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68 Sediment facies and geochemistry of Upper Jurassic mudrocks in the central North Sea area

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The Upper Jurassic (Oxfordian to Portlandian) mudrocks of part of the central North Sea and adjacent Scottish mainland have been examined for their sedimentary and geochemical characteristics. The three main facies groups recognized are (a) silt-laminated mudrocks, deposited as turbidites adjacent to active fault margins, (b) fissile-laminated mudrocks of mainly hemipelagic/part turbiditic origin occurring primarily in the basin centres, and (c) silty bioturbated mudrocks deposited mainly in shallow seas on the platform side of graben faults. Stratigraphically, the silty bioturbated facies are more common in the Oxfordian–Lower Kimmeridgian, and the fissile-laminated facies in the Upper Kimmeridgian–Portlandian. The facies groups are readily distinguished on the basis of their geochemical characteristics, with the fissile-laminated facies being most closely analogous to black shales from elsewhere in the stratigraphic record. They show a high organic carbon content (up to 15%), consisting mainly of marine sapropelic kerogens, which show gas chromatographic traces dominated by alkanes and a high pristane: phytane ratio. The S content is particularly high, together with relatively high Fe_2O_3 and P_2O_5 values. Trace-element enrichment includes Mo, Ni, Se, U and V and, to a lesser extent Co, Cr, Cu and Zn. These characteristics suggest deposition under periodically anoxic bottom water, and make the fissile-laminated facies the best potential source-rocks in the region.

INTRODUCTION

This paper reports preliminary results from work in progress on the Upper Jurassic (Oxfordian/Portlandian) mudrocks, some of which have acted as source-rocks for most of the North Sea oil reserves. The broad aims of this work are to relate detailed studies of sediment facies to both their inorganic and organic geochemical characteristics, in order to better understand the depositional environment, geochemical mobility during diagenesis, and the relationship of these to hydrocarbon source-rock quality.

The data presented here are from selected wells and onshore outcrops in three areas of study (Fig. 1): (1) the western margin of the southern Viking Graben in the vicinity of the Brae, Toni, Thelma and Tiffany oilfields; (2) the Outer Moray Firth–Witch Ground Graben in the vicinity of the Piper and Tartan oilfields; and (3) the onshore time equivalents exposed near Helmsdale in north-east Scotland.

There have been few general reviews of Late Jurassic sedimentation in the North Sea and sur-

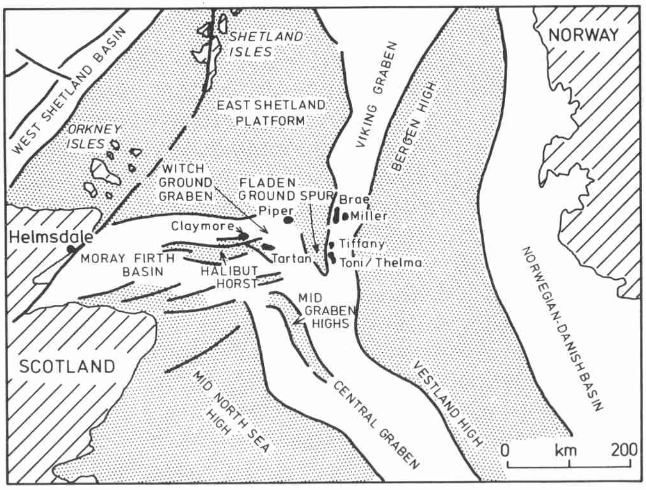

Fig. 1. Map showing main structural elements of the central North Sea and the principal oilfields in the study area.

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rounding areas (e.g. Barnard and Cooper, 1981; Cornford, 1984; Fuller, 1975; Neves and Selley, 1975; Tyson *et al.*, 1979) and some more detailed work on selected areas. The Brae Field sediments have been discussed by Harms *et al.* (1981, 1983), Stow (1983) and Stow *et al.* (1982), and are now generally thought to have been deposited in a slope apron or basinal setting (e.g. Turner *et al.*, this volume). The Piper Field sediments have been described by Williams *et al.* (1975) and Maher (1981), and are interpreted as more marginal to shallow-marine in origin. There have been many more studies of the onshore rocks of equivalent age in north-east Scotland, the latest interpretation of sedimentation on a fault-controlled submarine slope being given by Pickering (1984).

For recent more general studies of Upper Jurassic stratigraphy and sedimentation in Britain, the reader is referred to papers by Cope *et al.*, (1980), Gallois (1978, 1981), and Morris (1980). The very limited work on inorganic geochemistry is reported by Cosgrove (1970), Bjorlykke *et al.* (1975) and Dypvik *et al.* (1979), while Cornford (1984) deals briefly with aspects of the organic petrography and geochemistry.

REGIONAL SETTING AND STRATIGRAPHY

The study area (Fig. 1) is structurally quite complex, probably owing its origin in part to the locus of a failed triple junction in the North Sea (Whiteman *et al.*, 1975). The three arms of this triple junction designate the three dominant structural trends: the N–S-trending Viking Graben, the E–W-trending Witch Ground Graben and the NW–SE-trending Central Graben.

Although fault movement certainly occurred during the Permo-Triassic (Beach, 1984), the major phase of activity took place during the Cimmerian orogenic events of the Mid and Late Jurassic (Brooks and Chesher, 1975), preceded by extensive volcanicity in the Outer Moray Firth region of Bajocian to Bathonian age (Fall *et al.*, 1982; Howitt *et al.* 1975; Woodhall and Knox, 1979).

Late Jurassic sedimentation in the study area was strongly influenced by the dual controls of Cimmerian tectonics and eustatic sea-level rise. The regional Late Jurassic transgression led to the covering of Mid-Jurassic near-shore and shallow-water sands and lignites with fully marine muds, marls and thin limestones of Callovian–Oxfordian age and, finally, to the widespread deposition of Kimeridgian–Portlandian organic-rich muds (the Kimmeridge Clay Formation). However, local uplift in the Outer Moray Firth led, during the Oxfordian and Early Kimmeridgian, to the accumulation of more marginal-marine sediments which now form the main reservoir sandstones of the Piper, Tartan and Claymore fields. Continued movement along the basin-margin faults led to the resedimentation of much coarse-grained detritus down fault-controlled slopes into moderately deep water. The conglomerates and sandstones deposited in this way are closely interdigitated with Kimmeridgian black shales, forming the main reservoir units of the Brae and related fields and being exposed on land as the Helmsdale Boulder Beds.

The oilfields found in the region occur mainly on the basin flanks in tilted fault-block structures. They are capped by either the topmost Kimmeridge Clay Formation or by the regionally sealing Campanian Marls, and are sourced by the Kimmeridge Clay, which reached peak maturity in the Graben centres during the Early Tertiary (Fisher and Miles, 1983).

SEDIMENT FACIES

There is a wide variety of mudrock facies that can be identified within the Late Jurassic sediments of the area. These can be arranged in three main facies groups: (a) silt-laminated non-bioturbated mudrocks; (b) fissile-laminated non-bioturbated mudrocks; and (c) silty bioturbated mudrocks (Fig. 2). We describe below the main characteristics and distribution of each of these facies groups.

Silt-laminated mudrocks

These sediments comprise grey and dark grey mudstones with a variable proportion of millimetric- to centimetric-scale silt laminae. The silt laminae are commonly continuous across the width of core sections and over metres or tens of metres of correlatable section on the Helmsdale foreshore. They may be parallel sided or more wavy and lenticular in geometry, and with both sharp and gradational upper and lower contacts. Slight normal grading of individual laminae is common and thin (2–4 cm) graded–laminated units can be recognized. The range of microstructures observed include scoured and load-cast bases with flame structures and pseudonodules, parallel and cross lamination, fading ripples and low-amplitude ripples (e.g. Stow and Shanmugam, 1980). Bioturbation is absent or very rare.

In thin section (Fig. 3), the silt laminae are seen to occur also on a very fine micrometric scale with the silt-mud lamina separation being rather less distinct than from visual observation. The silts are quartz-rich with minor feldspars and trace accessories, the muds are organic-rich and clay-rich (illite–chlorite dominant) with common iron–sulphide framboids and less common marine macrofossils (e.g. ammonites). The back-scattered electron micrograph images (Fig. 3) show clearly that the parallel fabric is due to this separation of quartz-silt from organic clay-rich layers.

The combination of microstructures observed, the close association of this facies with coarser-grained resedimented facies (sandstone and conglomerate turbidites and debrites) and the common occurrence of slump structures all favour our interpretation of the silt-laminated mudrocks as dominantly of turbidite origin. This is in agreement with several earlier studies (e.g. Pickering, 1984; Stow *et al.* 1982; Turner *et al.*, this volume).

The silt-laminated facies group can be subdivided into about five different facies on the basis of the relative proportions of silt to mud. At the one extreme, the silt laminae are thick and closely spaced and the facies grades into a thin-bedded fine-grained sandstone facies. At the other extreme, there are only very few, thin, commonly indistinct silt laminae in a fine mudstone, and the facies becomes very similar to the fissile-laminated mudrocks described below.

Fissile-laminated non-bioturbated mudrocks

The fissile-laminated mudrocks are dark grey to grey–black in colour, very fine-grained and with a

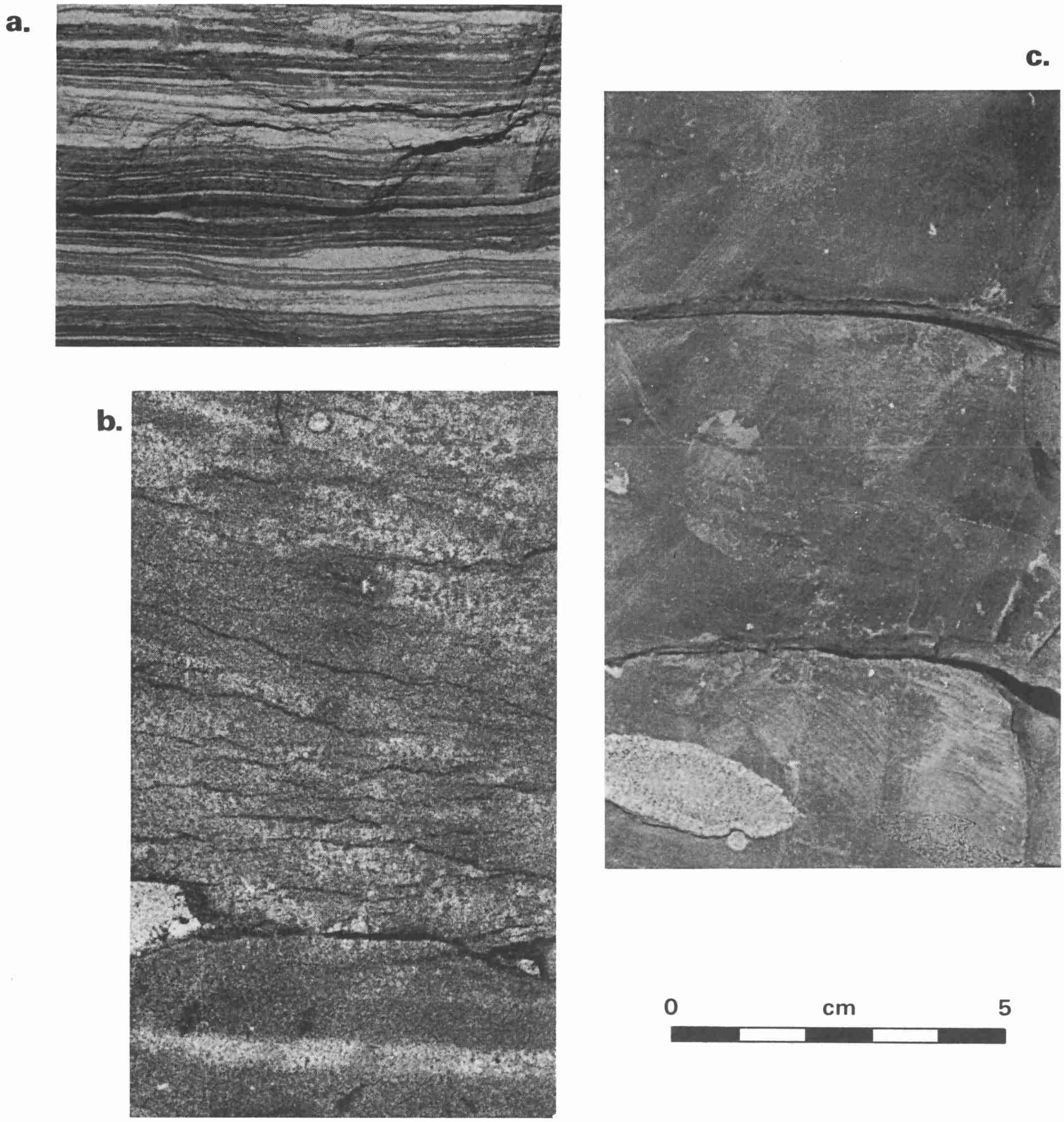

Fig. 2. Photographs of the three main fine-grained facies groups identified in the Upper Jurassic sediments of the study area: (a) silt-laminated mudrocks; (b) fissile-laminated mudrocks; and (c) silty bioturbated mudrocks.

very uniform appearance. There is mostly an absence of silt laminae and a lack of bioturbation. In some cases there is colour banding on a centimetric scale, with an alternation of grey and black layers that show no obvious difference apart from that of colour. At outcrop and in cut cores exposed to atmospheric conditions, there is commonly a yellowish staining developed in parts of the facies, particularly in the darker-coloured black bands. This is presumed due to oxidation of finely dispersed iron sulphide and the release of free sulphur.

Thin sections and back-scattered electron micrograph images (Fig. 3) emphasize the very fine-grained nature of these mudrocks, the dominance of clays and organics and a well-developed parallel fabric or fissibility. The sinuous nature of the fabric is evident, with organic matter and clays woven around silt-sized particles and lenses. The silt material is commonly mainly carbonate, although some detrital quartz and feldspar is also present. The clay fraction comprises illite and chlorite, together with variable amounts of smectite and mixed-layer clays. Iron sulphide framboids are common throughout and marine macrofossils (including ammonites, belemnites and bivalve shell fragments) and microfossils (dinoflagellate cysts) are locally present.

The processes involved in deposition of the fissile-laminated facies were probably mainly hemipelagic/pelagic in nature. The fine grain size, common carbonate and macrofossils, marine-derived kerogens (see below) and absence of structures, apart from a fissile lamination, are all factors that would support this interpretation. However, some deposition may also have occurred as distal mud turbidites.

The fissile-laminated facies group can be subdivided into two different facies, the one lighter coloured, more silty and less fissile, the other darker coloured, very fine-grained and highly fissile. The latter commonly becomes yellow-stained on exposure to dry atmospheric conditions.

Silty bioturbated mudrocks

The silty, bioturbated mudrocks are greyish and brownish in colour and rather variable in character.

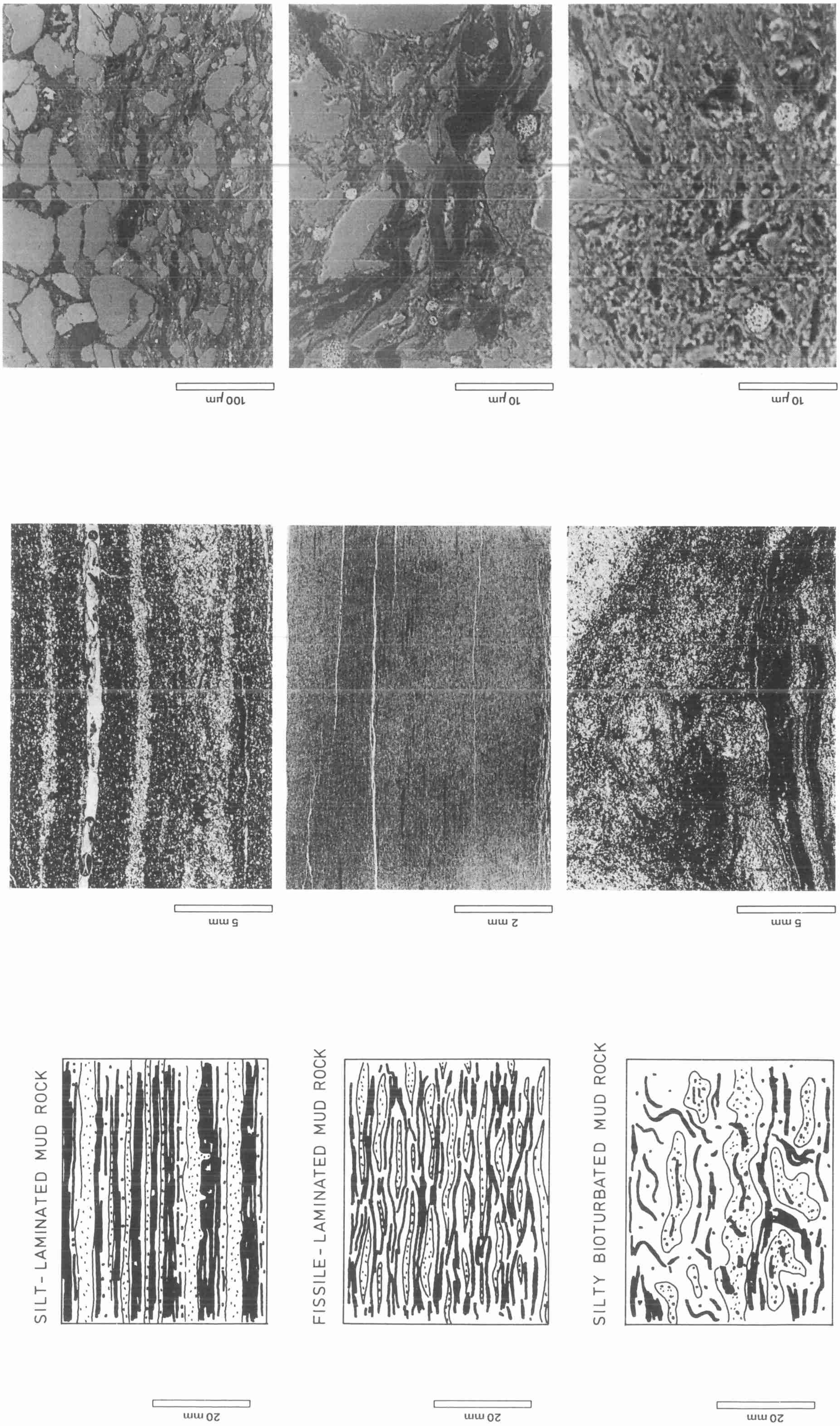

Fig. 3. Thin-section and back-scatter electron micrographs showing typical fabric type in the three facies groups: (a, b) silt-laminated mudrocks; (c, d) fissile-laminated mudrocks; and (d, e) silty-bioturbated mudrocks.

They are generally silty or sandy, having both dispersed silt in a mud matrix and irregular, discontinuous lenses and pockets of silt. Bioturbation and borrowing are common and may be developed to a high degree. Where silt/fine sand laminae and thin beds occur, they typically have irregular boundaries and show evidence of bioturbational disruption.

Thin-section study and back-scattered electron micrograph images (Fig. 3) show very little more in the way of structure. The sediment is very silt-rich and the fabric appears quite random. There is a more mixed silt mineralogy, with dominant quartz and minor feldspars, carbonate, micas and heavy minerals. Bivalve shell debris, together with ammonites and belemnite fragments, is common throughout. The clay fraction is typically dominated by illite and chlorite, but may have significant admixtures of kaolinite. Pyrite framboids are less common than in either of the other facies groups, and the amount of total organic carbon is variable but commonly low.

Bioturbation has largely obscured any diagnostic sedimentary structures, but a general interpretation of the facies would be one of various shelf and slope depositional processes in a relatively shallow-water setting. Where the bioturbated muds are interbedded with silt-laminated muds, then a period of non-turbiditic slope sedimentation might be inferred.

Facies distinctions within the group are not clear-cut. Rather, there is a gradation between less silty, darker coloured, more organic-rich mudrocks with small-sized burrows (e.g. *Chondrites* type) and more sandy, paler coloured, organic-poor mudrocks with interbedded sandstones or siltstones, in which the burrows are larger-sized vertical and oblique tubes.

FACIES DISTRIBUTION

Regional patterns

There are marked regional and stratigraphic controls on the distribution of three main facies groups described above. The silt-laminated mudrocks are most commonly found on the downthrown sides of syndepositionally active faults (see Fig. 1), in close association with coarse-grained resedimented conlomerates, sandstones and pebbly mudstones, for example the west flank of the Viking Graben, the north flank of the Witch Ground Graben and adjacent to the Helmsdale fault. The fissile-laminated mudrocks occur in a similar setting and in association with the silt-laminated facies, but typically in a more distal or more basinal setting, for example the central Viking Graben or central parts of the Witch Ground Graben. The silty bioturbated facies is most common on the platform side of basin-margin fault zones, in association with shallow-water sandstones and siltstones, for example the Piper Embayment on the west of the Fladen Ground Spur and neighbouring horst-block structural highs (see Fig. 1).

These generalizations on regional facies distribution are not always strictly adhered to (Fig. 4). In the Helmsdale area, for example, although silt-laminated mudrocks are the dominant fine-grained facies, they are also interbedded with silty-bioturbated mudrocks and, more rarely, with fissile-laminated mudrocks. On the western margin of the Viking Graben adjacent to the Fladen Ground Spur, cored wells from the Brae, Toni, Thelma and Tiffany fields again show dominant silt-laminated mudrocks, some interbedded fissile-laminated mudrocks, but an almost complete absence of the silty bioturbated facies. Wells in the Piper area are generally more sandy than muddy, and with the silty, bioturbated mudrocks dominant amongst the fine-grained facies. However, both the other facies groups are represented.

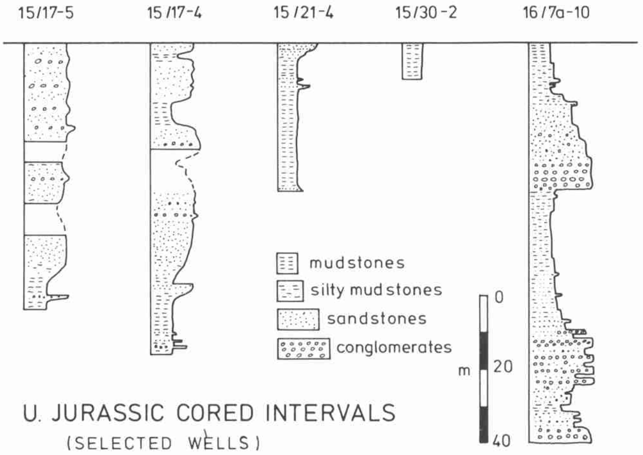

Fig. 4. Examples of vertical facies sequences from some of the wells examined in this study.

Vertical facies sequences

Mesoscale vertical sequences of facies can be recognized over 10–40 m of section in various wells and in outcrop (Fig. 4). Fining-upwards sequences are most common in the areas dominated by coarse-grained resedimented facies together with the silt-laminated mudrocks (e.g. Stow *et al.*, 1982; Stow, 1984; for the Brae Field). These sequences are less evident in the Helmsdale sections, where a more irregular alternation of coarse and fine-grained facies seems prevalent. Rather curious 'oscillation sequences' have been noted in dipmeter logs from fine-grained sections in wells of the Brae Field. These have been interpreted as the result of prograding mud lobes on a slope apron (Stow *et al.*, 1982), although a more recent detailed study has suggested the importance of differential compaction in their formation (Cohen *et al.*, this volume).

The Piper area wells show mixed fining-upwards and coarsening-upwards sequences of variable scales (from a few metres to a few tens of metres), together with a more irregular alternation of facies.

Stratigraphic variation

In general terms, there is an upward coarsening of facies over 100–200 m of section through the Oxfordian–Kimmeridgian Piper Formation, followed by an upward fining over 200–600 m of section through the Kimmeridge Clay Formation. The lower parts of the Piper Formation are characterized by silty, bioturbated mudrocks, whereas the upper parts have typically shallow-water sandstones. The lower Kimmeridge Clay Formation is dominated by breccias, conglomerates and pebbly sandstones, and then fines upwards through sandstones to silt-laminated mudrocks in the Upper Kimmeridgian and fissile-laminated mudrocks in the Portlandian interval.

SEDIMENT GEOCHEMISTRY

About 60 samples were selected from four wells in the Outer Moray Firth area and from outcrops on the

Table 1. Average elemental compositions in the three main facies groups (oxide values and *S* are in wt% and trace element values are in ppm). Laminated = silt-laminated mudstones ($n = 10$). Fissile = fissile laminated non-bioturbated mudstones ($n = 18$). Bioturbated = silty bioturbated mudstones ($n = 28$).

	Laminated			*Fissile*			*Bioturbated*		
	$\bar{x}$	*min.*	*max.*	$\bar{x}$	*min.*	*max.*	$\bar{x}$	*min.*	*max.*
SiO_2	60.59	49.0	71.7	51.61	42.2	59.4	63.30	53.2	87.6
Al_2O_3	10.76	8.1	11.7	11.61	9.6	13.9	13.59	3.5	20.0
TiO_2	0.53	0.3	0.6	0.57	0.5	0.6	1.43	0.3	2.0
Fe_2O_3	4.68	2.7	5.7	9.05	4.3	17.1	5.91	2.3	9.5
MgO	0.53	0.4	0.8	1.31	0.9	1.7	0.75	0.2	1.1
CaO	2.92	0.15	10.7	1.92	1.4	3.0	1.02	0.2	8.4
Na_2O	0.31	0.1	0.5	0.67	0.4	0.9	0.57	0.2	0.8
K_2O	2.06	1.8	3.1	2.61	2.2	3.1	2.44	0.7	3.1
MnO	0.03	0.0	0.1	0.03	0.0	0.1	0.03	0.0	0.1
P_2O_5	0.06	0.0	0.1	0.24	0.2	0.4	0.11	0.0	0.3
LOI	18.25	9.5	20.8	21.02	15.0	26.8	10.81	3.9	15.7
S	6.65	3.4	8.4	8.14	2.9	12.4	4.17	2.4	7.4
As	25	16	38	57	21	87	11	1	21
Ba	411	265	540	341	226	620	459	213	647
Br	17	10	21	2	0	4	6	3	9
Ce	74	53	90	94	80	111	101	34	143
Cl	2 155	1 402	2 593	664	305	1 110	1 009	165	2 665
Co	51	7	92	51	26	90	11	4	20
Cr	73	56	81	114	86	140	85	39	108
Cu	31	20	58	65	45	96	18	10	30
Ga	12	8	14	15	12	18	17	5	24
La	28	14	41	34	24	43	47	12	67
Mo	60	6	89	151	107	187	2	0	9
Ni	118	44	154	313	203	386	33	5	62
Nb	14	10	22	15	12	18	43	11	65
Pb	20	15	28	22	17	26	26	7	35
Rb	82	72	114	111	93	136	87	26	136
Sb	5	2	13	7	3	12	1	0	3
Se	7	1	11	54	32	66	0	0	2
Sr	91	51	202	171	141	206	186	62	338
Th	8	4	11	8	5	11	21	5	14
U	7	0	12	24	18	40	3	0	6
V	184	101	276	534	347	782	129	29	173
Y	24	16	28	33	27	61	29	10	46
Zn	176	36	288	543	205	2 815	95	14	406
Zr	236	194	286	137	122	171	419	214	630

Helmsdale foreshore, to provide a representative sample set of the different fine-grained facies groups identified. The samples were analysed both for major elements and 26 trace elements on a Philips PW1400 X-ray fluorescence spectrometer at Nottingham University.

Although, at this preliminary stage of our investigations, the data set is not large and the different facies are associated mainly with different wells, nevertheless some interesting patterns are evident.

Inorganic composition

In Table 1 we have shown average values for the major and trace-element compositions in order to compare the three main facies groups. The silt-laminated mudrocks tend to be relatively SiO_2-rich (apart from some samples of bioturbated muddy sandstone) and Al_2O_3-poor (average ratio of about 6:1). They are relatively low in nearly all the other major and trace elements analysed for, apart from CaO which varies from 0.2 to 10.8% (perhaps due to variation in carbonate cement), and Cl which averages 2155 ppm (probably reflecting sea-water contamination of outcrop samples). The LOI (loss on ignition) value of 16% we take as an indication of the relative proportions of volatile components, which in these samples will consist primarily of organic carbon and H_2O in clay minerals. Sulphur is also quite high, averaging around 6.65%.

The fissile-laminated facies, by contrast, have a lower SiO_2 value (50%) and relatively high Fe_2O_3, MgO, P_2O_5 and S concentrations. The trace element values are mostly high, especially the known organophile elements, Mo, Ni, Se, U, V and, to a lesser degree, Co, Cr, Cu and Zn. This corresponds to a high LOI average value of 18.25% presumably reflecting a high content of organic carbon. The silty bioturbated facies have a high SiO_2 content (average 63.6%) and high major element concentrations for Al_2O_3, TiO_2 and K_2O, with more variable amounts of CaO, Fe_2O_3 and MgO. The only trace elements that show relative enrichment compared with the other facies are Ba and Zr, whereas the LOI and S values are the lowest of the three facies groups.

Element cross-plots

The *x*–*y* plots of various trace elements show very clearly the distinction between the main facies groups. For example, plots of V versus U and V versus Se (Fig. 5) show the enrichment of these organophile elements in the fissile-laminated mudrocks, whereas a plot of Zr versus Y (Fig. 6) shows low values of Zr in this facies and a fair spread of concentrations through the other two facies. This range of Zr values

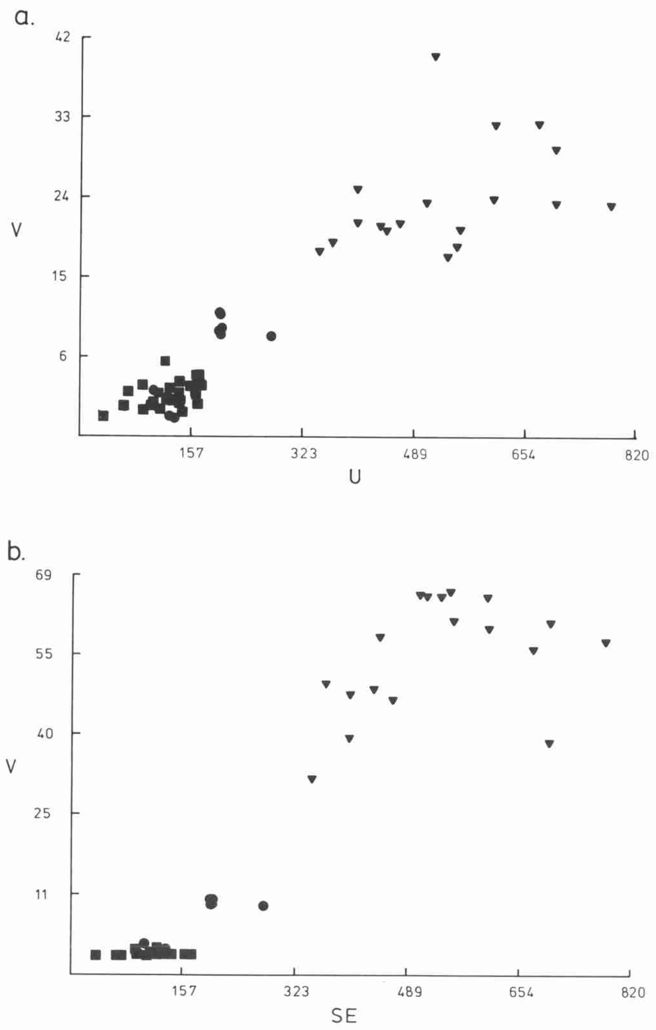

Fig. 5. Trace element cross-plots for (a) V versus U and (b) V versus Se. Concentrations in ppm. Solid circles = silty-laminated facies; solid triangles = fissile laminated facies; solid squares = silty bioturbated facies.

with only limited variation in Y suggests more of an inorganic sediment-source control, probably more stratigraphic than regional.

The plot of TiO_2 versus V (Fig. 7) shows a more or ss constant very low V content over a range of TiO_2 values for the silty bioturbated facies, whereas the

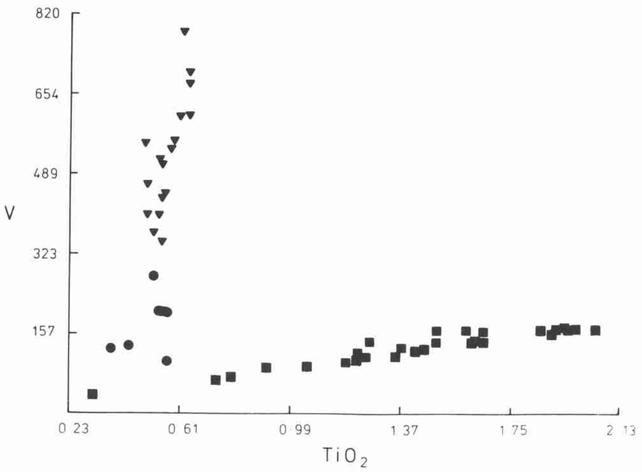

Fig. 7. Major element and trace element x–y plot for TiO_2 versus V. Concentrations in percent (TiO_2) and ppm (V). Solid circles = silt-laminated facies; solid triangles = fissile laminated facies, solid squares = silty bioturbated facies.

silt-laminated and fissile-laminated facies have constant low TiO_2 contents for a wide range of V concentrations. This spread of V content appears to be facies related: the silt-laminated group can be divided into facies that are more or less laminated at approximately 160 ppm V, the fissile-laminated group into the yellow-stained, more organic-rich facies (300–500 ppm), and the grey–black banded, less organic-rich facies (500–800 ppm). This suggests that V content is not related to the content of organic carbon.

The x–y plots of major elements are also interesting. For example, the SiO_2 versus Al_2O_3 (Fig. 8) shows a steady decrease in Al_2O_3 content over the ranges of 50–70% SiO_2 for the silty bioturbated facies, and up to 90% SiO_2 for few more sandy samples analysed. This reflects a decrease in clay minerals with increasing quartz content of the mudrocks. However, the more organic-rich fissile-laminated facies shows the reverse trend, with Al_2O_3 increasing over the 40–60% SiO_2 range, indicating that there is minimal quartz, and that most of the SiO_2 measured is in clay minerals. The silt-laminated mudrocks do not lie clearly on either of these trends.

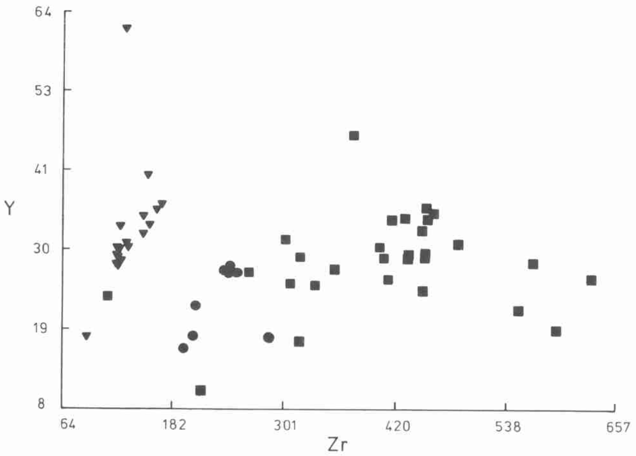

Fig. 6. Trace element cross-plot for Zr versus Y. Concenrations in ppm. Solid circles = silt-laminated facies; solid triangles = fissile laminated facies; solid squares = silty bioturbated facies.

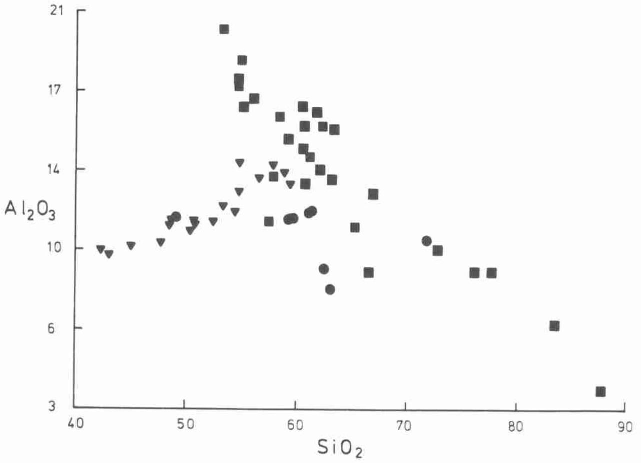

Fig. 8. Major element x–y plot for SiO_2 versus Al_2O_3. Concentrations in percent. Solid circles = silt-laminated facies; solid triangles = fissile laminated facies; solid squares = silty bioturbated facies.

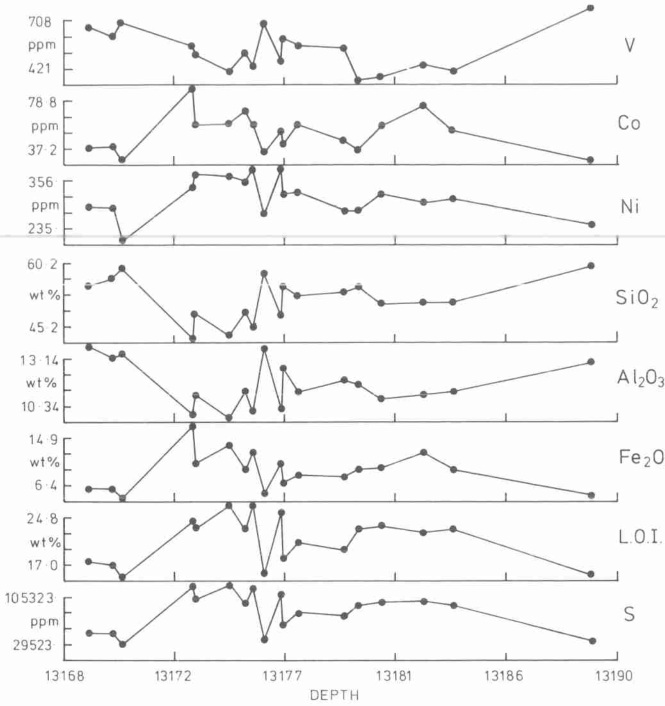

Fig. 9. Downhole geochemical variation for selected elements for well 15/30-1. Depths in feet.

Downhole trends

Plots of major and trace element variation downhole are shown for two wells, 15/30-1 having the more organic-rich fissile-laminated facies (Fig. 9) and well 15/21-4 having the more bioturbated facies (Fig. 10). The depth ranges of samples are clearly insufficient to show any stratigraphic variation that may exist, but several interesting points are evident from the sections examined.

In well 15/30-1, the SiO_2 and Al_2O_3 are seen to vary closely together and in opposition to LOI, Fe_2O_3 and S content. These trends reflect the fact that the SiO_2 is bound up with Al_2O_3 in the clay mineral fraction, and that the organic carbon (reflected by LOI content) has not been co-deposited with the clays but does appear to be closely associated with iron sulphides, as might be expected. Of the typical organophile trace elements, Co and Ni vary with LOI but V is in opposition and appears, therefore, to be bound in the clay fraction rather than with the organic matter.

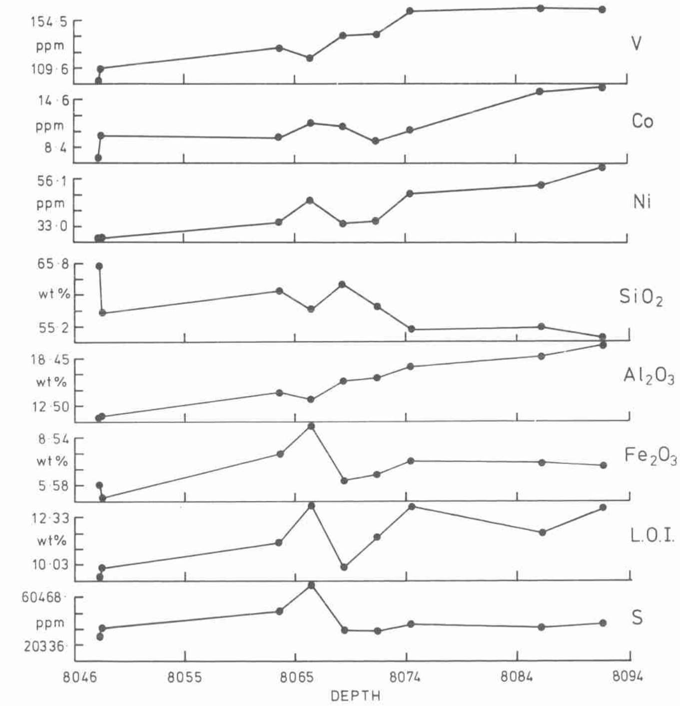

Fig. 10. Downhole geochemical variation for selected elements for well 15/21-4. Depths in feet.

In well 15/21-4, the trends are not so clearly defined. The Al_2O_3 and SiO_2 tracks appear mainly opposed but with parts that show slight co-variation. Most of the other elements, including V, approximately follow the LOI trend in opposition to SiO_2.

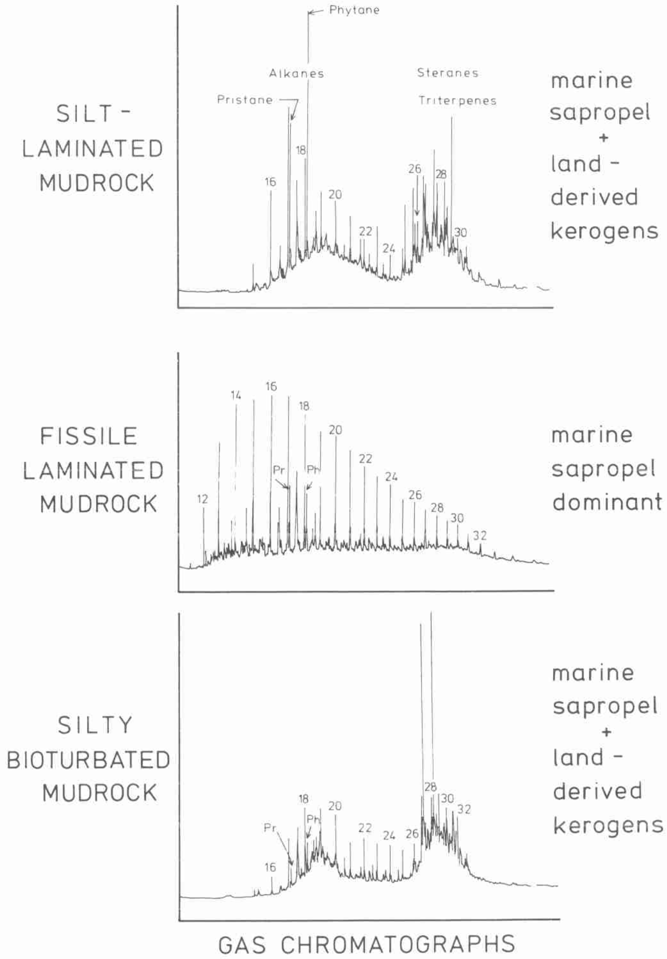

Fig. 11. Typical gas chromatography traces and organic petrographic data for the three main facies groups identified.

Organic petrography and geochemistry

Only very preliminary studies have been carried out on the organic matter and its geochemical characteristics. The results, however, show clear facies differences (Fig. 11).

The average organic carbon content of the silt-laminated facies analysed is about 5%. It consists of predominantly terrestrial woody (vitrinites and inertinites) and herbaceous material (spores and pollen) with a variable admixture of a marine sapropelic component (i.e. kerogens types II and III, Tissot and Welte, 1978). The size of the organic matter varie from 0.03 mm to 8 mm in length, being longer on average (1–2 mm) in the highly silt-laminated facies

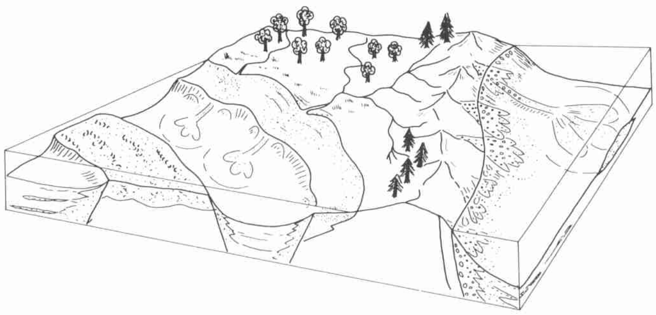

Fig. 12. Depositional environmental summary for the Upper Jurassic of the Outer Moray Firth and south Viking Graben.

and smaller-sized (average 0.1–0.5 mm) in the less laminated mudrocks. Typically, the lath-shaped organic debris have length-to-width ratios of 2:1 to 3:1 and show preferential orientation on bedding and lamination surfaces. Where measurement was possible, this preferential orientation is parallel to groove marks on the base of beds or to other indications of current direction.

A representative example of a gas chromatograph from the silt-laminated facies is shown in Fig. 11. There is clearly a mixture of dominant terrestrially derived steranes and triterpanes with subordinate marine-derived alkanes (Hunt, 1978). The low pristane:phytane ratio also suggests a greater terrestrial input.

The fissile-laminated facies has a very high average organic-carbon content of around 15%. Kerogen isolation, followed by palynomorph preparations, show that much of the organic matter is amorphous in nature and probably represents bacterially degraded marine algal material. In addition, there are degraded spores and pollen, dinocysts and black opaque woody particles. Most of this material is very fine grained, with the woody debris rarely up to 3 mm in length. A typical gas chromatograph (Fig. 11) shows clearly the marine signature, having dominant alkanes and a high pristane:phytane ratio.

Relatively lower contents of organic carbon (average 2–3%) characterize the silty bioturbated facies. Otherwise, the organic petrographic and geochemical characteristics are quite similar to those of the silt-laminated facies described above. Terrestrial woody debris is ubiquitous together with spores, pollen and some amorphous marine sapropelic material. The gas chromatograph (Fig. 11) again shows the dual terrestrial/marine influences, with a low pristane:phytane ratio indicating a dominance of the former.

DISCUSSION

Depositional environments

The study area was structurally and palaeogeographically varied during the Late Jurassic, and therefore a number of different sedimentary environments of deposition existed (e.g. Brown, 1984). The three fine-grained facies groups recognized mostly, though not entirely, reflect deposition in markedly different environments. All, however, were fully marine (Fig. 12).

The silt-laminated facies are mostly of turbiditic origin and were deposited around the mainly faulted margins of the graben system that existed in the area. They occur typically in slope-apron, small submarine-fan, fan-delta and marginal basin–plain settings (e.g. Stow, 1984). The silt-laminated facies die out rapidly towards the basin centres, where they are replaced by the more homogeneous fissile-laminated facies, which appear to be of part hemipelagic and part distal turbidite origin. It is interesting that these silty turbidites do not extend far into the depositional basins, even though the well-developed sedimentary structures would suggest fully mature turbidity currents. The turbidity currents may therefore have been frequent but relatively small in size, depositing all the silt load within 5–15 km of their point of origin and carrying only the finer clays and organics into the basin centres to mix with the pelagic rain of biogenic material.

The frequency of turbidity currents and the apparent preference of the silt-laminated mudrocks for the Kimmeridgian part of the succession (although stratigraphic control is not everywhere very precise), together with the major input of coarse clastic resedimented deposits at this time, suggests that the major phase of tectonic activity in this area was during the Kimmeridgian. The fissile-laminated facies tends to become more widespread, extending over the slope apron and marginal shelves as well as basin centres in the youngest Kimmeridgian and Portlandian stages. This may reflect decreased tectonic activity and/or a relative rise in sea level during this time.

The silty bioturbated facies by contrast appear most commonly to reflect deposition in shallower shelf waters (e.g. Maher, 1980, 1981) on the platform side of basin-margin faults or on more isolated highs within the grabens. Little evidence remains of the actual depositional processes involved, as burrowing and bioturbation have commonly been moderate to intense. Silty bioturbation mudrocks also occur in association with the silt-laminated facies, where they presumably reflect deposition in deeper waters, perhaps by slope processes, followed by variable degrees of bioturbational disruption of the original structures.

Geochemical characteristics

Inorganic geochemistry is clearly a very good way of distinguishing between the different facies groups, as well as of making more subtle distinctions between facies within the groups. These geochemical differences partly reflect input from different source areas and/or different source rocks. For example, relatively high TiO_2 concentrations (average 1.4%) in the Oxfordian – Lower Kimmeridgian rocks presumably reflect input from basic volcanic rocks at that time, whereas by Upper Kimmeridgian–Volgian time the average TiO_2 contents of the sediments had reduced to 0.5% indicating a major reduction in supply from this type of source-rock.

Certain geochemical distinctions, however, reflect directly or indirectly the relative anoxicity of the depositional environment and the quantity (and perhaps quality) of organic carbon preserved in the sediments. These factors appear to have differed for each of the three facies groups. Whereas all three groups have total organic carbon contents higher than 'normal marine mudrocks' (i.e. 2–15%), it is the fissile-laminated mudrocks that are most closely analogous to true black shales of other areas and ages (e.g. Arthur *et al.*, 1984; Dean *et al.*, 1984; Demaison and Moore, 1980).

In addition to their high organic carbon content (up to 15%), the fissile-laminated mudrocks show remarkably high sulphur values (averaging 10%). This suggests that the S:C ratios are somewhat higher than the 0.4 ratio typical of modern anoxic sediments, which may imply deposition under an anoxic water column rather than having only anoxic sediment pore waters (Leventhal, 1983). It would seem likely that much, if not most, of this sulphur is tied up in metal sulphides, particularly iron sulphides. Phosphorous concentrations are also relatively high in the fissile-laminated mudrocks (average 0.25% P_2O_5), which again supports the inference of an anoxic depositional environment (Froelich *et al.*, 1982; Suess, 1980).

The trace-element enrichment found in the fissile-laminated facies is also analogous to that reported for various black shales by many investigators (e.g. Brongersma-Sanders *et al.*, 1980; Calvert and Price, 1970; Dean *et al.*, 1984; Vine, 1970; Vine and Tourtelot, 1969). It is not clear whether this association of high trace-element concentrations (especially Cr, Cu, Mo, Ni, V, Zn) with organic carbon is the result of concentration of these elements by organisms, by chemical sorption onto organic detritus, clay minerals, etc. or by co-precipitation with metallic sulphides.

Neither is it fully understood why different black shales show slight differences in the elements that are enriched. Dean *et al.* (1984) have suggested that some of this variation, within the same succession of Mid-Cretaceous black shales in the South Atlantic, is due to differential mobility of trace elements during diagenesis.

Our data certainly show high enrichment in the less mobile elements, Mo and V, and lesser enrichment in some of the more mobile elements, Co, Cr and Cu. However, the fissile-laminated facies are also highly enriched in Ni, which Dean *et al.* (1984) consider to be one of the more mobile elements. The high Se concentrations we have found may suggest that we should add this element to those typically reported as organophile. Selenium analyses have not normally been reported by other investigators.

One insight into the mode of trace-element concentration comes from our data on vanadium. This element clearly shows variation with clay content (SiO_2 and Al_2O_3), rather than with organic-carbon content (LOI values). The other enriched species covary with LOI, Fe_2O_3 and S. We suggest, therefore, that V in the fissile-laminated mudrocks has co-precipitated with clays, rather than by organometallic complexing as proposed by Lewan and Maynard (1982). Sorption onto metal sulphides in a (partly) anoxic water column may have been important for some or all of the other enriched species.

Anoxicity and source-rock quality

The worldwide occurrence of organic-rich black shales in Late Jurassic sediments, as reported by many authors, suggests to us a global low-oxygen 'event' during this interval of time (e.g. Hallam and Bradshaw, 1979; Jenkyns, 1980). This led to enhanced preservation of organic matter in many areas and the subsequent development of actual and potential hydrocarbon source-rocks.

We do not speculate on what global conditions may have caused this event, but suggest that through much of the Late Jurassic, and particularly the Late Kimmeridgian–Portlandian stages, the North Sea area was held poised at relatively low bottom-water oxygen levels (cf. Cornford, 1984; Tyson *et al.*, 1979). This allowed different areas within the North Sea to preserve greater than normal amounts of organic matter (especially inactive terrestrial organics) and, at certain periods, to 'flip' into more fully anoxic bottom-water conditions allowing for preservation of large amounts of both marine and terrestrial organic matter.

A combination of factors was most likely responsible for the development of anoxicity in any one part of the North Sea, including: (a) high sea level leading to broad shelf areas, restricted water circulation, near-shore plankton factories and an expanded oxygen minimum zone; and (b) increased tectonic activity leading to an irregular basin/swell topography, further restriction of circulation, high input of sediments and terrestrial organic matter, and hence a better chance of preserving organic matter.

The quiet, deep-basin depositional setting, the probability of bottom-water anoxicity, the high organic content and dominance of marine sapropelic-type kerogens, and the subsequent thick sedimentary accumulation makes the fissile-laminated facies the best potential source-rocks for hydrocarbons in the area.

In some cases, the silt-laminated mudrocks were probably also deposited under anoxic conditions, particularly where they are associated with the fissile-laminated facies. In these instances, the abundance of silt laminae to aid primary migration out of the source-rocks makes this facies also an important potential source of hydrocarbons. The silty bioturbated mudrocks have probably not contributed to hydrocarbon generation in this area of the central North Sea.

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DISCUSSION

Question (Holger Lingreen, Institute of Mineralogy, U. of Copenhagen, DK 1350):

I am especially interested in your interpretation of the silt-laminated mudrocks. Your method apparently comprised electron backscatter microphotos and total mineralogical composition of the laminae together with elemental determination of variations across the laminae. I think that an electron microprobe investigation combined with more detailed investigations by X-ray diffraction and thermal analysis of selected sections of the laminae might reveal that several of the silt grains are carbonates and that a more complex mineralogy might be better explained from a combined effect of diagenesis and sedimentology rather than from sedimentology alone. Please note the description of the microfractures in my own talk and the carbonate bands in the core of 2/11-1 described in my paper in AAPG Bulletin **v. 69,** *1985, p. 525–36.*

Answer (D. A. V. Stow):

The authors thank Mr Lindgreen for his helpful comments. Indeed the silty lenses in the fissile-laminated facies do commonly contain a significant proportion of carbonate as well as siliciclastic grains. We suspect that, where this carbonate is of diagenetic origin, it has not migrated further than from the associated mud laminae, so that the higher carbonate values do reflect a facies characteristic. This carbonate may have been derived from the biogenic content rather than as detrital grains.

Question (Paul B. Wignall, Dept. of Geological Sciences, U. of Birmingham, B15 2TT):

Within your deeper water Type 2 shale facies, is it possible to detect fluctuating benthic oxygen levels on a half to one metre scale as so well developed at the type locality of the Kimmeridge Clay at Dorset?

Answer (D. A. V. Stow):

The thicknesses of the fissile shale facies so far encountered in cored sections are relatively small. Although there is some preliminary indication from facies variations of both regular and irregular fluctuation in possible benthic oxygen levels, our data base is not yet adequate to be certain. The facies variations noted are certainly not as clearly defined as at Kimmeridge Bay in Dorset.

Question (Dr. A. P. Tilbrook, 155/A32 AEE Winfrith, Dorchester, Dorset):

Particularly in the Brae area, the deposition of the various source rocks appears to be very disorganised. Are the authors aware of any stochastic technique which can be employed to model the lateral extent of any of the units of the three types of source rocks described? Is there likely to be any correlation between bed thickness and lateral extent? Have any studies been performed on outcrops (i.e. at Helmsdale) to give a picture of the probable lateral extent of the different facies types?

Answer (D. A. V. Stow):

The deposition of fine-grained sediments in the Brae area is not so much disorganised as complex. Unravelling that complexity will come first from fully understanding the local depositional systems. At that stage, it might well be useful to try a statistical probability technique in order to assess the likely volume of different source rock facies present. Our work on the Helmsdale foreshore does indicate that the thicker a particular facies the greater its lateral extent is likely to be. However, the Upper Jurassic section at Helmsdale is very broken with normal faulting making extensive lateral correlation of beds impossible.