure 3-3. Sacquoy Sandstone Member.

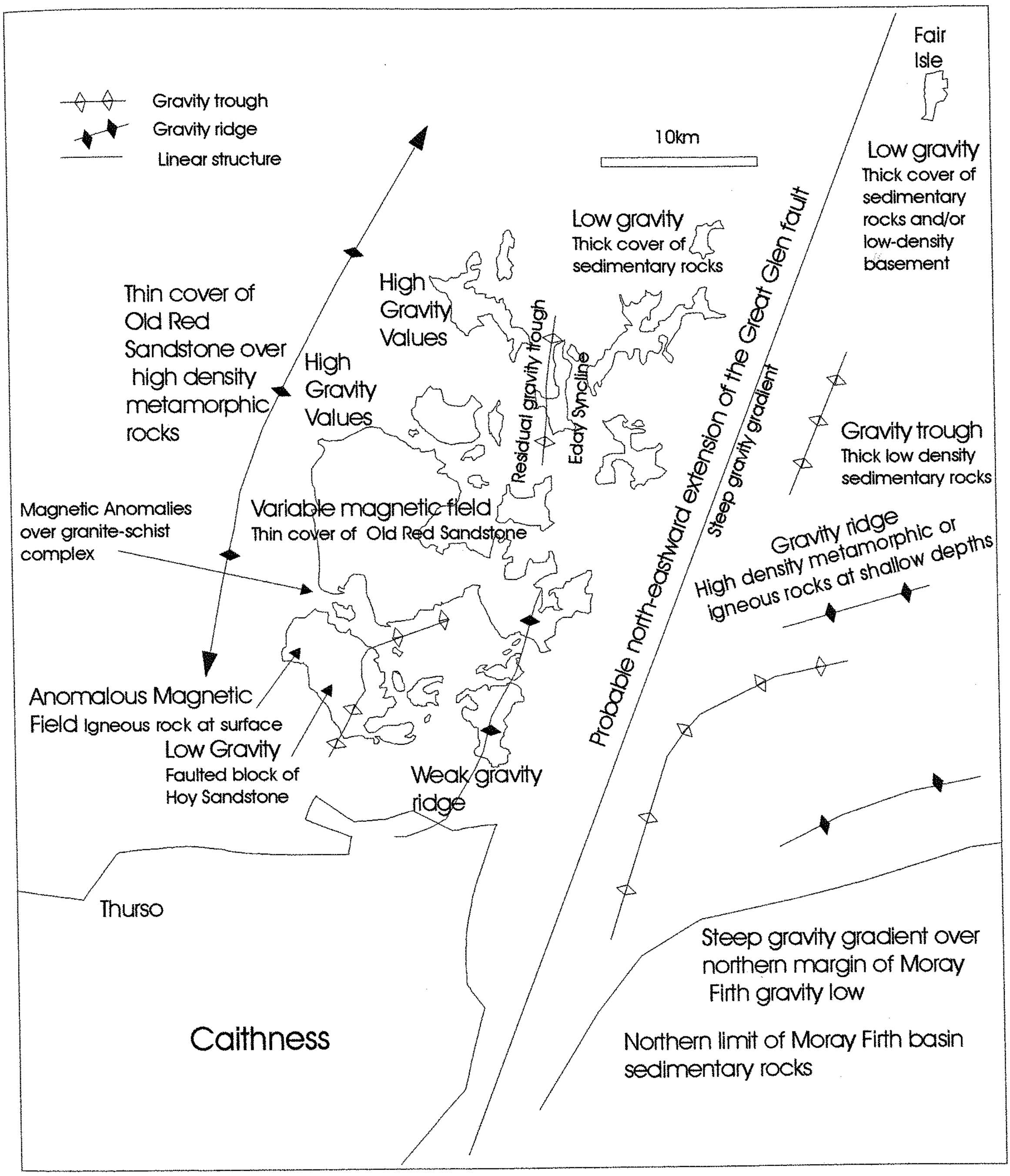
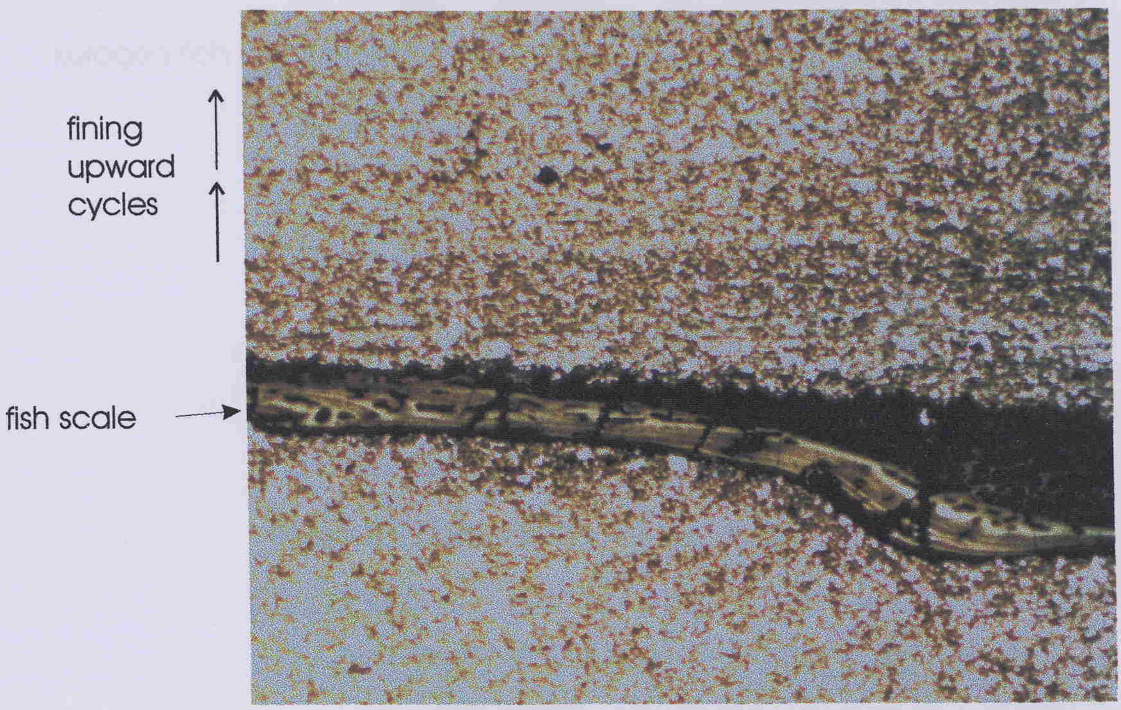
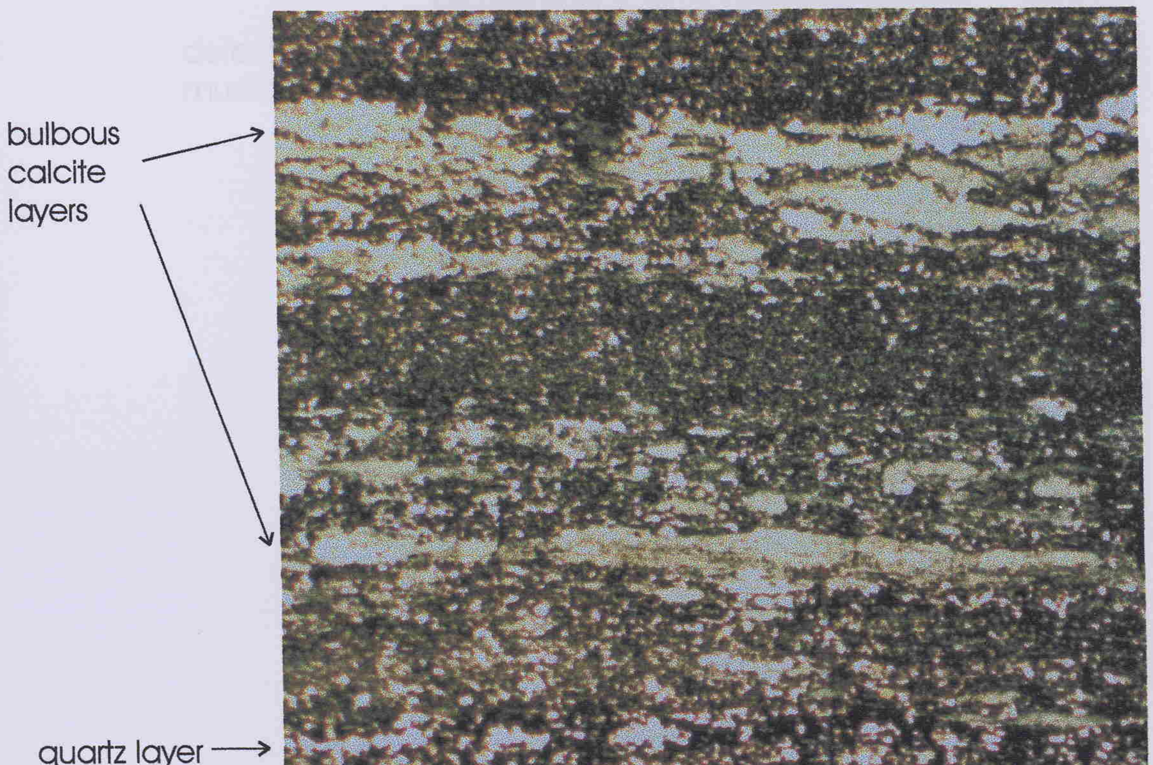


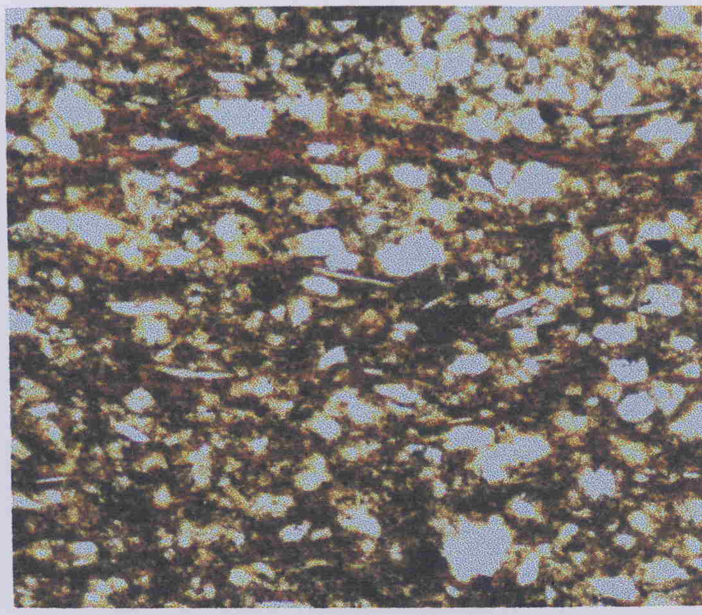
Figure 3-4. Regional geological structure of Orkney as interpreted from geophysical and geological data (after McQuillan 1968).



a. Laminite x.12.5 PPL. Flotta.

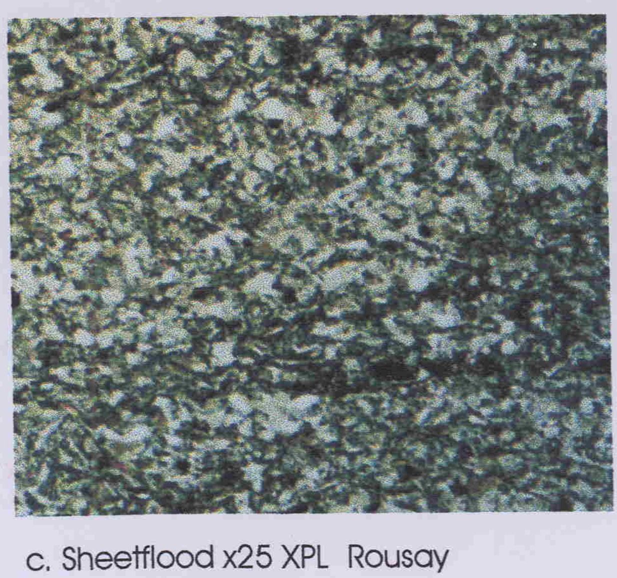


b. Laminite x12.5 XPL. Head of Work



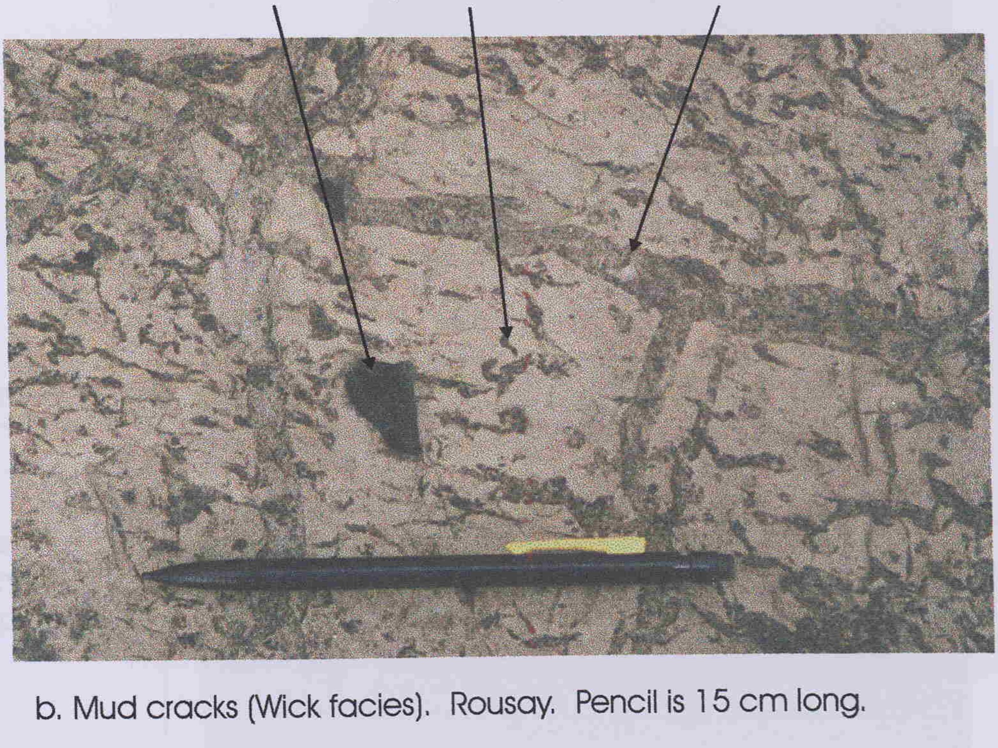
a. Laminite x100 PPL. Flotta

b. Wick facies x12.5 XPL. Head of Work

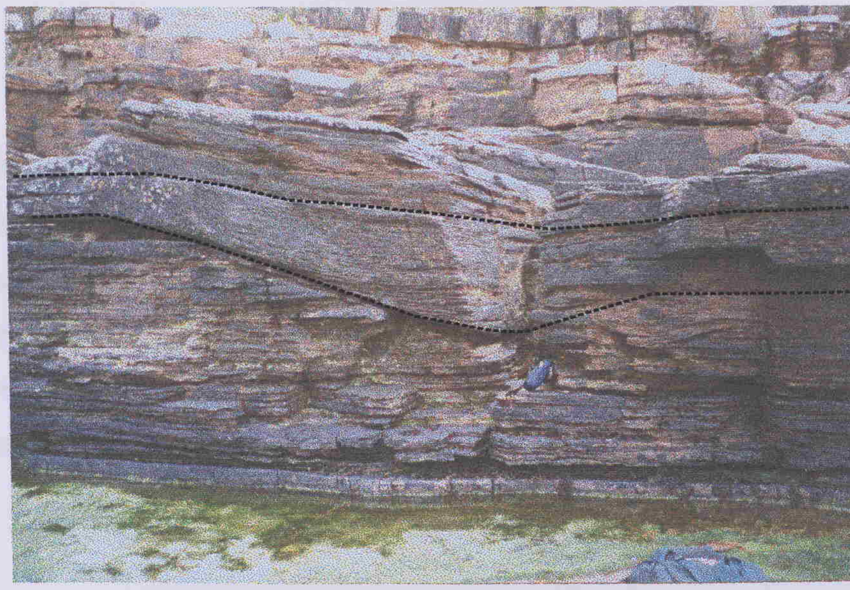


c. Sheetflood x25 XPL Rousay

a. Laminite facies. Rousay. Pencil is 15cm long.



b. Mud cracks (Wick facies). Rousay. Pencil is 15 cm long.



a. Channel facies, Westray. Camera case is 20 cm long.

b. Mixed flats, Rousay. Pencil is 15cm long.

c. Sheetflood facies, Rousay. Pencil is 15cm long.

4 Sampling and Methods

This chapter addresses the collection and analysis of the organic matter containing rocks of the Rousay Flagstone Formation. Where appropriate, a brief description of the theory behind the procedures used is included, as well as a discussion of any uncertainties in the method. The analytical techniques deal with two main areas, those of palynomorph variation and kerogen maturity.

4.1 Sampling

Using the lithostratigraphic framework (Figure 2-1) as a guide, five lake cycles were sampled wherever they outcropped throughout Orkney. These cycles were the first two cycles in the Rousay Flagstone Formation - numbers 25 and 26 up from the Sandwick Fish Bed, one from the middle (cycle 33) and the uppermost two lakes (cycles 36 and 37). Only the visibly organic matter containing part of each lake cycle was sampled i.e. containing laminite, near laminite, dark silt, Wick or mid grey silt facies. Where possible the lake sediments were sampled every 5-10 cm within laminite facies and every 10-20 cm throughout the other organic matter containing facies.

To avoid unnecessary geological vandalism, and to avoid carrying around large hammers, the samples were taken only from the surface of the exposure. Care was taken to select samples with a minimal amount of recent organic contamination (lichen, guano etc). However most of the samples were taken from coastal sections where frequent storms would keep the exposures reasonably fresh.

The samples were bagged, labelled and taken to Southampton for analysis. Out of the five sampled cycles only the samples from cycles 26 and 36 were analysed in detail. These two cycles were chosen because they were most frequently exposed across Orkney and secondly they represented lake cycles from the top and bottom of the Rousay Flagstone Formation and would give an indication of how lake conditions changed through time as well as across the basin.

Methods

Three techniques were used to study the organic matter contained within the lacustrine sediments. These were:

- Palynology using transmitted light microscopy to examine kerogen chemically separated from its host rock. Conventional rock thin sections of key facies types were also described using transmitted light microscopy.
- Reflected light microscopy to determine spore exine reflectivity.
- Elemental analysis of the organic matter contained within the lacustrine rocks to calculate the total organic carbon (TOC) content and atomic hydrogen/carbon and oxygen/carbon ratios.

Appendix 2 gives the full results of this work.

4.2 Palynology

The three aspects of the kerogen studied under transmitted light were:

- The absolute number of whole spores found per gram of rock
- The diameter variation of spore species *Rhabdosporites langii*
- Spore colour variation as an indicator of kerogen maturity

Other methods of characterising the kerogen variation in the Orcadian rocks were experimented with, but the results were seen to be of little value. These methods are summarised at the end of this chapter, but the results gained from them are not presented.

4.21 Absolute spore number counts

In general the main aim of any palynological study, is to describe how palynomorph ratios change throughout a basin and from this make an assessment of the environmental conditions that were present in the basin at the time of deposition. Several factors make the palynology of the Rousay Flagstone Formation difficult to study. As is typical for lacustrine sediments the organic matter is predominantly amorphous organic matter (AOM) of algal origin, which tends to mask other palynomorphs present (Tyson 1995). The palynomorphs that are present are of limited variety – spores and a very small percentage of woody material. Also there are no other ubiquitous palynomorphs that could be used as a standard to ratio against the other palynomorphs. Additionally the arid environment of deposition is not suited to the preservation of spores in good condition (Horowitz 1992).

One way of characterising palynomorph variation across the basin is to count the total numbers of spores found in a known weight of rock. This would give an absolute number of spores found in each location, which would provide information on spore distribution within the basin. The figures gained from this analysis were called '**abspore**' for convenience.

Obviously the most important issue in this procedure is that exactly the same operations were applied to each rock sample, and that no kerogen was accidentally 'lost' during processing, assuring that any variation in spore numbers is due to environmental factors rather than differences in processing. From each location, three or more samples were analysed in this manner.

Method

One gram of rock was cleaned, dried and then crushed to granules of 1 or 2 mm in diameter. It was then processed to produce kerogen isolates using standard demineralisation techniques. This involves treating the sample with HCl then HF followed by sieving at 20 µm and a 30 second treatment in boiling HCl to remove neoformed fluorides. As stated before, extreme care was taken to retain the entire kerogen fraction greater than 20 µm.

It is uncertain what percentage of the kerogen is lost when sieving at 20 µm. However all of the key species of spores found in the Orkney Flagstone Group are larger than 20 µm in diameter and so were not lost by sieving. For example *Rhabdosporites langii,* a spore characteristic of the Rousay Flagstone Formation has a range of equatorial diameter from 50 to 200 μm (Marshall 1996, Richardson 1965). Speed is the main advantage of sieving at 20 μm as opposed to finer meshes.

The spores from the rock sample were then concentrated by removing as much AOM as possible. This was achieved by exposing the samples to ultrasonic disruption using a Sonics & Materials 300W Vibra~cell. A 30 second treatment removes most of the AOM from the samples whilst keeping to a minimum damage to the spores.

The spore rich residue was then washed into small plastic tubes marked to a level of known volume (3ml). The capped tubes were shaken well to ensure equal distribution of spores throughout the water volume. A calibrated pipette was used to dispense 500 μl of the suspension onto a coverslip. After the water had completely evaporated from the coverslips, they were mounted onto standard glass microscopy slides using Elvacite 2044 resin.

Spores are readily identifiable and easily counted. The key features of the spores and how they differ from other particles that may be found on the kerogen isolate slide are presented in Table 4-1. Generally anything that was not a definite shape such as spores, woody tissue, bitumen or pyrite was identified as AOM, unless it was obviously contamination such as fragments of lichen that had escaped the cleaning process.
The total number of intact spores on the slide was counted to provide a number of spores per 500 μl of isolate solution. That number was multiplied by six to get the total number of spores per gram of rock i.e. the number of spores in 3 ml of isolate.

Kerogen	Shape	Internal structure	Other
AOM	Unstructured and fluffy appearance, sometimes spherical	Mottled with inclusions of wood and pyrite	Colour ranges from tan to black, Large size range from microns to millimetres
Spores	Generally spherical, distinct edge	May be present, walls clear not mottled	May be pitted by impressions of pyrite or dolomite
Wood	Rectangular/ Angular	Holey appearance	Dark brown colour sometimes with reddish tinge
Bitumen	Angular, cavity filling	None, semi-transparent	Glassy, various shades of brown
Pyrite	Angular	Opaque	Appears metallic under reflected light

Table 4-1. Particles seen in kerogen isolate slides.

Error bars

For sake of accuracy, slides from three of the sixteen sampled locations were recounted. The average inaccuracy was 10% distributed randomly across all of the samples.

4.22 Spore diameter variation

It is known that the size of a spore can have an effect how it is transported by water or wind (Holmes 1994, Horowitz 1992). To assess any transportational sorting in the Rousay Flagstone Formation, the diameter of the common and easily recognisable spore, *Rhabdosporites langii* was measured as it occurred across Orkney. *R. langii* has the advantage of having range of equatorial diameters from 50 μm to over 200 μm (Marshall 1996). This allows the size variation of one species to be studied throughout the basin.

Method

An Olympus BH-2 microscope with a manually moved micrometer stage was used to study the slides produced for the absolute spore count (abspore) method above. Each slide was searched for all complete *R. langii* specimens using the X20 objective lens. The key features of *R. langii* are listed in Table 4-2, and photomicrographs of two specimens are presented in Figure 4-1. When a suitable specimen was found its diameter was measured using the microscope's eyepiece graticule under the X40 objective. In the case of non-spherical spores the eyepiece graticule was rotated to parallel the axis of maximum length.

The measurements from the eyepiece graticule (at X40) were then converted into microns (by multiplying by 2.5). The measurements were averaged, to give an average spore diameter for *R. langii* for each location.

The main limitation of this method is the general paucity of well preserved spores within the Rousay Flagstone Formation.

Outer surface covered with small cones and rods up to 1.5 µm in height.
Two walled although inner wall my not be visible
Folds formed on outer surface
Rounded shape
Maximum equatorial diameter exoexine 258 µm
Maximum equatorial diameter intexine 193 µm

Table 4-2. Key characteristics of *Rhabdosporites langii* (from Marshall 1996)

4.23 Visual spore colour identification as a measure of maturity

Spore colour variation is a quick and easy way of quantifying thermal maturity variations in a sedimentary basin (Marshall et al. 1985). In the same way that the reflectivity of exinite increases with thermal maturity, spores become progressively darker brown the more they are heated. This colour change can be quantified with the use of a spore colour standard chart, which assigns a particular number to a particular fossil colour although Marshall (1992) states that colour change is only a reliable indicator of maturity up to the inception of oil generation. Above vitrinite reflectivities of 0.6% a single spore sample can have a colour range from yellow to brown.

This thesis uses both exinite reflectivity and spore colour variation to provide some degree of confidence in the resulting maturity estimates. It is possible to correlate spore colour with an absolute maturity index such as vitrinite reflectivity. In this case however, relative maturity changes give all the information that is needed.

S. Hillier (1989) in his thesis outlines a number of problems with the use of spore colour measurement, especially when it is used to compare maturity figures between basins. Three of the key problems are summarised briefly below:

- It is a subjective technique affected by such factors as colour perception and individual operator bias.
- Separate colour schemes are based on assessing colour in different ways – using thick walled or thin walled areas would give different results.
- High levels of AOM in samples can inhibit the spores from reflecting the true level of maturity (Marshall 1998, Hillier 1989).

These points although of concern, do not represent a problem for the use of spore colour variation as used in this thesis, because what is required is simply a relative measure of spore colour variation within a single basin. The problems of operator bias can be removed because all the observations were made within a single 48 hours period by one person. Also only the thinnest edges of clearly identified spores were measured. Finally AOM suppression can be taken almost as a constant across the basin because most of the samples contain high percentages of AOM compared to spores.

Method

The samples richest in spores were selected from the slides prepared for the abspore counts (section 4.21). Twenty or so spores from each sample were studied under transmitted light and compared to the Munsell Thermal Alteration Index (TAI) standards chart (matte finish) Version #2 (1984), to assess the average spore colour for each slide. Spore colours were given TAI numbers from Table 6.

The Munsell Color chart numbers are difficult to manipulate in spreadsheet packages (being in the form of e.g. 4+, 5-). To aid analysis the numbers were converted into the whole number colour scale used in Hillier & Marshall (1992) which is based on the Phillips Petroleum Company colour standard.

Organic Thermal Maturity	TAI V #2	Phillips spore colour	Value/ Chroma	Hue
Immature	1	1	9/4	7.5Y
	1+	2	9/8	7.5Y
	2-	3	8.5/12	5Y
	2	4	8/12	2.5Y
Mature main phase of liquid petroleum generation	2+	5	7/12	10YR
	3-	6	6/10	10YR
	3	7	5/6	10YR
	3+	8	4/4	10YR
Dry gas Or barren	4-	9	3/2	10YR
	4	10	2.5/1	10YR
	(5)	11		

Table 4-3. Spore colour chart modified from Hillier & Marshall (1992) and TAI standards chart version #2 (1984).

4.24 False starts

As stated at the start of this section two methods of kerogen characterisation were found to be of little value. For the sake of completion, summaries of these methods are presented here.

Palynomorph ratios (Relative spore counts)

Kerogen isolates from all of the sampled locations were produced using standard HCl/HF demineralisation techniques as were the absolute spore number samples. However the samples were not weighed and were not subjected to ultrasonic disruption. The aim of this was to produce kerogen isolates that were compositionally as close as possible to the original organic matter deposited in the lake. The relative numbers of particles of AOM, spores and woody material were counted use of an Olympus BH-2 binocular microscope fitted with a Swift Model F point counter and automatic stage. 300 counts were made on every slide. This allowed relative percentages of the three palynomorph types to be produced. Two main issues became evident:

- Very little woody material was found (at most 1 or 2 counts per slide). This was to low a concentration to produce any meaningful statistics about wood distribution in the Orcadian lake.
- Most samples contained in excess of 90% AOM, the rest being mainly spores with on average 1% woody material. It became evident that any variation in spore % could equally be attributed to relative increases in AOM %, rather than to variation in actual spore numbers.

Spore diameter variation

Using the slides produced for the relative spore counts, the diameters of all spores seen were measured irrespective of species to see if any general trends of spore size variation were seen across Orkney. This approach was flawed in that too many uncertainties existed into what could be causing any observed spore diameter variation.

4.3 Exinite Reflectivity

The most common way of measuring potential source rock maturity is by using vitrinite reflectance. This relies on the fact that the preserved lignin and cellulose components of plant tissues (vitrinite) increase in reflectivity as they are heated (Killops & Killops 1993). Measurement of the reflectance using a UMSP 50 microscope gives a direct measure of the thermal maturity of the sediment (Hillier & Marshall 1992).

The lacustrine sediments of Rousay Flagstone Formation have very little vitrinite present within them. This is probably due to the distal location of Orkney within the Orcadian basin during this time. In such distal settings woody particles would tend to be deposited in more proximal locations. For example in the south-east Shetland basin, the Devonian sediments were deposited in a very proximal location rich in plant fragments (Allen & Marshall 1981). The kerogen found within the lacustrine sediments of the Rousay Flagstone Formation was composed predominantly of amorphous organic matter with lesser spores, suggesting a distal location for Orkney in the Devonian lake.

Fortunately, spores (or the sporinite component of exinite) also increase in reflectance as source rocks become more mature. This allows measurement of exinite to give an indication of the maturity of the Orcadian rocks.

As an alternative to vitrinite reflectivity, exinite reflectivity has its limitations. The range of temperatures over which exinite is sensitive is generally lower and not as broad as that of vitrinite (0.2-1% vitrinite equivalent) (Smith & Cook 1980). The other main problem was the general scarcity and poor preservation of spores in the Rousay Flagstone Formation. The scarcity of spores and relative abundance of amorphous organic matter (AOM) can lead to AOM suppression (Marshall, Brown & Hindmarsh 1985, Hillier 1989) i.e. a tendency for spores in AOM rich sediments to have paler colours and lower reflectivities than similar spores from AOM poor sediments. Many samples were screened to locate suitable spore rich samples.

Method

The kerogen isolates richest in spores were selected from the slides produced for the palynomorph ratio counts (see 4.24). The samples were subjected to ultrasonic disruption to remove the amorphous organic matter leaving a spore rich residue. The residue was then prepared as a polished thin section as described by Hillier & Marshall (1988). The method involves 'coating a cover slip with a releasing agent, enabling it to be removed from a thin layer of resin mounted on a glass slide. The resin layer contains the organic particles and is left with a smooth, flat surface, which facilitates polishing' (Marshall & Hillier 1988).

A UMSP 50 microscope was used to measure the exinite reflectance of the spores on the polished slides. A spinel standard of 0.419% reflectivity was used. Further information on the use of the UMSP 50 can be found in Hillier & Marshall (1992). When using the UMSP50 to measure the exinite reflectivity care must be taken to measure only the polished surfaces of spores on the slide. When observing the polished slides under reflected light most features appear as shades of grey. Spores were identified by their oblong, rounded shape and often by their double walled nature. Tiny pits associated with the polishing process can be focussed on to ensure the surface is in focus.

Reflectance data are collected and edited using the UMSP50's dedicated software. Where possible at least 20 readings were taken from each slide to calculate an average reflectance figure.

4.4 Elemental Analysis

The Carlo Erba EA1108 Elemental Analyzer can measure the carbon, hydrogen, nitrogen, sulphur and oxygen content of source rocks. Knowledge of the atomic carbon content in the form of total organic carbon (TOC) gives an indication of the hydrocarbon potential of a rock. Hydrogen and oxygen data in the form of atomic H/C and O/C ratios can give information on the type of kerogen present in a rock and how thermally mature it is (Tyson 1995). The nitrogen and sulphur content of the samples were not required for this thesis. The following is a brief account of how the Elemental Analyzer operates.

Source rock samples are combusted and the resulting gases chromatographically separated and detected by a thermal conductivity detector (TCD) (Figure 4-2). Sample combustion is carried out in one of two separate reactors that are independently heated and connected to their own chromatographic columns. One reactor system performs oxidation and reduction to determine C, H and N content. The second reactor is for O or S.

CHN determination

The samples are oxidised in an atmosphere enriched in oxygen. This converts all organic and inorganic substances into combustion products. The resulting gasses pass through a reduction furnace and are swept into a chromatographic column by the carrier gas (helium) where they are separated by the chromatographic column and detected by a TCD.

Oxygen determination

The samples are weighed into silver capsules and introduced into the pyrolysis chamber where they are combusted in the presence of carbon. The resulting CO gas is swept through the chromatographic column by the helium carrier gas and is detected by the TCD.

The Elemental Analyzer has an accuracy of better than 0.3% absolute value (0.5-3.0mg sample) and a reproducibility of better than 0.2% absolute value (0.5-3.0mg sample) for C, H, N, S and O.

4.41 Total Organic Carbon (TOC)

Several TOC measurements were calculated for each sampled location in lake cycles 26 and 36. This provided a profile of how organic carbon deposition varied as the lake sediments were deposited. The figures from each location were averaged to provide a single value representative of that lake cycle in that location. This allowed comparison of TOC content across Orkney. TOC figures are always given as a weight percentage.

Method

The cleaned rock samples were ground to a fine powder using an agate pestle and mortar, and divided into two parts. One part was treated with Analar grade HCl to remove any inorganic carbon in the form of carbonate, and then neutralised by dilution. Both the acidified and non-acidified parts of the sample placed in weighed tin capsules and processed in the Elemental Analyzer.

The machine was calibrated with an acetanilide standard (standard 71.09% carbon). After every five samples a standard was run, if it was within 0.3% of the theoretical value the samples needed no correction. If the samples were up to 0.6% from the theoretical value, they were corrected by averaging them with the current standard value. If the acetanilide standard produced carbon readings greater than 0.6% from the theoretical value for 3 consecutive analyses, the machine was recalibrated.

The Elemental Analyzer only measures the percentage of carbon in each sample. In order to calculate the TOC, corrections need to be made to remove the influence of carbon in the form of carbonate (especially calcite) contained within the samples.
This is done using the following equation:

$$\text{TOC }\% = 100 \quad \text{x} \quad \frac{((8.33 \text{ x } C_T)/100-1)}{8.33-(100/C_A)}$$

Where C_T = total carbon of the sample, C_A = carbon content of the acidified sample and 8.33 = the molecular weight of calcite/molecular weight of carbon.

The results were either plotted individually on the individual lake profiles (Figures 5-1 to 5-4), or averaged to give a spot TOC value for each location (Figure 5-17).

4.42 TOC profiles as a measure of weathering

An attempt was made to quantify the degree of carbon loss experienced by the exposed rocks as a result of weathering. Since no coring equipment was available, an outcrop of rock was needed in which one face had been exposed for a long time i.e. since the glaciers retreated, and another face exposed recently, to enable the sampling of the same layer of rock at various distances from the exposed surface. Loth Quarry (HY601343) on Sanday was selected, because although not currently in use, quarrying had only stopped five years previously leaving relatively fresh rock faces. In two separate locations, samples were taken from organic rich sandy shales. Care was taken to limit the sampling to the same horizon in each location.

The samples from the two profiles (Loth profile #1 and Loth profile #2) were washed and analysed for TOC in the manner described above. Furthermore the samples from Loth profile #2 were de-mineralised (as in section 4.21) to see what aspects of the rock's organic component were changing. To do this slides of the isolated organic matter were prepared and the occurrence of Devonian spores, AOM, and recent organic contamination were counted. Recent organic contamination is easily identified because it is neither as dark or as corroded as the organic matter from the Devonian sediments. The recent organic contamination was generally in the form of spores or roots.

4.43 Atomic hydrogen/carbon and oxygen/carbon ratios

Using pure kerogen isolated from the rock samples by standard palynological processing it was possible to calculate the atomic H/C and O/C ratios of the kerogen itself. These parameters can indicate the type and maturity of the kerogen, as well as possible weathering effects (Durand & Monin 1980).

Opinion regarding the main kerogen type of the Orkney Flagstone Group varies from Type II to IIIA (Marshall et al 1985), Type I or Type II (Duncan & Hamilton 1988) to Type I (Trewin 1989). There are two possible causes of this difference in opinion. Firstly the samples for these studies have been collected from a variety of locations and stratigraphic horizons throughout the Orcadian Basin. These are known to have different palynomorph constituents and hence different kerogen types. For example Marshall (1995) notes the extremely low numbers of spores recovered from the Rousay Flagstone Formation compared to the Stromness Flagstone Formation, and Allen & Marshall (1981) note that wood dominates the preserved organic matter in south east Shetland. Secondly the samples were taken from areas of different thermal maturity (Hillier & Marshall 1992) and hence differing atomic H/C ratios.

Study of the Rousay Flagstone organic matter rich sediments in this thesis (section 4.24 and 4.21) found that AOM is by far the most common component of the kerogen in these rocks (generally around 90% of particles counted). Thus by definition the spore deficient Rousay Flagstone Formation should be defined kerogen Type I, compared to the other Orkney Flagstone Formation which are far richer in spores, which are kerogen Type II.

Type I kerogen is characterised by high H/C ratios (1.5-1.8) and initial O/C ratios that are generally < 0.1 Tyson 1995 p 367) and are typical of lacustrine environments. When Type I kerogen matures thermally, hydrocarbons are given off which are relatively rich in hydrogen compared to carbon. The more mature the source rock the more it is relatively depleted in hydrogen. This means that the H/C ratio of Type I kerogen decreases more markedly than the O/C, as can be seen on the standard Van Krevelen diagram in Figure 4-3. Thus H/C ratios are more sensitive to maturity changes in Type I kerogen. For this reason more H/C ratios were measured than O/C ratios.

O/C and H/C ratios were calculated for two complete cycles (cycle 26 Evie and Surrigarth) to give an indication of the O/C ratios for the area. For the rest of the basin, only 2-3 H/C ratios were calculated for each location (mostly from cycle 26). TOC values and visual kerogen identification was used to select samples with the highest TOC's and lowest spore contents to ensure only AOM rich, Type I kerogen was analysed.

North (1983) proposes a figure of 1.92 for the average H/C ratio for living organisms. This suggests that a figure from Devonian samples close to or above this figure would imply contamination or alteration of the kerogen. Thus before any analysis was attempted on the results of the H/C ratio data, 4 samples that produced H/C values greater than 2 were discounted from the data set. Three of these samples had H/C ratios of between 2 and 3 and came from Hoxa and Halcro Head; another sample from Hoxa Head had a H/C ratio of 10. These values are thought to be too great to represent uncontaminated kerogen.

Method

The Elemental Analyzer has to be reconfigured to measure oxygen, from its more usual carbon and hydrogen measuring configuration. The sample run times for hydrogen and oxygen are around 15 minutes compared to 3 minutes for carbon. The pure kerogen samples (as prepared for palynomorph ratio work) were transferred from aqueous suspension to pre-weighed tin capsules (silver capsules for oxygen determination). The samples were dried for 24hrs and then kept in a desiccating chamber. The capsules were then re-weighed allowing the weight of the kerogen to be known. This figure was entered directly into the machine and the kerogen samples were then run as usual.

The standards used have to contain carbon, hydrogen and oxygen such as acetanilide or sulphanylamide.

The carbon, oxygen and hydrogen values produced were combined with the atomic weight of the appropriate elements to provide oxygen/carbon and hydrogen/carbon ratios as follows:

$$\text{Atomic O/C} = \frac{\%O}{16} \Big/ \frac{\%C}{12}$$

Where 16 is the atomic weight of oxygen and 12 is the atomic weight of carbon.

$$\text{Atomic H/C} = \frac{\%H}{1} \Big/ \frac{\%C}{12}$$

Where 1 is the atomic weight of hydrogen and 12 is the atomic weight of carbon.

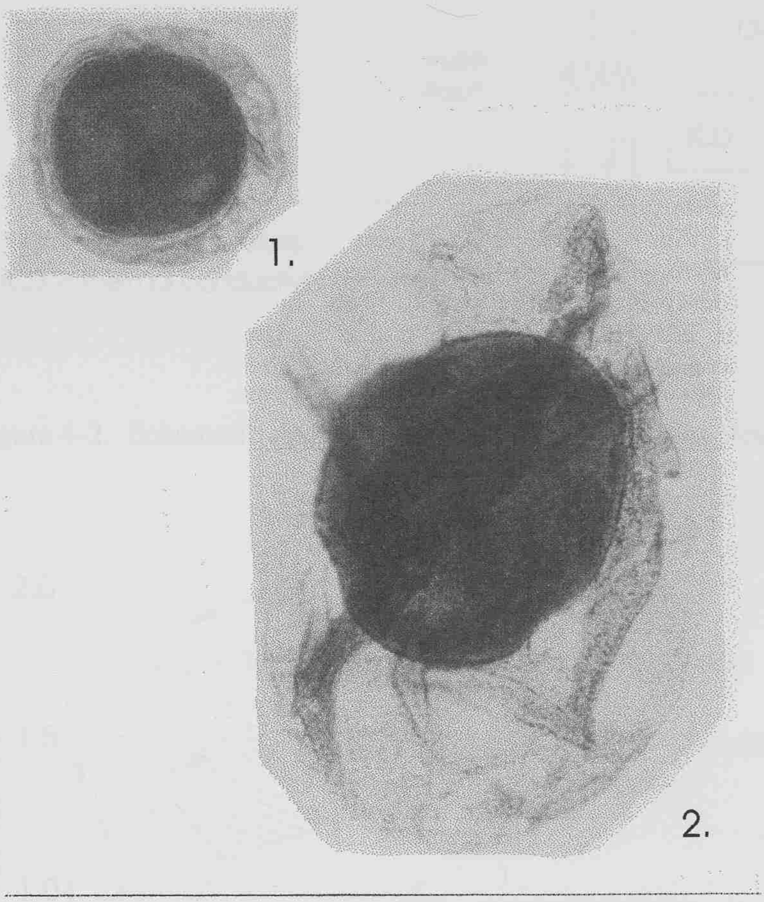


Figure 4-1. *Rhabdosporites langii*, both specimens at x500
1. Specimen from lower end of size range
2. Specfimen from upper end of size range
From Marshall 1996.

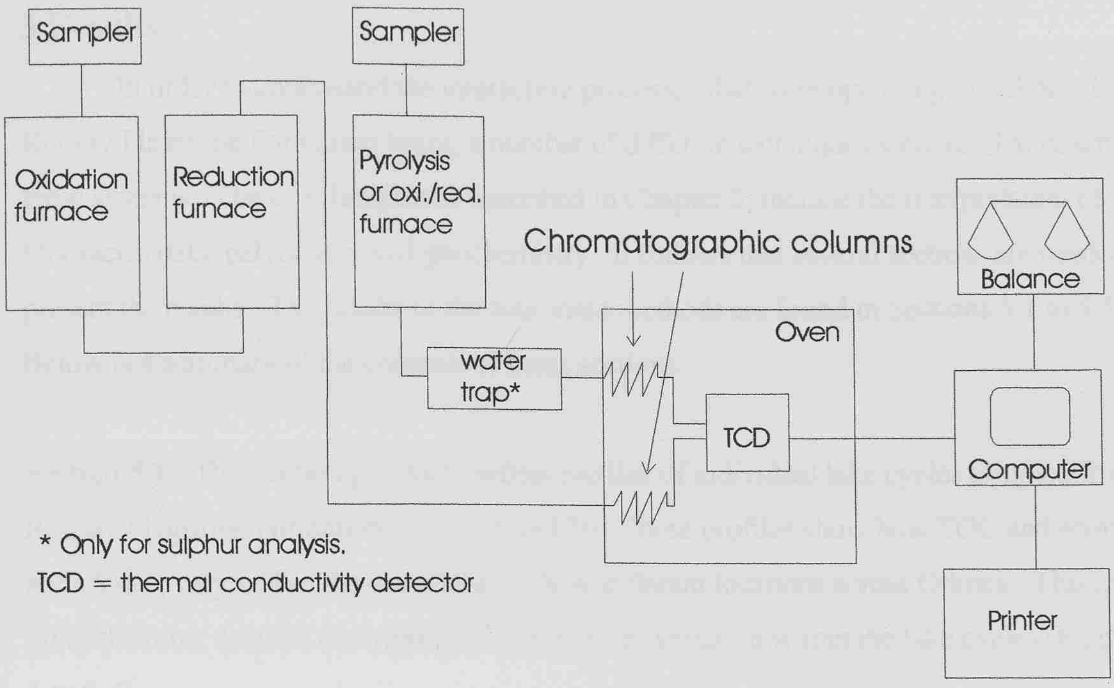


Figure 4-2. Schematic diagram of a Carlo Erba Elemental Analyzer 1108.

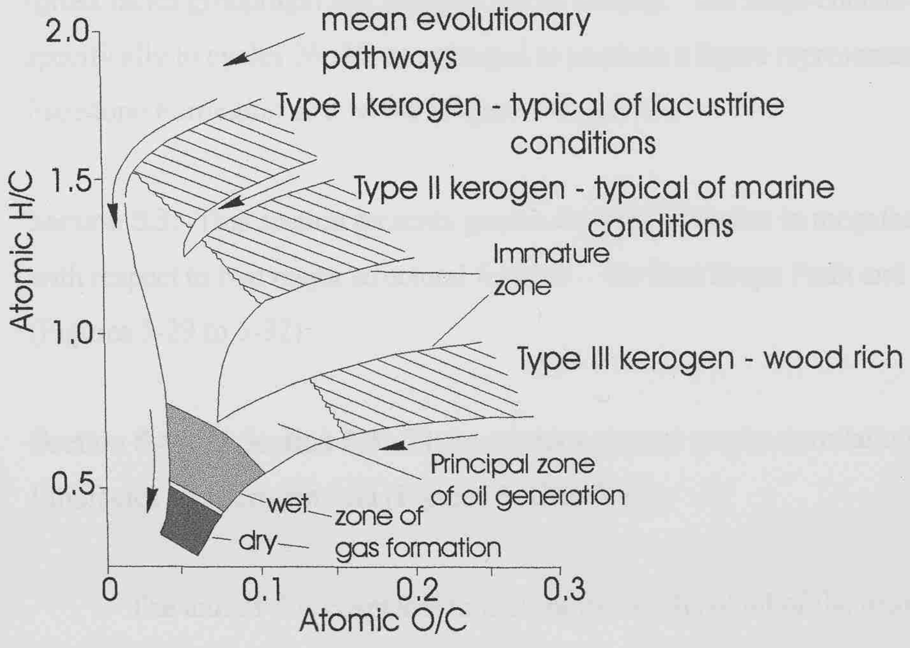


Figure 4.3. Van Krevelen diagram, showing variation in H/C and O/C ratios with increasing maturity.

5 Results

In order to understand the interacting processes that were operating in Orkney during Rousay Flagstone Formation times, a number of different techniques were used to describe these systems. These techniques as described in Chapter 3, include the interpretation of lithofacies data, palynology and geochemistry. It follows that several sections are needed to present the results. The results of the four main methods are found in Sections 5.1 to 5.5. Below is a summary of the contents of these sections.

Section 5.1: This section presents vertical profiles of individual lake cycles sampled from Rousay Flagstone Formation cycles 26 and 36. These profiles show how TOC and spore abundance, vary within the same lake cycle at different locations across Orkney. This method gives the most detailed description of sedimentary variation within the lake cycles (Figures 5-1 to 5-4).

Section 5.2: This section presents maps showing the spatial variation of facies, megafacies (gross facies groupings) and kerogen across Orkney. The maps contain data referring specifically to cycles 26, 36, or averaged to produce a figure representative of the Rousay Flagstone Formation as a whole (Figure 5-6 to 5-28).

Section 5.3: This section presents graphs showing variation in megafacies across Orkney, with respect to two major structural features – the East Scapa Fault and the North Scapa Fault (Figures 5-29 to 5-32).

Section 5.4 and Section 5.5: These sections present graphs correlating various aspects of the lithofacies and kerogen data (Figures 5-33 to 5-40).

The aim of this chapter is to present the results of all of the techniques used in this thesis. Due to the large selection of data produced during the course of this thesis, a large number of techniques and different ways of presenting the data were used. Not all of these methods proved equally useful. Thus, although a figure may be presented and commented on in this section, it may not be referred to again in the Discussion (Chapter 6). Summaries of all palynological, lithofacies and megafacies data used are presented in Appendices 2, 3 and 4.

5.1 Individual lake profiles

As described in Section 3.2, lake profiles show how TOC and numbers of spores per gram of rock (abspore) vary through the lower, organic matter rich part of lake cycles 26 and 36 where they were sampled across Orkney. Figure 2-2 shows the locations of the lake profiles

The profiles are plotted as graphs. Rotating the page through 90 degrees will help interpretation by displaying the graphs in a log-type format. Microfacies type is always represented in the form of bar charts and the X-axes represent the vertical section up through the lake in centimetres. These graphs are presented in Figures 5-1 to 5-4. Table 5-1 lists the main trends for each location.

Summary

Three main results were apparent from the graphs. The first result is that facies indicative of a shallow water depositional environment and containing organic matter, such as Wick (microfacies 4) and grey silt facies (microfacies 5) are commonest at the base of most lake cycles. Progressing up through each cycle these facies are generally replaced by deeper water facies such as laminites, near laminites and dark silts (microfacies 1-3). Towards the top of the lacustrine phase, shallower water facies return. This demonstrates that the Orcadian lakes were experiencing gradual and cyclical water level variation.

The second result is that there is a definite correlation between water depth as suggested by facies type, and TOC content. Most graphs show that higher TOC values occur in the deeper water facies such as laminite, near laminite and dark silt. This, when combined with the fact that most of the cycles tend to show a shallow-deep-shallow facies profile, means that the TOC profiles in many cases, tend to be symmetrical with the highest TOC values occurring around the mid-point of the lake profile.

The third point deals with the distribution of spores per gram of rock (abspore) in the lake profiles. Of the seventeen locations analysed, three had very low spore numbers (Wars Ness 26, Stronsay 26, Head of Work 26 (Figures 5-2g, 5-3d, 5-3f). Hoxa Head 26 (Figure 5-4d) was discounted because of an insufficient spread of sample points. Of the remaining thirteen, eight occurred on the west side of the East Scapa Fault. Of these eight, six locations showed that higher numbers of spores were associated with deeper water facies such as laminites, near laminites and to a lesser extent dark silts. Hoxa Head 36 (Figure 5-4f) and South Halcro Head 26 (Figure 5-4h), both in the south, were the only location to the west of the East Scapa Fault in which high spore numbers were associated with relatively shallow water facies. East of the East Scapa Fault, only one location showed this trend – North Faray (Figure 5-2b). The other four locations east of the fault showed the opposite – a tendency for greater numbers of spores to be found in shallower water facies. To summarise, west of the East Scapa Fault more spores are found in deeper water facies, and to the east and south more spores are found in shallower water facies (Figure 5-5).

A further trend of interest see in Figure 5-5 is that low numbers of spores are found in the central area of Orkney, east of the East Scapa Fault. This trend is illustrated in detail in Figure 5-20. A full discussion of these points is given in Chapter 6.

Figure	Location/cycle number	Shallow-deep-shallow facies profile	Higher TOC in deeper water facies	High spore numbers in shallow water facies	High spore numbers in deeper water facies
5-1a/b	Evie 26	YES	YES		YES
5-1c/d	Rousay 26	YES	YES		YES
5-1e/f	Rousay 36	YES	YES		YES
5-1g/h	Noup 36	YES	YES		YES
5-1i/j	Surrigarth 26	YES	APPROX	YES	
5-2a/b	North Faray 36	YES	YES		YES
5-2c	Fers Ness 26	YES	YES	Uncertain	
5-2d/e	Fers Ness 36	NO	YES	YES	
5-2f/g	Wars Ness 26	YES	YES	N/A	
5-2h/i	Spurs Ness 26	YES	APPROX	YES	
5-3a/b	Loth 36	YES	YES	YES	
5-3c/d	Stronsay 26	YES	NO	Uncertain	
5-3e/f	Head of Work 26	YES	YES	Uncertain	
5-3g	Tankerness 26	NO	APPROX	N/A	
5-3i	Burray 26	YES	APPROX	N/A	
5-4a/b	Flotta 26	YES	YES		YES
5-4c/d	Hoxa 26	NO	APPROX	YES	
5-4e/f	Hoxa 36	YES	YES	YES	
5-4g/h	South Halcro 26	YES	YES	Uncertain	
5-4i/j	North Halcro 36	NO	NO		YES

Table 5-1. Summary of lake profile graphs. See text for an explanation of the column headings. N/A= not analysed. Approx. = approximately fits trend.

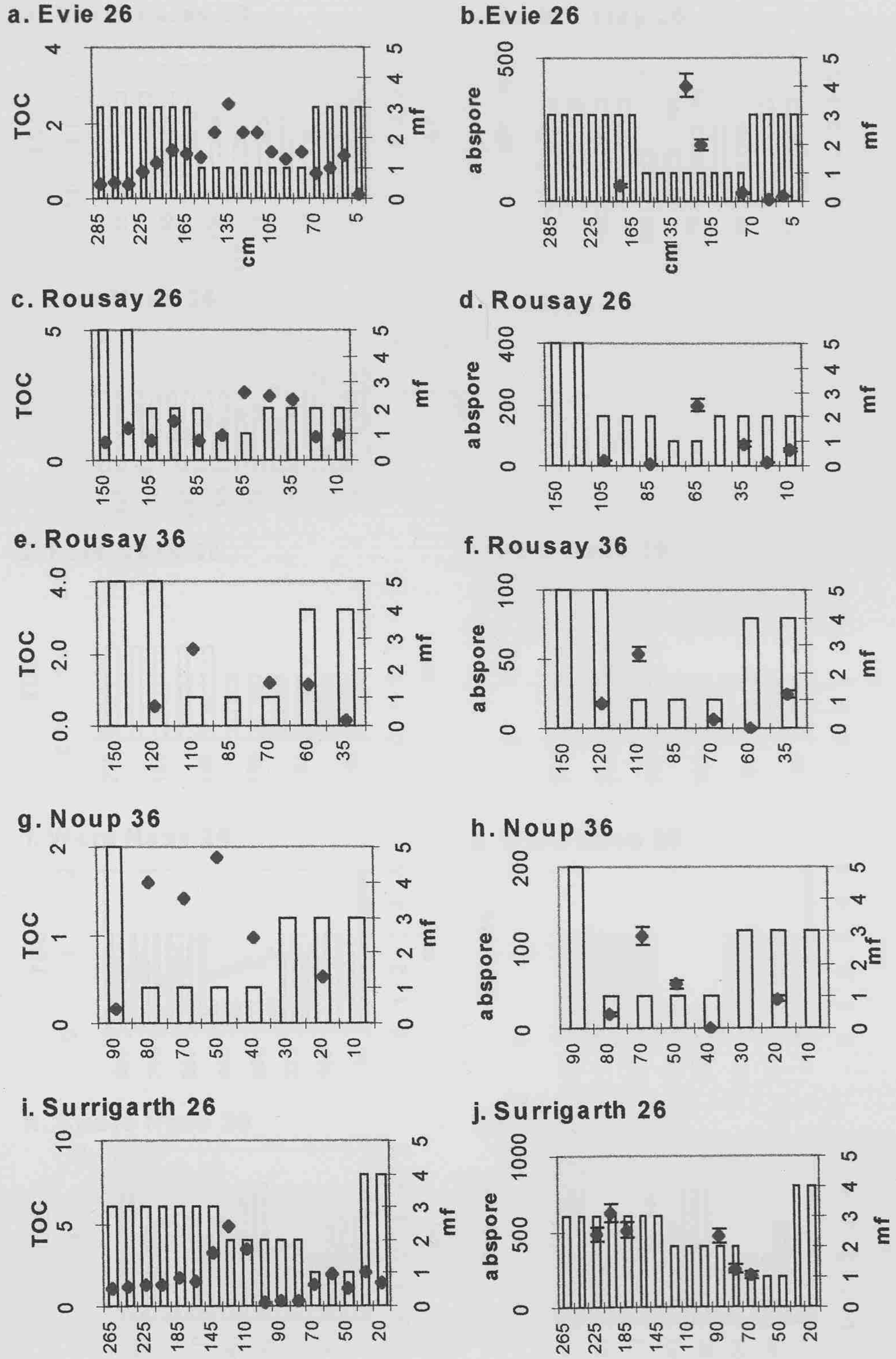


Figure 5-1. Lake profile graphs cycles 26 and 36. Showing TOC and abspore (spores per gram of rock) variation through the lake. Microfacies (mf) always shown as bar chart. Microfacies code: 1=laminite, 2=near laminite, 3=dark silt, 4=wick, 5= grey silt. X-axes represent the vertical distance through lower part of the lake cycle in centimetres. Abspore error bars +/- 10% (see section 4.21). **Turn page on side for log-type profile.**

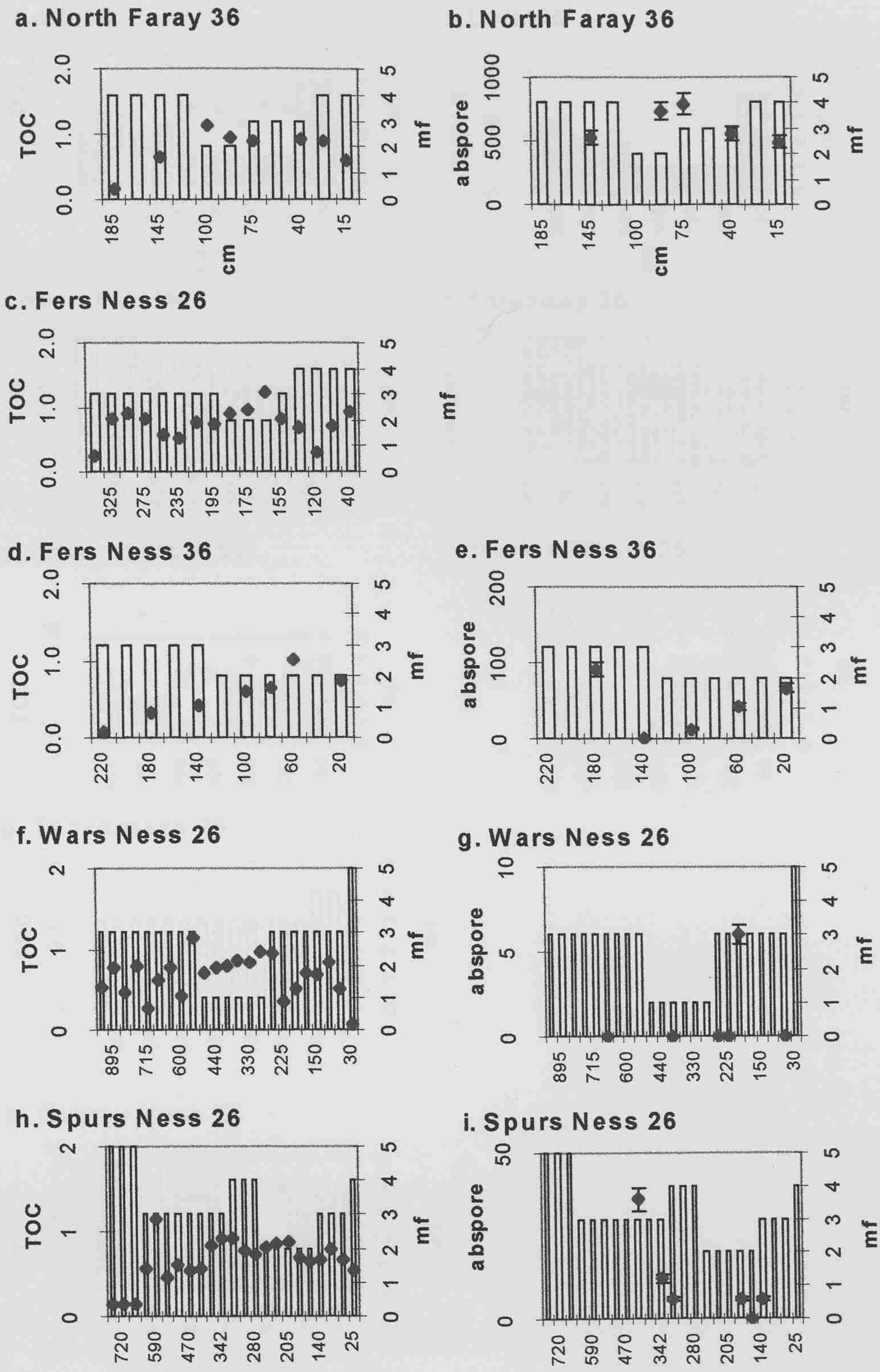


Figure 5-2. Lake profile graphs cycles 26 and 36. Showing TOC and abspore (spores per gram of rock) variation through the lake. Microfacies (mf) always shown as bar chart. Microfacies code: 1=laminite, 2=near laminite, 3=dark silt, 4=wick, 5= grey silt. X-axes represent the vertical distance through lower part of the lake cycle in centimetres. Abspore error bars +/- 10% (see section 4.21).
Turn page on side for log-type profile.

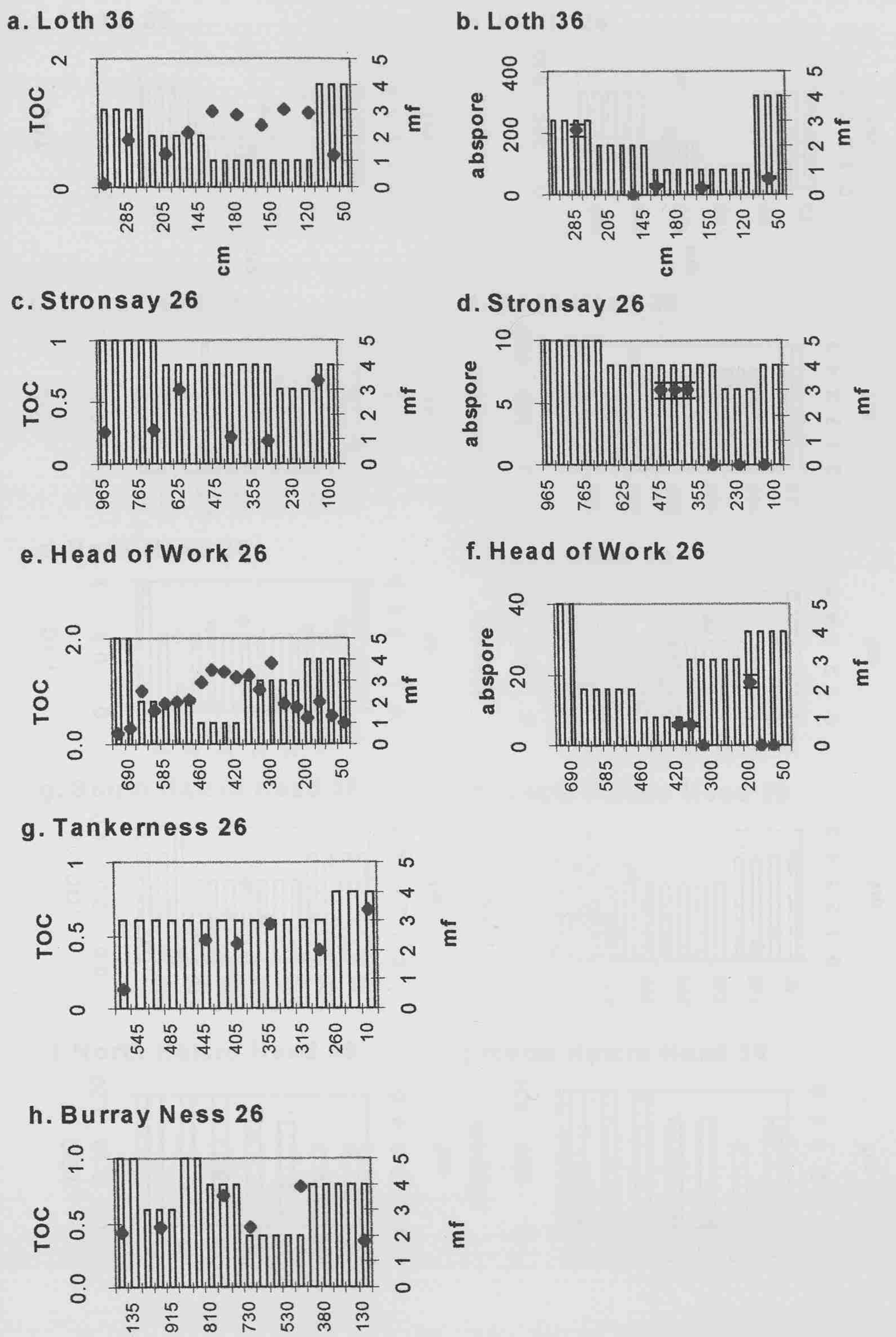


Figure 5-3. Lake profile graphs cycles 26 and 36. Showing TOC and abspore (spores per gram of rock) variation through the lake. Microfacies (mf) always shown as bar chart. Microfacies code: 1=laminite, 2=near laminite, 3=dark silt, 4=wick, 5= grey silt. X-axes represent the vertical distance through lower part of the lake cycle in centimetres. Abspore error bars +/- 10% (see section 4.21).
Turn page on side for log-type profile.

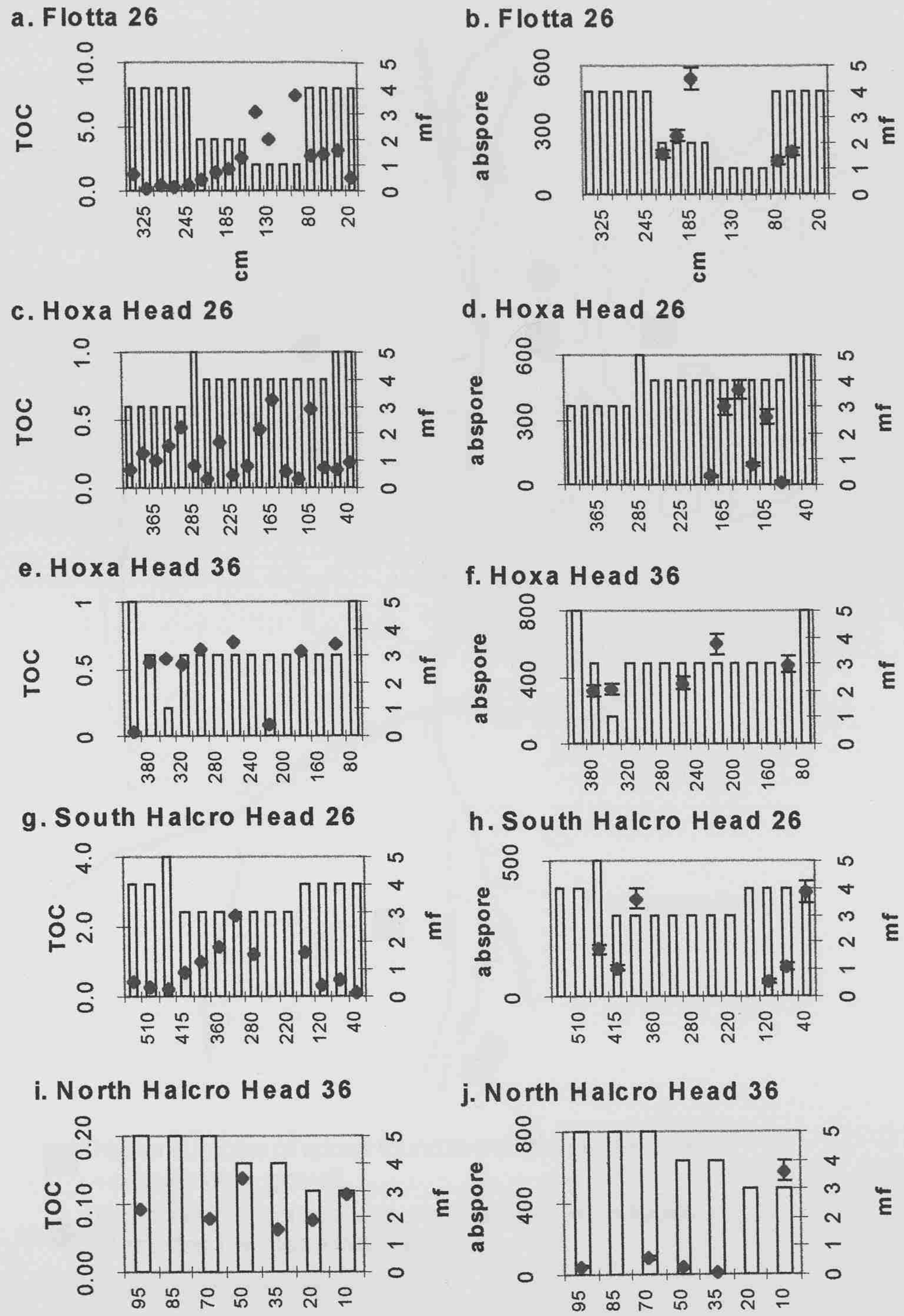


Figure 5-4. Lake profile graphs cycles 26 and 36. Showing TOC and abspore (spores per gram of rock) variation through the lake. Microfacies (mf) always shown as bar chart. Microfacies code: 1=laminite, 2=near laminite, 3=dark silt, 4=wick, 5= grey silt. X-axes represent the vertical distance through lower part of the lake cycle in centimetres. Abspore error bars +/- 10% (see section 4.21). **Turn page on side for log-type profile.**

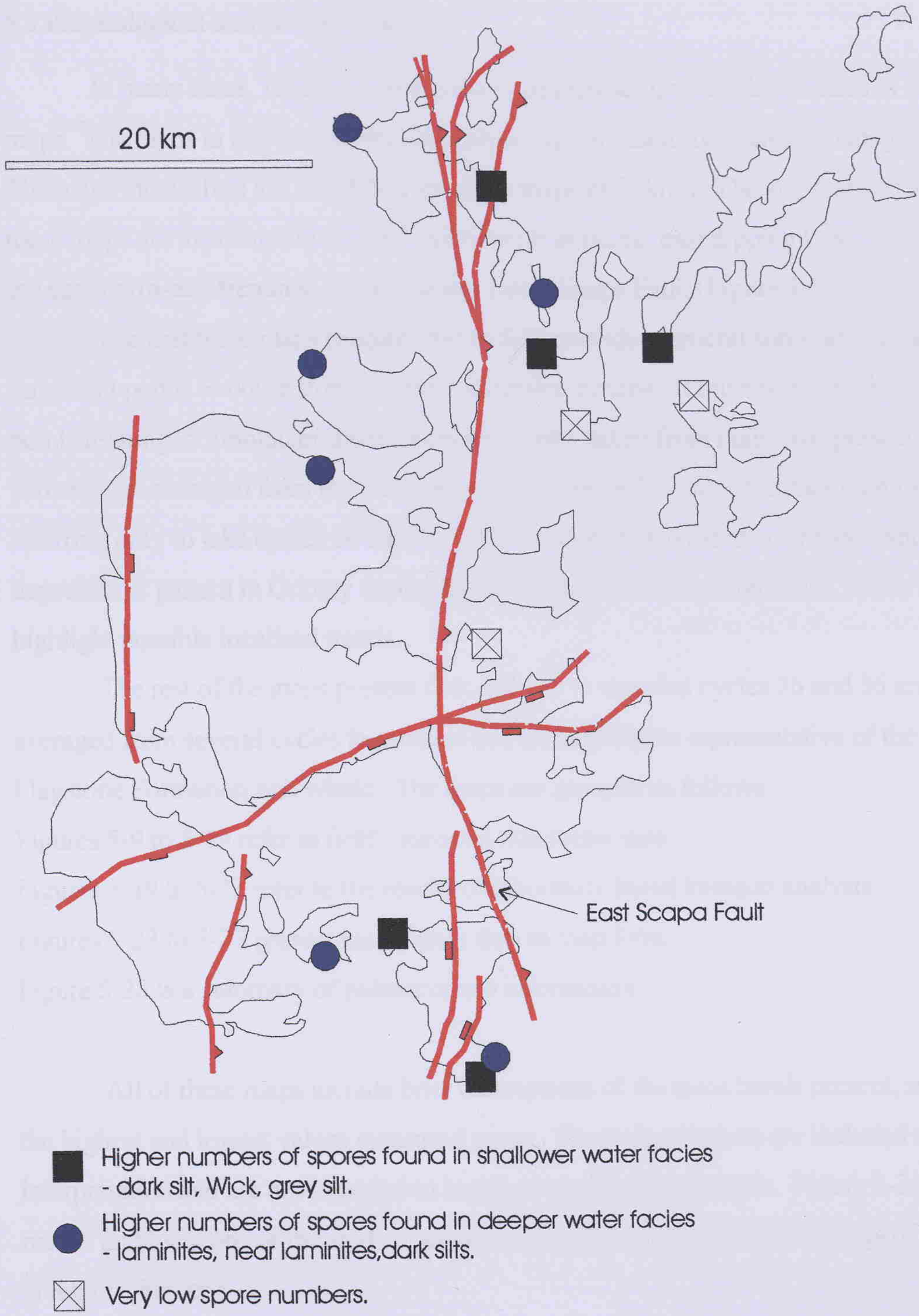


Figure 5-5. Summary map showing the relationship between absolute spore numbers, facies type and position within the basin.

5.2 Palynological and facies maps

In many cases, the most effective way of representing the distribution of data is on maps. The maps in this section include palynological, maturity, facies and megafacies data. The maps themselves are simplified structure maps of Orkney. The key features to note on these maps are the centrally situated north-south trending, east dipping East Scapa Fault and the east-north-east trending, south dipping North Scapa Fault (Figure 1-5).

The first three maps (Figures 5-6 to 5-8) provide a general summary of the most important points to come from the more specialised maps. It must be noted that the key points relating to lithofacies distribution are mostly taken from maps that present facies percentages averaged from the entire Rousay Flagstone Formation, rather than from maps referring only to lake cycles 26 and 36. This is done to provide an averaged indication of the depositional pattern in Orkney during Rousay Flagstone Formation times, rather than to highlight possible localised trends.

The rest of the maps present data specific to sampled cycles 26 and 36 and data averaged from several cycles to produce one average figure representative of the Rousay Flagstone Formation as a whole. The maps are grouped as follows:

Figures 5-9 to 5-19 refer to field measured lithofacies data.

Figures 5-19 to 5-23 refer to the results of laboratory based kerogen analysis.

Figures 5-23 to 5-27 present megafacies data in map form.

Figure 5-28 is a summary of palaeocurrent information.

All of these maps include brief descriptions of the main trends present, such as where the highest and lowest values measured occur. These descriptions are included as an aid to interpretation and are not intended to highlight any localised trends. Figure 2-2 provides the names and locations of the studied sections. A full discussion of the findings of these maps is given in Chapter 6.

5.21 Description of the lithofacies maps

One of the most important points to come from these maps is that the lake cycles to the east of the East Scapa Fault (ESF) are almost always thicker than the lake cycles to the west, often by as much as 100% (Figure 5-9). This trend was noted by Astin (1990), where he saw that the Rousay Flagstone Formation lake cycles in the Rousay section of his stratigraphic framework were thinner than the Rousay Flagstone Formation cycles on the island of Eday (Figure 1-4). What the lithostratigraphic correlation (Figure 2-1) and the maps (Figure 5-9) show, is the extent of the thickness differential across Orkney.

A point to note from Figure 5-9a, is the thickness of 2250cm measured for cycle 26 in the Huip Ness section of Stronsay. This unusually great thickness may be the result of a fault repetition that was obscured by sand when the section was logged.

Figure 5-6 is a summary map of lacustrine dominated facies distribution. It shows that although the greatest percentages of laminite and near laminite facies are found in the north and west of the area, the greatest percentages of organic matter rich sediments are found in the south and south east. The proportion sandy dark silt facies is highest in the south east of Orkney. Most is found on the east side of the ESF, although one location to the west also contains a high proportion of this facies.

The distribution of fluvially dominated facies is summarised in Figure 5-7. In general, the greatest proportion of sand rich facies (wavy sands, sheetfloods, channels and conglomerates) are found in the north of Orkney, and to the west of the ESF. This trend is similar to that of sheetflood facies. High percentages of sheetflood facies are found in the north west and less commonly in the north east of the area.

The medium/coarse grained sheetflood facies type is rare in cycle 26 (Figure 5-19a) but is more common in cycle 36 (Figure 5-19b). Figures 5-19c and 5-7 show that when averaged for the entire Rousay Flagstone Formation, this facies is mostly found in the extreme south of Orkney and to the east and west of the ESF in the north.

5-22 Description of the kerogen distribution maps

Several aspects of kerogen type share similar trends, as is shown in Figure 5-8. The highest TOC values are found mostly to the west of the ESF as well as immediately to the east of the ESF in the far north of the area. The greatest numbers of spores are also found to the west and north east of the ESF. Furthermore, Figure 5-20 shows that cycle 36 generally has higher maximum spore numbers than cycle 26.

Figure 5-8 also shows that the greatest atomic H/C ratios are found to the west and north east of the ESF. Note also, that as shown on the Figure 5-23a, that to the west of the ESF, the average H/C ratio is 0.5 higher in value than the average to the east of the fault.

Figure 5-8 shows that the *Rhabdosporites langii* spores with the greatest diameters are found in the north east and south west of the area. It is also notable that the spores in cycle 36 are on average 7 microns larger in diameter than those in cycle 26 (Figure 5-23b).

5-23 Description of the maturity data maps

The thermal maturity of the lake sediments of Orkney was measured for two reasons. Firstly, to estimate the general maturity of the lake sediments to provide a reliable maturity figure for use when calculating potential source rock productivity and burial histories for Orkney. Secondly, to see if any differences in sediment maturity were caused by fault movements taking some rock units to greater depths than others. This is an important point, because if tectonic motion was responsible for variation in TOC and H/C ratios, these parameters could not be used to deduce sedimentological trends.

Two faults on Orkney that may have exhibited large-scale movement are the East Scapa Fault and the North Scapa Fault (Figure 1-5)(Astin 1985). However, both exinite reflectivity and visual spore colour analysis (Figure 5-22a and b) showed no significant variation in the thermal maturity of the sediments across either of these faults. Thus, any variation in TOC and H/C ratios must be caused by changes in the sedimentary environment.

An important point regarding Figure 5-22a, is that the figures in brackets relate to spores collected from light green sandy siltstone by J. Marshall (Southampton) during previous fieldwork. The spores not in brackets came from dark amorphous organic matter rich siltstones collected specifically for this thesis. The difference in host facies type can explain the differences in exinite reflectivity seen in the two sets of spores. Firstly the light green siltstone contains very little amorphous organic matter (AOM), and thus the entrapped spores have not had their reflectivity kept artificially low by AOM suppression (Hillier & Marshall 1992, Marshall 1998)(see Section 4.23). The organic matter contained within the dark siltstones consist of around 90% AOM (Section 4.24). This suggests that the spores present will have experienced AOM suppression, which reduced their reflectivity relative to the spores of the same thermal maturity from the light green silt.

Secondly, the light colour and lack of AOM in the green siltstone also indicates that the sediments had been exposed to a more oxygen rich environment. Horowitz (1992) states that spores are much better preserved in black organic matter rich sediments than in oxidised silts. Partial oxidation may have altered the reflectivity of the spores from the light green silts.

Thus Figure 5-22a contains two sets of spores that have experienced different physical and chemical processes, within the same thermal maturity regime. The small size of the data set means that, it is very difficult to assess the degree of AOM suppression or oxidation that the spores have experienced. Thus, the exinite reflectivity figures of the two sets cannot be directly compared. What can be assumed, however, is that separately the two groups of spores have experienced roughly the same degree of alteration or suppression. Thus although the range of the two sets of reflectivity figures are different, they show the same trend of minimal reflectivity variation across the ESF.

Spore colour variation studies have inherent inaccuracies associated with them (Section 4.23). Figure 5-22b, shows that the spores studied across Orkney, mostly from the same facies types, show a similar range of spore colours, both east and west of the ESF. Yule (1998) has shown that at exinite reflectivities of between 0.1 and 0.3, spores exhibit an extremely wide range of luminance (a quantitative component of colour at 546nm). This variation in spore colour at low levels of maturity is probably responsible for the range of spore colours observed in Figure 5-22b.

5-24 Description of the megafacies distribution maps

Figures 5-24 to 5-27 show in map form, the distribution of the megafacies in terms of thicknesses and percentages. The points to note from these maps are that; slightly more lacustrine megafacies type is present to the east and south east of the ESF and slightly more emergent megafacies type is present to the west of the ESF. Most fluvial megafacies type is found in the north and north west.

5-25 Description of the palaeocurrent maps

Not all of the palaeocurrent data presented in Figure 5-28 came from sections of known stratigraphic position as defined by the lithostratigraphic framework of the Rousay Flagstone Formation (Figure 2-1). However, their approximate stratigraphic position could be estimated by proximity to the Eday Group and by their general sedimentological character. The basic results of these maps are:

In the Upper Stromness Flagstone Formation currents in the west of Orkney flow towards the south east, south west and north east, and currents in the east of Orkney flow towards the south, south west and south east.

In the lower half of the Rousay Flagstone Formation currents in the west and south of Orkney flow towards the east and north east, and currents in the east of Orkney flow towards the south west and north.

In the upper half of the Rousay Flagstone Formation currents in the south and east of Orkney flow towards the north and north east and currents in the north of Orkney flow towards the south west and south east.

To summarise, the lower half Rousay Flagstone Formation shows current flow from the west and from the north east which changes in the upper half of the Rousay Flagstone Formation to flow from the south west and the north west.

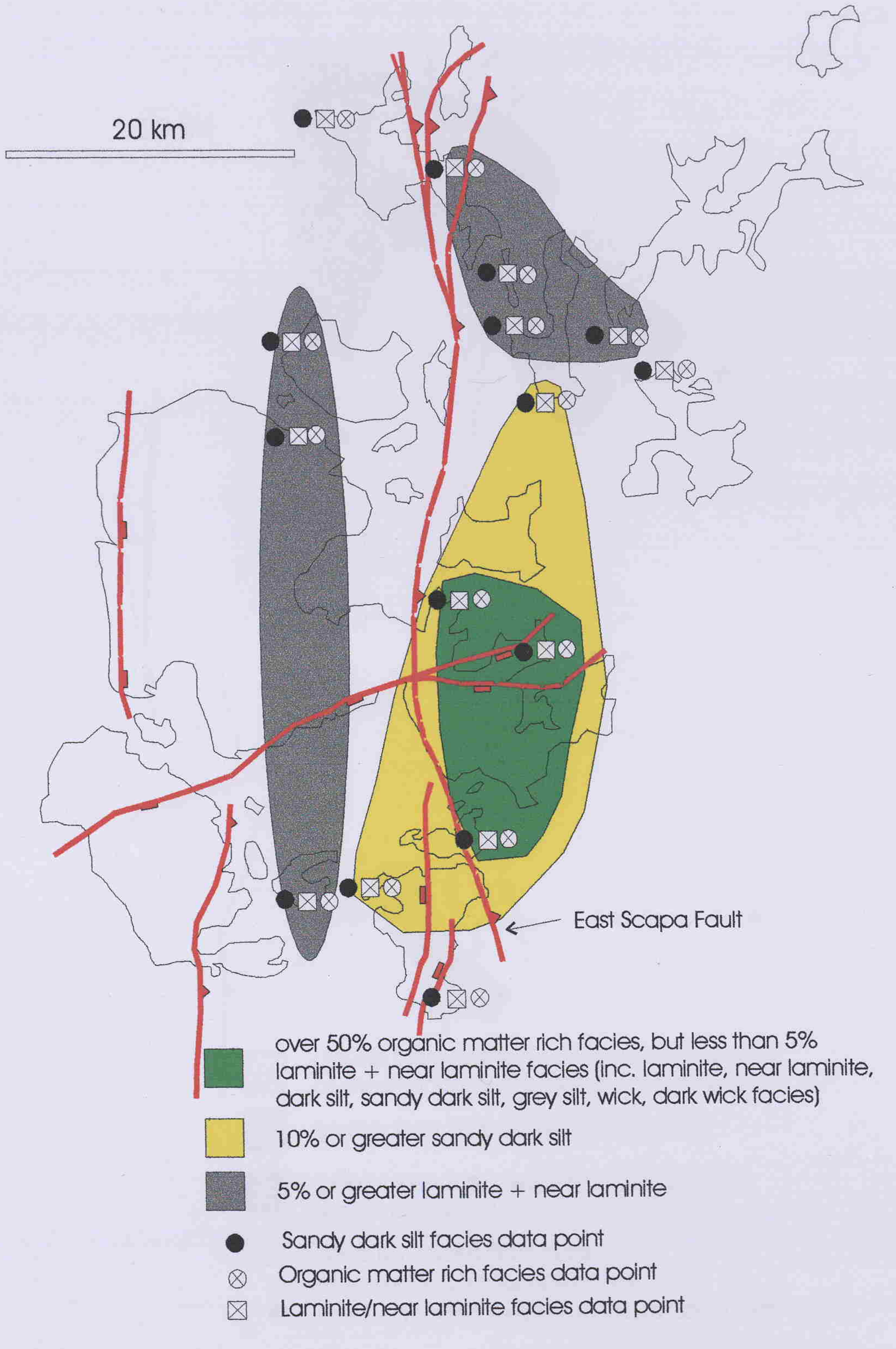


Figure 5-6. Key findings - lacustrine facies. Showing the locations of the greatest values of each facies.
The 'data point' symbols indicate where specific information was available.
Data source: Figures 5-10c, 5-12c and 5-14c.

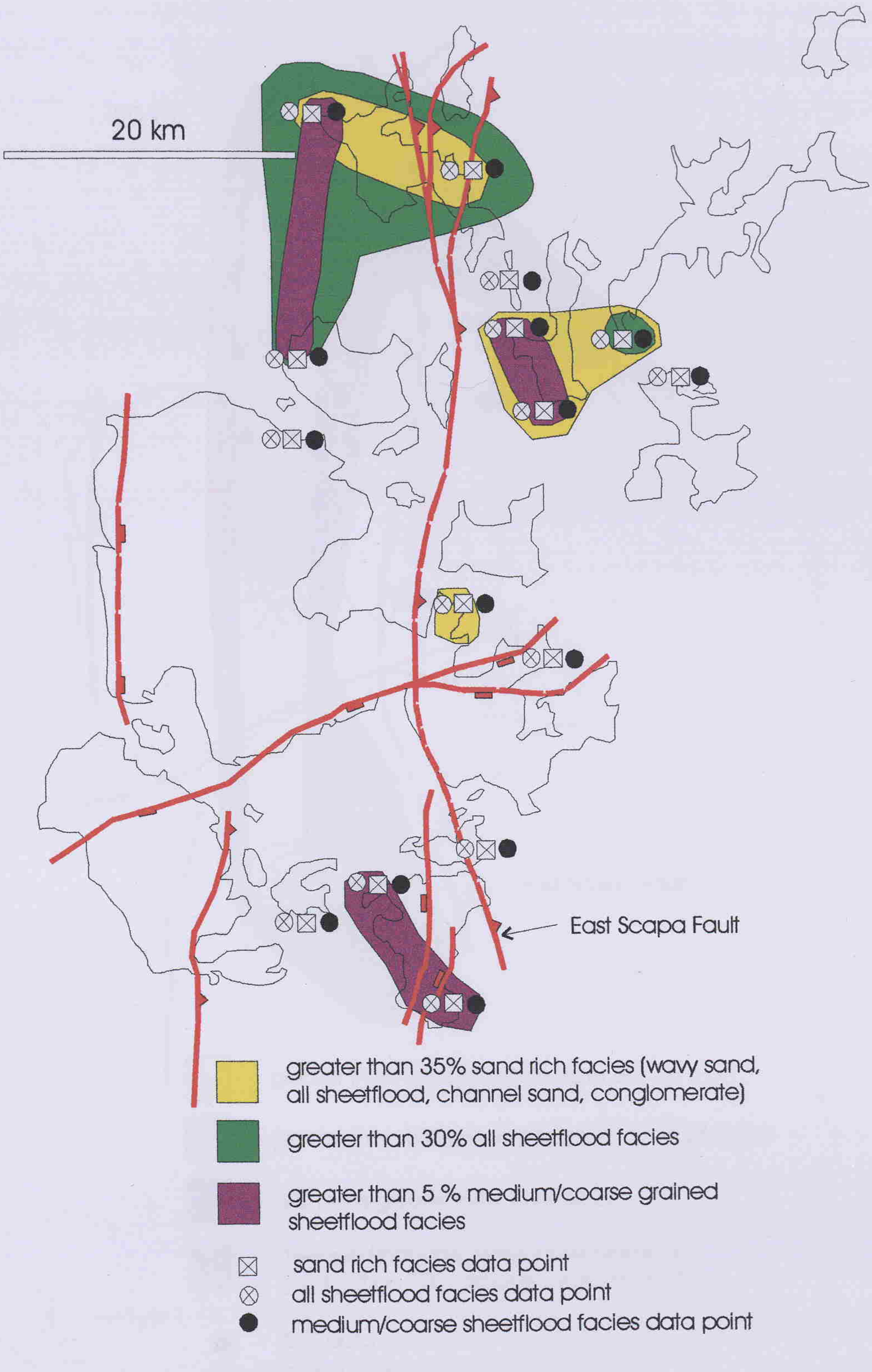


Figure 5-7. Key findings - fluvial facies.
Showing the locations of the greatest values of each facies.
The 'data point' symbols indicate where specific information was available.
Data source: Figures 5-15c, 5-17c and 5-19c.

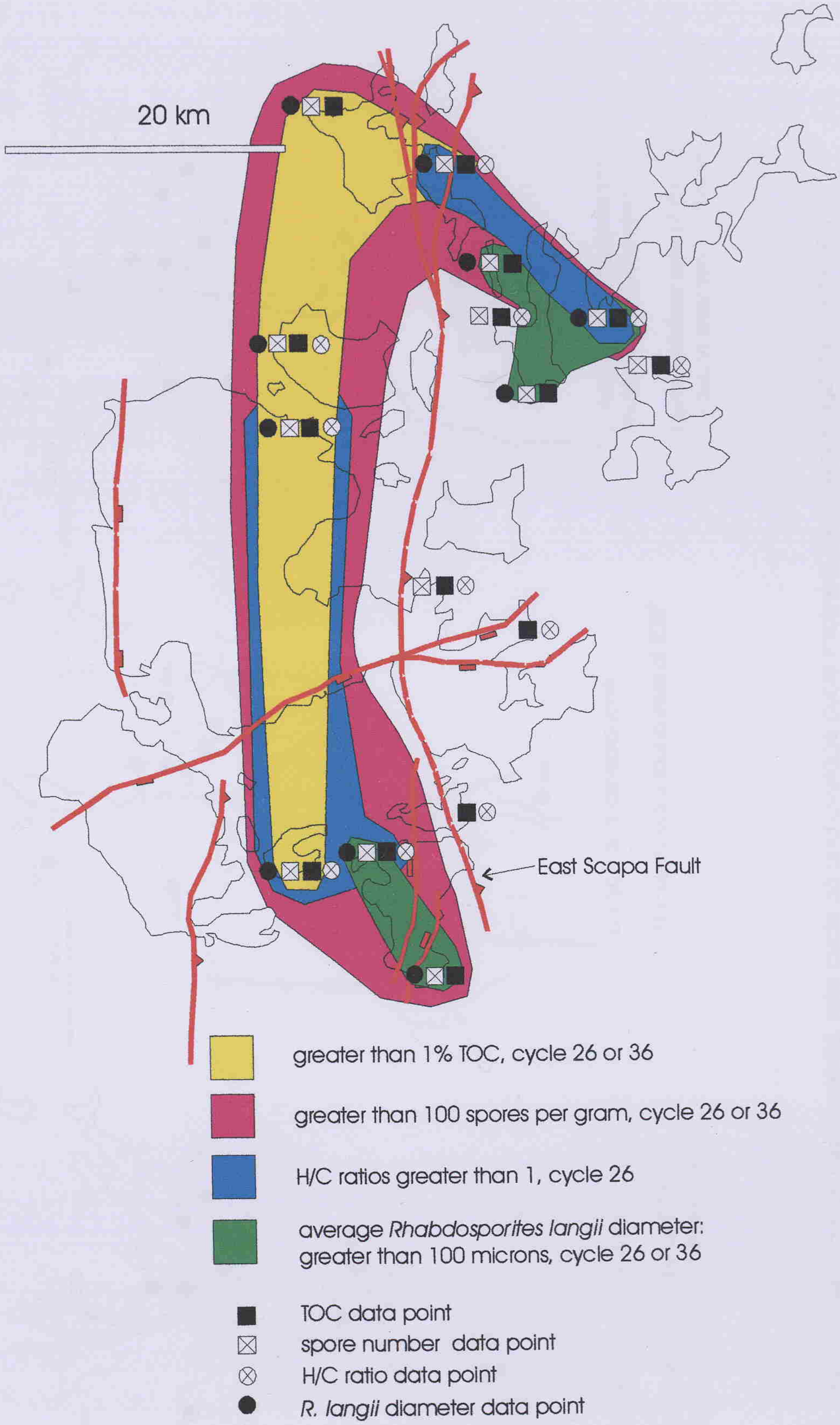


Figure 5-8. Key findings - kerogen data.
Showing the locations of the greatest values of each feature.
The 'data point' symbols indicate where specific information was available.
Data source: Figures 5-20a,b, 5-21 a,b, 5-22a,b, 5-23a,b.

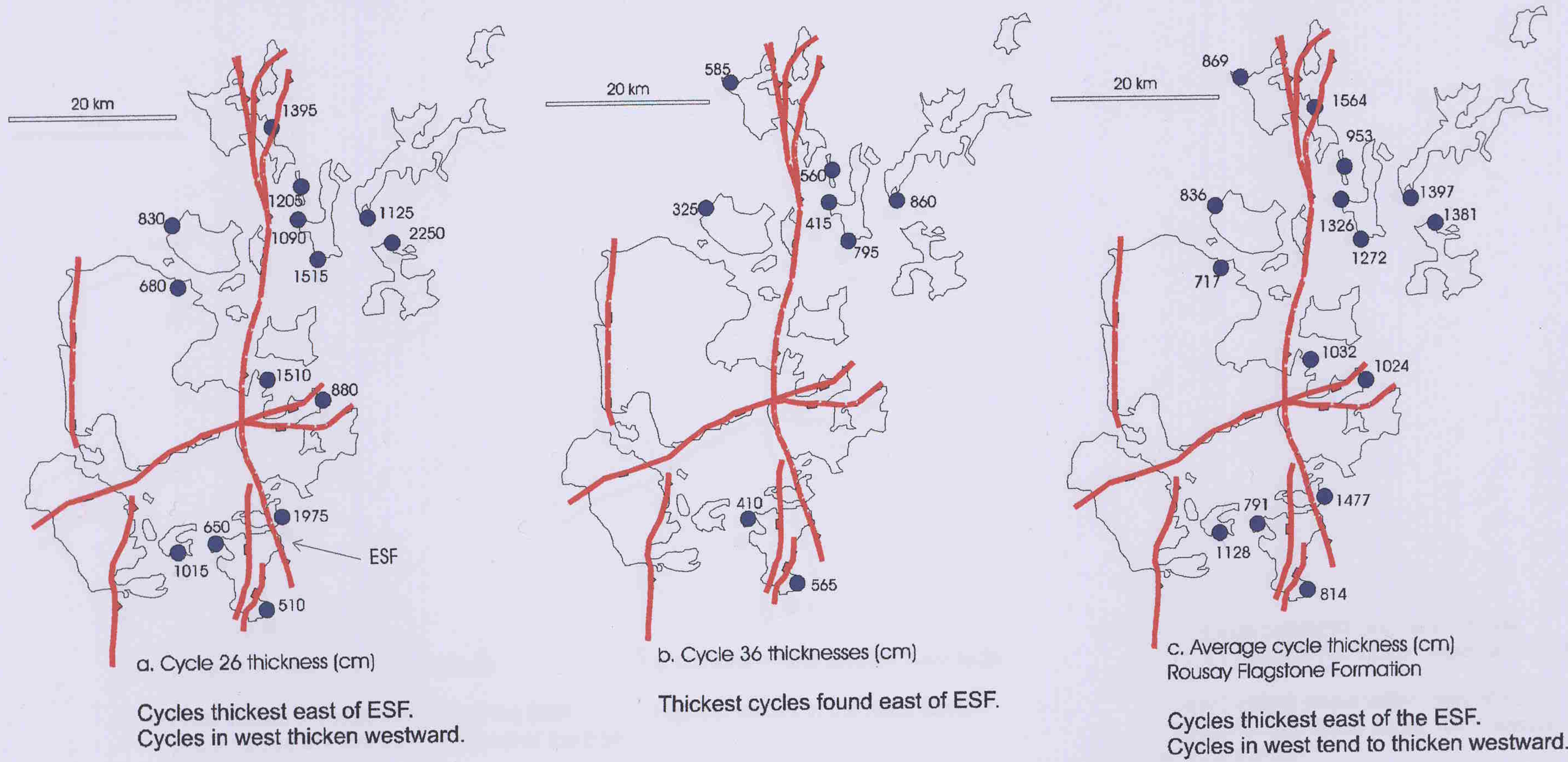
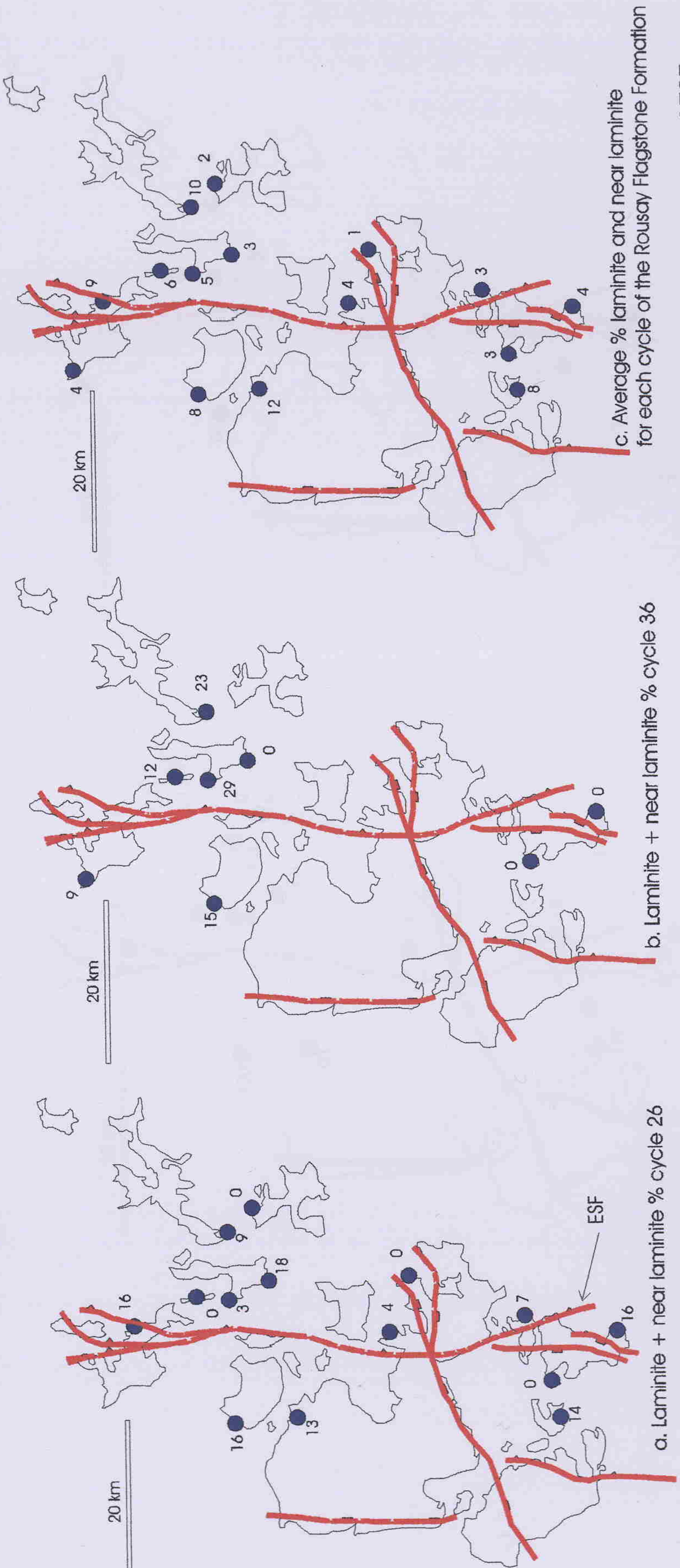


Figure 5-9. Thicknesses in cm of lake cycle 26, lake cycle 36 and average cycle thickness for Rousay Flagstone Formation
ESF=East Scapa Fault.



a. Laminite + near laminite % cycle 26

Lowest values immediately east of the ESF.
Highest values 5-10km east and west of the ESF.

b. Laminite + near laminite % cycle 36

Highest values in the north east.

c. Average % laminite and near laminite for each cycle of the Rousay Flagstone Formation

Lowest values found within 5km of ESF.
Highest values found about 10km east and west of the ESF.

Figure 5-10. Percentage laminite and near laminite facies. cycle 26, cycle 36 and averaged for whole Rousay Flagstone Formation
ESF = East Scapa Fault

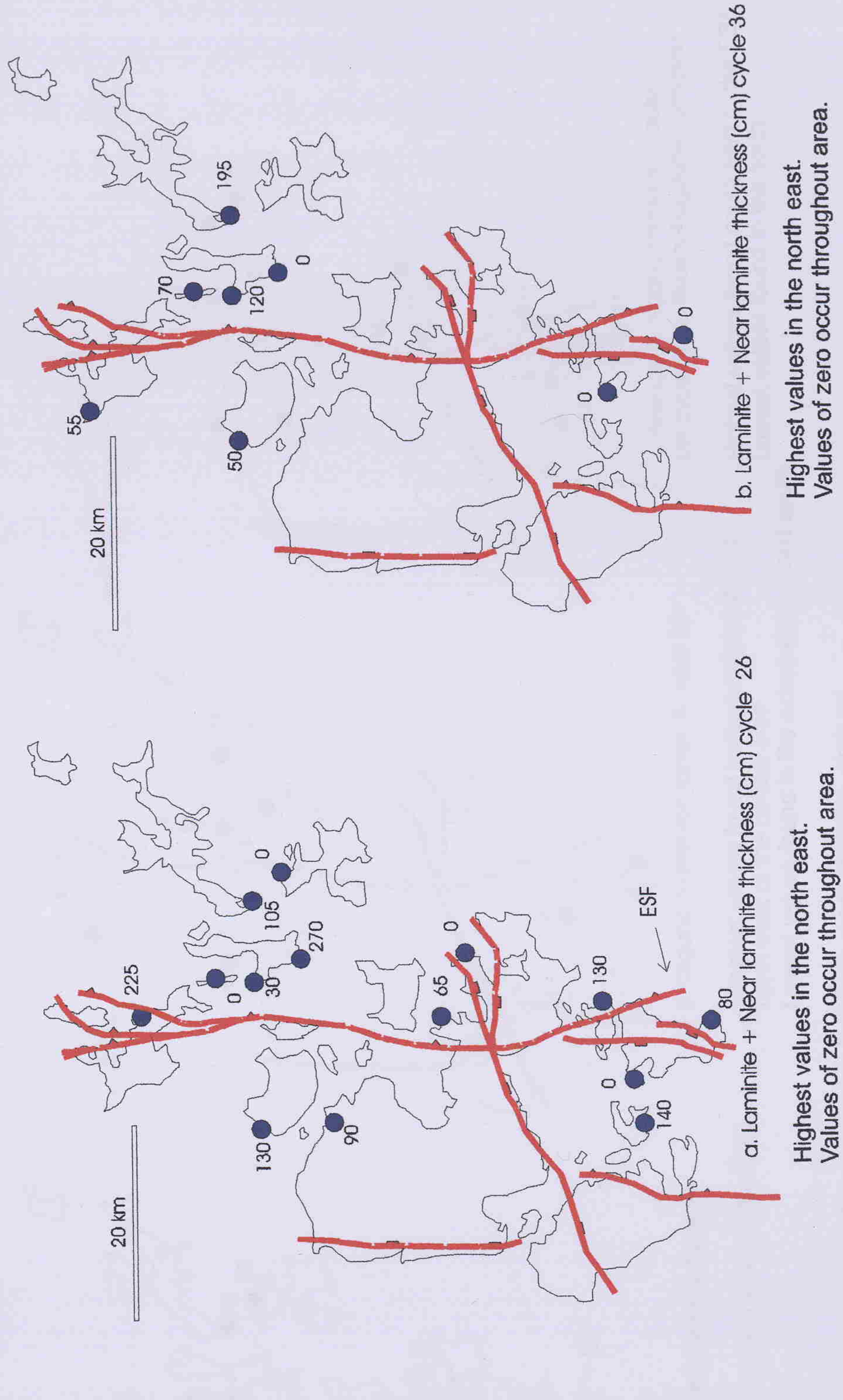
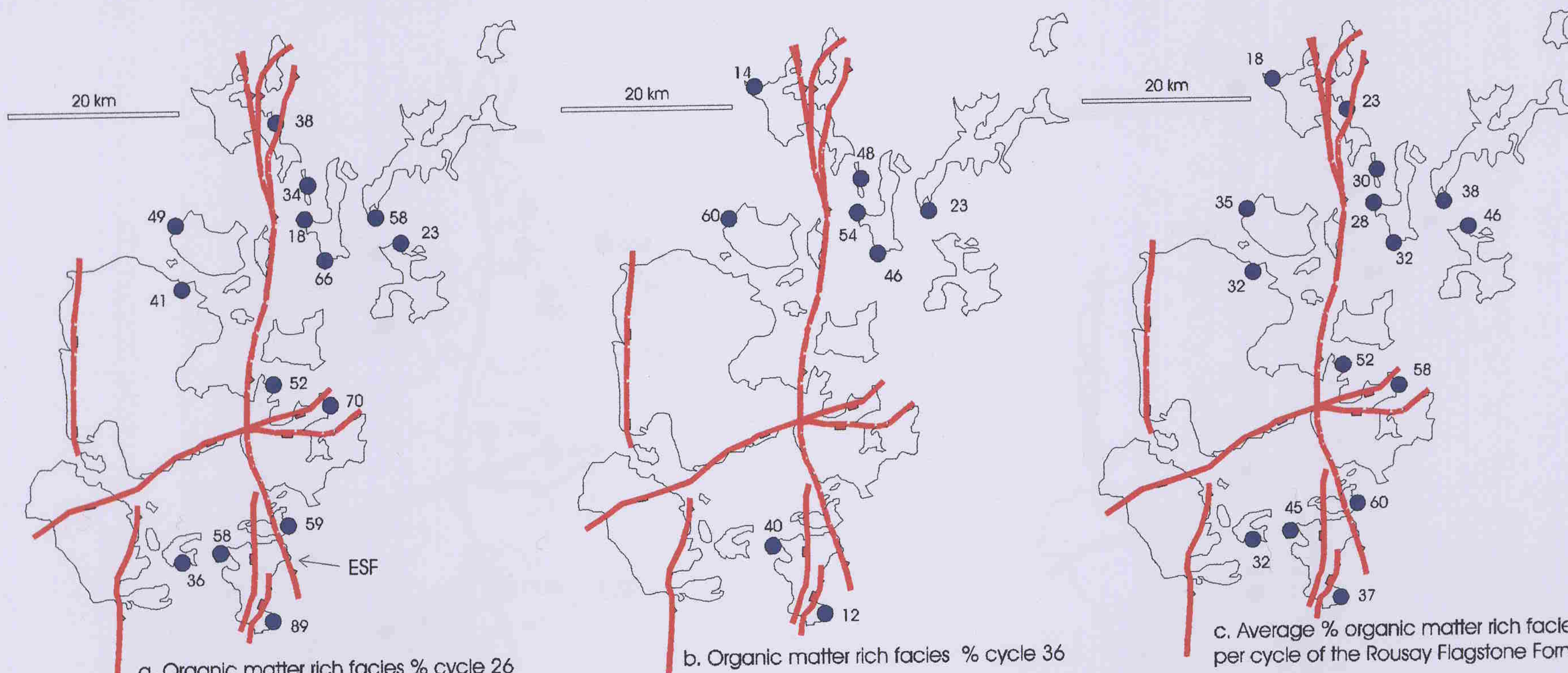


Figure 5-11. Thickness laminite + near laminite facies cycles 26 and 36 Rousay Flagstone Formation
ESF = East Scapa Fault.



a. Organic matter rich facies % cycle 26

Greatest values east and south of the ESF.

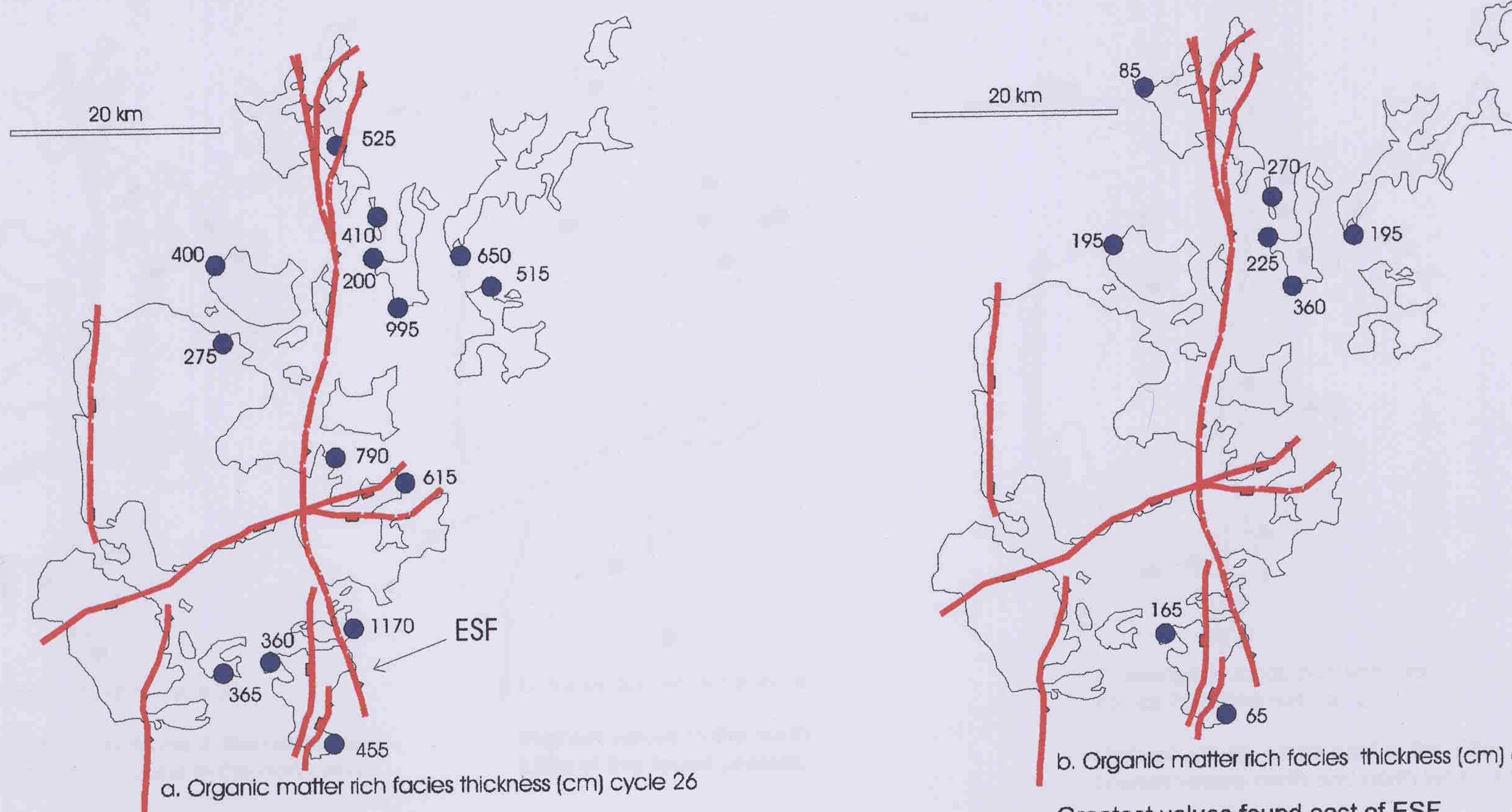
b. Organic matter rich facies % cycle 36

Greatest values found immediately north and north west of the central area.
Lowest values found in the extreme north and south.

c. Average % organic matter rich facies per cycle of the Rousay Flagstone Formation

Highest values found south east of the ESF.
Lowest values found in the north.

Figure 5.12. Percentage organic matter rich facies (laminite, near laminite, dark silt, sandy dark silt, grey silts, wick, dark wick)cycle 26, cycle 36, and averaged per cycle of the Rousay Flagstone Formation
ESF = East Scapa Fault.



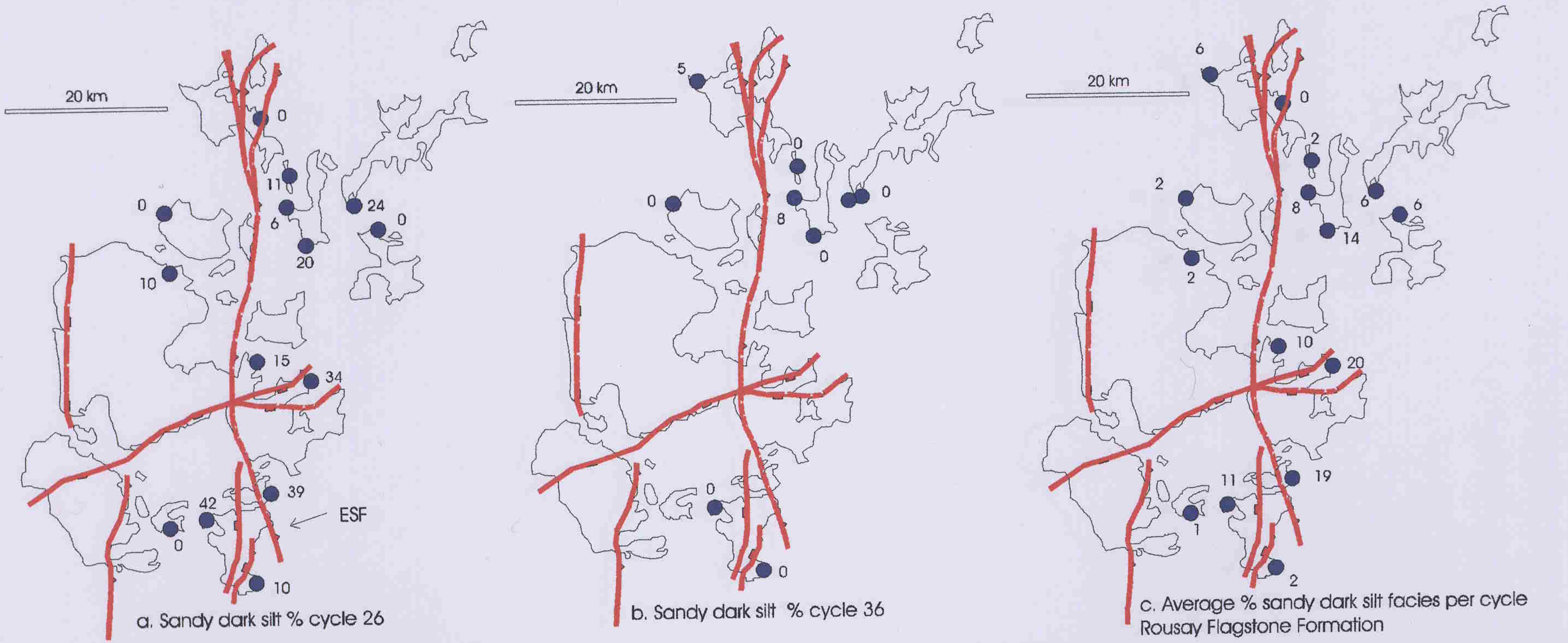
a. Organic matter rich facies thickness (cm) cycle 26

Highest values found south and east of ESF.
Lowest values found west of the ESF.

b. Organic matter rich facies thickness (cm) cycle 36

Greatest values found east of ESF.
Lowest values found west of ESF.

Figure 5-13. Thickness (cm) of organic matter rich facies (laminite, near laminite, dark silt, sandy dark silt, grey silts, wick, dark wick) cycles 26 and 36 Rousay Flagstone Formation
ESF = East Scapa Fault.



a. Sandy dark silt % cycle 26

Highest values found in the south east.
Lowest values found in the north west.

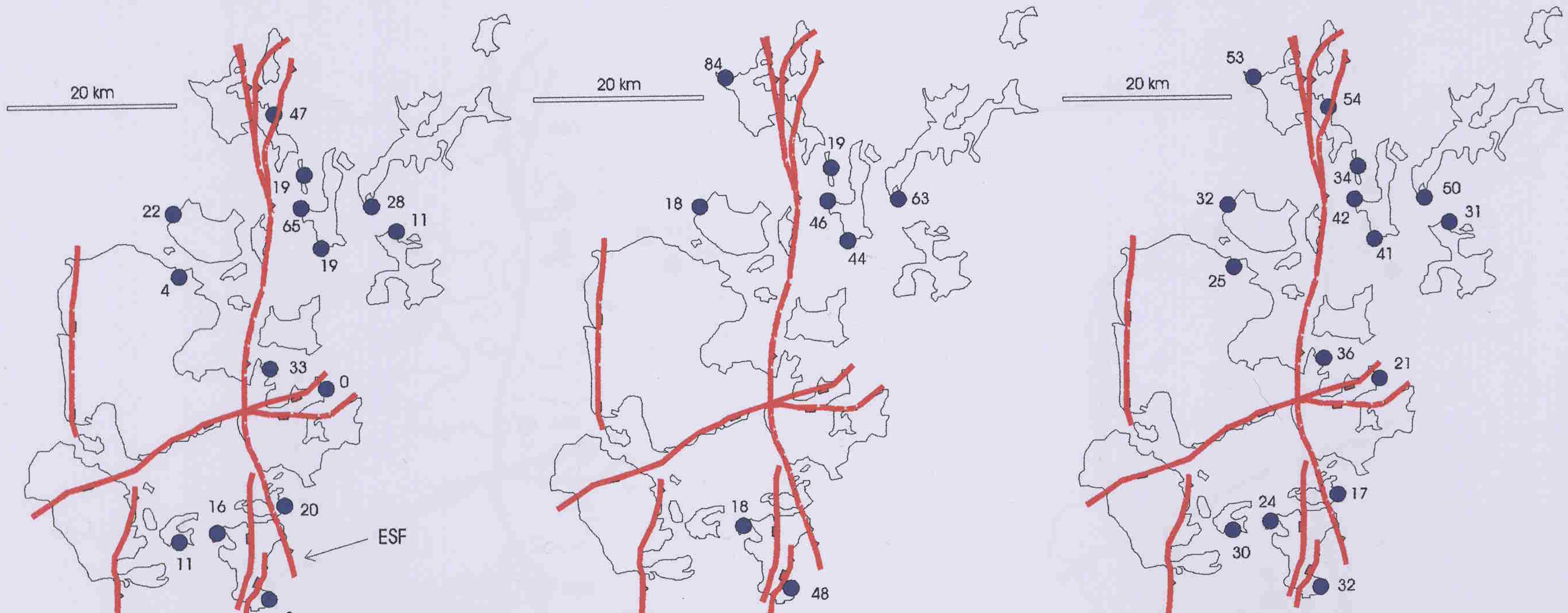
b. Sandy dark silt % cycle 36

Highest values in the north.
Little of this facies present.

c. Average % sandy dark silt facies per cycle
Rousay Flagstone Formation

Highest values south east of the ESF.
Lowest values north and north west of the ESF.

Figure 5-14. Percentage sandy dark silt facies cycle 26, cycle 36 and averaged per cycle of the Rousay Flagstone Formation
ESF = East Scapa Fault.



a. Sand rich facies % cycle 26

Greatest values immediately east of the ESF.

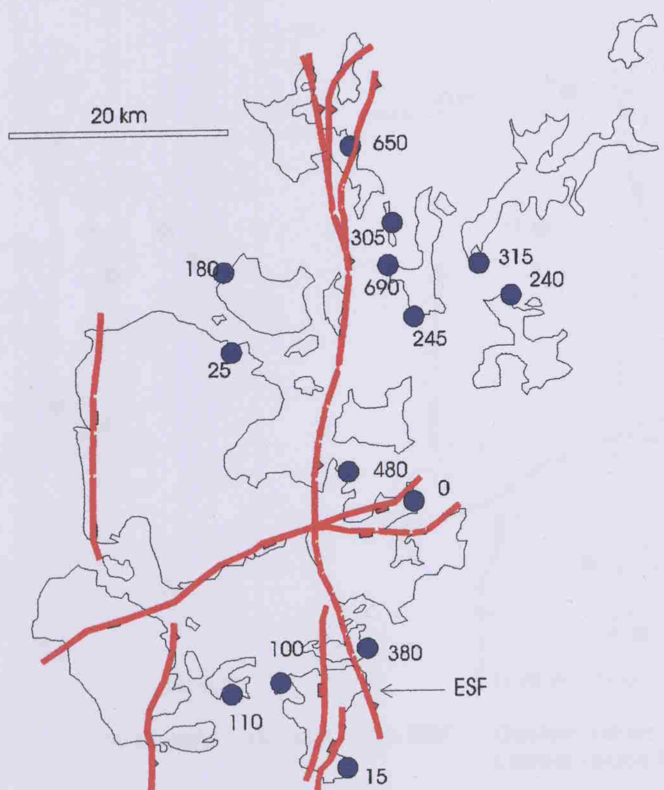
b. Sand rich facies % cycle 36

Greatest values found in the north and north west.

c. Average sand rich facies % per cycle of the Rousay Flagstone Formation

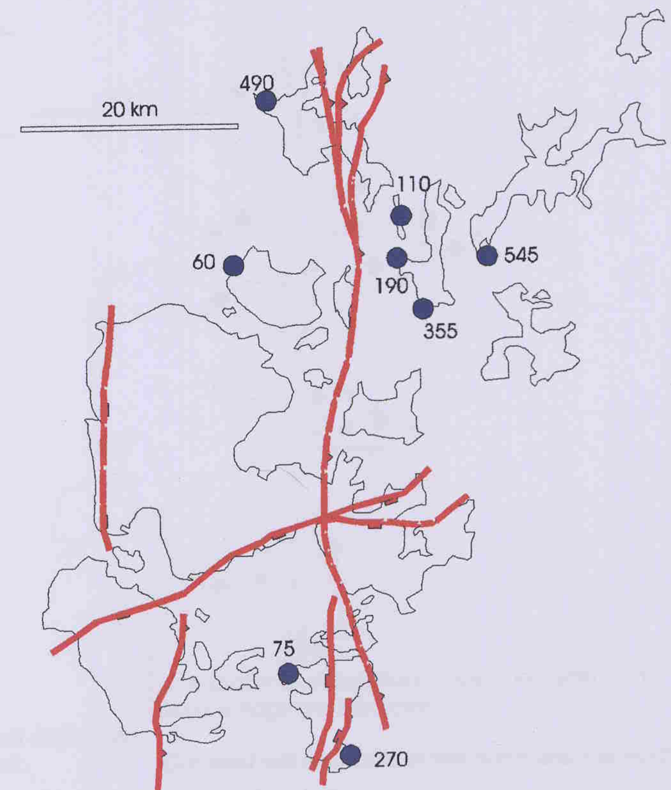
Greatest values found to the north and north east of the ESF.

Figure 5-15. Percentage sand rich facies (wavy sand, sheetfloods, channels, conglomerates) cycle 26, cycle 36 and averaged for entire Rousay Flagstone Formation. ESF = East Scapa Fault.



a. Sand rich facies thickness (cm) cycle 26

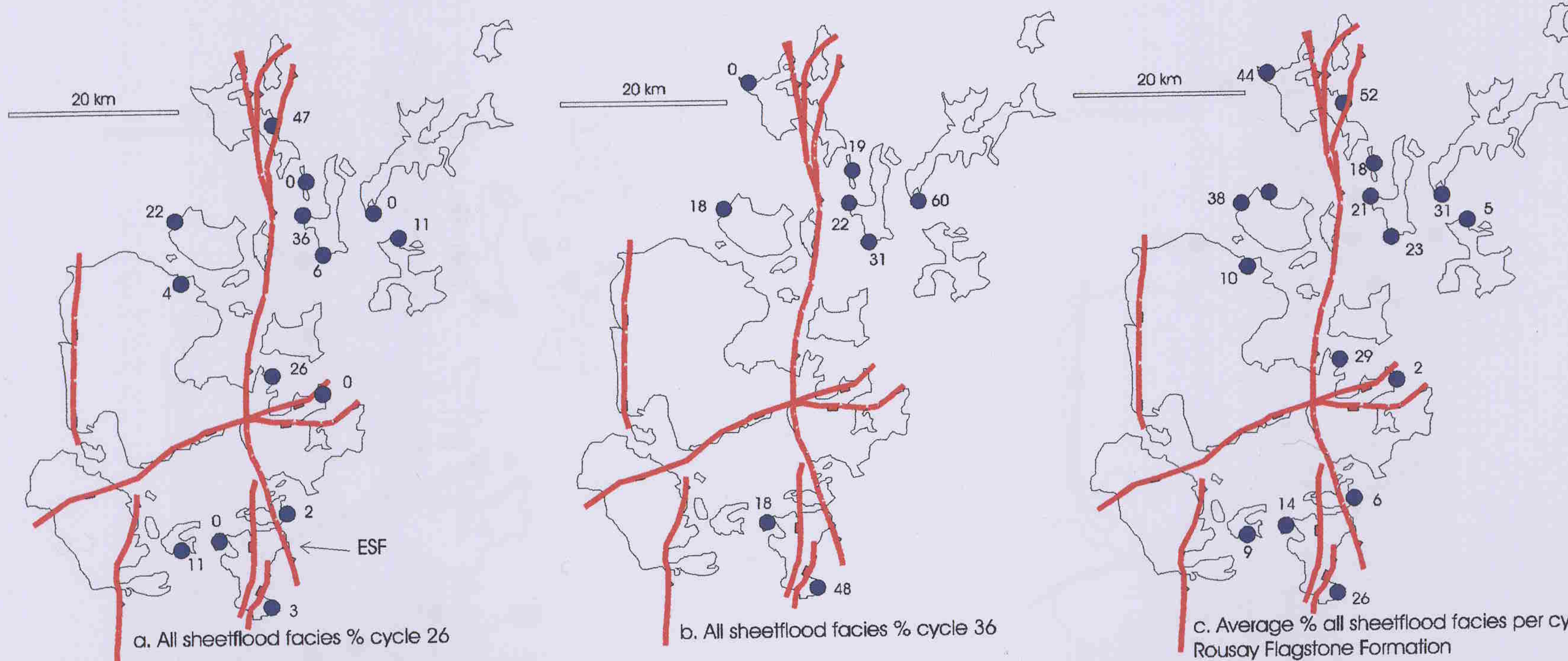
Greatest values found east of the ESF.



b. Sand rich facies thickness (cm) cycle 36

Greatest values found in the north and north east

Figure 5-16. Thicknesses sand rich facies (sheetfloods, channels, wave rippled sandstones, conglomerates)cycles 26 and 36
EST = East Scapa Fault.



a. All sheetflood facies % cycle 26

Greatest values immediately north east of the ESF.

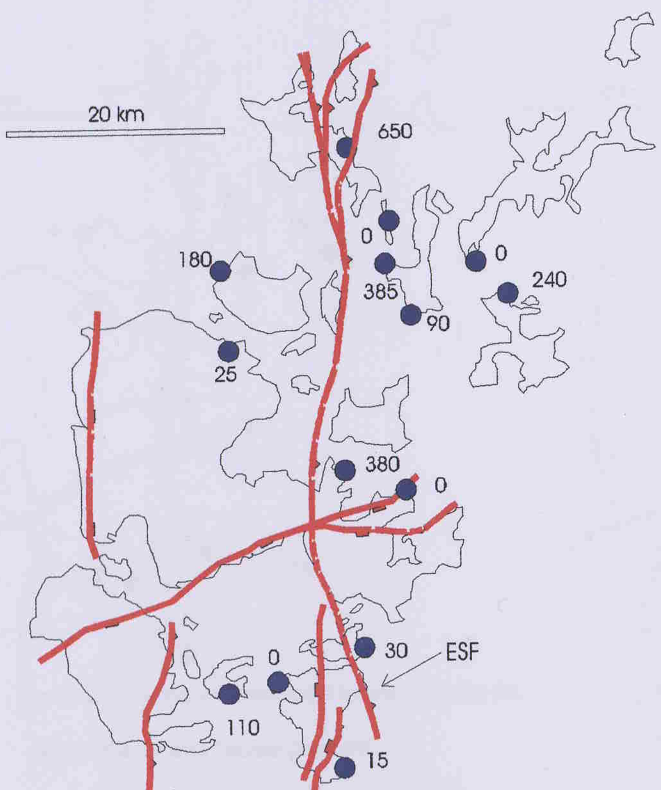
b. All sheetflood facies % cycle 36

Geatest values found in the north east and south.
Lowest values found in the north west.

c. Average % all sheetflood facies per cycle of the Rousay Flagstone Formation

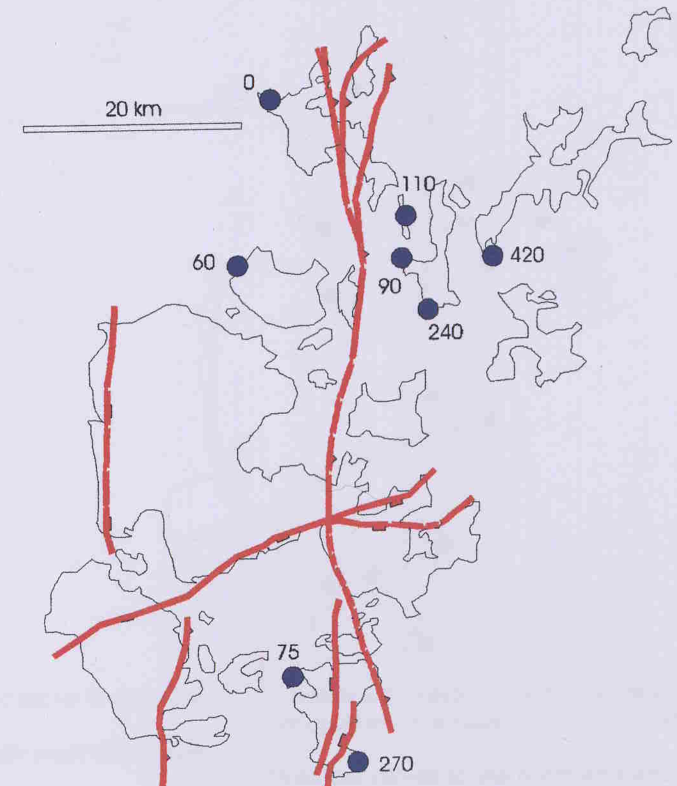
Greatest values found in the north and the north west.

Figure 5-17. Percentages of all sheetflood facies in cycle 26, cycle 36 and averaged for all the Rousay Flagstone Formation
ESF = East Scapa Fault.



a. Thickness all sheetflood facies (cm) cycle 26

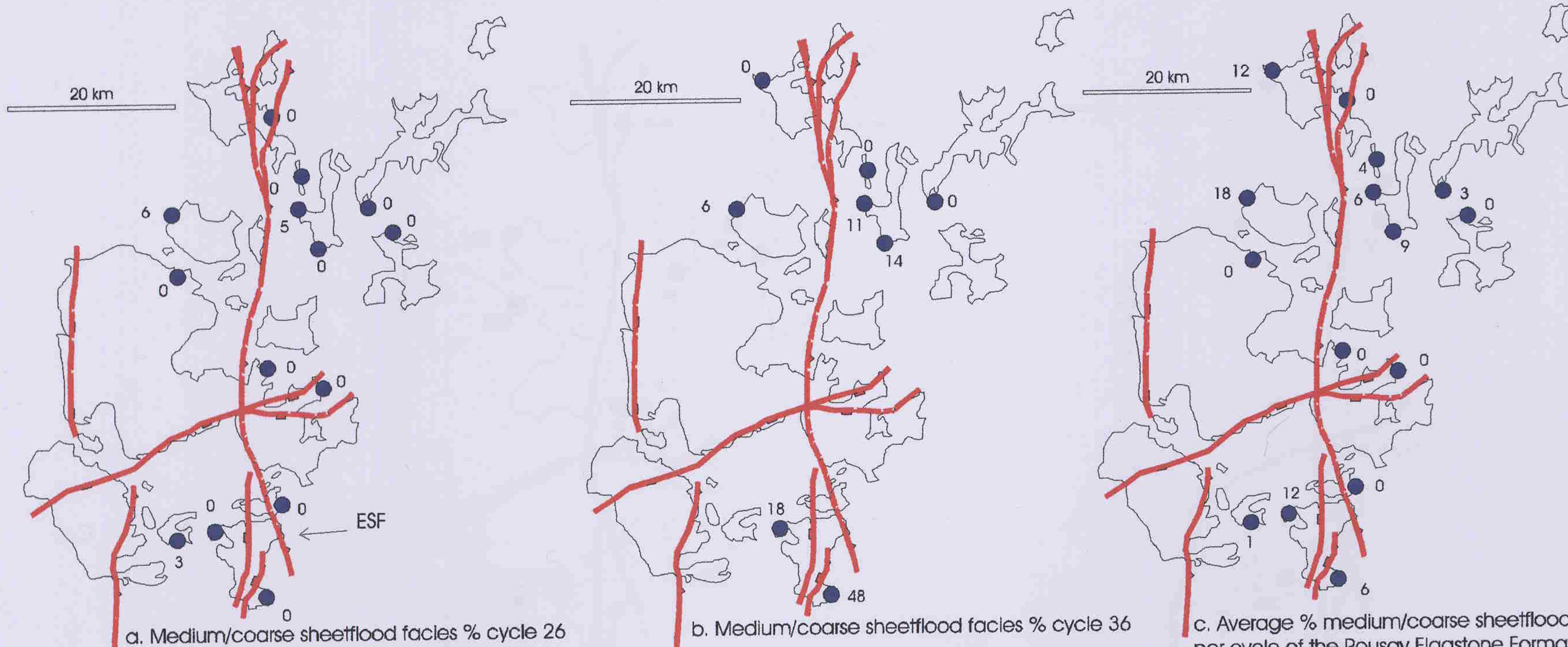
Greatest values found north and east of the ESF.
Lowest values found west of ESF.



b. All sheetflood facies thickness (cm) cycle 36

Greatest values found north east of the ESF and in the extreme south.

Figure 5-18. Thicknesses of all sheetflood facies cycles 26 and 36 Rousay Flagstone Formation
ESF = East Scapa Fault.



a. Medium/coarse sheetflood facies % cycle 26

Very little of this facies present.

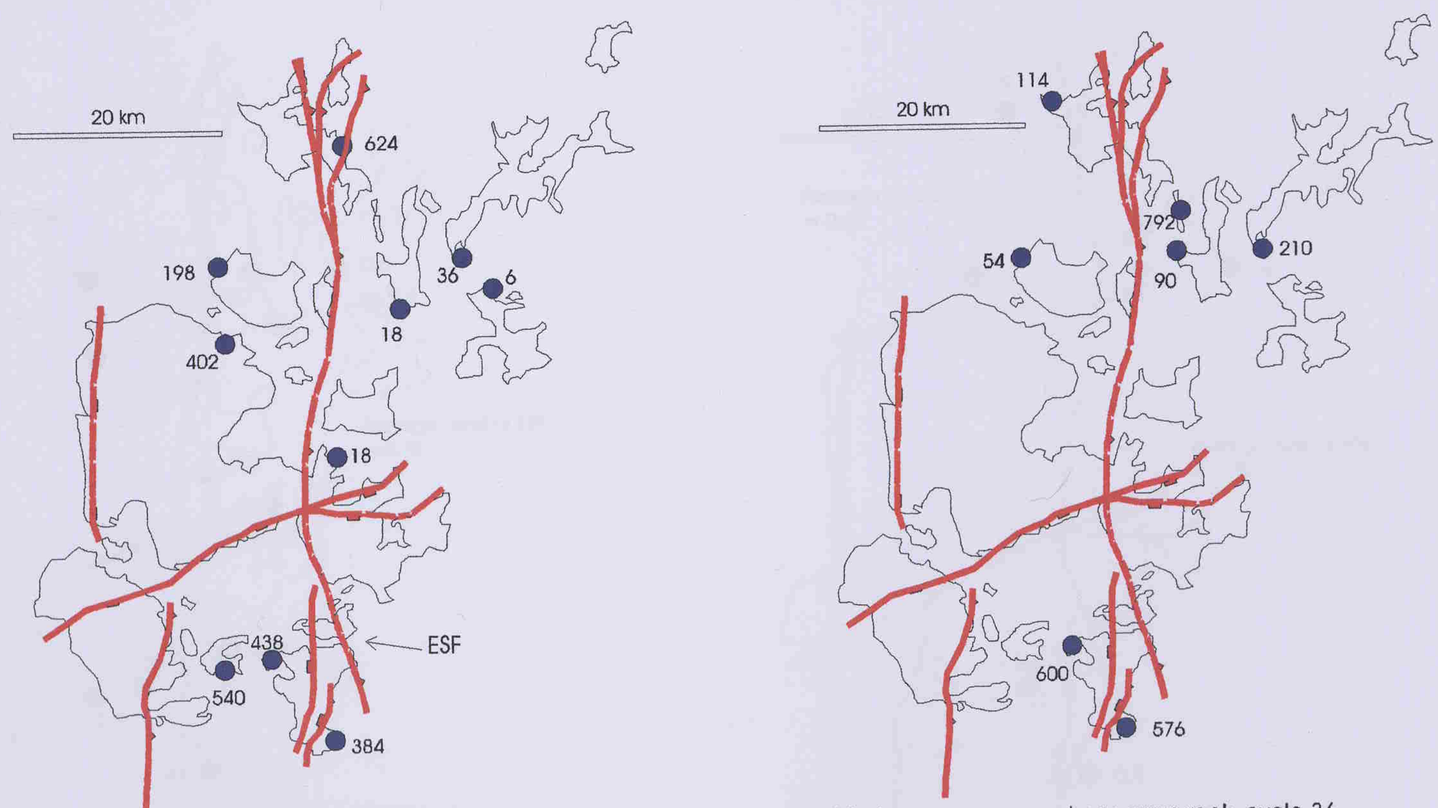
b. Medium/coarse sheetflood facies % cycle 36

Greatest values to the south west of the ESF.

c. Average % medium/coarse sheetflood facies per cycle of the Rousay Flagstone Formation

Greatest values to the north and west of the ESF.

Figure 5-19. Percentage medium and coarse sheetflood facies in cycles 26, cycles 36 and averaged for the entire Rousay Flagstone Formation ESF = East Scapa Fault.



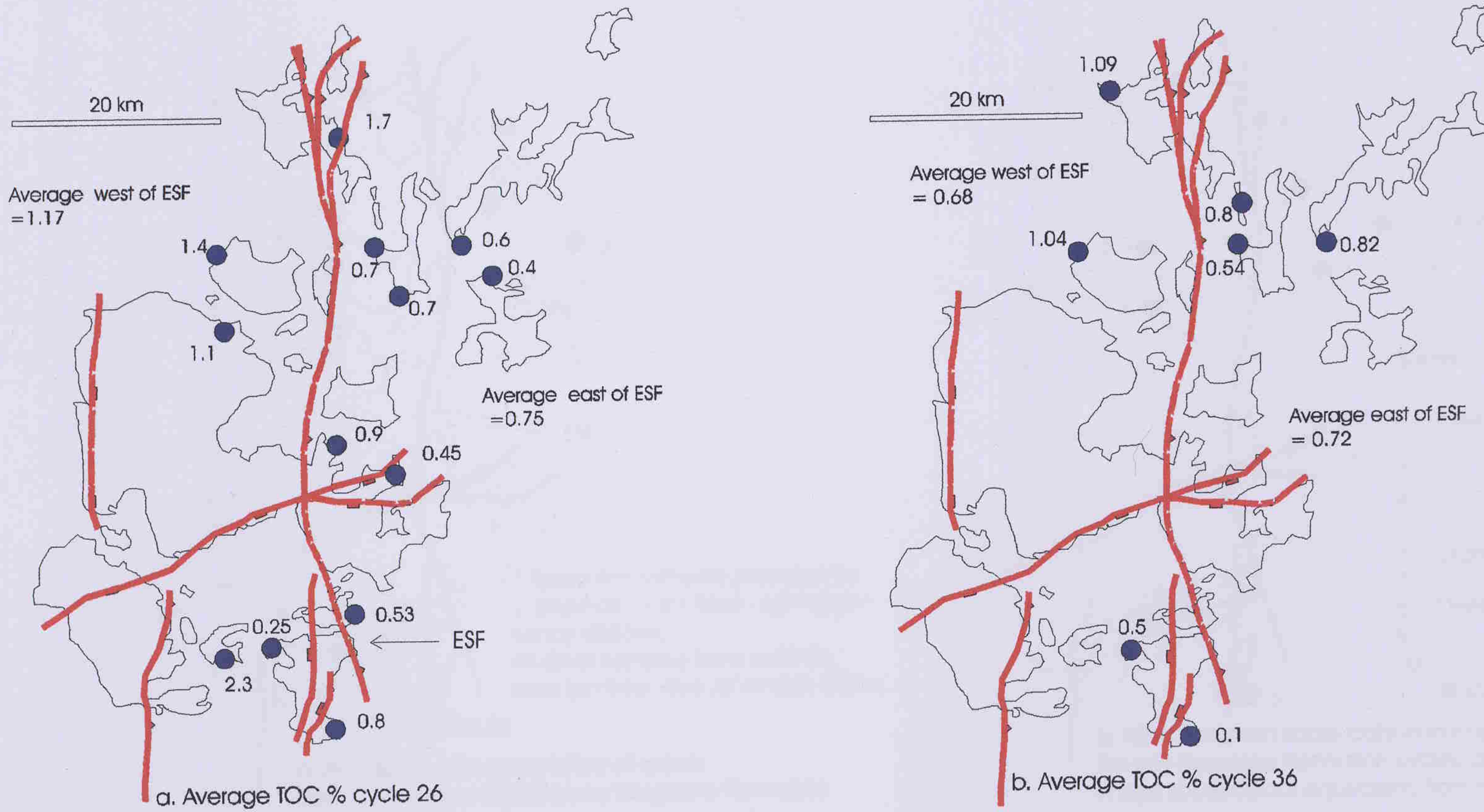
a. Maximum spore count per gram of rock, cycle 26

Greatest numbers of spores found in the north, west and south.
Average maximum spore count = 266.

b. Maximum spore count per gram rock, cycle 36

Greatest numbers of spores found in the north and south.
Average maximum spore count = 348.

Figure 5-20. Maximum number of spores per gram of lacustrine rock sampled in cycles 26 and 36, Rousay Flagstone Formation. ESF = East Scapa Fault.



Greatest values found in the north and west.
Lowest values found east of centre and in the south.

Greatest values found in the north and west.
Lowest values found east of centre and in the south.

Figure 5-21. Average TOC distribution. Cycles 26 and 36 Rousay Flagstone Formation
ESF = East Scapa Fault.

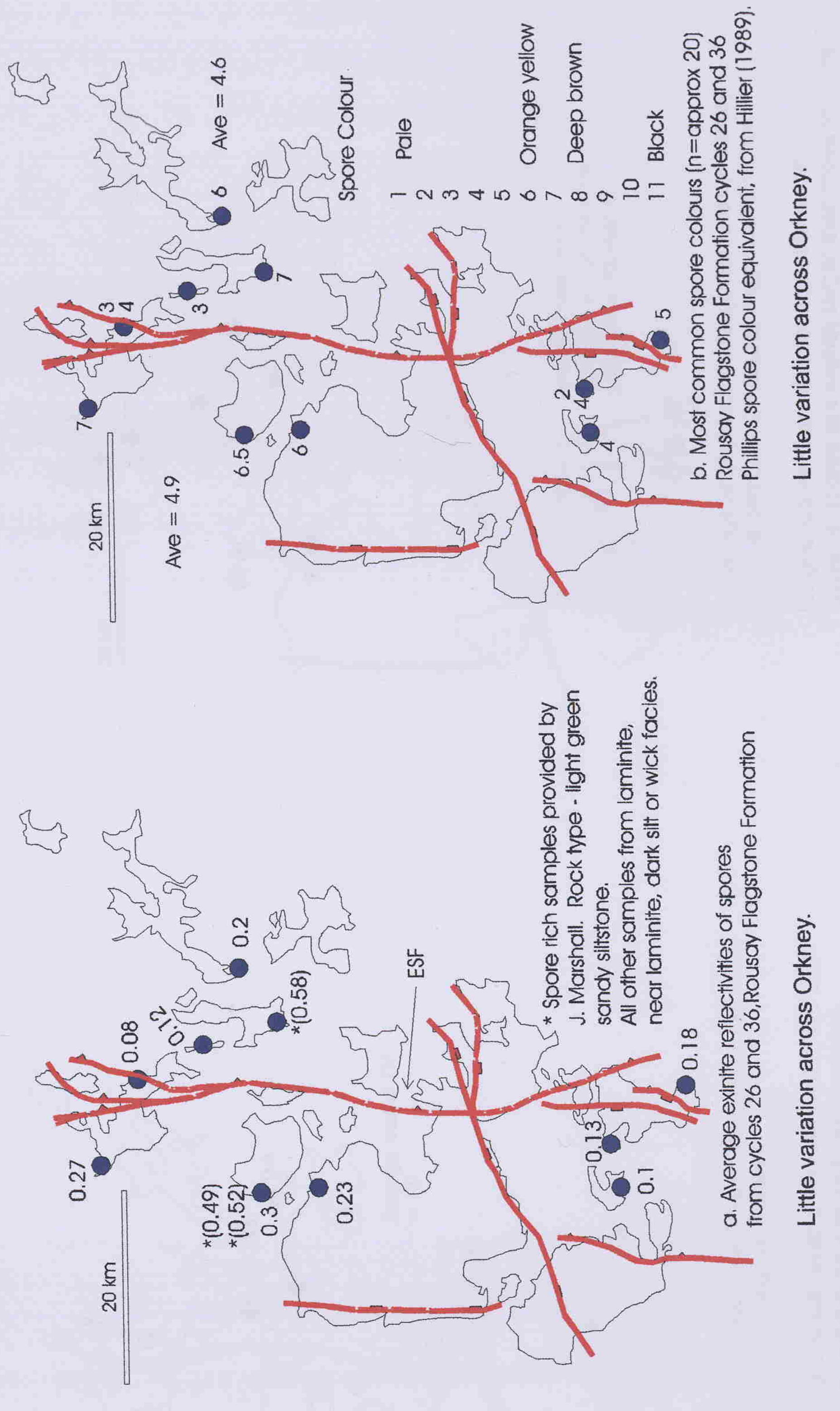
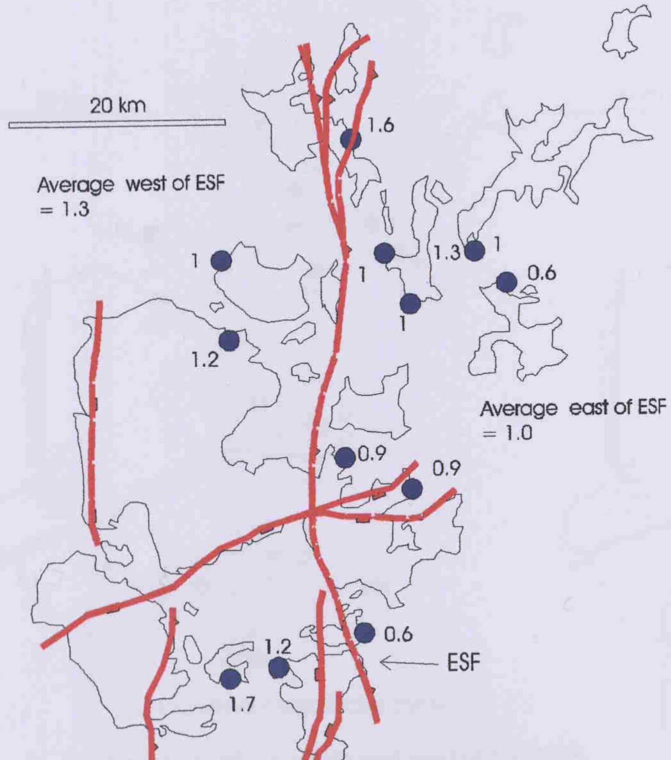
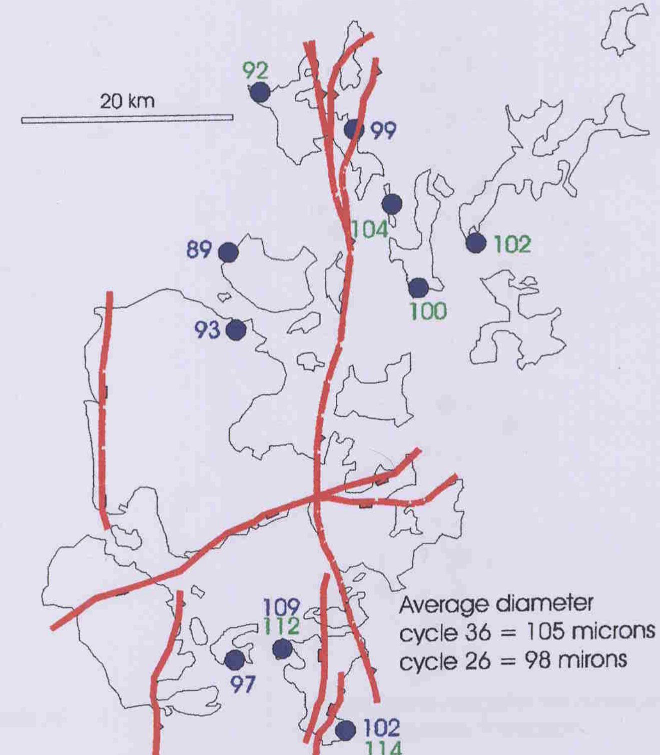


Figure 5-22. Exinite reflectivity and spore colour results.
ESF = East Scapa Fault.



a. Average H/C values cycle 26 Rousay Flagstone Formation
approximately 3 samples per location

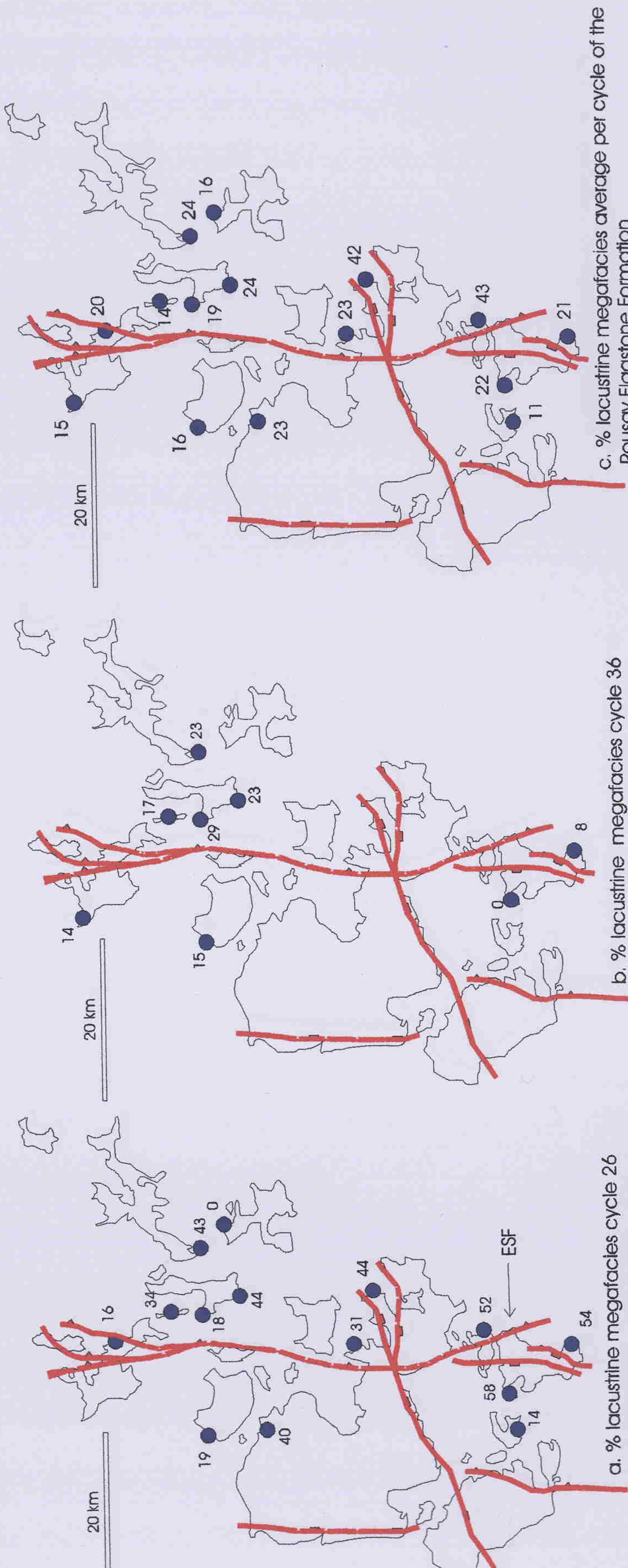
Greatest values south west and north east of the ESF.
Lowst values found in central and eastern areas.



b. Average *Rhabdosporites langii* diameters (microns)
cycle 26 and cycle 36 Rousay Flagstone Formation

Largest spore diameters found in the south.
Cycle 36 spores are slightly larger than those in cycle 26.

Figure 5-23. Average H/C values and average *Rhabdosporites* diameters
ESF =East Scapa Fault.



a. % lacustrine megafacies cycle 26

Greatest values south and east of the ESF.

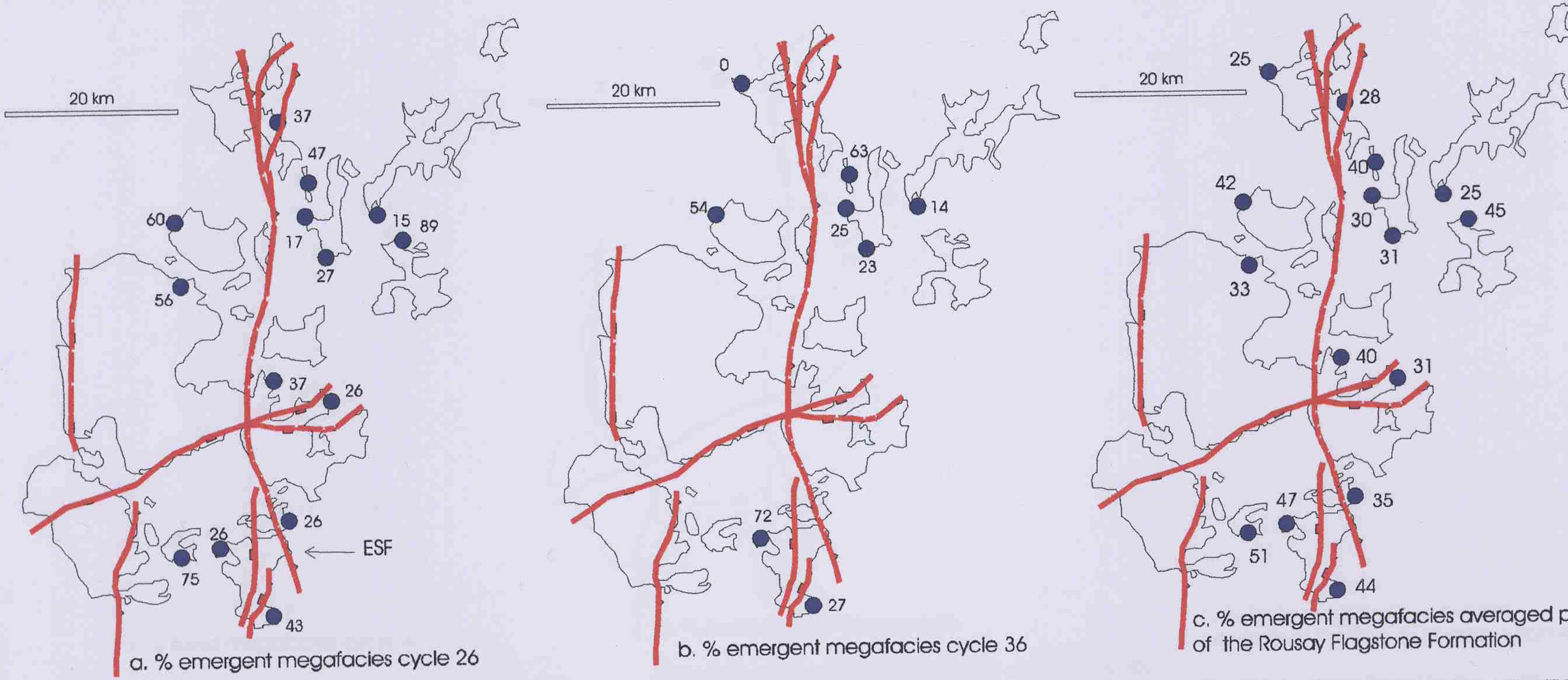
b. % lacustrine megafacies cycle 36

Greatest values north east of ESF.

c. % lacustrine megafacies average per cycle of the Rousay Flagstone Formation

Greatest values found east of the ESF.

Figure 5-24. Lacustrine megafacies percentages cycle 26, cycle 36 and average per cycle of the Rousay Flagstone Formation
ESF = East Scapa Fault.



a. % emergent megafacies cycle 26

Greatest values west of the ESF and in the far east.

b. % emergent megafacies cycle 36

Greatest values west of ESF.

c. % emergent megafacies averaged per cycle of the Rousay Flagstone Formation

Greatest values found west of the ESF and in the far east of the area.

Figure 5-25. Emergent megafacies cycle 26, cycle 36 and averaged per cycle of Rousay Flagstone Formation
ESF = East Scapa Fault.

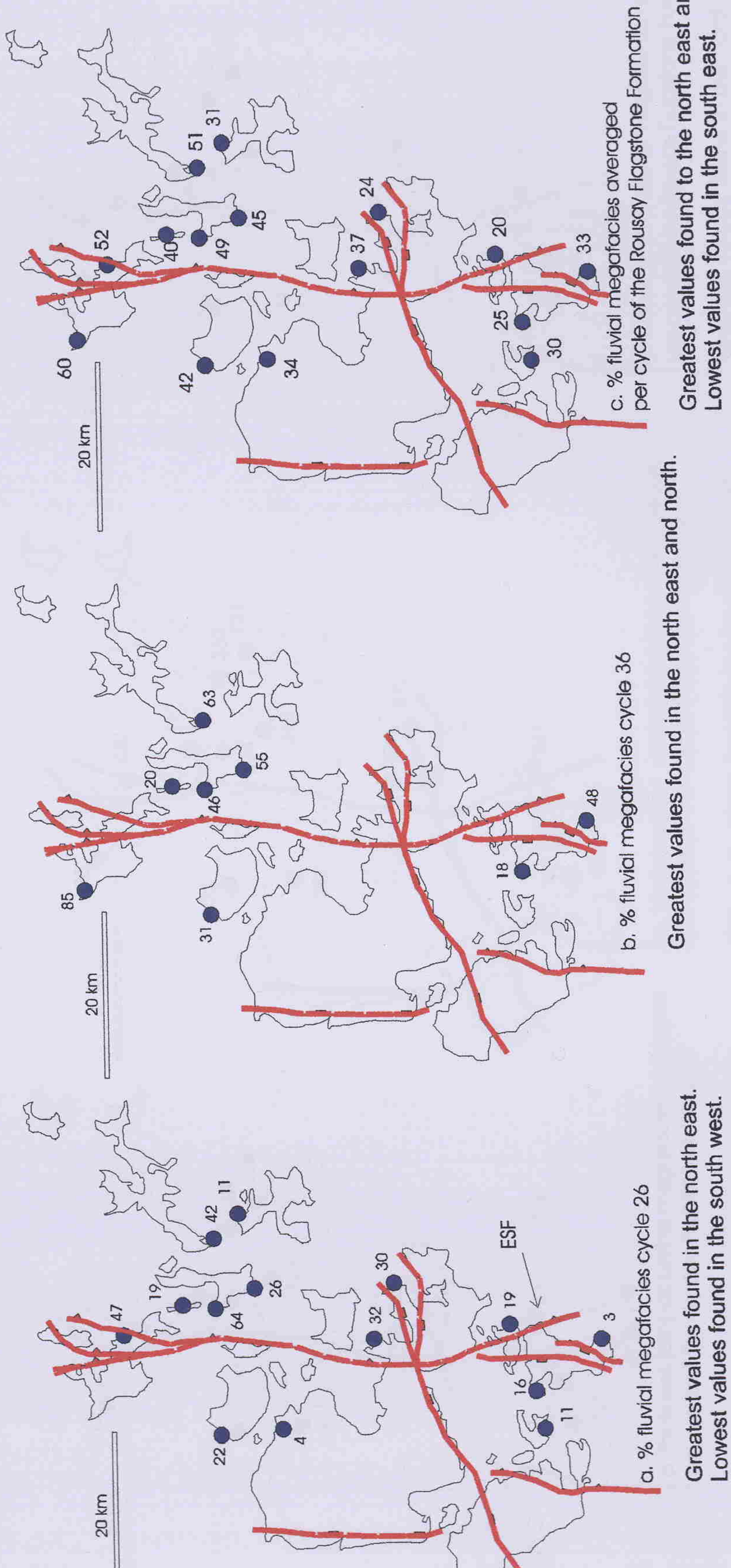


Figure 5-26. Fluvial megafacies cycle 26, cycle 36 and averaged for Rousay Flagstone Formation
ESF = East Scapa Fault

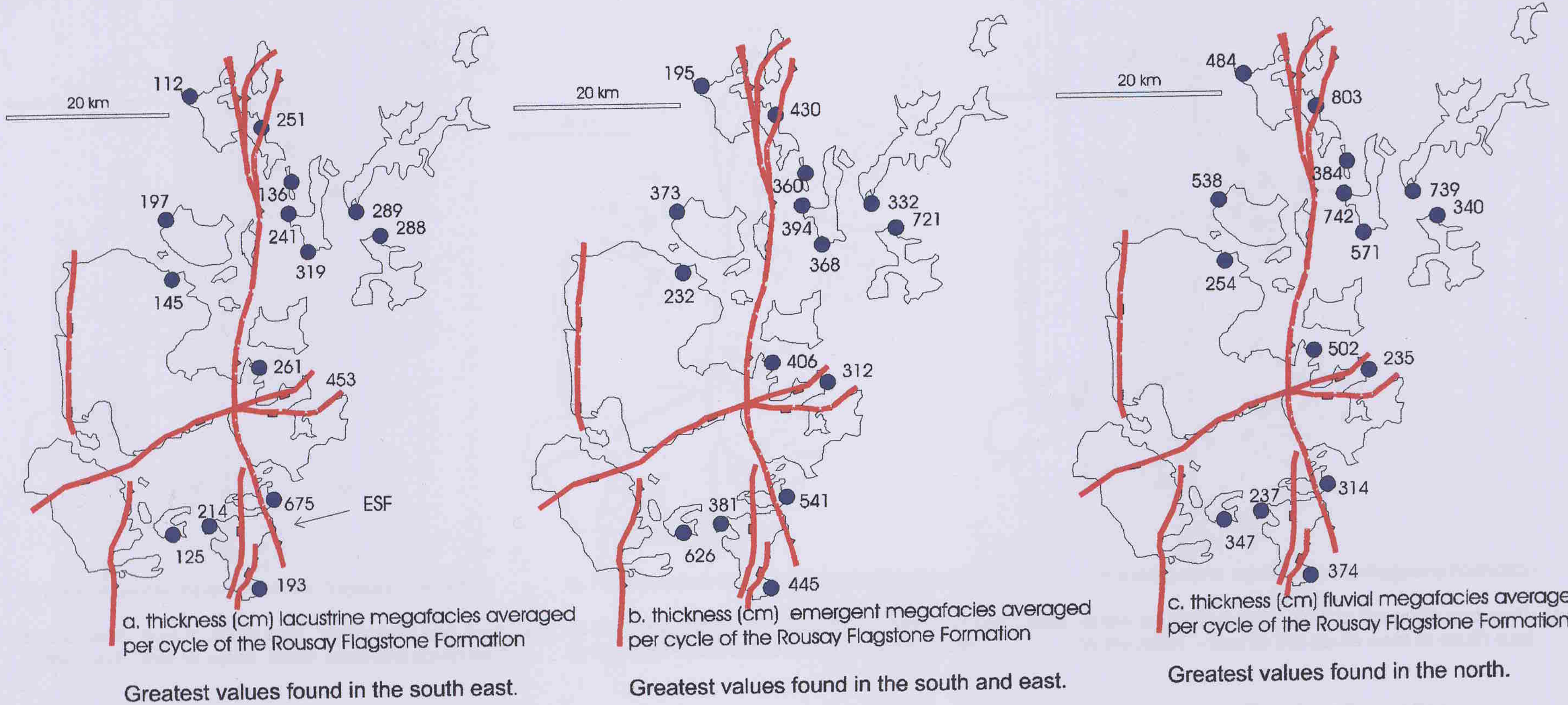
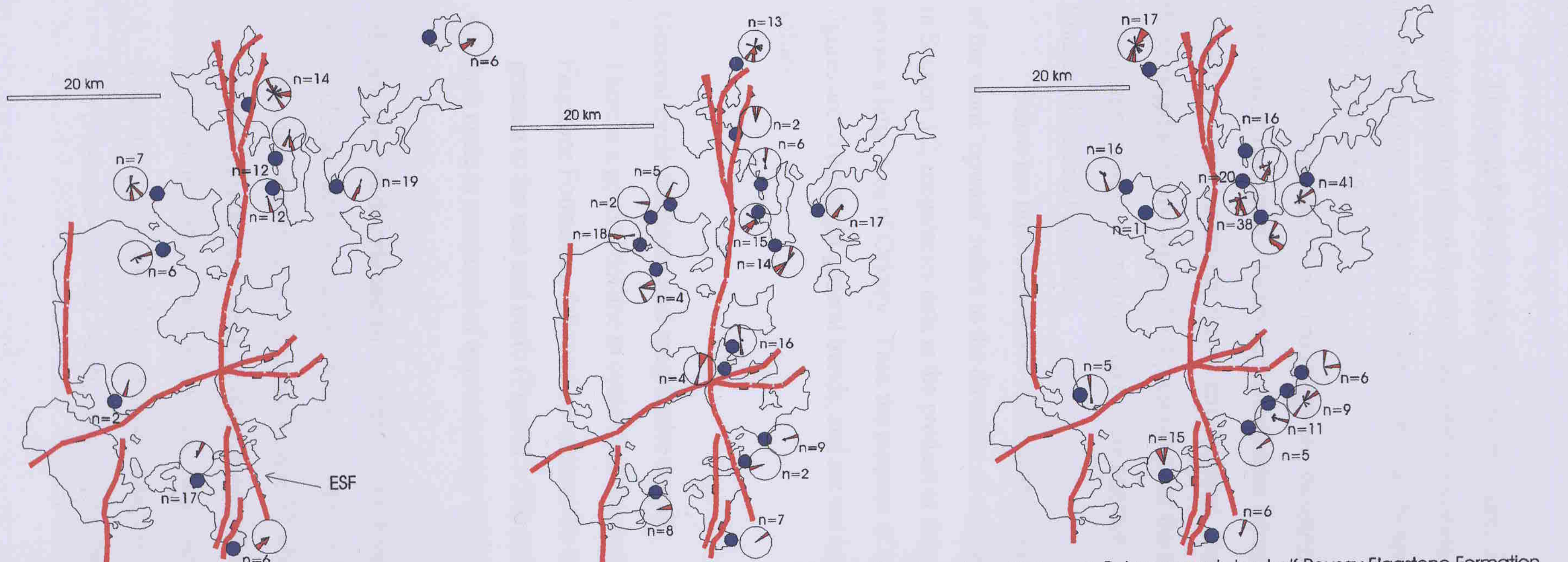


Figure 5-27. Megafacies thicknesses averaged per cycle Rousay Flagstone Formation
ESF = East Scapa Fault.



a. Palaeocurrents Upper Stromness Flagstone Formation

In the west - flow to south east, south west and north east.
In the east - flow to south, south west and south east.

b. Palaeocurrents lower half Rousay Flagstone Formation

In the west and south - flow to the east and north east.
In the east - flow to the south west and north.

c. Palaeocurrents top half Rousay Flagstone Formation

In the south and east - flow to the north and north east.
In the north - flow to the south west to south east.

Figure 5-28. Palaeocurrent directions for the Upper Stromness Flagstone Formation and the top and base of the Rousay Flagstone Formation.
ESF = East Scapa Fault. Only well defined current ripples measured.
Some of the palaeocurrent data comes from sections biostratigraphically positioned (Wilson et al. 1935) rather than lithostatigraphically placed using the framework presented in this thesis (Figure 2-1).

5.3 Megafacies graphs

The megafacies graphs presented in Figures 5-29 to 5-32, illustrate how the megafacies ratios of ten Rousay Flagstone Formation lake cycles vary with respect to two of the main structural features of Orkney: the East Scapa Fault (ESF) and the North Scapa Fault (NSF) (Figure 1-5).

The three megafacies groupings are; lacustrine – facies deposited under permanent water cover; emergent – facies deposited under intermittent water cover; and fluvial – facies deposited in a higher energy fluvial environment. Section 3.3 provides full definitions of the three megafacies and Appendix 4 presents all of the megafacies data used. The X-axis of these graphs always refers to the lake cycle number. Note that cycle 25 marks the start of the Rousay Flagstone Formation.

Below are brief summaries of the main trends seen in Figures 5-29 to 5-32. The use of the word 'upward' refers to the direction of stratigraphic younging. Additionally, as stated in Section 3.2, megafacies data is the product of data averaged from several lake cycles, from across a large area of Orkney. Thus the purpose of any quoted thickness and percentage figures are to highlight general trends, and are not intended to be used as absolute, specific values.

General cycle thickness and megafacies trends:

- There is a general decline in cycle thicknesses upwards through much of the Rousay Flagstone Formation, followed by an increase in cycle thickness in cycle 37, which is greatest to the east and north (Figures 5-29a and 5-30a).
- Each cycle is composed of approximately 1/3rd of each megafacies type (Figure 5-31a).

Megafacies trends relating to the East Scapa Fault

- Cycles are generally thicker to the east of the ESF by about 0.5 metres (Figure 5-29a). The main exception to this trend is cycle 32 where cycles to the west of the ESF are thicker. This is solely because of the presence a thick accumulation of lacustrine and emergent megafacies at North Halcro Head (see Appendix 4).
- Generally a greater thickness and percentage of lacustrine megafacies occurs east of the ESF (Figures 5-31b and 5-29b). In cycle 32, the large accumulation of lacustrine facies at

North Halcro Head is responsible for the most significant variation from this trend (see Appendix 4).

- 9 out of the 11 cycles show between 5 and 20% more emergent megafacies west of the ESF (Figure 5-31c).
- Across the ESF the percentages of fluvial megafacies remain similar, but are on average 1m thicker in the east (Figure 5-29d and 5-30d).
- Percentages of fluvial megafacies east and west of the ESF increase by 20- 40% between cycles 34 and 37 (Figure 5-31d).

Megafacies trends relating to the North Scapa Fault

- Cycles north of the NSF are slightly thicker than cycles to the south (Figure 5-30a).
- North of the NSF, lacustrine megafacies percentages remain relatively constant (Figure 5-32a), but emergent percentages gradually decline upward (Figure 5-32b) and fluvial percentages gradually increase upward (Figure 5-32c).
- Fluvial megafacies are between 10 and 20% greater and 1m thicker north of the NSF. (Figures 5-30d and 5-32c).
- Percentages of fluvial megafacies north and south of the NSF increase by 40% between cycle 34 and 37 (Figure 5-32c).

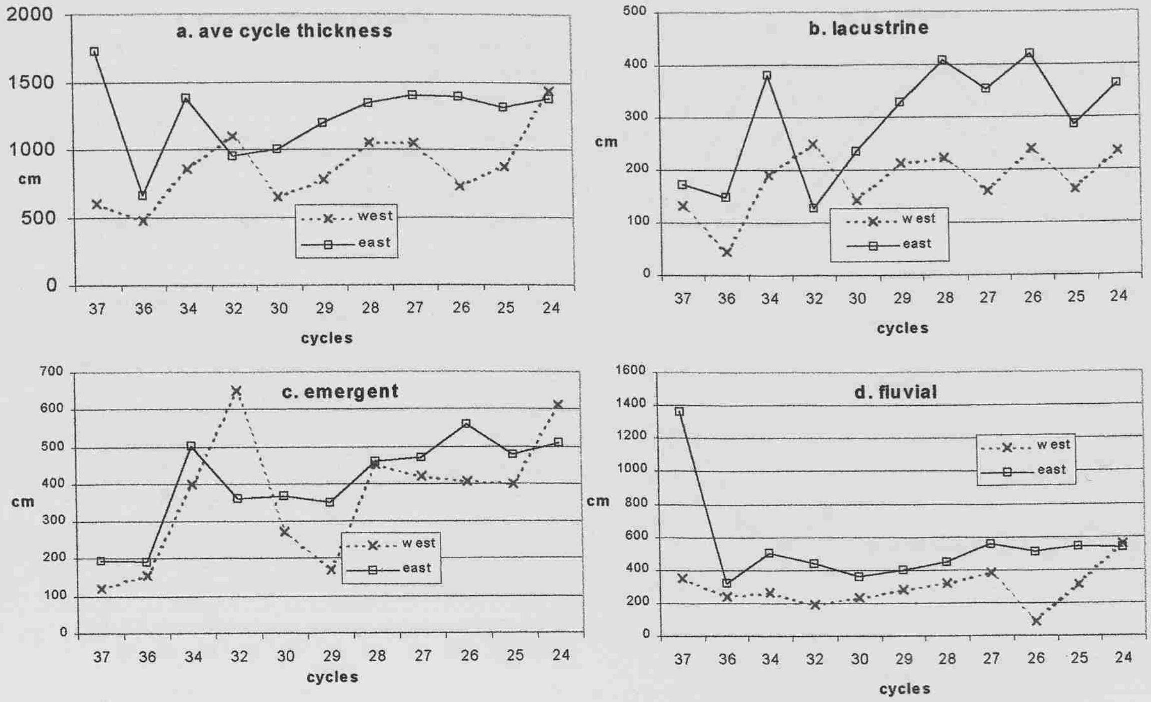


Figure 5-29. Megafacies thickness variation west and east of the East Scapa Fault for selected cycles of the Rousay Flagstone Formation.

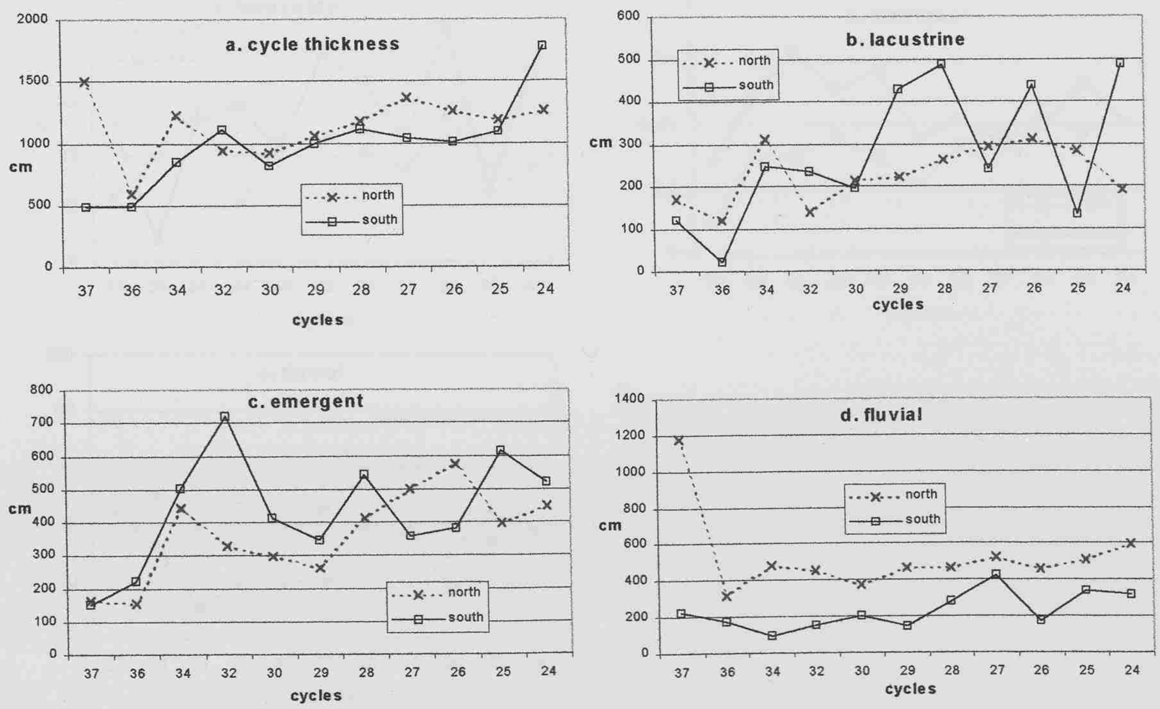


Figure 5-30. Megafacies thickness variation north and south of North Scapa Fault for selected cycles of the Rousay Flagstone Formation.

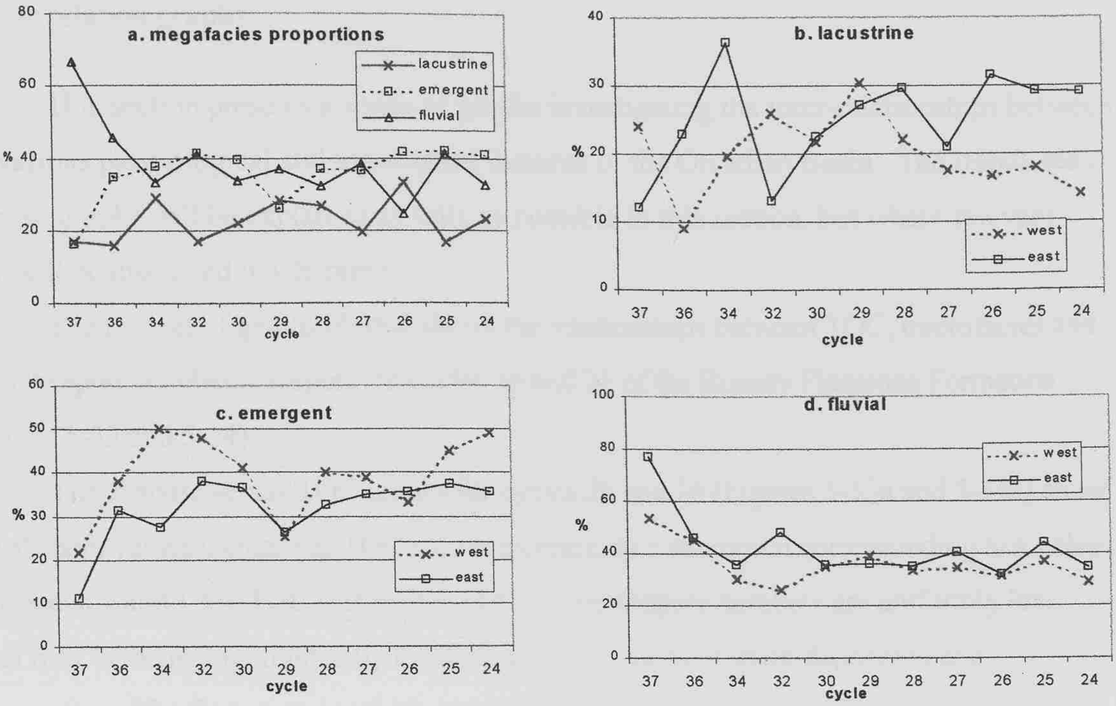


Figure 5-31. Megafacies percentage variation west and east of the East Scapa Fault for selected cycles of the Rousay Flagstone Formation.

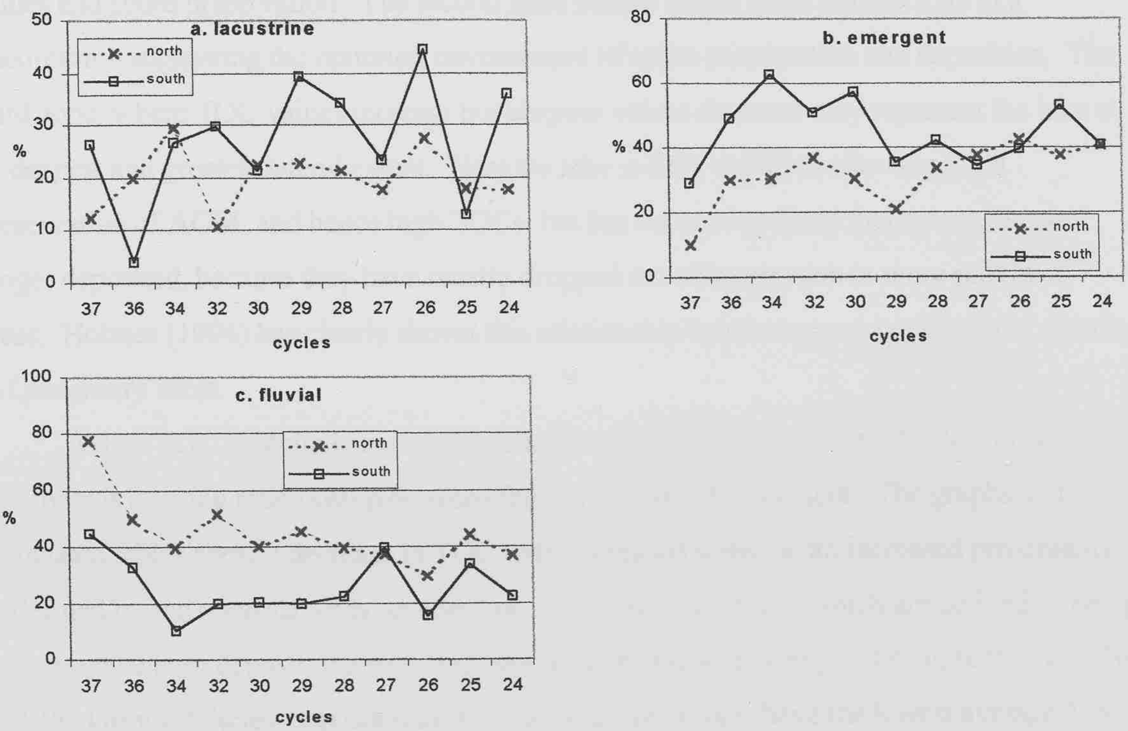


Figure 5-32. Megafacies percentage variation north and south of the North Scapa Fault for selected cycles of the Rousay Flagstone Formation.

5.4 Correlation graphs

This section presents a series of graphs investigating the inter-relationships between the various palynological and lithological features of the Orcadian Basin. The trends seen in these graphs will be explained as fully as possible in this section, but where relevant they will be discussed in Chapter 6.

The first set of graphs plotted shows the relationships between TOC, microfacies and absolute spore numbers (abspore) in cycles 26 and 36 of the Rousay Flagstone Formation (Figures 5-33 and 5-34).

The abspore versus TOC graphs for cycles 26 and 36 (Figures 5-33a and 5-34a) show that abspore values increase as TOC values increase, to a maximum corresponding to a value of between 1 and 1.5% TOC. At higher TOC values abspore numbers are uniformly low. What may be being highlighted by the data, are three zones of spore deposition and preservation. The first zone, in which spore numbers are increasing with increasing TOC, may represent a shallow, ephemeral lake environment, where TOC values are low and spore preservation is poor. Through time the lake deepens and stratifies allowing enhanced TOC values and spore preservation. The second zone occurs where spore numbers are at a maximum – suggesting the optimum environment of spore preservation and deposition. The third zone, where TOC values increase but abspore values decrease may represent the lake at its deepest and greatest lateral extent. Here the lake is fully stratified allowing good preservation of AOM, and hence high TOCs, but has become so distal that spores are no longer deposited, because they have mostly dropped out of suspension in more proximal areas. Holmes (1994) has clearly shown this relationship between spore numbers and distality in Quaternary lakes.

When TOC is plotted against microfacies type (Figures 5-33b and 5-34b) it is clear that there is a strong relationship between facies type and TOC content. The graphs and associated tables show a decrease in TOC with decreased water depth/increased proximality as defined by the microfacies types (Section 3.2). Laminite facies, which are defined as being the sub-wave base deposit of a stratified lake have the highest average TOC in both cycles 26 and 36. Grey silt facies, deposited in shallow, oxic conditions, have the lowest average TOC in cycles 26 and 36. This trend validates the environments of deposition assigned to each microfacies/facies type in Chapter 3.

The graphs of abspore versus microfacies (Figures 5-33c and 5-34c) support the findings of the abspore versus TOC graphs (Figures 5-33a and 5-34a). What can be seen from these graphs is that the highest numbers of spores are found in the dark silt microfacies. This facies type is thought to be intermediate in nature, between the deep water, stratified, anoxic laminite facies, and the shallow water, higher energy, dysoxic Wick and grey silt facies. Figures 5-33c and 5-34c suggest that it is in dark silt facies that the optimum conditions of low oxygen content, low depositional energy and proximity to source occur for the deposition and preservation of spores were found. Thus, these four graphs (Figures 5-33a, 5-33c, 5-34a and 5-34c) show how spore concentration and TOC concentration are related to depositional environment.

Figure 5-35 combines Figures 5-33b and 5-34b, and compares how the average TOC of each microfacies type changes between cycles 26 and 36. What is immediately evident is that the average TOC values of cycle 26 are always greater than cycle 36. Also, the difference in average TOC values between the two cycles increases in progressively deeper water facies; a difference of 0.2% for grey silt and wick facies, increasing to a difference of 0.5% in laminite and near laminite facies. This reduction in average TOC value may be an indication of changing palaeoenvironment between the bottom and top of the Rousay Flagstone Formation. This point will be discussed in Chapter 6.

The next three graphs (Figure 5-36 a, b, and c), illustrate how atomic H/C ratios vary with spore content, TOC and microfacies. Note that all of the H/C measurements came from cycle 26 locations only.

Despite the low number of data points, Figure 5-36a suggests a positive relationship between H/C ratio and absolute spore numbers. This is not a causal relationship (i.e. the increase in spores is not *causing* an increase in H/C ratio), for two reasons. Firstly, the increase in spore numbers is from zero to 200 spores per gram. Comparatively, this is an extremely small total number of spores, for example contemporary lakes can contain one hundred thousand spores per gram (Holmes 1994). Thus, the small numbers of spores will not alter the geochemistry of the AOM dominated kerogen. Secondly, it is known that the initial H/C ratio of exinite (spores) is 1.2 or greater, and the initial H/C ratio of alginite (the main component of AOM) is 1.5 or greater (North 1983). Thus, it is probable that any significant addition of spores to an AOM rich kerogen would *reduce* the H/C ratio rather than increase it. What may be being demonstrated in Figure 5-36a, is that more spores accumulate in areas that have higher H/C ratios. Obviously, the lack of data leaves this trend extremely subjective and more data is needed before any definite comments are made.

Figure 5-36b shows the relationship between atomic H/C ratios and TOC content. What can be seen from this graph is a general increase in H/C values up to about 2% TOC.

Above this value, H/C values remain constant. The first zone of low H/C and TOC values may represent kerogen from shallow water deposits, where kerogen preservation is not optimal and/or other kerogen with lower H/C ratios are more prevalent. The second zone, where TOC increases and H/C is static, could represent a deeper water environment where AOM-rich kerogen accumulates, and is not oxidised or diluted by other kerogen. The two zones seen in this graph could be analogous to the zones seen in the graphs of spore numbers versus TOC (Figures 5-33b and 5-34b).

The possible zonation of H/C ratios is seen again in Figure 5-36c; a plot of H/C ratios against microfacies. Normally high H/C values are not associated with high TOC values, because the kerogen is diluted by phytoclasts and spores, which have generally lower TOC contents. This is not the case here because Figure 5-36c shows that slightly higher H/C ratios are found in deeper water facies. This could be being caused by AOM (high initial H/C ratio) being the predominant component of the kerogen found in deeper water facies. If this is the case, the trend supports the findings of the graph of TOC versus H/C (Figure 5-36b), where different depositional zones are though to account for varying H/C values. However, the very slight differences between the values must always be noted when considering the implications of this graph.

The relationship between the methods used to determine the thermal maturity of the Orcadian sediments is illustrated in Figure 5-37. The data used is from sediment samples that had both been measured for exinite reflectivity and spore colour. The basic trend is that spore colour increases as exinite reflectivity increases. This positive trend validates the use of both of these methods of thermal maturity determination for the lake sediments. Figure 5-37 also shows that the rate of change of spore colour decreases with increasing exinite reflectivity. This is because spore colour loses its sensitivity as a temperature gauge at vitrinite reflectivities of 0.7 or above, which corresponds to exinite reflectivities of 0.3 to 0.2 (Marshall 1991). Most of exinite reflectivity measurements from Orkney are below 0.3 (Figure 5-22a), which suggests that the variation in spore colours observed in Figure 5-22b, represent the actual thermal maturity regime of the Rousay Flagstone Formation.

Figure 5-38 was plotted to investigate palaeoenvironmental control on exinite reflectivity. By plotting microfacies type against exinite reflectivity, it was hoped to highlight the effects of AOM suppression in the deeper water facies, or spore darkening by surface exposure in the shallow water facies. Both of these effects would have resulted in a relative reduction in exinite reflectivity figures in the deeper water facies. However, within the limited range of samples measured, there is little variation in exinite reflectivity across the range of microfacies types.

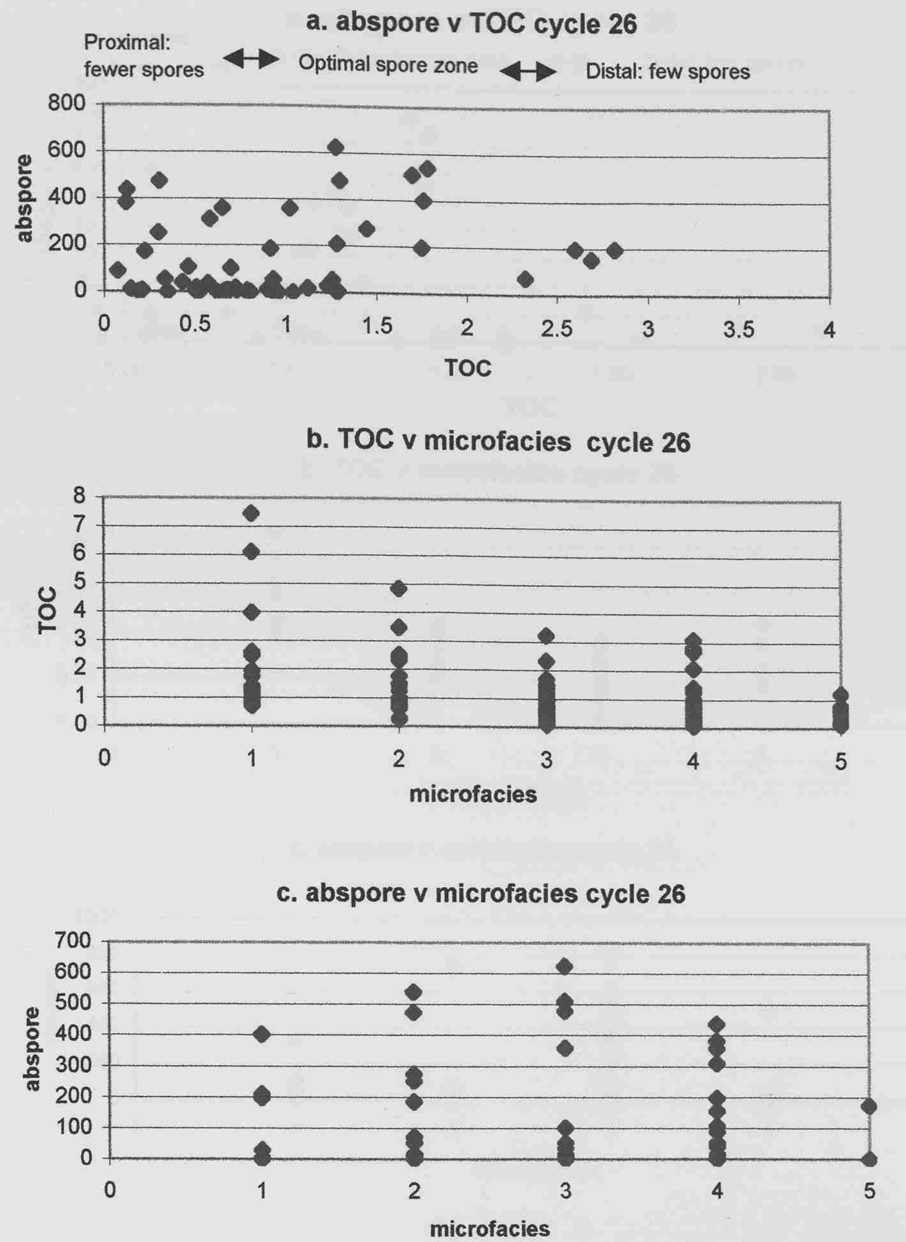
The standard way of depicting the maturity trends and kerogen type of organic matter is by using a Van Krevelen diagram (Figure 4-3). H/C and O/C ratios were measured for samples from the organic matter rich section of cycle 26 from Evie and Surrigarth, and plotted on two of these diagrams (Figure 5-39).

Figure 5-39a shows that there are two distinct data clusters from the Evie samples. One cluster is within the oil production range for Type II kerogen, with H/C ratios between 1 and 1.5, and O/C ratios between 0.05 and 0.15. The other cluster has typical Type II kerogen H/C ratios (between 1 and 1.5), but has extremely high O/C ratios (0.29 to 0.37), higher than the values normally given for oxygen rich Type III kerogen (Killops & Killops 1993). An explanation for this trend can be found in Figures 5-40c, which is part of a series of graphs that show variation in O/C and H/C ratios with progression through the lake profiles of Evie and Surrigarth. These graphs are similar to Figures 5-1 to 5-4, which show variation in spore numbers and TOC with progression through the lake profile. Figure 5-40c shows that these high O/C values are related specifically to shallower water microfacies types, and thus cannot be the result of recent organic contamination. Figure 5-40d shows that the H/C ratios for Evie remain relatively constant throughout the lake profile. Had there been simply a high concentration of woody material in the dark silt facies, the H/C ratios would be expected to decrease, complementing the increase in O/C ratios. Additionally transmitted light microscopy failed to show any large quantities of woody material (Section 4.24 and Table 4-1). The most likely explanation of the high O/C ratios is the presence oxygen rich AOM. The second Van Krevelen diagram (Figure 5-39b) for Surrigarth, shows most data points clustered into the Type I kerogen field, on or just above the zone of oil production. Three outlying points show Type II kerogen characteristics. Like the high O/C ratio data points in Figure 5-39a, these data points are associated with shallower water microfacies types (Figure 5-40a).

The differences between the kerogen samples of Evie and Surrigarth (as shown in Figures 5-39a and b and Figures 5-40a to d) must be caused by variation in depositional environment and original kerogen type. The other possible mechanism of change is that of differential thermal maturity between the two locations caused by substantial fault movement. However, it is known from exinite reflectivity studies (Figure 5-22), that there is no significant variation in thermal maturity across Orkney, that could have been caused by differential fault movement. This view is supported by Figure 5-23a, which shows that the

H/C values of the Orcadian sediments seem related to their overall position within the basin, rather than their position relative to faults.

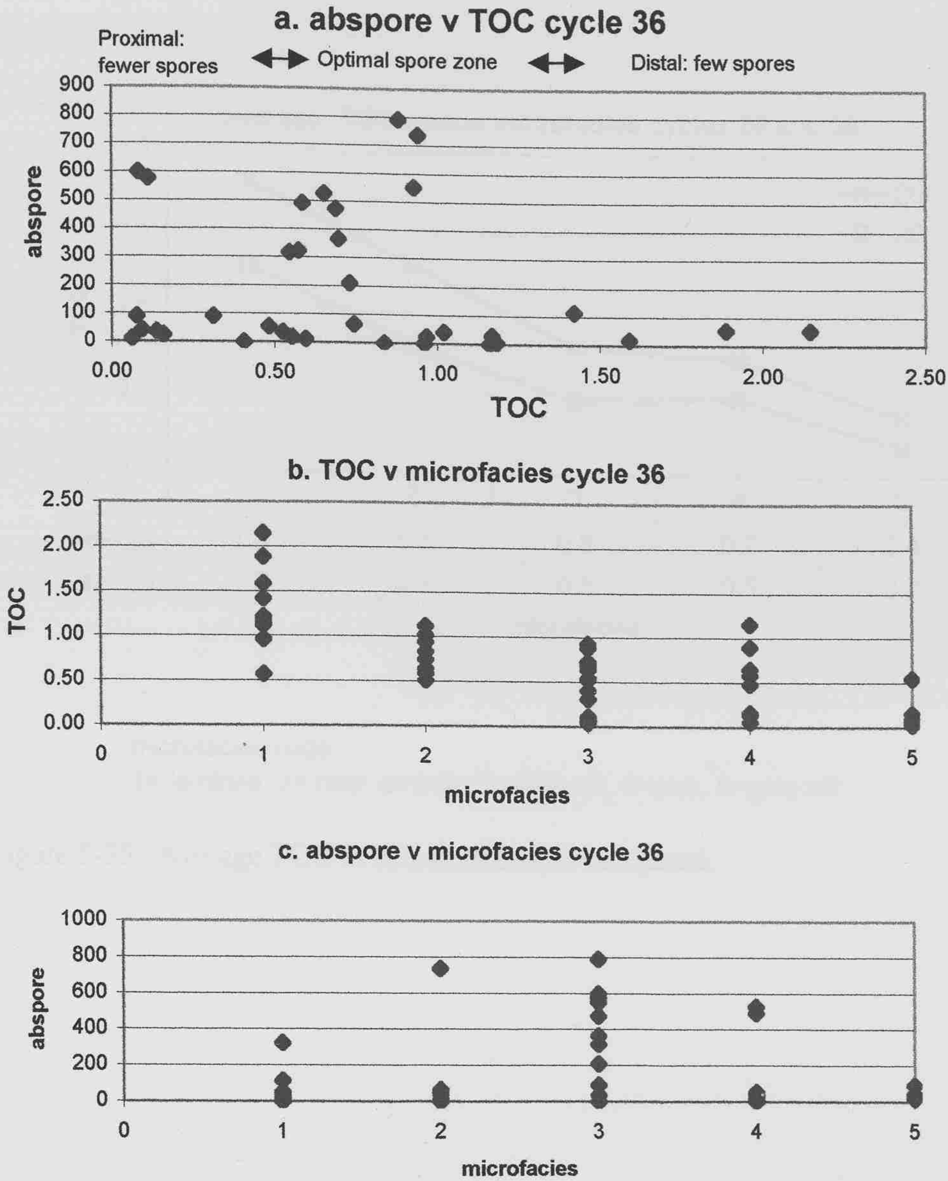
Figures 5-40a to d are, as mentioned previously, four graphs that illustrate how H/C and O/C vary vertically through lake profiles from Evie and Surrigarth. They are exactly similar in format to Figures 5-1 to 5-4. The main points to note from these graphs are that the O/C ratio tends to be higher in shallower water facies, and that H/C ratios vary little across the lake profiles.



	TOC				abspore
microfacies	min	max	average		max
1	0.7	7.46	1.84	n=26	402
2	0.24	4.84	1.26	n=29	540
3	0.1	3.24	0.78	n=72	624
4	0.07	3.1	0.7	n=45	438
5	0.13	1.21	0.38	n=17	174

microfacies code:
1= laminite, 2=near laminite, 3=dark silt, 4= wick, 5 = grey silt

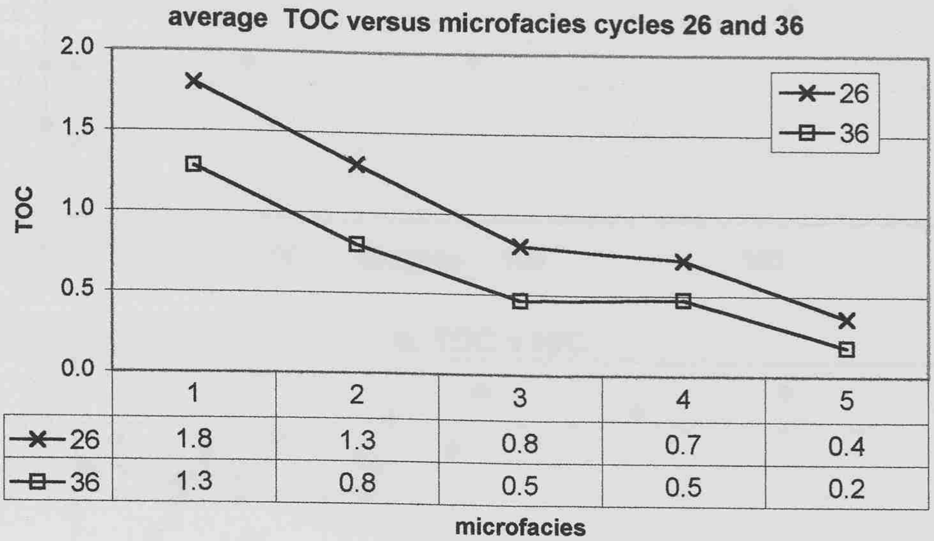
Figure 5-33. TOC, abspore (spores per gram) and microfacies variation in cycle 26.



	TOC				abspore
microfacies	min	max	average		max
1	0.57	2.15	1.28	n=12	324
2	0.51	1.12	0.8	n=8	738
3	0.04	0.93	0.46	n=17	792
4	0.06	1.16	0.48	n=9	528
5	0.03	0.55	0.18	n=5	90

microfacies code:
1= laminite, 2=near laminite, 3=dark silt, 4= wick, 5 = grey silt

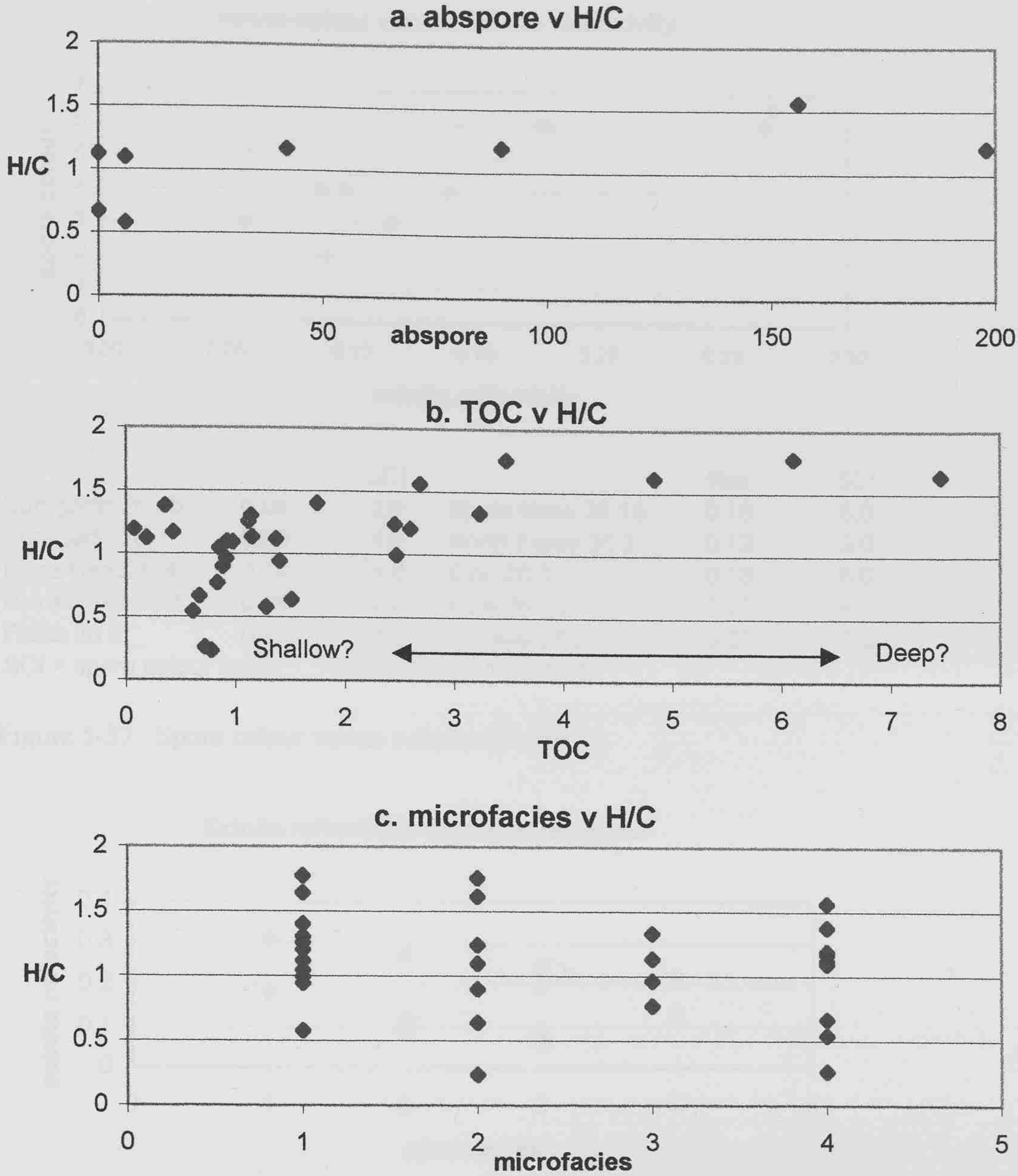
Figure 5-34. TOC, abspore (spores per gram) and microfacies variation in cycle 36



	1	2	3	4	5
26	1.8	1.3	0.8	0.7	0.4
36	1.3	0.8	0.5	0.5	0.2

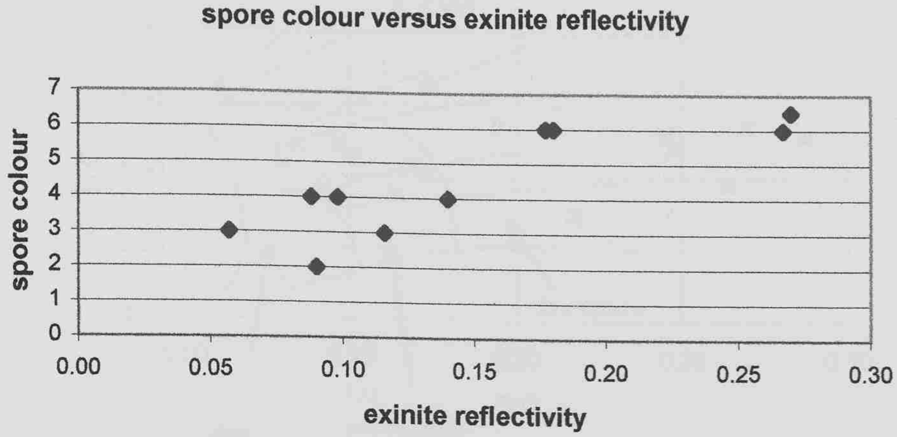
microfacies code:
1= laminite, 2= near laminite, 3=dark silt, 4=wick, 5=grey silt

Figure 5-35. Average TOC in cycles 26 and 36 compared.



	H/C				microfacies code:
microfacies	min	max	average		1= laminite
1	0.58	1.78	1.2	n=11	2= near laminite
2	0.24	1.76	1.1	n=7	3 = dark silt
3	0.77	1.33	1.1	n=4	4 = wick
4	0.26	1.56	1	n=9	5= grey silt

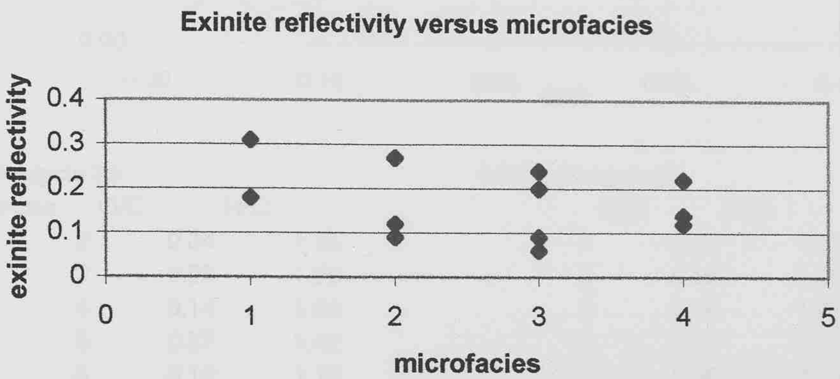
Figure 5-36. H/C ratio, abspore (spores per gram) and microfacies variation in cycle 26.



	Rex	SCI		Rex	SCI
Surrigarth 26 15	0.06	3.0	Spurs Ness 26 15	0.18	6.0
Surrigarth 26 7	0.09	4.0	North Faray 36 2	0.12	3.0
Hoxa Head26 4	0.14	4.0	Evie 26 8	0.18	6.0
Hoxa Hoxa 36 4	0.09	2.0	Evie 26 10	0.27	6.0
Flotta 26 9	0.10	4.0	Rousay 26 2	0.27	6.5

SCI = spore colour index Rex = exinite reflectivity

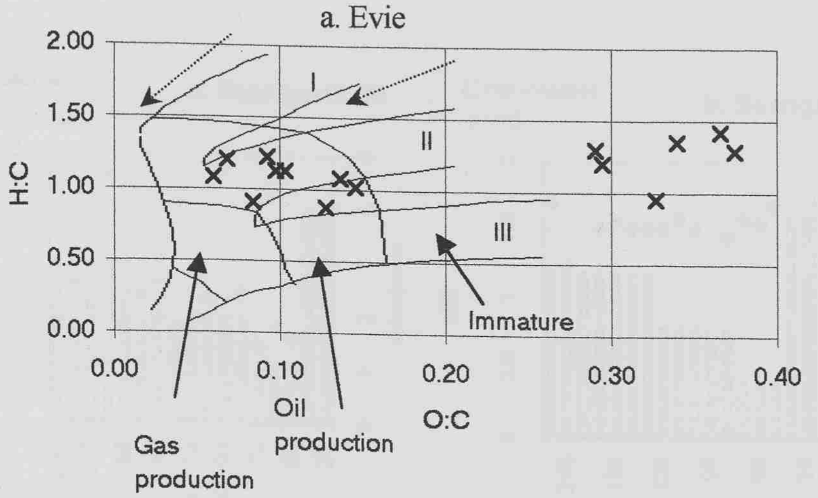
Figure 5-37. Spore colour versus exinite reflectivity.

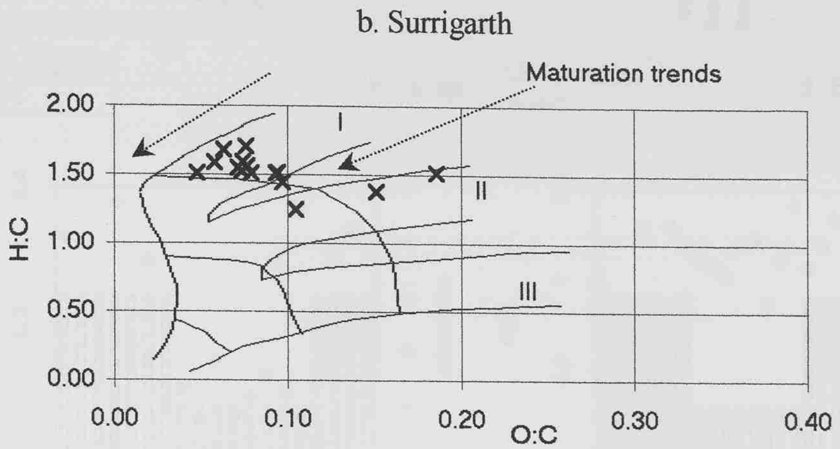


	microfacies	Re
Evie 26	1	0.31
Evie 26	1	0.18
Flotta 26	2	0.12
Hoxa Head 26	4	0.14
Rousay 26	2	0.27
Spurs Ness 26	4	0.22
Spurs Ness 26	3	0.2
Surrigarth 26	2	0.09
Surrigarth 26	3	0.06
Halcro Head 36	3	0.24
North Faray 36	4	0.12
Hoxa Head 36	3	0.09

microfacies code:
1 = laminite 2 = near laminite
3= dark silt 4 = wick
5 = grey silt

Figure 5-38. Exinite reflectivity versus microfacies.





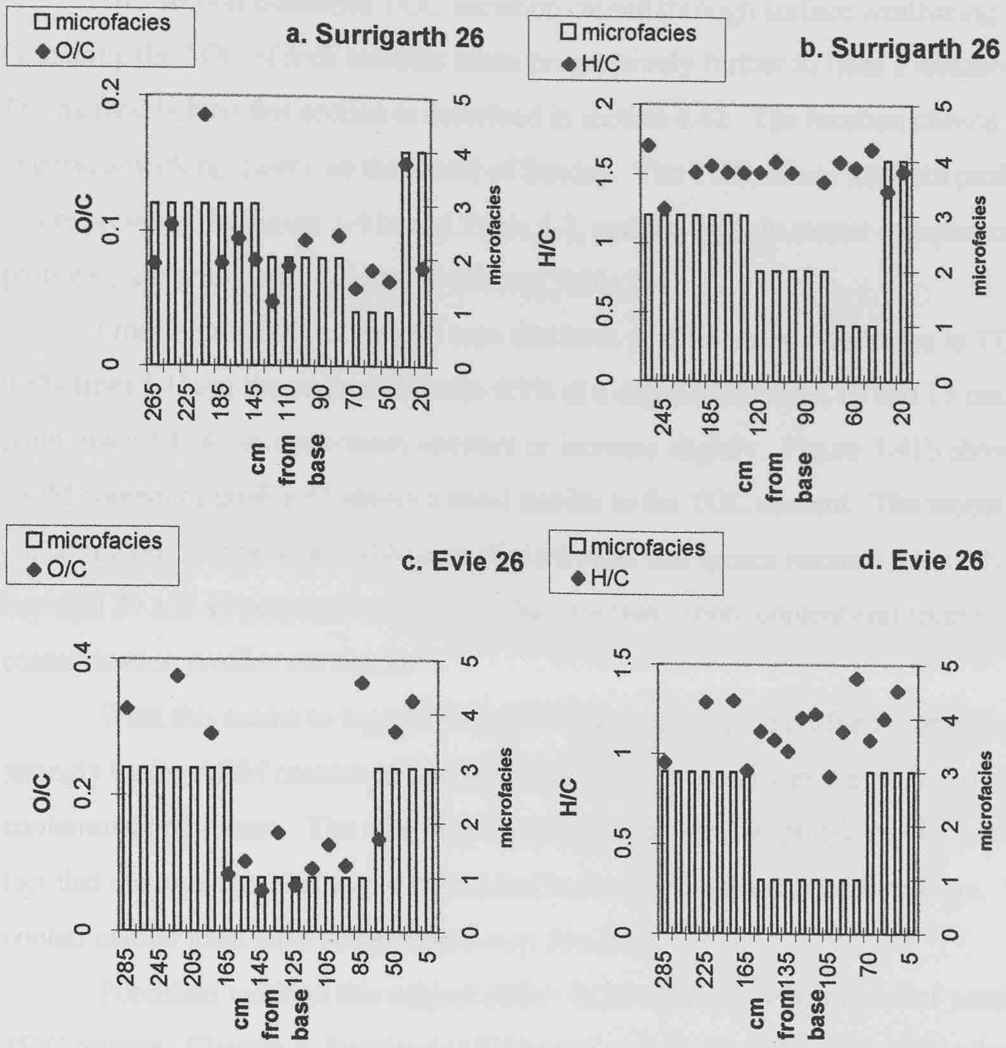
Evie cycle 26

sample	O/C	H/C
2	0.34	1.35
3	0.29	1.20
4	0.14	1.08
5	0.37	1.42
6	0.10	1.13
7	0.13	0.88
8	0.09	1.22
9	0.07	1.20
10	0.15	1.02
11	0.06	1.08
12	0.10	1.13
13	0.08	0.91
14	0.29	1.30
16	0.37	1.29
19	0.33	0.95

Surrigarth cycle 26

	O/C	H/C
1	0.07	1.52
2	0.15	1.38
3	0.06	1.68
4	0.07	1.55
5	0.06	1.59
6	0.10	1.44
8	0.09	1.51
9	0.07	1.59
10	0.05	1.51
11	0.08	1.51
12	0.09	1.51
13	0.08	1.56
14	0.19	1.51
16	0.10	1.25
17	0.08	1.71

Figure 5-39. Van Krevelen diagrams showing H/C and O/C ratios for cycle 26 Evie and Surrigarth.



microfacies code:
1= laminite, 2=near laminite, 3=dark silt, 4= wick, 5 = grey silt

Figure 5-40. H/C and O/C ratios plotted on lake profiles, cycle 26, Evie and Surrigarth. **Turn page on side for log-type profile.**

5.5 Loth Quarry TOC profiles

This section quantifies TOC variation caused through surface weathering, by measuring the TOC of rock samples taken progressively further in from a weathered surface. The method behind this section is described in section 4.42. The location chosen was Loth Quarry, a working quarry on the island of Sanday. The TOC values for Loth profiles #1 and #2 are presented in Figure 5-41a and Table 5-3, and the organic matter components of Loth profile #2 are presented in Figure 5-41b and Table 5-4.

From Figure 5-41a it can be seen that both profiles show a **decrease** in TOC by about 0.3% from 1.1% at the surface down to 0.9% at a depth of between 10 and 15 cm. From this point inward TOC values remain constant or increase slightly. Figure 5-41b shows that the AOM content of profile #2 shows a trend similar to the TOC content. The recent contamination component in the form of plant roots and spores remains relatively constant at between 20 and 40 percent throughout. The Devonian spore content and recent contamination profiles are similar.

What this seems to suggest is that TOC variation in the profile is controlled most strongly by the AOM content of the rock, rather than proximity to the surface or amount of contamination present. The relatively constant contamination profile can be explained by the fact that the rock face that was sampled had been exposed for around five years. The contamination must have accumulated over this time.

Published work on this subject differs in its opinion on the effects of weathering on TOC content. Clayton & Swetland (1978) and Leythaeuser (1973) found that the organic matter content of source rocks decreased towards the weathered surface. Both of these works took their samples from Utah, an extremely arid environment where surface weathering is extreme. Alternatively, Forsberg & Bjoroy (1981) studied TOC profiles from Spitsbergen and found that weathering scarcely affected the TOC of the samples.

It seems clear that the main difference between the first two references and the third reference, is that of environment of exposure. Clearly, both the Loth Quarry samples and the Spitsbergen samples would not have experienced such extreme (hot) weather, when they were exposed on the surface. Thus, it is shown that the rocks from Loth Quarry and the rest of Orkney have not lost an appreciable amount of organic matter by recent weathering.

	Loth #1		Loth #2	
Sample	cm from surface	TOC	cm from surface	TOC
1	0	1.12	2	1.12
2	2	1.16	3	1.00
3	4	1.04	6	0.77
4	7	0.89	9	0.8
5	10	0.88	13	0.73
6	15	0.86	15	0.62
7			18	0.69
8			20	0.85
9			22	0.74
10			33	0.87
11			51	0.88

Table 5-2. TOC results for both profiles, Loth Quarry.

Sample	cm from surface	TOC	AOM%	Spore %	Contamination %
1	2	1.22	59	20	21
2	3	1.00	67	16	17
3	6	0.77	72	12	16
4	9	0.8	60	20	20
5	13	0.73	20	47	33
6	15	0.62	28	43	29
7	18	0.69	28	27	43
8	20	0.85	50	29	21
9	22	0.74	38	35	27
10	33	0.87	39	43	18
11	51	0.88	22	61	17

Table 5-3. Organic matter components Loth profile #2.

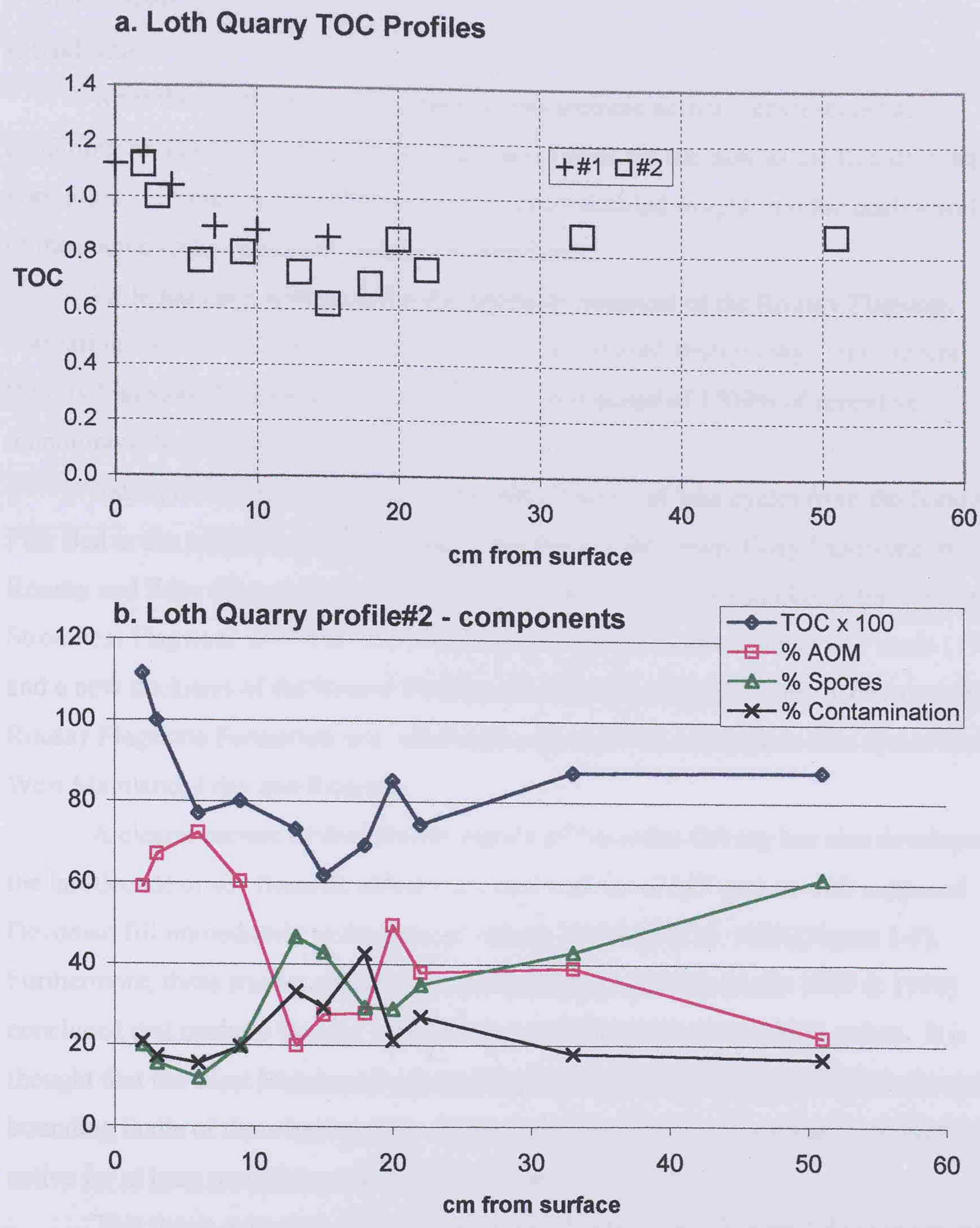


Figure 5-41. Graphs of Loth Quarry profiles #1 and #2, showing TOC, palynomorph and contamination variation.

6 Discussion

Introduction

What this research hopes to show is how tectonic activity, environmental conditions and Devonian flora interacted to form what we see now as the Rousay Flagstone Formation. Ultimately this information also gives detailed insight into the quality and type of the source rocks deposited in the Orcadian Basin.

Little has been written about the palaeoenvironment of the Rousay Flagstone Formation, mainly because of a lack of a coherent internal stratigraphy. Until recently, the Rousay Flagstone Formation was thought to be composed of 1500m of repetitive, monotonous lacustrine sediments (Wilson et al. 1935).

Astin (1990) changed this by correlating a series of lake cycles from the Sandwick Fish Bed in the north west of Mainland, to the base of the Lower Eday Sandstone in Rousay and Eday (Figure 1-4). This correlation produced both a thickness for the Upper Stromness Flagstone of 325m (which agrees with the previous estimates of Fannin (1970)), and a new thickness of the Rousay Flagstone Formation of about 200m. Consequently, the Rousay Flagstone Formation was redefined in terms of 14 correlatable lake cycles found in West Mainland, Eday and Rousay.

A clearer picture of the tectonic regime of Devonian Orkney has also developed in the last decade or so. Seismic surveys revealed a series of half graben with supposed Devonian fill immediately to the west of Orkney (Coward et al. 1989)(Figure 1-7). Furthermore, these studies and onshore sedimentological work (Astin 1985 & 1990) concluded that onshore Orkney was the exhumed fill of at least two half graben. It is thought that the West Mainland Fault and the East Scapa Fault (Figure 1-5) are the main bounding faults of these half graben. Furthermore, there is evidence that these faults were active for at least part of the mid Devonian (Astin 1985 & 1990).

This thesis extended Astin's framework of lake cycles (Figure 1-4) to cover most of Orkney (Figure 2-1). This has enabled the study of the sedimentary processes that operated in Orkney during Rousay Flagstone Formation times. Particular attention was given to the distribution, type and quality of the organic matter preserved within the lake sediments.

A great deal of information relating to the sedimentary rocks of the Rousay Flagstone Formation was gathered in the course of this thesis. As stated in Chapter 3 the lacustrine cycles were initially defined in terms of 14 key facies types. To aid interpretation these primary facies were redefined in broader depositional categories – the 'megafacies' categories, and some of the key facies were grouped together e.g. laminite and near laminite facies. This simplification of the facies was done in recognition that it would be geologically unreasonable for there to be any continuity of individual facies types between the locations within the lithostratigraphic framework. The thicknesses and percentages of facies measured at each location is presented in Appendix 3, and a summary of the megafacies data produced is presented in Appendix 4.

Thus, it must be emphasised that this part of the thesis dealing with sedimentary trends, necessarily tries to differentiate between what may be basin wide trends, and events of only local significance. Below is a list of what may be considered the most important trends to come from the sedimentological data, and which will be considered during the course of this discussion.

Summary of key trends (see Figures 6-1 to 6-3):

- Increase in average cycle thickness from west to east across the East Scapa Fault.
- Tendency for laminites and near laminites to be deposited to the west of the East Scapa Fault and in the north of the area.
- Maximum TOC, H/C and spore number values are found to the west of the East Scapa Fault and in the north of the area.
- Greatest thicknesses of organic matter rich sediments immediately to the east of the East Scapa Fault.
- Sandy dark silts are found mainly in south and east
- Most sand deposition is found in the north and south of the area, and to the east of the ESF.
- Coarser sediments found in the north and south of the area.

6.1 The effect of fault movement on sedimentation

The first point to highlight from the data is one that lies outside of the smaller sub-categories presented in the rest of this discussion. The effect that the East Scapa Fault has had on the overall thickness of the lake cycles must be discussed before going into further detail.

It is self evident that sedimentation in a series of actively extending half graben will be strongly controlled by the fault pattern (Leeder & Gawthorpe 1987). In studies of modern half graben systems, the geometry of the faults is usually readily visible. In Orkney, however, faults are rarely exposed, being mostly covered in water or farmland. Thus, this thesis relies on less direct evidence of fault movement, mostly in the form of sedimentary facies and thickness changes as observed from the stratigraphic framework (Figure 2-1). It is thought that at least two main faults in Orkney strongly influenced sediment distribution during the Middle Devonian. These are the North Scapa Fault (NSF) and the East Scapa Fault (ESF). Both Astin (1985 & 1990) and Coward et al. (1989) have acknowledged that these faults are major structural features in Orkney and are related to sedimentation patterns. Additionally, studies of the Devono-Carboniferous Horton Group of Cape Breton Island (Hamblin & Rust 1989) have shown that faults effected sedimentary deposition strongly in this palaeogeographically similar area. From the Horton Group there was evidence that tectonic movement controlled the distribution of fluvial facies and laminites throughout the basin. So clearly there is precedence that sedimentological fieldwork in Devonian continental basins can reveal a great deal about the palaeoenvironment and tectonic regime of those times.

The results also suggest that faults outside the area of the correlation diagram (Figure 2-1) directly influenced some of the sedimentary trends encountered. However since these faults are not contained within the lithostratigraphic framework their impact cannot be directly assessed. These faults include the West Mainland Fault, the Brims-Risa Fault (Figure 1-5) and the graben bounding faults imaged to the north west of Orkney (Figure 1-7). For example, palaeocurrent data (Figure 5-28) and clast-size distribution studies (Figure 3-3) indicate that the Sacquoy Sandstone Member originated from an exposed footwall to the north west of present day Orkney. Thus, clearly the sedimentation of Devonian Orkney was affected by faults other than the East Scapa Fault and the North Scapa Fault.

The main indication of active fault movement during the deposition of the Rousay Flagstone Formation, is the consistent change in lake cycle thicknesses across the trend of the ESF. Figure 5-9c shows that lake cycles are on average 6 to 7m thicker to the east of the ESF. Although this trend was noted by Astin (1990) in his stratigraphic correlation of the north of Orkney (Figure 1.4 & 1-6), these figures show that the trend of thickness variation is present along the length of the ESF. Furthermore, Figure 5-29a shows that the thickness difference across the ESF occurred for the duration of the Rousay Flagstone Formation.

This is entirely in agreement with the existing view of Orcadian tectonics. This states that the Devonian sediments were deposited in a series of half graben within a slowly subsiding and extending basin (Astin 1985, McClay et al. 1986, Coward et al. 1989). It is thought that the eastward dipping, East Scapa Fault is an exhumed graben-bounding fault similar to the faults imaged on seismic to the west of Orkney (Figure 1-7). Thus, the footwall of the half graben (the area to the west of the East Scapa Fault) experienced uplift relative to the hangingwall to the east of the fault according to the half graben model proposed by Leeder & Gawthorpe (1987) (Figure 6-4).

Work by Astin (1985 & 1990) suggests that although the ESF was active during the deposition of the Rousay Flagstone Formation and the overlying Lower Eday Sandstone, the style of the fault's movement was different for these two formations, as revealed by the two formations' different styles of sedimentation. The Lower Eday Sandstone is typified by fluvial channel, conglomerate and aeolian sandstone deposition. These sediments are thought to have been formed by increased erosion during a period of enhanced footwall uplift (Astin 1985, Marshall 1995). This contrasts with the largely low energy lacustrine sediment dominated, Rousay Flagstone Formation, which was deposited in a largely non-erosive environment. This suggests that during Rousay Flagstone Formation times, the area to the west of the ESF did not experience significant relative uplift. Rather, the ESF extended slowly, producing only small differences in accommodation space along its length. This caused relatively thinner lake cycles to be deposited on the uplifted footwall compared to the cycles deposited in the hanging wall, which produced the distinctive cycle thickness patterns seen in Figure 5-9c.

The North Scapa Fault is thought to have been active at least during the deposition of the Lower Eday Sandstone (Astin 1985). However, cycle thickness variation (Figure 5-30a) indicates that for much of duration of the Rousay Flagstone Formation, lake cycles did not differ greatly in thickness across this feature. The large increase in cycle thickness in the north, between cycles 36 and 37 (Figure 5-30a) can be attributed to massive fluvial input (Figure 5-30d) in the north of Orkney towards the end of Rousay Flagstone Formation times. It was not caused directly by fault movement. This suggests that there was little significant movement on the North Scapa Fault during this time. It may be noted that there is more fluvial megafacies present in the north compared to the south (Figure 5-30d and 5-32c). This is probably not linked to movement on the North Scapa Fault, but related to alluvial fan deposition in the north.

Thus, it is clear that movement on the ESF was the main control on overall sedimentary package thicknesses in this area of the Orcadian basin. What remains to be discussed is to what degree did the fault control the more detailed aspects of sedimentation during Rousay Flagstone Formation times. These points are covered in the following sections.

6.11 A transfer zone in the North of Orkney

A clear deviation from the overall east-west thickness trend occurs on the island of North Faray, between Westray and Eday (Figure 1-1). The lake cycles on this island are on average 3-4m thinner than the locations north and south of it (Figure 5-9). Additionally this location has approximately 10% less fluvial megafacies (Figure 5-26c) and 8% less sand rich facies (Figure 5-15c), on average for the Rousay Flagstone Formation. Also the actual thickness of lacustrine megafacies is on average 1m less per cycle for the Rousay Flagstone Formation (Figure 5-27a).

A possible explanation for the observed trends can be seen from the structure map of Orkney (Figure 1-5). The map shows that North Faray is located immediately to the east of the splay of the ESF. This splaying geometry is typically associated with the termination of faults and the transfer of stress from one half graben system to another (Figure 6-5) (Roberts & Yielding 1994). If this was the case the throw of the ESF would be declining northward, and the transfer zone formed by the splaying faults would be linking with an as yet unmapped fault to the north of the island of Sanday. Transfer zones are commonly zones of enhanced depositional slope that facilitate transfer of sediment from the upraised footwall of one fault block into the depocentre of the adjacent half graben (Figure 6-6) (Gawthorpe & Hurst 1993).

The sedimentary trends of North Faray can be explained if it is assumed that the island was located in a zone of localised enhanced depositional slope in a transfer zone. The enhanced slope would mean that sediments would generally be transported through this area into the depocentre to the south, rather than be deposited in that area. This is supported by the predominant palaeocurrent flow to the south west (Figure 5-28). Lack of more information from that area precludes further analysis.

6.12 Differential compaction

A mechanism commonly used to explain sedimentary thickness variations across faults is that of differential compaction. This operates when sedimentary units of the same depositional thickness are differentially compacted because of differential overburden weight acting locally, most commonly in the hangingwall of a half graben (Allen & Allen 1990). This mechanism cannot have had a significant effect on the sedimentary thicknesses across the ESF, because the sediments of the Rousay Flagstone Formation are thicker in the hanging wall where occur the greatest thicknesses of overburden (Figure 5-9c). Additionally with differential compaction, sedimentary units would be expected to be thinner at the base of the Formation and increase in thickness upward because of reduced overburden weight. The opposite is true of the Rousay Flagstone Formation where lake cycles get thinner with towards the top of the unit (Figure 5-29).

6.2 The distribution of specific facies types across Orkney

Introduction

To aid discussion it can be said that the Orkney Flagstone Group (Figure 1-2) is composed of two main types of sediment, approximating the end members of the depositional environments found in the Orcadian Basin at this time. These are facies that were deposited in a lacustrine environment, and facies that were deposited in rivers or as fans. The fourteen or so lake cycles of the Rousay Flagstone Formation represent the fluctuations between lake dominated and fluvially dominated sedimentation. The two types of sediments appear very different in the field, the first type, being very dark in colour and fine grained. The second type is lighter coloured and coarser grained. The transition between lake dominated sedimentation and fan dominated sedimentation is thought to have been geologically rapid (Rogers & Astin 1991). Thus, it seems valid to divide this part of the discussion into a section dealing with the sediments deposited primarily in a lacustrine setting and a section dealing with sediments deposited by rivers or fans.

6.21 The controls on the distribution of lacustrine sediments

The lacustrine sediments of the Rousay Flagstone Formation are generally distinguished by being fine grained and dark coloured. For the purpose of this section, 'lacustrine sediments' will be defined as sediments that were deposited at least partly under anoxic lacustrine conditions and thus have a measurable TOC content. This means that facies such as 'Wick' and 'grey silt', which although which were defined as 'Emergent' in the megafacies classification, are regarded as predominantly lacustrine in nature. This reclassification is permissible, because the organic matter contained within these facies was clearly deposited in lacustrine conditions. Table 6-1 provides a summary of the proportion of lacustrine or partly lacustrine sediments found on average in each lake cycle. A more detailed breakdown of this data can be found in Appendix 3. An important point to take from this table is that 37% of lake cycles are composed of organic matter rich sediments.

Facies	Percentage of facies in an average cycle	Thickness of facies in an average cycle (cm)
Laminite	2	25
Near laminite	3	35
Dark silt	9	93
Sandy dark silt	7	73
Wick	14	146
Grey silt	2	22
All OM facies	37	394
Average cycle thickness		1064

Table 6-1. Percentages and thicknesses of organic matter rich sediments, for the average lake cycle, Rousay Flagstone Formation.

6.21i Distribution of laminite and near laminite facies

Laminite and near laminite facies have been grouped together in this section. This is mainly because differentiation between the two facies depended solely on subtle changes in the lithology, that may have been obscured in the field. Both laminite and near laminite facies will be referred to as 'laminite'.

To illustrate the presence of laminite facies an arbitrary figure of 5% cycle content was chosen to represent areas of greater than average laminite presence. Figures 5-6 and 5-10 show that lake cycles with the greatest proportion of laminite and near laminite facies occur in two areas of Orkney.

The first area is a north-south trending zone, approximately 5km west of the ESF. The occurrence of laminites in this location can be explained by the structural geometry of the Orcadian Basin. The laminite rich area is thought to correspond to a position on the uplifted footwall close to the fulcrum point of the half graben (Leeder & Gawthorpe 1987) (Figure 6-4). Laminites are known to form in areas of reduced oxidation potential, with little water movement and limited sediment input (Donovan 1975). It can be demonstrated that this location on the half graben structure would provide optimum conditions for the formation of laminites.

Firstly, it is known that one of the main areas of sand rich facies and sandy dark silt (Figures 6-1 & 6-3) accumulation is immediately to the east of the ESF. Although enhanced thicknesses of organic matter rich sediments do occur in the downthrown hanging wall, laminites are not common. Due to the fine grained and finely laminated structure of laminites, they would not form in areas of high clastic input. The sand that accumulated to the east of the ESF could have come from two possible sources: locally from footwall fans (Leeder & Gawthorpe 1987), and distally brought in by turbidity currents from the north and south (see later). It is suggested that one of the factors that allowed enhanced laminite deposition in this area is that of reduced sand input.

It is also known that laminites do not form readily in areas of areas of rapid bottom current activity (Talbot & Allen 1996), currents tending to disturb the fine lamination of the newly deposited sediment. As previously stated, it is thought that turbidity currents played an important role in introducing sediment into the basin. So it is thought that the area immediately to the west of the ESF experienced less current activity than the area to the east.

Thus, it seems by virtue of the area's slightly uplifted position within the half graben, that fewer turbidity currents were active and less sand was deposited to the west of the ESF. This meant that an environment relatively more conducive to the formation of laminites existed to the west of the ESF during Rousay Flagstone Formation times.

The effect that difference in relative elevation had on facies types across the half graben can be observed from megafacies data. It can be seen that generally more lacustrine megafacies tend to be deposited to the east of the ESF (Figures 5-29b & 5-31b), and that more emergent megafacies are deposited to the west of the ESF (Figures 5-29c & 5-31c). This suggests that conditions on the uplifted footwall of the half graben meant that the sediments were more likely to be deposited in shallower water and be sub-aerially exposed. Conversely, in the downthrown hanging wall, to the east of the ESF depositional conditions would be more prone to lacustrine facies under permanent water cover.

There is no conflict between the fact that both laminites and emergent megafacies are most common on the upthrown footwall. What is shown is that the upthrown block tended to mostly have shallower water facies associated with it. However, when the water depth was greatest over the entire basin, the central strip of the footwall provided the best location for the formation of laminites for the reasons discussed above.

The second location of high laminite and near laminite occurrence is in the north eastern part of Orkney, adjacent to the splay in the ESF (Figure 6-1 & 5-10). This location is very close to the ESF, and seems initially to contradict the previous assumption that laminites are not found close to footwall scarps. However, the fact that the ESF in that area has splayed may account for the occurrence of the laminite facies. As discussed in

Section 6.2 this area may have been be acting as a transfer zone between the half graben formed by the ESF and an unidentified half graben that is thought to be located to the north.

Proximity to a transfer zone could enhance laminite deposition by several possible mechanisms. They are generally related to the fact that laminites generally form in areas of reduced clastic input. Due to the lack of direct information about the transfer zone it is uncertain which of the mechanisms operated, and to what extent they controlled the sediment distribution.

The first reason for reduced clastic input into this area is that due to the nature of the splay, the throw of the ESF has split into at least two faults of presumably lesser throw (Figure 1-5). These faults would act as natural breaks to sediment flow coming at right angles off the footwall scarp and into the basin (Figure 6-6). Thus, it is possible that any sand being eroded off the ESF scarp was being ponded behind these splay faults, and was not interfering with the formation of the laminites. Tiercelin (1990) observed similar tectonic segregation in Lake Tanganyika.

Alternatively, it has been show that variability in fault throws along half graben, can result in the central part of the half graben breaching the surface, but the tips of the faults remaining blind (Gawthorpe et al. 1997). Growth folds may form above the blind fault tips. If the ESF behaved in the manner of typical graben bounding faults, it would be expected to decline in throw towards the north and south (Figure 6-6). The splaying of the ESF suggests that the northern tip of the fault was located in that area.

Thus, during the time of the Rousay Flagstone Formation, the part of the ESF located in central Orkney may have breached the surface. If the fault had breached the surface, footwall fans may have formed, introducing sand locally into the lake. However, the lesser throw of the fault segments in the north may have meant that they did not breach the surface. This would mean there were no exposed fault scarps in the area from which sand could be directly sourced. Laminites would be more likely to form in this area of reduced sand input. Additionally, and more importantly if the ESF had not breached the surface, the area in the north of Orkney would have been an area of uplift relative to the depocentre to the south (Figure 6-6). Laminites could have formed in that area for the same reasons they formed west of the ESF, as discussed above.

6. 21ii Distribution of sandy dark silt and organic matter rich facies

Aside from laminite and near laminite facies, two other lacustrine facies groupings were studied. These are the distribution of all organic matter rich (OM rich) facies, and the distribution of sandy dark silts.

OM rich facies include all sediments that contained preserved organic matter, and thus must have experienced anoxia or hypersalinity and/or rapid sedimentation at some stage of their deposition. This grouping includes laminite, near laminite, dark silt, sandy dark silt, Wick and grey silt facies.

Figure 5-6 shows that the area of Orkney containing most OM rich facies lies to the east of the ESF, around the easterly extension of the North Scapa Fault (NSF). However, Figure 5-12c shows that the values above 50% as shown in Figure 5-6 (and 6-1) are unusually high, held by only three locations. The majority of values for OM rich facies content are between 20 and 40% throughout Orkney. This suggests that organic matter accumulation and preservation across Orkney was on average quite uniform, as would be expected in the widespread lacustrine environment that is envisaged as being present during Rousay Flagstone Formation times. The uniform distribution of this facies grouping is also predictable, because it represents the total of all environments in which organic matter was preserved. Thus, organic matter variation related to depositional environment change would not necessarily show up.

The greatest thicknesses of OM rich facies are clustered in the south eastern part of Orkney (Figure 5-12c). This area is also notable for having lower proportions of fluvial megafacies than the other sites to the east of the ESF (Figure 5-26c). Additionally, the average thickness of the cycles in this area is not greater than the other cycles to the east of the ESF (Figure 5-9). The proportional increase in OM rich facies is matched by a reduction in actual thickness of fluvial sediments. The presence of greater than average proportions of OM rich facies may have been a product of the distality of that location. It can be seen that there is a general palaeocurrent trend of flow towards the central part of the basin (Figure 5-28 & 6.1). Thus, during the Rousay Flagstone Formation times, this area must have represented the most distal area of Orkney. Fluvial sands from terminal fans were probably deposited more proximally to the north and south, as shown by the general lack of fluvial sediments in that area (Figure 6-3). This would mean that proportionally more of the cycle was made of lacustrine facies.

Additionally, it has been shown that any agitation of lake water tends to winnow organic matter towards progressively deeper, or in this case more distal waters (Huc et al.

1990). Thus, the action of turbidites or density flows would result in the concentration of organic matter towards the centre of the lake. This factor can also help explain the high quantities of OM rich facies in the central Orkney area.

Note that the area containing most OM rich facies does not coincide with the areas of high laminite occurrence (Figure 6-1). This implies that the areas that are most suited to the accumulation of large quantities of organic matter are not necessarily suited to the formation of laminites. Thus, although organic matter may accumulate in areas of rapid sediment accumulation, a lower rate of sediment accumulation is needed to form laminites.

The distribution of sandy dark silt facies is shown on Figures 6-1 and 5-14. Sandy dark silt facies is of particular interest, because it represents the impingement of fluvial and fan systems into deep water lacustrine conditions. The location of significant quantities of this facies can provide information on the behaviour of the rivers in the Orcadian basin, when the lakes were at their deepest, and widest lateral extent.

Although the definition of this facies was arbitrary, (dark silts containing noticeably more sand than usual) observation of the occurrence of this facies has proven useful. Although this facies occurred infrequently throughout Orkney, the greatest proportion of this facies was found to the east of the ESF and to the west of the ESF in the south of the area. The presence of significant quantities of sand in these deeper water facies suggests that there was enhanced fluvial input in these areas carrying suspended sand. There are two possible sources of sand input in this area.

The first source could have been small footwall scarp derived terminal fans. The sediment influx from these features would have been extremely localised (Leeder & Gawthorpe 1987) and there is little evidence of the existence of these features. This is because for the fans to develop, significant erosion of underlying sediment would have had to occur. Throughout the Rousay Flagstone Formation, no instance of significant fluvial incision was noted. The only possible evidence for a footwall scarp fan in Orkney is the localised occurrence of a large proportion of fluvial sand at Head of Work – immediately north of the easternmost extension of the North Scapa Fault (Figure 6-3).

The second source of sediment could have been from large prograding alluvial fans introducing sediment into the deep lake environment in the form of turbidity currents, when the lakes were at their widest extent. This contrasts with Figure 6-3, which illustrates that the central and eastern part of Orkney did not experience much sand rich sedimentation during the upper fluvially dominated part of each lake cycle. This factor is attributed to the distality of that area, meaning that terminal fans to the north and south would have deposited their sediment load in more proximal areas.

As mentioned in Section 3-1, one of the mechanisms that can introduce coarse silt to fine sand sized particles into deep water sediments is the density flow (Talbot & Allen 1994). Density flows can either flow along the bottom of a basin (turbidites or underflows), along the thermocline (interflows) or along the surface of the lake (overflows). Figure 6-7 illustrates the various types of density current. Turbidity currents provide a mechanism that can account for the central position of the highest proportion of sandy dark silt facies. These currents carry fine sediment in suspension and as the currents loose velocity, their capacity for transporting sediment declines, causing the sediment to drop out of suspension. Information from Lake Tanganyika records the presence of coarse sediment in the deepest part of the lake that was carried there by turbidity currents (Tiercelin 1990). This is also seen in the Culpeper Basin (Jurassic/Triassic) where graded sand beds are found in black shales. These sands were deposited from the fronts of lacustrine deltas by sediment laden river water in the form of turbidites (Gore 1988). Additionally, studies of Lake Tanganyika show the entry points of the sediment laden underflows to be extremely laterally limited, beyond which the flows spread out to cover a wider area (Talbot 1996). Palaeocurrent data from the Rousay Flagstone Formation (Figures 5-28b & c & 6-1) indicates that the predominant direction of flow in that area was approximately from the south west and north west, with a lesser trend from the north east. Palaeocurrent data with similar trends from the overlying Lower Eday Sandstone (Figure 1-2) has been interpreted as evidence of two large prograding alluvial fans sourced to the south and north of Orkney (Astin 1985).

Thus, it is envisaged that fine sand was introduced into the organic matter rich, distal part of the lakes by dilute turbidity currents or density flows (Figure 6-7). These currents were sourced from terminal fans located to the north and south of Orkney and entered the basin thought channelised entry points. This explains why sandy dark silt facies are not so common in the extreme north and south of Orkney, areas in which fluvial input may have been more confined.

6.22 Synthesis and explanation of the sedimentary trends seen in the lacustrine sediments of the Rousay Flagstone Formation

As defined at the start of this section, 'lacustrine' sediments are sediments thought to have been deposited at least partly under standing water, and thus had developed some preserved organic matter content. Clearly, this is an important definition, since it should encapsulate all of the sediments that could potentially be source rocks. These sediments occupy around 40% of each lake cycle, that is 4 metres of the average 11 metre thick cycle. This means that there should be about 56m of rock with a significant TOC content contained within the 14 cycles of the Rousay Flagstone Formation.

The key point to be gained from this section is the limits and controls on the distribution of laminite facies within the Devonian half graben system. The distribution of this facies is a compromise between deposition in the deepest most distal parts of the basin, where conditions are most anoxic and in theory, the bottom water is most still. However, it has been shown that these distal/deep locations can be the focus of dilute, oxygen rich, sediment bearing turbidites, sourced from terminal fans to the north and south.

Therefore laminites are generally found in areas that were anoxic, but could provide suitable protection from inflowing turbidites. Two areas of enhanced laminite deposition were noted in Orkney. The first area was on the upthrown footwall of the ESF. The slow extension of the ESF meant that although the footwall was relatively uplifted (and so avoided turbidites), it was not uplifted to the extent that the depositional environment was overly oxygen rich (Figure 6-1). The second area was seen to be located at the northern splay of the ESF. It is thought that the throw of the ESF was declining northward at this point, and a transfer zone formed between the ESF and another graben bounding fault presumably to the north of the island of Sanday (Figure 6-1 & 6-6). The presence of the transfer zone would have modified many of the sedimentary processes that occurred in the northern area. One of these modifications would have been that the area would have been uplifted relatively to the depocentre to the south. The location would also have been suitably far north for turbidites, entering the basin from a channelised point source, to bypass the area entirely.

The results of the turbidite activity can be seen to the east of the ESF and in the south of Orkney (Figure 6-1). High concentrations of laminites are not deposited in these areas, although the hanging wall dip slope is commonly the main location of laminite formation. Instead, sand rich dark silts are deposited in these areas, together with enhanced thicknesses of other non-laminite, lacustrine facies. The average TOC for the non-laminite organic rich facies is 0.5% (Table 6-2). It is thought that rocks with a TOC lower than 0.5% cannot be source rocks (Allen & Allen 1990). This means that the sediments to the east of the ESF are at the limit of potential source rock quality.

6.3 The controls on the distribution and preservation of organic matter

Introduction

Detailed sedimentary logging allowed the Rousay Flagstone Formation to be constrained in a precise lithostratigraphic framework (Figure 2-1). Two lake units were sampled in detail across Orkney and selected samples were palynologically processed. This has allowed an in-depth investigation into how the quality and type of preserved organic matter changes across the exhumed remains of two Devonian half graben.

The first point to become obvious, was how did the preserved organic matter in the lake sediments become dominated by AOM (Section 4.24). Generally, over 90% of the organic matter is composed of AOM, the remainder being spores or woody material. The low numbers of well preserved palynomorphs led to difficulties in ascertaining absolute numbers and ratios of types present in the Orcadian lake at this time. Two methods of quantifying the palynomorph content of Rousay Flagstone Formation lake sediments were attempted. The first method attempted to measure the ratio of particulate AOM to spores in whole kerogen suspensions (Section 4.24). This method only highlighted the overwhelming dominance of AOM in these sediments, with any change being attributable to variation in AOM content rather than variation in spore content. The second method involved counting all the spores liberated from 1 gram of rock, after most of the AOM had been removed by ultrasonic disruption (Section 4.21). This provided figures of absolute spore numbers contained in the lake sediments.

The importance of the stratigraphic framework is that it revealed subtle trends in the organic matter distribution, which would never have been apparent from unconstrained sampling across Orkney.

6.31 The thermal maturity of the Rousay Flagstone Formation

An important result to come from the programme of sampling single lake cycles, is that there is no significant variation in thermal maturity across Orkney (Section 5.23). This shows that at no time was there sufficient movement on any of the Orcadian faults, to cause differential maturity regimes to form across Orkney. Thus, any observed trends in thermally sensitive geochemical indicators, such as TOC or H/C ratios, were caused by environmental and preservation related factors, rather than variations in burial history.

Exinite reflectivity figures for AOM rich sediments from the Rousay Flagstone show a range of values from 0.1 to 0.3 across Orkney (Figure 5-22). Exinite reflectivity values have been shown to be more variable than vitrinite (R_o) over the range of 0.5-1.5 R_o (Smith & Cook 1980). Therefore, exinite values can be converted directly to vitrinite values to establish the thermal maturity of the lacustrine sediments. Figure 6-8 is a cross-plot of exinite and vitrinite values from Devonian and other sources. It shows that the exinite reflectivity range in Orkney corresponds to a vitrinite reflectivity range of 0.5 - 0.7.

Vitrinite reflectivity (R_o) may be correlated with the main zones of hydrocarbon maturation. The generally accepted thresholds of petroleum generation from (Allen & Allen 1990) are as follows:

$R_o < 0.55$	Immature
$0.55 < R_o < 0.8$	Oil & gas generation
$0.8 < R_o < 1.0$	Cracking of oil to gas
$1.0 < R_o < 2.5$	Dry gas generation

It should be emphasised that the direct relationship between hydrocarbon generation and changes in vitrinite reflectivity are poorly understood. The 'thresholds' given should not be taken as absolutes.

In Section 5.23, it was suggested that the AOM rich sediments had experienced AOM suppression, leading to a reduction in exinite reflectivity. This means that the exinite reflectivity figures of 0.1 to 0.3 should be regarded as a minimum. However, exinite reflectivity figures from AOM poor, potentially oxidised sediment are also presented in Figure 5-22. These figures range from 0.49 to 0.58, which equates to an exinite range of 0.7 to 0.9. These figures may be regarded as a maximum for unaltered, Rousay Flagstone Formation, lacustrine sediments. Whichever set of figures are used, it is clear that the Middle Devonian source rocks of Orkney are mature for hydrocarbon generation. This supports the results of previous studies based on vitrinite reflectivity (Marshall *et al.* 1985). The fact that the lacustrine rocks of Orkney are mature is intuitively obvious because of the abundant bitumen impregnated sandstone common throughout Orkney (Astin 1990).

Spore colour as an indicator of thermal maturity is by its nature, less accurate than exinite reflectivity. However, the average SCI of the Rousay sediments was around 5 (Figure 5-22b). This equates, approximately of a vitrinite reflectivity of slightly below 0.7 (Hillier & Marshall 1992). This is within the maturity range defined by exinite reflectivity.

Thus, to summarise, the lacustrine source rocks of the Rousay Flagstone Formation are thermally mature for hydrocarbon generation. It is also clear that although there is a range of maturity values, that differential fault movement in the basin did not cause any variation in the burial histories of any of these sediments.

6.32 TOC and H/C variation across Orkney

Introduction

The two main geochemical parameters used to characterise kerogen variation in the Rousay Flagstone Formation were TOC content and atomic H/C ratio. TOC content is a measure of the amount of organic material contained within sediments, and is thus a measure of source rock richness. H/C ratios, a measure of the proportion of hydrogen and carbon, can indicate the type of kerogen being measured, if the thermal maturity is known. A limited number of O/C ratios were measured. This parameter is generally more useful in the characterisation of wood rich kerogen, by virtue of it's relative richness in oxygen.

The above geochemical indicators were used primarily to gauge environmental conditions, since other controlling factors could be seen as being constant. Firstly, thermal maturity is seen to be uniform across Orkney, so variations in maturation history as caused by fault movement did not alter the Devonian kerogen. Note also that reflected light microscopy has shown that kerogen type is relatively uniform Type I across Orkney, with AOM being the overwhelming component of the kerogen (see Section 4.24).

Note that the causes of variation in the geochemical parameters can be ambiguous. Thus, variations in H/C ratio could represent either variations in the palynomorph ratios in the kerogen. Alternatively, it could represent variation in the effectiveness of kerogen preservation, since oxidation of kerogen leads to a reduction in H/C ratio (as discussed in Section 5.4). Similarly, variation in TOC could be due to variation in the absolute bulk of organic matter being deposited in the lake, or variation in the effectiveness of kerogen preservation. Therefore as many factor as possible should be taken into consideration before interpretation of the geochemical parameters is made.

6.32i TOC and facies type

Both lake profiles (Figure 5-1 to 5-4) and facies graphs (Figures 5-33 and 5-34) show that there is a strong relationship between TOC content and facies type. Laminite facies have the highest average TOC of 1.55% and grey silt facies have the lowest average TOC of 0.3% (Table 6-2). Thus, TOC values tend to be highest in deeper water facies, towards the middle of the lacustrine phase, and lowest when shallow water facies are deposited, at the top and base of the lacustrine phase. This relationship is clearly related to the different depositional environments experienced by the various facies. Laminites have the highest TOC because they were deposited in an anoxic, low energy environment with little sediment input. According to most models of lacustrine deposition this would most probably have occurred in the most distal or deepest part of a lake, an environment well suited to the preservation of organic matter (Donovan 1975). Note however, that it was concluded above, that in Orkney, laminites tended to form in relatively uplifted areas away from the influence of turbidity currents, whereas the most distal areas of the lake tended to be foci for sand deposition. This difference between Orkney and existing lacustrine models, emphasises the usefulness of detailed sampling and logging in basin analysis. Average TOC progressively declines in the facies that were deposited in more oxic, higher energy and sediment rich environments (as defined in Section 3.1), such as dark silt, Wick and grey silt facies. These facies were probably deposited in areas more proximal to the margins of the lake, or in areas prone to sediment influx from turbidites.

Note that if the information from Tables 6-1 and 6-2 are considered together, it can be seen that 37% of each lake cycle contains sediments averaging 0.8% TOC, and 5% of each lake cycle contains sediments averaging 1.3% TOC.

Microfacies	**Average TOC (cycles 26 & 36)**
Laminite	1.55
Near laminite	1.05
Dark silt	0.65
Wick	0.6
Grey silt	0.3
All facies	**0.8**

Table 6-2. Average TOC from organic rich facies, cycles 26 and 36.

6.32ii TOC, H/C and facies type

The relationship between TOC and H/C ratios is less clear, mainly due to low numbers of H/C analysis made (Figure 5-36b). As outlined in Section 5.4, samples with low H/C values and low TOC values probably came from proximal or shallow areas of the basin, where the preservation potential of the organic matter was low. Samples with high H/C and TOC values probably came from deeper or more distal areas with abundant well preserved AOM. This theory is supported by Figure 5-36c, which shows that samples from deeper water microfacies have slightly higher H/C ratios than samples from shallower water facies. The H/C ratios for laminite facies were highest probably because they were richest in unoxidised AOM. The H/C ratios were lowest for dark silt and Wick microfacies because their kerogen is a mixture of AOM and terrestrial kerogen, and that these facies were exposed to more oxic, higher energy conditions.

6.32iii TOC and H/C, spatial variation

The distribution of high H/C ratios and high TOC values across Orkney are similar (Figure 6-2). The greatest values are found to the west of the ESF, and in the north east. The lowest values to the east of the ESF. This distribution is very similar to the distribution of laminite and near laminite facies (Figure 6-1). Since it has been shown that there is a link between TOC, H/C and environment of deposition (Figures 5-33b, 5-34b and 5-36c), the similarity between these factors and the distribution of laminites and near laminites is significant. It is clear that the environmental conditions that are needed to maximise TOC preservation and H/C ratios are the same conditions in which laminites form. Evidently, these conditions did not occur uniformly across Orkney. The evidence suggests that the ESF modified the geochemical aspects of the Rousay Flagstone Formation, in a similar way to how it modified the distribution of the lacustrine sediments.

One of the clearest trends, are the low values of TOC and H/C immediately to the east of the ESF (Figure 6-2). In theory, this location in the downthrown, hanging wall of a half graben should have the deepest water, highest anoxia and greatest organic matter preservation. However, as discussed in Section 6.31, the area immediately east of the ESF was prone to sediment influx from large terminal fans to the south and north and possibly footwall fans. The sand rich sediment would have been transferred from their source to the depths of the lake by dilute turbidity currents (Rogers & Astin 1991). These currents would also have introduced oxygen rich waters from above the thermocline, into the anoxic areas of the lake. This mechanism would explain several of the trends seen in the lacustrine sediments. The incoming sediment in the form of turbidity currents would have diluted the organic matter in the area to the east of the fault and thus reduced the TOC. The oxygenated water of the turbidity currents would have partially oxidised the organic matter, reducing the H/C ratios. Huc et al. (1990) noted this effect in Lake Tanganyika where density currents introducing clastics into the deeper areas of the lake were seen to reduce the TOC of the sediments.

The highest TOC and H/C values are found to the west of the ESF and in the north east (Figure 6-2). This location is very similar to the location of where most laminite facies occur (Figure 6-1). The same mechanism is thought to account for both of the trends. The areas containing high TOC and H/C values may be relatively uplifted compared to the main depocentre to the east of the ESF (Figure 6-6). This would have meant that turbidity currents would not have deposited sediment or introduced oxygenated water into these areas. Alternatively, fault compartmentalisation may have caused sediment to be come ponded in specific areas of the basin.

A notable variation between the trends of laminite distribution and TOC-H/C variation occurs in the south of the area. Hoxa Head in the south west records high H/C ratios (Figure 5-23a) but low TOC (Figure 5-21) and low laminite occurrence (Figure 5-10c). This trend may have arisen because both Hoxa Head and Halcro Head (which was not analysed for H/C) contained very high quantities of spores (Figure 5-20 and 5-4). Additionally note from Figures 6-1 and 6-3 that these locations are rich in coarse sediment and sandy dark silt. Thus, what may have been happening in South Ronaldsay is that large numbers of spores from the south (see later) had produced a high H/C ratio, but yet the sand rich environment did not favour the formation of laminites. Sand dilution would not overly effect H/C ratios, because they are a figure relating to the kerogen within a sediment, rather than a figure relation to the whole sediment (as TOC is). Therefore the AOM poor, low TOC kerogen in the south of the islands was augmented by increased spore numbers from the south.

Thus, TOC and H/C distribution are controlled by the same processes that effected the lacustrine facies generally. The maximisation of TOC and H/C seems to be a compromise between water deep enough to be anoxic, and isolated enough to avoid the detrimental effects of oxygen rich turbidites.

Two sets of O/C and H/C analysis were run for the kerogen isolated from Surrigarth and Evie (both cycle 26). This enabled Van Krevelen diagrams and a modification of the TOC profiles to be produced (Figures 5-1 to 5-4). The Van Krevelen diagrams (Figure 5-39) generally were, as would be expected, considering the other geochemical data already produced. Both samples were in or close to the zone on hydrocarbon generation and the samples were either type II or a mixture of type I and II kerogen. These results had already been given by exinite reflectivity studies and transmitted light palynology. What was unusual about the Van Krevelen diagram for Evie (Figure 5-39a) was a cluster of values of average H/C ratio but of very high O/C. Figure 5-

40c, shows that in Evie, the samples with high O/C ratios were associated with shallower water facies that the other samples. The unsatisfactory explanation to this trend must be that a component of the kerogen in the samples, had an H/C ratio similar to type I or II kerogen, but had a greatly increased oxygen content.

A general point to note from Figure 5-40 is that O/C ratios are far more sensitive to facies change than H/C ratios are. This must be a factor of the overwhelming dominance of AOM in the kerogen of these locations, acting as a buffer to variation in H/C. Conversely any addition of oxygen rich palynomorphs would have caused changes to the oxygen poor kerogen.

6.33 Spore variation across Orkney

The lithostratigraphic framework was used to study several aspects of spores from the Rousay Flagstone Formation. The two main ones were the absolute numbers of spores contained within the lake sediments and the variation in diameter of *Rhabdosporites langii*, a common Devonian spore. The procedures used are described in 4.21 and 4.22.

6.33i Spore number variation

The variation in spore number across Orkney is presented as numbers of spores per gram of rock, for various locations from cycles 26 and 36. This was done by palynologically processing 1 gram of rock and removing all the AOM by ultrasonic disruption. In this way, the actual numbers of spores present in the sediment could be counted directly (see section 4.21), producing an *absolute* number of spore per gram for each sample. Several samples from each location were processed in this way and the highest count encountered was used in the map representation of the data (Figure 5-20a&b). What is clear from the data is that comparatively low numbers of spores were found in the lacustrine sediments of Orkney (Figures 5-1 to 5-4).

One way of quantifying spore distribution in Orkney, was to show the maximum number of spores counted from each location (Figure 5-20 a and b and summarised in Figure 6-2). Both cycle 26 and 36 show similar trends of maximum numbers of spores occurring in the north and south of the area, with reduced numbers in central and eastern parts. It is also apparent that the highest numbers of spores are found to the west of the ESF. Thus, the distribution of spores (Figures 6-2 and 5-20) is similar in nature to the distribution of TOC, H/C ratios and laminite facies (Figures 6-1 and 6-2). Unlike AOM, which forms *in situ*, spores generally have to be transported before they are incorporated into lacustrine source rocks. In modern semi-arid environments fluvial systems are the main mechanisms for long to medium distance spore transport (Streel & Richelot 1994).

Spores due to their buoyant nature are generally carried as suspended load within the water column, carried along with the fine silt and clay grade sediments (Holmes 1994). This means that when spores were introduced into the Orcadian lake, they were probably incorporated in inter- or overflow currents (Figure 6.7) rather than underflow currents that carried coarser sediments. This would mean that spore distribution would not be as effected by lake bottom topography, as sand dispersal would. This would mean that the uplifted footwall of the ESF probably did not influence the distribution of spores significantly. However, it is known that spores drop out of suspension when fluvial currents rapidly lose velocity after entering a lake, meaning that within a lacustrine setting, more spores tend to be found close to points of fluvial input (Holmes 1994). It follows that the Orcadian river systems as shown by palaeocurrent data, will have influenced the distribution of spores in the Rousay Flagstone Formation. This is shown as the main accumulations of spores in the northeast, northwest and in the south, corresponds with the main palaeocurrent trends in Orkney which indicate flow from the south, north west and north east (Figure 5-28).

An additional factor will have effected the eventual numbers of spores isolated from the source rock, that of preservation. In previous sections, the influx of dilute turbidites has been invoked as a mechanism that reduced TOC and H/C values as well as limiting the formation of laminite facies. Clearly, if the oxygenated water introduced by turbidites degraded the kerogen enough to reduce TOC values, the oxygen would also have had a detrimental effect on the preservation of the spores contained within the sediment.

6.33ii Spore diameter

It is known that fluvial transport can have a sorting effect on spores of different sizes (Holmes 1994), where larger diameter spores are found closer to sites of fluvial input, than in more distal settings. Thus, spore diameter variation is another parameter that could provide insight into environmental conditions during Rousay Flagstone Formation times. The spore *Rhabdosporites langii* has a natural variation in diameter from between 50 and 200 μm and is common in the Middle Devonian lacustrine sediments of Orkney. For every slide prepared for absolute spore counting, the diameters of around 20 specimens of *R. langii* were measured. These diameters were averaged for each site and plotted on Figure

5-23b & 6-2. The main trends to be visible from this map are that the largest spores are found in the north east and south of Orkney, however these changes are in the order of 10 microns. When the errors inherent in the measuring process are accounted for, these variations are not significant. More significantly it can be seen that the largest change in spore diameters occurs in the in the south of the area, between cycle 26 and 36. What is seen is that spore diameters increase upwards. What this could imply is that the source of fluvial input in the south prograded further into the basin in cycle 36 than it did in cycle 26, suggesting that the environment was drier during late Rousay Flagstone Formation times. As to why the increasing aridity did not effect the fluvial sources to the north west and north east is unclear. This point is addressed in context in Section 6.5.

6.33iii Spore numbers versus TOC and H/C

A series of graphs were plotted showing the relationship between abspore (absolute spore numbers) and other parameters such as microfacies type, TOC and H/C. The key trends and conclusions from these graphs are presented in Section 5.4, but will be reiterated in this section.

There is a relationship between TOC and spore numbers that is linked to depositional environment. It can be seen that in both sampled cycles (Figures 5.33a & 5-34a), TOC and spore numbers increase up to a value of between 1 and 1.7% TOC. If an environmental mechanism is envisaged for this change, it would represent the change from a proximal to a moderately distal lacustrine environment. This would be because in the most proximal environments, neither TOC nor spore preservation would be high because of the reduced anoxia in the shallow water environment. With progressively more distal and deep settings, anoxia would increase and depositional energy would decrease producing conditions ideal for the deposition and preservation of spores and the accumulation of high TOCs. With TOC values above 1 to 1.7%, the numbers of spores declines almost to zero. This could represent environments so distal that spores transported by fluvial currents have already dropped out of suspension. However, conditions in this distal part of the lake would be ideal for the accumulation of high organic carbon contents, in the form of AOM rich kerogen.

The distribution of spores with respect to microfacies (Figures 5-33c and 5-34c) supports this trend. In both graphs, maximum spore numbers are found in the dark silt facies. Dark silt facies are known to represent intermediate lacustrine environments, between laminite and Wick type facies (Section 3). Thus, it is logical that the facies deposited in this environment would have greatest numbers of spores for the same reasons that the intermediate TOC values of Figures 5-33a and 5-34a also has high spore numbers.

Although little data is available, the plot of abspore and H/C (Figure 5-36a) suggests a positive relationship between the two variables. As stated in Section 5.4, it is certainly not a causal relationship, rather it reflects the fact that larger numbers of spores are found in the same areas as high H/C ratios (Figure 6-2). More data relating H/C to spore numbers is needed before anything definite can be said about this trend

What is clear from these results is that across Orkney there are very definite areas of enhanced preservation potential, where spores are most numerous, TOC's and H/C's are higher and laminites tend to form. There areas are located to the west of the ESF and in the northeast, seem to be controlled by position relative to active faults and position relative to fluvial input.

6.33iv Profiles

The lake profiles (Figures 5-1 to 5-4) represent the most detailed analysis of spore distribution with respect to facies type in this thesis. However, it can be seen from Figures 5-1 to 5-4 that the lake profiles were not sampled for spore content (abspore) in a rigorous manner. The rock samples were taken to provide information on basin wide trends, not to describe detailed sedimentological variation. Thus, the trends seen in these profiles must be regarded in the most general of terms.

The profiles show a trend for greater numbers of spores to be found in deeper water facies to the west of the ESF (as illustrated in Figure 5-5). Conversely, in the south of Orkney and to the east of the ESF more spores are found in shallower water facies. This change is not related to variation between lake cycles 26 and 36 because the trend is found equally in both cycles. It can be shown that the change in numbers of spores with respect to facies type is related to preservational effects and distance from source.

In modern semi-arid environments fluvial systems are the main mechanisms for long to medium distance spore transport (Streel & Richelot 1994). It follows that the Orcadian river systems as shown by palaeocurrent data, will have influenced the distribution of spores in the Rousay Flagstone Formation. The main palaeocurrent trends in Orkney indicate flow from the south, north west and north east.

It seems that the upthrown footwall of the ESF influenced the distribution of the spores (Figure 5-5) in a similar way to how it influenced the distribution of laminite facies (Figure 6-1). A possible mechanism that could explain this trend is that because the north west of the area was uplifted relatively to the east, it experienced less permanent water cover. This is supported by Figures 5-31c, which shows that emergent megafacies are more common to the west of the ESF. Due to proximity to source in this area, as indicated by pebble clast analysis (Figure 3-3), there should be no shortage of spores in the north of Orkney. This suggests that preservation must be the main control on the numbers of spores observed. Thus, the fact that lower numbers spores in the north west of Orkney are found in shallow water facies, suggests that the relatively uplifted, emergent environment was not suited for the preservation of large numbers of spores. More spores were preserved in the deeper water facies presumably because less oxygen was present.

To the east of the ESF, a different distribution of spore numbers is present. In the north east, most locations show that most spores are found in shallower water facies. Further to the south very low numbers of spores are found in all facies. In contrast to the west of the ESF, the area to the east is relatively downthrown, has a lower proportion of emergent megafacies (Figure 5-31c) and has a fluvial source to the north east and north west (Figure 5-28). A possible explanation for this trend could be related to water level and proximity to source. When the water level in the lake was low, rivers from the north east would prograde into the basin and deposit spores in high numbers in the shallow, yet anoxic sediments to the east of the ESF. During high water levels, when the deep water sediments were being deposited, the rivers would be discharging their suspended spore load at some point further to the north east, closer to the lakes margin. This would mean that the deep water sediments would have relatively fewer spores. This trend has been observed in modern lakes (Holmes 1994). Beyond a certain point, all rivers flowing into the basin will have lost most of their suspended load of spores. Basinward of this point, few spores will be deposited in the sediment. This accounts for the low numbers of spores from all facies found in the central part of the basin.

Three locations in the central, eastern part of Orkney yielded very low numbers of spores. This is consistent with the mechanisms described above, because the main fluvial sources to the basin were located to the south, north west and north east. This would mean the central eastern area of the basin would the most distal part of the basin. Thus, most spore deposition occurred in shallower water lacustrine facies around the margins of the lake. It fits the model of kerogen distribution, that this most distal part of the Orcadian lake would have received least spores.

Three locations in Orkney (North Faray 36, Hoxa Head 36 and Halcro Head 26) do not agree with the general trends relating spore numbers to facies types, outlined above, having high numbers of preserved spores. Although no definite explanation for these trends can be given, it can be speculated upon, that some virtue of the geography of these locations, made them prone to spore accumulation.

However, as stated previously, due to the sampling procedures involved, these profiles are inherently flawed as a detailed indicator of small scale kerogen variation. Potential mechanisms that could account for these variations in trends could be speculated upon, for no real benefit.

6.34 Synthesis of the distribution and preservation of organic matter

The first point of note about the preserved organic matter of the Rousay Flagstone Formation, is its limited variety. The vast majority of kerogen identified by transmitted light microscopy was AOM. The bulk of the rest of the kerogen was composed of spores of varying degrees of preservation. A minor percentage of woody material was also present. Although the high proportion of oil prone AOM in the kerogen could be good for potential hydrocarbon production, the lack of notable palynomorphs limited what analysis could be carried out on the kerogen samples. Exinite reflectivity and spore colour analysis shows that the kerogen of the Rousay Flagstone Formation is thermally mature and should be currently generating hydrocarbons (Figure 5-22).

The main result from approximately 200 TOC analysis is that the average TOC of the lacustrine facies of the Rousay Flagstone Formation in 0.8% (Table 6.2). Laminite facies have the highest TOC of 1.55% and grey silt facies have the lowest TOC of 0.3%. Clearly, the variation in TOC is related directly to depositional environment, with the highest TOC content being found in the more anoxic environments and less TOC being found in more proximal, higher energy facies (Figure 5-33b & 5-34b). Around 30 H/C analysis were made from cycle 26, giving an average of 1.1 (Figure 5-36). Limited data suggests that higher H/C values are associated with low energy anoxic facies.

Correlations between spore numbers and facies types suggest that the greatest numbers of spores are found in intermediate type lacustrine facies – namely 'dark silts'. It is suggested that this facies provides the best depositional compromise between oxygen rich proximal facies, which would be closer to the source of the spores, but would have a lower chance of preservation. Or anoxic, distal facies (Figures 5-33b & 5-34b), which would have the preservation potential, but would not have the supply of spores. The fact that maximum numbers of spores are found associated with intermediate TOC values (which equate to intermediate type facies), support this observation (Figure 5-33a & 5-34b).

Spatially the highest TOC and H/C values corresponded to areas of enhanced laminite deposition (Figure 6-1 and 6-2). These areas are to the west of the ESF and in the north east of Orkney. Both of these locations were uplifted relative to the rest of the basin during the lacustrine phase of deposition in the lake cycles. The area to the west of the ESF was raised because it was the footwall of an actively extending half graben, and the area to the north east was uplifted because it was associated with a transfer zone. The merit of deposition on areas of relative uplift was that sediment bearing, oxygen rich turbidity currents tended to bypass these areas. Downthrown areas, especially to the east of the ESF experienced common inundation by these currents and consequently experienced reduced TOC and H/C values.

High spore numbers are found in the same locations as high TOC and H/C values (Figure 6-2). Spores were introduced into the basin by currents from the south, north east and north west, and were found in greatest numbers where preservation potential was highest, as indicated by high TOC and H/C values. In other areas, it is thought that oxygenated bottom currents degraded the spores. Spore diameters were an accurate indication of source of fluvial input, with the largest spores being found in the south and north east of the area.

6. 4 Distribution of fluvially dominated sediments

This thesis is primarily concerned with the distribution of the lacustrine sediments and the kerogen contained therein, throughout Orkney. Additionally, the process of gathering field data produced a great deal of information pertaining to the fluvially dominated sediments of the Rousay Flagstone Formation. These lithologies (sheetfloods, wavy sandstone and silts etc) typically make up on average 60% of a typical Rousay Flagstone Formation lake cycle (Table 6-1). However, since the clastic component of the lake cycles is not the primary concern of this thesis they were not studied in detail. Thus, the following description of the clastic lithologies of the Rousay Flagstone Formation is correspondingly brief. A summary of the main trends seen in the fluvial facies is presented in Figure 6-3. There are clearly three main areas of enhanced fluvial deposition. One occurs in the far south and two in the north, approximately east and west of the ESF. A fourth location may be the Head of Work, where an accumulation of sand rich facies occurs.

As is discussed in Section 3 most non-lacustrine sedimentation within the Rousay Flagstone Formation can be attributed to sedimentation by terminal fans. The various styles of fluvial deposition relate to where on the terminal fan the sediments were deposited. Palaeocurrent maps (Figure 5-28) suggest the presence of at least three sources of terminal fan progradation. These are from the south or south west, from the west or north west and from the north east. This agrees with the work of Astin (1985 & 1990) who suggested the presence of three fans during upper Rousay Flagstone Formation and Lower Eday Group times. Thus, the three main areas of sand deposition can be attributed to the progradation of three terminal fans towards the centre of what is now Orkney. The occurrence of the coarse sandstone (Figure 5-19 & 6-3) gives an indication of the proximal/distal relationship between the terminal fans and the basin. Most of the coarsest sediment occurs at the point closest to where the fans would enter the basin, according to the palaeocurrent data. Additionally, a clast size distribution plot (Figure 3-3) shows a clear decline in clast size away from the north west.

The fourth location of enhanced sand deposition (the Head of Work) could be the location of a footwall fan. The reasons for this are firstly its remoteness from the other centres of sand deposition suggest another mechanism for its formation. Secondly, if as discussed before, the throw of the fault was decreasing northwards towards the splay, the location at the Head of Work, may represent the ESF exhibiting its greatest throw. If this was the case the fault may have breached the surface, and its footwall would have been liable to erosion, which would have formed the footwall fan. However, other than its location within the basin, there is no evidence that a footwall fan formed in this or any other location in Orkney.

As stated at the start of this section, most non-lacustrine sediments in the Rousay Flagstone Formation are thought to be the products of several prograding terminal fans. A comparison of the summary map (Figure 6-3) and the established model of terminal fan deposition (Figure 3-2) (Kelly & Olsen 1993), shows that from the information available, there is a good correlation. The model proposes that close to the point of inception sediments will be coarser and be dominated by channel sands and sheetfloods. Progressing away from this point sands will become finer and channels and sheetfloods will become less common. With increasing distality playa type sediments, silts and mudflats will become more common. The Orcadian fluvial sediments behave in such a manner as to suggest that this is what the depositional regime was during the Rousay Flagstone Formation.

The effect of faults on fluvial sedimentation

In sedimentological studies of the Lower Eday Sandstone (Astin 1985), the fault control on fluvial and aeolian sedimentation is obvious. Field logging has shown thick accumulations of aeolian sands and conglomerates on the hanging wall slope immediately east of the ESF. Thus, it is clear that at this time, the ESF was extending significantly, providing the accommodation space necessary for enhanced thicknesses of sediment to accumulate in the downthrown hanging wall area.

This trend is present in the Rousay Flagstone Formation but is less pronounced. It can be seen that for the duration of the Rousay Flagstone Formation 1 to 2 m more fluvial megafacies were deposited to the east of the ESF (Figure 5-29). This effect can also be seen in the sheetflood and sand rich facies thickness trends (Figures 5-18 and 5-16). The thickness change across the ESF is not restricted to fluvial megafacies alone, it can be seen that lacustrine megafacies are in addition, considerably thicker to the east of the ESF (Figure 5-29b).

In summary, the effect of fault motion on the distribution of fluvial sediments in the Rousay Flagstone Formation is subtle. Gradual, persistent fault movement during this time has meant that there is a uniform increase in most facies types in the hanging wall of the half graben. This contrasts with the rapid accumulation of aeolian sediments in Lower Eday Sandstone times.

6.5 A changing environment

As well as lateral changes, the use of the lithostratigraphic framework has given insight into how conditions changed over the duration of the Rousay Flagstone Formation. Several features of the Rousay Flagstone Formation can be seen to be changing progressively upward through time. Lake cycle thickness declines progressively from cycle 24 to cycle 36 (Figure 5-29a, 5-30a) both to the east and west of the ESF. There also is an increase in the proportion of fluvial megafacies (5-31a) towards the top of the Rousay Flagstone Formation.

Additionally factors can be seen to change between the two sampled cycles. Firstly, there is a universal decline in average TOC within all of the lake facies between cycle 26 and 36 (Figure 5-35). Secondly, the average size of *Rhabdosporites langii* is seen to increase between cycle 26 and 36 (5-23b). These four factors may be interpreted as an indication that the Orcadian lakes were contracting in size – reduced lake thickness, reduced TOC, increased fluvial input and indication of greater proximity to source areas as indicated by larger spores (Holmes 1994). Progressive climate change towards a dryer environment is a mechanism that can realistically explain these variations in the sedimentary record. This interpretation is in agreement with the work of Astin (1990) who also suggested drier conditions towards the top of the Rousay Flagstone Formation.

Recent work by J. Marshall (*pers. comm.*) has shown the simultaneous appearance of the same suite of spore species in Orkney and Greenland at the start of Eday Flagstone Fm. times (Figure 1-2). This is compelling evidence towards the notion that the main sedimentological variations in the greater Orcadian Basin (i.e. the change between flagstone and sandstone deposition) were caused by large scale climatic variation, rather than localised tectonic change. In other words, localised tectonism could not have caused basin wide environmental conditions to change to the extent that similar flora occur at the same time across a range of several hundred kilometres.

Another temporal change that may have occurred in Orkney was that the rate of fault movement increased towards the top of the Rousay Flagstone Formation. The most significant indication of this is the presence of the Sacquoy Sandstone Member (Section 3.1). This unit of pebbly fluvial sandstone occurs in cycle 35 of the Rousay Flagstone Formation. Although similar pebbly units occur in overlying Rousay Flagstone cycles on the islands of Eday, Westray and Sanday, the Sacquoy Sandstone Member is the coarsest sediment seen in the lowermost 600m of the Orkney Flagstone Group. Clast composition and palaeocurrent information (Figure 5-28c), together with geophysical information

(Astin 1990)(Figure 3-4) suggest the source of the Sacquoy Sandstone Member was a ridge of exposed metamorphic basement located to the north west of Westray. Pebble clast size distribution (Figure 3-3) and palaeocurrent information (Figure 5-28) support the view of Astin (1990), that the sandstone was distributed in a south easterly direction across Orkney by an alluvial fan located to the north west of Westray. Thus, it is proposed that during the upper part of the Rousay Flagstone Formation increased fault movement in the half graben to the north west of Orkney revealed the metamorphic basement of the area. Erosion associated with this uplift caused clasts of the basement to be dispersed to the south east across Orkney by alluvial fans.

Variation in palaeocurrent direction also suggests this period of footwall uplift in the latter half of the Rousay Flagstone Formation. Palaeocurrent directions in the north west of Orkney change from predominantly eastward flow in the lower half of the Rousay Flagstone Formation to south east flow in the upper half of the Rousay Flagstone Formation (Figures 5-28b and 5-28c). This change could have been caused by movement on the northern extension of the West Mainland Fault, which deflected eastward current flow towards the south east. This suggestion refines the theory of Astin (1990), who suggested that an area of exposed basement to the west of Rousay channelled sands in the form of a terminal fan eastward across Rousay and Eday. The greater spread of palaeocurrent data in this thesis and the discovery of the Sacquoy Sandstone Member in Westray, suggest that the exposed area of basement also occurred to the west of Westray. Thus, palaeocurrent data and clast distribution patterns suggest that a fault or faults to the north west of Orkney became active or increased their rate of movement during the upper part of the Rousay Flagstone Formation.

It is uncertain whether the East Scapa Fault actually breached the surface during this time. No examples of exposed footwall scarps were found, and there is little indication of fluvial incision into underlying sediments. Had the ESF been exposed, an increase in clast size would perhaps been expected immediately to the east of the fault, indicating a local provenance of the clasts. This trend is not seen, and the large clasts seen in Fers Ness, west Eday can be seen to be a continuation of the clast distribution trend from the north west.

The accumulation of sand in the Head of Work and Eday locations (Figures 6-3 and 5-16), does suggest that some sand may have been sourced from the footwall scarp (Figure 6-4) of the ESF. What can be said is that basement was not exposed, since no metamorphic clasts could be attributed to this fault.

Thus, it appears that there were two different outcomes of fault movement in this area of the Orcadian Basin. To the north west of Orkney footwall uplift caused metamorphic basement to be exposed and a pebbly sandstone unit to be produced. However, in the area associated with the ESF, it is uncertain whether the fault breached the surface, and definitely, no basement was exposed.

Two mechanisms could account for these different outcomes. Firstly the two styles of fault movement could indicate that fault to the north east of Orkney was extending more than the ESF i.e. different rates of fault movement were occurring across the basin. Alternatively, it is know that the Devonian lacustrine sequences are a lot thinner in areas with shallower basements (Donovan 1975). This would mean that a lesser amount of footwall uplift would be needed to expose basement in more proximal areas of the basin. Both of these mechanisms may have contributed to the sedimentary architecture of the Orcadian Basin. It would be impossible to say categorically what caused the observed differences.

The pulse of enhanced fault movement was short lived as shown by the resumption of predominantly lacustrine conditions for three or four cycles above the Sacquoy Sandstone Member. This return to lacustrine conditions did not last long, because above these cycles, the Lower Eday Sandstone (Figure 1-2) was deposited, marking the start of an extended period of predominantly fluvial and aeolian deposition (Mykura 1976). Since the Lower Eday Sandstone frequently contains conglomeratic material it is suggested that both enhanced footwall movement and an increasingly arid environment contributed to the formation of this unit (Astin 1985, Marshall 1996).

6.6 Palaeoenvironmental reconstruction

This section presents a viable model of the processes that were operating in Orkney during Rousay Flagstone Formation times. By using the disciplines of structural geology, sedimentology and geochemistry, a picture of how the various processes that were operating in the basin interacted to produce the rock formations we see today.

The Orcadian landscape at this time was composed of permanent and semi-permanent lakes that existed over a series of half graben formed by the collapse of the Caledonian orogen. The mid Devonian climate varied between two extremes. In one extreme the environment was wet enough to extend a large lake beyond the extent of present day Orkney, in which numerous flora and fauna existed. Conversely, the climate could be so arid that playa lake conditions predominated in which gypsum commonly crystallised, and the predominant sedimentary facies were sheetfloods and fluvial channels. These climatic changes are represented by the change from silt dominated to sand dominated deposition in every lake cycle.

The lithological record clearly shows that this variation in climate was cyclic, for the duration of much of the Middle Devonian. It is thought that each approximately 11m thick wet to dry cycle represented planetary orbital cyclicity on the scale of 123,000 years. However, it is now evident that the underlying tectonic pattern of Orkney influenced and modified the effects of this cyclicity, causing localised variations in the sedimentary record of Orkney.

Two models are presented to illustrate the palaeoenvironment of the Rousay Flagstone Formation during the two extremes of environment. Figure 6-9 represents sedimentation in the lacustrine dominated wet phase of the cycle and Figure 6-10 represents sedimentation in the fluvial dominated dry phase of the cycle. These models complement the following discussion.

It has been shown that a main north-south trending half graben bounding fault, called the East Scapa Fault (ESF), was slowly extending for the duration of the Rousay Flagstone Formation. Lack of exposure makes it unclear whether other faults in the area were extending in a similar manner during this time. The topographic expression of this fault appears to have had a controlling effect on the types of facies deposited in the half graben, and ultimately the kerogen quality of the lacustrine source rocks. The main effect that the fault had was to influence the distribution of laminites across Orkney (Figure 6-9). It is thought that the topographic expression of the fault and its northern splay removed the areas of laminite deposition from the effects of oxygen rich, turbidity currents. The areas of laminite deposition on the upthrown footwall of the fault and on its splay in the north were characterised by high TOC and H/C values. The focus of the deposition of the turbidity currents was immediately to the east of the ESF. The sediments in this area are characterised by high sand content, low TOC and H/C values and little laminite deposition.

The composition of the organic matter contained in the Rousay Flagstone Formation sediments was monotonous, with by far the most common palynomorph being AOM. However, variations in the numbers of spores present in the organic matter were notable. The highest numbers of spores were associated with areas of fluvial input, and areas of enhanced organic matter preservation. This meant that most spores were found in the areas of highest TOC and H/C values and most laminite deposition – to the west of the ESF and close to the fault's northern splay. This is because conditions immediately to the east of the ESF were dominated by turbidity currents. The oxygenated water introduced by these currents would reduce the preservation potential of that area, causing that fewer spores to be preserved.

There were three main areas of fluvial input into the basin, all of which have been seen to persist into at least Lower Eday Sandstone times. The sources were to the south, the northeast and northwest. The sources to the south and northeast acted as conduits for sediment and spores for the duration of the Rousay Flagstone Formation (Figure 6-10). Spore diameter variation suggests that the source to the northwest was not close to the source of the spores in that area. However, the Sacquoy Sandstone Member originated from the northwest, and it represents by far the coarsest sediments seen in the Rousay Flagstone Formation. Thus, it seems that although the fluvial source to the north west of Orkney is proximal to the source of the Sacquoy Sandstone, it is distal to the source of the spores in Orkney.

It is thought that environmental conditions got progressively dryer towards the top of the Rousay Flagstone Formation. This trend is supported by sedimentological and palynological data, shows the gradual change from wet conditions characterising the Orkney Flagstone Group, to the dryer conditions of the Eday Sandstone Formation. The mechanism for this change in environment is thought to be planetary controlled climatic variation.

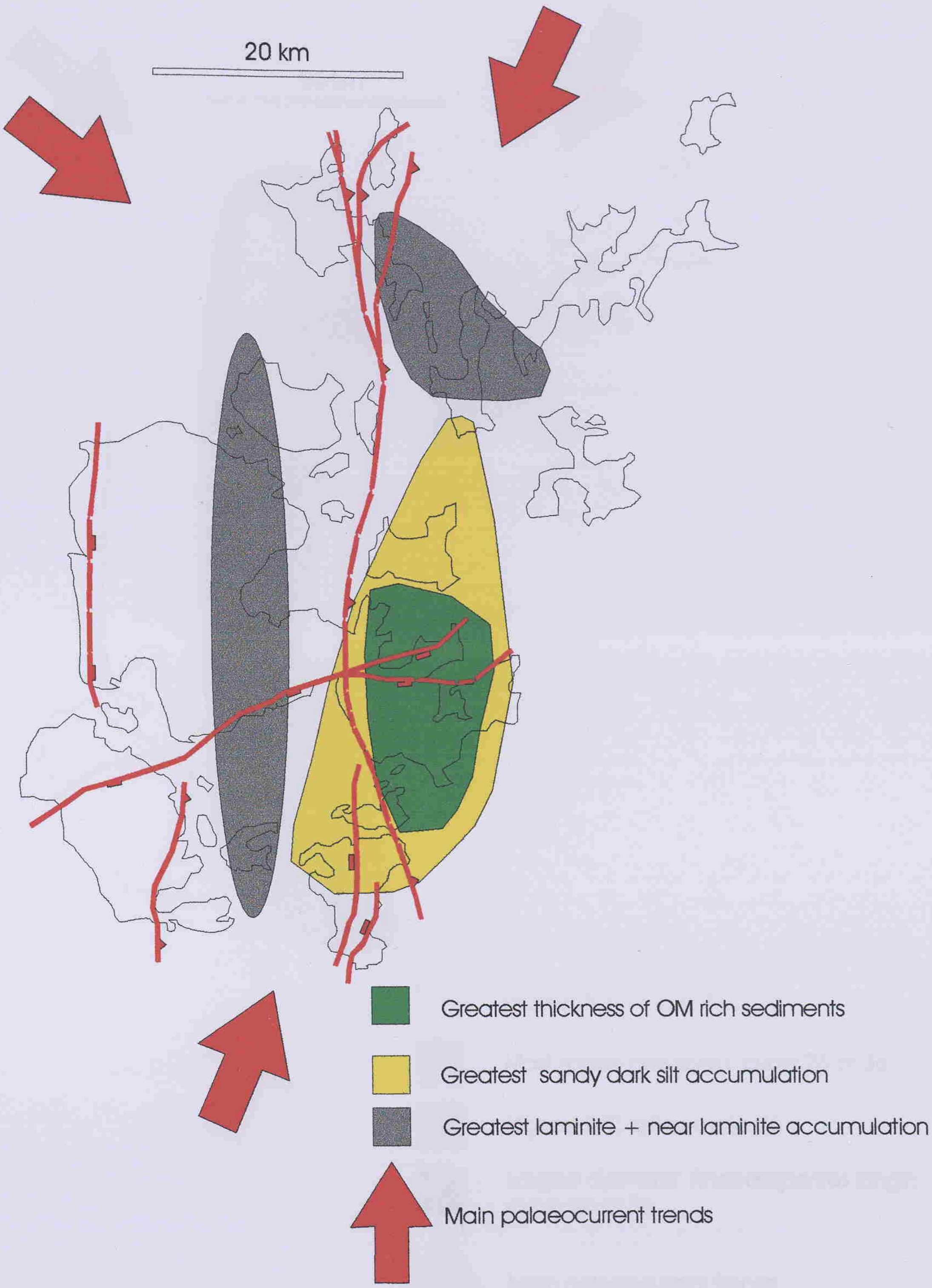


Figure 6-1. Main trends relating to lacustrine phase deposition in the Rousay Flagstone Formation.

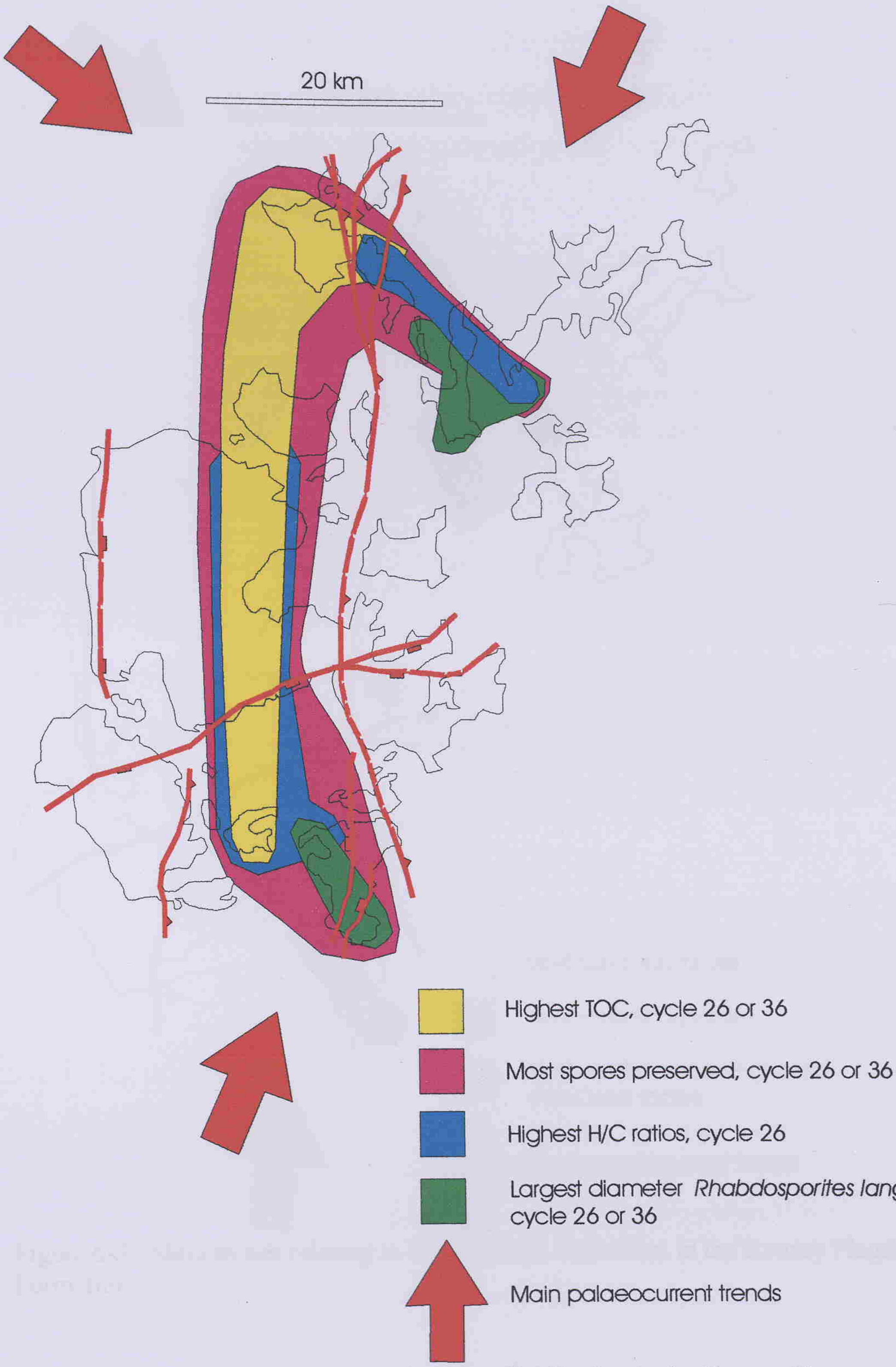


Figure 6-2. Main trends relating to kerogen distribution in the Rousay Flagstone Formation.

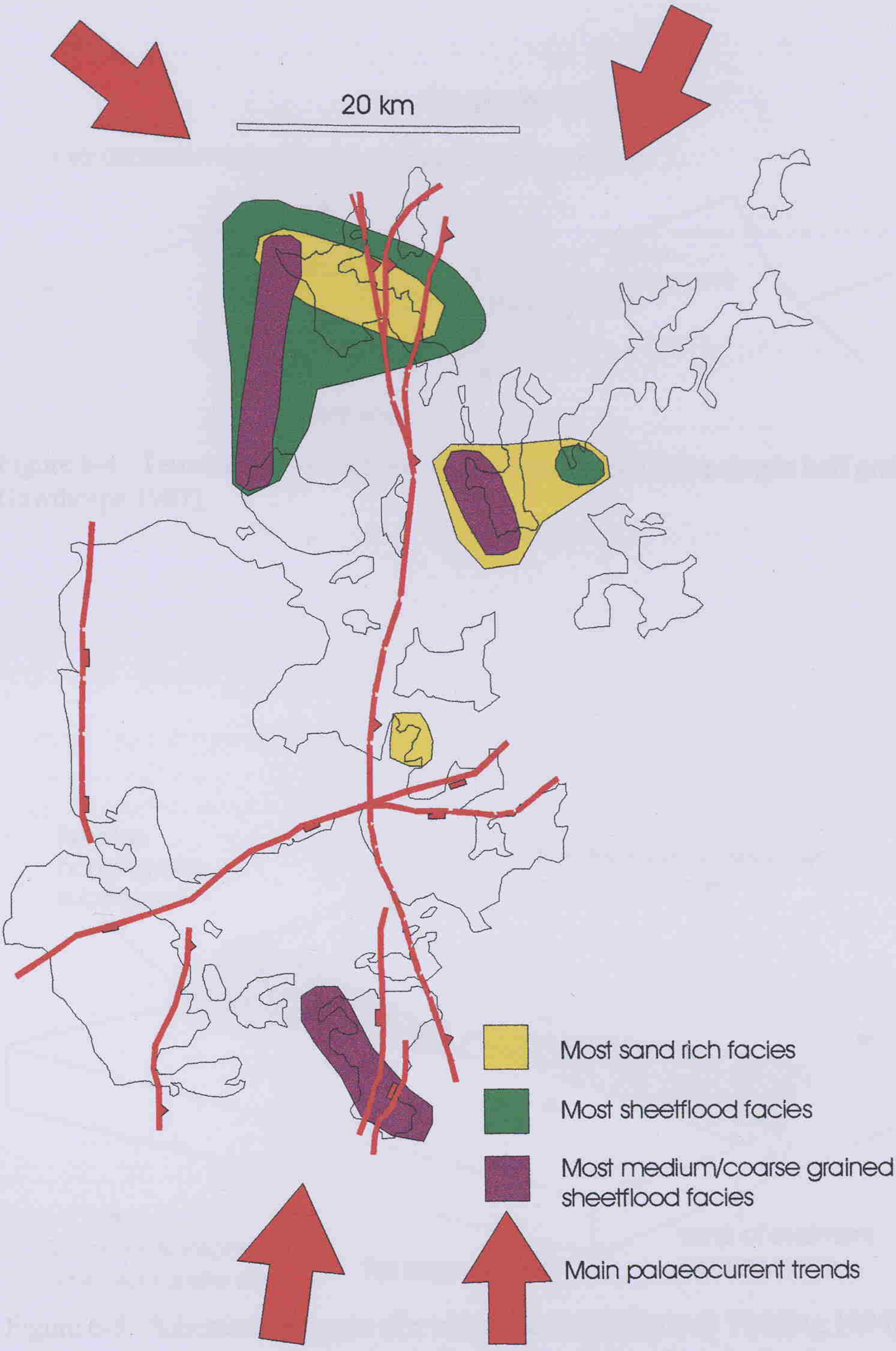


Figure 6-3. Main trends relating to fluvial phase deposition in the Rousay Flagstone Formation.

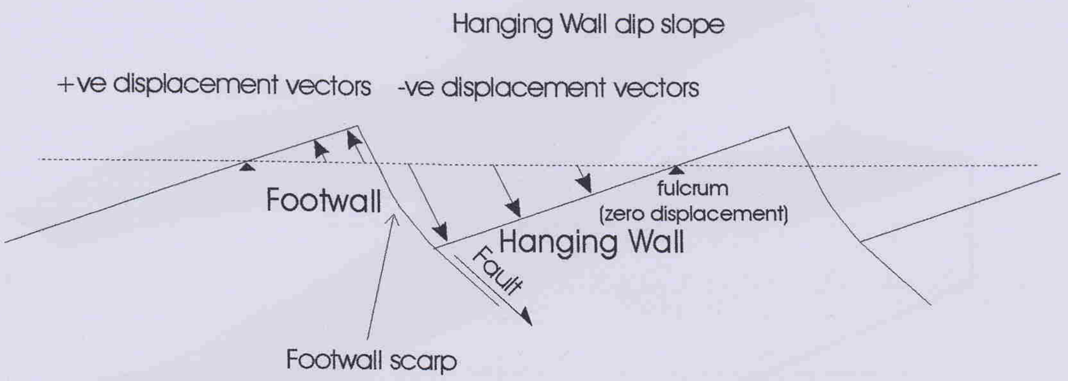


Figure 6-4. Terminology of tectonic slopes, associated with a simple half graben (Leeder & Gawthorpe 1987).

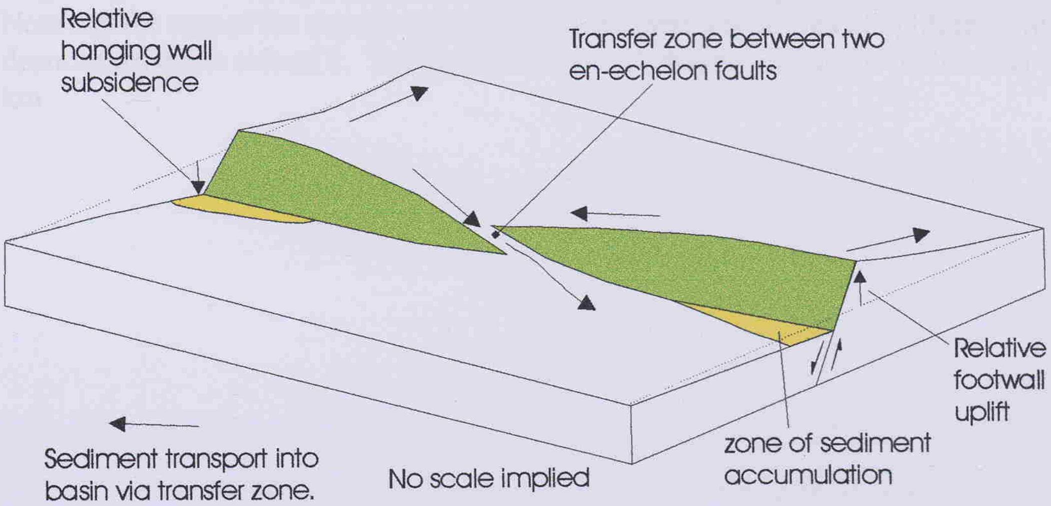


Figure 6-5. Schematic diagram of a transfer zone (Roberts & Yielding 1994).

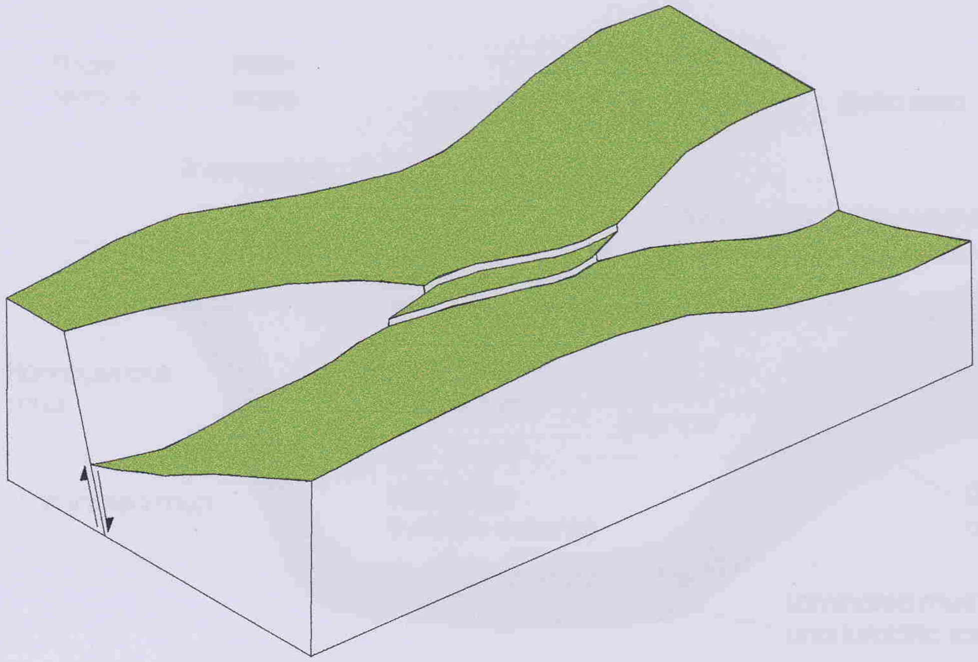


Figure 6-6. Diagrammatic representation of a synthetic relay ramp (Gawthorpe & Hurst 1993), which is a possible model for the structure of northern Orkney. In this view, the ESF would be coming in from the left, the island of Westray would occur in the centre of the diagram (across the splays) and the fault coming in from the right would be north of Sanday. Note that the area of the transfer zone itself (in the centre) is an area of uplift relative to the depocentres either side of it. The length of the block diagram would be in the order of 20-40 km.

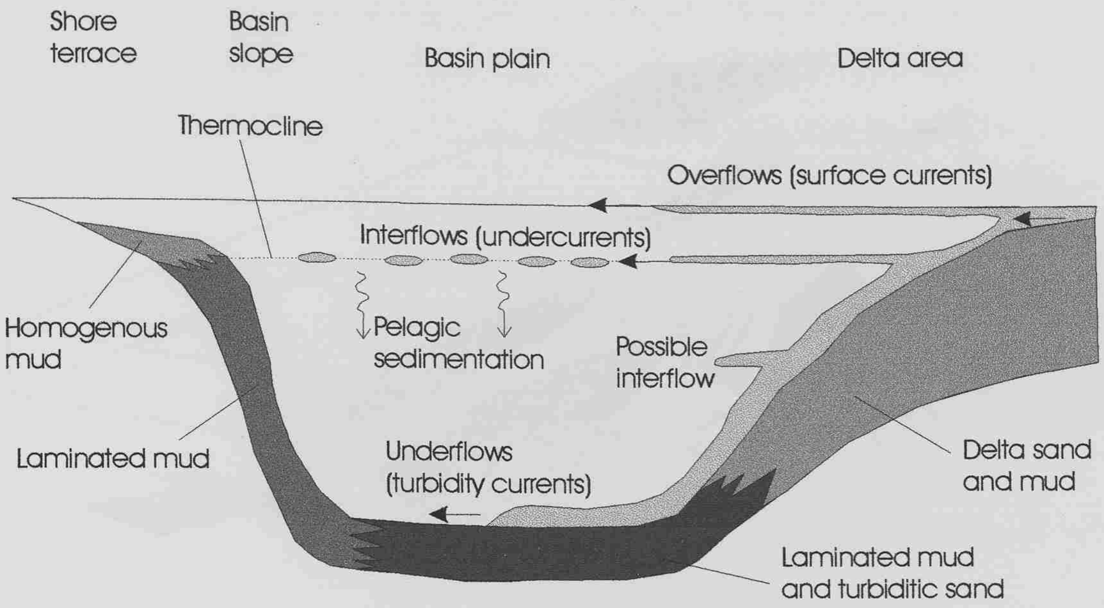


Figure 6-7. Terminology associated with sediment input into lakes (Talbot & Allen 1994).

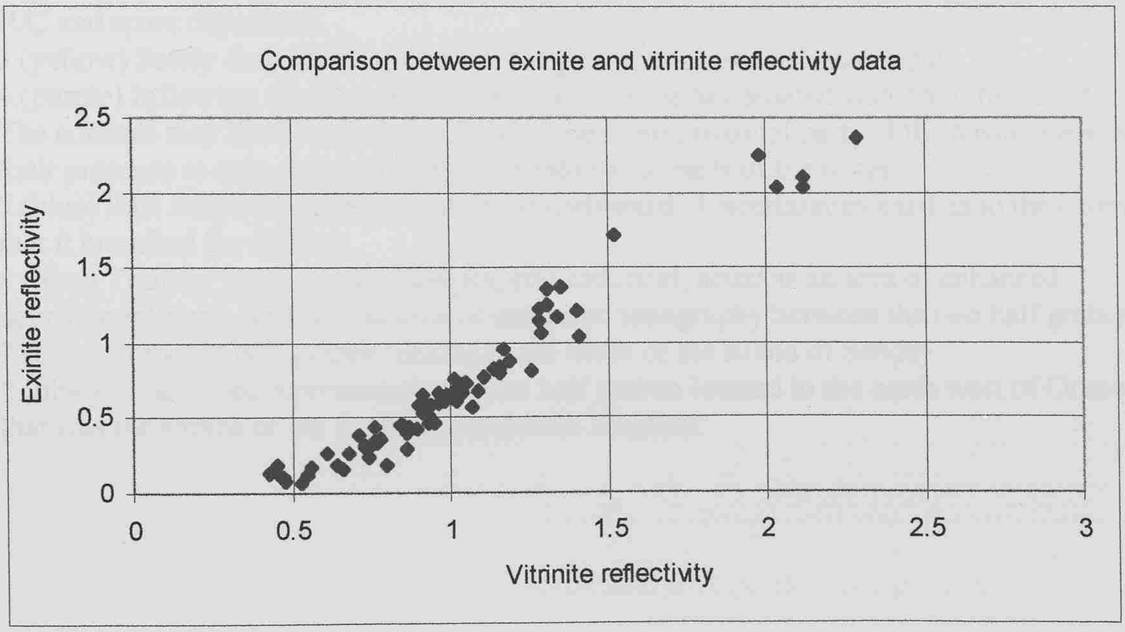


Figure 6-8. Comparison of the reflectivity of exinite and vitrinite samples from the Lower Old Red Sandstone of Scotland and other locations.
Data compiled from Marshall et al. 1994 and Smith & Cook 1980.

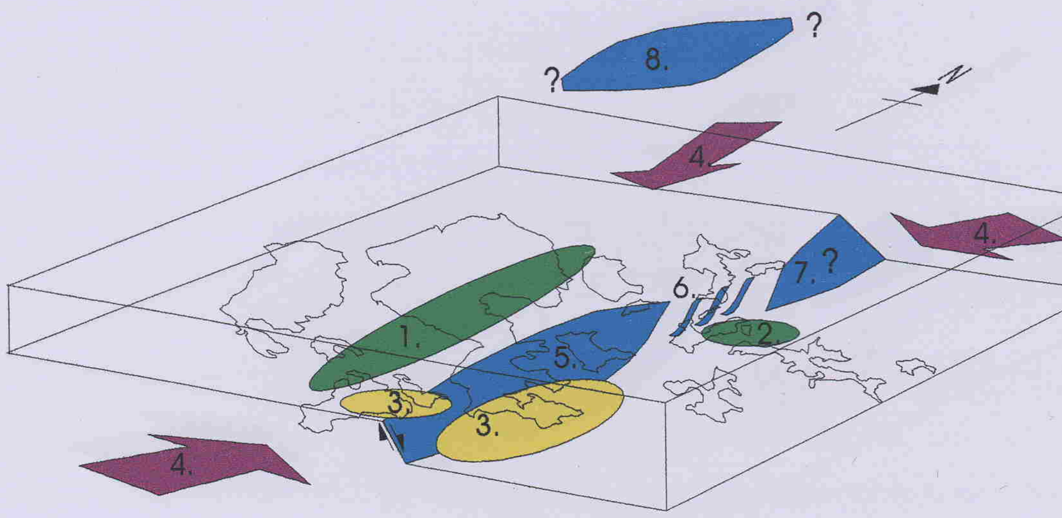


Figure 6-9. Model of lacustrine phase, sediment deposition in a typical cycle of the Rousay Flagstone Formation. The map of Orkney is provided to aid orientation.
1.(green) Enhanced laminite deposition on footwall high, with correspondingly high TOC, H/C and spore deposition.
2.(green)Enhanced laminite deposition in transfer zone, with correspondingly high TOC, H/C and spore deposition.
3.(yellow) Sandy dark silt deposition in hanging wall close to fluvial input.
4.(purple) Inflowing dilute turbidity currents carrying oxygenated water and fine sand. The currents may have been channelised in the more proximal parts of the basin, meaning their presence is only detected in more distal/central parts of the basin
5.(blue) East Scapa Fault, throw declining northward. Uncertainties exist as to the extent that it breached the surface.
6.(blue) Transfer zone – could have trapped sediment, acted as an area of enhanced depositional slope, and was an area of enhanced topography between the two half graben.
7.(blue) Proposed half graben located to the north of the island of Sanday.
8.(blue) Generalised representation of the half graben located to the north west of Orkney that was the source of the Sacquoy Sandstone Member.

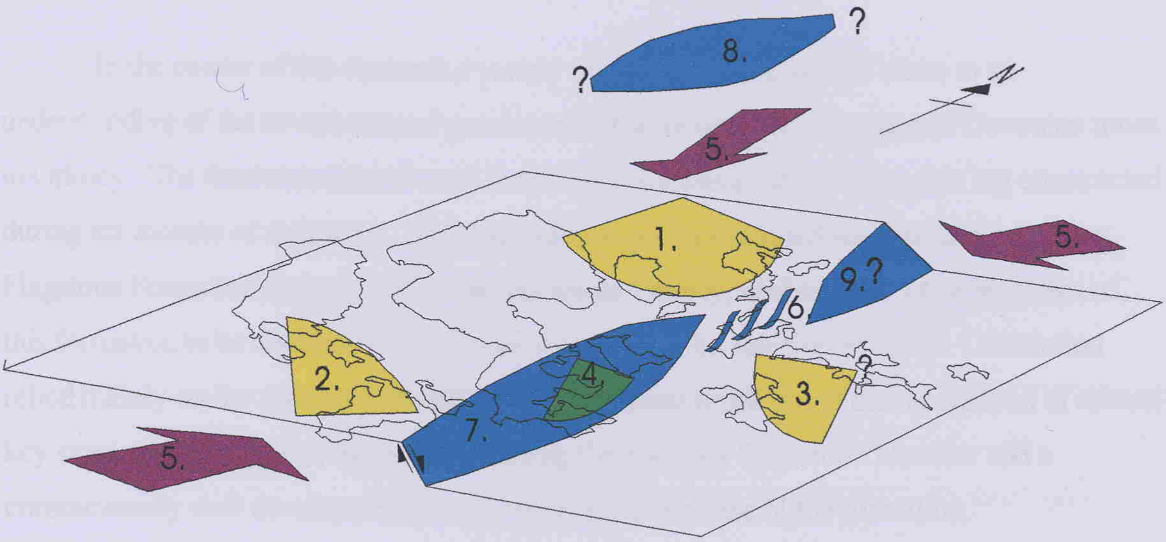


Figure 6-10. Model of fluvial phase, sediment deposition in a typical Rousay Flagstone Formation cycle. The map of Orkney is provided to aid orientation.
1.(yellow) Alluvial fan to the north west, thought to be the source of the sheetfloods and other fluvial facies in the north west of Orkney. The fan is the distributory mechanism for the Sacquoy Sandstone Member, and thus may have been sourced from 8. The influence of the fan can also be seen east of the ESF by the presence of the Sacquoy Sandstone Member on the islands of Sanday and Eday.
2.(yellow) Alluvial fan to the south. The fan caused enhanced deposition of coarse sheetfloods and spores in the southern area of Orkney.
3.(yellow) Alluvial fan to the north east. Nature and location of source area of this fan is uncertain, but thought to be related to other half graben to the north east of Orkney.
4.(green) Location of a possible footwall fan on the breached footwall scarp of the ESF.
5.(purple) Generalised palaeocurrent directions
6.(blue) Possible transfer zone between two half graben
7.(blue) East Scapa Fault, it is uncertain to what extent this fault breached the surface during Rousay Flagstone Formation times.
8.(blue) Exposed footwall to the north west of Orkney. The source of the Sacquoy Sandstone Member.
9.(blue) Half graben thought to exist to the north of Sanday. May have controlled sediment distribution from the north east.

7 Conclusions

In the course of this research a variety of methods were used to come to an understanding of the environmental processes that were operating during mid Devonian times in Orkney. The fundamental tool used in this analysis was a lithostratigraphic log constructed during six months of fieldwork. This log linked together extended sections of the Rousay Flagstone Formation from several locations across Orkney, enabling the 14 or so cycles of this formation to be correlated, and two of the cycles to be sampled in detail. Correlation relied mainly on the matching of sedimentary thickness profiles and the recognition of several key stratigraphic markers, the main two being the Sacquoy Sandstone Member and a conspicuously well developed lake unit occurring at the base of the formation.

The correlation allowed the sedimentary processes operating in different parts of the Devonian lake system to be directly compared. The features studied included the lacustrine and fluvial dominated processes and a detailed analysis of the kerogen present in the lake sediments.

The main finding of this research has been the extent to which the East Scapa Fault (ESF) caused variation in the sedimentary processes operating in Orkney during Rousay Flagstone Formation times. It is thought that by slowly extending throughout this period, the fault caused certain areas of Orkney to experience continued relative uplift. The prolonged topographic expression of the half graben modified most of the basin wide processes that were occurring at this time.

Two aspects of the structure of the half graben were of greatest influence. Firstly the uplifted footwall of the half graben provided an environment away from the influence of inflowing turbidity currents. The quiescent environment developed in this area allowed the greatest degree of laminite facies formation. It was found that high TOC, H/C and spore numbers were associated with the areas of enhanced laminite deposition.

The second area of interest was a transfer zone located at the northern splay of the ESF. The zone acted as a linkage zone between the ESF and a half graben to the north of Orkney. Because if its physical situation between adjacent half graben depocentres, sedimentation was affected by the relative uplift of the area, in a similar manner to the uplifted footwall area to the west of the ESF. Additionally had any of the linking faults within the transfer zone been exposed, they would have acted as tectonic partitions.

The main agent that was detrimental to the formation of good quality source rocks in Orkney is thought to have been turbidity currents. These currents would have originated from the three main areas of fluvial input in the basin at this time. These areas to the north east, north west and to the south were typified by terminal fan deposition. Turbidity currents carrying sediment and oxygenated water from these fans would bypass the shallower and more uplifted areas of Orkney and preferentially deposit in the more distal and downthrown areas. The action of these currents can be seen to control the distribution of laminite and near laminite facies, as well as reducing TOC, H/C and spore numbers. The area immediately to the east of the ESF was the main location to have experienced reduction in kerogen quality because of turbidite deposition. And although the organic matter containing sediments in this area are relatively thick, their low TOC content means that they would make poor source rocks.

During the dryer part of each lake cycle, sheetfloods, silts and fluvial channels prograded out from their source areas to the north and south, into the more central parts of Orkney. This lead to the formation of the sand rich facies overlying organic rich facies package that typifies sedimentation in the Rousay Flagstone Formation. A single cycle representing a full transition from lacustrine to fluvial conditions is on average 11m thick. The sand rich facies commonly show proximal/distal variation, with coarser sediments generally being deposited closer to the sources of the terminal fans.

The organic matter preserved within the Rousay Flagstone Formation is predominantly composed of amorphous organic matter, making the main kerogen type Type I. About 40% of each Rousay Flagstone Formation lake cycle contains measurable organic matter, on average about 0.8%. The amount of organic matter is controlled by facies type, with laminite facies having the highest average TOC (1.55%) and grey silts having least (0.3%).

It was found that the rocks exposed at the surface had experienced no significant TOC reduction due weathering. This means that the TOC values presented in this thesis need not be corrected to estimate sub-surface TOC values. The average H/C ratio for these sediments is 1.1, typical of Type I kerogen.

The greatest numbers of spores are found closest to the points of fluvial inflow – in the north west, north east and in the south. However, the low numbers of spores present in the organic matter (maximum of hundreds per gram) are unlikely to effect the bulk geochemistry of the kerogen. Spore diameter variation shows proximal/distal variation, with the largest spores being found closest to their sources.

Exinite reflectivity and spore colour variation analyses from across Orkney indicate that the thermal maturity of the sediments is equivalent to a vitrinite reflectivity of 0.5 to 0.9. This figure is within the thermal range of hydrocarbon generation. Additionally the uniform spread of maturity values across Orkney indicates that fault movement was never great enough to cause differential thermal maturity regimes to form across Orkney.

As a final point the key results of this work relating to hydrocarbon production are reviewed:

- The Rousay Flagstone Formation is laterally extensive, covering at least 400 km^2.
- It is between 150 to 200m thick.
- Of this thickness, 40% contains on average 8% organic carbon.
- The dominant kerogen type is AOM rich, Type I.
- Its thermal maturity has not exceeded that of oil and gas generation.
- Rivers entering the basin have in some areas reduced TOC content almost to non-source rock levels.
- In other areas tectonic effects have enabled good source rocks to accumulate.

Although the Beatrice accumulation in the Inner Moray Firth, has proven that Devonian source rocks can produce commercial quantities of hydrocarbons, little is known about the factors controlling the distribution of these source rocks outside of the Moray Firth. It is hoped that this thesis has highlighted the possibility that significant Devonian plays could occur in other parts of the northern North Sea.

8. References

Allen, P. A. & Allen J. R. 1990. *Basin Analysis, Principles & Applications.* Blackwell Scientific Publications.

Allen, P. A. & Marshall, J. E. A. 1981. Depositional environments and palynology of the Devonian south-east Shetland basin. *Scottish Journal of Geology*, **17**, 257-73.

Astin, T. R. 1985. The palaeogeography of the Middle Devonian Lower Eday Sandstone, Orkney. *Scottish Journal of Geology,* **21,** 353-375.

Astin, T. R., 1989. The later stages of the Devonian Orcadian Basin in Orkney. *Unpublished.*

Astin T. R. 1990. The Devonian lacustrine sediments of Orkney, Scotland; implications for climate cyclicity, basin structure and maturation history. *Journal of the Geological Society, London,* **147,** 141-151.

Astin, T. R. & Rogers, D. A. 1990. "Subaqueous shrinkage cracks" in the Devonian of Scotland reinterpreted. *Journal of Sedimentary Petrology,* **61,** 850-859.

Astin, T. R. & Rogers, D. A. 1992. "Subaqueous shrinkage cracks" in the Devonian of Scotland reinterpreted - reply. *Journal of Sedimentary Petrology,* **62**, 923-924.

Bailey, N. J. L., Burwood, R. & Harriman, G. E. 1990. Application of pyrolysate carbon isotope and biomarker technology to organofacies definition and oil correlation problems in North Sea basins. *Organic Geochemisty,* **16**, 1157-1172.

Baskin D.K. 1997. Atomic H/C ratio of Kerogen as an Estimate of Thermal Maturity and Organic Matter Conversion. *AAPG Bulletin,* **81** no. 9, 1437-1450.

Bradley, W. H. 1973. Oil Shale Formed in Desert Environment Green River Formation, Wyoming. *Geological Society of America Bulletin,* **84**, 1121-1124.

Brewer, J. A. & Smythe, D. K. 1984. MOIST and the continuity of the crustal reflector geometry anlong the Caledonian-Appalachian orogen. *Journal of the Geological Society London,* **141,** 105-120.

Chowdhury, A.H. & Noble P.A. 1996. Organic carbon and pyrite sulphur relationships as evidences of bottom water conditions of sedimentation, Albert Formation fine-grained lacustrine sediments, New Brunswick, Canada. *Marine and Petroleum Geology* **13** no.1 79-90.

Clayton J. L. & Swetland, P. J. 1978. Subaerial weathering of sedimentary organic matter. *Geochimica et Cosmochima Acta,* **42,** 305-312.

Coward, M. P. & Enfield, M. A. 1987. The structure of the West Orkney and adjacent basins. *In:* Brooks, J. & Glennie, K. (eds) *Petroleum Geology of North West Europe.* Graham & Trotman 687-696.

Coward, M.P., Enfield, M. A., & Fischer, M. W. 1989. Devonian basins of Northern Scotland: extension and inversion related to Late Caledonian-Varsican tectonics. *In*: Cooper, M. A. and Williams, G. D. (eds) *Inversion Tectonics*. Geological Society Special Publication, **44** 275-305.

Donovan, R. N. 1975. Devonian lacustrine limestones at the margin of the Orcadian Basin, Scotland. *Journal of the Geological Society London* **131** 489-510.

Donovan, R. N. 1980. Lacustrine cycles, fish ecology and stratigraphic zonation in the Middle Devonian of Caithness. *Scottish Journal of Geology*, **16**, 35-50.

Donovan, R. N. & Foster, R. J. 1972. Subaqueous shrinkage cracks from the Caithness Flagstone Series (Middle Devonian) of Northeast Scotland. *Journal of Sedimentary Petrology*, **42**, 309-317.

Donovan, R. N., Foster, R. J & Westoll, T.S. 1974. A Stratigraphical Revision of the Old Red Sandstone of North-eastern Caithness. *Transactions Royal Society of Edinburgh*, **69** no. 8.

Duncan A. D. & Hamilton R. M. F. 1988. Palaeolimnology and organic geochemistry of the Middle Devonian in the Orcadian Basin. *In:* Fleet, A. J., Kelts, K. and Talbot, M.R. (eds) *Lacustrine petroleum source rocks*. Geological Society Special Publication, **40**, 173-201.

Duncan W. I. & Buxton N. W. K. 1995. New evidence for evaporitic Middle Devonian lacustrine sediments with hydrocarbon source potential on the East Shetland Platform, North Sea. *Journal of the Geological Society, London*, **152**, 251-258.

Durand, B. & Monin J. C. 1980. Elemental analysis of kerogens (C, H, O, N, S, Fe), in *Kerogen: Insoluble Organic Matter From Sedimentary Rocks* (ed. B. Durand) Editions Technip, Paris, 113-142.

Enfield, M. A. & Coward, M. P. 1987. The Structure of the West Orkney Basin, northern Scotland. *Journal of the Geological Society, London*, 144, 871-884.

Eugster, H. P. & Surdam R. C. 1973. Depositional Environments of the Green River Formation of Wyoming: A Preliminary Report. *Geological Society of America Bulletin*, **84**, 1115-1120.

Fannin, N. G. T., 1970. *The sedimentary environment of the Old Red Sandstone of Western Orkney*. Unpublished PhD thesis, University of Reading, UK.

Flett, J. S. 1897. On the discovery in Orkney of the John o'Groats Horizon of the Old Red Sandstone. *Proceedings of the Royal physics Society, Edinburgh*, **13**, 255-1257.

Forsberg, A. & Bjoroy, M. 1981. A Sedimentological and Organic Geochemical Study of the Botneheia Formation, Svalbard, with special Emphasis on the Effects of Weathering on Organic Matter in Shales. Advances in Organic Geochemistry 1981, 60-68.

Gawthorpe, R. L., Hurst, J. M. & Sladen, C. P. 1990. Evolution of Miocene Footwall-derived Coarse-Grained Deltas, Gulf of Suez, Egypt: Implications for Exploration. *AAPG Bulletin*, **74**, 1077-1086.

Gawthorpe, R. L. & Hurst, J. M. 1993. *Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy.* Journal of the Geological Society, London, **150,** 1137-1152.

Gawthorpe, R. L., Sharp, I., Underhill, J. R. & Gupta, S.1997. *Linked sequence stratigraphic and structural evolution of propagating normal faults.* Geology, **25,** 795-798.

Gore, P. J. W. 1988. Late Triassic and Early Jurassic lacustrine sedimentation in the Culpeper basin Virginia. *In*: Manspeizer (ed) *Triassic-Jurassic Rifting.* Elsevier.

Hamblin, A. P. & Rust, B. R. 1989. *Tectono-sedimentary analysis of alternate-polarity half-graben basin-fill successions: Late Devonian-Early Carboniferous Horton Group, Cape Breton Island, Nova Scotia.* Basin Research **2** 239-255.

Herries, R. D. 1988. *The sedimentology and diagenesis of a Middle Devonian Fluvio-lacustrine sequence; the Rousay Flagstones, Westray, Orkney Islands.* MSc. thesis, University of Reading, UK.

Hillier, S. 1989. *Clay mineral diagenesis and organic maturity indicators in Devonian lacustrine mudrocks from the Orcadian Basin, Scotland.* PhD thesis, University of Southampton.

Hillier, S. & Marshall, J. E. A. 1988. A rapid technique to make polished thin sections of sedimentary organic matter concentrates. *Journal of Sedimentary Petrology*, **58 no.4**, 754-755.

Hillier, S. & Marshall, J. E. A. 1992. Organic maturation, thermal history and hydrocarbon generation in the Orcadian Basin, Scotland. *Journal of the Geological Society, London,* **149,** 491-502.

Hippler, S. J. 1993. Deformation Microstructures and Diagenesis in Sandstone Adjacent to an Extensional Fault: Implications for the Flow and Entrapment of Hydrocarbons. *AAPG*, **77,** 625-637.

Holmes, P. L. 1994. The sorting of spores and pollen by water: experimental and field evidence. *In*: Alfred Traverse (ed) *Sedimentation of organic particles.* 9-32.

Horowitz, A. 1992. *Palynology of arid lands.* Elsevier Press, 79-147.

House, M. R., Richardson, J.B., Chaloner, W. G., Allen, J. R., Holland, C. H. & Westoll, T.S. 1977. A correlation of Devonian rocks of the British Isles. *Special report of the Geological Society of London*, **7**.

Huc, A.Y., Le Fournier, J., Vandenbroucke, M. & Bessereau, G. 1990. Northern Lake Tanganyika - An example of organic sedimentation in an anoxic rift lake. *In* Barry Katz (ed) *Lacustrine basin exploration - Case studies and modern analogues.* AAPG Memoir **50**.

Janaway, T. M. & Parnell, J. 1989. Carbonate production within the Orcadian Basin, northern Scotland: a petrological and geochemical study. *Palaeogeography, Palaeoclimatology, Palaeoecology.* **70,** 89-105.

Katz, B. J. 1995. A survey of rift basin source rocks. *In*: Lambaise J.J. (ed). *Hydrocarbon Habitat in Rift Basins.* Geology Society Special Publication **80** 213-242.

Katz, B. J. 1995. Factors Controlling the Development of Lacustrine Petroleum Source Rocks – An Update. *In:* Palaeogeography, palaeoclimate and source rocks. *AAPG studies in Geology* **40** 61-79.

Kelly, S. B. & Olsen, H. 1993. Terminal fans - a review with reference to Devonian examples. *Sedimentary Geology,* **85,** 339-374.

Killops, S. D. & Killops, V. J. 1993. *An Introduction to Organic Geochemistry.* Longman Scientific & Technical.

Lambiase, J. J. & Bosworth, W. 1995. *Structural controls on sedimentation in continental rifts. In*: Lambiase (ed.) Hydrocarbon habitat in Rift Basins. Geological Society Special Publication No.80, 117-144.

Leeder, M. R. & Gawthorpe, R. L. 1987. Sedimentary models for extensional tilt-block/half graben basins. *In*: Coward, M. P. Dewey and Hancock *(eds) Continental Extension Tectonics.* Geological Society Special Publication **28**, 139-152.

Leythaeuser, D. 1973. Effects of weathering on organic matter in shales. *Geochimica et Cosmochima Acta*, **37**, 113-120.

Marshall, J. E. A. 1991. Quantitative spore colour. *Journal of the Geological Society, London*, **148**, 223-233.

Marshall, J. E. A. 1996. *Rhabdosporites langii, Geminospora lemurata* and *Contagisporites optivus*: an origin for heterospory within Progymnosperms. *Review of Palaeobotany and Palynology,* **93**, 159-189.

Marshall, J. E. A. 1998. The recognition of multiple hydrocarbon generation episodes: an example from the Devonian lacustrine sedimentary rocks in the Inner Moray Firth, Scotland. *Journal of the Geological Society, London*, **155**, 335-352.

Marshall J. E. A., Brown, J. F. & Hindmarsh, S. 1985. Hydrocarbon source rock potential of the Orcadian Basin. *Scottish Journal of Geology*, **21**, 301-320.

Marshall, J. E. A., Haughton, P.D.W. & Hillier S.J. 1994. Vitrinite reflectivity and the structure and burial history of the Old Red Sandstone of the Midland Valley of Scotland. *Journal of the Geological Society, London*, **151**, 425-438.

McClay, K. R., Norton, M. G., Coney, P. & Davis G. H. 1986. Collapse of the Caledonian orogen and the Old Red Sandstone. *Nature* **323** 147-149.

McQuillin, R.1968. Geophysical surveys in the Orkney Islands. *IGS Geophysical paper* No. **4**.

Miller, H. 1849. *Footprints of the creator*. Edinburgh.

Miller, H. 1858. *The cruise of the Betsey*. Edinburgh.

Murchison, R. I. 1859. On the succession of the Older Rocks in the Northernmost counties of Scotland: with some observations from the Orkney and Shetland Islands. *Quarterly Journal of the Geological Society, London.* **15** 353-418.

Mykura, W. 1976. *British Regional Geology, Orkney and Shetland.* HMSO.

North, F. K. 1985. *Petroleum Geology.* Allen & Unwin.

Parnell, J. 1985. Hydrocarbon source rocks, reservoir rocks and migration in the Orcadian Basin. *Scottish Journal of Geo*logy **21,** 321-336.

Plimmer R. S. 1974. *The sedimentology and stratigraphy of the Middle Old Red Sandstone Rousay Group of the Orkney Islands.* Unpublished PhD thesis. University of Newcastle upon Tyne.

Raiswell, R. & Berner, R. A., 1987. Organic carbon losses during burial and thermal maturation of normal marine shales. *Geology* **15**, 853-856.

Richardson, J. B., 1965. Middle Old Red Sandstone spore assemblages from the Orcadian Basin North-East Scotland. *Palaeontology* **7**, 559-605.

Roberts, A. & Yielding, G., 1994. Continental Extensional Tectonics. *In:* Hancock, P.L (ed), Continental Deformation 223-250. Pergamon Press Ltd.

Rogers, D. A. 1987. *Devonian correlations, environments and tectonics across the Great Glen Fault.* PhD thesis, University of Cambridge, UK.

Rogers, D. A. & Astin, T. R. 1991. Ephemeral lake, mud pellets and wind-blown sands and silts: reinterpretation of Devonian lacustrine cycles in northern Scotland. *Special Publication of the Association of Sedimentologists,* **13**, 199-221.

Saxon, J. 1975. *The Fossil Fishes of the North of Scotland.* Caithness Books.

Smith, G.C. & Cook, A.C. 1980. Coalification paths of exinite, vitrinite and inertinite. *Fuel*, **56**, 641-646.

Smoot, J.P. 1983. Depositional subenvironments in an arid closed basin; the Wilkins Peak Member of the Green River Formation (Eocene), Wyoming, U.S.A. *Sedimentology*, **30**, 801-827.

Streel, M. & Richelot, C. 1994. Wind and water transport and sedimentation of miospores along two rivers subject to major floods and entering the Mediterranian Sea at Calvi (Corsica, France). *In*: Traverse, A.(ed) *Sedimentation of organic particles.* 59-67.

Talbot, M.R. & Allen, P. A. 1996. Lakes. *In:* Reading (ed) *Sedimentary environments, processes, facies and stratigraphy*, 83-124. Blackwell Science 1996.

Tiercelin, J. J. 1990. Rift-basin sedimentation: responses to climate, tectonism and volcanism. Examples from the East African Rift. *Journal of African earth Sciences.* **10,** no.1/2, 283-305.

Trewin, N. H. 1986. Palaeoecology and sedimentology of the Achanarras fish bed of the Middle Old Red Sandstone, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **77**, 21-46.

Trewin, N. H. 1989. The petroleum potential of the Old Red Sandstone of northern Scotland. *Scottish Journal of Geology*, **25**, 201-225.

Trewin, N. H., 1992. "Subaqueous shrinkage cracks" in the Devonian of Scotland reinterpreted - Discussion. *Journal of Sedimentary Petrology*, **62**, 921-922.

Tyson, R. V. 1995. *Sedimentary Organic Matter.* Chapman & Hall.

Yule B. 1998. *The chemical and structural evolution of sporopollenin, using vibrational spectroscopy.* Unpublished PhD thesis, University of Southampton.

Wilson, G. V., Edwards, W., Knox, J., Jones, R. C. B. & Stephens, J. V. 1935. *The Geology of the Orkneys.* Memoir of the Geological Survey, Great Britain.

Appendix 1

List of locations logged during the summers of 1996 & 1997

All locations logged during the field seasons of 1996 & 1997

This chapter lists all of the sections that were logged during the summers of 1996 and 1997, whether they were used in the thesis or not. Sections marked '*' are those that were used in the correlation of the Rousay Flagstone Formation. Particular care was taken to avoid sections with more than slight faulting to maintain maximum confidence in the stratigraphic framework.
A number of the sections described below were described by Plimmer (1974), in his thesis on the stratigraphy of the Rousay 'Group'.

The Northern Isles

Westray

Westray is one of the largest of the Northern Isles and lies to the north west of the island group. Previously it was thought that the island was composed entirely of Rousay Formation sediments, however it can now be seen to contain significant amounts of Upper Stromness Flagstone.
The island is broadly anticlinal with the axial trace passing north-south through the Bay of Cleat and the Bay of Tuquoy. A series of north-south trending faults have been mapped between the Bay of Brough and Rack Wick. These may be a continuation of the East Scapa Fault.

*Noup Head

Location: North facing coast from inlet east of Clemmar (HY408494) to the tectonic 'wiggle' at Hesti Geo and then past approximately 1km of clifftop exposure to where accessible exposure starts again (HY395501) to the hill below the lighthouse on Noup Head itself (HY393499).
Structure: The strata are essentially flat lying which allows them to be fairly confidently followed across a 1km long inaccessible section. A large ruck at Hesti Geo although spectacular to look at is thought to occur within one cycle, and thus no offset has occurred. Several other smaller rucks and decollements are present, but strata can be traced across them.
Outcrop quality: In the section before Hesti Geo the rocks are excellently exposed in a broad intertidal zone. In the extreme northwest of Noup Head the exposure is intermittent, with a lot of scree and scrubby plants.
Stratigraphic position: A thin pebble band which is probably the equivalent of the Sacquoy Sandstone Member on Rousay, occurs at the resumption of the section (after the clifftop section) halfway down the cliff face. This allows the section to be placed towards the top of the Rousay Group.
Length of logged section: 128m of Rousay Formation sediments.

* Surrigarth

Location: Northeast facing shoreline between Surrigarth (HY492452) and Swart Hellia Geo (HY497437), approximately 1km to the southeast.
Structure: These rocks occupy the eastern limb of a syncline whose hinge plunges in a northerly direction through Surrigarth. The strata dip at moderate angles to the east.
Along the section numerous small rucks and folds occur, however the strata can easily be traced across these structures, since little faulting occurs in this section.
Outcrop quality: The section is essentially non-tidal, with outcrop often taking the form of small cliffs. The outcrop is narrow in the southeast but broadens out nearer Surrigarth. Generally excellent exposure, but with lichen occasionally obscuring the rock.
Stratigraphic position: This section is composed of around 15 cycles of Upper Stromness Formation, in which the laminite facies are typically poorly developed. The return of well-developed laminites is thought to mark the start of the Rousay Formation. Four cycles of Rousay Formation sediments are present. This section when combined with the Noup Head section represents the entire Rousay Flagstone Formation on Westray.
Length of logged section: 62m of Rousay Flagstone Formation and 220m of Upper Stromness Formation.

Bow Head

Location: North facing coast from the most northeasterly point (HY461531) to the east side of The Taing (HY455350).
Structure: The section starts to the west of a small fault of limited throw. The strata dip at around 10 degrees to the west-northwest.
Outcrop quality: Very good, broad intertidal exposure.

Stratigraphic position: Uncertain position, possibly on the boundary between the Upper Stromness Flagstone Formation and the Rousay Flagstone Formation. Indicated by return to well developed laminites after four cycles of poorly developed lake sediments.
Length of logged section: Possibly 28m Upper Stromness Formation and 21m Rousay Flagstone Formation.

Narr Ness/Rack Wick

Location: A series of fault disjointed sections from Rack Wick (HY440502) to Sui Geo (HY434500).
Structure: The beds are horizontal at the start of the section at Rack Wick but dips increase to around 20 degrees to the west near Sui Geo. This section contains many north south faults of uncertain throw.
Outcrop quality: Good, broad intertidal exposure.
Stratigraphic position: Uncertain, within the Rousay Formation.
The feature that makes this section of interest is a large (6m thick) package of south flowing stacked channel sands which seems not to have been noted before. This must represent a large river system. Further work will study the effects this river had on the surrounding lake facies, and try to pick it out at other locations to the south.
Length of logged section: About 85m.

Ouse Ness

Location: The north side of Bay of Pierowall - a south south east facing shore between Gill Pier (HY447489) and the north south trending fault at Ouse Ness (HY459494).
Structure: Beds dip at around 10 degrees to the west north west.
Outcrop Quality: Poor intertidal exposure with sand, gravel and seaweed covering the strata. Towards the southwest of the section (300m m east of Gill Pier) 3-4 m high cliffs are present.
Stratigraphic position: Due to the poor exposure this section's position is uncertain.
Length of logged section: 139m.

Weather Ness

Location: South west facing shore from Sands of Woo (HY519409) to Sand Geo (HY520405).
Structure: The beds dip at around 20 degrees to the east north east. Several small faults are present from Morris Geo (HY516407) to Sand Geo. It is the increase in faulting that limited logging any further east.
Outcrop Quality: Excellent exposure on low clean cliffs, although towards the eastern end of the section the cliffs become quite high.
Stratigraphic position: Uncertain. It's published position on the unfaulted western limb of the Eday syncline may mean that it is in fact in the Upper Stromness Flagstone Formation, given the reduction in Rousay Flagstone Formation thickness.
Length of logged section: 72m.

Bay of Kirbist

Location: The south west facing coastline of Westray from Muckle Water (HY430429) to Hoo Nager (HY423436).
Structure: Unfaulted strata dipping gently to the north west.
Outcrop quality: Well exposed low cliffs and wavecut platform mostly above high tide mark
Stratigraphic position: probably Upper Stromness Flagstone Formation.
Length of logged section: About 40m

Papa Westray

Introduction: This small island lies just to the northeast of Westray. The island is thought to be composed entirely of Rousay Formation sediments. The southern two-thirds of the island is broadly synclinal. Two northeast southwest trending faults cut across the upper part of the island. The northern most part of the island is unfaulted.

Mull Head

Location: Westward facing coast from Geo of Odderaber at (HY494559) to Green Tables (HY494555).
Structure: The majority of this section is flat or dips gently to the north. As the northern end of the section is approached, dips start to increase towards a large fold beyond the end of the section.
Outcrop quality: Excellent exposure occurs along the section, which is composed of a series of gently sloping dip slopes and small (4m high) cliffs.

Stratigraphic position: The placing of this section is uncertain. However the presence of well defined laminites in the lowermost cycle, and by cycle thickness comparisons with the nearest logged section (Bow Head) suggests that in this section could represent the base of Rousay Flagstone Formation.
Length of logged section: 45m Rousay Flagstone Formation.

Vest Ness
Location: south west facing shoreline from Horse Flags (HY483494) to the point of Vest Ness (HY486488).
Structure: The beds begin horizontal at Horse Flags but dips increase to about 45 degrees to the ESE at Vest Ness. Numerous small faults are present towards Vest Ness.
Outcrop Quality: Poor - heavy seaweed and lichen cover.
Stratigraphic position: Uncertain.
Length of logged section: 60 m.

Holm of Papa Westray
This very small island off the east coast of Papa Westray is inhabited only by several thousand Arctic Terns. The island is crossed by several north-east trending faults of uncertain throw. Time and angry birds allowed only a short section to be logged.

Dog Bones
Location: East side of Holm of Papa Westray from (HY507523) to (HY505524).
Outcrop quality: Good. Fascist seabirds off-putting.
Stratigraphic position: Uncertain, mainly fish rich near-laminites.
Length of logged section: 31m, Rousay Formation?

Rousay
Introduction: Most of the exposure in Rousay lies to the west and northwest of the island within the Empty Quarter (so named because of the mass evictions carried out during the Highland clearances). The coastline to the east and south of the island is generally too low lying to allow logging. The coastline in the extreme northwest has stretches of high inaccessible sea cliffs.
The cyclical nature of the lacustrine sedimentation is visible as prominent terraces crossing the slopes of the hills of Rousay (Blotchnie Fiold (HY370334) and Ward Hill (HY384300)).

* West Rousay
Location: The west and northwest facing coast of Rousay from Sinians of Cutclaws (HY363317) to Sacquoy Head (HY382350). A coastal stretch of 1200m with inaccessible cliffs occurs in this section between Bring Head (HY370338) and Little Lobust (HY379346). Trigonometry, thickness comparisons with others sections, cycle counting and the generally shallow dip of the sediments, show that only about 40m of section cannot be logged due to this break in exposure. This agrees well with Astin's (1990) estimate of inaccessible section.
An additional 10m of section was logged using climbing equipment to access the vertical cliffs at the base of the Sacquoy Head section.

Structure: The coast to the south of Sinians of Cutclaws is moderately faulted, with several cases where fault throw is uncertain. The strata along the coast north of Sinians of Cutclaws are flat lying or gently dipping to the north. It is only at Digger (HY365325) that there is any tectonism evident. Trending in a northerly direction across the bay is a large ruck which offsets the strata by about 5 m. However it is fairly certain that individual beds can be followed across the feature.
Outcrop quality: The coast between Sinians of Cutclaws and Bring head provides good, broad intertidal exposure with the exception of Digger Bay where cobbles blanket the shore, obscuring some strata. Northeast of Little Lobust moderate quality clifftop exposure dominates. Peat deposits and loose rubble hampered logging.
Stratigraphic position: The section includes the entire Rousay Flagstone Formation.
The southern part of the section, before the break in exposure, contains 9 Upper Stromness Formation cycles and 4 Rousay Formation cycles. The junction is picked as where well developed lake facies return to the cycles, after an extended period of poor lake development. The 3 cycles north of the break in exposure are thought to be close to the top of the Rousay Formation. The lowermost cycle contains the pebbly sandstone Sacquoy Sandstone Member.
Length of section logged: South of the gap 88m of Upper Stromness Flagstone Formation and 43m of Rousay Flagstone Formation were logged. North of the gap 45m of Rousay Flagstone Formation was logged.

Saviskaill Head

Location: Headland on the north coast of Rousay. Logged from the east as far as safety would allow (approx. (HY400350)) to just west of the arch at Helliasour (HY399349).
Structure: This section occurs just to the east of a large reverse fault. No other structural features occur in this area. The strata in the eastern part of Saviskaill Head dip at around 5 degrees to the west, with the dip increasing towards the west.
Outcrop quality: The ascent of the cliff face on the eastern part of the section provides moderately exposed strata between peaty ledges and slopes. The rest of the section is along clifftop with sporadic rubble and peat cover.
Stratigraphic position: The return of improved quality lake facies at the base of the third logged cycle allows the section to be tentatively placed at the junction between Upper Stromness Formation and the Rousay Formation. However it must be noted that the thickness of the cycles is significantly less than their equivalents on the west coast. This could either mean that the cycles have been stratigaphically misplaced or that the active fault to the west of this section either had some effect on the deposition of the sediments.
Length of section logged: Possibly 19m Upper Stromness Flagstone Formation and 18m Rousay Flagstone Formation.

Ward Hill

Location: Hill on the south west coast of Rousay logged from cairn at top (HY384298) to the south west (HY383295).
Structure: Near horizontal beds, possible large fault downthrowing Sacquoy Member to the east by about 10m.
Outcrop quality: Hillside exposure composed of well exposed low cliffs and grass covered benches.
Stratigraphic position: The presence of Sacquoy Sandstone Member puts this section at the top of the Rousay Flagstone Formation.
Length of logged section: About 50m of Rousay Flagstone Formation.

Eynhallow

This small island in the Sound midway between Mainland and Rousay is beautiful, uninhabited and expensive to get to. Beside day trips to it arranged by the RSPB, passage can be arranged by asking at the Pier Restaurant in Rousay.

Fint

Location: North east lobe of Eynhallow from (HY366295 to (HY367293).
Structure: Beds dip gently to the south east. Not faulted.
Outcrop quality: Good intertidal/ shore head.
Stratigraphic position: Uncertain, possibly base Rousay Flagstone Formation.
Length of logged section: 33.25m.

Eday

The Eday syncline, which dominates all of Eday, is one of the most prominent geological features in Orkney. The northerly plunge of the syncline means that generally, any transect going from north to south across the island will encounter successively older rocks. Thus Rousay Formation rocks and older occur in the south of the island, and on the western limb of the syncline. The rest of the island is Eday Group age.

*Wars Ness

Location: The south east facing coast on the west side of the Bay of Greentoft (HY557288), from the point of Wars Ness (HY550280) to Dyke End (HY549289).
Structure: The beds in this area dip at around 10 degrees to the northwest. No faulting is seen.
Outcrop quality: The first two or three cycles logged to the west of Bay of Greentoft, were obscured by seaweed. A distinctive stromatolite horizon helped correlation across the worst of the exposure. The section is generally a moderately exposed broad intertidal zone.
There is a gap in exposure caused by the presence of a pebbly storm beach on the point of Wars Ness. It is estimated that only 8m of section is lost.

The rest of the section from Wars Ness to Dyke End is very well exposed, but in the form of a series of bays and cliffs, so some climbing is required.
Stratigraphic position: This section comprises most of the Rousay Flagstone Formation. The only gap being that of the storm beach at Wars Ness. The base of the Rousay Formation is recognised as a change from a cycle containing poorly developed lake facies to the appearance of laminite facies. Near the top of the section several pebbly sandstone horizons were seen. It is thought that lowermost of these represents the Sacquoy Sandstone Member. Several lake cycles occur above the Sacquoy Sandstone Member, but they deteriorate into poorly defined sands and silts close to the junction with the Eday Group. Close to the junction about 6m of sediment is strongly reddened.
Length of outcrop logged: 210m Rousay Flagstone Formation including the 8.5m gap, and 7m Upper Stromness Flagstone Formation.

* Fers Ness.

Location: The coast around the head of Fers Ness from north of Rammy Geo (HY529339) to the western corner of Fers Ness Bay (HY534338).
Structure: Several faults of small displacement are present in this section. A few decollements occur within the lower parts of some cycles. Generally the strata dip towards the east at about 30-40 degrees.
Outcrop quality: Generally good, narrow intertidal exposure. In a few places sand obscures the rocks, but no more than 4m total is lost.
Stratigraphic position: This section includes all of the Rousay Flagstone Formation. The base of the Formation is not particularly clear, with the return to well developed lake facies not being as pronounced as in other sections. However the base can be confidently identified by comparison with the Wars Ness section.
As with the Wars Ness section, the top of the Rousay Flagstone Formation contains the Sacquoy Sandstone Member and reddened sediments.
Length of logged outcrop: 33m Upper Stromness Flagstone Formation and 200m Rousay Flagstone Formation.

*North Faray

North Faray is a small thin island lying between the tips of Westray and Eday. It is generally uninhabited, with any traffic to the island being associated with sheep care. Passage can be arranged in the Pierowall Hotel, Westray.
Location: The northern part of North Faray called Quoy Noust from The Point of Ring (HY528381) to Muller Geo (HY531378).
Structure: A few small north south trending faults of negligible throw cut the eastward dipping strata. At the top of the section (Muller Geo) faults of larger throw occur.
Outcrop quality: Generally intertidal, with some beachhead, low cliff outcrops.
Stratigraphic position: Rousay Flagstone Formation
Length of logged section: 60 m Upper Stromness Flagstone and 120 m Rousay Flagstone Formation.

Sanday

Sanday gets its name, presumably, from the vast quantity of sand that has accumulated around its shores, which greatly limits the degree of exposed rock present.
With the exception of the southwestern peninsula the rocks of the island are thought to be Rousay Flagstone Formation. It is only in the southwest of the island that faults of considerable throw have exposed Eday Group sediments. A large number of faults of small throw are present in the northwest and eastern extremities of the island making logging impractical.

*Spur Ness

Location: The south facing shore of Spur Ness (HY607332). Logging starts to the west of the zone of folding and faulting associated with the major NNW-SSE trending fault running along the west side of the Bay of Stove (HY6034). Logging stops where the headland changes direction (HY603333).
Structure: The strata generally dip at 20-30 degrees to the west. The presence of small faults and folds along this section, increases the dip in some cases up to 70 degrees. The faults are all of little throw, and strata can be followed across them.
Outcrop quality: 4-5m high scarps flank most of the section, causing most of the exposed section to be found in the intertidal zone. Where sand obscures the rock in the many small cove on this section, the strata is nearly always fully exposed closer to the low tide mark.

Stratigraphic position: This section contains ten cycles of Upper Stromness Flagstone Formation and 8 cycles of Rousay Flagstone Formation. The base of the Rousay is placed after a particularly thick, poorly defined cycle.
Length of logged section: 147m Upper Stromness Flagstone Formation and 103m of Rousay Flagstone Formation.

*Loth Quarry
Location: This section is the lateral continuation of the Spur Ness section. There is in fact considerable overlap between the two sections. The quarry is a recent feature, having been created for the building of the new 'roll on–roll off' pier at Loth about 10 years ago. The section runs from the first exposed face in the quarry (HY602342) along the side walls of the quarry, and out along the coast to Sherry Geo (HY600344).
Structure: The beds dip towards the west at around 30 degrees. No faults were seen. One decollement horizon is present.
Outcrop quality: Within the quarry there is 100% exposure, however because the quarry is recent there is a lot of loose material around, so extreme caution is needed when examining the rock. The coastal part of this section is narrow and intertidal, but does give almost 100% exposure.
Stratigraphic position: A bed of granular sandstone was found in the middle of this section, which is assumed to be the equivalent of the Sacquoy Sandstone Member, placing this section in the upper half of the Rousay Formation. The Spur Ness section and the Loth Quarry sections can be confidently correlated, since there is no evidence of any major faults in the 500m between the two sections. The overlapping cycles are also very similar in thickness. Joining the two sections provides a complete succession of the Rousay Flagstone Formation.
Length of logged section: 160m Rousay Formation.

Noust of Ayre
Location: The north and northwest facing coastline between the west side of Noust of Ayre (HY649415) and Rives Geo (HY645411).
Structure: The section starts beyond the many northeast-southwest trending faults of uncertain throw to the immediate west of the Noust of Ayre. The beds dip 10-15 degrees to the northwest.
Outcrop Quality: Good exposure above the HWM, and in a series of small cliffs and coves in the intertidal zone.
Stratigraphic position: The return of better quality lake faces, after a thick cycle containing poorly developed lake facies suggests that the third cycle in this section possibly is the lowermost cycle in the Rousay Flagstone Formation. 'Horse tooth' stromatolite present.
Length of logged section: 45m Upper Stromness Formation and 43m Rousay Formation.

Shapinsay
This rather flat uninteresting island lies close to Mainland. Its flatness has reduced coastal exposure.

Sandy Geo
Location: The extreme north east coast of Shapinsay to the east of Sandy Geo (HY535225).
Structure: Flat lying to gently eastward dipping flags. The section becomes increasingly faulted towards Geo of Ork (HY541225), with several north south trending faults of uncertain throw.
Outcrop quality: Sandy intertidal exposure.
Stratigraphic position: The presence of stromatolites may place this section at the base of the Rousay Formation, but precise placement is difficult.
Length of logged section: 49m.

Noust of Osted
Location: Half way along south coast of Shapinsay. Section starts to the west of Noust of Osted (HY495163), and finishes at The Head (HY493162).
Structure: Beds dip 20 to the south. Small faults present.
Outcrop quality: Extremely tidal section, sand obscures some of the rock.
Stratigraphic position: Possibly the base of the Rousay Flagstone Formation.
Length of logged section: 35m

Stronsay
The island of Stronsay is cut by numerous faults of large throw. This has led to a lack of good unfaulted sections to log on this island.

*Huip Ness
Location: Northeast facing coast of the northern most tip of Stronsay. Section starts north of the faulted zone at the cairn (HY647 300), and ends at the end of exposure on the Point of Comely (HY641308).
Structure: Beds dip at 10 degrees to the north west. Section interrupted by several faults, but correlation across is possible.
Outcrop quality: Intertidal low coastal, and some low cliffs above HWM. Good in the southern part of the section, sandy and pebbly bays occur in the northern half of the section. Section becomes increasingly seaweed covered towards its end.
Stratigraphic position: Correlation with the Sanday sections suggest this section is mostly Rousay Flagstone Formation.
Length of logged section: 153m

*Bight of Aith
Location: The Bight of Aith is on the south west facing coast of the Bay of Holland.
Section starts on the south westerly tip of the Bight of Aith (HY645241) and continues south east till the outcrop is covered in drift (HY647239).
Structure: Beds dip gently towards the east north east. Section frequently highly brecciated and faulted by numerous faults of small throw. Section measurements may be unreliable.
Outcrop quality: Poor, sand covered intertidal.
Stratigraphic position: Forms the border between Eday Sandstone and the Rousay Flagstone Formation.
Length of logged section: 92m.

North Ronaldsay
This is a fantastic island, lying to the extreme north east of Orkney. The island's extreme lack of topography allows winter storms to carry waves right across it.
The sedimentary successions seen on this island have been assigned a Rousay Flagstone Formation age (Wilson 1935), but the sections logged could not be correlated with any other Rousay succession.

Doo Geo
Location: West side of North Ronaldsay from Doo Geo (HY749537) south down to cobbly bay close to Loch Gretchen (HY749531).
Structure: Beds dip to SSE dip increasing from 5 at start to near vertical at the fault zone.
A fault with 25 cm gouge at Gairsna Geo, strike slip with no obvious cut out. Increasing number of faults of small throw southwards. Section terminates in wide brecciated fault zone in the bay at south of section.
Outcrop quality: Clean well exposed low coastal cliffs and wave cut platform.
Stratigraphic position: Uncertain.
Length of logged section: 80m

The Lurn
Location: South west facing headland on the south western edge of North Ronaldsay. Section starts at 'castle'-like structure of faulted blocks on shore at The Lurn (HY749531), ends at the corner where coast changes to face south east (HY749521).
Structure: Beds dip to the south east. Frequent small faults of little throw. Section ends at normal fault of unknown throw.
Outcrop quality: Clean, low coastal cliffs and wave cut platform.
Stratigraphic position: Uncertain.
Length of logged section: 26m

Dennis Ness

Location: Northern tip of north east facing coast on the north eastern point of North Ronaldsay. Section from Versa Geo (HY786562) to Point of Sinsoss (HY785565).
Structure: Beds gently dipping to the north west. Occasional faults of small throw.
Outcrop quality: Clean, wave cut platform.
Stratigraphic position: Uncertain.
Length of logged section: 62m

West Mainland

About a third of west Mainland is composed of Rousay Formation sediments, although doubt could be placed on the accuracy of the boundaries of the formations marked by the Geological Survey.
The uninterrupted transition from Upper Stromness Flagstone Formation to Rousay Formation is traditionally placed on the north Mainland coast, south of Eynhallow at Evie.

*Evie

Location: The section is the north east facing coastline running from a slurry outflow 50m west of the Know of Grugar (HY355273), to an undercut brough at the Knowe of Stenso (HY364268).
Structure: The beds dip at between 5 and 10 degrees to the east. Several small north south trending faults are seen, but are thought to have small displacements.
Outcrop quality: Moderate, intertidal exposure, with low cliffs also present in the section. Difficulties are experienced towards the east of the section as sand tends to obscure the rock in several places.
Stratigraphic position: This section includes the top of the Upper Stromness Flagstone Formation and the base of the Rousay Flagstone Formation. The boundary is indicated by the return of well defined laminite facies in the base of the Rousay Flagstone Formation.
Length of logged section: 54m Upper Stromness Formation and 49m Rousay Formation.

Muckle Billia Fiold

Location: On north west slope of Muckle Billia Fiold (HY352239), near Woodwick, north coast of Mainland. Exposure found at the side of peat track that joins the B9057 Dounby-Evie road at Breeran.
Structure: Beds dip 1-2 to the south west.
Outcrop quality: Extremely patchy, mainly along the drainage ditch at the side of the track.
Stratigraphic position: Upper Rousay Flagstone Formation. This section is important because it contains the Sacquoy Sandstone Member.
Length of logged section: approximately 18m.

Houton Head

Location: South west facing coast of Houton Head, Mainland. Section starts where the sand gives way to rock, south of Breck (HY039033) and finishes at the point of Houton Head (HY033039).
Structure: Beds dip at 4-6 to the south east. Faulting and brecciation very common.
Outcrop quality: Tidal section with lichen covering much of the exposed rock.
Stratigraphic position: Section covers the top of the Rousay Flagstone Formation and the base of the Eday Group.
Length of logged section: 46.3m Rousay Flagstone Formation.

East Mainland

This part of Orkney includes all of Mainland east of a line drawn north south through Kirkwall, Burray and South Ronaldsay. In contrast to the Northern Isles, the Geological Survey mapped lots of faults in this area. The validity of many of these faults is however in doubt. It is thought that they were put into explain missing units of the Eday Group (pers. comm. J. Marshall), rather than evoke a mechanism of lateral facies change.

Inganess

Inganess is a series of peninsulas to the immediate north east of Kirkwall.

*Head of Work

Location: North coast of the Head of Work, from west of the big stack (HY482140) to where section ends under seaweed on the north west extremity of the Head of Work (HY476411).
Structure: Beds dip at 20 to the west north west. Zone of deformation and faulting at north western end of section. Otherwise occasional small faults.
Outcrop quality: Low intertidal coastline. Little exposure at high tide.
Stratigraphic position: Base Rousay Flagstone Formation
Length of logged section: 97 m.

Skerry of Work
Location: East facing coast of the Bay of Meil and the Bay of Work. Section starts at noticeable east north east trending fault on west side of Bay of Meil (HY477122) and finishes under the sand of Bay of Work (HY479130).
Structure: Beds dip moderately to the north north east. Throughout section are zones of brecciation and faulting.
Outcrop quality: Intertidal exposure with poor exposure above HWM. Sand obscures some of section.
Stratigraphic position: Top Upper Stromness Flagstone Formation, base Rousay Flagstone Formation.
Length of logged section 132.2m

South Campi Geo
Location: South east facing coast at the far end of the Head of Work. Section starts at (HY484136) and finishes at (HY485138).
Structure: Beds dip at 15 to the north east. Occasional minor faults.
Outcrop quality: Good low cliff exposure above HWM.
Stratigraphic position: Uncertain – Rousay Flagstone Formation.
Length of logged section: 67m

*Tankerness
Location: Tankerness is a peninsula to the east of Kirkwall, and the section comprises the east facing coast from Gumpick (HY545088) to just south of Murton (HY 545097).
Structure: The beds dip at around 10 degrees to the north. The northern part of the section (from around Bothe Geo (HY545094) northwards) the section is cut by numerous north east trending faults of possibly considerable throw.
Outcrop quality: generally poor intertidal and patchy cliff top exposure.
Stratigraphic position: Probably bottom three-quarters of the Rousay Flagstone Formation.
Logged thickness: 130m with the upper 40m highly faulted.

Rose Ness
Location: These three sections occur as three consecutive units in Rose Ness - the south east corner of Mainland. They extend from Black Geo (ND522987) in the south up to Led Geo (ND527994) in the north.
Structure: in all cases the beds dip at between 15 to 25 degrees to the north northwest. The three sections are internally mostly unfaulted, but are separated by faults of potentially large throw.
Outcrop quality: Mainly good clifftop exposure where vegetation has been removed by storms, as well as clean inclined bedding planes between geos.
Stratigraphic position: The stratigraphic position of the rocks is uncertain. However, in the section, between Dishan (ND524988) and Pantie Geo (ND424989), a granule rich sandstone bed was seen with overlying reddened silts. The rare occurrence of particles larger than sand, suggests that the granule bed may represent the Sacquoy Sandstone Member. The reddened sediment may also be indicative of the top of the Rousay Formation.
The relative positions of the three fault bounded sections is uncertain due to the shortness of the individual sections, the fact that the sections do not resemble and stratigraphically fixed section nearby and uncertainty over the magnitude of the throws of the block bounding faults.
Logged thickness: Rose Ness 1: 47m, Rose Ness 2: 47m, Rose Ness 3: 50m.

Deerness
Deerness is the most easterly part of Mainland, and is connected to Mainland proper by a short causeway. The junction between the Eday Group and the Rousay Flagstone Formation is seen three times in this area.

Stembister

Location: South east facing coast at Stembister (HY541025), south east Mainland. Short coastal section to the south west of the farm. Inaccessible cliff sections to the south.
Structure: Beds dip at 10 to the north north east. Not faulted.
Outcrop quality: Low coastal cliffs, good exposure.
Stratigraphic position: Boundary between Rousay Flagstone Formation and the Eday Group.
Length of logged section: 12.4m RFF

Taracliff Bay

Location: South west facing coast forming the link between Deerness and Mainland. Section starts to the south east of the heavily faulted area in the north of the bay (HY552034), and continues on into the high cliffs south west of Craigfield (HY554032).
Structure: Beds dip gently to the east. Beyond zone of fracturing and brecciation at the start of the section frequent small strike slip faults.
Outcrop quality: Poor intertidal and grassy cliff.
Stratigraphic position: Boundary between Rousay Flagstone Formation and the Eday Group.
Length of logged section: 39m

Tammy Tiffy

Location: Approximately half way up the east facing coast of Deerness. Section start on the coast north east of Horraquoy (HY590054) and continues south towards the arches at Tammy Tiffy (HY589052).
Structure: Beds dip gently south east. Start of section moderately faulted with faulting becoming less common up section.
Outcrop quality: Good intertidal. Sand obscures some outcrop in lower part of section. Low cliffs in upper part of section.
Stratigraphic position: Boundary between Rousay Flagstone Formation and the Eday Group.
Length of logged section: 35m RFF.

Southern Isles

Introduction
This section includes all the logged islands that occur south of Mainland. Flotta, Burray and South Ronaldsay are composed of large fault bound blocks. No major folding occurs on these islands.

Burray Ness

Location: A north facing shore on the east side of Burray, from the point of Burray Ness (ND507965) to Muckle Geo (ND497965).
Structure: The northwesterly dipping beds decrease in dip westward, from 20 degrees at Burray Ness to 8 degrees at Muckle Geo. No faulting is present.
Outcrop quality: Outcrop occurs in a broad intertidal zone which is prone to high tides and winds. Difficulties in identifying lithologies are experienced due lichen growth.
Stratigraphic position: Possibly top two Upper Stromness Flagstone Formation cycles and bottom 8 Rousay Flagstone Formation cycles. Problems with correlation occur because the facies seen in this area are quite different to those seen elsewhere in Orkney. For example there are several well developed lake units with more than of 10m of organic matter rich sediment present - more than twice the average thickness of organic rich facies seen in the north. There is also very little fluvial facies development.
Logged thickness: 140m

*South Halcro Head

Location: East facing coast of Halcro Head from Rami Geo (ND472850) to the headland just south of Halcro Head (ND475855). Two parts of this section required climbing equipment to access.
Structure: Beds dip 20-30 north. Unfaulted. Immediately beyond the end of this section is a 5m thick recumbent, faulted fold, indicative of compression from the west.
Outcrop quality: Clean cliff faces, and scrubby intermittent cliff top exposure.
Stratigraphic position: Top 8 cycles of the Upper Stromness Flagstone Formation and bottom 5 Rousay Flagstone Formation cycles.

Length of logged section: 96.72m USFF, 34.55m RFF.

*North Halcro Head

Location: North east facing coast of Halcro Head to the south east of Quoyorally. Access to shore is gained by climbing down long grassy slope, and then following the shore to the south east as far as possible (ND469861). Section ends at large fault gap at Great Head (ND464863).
Structure: Beds dip at 20 to the north west. Fault of uncertain throw occurs at end of section.
Outcrop quality: Intertidal exposure at the base of high cliffs. Often covered in treacherous green slime.
Stratigraphic position: Upper portion of the Rousay Flagstone Formation
Length of logged section 77.6m

*Hoxa Head

Location: North west facing coast of Hoxa from Moi Geo (ND406935) to Croo Taing (ND415944), and then patchily half way along the north east facing coast.
Structure: Beds dip gently/moderately to the north east. Small faults occasionally cut section.
Outcrop quality: Good intertidal and exposed rock above HWM. Occasional sandy/cobbly bays occur but obscure little of the section. Last 10m of section poorly exposed – covered mostly with seaweed and sand.
Stratigraphic position: Top of Upper Stromness Flagstone Formation and most of the Rousay Flagstone Formation.
Length of logged section: 199.9m

South Hoxa Head

Location: South east facing coast of Hoxa from just east of the 'castles' (ND419935), north east to where the section disappears under the Sands of Wright (ND421936).
Structure: Beds dip 20 degrees to the northeast. Start of section dominated by faults of potentially large throw.
Outcrop quality: Moderate at the base of high sea cliffs.
Stratigraphic position: Uncertain – Rousay Flagstone Formation.
Length of logged section: 65m.

North Brough Ness

Location: West facing coastline of Brough Ness, between a highly (north-south) faulted zone in the south of Brough Ness (ND444829), north to where exposure stops near Burwick (ND443838).
Structure: The beds dip north northwest and decrease from 15 degrees in the south to 8 degrees in the north. Several small rucks and faults are present.
Outcrop quality: Poor. Exposure is in a wide flat intertidal zone, rich in seaweed and gavel.
Stratigraphic position: Uncertain, contains thick units of organic rich non-laminite facies containing stromatolites. Possibly Lower Stromness Flagstone Formation (Marshall 1998).
Logged thickness: 178m.

South Brough Ness

Location: South facing coastline east from Morris Geo (ND447826) to the boulder beach south of Liddel Loch (ND 454832).
Structure: The strata dip at 15 degrees to the north northwest. Several northeast southwest trending faults of small displacement occur towards the eastern end of the section.
Outcrop quality: Good exposure above the high water mark, which is scoured clean by waves and wind.
Stratigraphic position: Uncertain. One instance of red silt and a thick stromatolite horizon occur near the base of this section. Sheet floods are more prominent in this section than anywhere else in the south of Orkney. Cycle thicknesses are also not uniform. Possibly Lower Stromness Flagstone Formation (Marshall 1998).
Logged thickness: 106m.

Flotta

This island is situated between the islands of Hoy and South Ronaldsay. It is divided into a northern section composed of Eday Group sediments and a southern part composed of Rousay Flagstone Formation sediments, by a north west trending fault.

*Head of Banks

Location: Coast on the west side of Kirk Bay on the south side of the island. Section from ledge above LWM at the southernmost point (ND362923) to where outcrop disappears under beach near Whitehouse (ND363929).
Structure: Beds dip gently to the north north east.
Outcrop quality: The southern half of the section is composed of low cliffs above HWM, and the northern half is composed of tidal shoreline.
Stratigraphic position: Lower part of the Rousay Flagstone Formation.
Length of logged section: 62m

North Hoy

Aikel of Flett

Location: The north coast of Hoy at the Aikel of Flett (HY211051) - (HY028050). The location is easily found, because beyond this point the coast becomes seriously steep and inaccessible.
Structure: Unfaulted with strata dipping gently towards the south west.
Outcrop quality: The lower portion of this section is beautifully exposed wavecut platform, accessible only from above. The section passes upward into a poorly exposed stream section found by the position of a small waterfall. The transition into the overlying 'ashy sediments' of the Hoy volcanic succession is not seen.
Stratigraphic position: Upper Stromness Flagstone or the lower part of the Rousay Flagstone Formation, passing up into the Hoy Volcanic succession
Length of logged section: 55m.

Appendix 2

Palynological data from cycles 26 and 36 Rousay Flagstone Formation

Summary of palynological data, cycle 36, Rousay Flagstone Formation.

	sample	cm	mf	toc	abspore	R.D.	H/C	ave Re
Loth Quarry	1	50	4					
	2	70	4	0.5	54			
	3	100	4					
	4	120	1	1.1			1.3	
	5	130	1					
	6	140	1	1.2				
	7	150	1					
	8	160	1	1.0	24			
	9	170	1					
	10	180	1	1.1			1.26	
	11	190	1					
	12	120	1	1.2	30			
	13	145	2					
	14	165	2	0.8	0			
	15	185	2					
	16	205	2	0.5				
	17	225	2					
	18	255	3					
	19	285	3	0.7	210	102		
	20	315	3					
	21	345	3	0.0				
Hoxa Head	1	80	5					
	2	120	3	0.7	474	114		
	3	160	3					
	4	180	3	0.6				0.09
	5	200	3					
	6	220	3	0.1	600	117		
	7	240	3					
	8	260	3	0.7	366	117		
	9	280	3					
	10	300	3	0.6				
	11	320	3	0.5				
	12	360	1	0.6	324	104		
	13	380	3	0.5	318	110		
	14	405	5	0.0				

Key:

sample	sample number
cm	centimetres from base of cycle
mf	microfacies: 1=laminite, 2=near laminite, 3=dark silt, 4=Wick, 5= grey silt
toc	percentage total organic carbon of samle
abspore	Number of spores per gram whole rock, from kerogen treated by ultrasound
R.D.	Average diameter Rhabdosporites langii all spores from abspore isolates
H/C	Atomic hydrogen/carbon ratio of kerogen isolates
ave Re	Exinite reflectivity averege from approx.30 readings

Summary of palynological data, cycle 36, Rousay Flagstone Formation.

	sample	cm	mf	toc	abspore	R.D.	H/C	ave Re
Rousay	1	35	4	0.2	24			
	2	60	4	1.2	0			
	3	70	1	1.2	6			
	4	85	1					
	5	110	1	2.1	54			
	6	120	5	0.6	18			
	7	150	5					
Noup Head	1	10	3					
	2	20	3	0.5	36			
	3	30	3					
	4	40	1	1.0	0			
	5	50	1	1.9	54			
	6	70	1	1.4	114	92		
	7	80	1	1.6	18			
	8	90	5	0.2				
Halcro Head	1	10	3	0.1	576	124		
	2	20	3	0.1				0.24
	3	35	4	0.1	12			
	4	50	4	0.1	36			
	5	70	5	0.1	90	104		
	6	85	5					
	7	95	5	0.1	42			
North Faray	1	15	4	0.6	492	107		
	2	25	4	0.9				0.12
	3	40	3	0.9	552	102		
	4	55	3					
	5	75	3	0.9	792	102		
	6	90	2	0.9	738	102		
	7	100	2	1.1				
	8	125	4					
	9	145	4	0.7	528	104		
	10	165	4					
	11	185	4	0.2				
Fers Ness	1	20	2	0.7	66			
	2	40	2					
	3	60	2	1.0	42			
	4	80	2	0.6				
	5	100	2	0.6	12			
	6	120	2					
	7	140	3	0.4	0			
	8	160	3					
	9	180	3	0.3	90			
	10	200	3					
	11	220	3	0.1				

Summary of palynological data, cycle 26, Rousay Flagstone Formation.

	sample	cm	mf	toc	AOM%	abspore	S.D.	R.D.	H/C	H/C run 2	O/C	ave Re
Evie	1	5	3	0.10	95.7							
	2	30	3	1.12	83.0	18	83			1.35	0.34	
	3	50	3	0.78	82.7	6				1.20	0.29	
	4	70	3	0.67	92.7					1.08	0.14	
	5	85	1	1.23	90.3	30	87			1.42	0.37	
	6	95	1	1.02	98.0					1.13	0.10	
	7	105	1	1.20	95.7		85			0.88	0.13	
	8	115	1	1.75	96.0	198		87	0	1.22	0.09	0.31
	9	125	1	1.76	97.7	402	107	99		1.20	0.07	
	10	135	1	2.47	95.3				1.00	1.02	0.15	0.18
	11	145	1	1.75	98.0		100.5		1.40	1.08	0.06	
	12	155	1	1.10	96.0					1.13	0.10	
	13	165	3	1.15	95.3		100			0.91	0.08	
	14	185	3	1.25	88.7	54				1.30	0.29	
	15	205	3	0.95	80.3		93					
	16	225	3	0.73						1.29	0.37	
	17	245	3	0.37	91.3		76					
	18	265	3	0.44								
	19	285	3	0.38			47.9			0.95	0.33	

Key:

sample	sample number
cm	centimetres from base of cycle
mf	microfacies: 1=laminite, 2=near laminite, 3=dark silt, 4=Wick, 5= grey silt
toc	percentage total organic carbon of samle
AOM%	Percentage AOM from a count of 300, from whole kergen isolate
abspore	Number of spores per gram whole rock, from kerogen treated by ultrasound
S.D.	Average spore diameter, all spores, whole kerogen isolate.
R.D.	Average diameter *Rhabdosporites langii* all spores from abspore isolates
H/C	Atomic hydrogen/carbon ratio of kerogen isolates
O/C	Atomic oxygen/carbon ratio of kerogen isolates
ave Re	Exinite reflectivity averege from approx.30 readings

Summary of palynological data, cycle 26, Rousay Flagstone Formation.

	sample	cm	mf	toc	AOM%	abspore	S.D.	R.D.	H/C	H/C run 2	O/C	ave Re
Hoxa Head	1	40	5	0.20	94							
	2	60	5	0.13	86							
	3	85	4	0.15	95.3	12						
	4	105	4	0.58	18.3	312	89	118				0.14
	5	125	4	0.07	44.0	90			1.19			
	6	145	4	0.13	23.7	438	93	100				
	7	165	4	0.65	64.0	360		108	11*	10.68*	* contamination	
	8	185	4	0.43	69.3	42	94		1.17			
	9	205	4	0.16	82.7							
	10	225	4	0.09	67.7							
	11	245	4	0.34	45.3		90					
	12	265	4	0.07	0.0							
	13	285	5	0.16	98.3							
	14	325	3	0.44	84.0							
	15	345	3	0.31	80.7		91					
	16	365	3	0.20	65.0							
	17	385	3	0.25	83.7							
	18	405	3	0.13	15.0		108					
Halcro Head	1	40	4	0.12	50.7	384	89	122				
	2	80	4	0.46	75.7	108		97				
	3	120	4	0.33	92.3	54	86					
	4	160	4	1.25	95.7				2.2*			
	5	220	3									
	6	240	3									
	7	280	3	1.21	83.3		93				* contamination	
	8	320	3	2.34	98.3				2.03*			
	9	360	3	1.41	94.3		79		3.06*	2.53*		
	10	380	3	1.02	95.3	360		112				
	11	415	3	0.69	94.0	102						
	12	450	5	0.22	63.3	174	86	75				
	13	510	4	0.28	82.3		87					
	14	550	4	0.40	93.0							
Flotta	1	20	4	1.03	96.7							
	2	40	4	3.10	98.0							
	3	60	4	2.82	95.3	198		102				
	4	80	4	2.69	95.3	156		104	1.56			
	5	100	1	7.46	96.0				1.64			
	6	115	1									
	7	130	1	3.98	87.3							
	8	145	1	6.11	90.7				1.78			
	9	165	2	2.53	84.3							0.12
	10	185	2	1.78	87.7	540		106				
	11	205	2	1.45	78.3	276		91				
	12	225	2	0.91	92.7	186	81	80				
	13	245	4	0.45	87.3							
	14	265	4	0.28	81.3		76					
	15	285	4	0.36	89.7							
	16	325	4	0.19	95.0		80					
	17	365	4	1.29	97.0							
Fers Ness	1	40	4	0.94	83.3		80.11					
	2	80	4	0.70	80.7							
	3	120	4	0.31	93.0		71.32					
	4	140	4	0.68	88.3							
	5	155	3	0.83	79.7		85.57					
	6	165	2	1.25	84.7							
	7	175	2	0.97	96.7		84.15		1.10			
	8	185	2	0.89	88.3							
	9	195	3	0.73	76.3		68.95					
	10	215	3	0.76	82.0							
	11	235	3	0.53	97.3		68.5					
	12	255	3	0.57	96.3							
	13	275	3	0.81	89.7		79.2					
	14	305	3	0.91	97.3				0.97			
	15	325	3	0.84	95.3		51.16		0			
	16	345	3	0.26	95.7							

Summary of palynological data, cycle 26, Rousay Flagstone Formation.

	sample	cm	mf	toc	AOM%	abspore	S.D.	R.D.	H/C	H/C run 2	O/C	ave Re
Surrigarth	1	20	4	1.42	98.3					1.52	0.07	
	2	40	4	2.09	98.7		110			1.38	0.15	
	3	50	1	1.07	97.3					1.68	0.06	
	4	60	1	1.95	96.0					1.55	0.07	
	5	70	1	1.28	95.3	210				1.59	0.06	
	6	80	2	0.30	95.7	252	83.23	102		1.44	0.10	
	7	90	2	0.30	96.0	474		103				0.09
	8	100	2	0.24	96.0		87.67			1.51	0.09	
AOM%/244	9	110	2	3.48	79.7				1.76	1.59	0.07	
	10	120	2	4.84	98.0				1.62	1.51	0.05	
	11	145	3	3.24					1.33	1.51	0.08	
	12	165	3	1.51	98.3					1.51	0.09	
	13	185	3	1.70	93.3	510	74.67	99		1.56	0.08	
	14	205	3	1.27	95.0	624		105		1.51	0.19	
	15	225	3	1.30	84.7	480	81.48	85				0.06
	16	245	3	1.14	91.0					1.25	0.10	
	17	265	3	1.05	95.3					1.71	0.08	
Huip Ness	1	100	4									
	2	140	4	0.67	80.7	0			0.67			
	3	190	3									
	4	230	3		83.3	0						
	5	270	3									
	6	315	4	0.19	94.3	0			1.12			
	7	355	4									
	8	395	4		82.0	6						
AOM%/150	9	435	4	0.21	96.0	6						
	10	475	4		90.3	6						
	11	515	4									
	12	585	4									
	13	625	4	0.60	95.0				0.54			
	14	665	4									
	15	715	5	0.28	92.0							
	16	765	5									
	17	815	5		91.0							
	18	865	5									
	19	965	5	0.26	69.7							
Spurs Ness	1	25	4	0.55	89.7							
	2	80	3	0.66	91.3		81.1					
	3	110	3	0.79	96.7							
	4	140	3	0.67	94.3	6	73.6					
	5	165	2	0.65	90.0	0						
	6	185	2	0.69	94.3	6	84.35					
	7	205	2	0.88	96.0				0.90			
	8	225	2	0.85	97.0		76.02					
	9	245	2	0.80	97.3				0.00			
	10	280	4	0.72	84.3		84.02					0.22
	11	310	4	0.77	98.0							
	12	330	4	0.92	96.0	6	69.95		1.10			
	13	342	3	0.92	98.7	12						
	14	390	3	0.84	94.0							
	15	430	3	0.57	67.0	36	72.36					0.2
	16	470	3	0.54	94.0							
	17	510	3	0.61	87.0		76.46					
	18	550	3	0.47	90.0							
	19	590	3	1.15	81.3							
	20	620	3	0.56	92.7		75.97					
	21	680	5	0.15								
	22	720	5	0.14								
	23	780	5	0.15								
Rousay	1	10	2	0.93	89	54	77.5					
	2	25	2	0.90	88.7	12						0.27
	3	35	2	2.32	93.7	72	88.12					
	4	45	2	2.46	98.0				1.24			
AOM%/263	5	65	1	2.60	99.2	198		89	1.21			
	6	75	1	0.98	96.7		82.18					
	7	85	2	0.73	96.3	6						
	8	95	2	1.51	97.0		85.83		0.64			
	9	105	2	0.72	94.0	18						
	10	125	5	1.22	95.3		80.54					
	11	150	5	0.67	88.3		94.5					

Summary of palynological data, cycle 26, Rousay Flagstone Formation.

	sample	cm	mf	toc	AOM%	abspore	S.D.	R.D.	H/C	H/C run 2	O/C	ave Re
Head of Work	1	50	4	0.41	92.3							
	2	100	4	0.52	95.3	0						
	3	150	4	0.80	93.0	0						
	4	200	4	0.51	94.3	18						
	5	225	3	0.70	97.7							
	6	280	3	0.78	96.7							
	7	300	3	1.52								
	8	340	3	1.04		0						
	9	380	3	1.28	98.3	6						
	10	420	1	1.28		6			0.58			
	11	430	1	1.37					1.12			
	12	440	1	1.40	98.0				0.95			
	13	460	1	1.16								
	14	505	2	0.84								
	15	545	2	0.79	99.3							
	16	585	2	0.76								
	17	625	2	0.64								
	18	655	2	1.02								
	19	690	5	0.31								
	20	720	5	0.18								
Wars Ness	1	30	4	0.07	96		44.3					
	2	75	3	0.51	97.0	0	40.8					
	3	130	3	0.83	98.3				0.77			
	4	150	3	0.69	98.3							
	5	170	3	0.70	98.3							
	6	210	3	0.50	96.0	6	55.4					
	7	225	3	0.35	97.3	0	76					
	8	240	3	0.95	97.0	0	60.7					
	9	290	1	0.97	98.7		50					
	10	330	1	0.83	98.0		47.3					
	11	370	1	0.85	99.7				1.05			
	12	410	1	0.78	98.0	0						
	13	440	1	0.76	98.0		53.8					
	14	470	1	0.71	99.7							
	15	560	3	1.15	98.3		52		1.13			
	16	600	3	0.42	97.0		54.8					
	17	640	3	0.77	98.0							
	18	685	5	0.62	98.0	0	50					
	19	715	3	0.27	97.3		56.9					
	20	800	5	0.78	98.3		52					
	21	870	5	0.47	98.3							
	22	895	3	0.77	97.0		69					
	23	935	5	0.53	98.0							
Tankerness	1	10	4	0.68	96.7				0.73			
	2	200	4						0.36			
	3	260	4									
	4	295	3	0.40	95.0							
	5	315	3		96.7							
	6	335	3									
	7	355	3	0.58	95.3							
	8	385	3									
	9	405	3	0.45	97.0				1.56			
	10	425	3									
	11	445	3	0.47	94.3							
	12	465	3									
	13	485	3		93.0							
	14	505	3									
	15	545	3									
	16	605	3	0.14	93.3							

Appendix 3

Breakdown of facies logged

Evie, Mainland. Facies thickness and percentage breakdown.

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CASF	CH	G/C	GAP
31	cm	465	20		80							195	170							
	%		4		17							42	37							
30	cm	430		50	110							130	15		85					40
	%			12	26							30	3		20					9
29	cm	800		180	155							110	195		20					140
	%			23	19							14	24		3					18
28	cm	735	25		190						385									135
	%		3		26						52									18
27	cm	990	90		110	60					170	70	55		45					390
	%		9		11	6					17	7	6		5					39
26	cm	680	90		120	65					380				25					
	%		13		18	10					56				4					
25	cm	920	195		50		60		10	45	60	140		180	180					
	%		21		5		7		1	5	7	15		20	20					
24	cm	490					135				205									150
	%						28				42									31
23	cm	785			50						370	255			30					80
	%				6						47	32			4					10
22	cm	1095					50				345	165		485	50					
	%						5				32	15		44	5					
21	cm	705				135	130				295			50	95					
	%					19	18				42			7	13					
20	cm	525			145		200				35		10		75					60
	%				28		38				7		2		14					11
19	cm	885								10	410			420	45					
	%									1	46			47	5					
18	cm	560			255						95			125	85					
	%				46						17			22	15					

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Fers Ness, Eday, Facies thickness and percentage breakdown

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
40	cm	420			150		30				80	160								
	%				36		7				19	38								
39	cm	2585			155						40	1470	40	150	180			550		
	%				6						2	57	2	6	7			21		
38	cm	1710			200	150					270					300	115	205	50	420
	%				12	9					16					18	7	12	3	25
37	cm	1830	35	35	70	45	215				190	160	150	80	115	190	90	435	20	
	%		2	2	4	2	12				10	9	8	4	6	10	5	24	1	
36	cm	415		120			70		35			100			45	45				
	%			29			17		8			24			11	11				
35	cm	1195			340							265			110	110	95	235	40	
	%				28							22			9	9	8	20	3	
34	cm	1680			140	180		110			365	800	25							60
	%				8	11		7			22	48	1							4
33	cm	1460	70		200	120					440	120		285	75					150
	%		5		14	8					30	8		20	5					10
32	cm	1115	125	110			35		40		410	120	10	170	25					70
	%		11	10			3		4		37	11	1	15	2					6
31b	cm	785							335		255	60		135						
	%								43		32	8		17						
31a	cm	2290		35	300	180					445	295	50	655	10	320				
	%			2	13	8					19	13	2	29	0	14				
30	cm	1135			95	45		100			335		290	150	70		25	25		
	%				8	4		9			30		26	13	6		2	2		
29	cm	1220			60	200		30				160	575	50	70		75			
	%				5	16		2				13	47	4	6		6			
28	cm	2020			30	280			85		900		65	455	95	105	5			
	%				1	14			4		45		3	23	5	5	0			
27	cm	1500	20	100	110	405					570			285	10					
	%		1	7	7	27					38			19	1					
26	cm	1090		30	110	60				10	180	315		335			50			
	%			3	10	6				1	17	29		31			5			
25	cm	790		50		130	40		145		125	125	120		35					
	%			6		16	5		18		16	16	15		4					
24	cm	1690							210	5	745			245	20	335	60	70		
	%								12	0	44			14	1	20	4	4		
23		1611				100				125	510	825			51					
						6				8	32	51			3					

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Loth Quarry, Sanday. Facies thickness and percentage breakdown.

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
39	cm	2190							130		360	210	120	1025	130		215			
	%								6		16	10	5	47	6		10			
38	cm	2150	110			35		190			400	100	195	885	165					70
	%		5			2		9			19	5	9	41	8					3
37	cm	1615	60	50	30	50						595	5	100	325	400				
	%		4	3	2	3						37	0	6	20	25				
36	cm	860		195							120	25		415	105					
	%			23							14	3		48	12					
35	cm	1400				45		625	100			7		410	60		35		35	80
	%					3		45	7			1		29	4		3		3	6
34	cm	1170			180	345					400			245						
	%				15	29					34			21						
33	cm	1670	485		75	295					130	670			15					
	%		29		4	18					8	40			1					
32	cm	1040	120		70				150			400		300						
	%		12		7				14			38		29						
31b	cm	800	100		200							300		200						
	%		13		25							38		25						
31a	cm	2015	100				105	420	100			1200			90					
	%		5				5	21	5			60			4					

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Noup Head, Westray. Facies thickness and percentage breakdown

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
38	cm	1060	75		165				95					700	25					
	%		7		16				9					66	2					
37	cm	826		50	110				60			140	115	330	20				1	
	%			6	13				7			17	14	40	2				0	
36	cm	585		55		30						490	10							
	%			9		5						84	2							
35c/b	cm	1170									70	405	45	115		520		15		
	%										6	35	4	10		44		1		
35a	cm	555									180	70	5		145	135	5		15	
	%										32	13	1		26	24	1		3	
34	cm	1100		15	80	165				50	250	70	110			210	100	50		
	%			1	7	15				5	23	6	10			19	9	5		
33	cm	290	40		35	30							50	135						
	%		14		12	10							17	47						100
32	cm	602		80	72						100		105	30		215				
	%			13	12						17		17	5		36				
31b	cm	750									325	10	140	180	100					
	%										43	1	19	24	13					
31a	cm	840									475		170		140	55				
	%										57		20		17	7				
30	cm	830			150	120				5	215	30		205	105					
	%				18	14				1	26	4		25	13					
29	cm	778		45	58	130				55	90		35	200	125			40		
	%			6	7	17				7	12		4	26	16			5		
28	cm	830			40	215					200		5	225	45		100			
	%				5	26					24		1	27	5		12			
27	cm	1660								165	495		60	565	265		60	50		
	%									10	30		4	34	16		4	3		

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Rousay. Facies thickness and percent breakdown.

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
37	cm	330	65	35	10	30			50							140				
	%		20	11	3	9			15							42				
36	cm	325		50			45		100		30		40		40		20			
	%			15			14		31		9		12		12		6			
35c	cm	247							90		60		17			80				
	%								36		24		7			32				
35b	cm	1175									320				40	590	65	35	115	
	%										27				3	50	6	3	10	
35a	cm	1707		55	100					97	540		130		140	285	360			
	%			3	6					6	32		8		8	17	21			
34	cm	625			10		35		145	15	105	75	60	135	45					
	%				2		6		23	2	17	12	10	22	7					
Gap	cm																			
27	%	870	85	50	45		75				345			250	20					
	cm		10	6	5		9				40			29	2					
	%																			
26	cm	830	55	75	25		245				250				130		50			
	%		7	9	3		30				30				16		6			
25	cm	1045	45	75	10	50	200	20		100	385	5		110	15	40				
	%		4	7	1	5	19	2		10	37	0		11	1	4				
24	cm	1895		40	130	45			55	135	280	430	35	685	60					
	%			2	7	2			3	7	15	23	2	36	3					
23	cm	1530				25	140		220	55	200	60		475	100	185		70		
	%					2	9		14	4	13	4		31	7	12		5		
22	cm	1090		45	195	125	20				185		35	360	95		30			
	%			4	18	11	2				17		3	33	9		3			
21	cm	860			120		130				315			270	25					
	%				14		15				37			31	3					
20	cm	1990			125	620	140		70		190	75		585	160			20		
	%				6	31	7		4		10	4		29	8			1		

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Spurs Ness, Sanday. Facies thickness and percentage breakdown.

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
31a	cm	2035	195	65	315			180			305	850	105		20					
	%		10	3	15			9			15	42	5		1					
30	cm	1095	155		90			125	340			110	60	215						
	%		14		8			11	31			10	5	20						
29	cm	1205	25			70		275	165			310	20	300	20					20
	%		2			6		23	14			26	2	25	2					2
28	cm	1105							95		75	795	130				10			
	%								9		7	72	12				1			
27	cm	1665	80	50	290	10		270	20		565		55	240	85					
	%		5	3	17	1		16	1		34		3	14	5					
26	cm	1125		105	110	270	30	135					160	315						
	%			9	10	24	3	12					14	28						
25	cm	1430			20	95		405				625	5	160	120					
	%				1	7		28				44	0	11	8					
24	cm	2575		175	345	325	245				20	725	45	290	305			55		45
	%			7	13	13	10				1	28	2	11	12			2		2
23	cm	1775	135	300	60	35		160			225	385	50	380	45					
	%		8	17	3	2		9			13	22	3	21	3					
22	cm	1395			175	410			70		200		150	340	50					
	%				13	29			5		14		11	24	4					
21	cm	235			20	40			90			75			10					
	%				9	17			38			32			4					
20	cm	915									165	735			15					
	%										18	80			2					
19	cm	1920							85	10	730	150		500	190	130	125			
	%								4	1	38	8		26	10	7	7			
18	cm	800			285	140			100		145			130						
	%				36	18			13		18			16						
17	cm	820				445			40		35	265			35					
	%					54			5		4	32			4					
16	cm	1245	200	100	110				65		195	560	15							
	%		16	8	9				5		16	45	1							

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Surrigarth, Westray. Facies thickness and percentage breakdown.

Cycles		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
28	cm	865		60	100				230		85			390						
	%			7	12				27		10			45						
27	cm	2620	30	15	130				140		590		345	1310	60					
	%		1	1	5				5		23		13	50	2					
26	cm	1385	85	140					300		210			340	310					
	%		6	10					22		15			25	22					
25	cm	1385	80	50	50		15		80	40	130	80	60	800						
	%		6	4	4		1		6	3	9	6	4	58						
24	cm	1225					50			190	525		170	150	140					
	%						4			16	43		14	12	11					
23	cm	2010							180		250	30	400	1130	20					
	%								9		12	1	20	56	1					
22	cm	851			211						280	60	90	190	65					
	%				25						33	7	11	22	8					
21	cm	845			110	170					380		30	140	15					
	%				13	20					45		4	17	2					
20	cm	3115								60	220	90	90	2685	10					
	%									2	7	3	3	86	0					
19	cm	1530								590			140	800						
	%									39			9	52						
18	cm	1295		20	330	400					170		45	200	50			80		
	%			2	25	31					13		3	15	4			6		
17	cm	1450			760	100					160	110	160	150	10					
	%				52	7					11	8	11	10	1					
16	cm	1075			220					260			70	470	25		30			
	%				20					24			7	44	2		3			
15	cm	1830			930				60	270				570						
	%				51				3	15				31						
14	cm	1150		390	80				50					610	20					
	%			34	7				4					53	2					
13	cm	1540	150		15				190		470		450	160	80		25			
	%		10		1				12		31		29	10	5		2			
12	cm	1315	70		60				30		535		200	190				230		
	%		5		5				2		41		15	14				17		
11	cm	1585			20		60			60	385	210	810		40					
	%				1		4			4	24	13	51		3					

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Wars Ness, Eday. Facies thickness and percentage breakdown

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
40	cm	975			110			420			50	115	65	100	60		55			
	%				11			43			5	12	7	10	6		6			
39	cm	935									570	245		45			75			
	%										61	26		5			8			
38	cm	1525	100	130	40	80		30			430	350	55	45	20		240			
	%		7	9	3	5		2			28	23	4	3	1		16			
37	cm	1746	140					40	45		95	100		85		980	170	90	1	
	%		8					2	3		5	6		5		56	10	5	0	
36	cm	795			120	60		180				105	80	75	65	110				
	%				15	8		23				13	10	9	8	14				
35	cm	905			5	80			210			260		20		85	245			
	%				1	9			23			29		2		9	27			
34	cm	1745			90	570		65			395	600			25					
	%				5	33		4			23	34			1					
33	cm	1695		175	60	400	65				560	115	45	145	100					30
	%			10	4	24	4				33	7	3	9	6					2
32	cm	790									290	165	25	205	105					
	%										37	21	3	26	13					
31b	cm	850																		850
	%																			100
31a	cm	2145			120	555	55				550	80	15	270	240			260		
	%				6	26	3				26	4	1	13	11			12		
30	cm	1055		30	80	260					75	300	5	285	20					
	%			3	8	25					7	28	0	27	2					
29	cm	1265			190	380	115				185	395								
	%				15	30	9				15	31								
28	cm	1100		10	50	140					250	320	25		270			30		
	%			1	5	13					23	29	2		25			3		
27	cm	1465			315	460					595			45	50					
	%				22	31					41			3	3					
26	cm	1515	70	200	100	300	45	280			85	155	140		90					50
	%		5	13	7	20	3	18			6	10	9		6					3
25	cm	1115					60	455	60			430		110						
	%						5	41	5			39		10						
24	cm	720			10							595			115					
	%				1							83			16					

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Burray Ness. Facies thickness and percentage breakdown

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
31	cm	1405	205	235	415	330	90					130								
	%		15	17	30	23	6					9								
30	cm	680			250			430												
	%				37			63												
29	cm	1535			680	60		645												150
	%				44	4		42												10
28	cm	1615	100	130	35	765		100			485									
	%		6	8	2	47		6			30									
27	cm	1305				150				10		625	110	410						
	%					11				1		48	8	31						
26	cm	1975	50	80	130	765	20	125			375	350			30					50
	%		3	4	7	39	1	6			19	18			2					3
25	cm	1750				175	35	325	20	30	715	450								
	%					10	2	19	1	2	41	26								
24	cm	1965	250	140	805	20	190	250				270								40
	%		13	7	41	1	10	13				14								2

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

North Faray. Facies thickness and percent breakdown.

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
37	cm	1115		115		90		30			105			465		310				
	%			10		8		3			9			42		28				
36	cm	560		70	25			175			180			75	35					
	%			13	4			31			32			13	6					
35	cm	1025			40	70		100			80			230		455			50	
	%				4	7		10			8			22		44			5	
34	cm	980		220		80	70							520	90					
	%			22		8	7							53	9					
33	cm	1120	100		140			160		25	260	345						90		
	%		9		13			14		2	23	31						8		
32	cm	600						205			100			165				130		
	%							34			17			28				22		
31	cm	1875		60				265			900	265	120				35			190
	%			3				14			48	14	6				2			10
30	cm	655			80						275									300
	%				12						42									46
29	cm	1035						315					445	250	25					
	%							30					43	24	2					
28	cm	780			50		155	45			170	200			40					120
	%				6		20	6			22	26			5					15
27	cm	620						50			130	255								185
	%							8			21	41								30
26	cm	1205			280	130				265	305	225								
	%				23	11				22	25	19								
25	cm	985		200				255			70	395			65					
	%			20				26			7	40			7					
24	cm	645				230					250	165								
	%					36					39	26								
23	cm	1355				200	25		55		485	255		80	170		85			
	%					15	2		4		36	19		6	13		6			

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Flotta. Facies thickness and percent breakdown

Cycles		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
30	cm	860	115	30				105			320	220			70					
	%		13	3				12			37	26			8					
29	cm	680		20				275			90	210			55					30
	%			3				40			13	31			8					4
28	cm	1745		40	60	115		215	30		480	435		80	130	40				120
	%			2	3	7		12	2		28	25		5	7	2				7
27	cm	1340	105					205	20	10	615	325			40		20			
	%		8					15	1	1	46	24			3		1			
26	cm	1015	60	80				225		45	495				80	30				
	%		6	8				22		4	49				8	3				

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Head of Work, East Mainland. Facies thickness and percentage breakdown.

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
31	cm	735			365	290		40				40								
	%				50	39		5				5								
30	cm	915			130			280			70			435						
	%				14			31			8			48						
29	cm	750		85	20	130		185	20					310						
	%			11	3	17		25	3					41						
28	cm	1140		45	130	55		500			80	320			10					
	%			4	11	5		44			7	28			1					
27	cm	855			30			215	55		195	40		255	65					
	%				4			25	6		23	5		30	8					
26	cm	1510		65	180	230	100	215		25	215	100		190	190					
	%			4	12	15	7	14		2	14	7		13	13					
25	cm	1020	55		70	240	80	140			220			215						
	%		5		7	24	8	14			22			21						
24	cm	1345			280	305	110	110	95			420			25					
	%				21	23	8	8	7			31			2					
23	cm	800			35				305		35	55		310	60					
	%				4				38		4	7		39	8					

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood, ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Hoxa Head, South Ronaldsay. Facies thickness and percentage breakdown.

Cycles		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
37	cm	455	60		180						50					165				
	%		13		40						11					36				
36	cm	410						165			130						75			40
	%							40			32						18			10
35	cm	1075				500					90					395	50			40
	%					47					8					37	5			4
34	cm	1040			280	120		240			275	30			15	50		30		
	%				27	12		23			26	3			1	5		3		
33	cm	1115							175		80	110	30			380	40			300
	%								16		7	10	3			34	4			27
32	cm	1020			310	140					450					120				
	%				30	14					44					12				
31	cm	550						190	40		220	100								
	%							35	7		40	18								
30	cm	500						275			165			60						
	%							55			33			12						
29	cm	570			265						165	140								
	%				46						29	25								
28	cm	1270		110	130	80		125			495	330								
	%			9	10	6		10			39	26								
27	cm	820		180		235		60	100				40	160	15					30
	%			22		29		7	12				5	20	2					4
26	cm	625			100	260					165	100								
	%				16	42					26	16								
25	cm	835			150						395	265					25			
	%				18						47	32					3			
24	cm	1415			255	175		65		10	785			100	25					
	%				18	12		5		1	55			7	2					
23	cm	925	75					200			95	70		195			190			100
	%		8					22			10	8		21			21			11
22	cm	840	80		230			30			400			100						
	%		10		27			4			48			12						
21	cm	1185						325	50		720	50			15		25			
	%							27	4		61	4			1		2			
20	cm	945	90		155	45		190			275					150				40
	%		10		16	5		20			29					16				4
19	cm	1045						100			505	45	10	170	45					170
	%							10			48	4	1	16	4					16
18	cm	680			110			20			190			160	50					150
	%				16			3			28			24	7					22
17	cm	310						105			175	30								
	%							34			56	10								
16	cm	600						60			375	165								
	%							10			63	28								

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Huip Ness, Stronsay. Facies thickness and percentage breakdown

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
34	cm	1770			725	150	45				675	175								
	%				41	8	3				38	10								
33	cm	1535			245			510			125	510			45					100
	%				16			33			8	33			3					7
32	cm	855						500				355								
	%							58				42								
31b	cm	725					120					565			40					
	%						17					78			6					
31a	cm	1150			165	135	180	395			245				30					
	%				14	12	16	34			21				3					
30	cm	1430			45	145	75	460			175	140		390						
	%				3	10	5	32			12	10		27						
29	cm	995		40				295												660
	%			4				30												66
28	cm	2295		345	140	650		250	305			505								100
	%			15	6	28		11	13			22								4
27	cm	800						140	100			560								
	%							18	13			70								
26	cm	2250						515			1495				240					
	%							23			66				11					

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

North Halcro Head, South Ronaldsay. Facies thickness and percent breakdown

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
39	cm	1220								35	305			170			80	200		430
	%									3	25			14			7	16		35
38	cm	2040								25	540			965		265	80			165
	%									1	26			47		13	4			8
37	cm	530						50			200				30	130			120	
	%							9			38				6	25			23	
36	cm	565			45			20			130						270			100
	%				8			4			23						48			18
35	cm	600		165			30	45					90		270					
	%			28			5	8					15		45					
34	cm	645			95		100	45		15	330					60				
	%				15		16	7		2	51					9				
33	cm	1120						215			650				255					
	%							19			58				23					
32	cm	1665		50		100		305	275		825			110						
	%			3		6		18	17		50			7						

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

South Halcro Head, South Ronaldsay. Facies thickness and percentage breakdown.

Cycle		Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
29	cm	1040				430		225				385								
	%					41		22				37								
28	cm	645			60	50		330						205						
	%				9	8		51						32						
27	cm	585						80			185			260						60
	%							14			32			44						10
26	cm	510		80	145	50		180		40					15					
	%			16	28	10		35		8					3					
25	cm	675			75			185			140	230			45					
	%				11			27			21	34			7					
24	cm	1955			180	120				30	745	830			50					
	%				9	6				2	38	42			3					
23	cm	1750				455				20	530	695		50						
	%					26				1	30	40		3						
22	cm	1340	80		265	240		140			360	195								60
	%		6		20	18		10			27	15								4
21	cm	1575	80		30	50		375		10	525	320		90	95					
	%		5		2	3		24		1	33	20		6	6					
20	cm	520				75					150	255	10		30					
	%					14					29	49	2		6					
19	cm	905	120		100	135				10	150	180			210					
	%		13		11	15				1	17	20			23					
18	cm	945		25	295	75		90			150	60		210	40					
	%			3	31	8		10			16	6		22	4					

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Tankerness. Facies thickness and percentage breakdown.

Cycle	cm	Thickness	L	NL	DS	SDS	MGS	DW	W	BS	MF	WSST	WSLT	ASF	SSF	M/CASF	M/CSSF	CH	G/C	GAP
32	%	635				100				20	285	140		90						
	cm					16				3	45	22		14						
31b	%	820			170	125	130	65				330								
	cm				21	15	16	8				40								
31	%	950			325	165	55	115	40		60	120								70
	cm				34	17	6	12	4		6	13								7
30	%	1215			295	85	175	125	55			440								40
	cm				24	7	14	10	5			36								3
29	%	1160			450	240					200	180								90
	cm				39	21					17	16								8
28	%	1400			560	190	80	155			220	195								
	cm				40	14	6	11			16	14								
27	%	1135	70		80	380		90			400	85					35			
	cm		6		7	33		8			35	7					3			
26	%	880			90	300		225					265							880
	cm				10	34		26					30							

Facies abbreviation key: L=laminite, NL= near laminite, DS=dark silt, SDS sandy dark silt, DW=dark Wick, W=Wick
BS=blue/grey silt, WSLT= wavy siltstone, WSST= wavy sandstone, MF=mixed flats, SSF=single sheetflood,
ASF=amalgamated sheetflood, M/CSSF=medium/coarse single sheetflood, M/CASF=medium/coarse amalgamated sheetflood
CH=channel, G/C=gravel/conglomerate, GAP=missing section.

Appendix 4

Megafacies data

Average thickness of megafacies by cycle,location and where on structure.

West of East Scapa Fault

cycle		lacustrine	emergent	fluvial
37	Noup Head	160	60	606
	Hoxa Head	240	50	165
	North Halcro	0	250	280
	average	133	120	350
36	Rousay	50	175	100
	Noup Head	85	0	500
	Hoxa Head	0	295	75
	Halcro Head	45	150	270
	average	45	155	236
34	Rousay	10	300	315
	Noup Head	260	300	540
	Hoxa Head	400	515	125
	Halcro Head	95	490	60
	average	191	401	260
32	Noup Head	152	100	350
	Hoxa Head	450	450	120
	Halcro Head	150	1405	110
	average	251	652	193
30	Evie	160	0	230
	Noup Head	270	220	340
	Flotta	145	425	290
	Hoxa Head	0	440	60
	average	144	271	230
29	Evie	335	0	325
	Noup Head	233	145	400
	Flotta	20	365	265
	Hoxa Head	265	165	140
	average	213	169	283
28	Evie	215	385	0
	Noup Head	255	200	375
	Flotta	215	725	685
	Hoxa Head	320	620	330
	Halcro Head	110	330	205
	average	223	452	319
27	Evie	260	170	170
	Rousay	180	420	270
	Noup Head	0	660	1000
	Flotta	105	850	385
	Hoxa Head	415	160	215
	Halcro Head	0	265	260
	average	160	421	383
26	Evie	275	380	25
	Rousay	155	495	180
	Flotta	140	765	110
	Hoxa Head	360	165	100
	Halcro Head	275	220	15
	average	241	405	86
25	Evie	245	175	500
	Rousay	180	705	170
	Hoxa Head	150	395	290
	Halcro Head	75	325	275
	average	163	400	309
24	Evie	0	340	0
	Rousay	215	470	1210
	Hoxa Head	430	860	125
	Halcro Head	300	775	880
	average	236	611	554

East of East Scapa Fault

		lacustrine	emergent	fluvial
37	Fers Ness	185	405	1240
	Wars Ness	140	180	1426
	Loth	190	0	1425
	average	172	195	1364
36	North Faray	95	355	110
	Fers Ness	120	105	190
	Wars Ness	180	180	435
	Loth	195	120	545
	average	148	190	320
34	North Faray	300	70	610
	Fers Ness	320	475	825
	Wars Ness	660	460	625
	Loth	525	400	245
	Huip Ness	100	1110	200
	average	381	503	501
32	North Faray	0	305	295
	Fers Ness	235	485	325
	Wars Ness	*0	290	500
	Loth	190	150	700
	Huip Ness	245	635	555
	Tankerness	100	305	230
	average	128	362	434
30	North Faray	80	275	0
	Fers Ness	140	435	569
	Wars Ness	370	75	610
	Spurs Ness	245	465	385
	Huip Ness	190	710	530
	Head of Work	235	205	310
	Tankerness	380	355	440
	Burray Ness	250	430	0
	average	236	369	356
29	North Faray	0	315	720
	Fers Ness	260	30	930
	Wars Ness	570	300	395
	Spurs Ness	95	440	650
	Huip Ness	40	295	0
	Head of Work	230	580	330
	Tankerness	690	200	180
	Burray Ness	740	645	0
	average	328	351	401
28	Surrigarth	160	315	390
	North Faray	50	370	240
	Fers Ness	310	985	725
	Wars Ness	200	250	645
	Spurs Ness	0	170	935
	Huip Ness	1135	555	505
	Head of Work	30	465	360
	Tankerness	750	455	195
	Burray Ness	1030	585	0
	average	407	461	444
27	Surrigarth	175	730	1715
	North Faray	0	180	255
	Fers Ness	635	570	295
	Wars Ness	775	595	95
	Spurs Ness	430	855	380
	Huip Ness	0	240	560
	Head of Work	475	555	480
	Tankerness	530	490	120
	Burray Ness	150	10	1145
	average	352	469	561
26	Surrigarth	225	510	650
	North Faray	410	570	225
	Fers Ness	200	190	700
	Wars Ness	670	410	385
	Spurs Ness	485	165	475
	Huip Ness	0	2010	240
	Head of Work	365	440	1235
	Tankerness	390	225	265
	Burray Ness	1025	520	380
	average	419	560	506
25	Surrigarth	180	265	940
	North Faray	200	325	460
	Fers Ness	180	310	280
	Wars Ness	0	575	540
	Spurs Nesss	115	405	910
	Skerry of Work	855	505	330
	Head of Work	585	315	445
	Burray Ness	175	1125	450
	average	286	478	544
24	Surrigarth	0	765	460
	North Faray	230	250	165
	Fers Ness	0	960	730
	Spurs Ness	845	265	1420
	Skerry of Work	210	175	365
	Head of Work	35	340	425
	Burray Ness	1215	440	270
	average	362	456	548

* incomplete cycle

Average thickness of megafacies by cycle,location and where on structure.

North of North Scap Fault

cycle		lacustrine	emergent	fluvial
37	Noup Head	160	60	606
	Fers Ness	185	405	1240
	Wars Ness	140	180	1426
	Loth	190	0	1425
	average	169	161	1174
36	Rousay	50	175	100
	Noup Head	85	0	500
	Fers Ness	120	105	190
	Wars Ness	180	180	435
	Loth	195	120	545
	North Faray	95	355	110
	average	121	156	313
34	Rousay	10	300	315
	Noup Head	260	300	540
	North Faray	300	70	610
	Fers Ness	320	475	825
	Wars Ness	660	460	625
	Loth	525	400	245
	Huip Ness	100	1110	200
	average	311	445	480
32	Noup Head	152	100	350
	North Faray	0	305	295
	Fers Ness	235	485	325
	Wars Ness	0	290	500
	Loth	190	150	700
	Huip Ness	245	635	555
	average	137	328	454
30	Evie	160	0	230
	Noup Head	270	220	340
	North Faray	80	275	0
	Fers Ness	140	435	569
	Wars Ness	370	75	610
	Spurs Ness	245	465	385
	Huip Ness	190	710	530
	Head of Work	235	205	310
	average	211	298	372
29	Evie	335	0	325
	Noup Head	233	145	400
	North Faray	0	315	720
	Fers Ness	260	30	930
	Wars Ness	570	300	395
	Spurs Ness	95	440	650
	Huip Ness	40	295	0
	Head of Work	230	580	330
	average	220	263	469
28	Evie	215	385	0
	Noup Head	255	200	375
	Surrigarth	160	315	390
	North Faray	50	370	240
	Fers Ness	310	985	725
	Wars Ness	200	250	645
	Spurs Ness	0	170	935
	Huip Ness	1135	555	505
	Head of Work	30	465	360
	average	262	411	464
27	Evie	260	170	170
	Rousay	180	420	270
	Noup Head	0	660	1000
	Surrigarth	175	730	1715
	North Faray	0	180	255
	Fers Ness	635	570	295
	Wars Ness	775	595	95
	Spurs Ness	430	855	380
	Huip Ness	0	240	560
	Head of Work	475	555	480
	average	293	498	522
26	Evie	275	380	25
	Rousay	155	495	180
	Surrigarth	225	510	650
	North Faray	410	570	225
	Fers Ness	200	190	700
	Wars Ness	670	410	385
	Spurs Ness	485	165	475
	Huip Ness	0	2010	240
	Head of Work	365	440	1235
	average	309	574	457
25	Evie	245	175	500
	Rousay	180	705	170
	Surrigarth	180	265	940
	North Faray	200	325	460
	Fers Ness	180	310	280
	Wars Ness	0	575	540
	Spurs Nesss	115	405	910
	Skerry of Work	855	505	330
	Head of Work	585	315	445
	average	282	398	508
24	Evie	0	340	0
	Rousay	215	470	1210
	Surrigarth	0	765	460
	North Faray	230	250	165
	Fers Ness	0	960	730
	Spurs Ness	845	265	1420
	Skerry of Work	210	175	365
	Head of Work	35	340	425
	average	192	446	597

South of North Scapa Fault

cycle		lacustrine	emergent	fluvial
37	Hoxa Head	240	50	165
	North Halcro	0	250	280
	average	120	150	223
36	Hoxa Head	0	295	75
	Halcro Head	45	150	270
	average	23	223	173
34	Hoxa Head	400	515	125
	Halcro Head	95	490	60
	average	248	503	93
32	Tankerness	100	305	230
	hox	450	450	120
	nhalc	150	1405	110
	average	233	720	153
30	Flotta	145	425	290
	Hoxa Head	0	440	60
	Tankerness	380	355	440
	Burray Ness	250	430	0
	average	194	413	198
29	Flotta	20	365	265
	Hoxa Head	265	165	140
	Tankerness	690	200	180
	Burray Ness	740	645	0
	average	429	344	146
28	Flotta	215	725	685
	Hoxa Head	320	620	330
	Halcro Head	110	330	205
	Tankerness	750	455	195
	Burray Ness	1030	585	0
	average	485	543	283
27	Flotta	105	850	385
	Hoxa Head	415	160	215
	Halcro Head	0	265	260
	Tankerness	530	490	120
	Burray Ness	150	10	1145
	average	240	355	425
26	Flotta	140	765	110
	Hoxa Head	360	165	100
	Halcro Head	275	220	15
	Tankerness	390	225	265
	Burray Ness	1025	520	380
	average	438	379	174
25	Hoxa Head	150	395	290
	Halcro Head	75	325	275
	Burray Ness	175	1125	450
	average	133	615	338
24	Hoxa Head	430	860	125
	Halcro Head	300	775	880
	Burray Ness	1215	440	270
	average	486	519	319

West of East Scapa Fault

cycle		lacustrine	emergent	fluvial
37	Noup Head	19	7	73
	Hoxa Head	53	11	36
	Halcro Head	0	47	53
	average	24	22	54
36	Rousay	15	54	31
	Noup Head	14	0	85
	Hoxa Head	0	72	18
	Halcro Head	8	27	48
	average	9	38	45
34	Rousay	2	48	50
	Noup Head	24	27	49
	Hoxa Head	38	50	12
	Halcro Head	15	76	9
	average	20	50	30
32	Noup Head	25	17	58
	Hoxa Head	44	44	12
	Halcro Head	9	84	7
	average	26	48	26
30	Evie	37	0	53
	Noup Head	33	27	41
	Flotta	17	49	34
	Hoxa Head	0	88	12
	average	22	41	35
29	Evie	42	0	41
	Noup Head	30	19	51
	Flotta	3	54	39
	Hoxa Head	46	29	25
	average	30	25	39
28	Evie	29	52	0
	Rousay			
	Noup Head	31	24	45
	Flotta	12	42	39
	Hoxa Head	25	49	26
	Halcro Head	17	51	32
	average	23	44	28
27	Evie	26	17	17
	Rousay	21	48	31
	Noup Head	0	40	60
	Flotta	8	63	29
	Hoxa Head	51	20	26
	Halcro Head	0	45	44
	average	18	39	35
26	Evie	40	56	4
	Rousay	19	60	22
	Noup Head			
	Flotta	14	75	11
	Hoxa Head	58	26	16
	Halcro Head	54	43	3
	average	37	52	11
25	Evie	27	19	54
	Rousay	17	67	16
	Hoxa Head	18	47	35
	Halcro Head	11	48	41
	average	18	45	37
24	Evie	0	69	0
	Rousay	11	25	64
	Hoxa Head	30	61	9
	Halcro Head	15	40	45
	average	14	49	29

East of East Scapa Fault

		lacustrine	emergent	fluvial
37	Fers Ness	10	22	68
	Wars Ness	8	10	82
	Loth	12	0	88
	average	10	11	79
36	North Faray	17	63	20
	Fers Ness	29	25	46
	Wars Ness	23	23	55
	Loth	23	14	63
	average	23	31	46
34	North Faray	31	7	62
	Fers Ness	19	28	49
	Wars Ness	38	26	36
	Loth	45	34	21
	Huip Ness	49	41	10
	average	36	27	36
32	North Faray	0	51	49
	Fers Ness	21	43	29
	Wars Ness	0	37	63
	Loth	18	14	67
	Huip Ness	0	58	42
	Tankerness	36	24	40
	average	13	38	48
30	North Faray	12	42	0
	Fers Ness	12	38	49
	Wars Ness	35	7	58
	Loth			
	Spurs Ness	22	42	35
	Huip Ness	13	50	37
	Head of Work	14	38	48
	Tankerness	31	29	36
	Burray Ness	37	63	0
	average	22	39	33
29	North Faray	0	30	70
	Fers Ness	21	2	76
	Wars Ness	45	24	31
	Spurs Ness	8	37	54
	Huip Ness	4	30	0
	Head of Work	31	27	41
	Tankerness	59	17	16
	Burray Ness	48	42	0
	average	27	26	36
28	North Faray	6	47	31
	Fers Ness	15	49	36
	Wars Ness	18	23	59
	Spurs Nesss	0	15	85
	Huip Ness	49	24	22
	Head of Work	54	33	14
	Burray Ness	64	36	0
	average	30	32	35
27	Surrigarth	7	28	65
	North Faray	0	29	41
	Fers Ness	42	38	20
	Wars Ness	53	41	6
	Spurs Ness	26	51	23
	Huip Ness	0	30	70
	Head of Work	4	54	42
	Tankerness	47	43	11
	Burray Ness	11	1	88
	average	21	35	41
26	Surrigarth	16	37	47
	North Faray	34	47	19
	Fers Ness	18	17	64
	Wars Ness	44	27	25
	Spurs Ness	43	15	42
	Huip Ness	0	89	11
	Head of Work	31	37	32
	Tankerness	44	26	30
	Burray Ness	52	26	19
	average	32	36	32
25	Surrigarth	13	19	68
	North Faray	20	33	47
	Fers Ness	23	39	35
	Wars Ness	0	52	48
	Spurs Ness	8	28	64
	Head of Work	36	43	21
	Burray Ness	10	64	26
	average	16	40	44
24	Surrigarth	0	62	38
	North Faray	36	39	26
	Fers Ness	0	57	43
	Spurs Ness	33	10	55
	Head of Work	43	23	33
	Burray Ness	62	22	14
	average	29	36	35

Average percentage of megafacies by cycle,location and where on structure.

North of North Scapa Fault

cycle		lacustrine	emergent	fluvial
37	Noup Head	19	7	73
	Fers Ness	10	22	68
	Wars Ness	8	10	82
	Loth	12	0	88
	average	12	10	78
36	Rousay	15	54	31
	Noup Head	14	0	85
	North Faray	17	63	20
	Fers Ness	29	25	46
	Wars Ness	23	23	55
	Loth	23	14	63
	average	20	30	50
34	Rousay	2	48	50
	Noup Head	24	27	49
	North Faray	31	7	62
	Fers Ness	19	28	49
	Wars Ness	38	26	36
	Loth	45	34	21
	Huip Ness	49	41	10
	average	30	30	40
32	Noup Head	25	17	58
	North Faray	0	51	49
	Fers Ness	21	43	29
	Wars Ness	0	37	63
	Loth	18	14	67
	Huip Ness	0	58	42
	average	11	37	51
30	Evie	37	0	53
	Noup Head	33	27	41
	North Faray	12	42	0
	Fers Ness	12	38	49
	Wars Ness	35	7	58
	Spurs Ness	22	42	35
	Huip Ness	13	50	37
	Head of Work	14	38	48
	average	22	31	40
29	Evie	42	0	41
	Noup Head	30	19	51
	North Faray	0	30	70
	Fers Ness	21	2	76
	Wars Ness	45	24	31
	Spurs Ness	8	37	54
	Huip Ness	4	30	0
	Head of Work	31	27	41
	average	23	21	46
28	Evie	29	52	0
	Noup Head	31	24	45
	North Faray	6	47	31
	Fers Ness	15	49	36
	Wars Ness	18	23	59
	Spurs Nesss	0	15	85
	Huip Ness	49	24	22
	average	21	34	40
27	Evie	26	17	17
	Rousay	21	48	31
	Noup Head	0	40	60
	Surrigarth	7	28	65
	North Faray	0	29	41
	Fers Ness	42	38	20
	Wars Ness	53	41	6
	Spurs Ness	26	51	23
	Huip Ness	0	30	70
	Head of Work	4	54	42
	average	18	38	38
26	Evie	40	56	4
	Rousay	19	60	22
	Surrigarth	16	37	47
	North Faray	34	47	19
	Fers Ness	18	17	64
	Wars Ness	44	27	25
	Spurs Ness	43	15	42
	Huip Ness	0	89	11
	Head of Work	31	37	32
	average	27	43	29
25	Evie	27	19	54
	Rousay	17	67	16
	Surrigarth	13	19	68
	North Faray	20	33	47
	Fers Ness	23	39	35
	Wars Ness	0	52	48
	Spurs Ness	8	28	64
	Head of Work	36	43	21
	average	18	38	44
24	Evie	0	69	0
	Rousay	11	25	64
	Surrigarth	0	62	38
	North Faray	36	39	26
	Fers Ness	0	57	43
	Spurs Ness	33	10	55
	Head of Work	43	23	33
	average	18	41	37

South of North Scapa Fault

cycle		lacustrine	emergent	fluvial
37	Hoxa Head	53	11	36
	Halcro Head	0	47	53
	average	26	29	45
36	Hoxa Head	0	72	18
	Halcro Head	8	27	48
	average	4	49	33
34	Hoxa Head	38	50	12
	Halcro Head	15	76	9
	average	27	63	11
32	Hoxa Head	44	44	12
	Halcro Head	9	84	7
	Tankerness	36	24	40
	average	30	51	20
30	Flotta	17	49	34
	Hoxa Head	0	88	12
	Tankerness	31	29	36
	Burray Ness	37	63	0
	average	21	57	20
29	Flotta	3	54	39
	Hoxa Head	46	29	25
	Tankerness	59	17	16
	Burray Ness	48	42	0
	average	39	35	20
28	Flotta	12	42	39
	Hoxa Head	25	49	26
	Halcro Head	17	51	32
	Head of Work	54	33	14
	Burray Ness	64	36	0
	average	34	42	22
27	Flotta	8	63	29
	Hoxa Head	51	20	26
	Halcro Head	0	45	44
	Tankerness	47	43	11
	Burray Ness	11	1	88
	average	23	34	40
26	Flotta	14	75	11
	Hoxa Head	58	26	16
	Hacro Head	54	43	3
	Tankerness	44	26	30
	Burray Ness	52	26	19
	average	44	39	16
25	Hoxa Head	18	47	35
	Halcro Head	11	48	41
	Burray Ness	10	64	26
	average	13	53	34
24	Hoxa Head	30	61	9
	Halcro Head	15	40	45
	Burray Ness	62	22	14
	average	36	41	23