Journal of Petroleum Geology, 5, 2, pp. 129-148, 1982

SEDIMENTOLOGY OF THE BRAE OILFIELD, NORTH SEA: FAN MODELS AND CONTROLS

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Submarine fans are important to the petroleum industry for their reservoir and source-rock potential. There are a variety of fan types that can be characterized by different fan models. In assessing which model, if any, is appropriate for a particular area or field it is important to evaluate the controls that operate to determine the type of fan developed. Most present-day fans that have been studied are deep-water oceanic; more work is required on modern examples of shallow-water, small-basin fans which are particularly relevant to hydrocarbon exploration.

Jurassic and Tertiary objectives are important in the North Sea and include both nearshore-sandstone and submarine-fan reservoirs. The Brae oilfield is an Upper Jurassic reservoir on the western faulted margin of the North Sea Central rift system. Detailed core, electric log, dipmeter and seismic data have been examined. The Brae field comprises at least three small overlapping submarine fans that form a sediment apron along the scarp margin and that were deposited by a variety of gravity-flow processes in a shallow basin below wave base. Tectonic control on fan development has resulted in up to six fining upwards megasequences (50-150) within the overall fining upwards basin fill (300-600 m). There has been a large intermittent supply of coarse detritus across a narrow littoral zone and down a steep slope. Short, sediment-laden rivers supplied mud and plant debris, and a complex interdigitation of coarse-and fine-grained facies has resulted.

The Brae fans are an important example of the fault-controlled, shallow, small basin type and are most closely analogous to the Jurassic fans of East Greenland. Reservoir characteristics are dependent on diagenesis, facies and fault distribution, and vary markedly along the fault margin. A clear understanding of the controls and models is essential for continued exploration and development in this part of the North Sea.

Introduction

Submarine fans are widespread base-of-slope sediment accumulations that have formed by the downslope re-sedimentation of unstable and unconsolidated primary deposits. Fans are of great practical importance in petroleum geology in that:

(a) they are very common sediment associations and have facies relationships that provide good source, reservoir and trapping potential; and (b) predictive models have been developed that can be used for hydrocarbon exploration and in the assessment of reservoir potential for field development.

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Numerous important hydrocarbon discoveries have been made in turbidite and associated sediments of Devonian to Tertiary age in the USA (see review by Walker, 1978), in the North Sea (Woodland, 1975; Illing and Hobson, 1981), and off the Brazilian coast (Tofelli and Barros, 1979). Vast new areas of petroleum potential lie beneath the slope and rise sequences of ocean margins (Yarborough *et al.*, 1979; Mattick *et al*., 1978; Wilde *et al*., 1978), where canyon and fan reservoirs may become economically viable in the near future.

However, a wide variety of facies geometries and associations on land and in the subsurface have been interpreted as fan sequences, and several significantly-different fan types clearly exist. In addition, not all turbidites are necessarily deposited on submarine fans, but few alternative models exist, so that the petroleum geologist is too easily tempted to adopt a fan model to explain a prospective turbidite sequence.

Correct recognition and interpretation of turbidite sediments is of great importance for evaluating reservoir geometry and distribution. In this regard, it is necessary not only to consider the most appropriate model, but also the range of controls that have been most influential in any given sequence. These controls are outlined below with some speculation as to their effects in producing different fan and non-fan associations. Some of the problems related to North Sea Tertiary and Jurassic fans are then outlined, followed by a sedimentological interpretation of the *Brae* field in the North Sea.

Fan models

A number of different fan models have been developed over the past 15 years in an attempt better to understand fan growth and the pattern of facies distribution. Five of

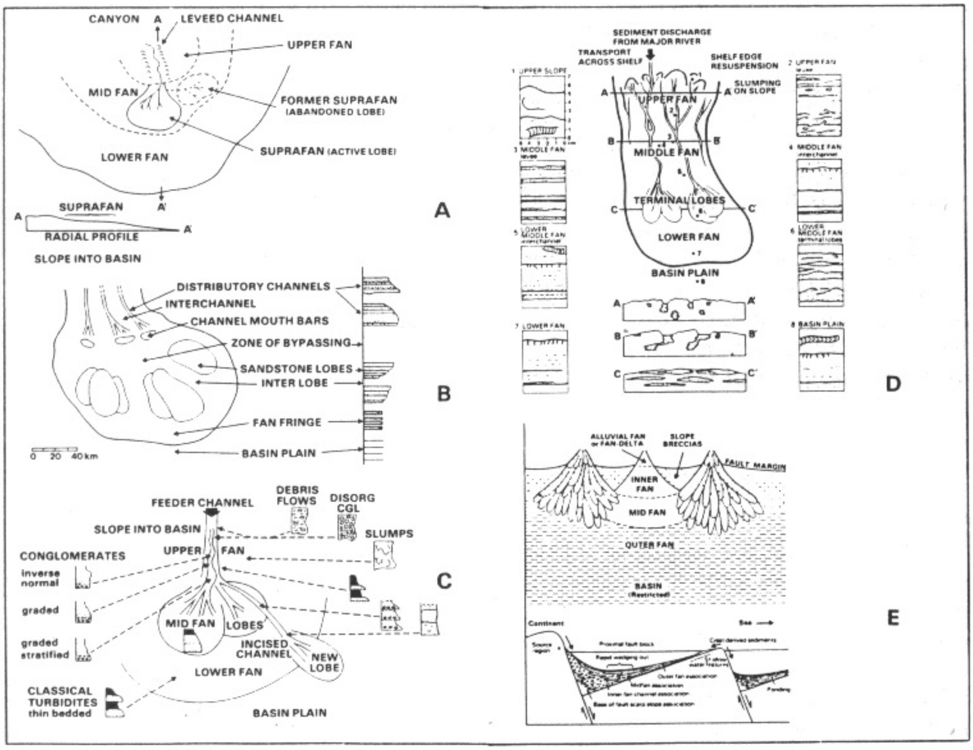


Fig. 1. Fan models. Coarse-grained facies (potential reservoir sequences) stippled for sands, open circles for conglomerates: (a) model (A) (after Normark, 1978); (b) model (B) (after Mutti and Ricci Lucchi, 1972); (c) model (C) (after Walker, 1978); (d) model (D) (after Stow, 1981); (e) model (E) (after Surlyk, 1978).

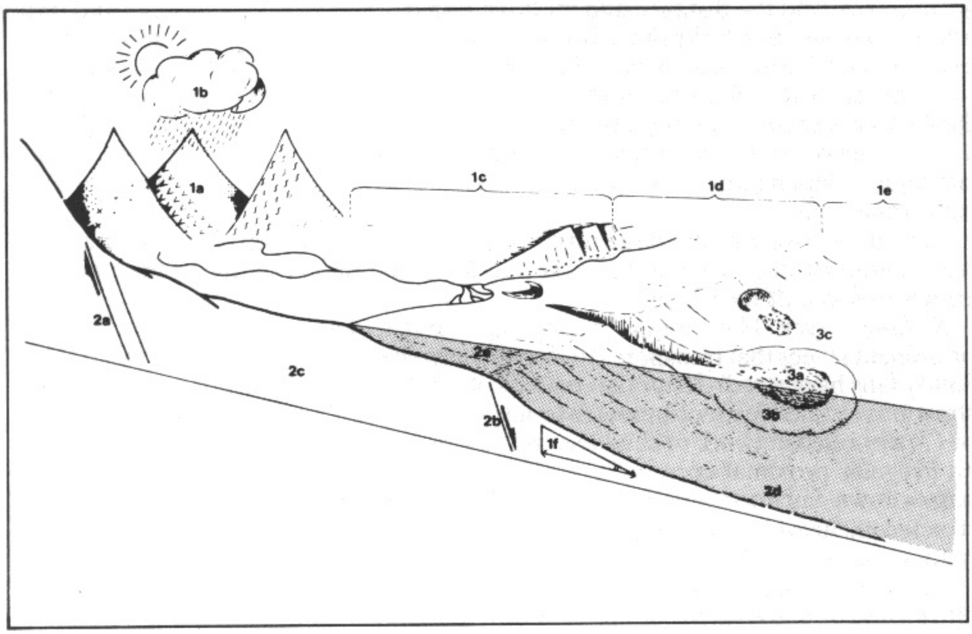


Fig. 2. Cartoon summary of controls on submarine fan development: 1a original source rock type; 1b climate and weathering; 1c continental plain and shelf widths; transport methods; 1d transitional source sediment type; 1e resedimenting process; 1f slope, gradient and width. 2a tectonic style in original source area; 2b tectonic style in transitional source zone; basin subsidence; 2c margin type; 2d receiving basin type (size, water depth, shape, etc); 2e sea level variation. 3a fan geometry; feeder system; 3b marine conditions; 3c marine biota.

the better documented models (Fig. l) serve to illustrate some of the range of fan types and features that can be expected.

Fans range in size from relatively-small (5-10 km radius) to moderately-large (100-200 km radius) to very-large (250-2,500 km radius). These are best described by models A, B and D respectively. Model C was designed as an “all-purpose” model; and model E for small fans (10-20 km radius) that overlap laterally to form a slope-apron sequence. The fan shape and hence the distribution of potential reservoir sandstones are also variable: from arcuate, to slope-parallel, to elongated perpendicular to the slope.

The sediment types and depositional trends can be characterized in some detail for the different models (Nelson and Kulm, 1973; Nelson and Nilsen, 1974; Mutti and Ricci Lucchi, 1972). Walker (1978) and Surlyk (1978) emphasize the character and distribution of the coarse-grained sediments and Stow (1979, 1981), those of the fine-grained sediments. This aspect of the models is very important for both interpretative and predictive purposes.

Controls

While these models can be extremely useful to the petroleum geologist, it is equally important that we know which model is most applicable to any given area or sequence, or whether an alternative environment is indicated. A rather different approach that may help answer this question is to consider the various factors that act as controls on fan development (Nelson and Kulm, 1973; Normark, 1978).

The numerous controls illustrated in Fig. 2 are closely interrelated and can, to some extent, be simplified. The rock type, tectonic activity and climate in the original source area, and the distance and mode of transport between the original and transitional sources all affect primarily the *type and amount of sediment* available for fan construction. Tectonic activity at the basin margin, the margin and basin type and the slope gradient and width can, for the most part, be characterized in terms of a particular *tectonic setting.* The internal controls listed are thought to act more to modify than to exert major control over fan types, and the various processes of resedimentation are largely dependent on the other variables. This leaves *sea-level* as the third most important control.

Careful assessment of a large number of modern and ancient fans for which we have sufficient data leads us to make the following observations on the probable effects of some of these controls.

Sediment type. High-input, muddy fans tend to have elongate channels with prominent levees that transport sands to the terminal lobes for down-fan (Model D). Sandy fans have a radial suprafan pattern of sands in the middle fan area and only a short gravel-filled feeder channel (Models A, B and C). Gravelly fans are dominated by (?) a braided network of channels and coarse inner fan lobes, and tend to produce an irregular proximal apron of gravel, sub-parallel to the strike of the slope, that passes down-fan into sands and basinwards into muds (Model E). Fans that are constructed exclusively from fine-grained sediments (e.g. mid-ocean pelagic oozes and muds) appear not to show any channel development.

Tectonic setting. Deep-water oceanic fans either on tectonically-active margins (strike-slip or convergent) or on passive margins are commonly mature in terms of morphology and sediment, mainly medium or large in size and widely spaced (Models A and D). The inter-fan sediments are similar (i.e. mixed turbidite-contourite-pelagite) but with no particular fan geometry. More shallow-water, small basin fans tend to be smaller and immature, coarser-grained and with less well-developed morphologies (Models B and C). In tectonically-active small basins there may be many irregularly-overlapping fans producing a slope-apron facies arrangement (Model E). Other small-basin turbidite-fill non-fan associations are also common.

Sea level. Worldwide or local changes in sea level can produce large-scale cyclicity, and progradational or abandonment facies sequences on fans or in other turbidite settings. Rejuvenation, channel incisement and lobe progradation into the lower fan may occur (Model C). A low sea-level stand may result in a more sandy fan, whereas a high sea-level results in a muddy fan.

North Sea hydrocarbon-bearing fans

Lower Tertiary sands of the North Sea have been found to contain very-significant hydrocarbon reserves (Parker, 1975) (Fig. 3). Following Late-Cimmerian (Late Jurassic) faulting and rifting, only minor movement occurred during deposition of the Cretaceous-Danian Chalk, although the North Sea graben system continued to subside. Chalk gave way to clastic sedimentation following Lower Palaeocene (Laramide) fault reactivation and graben subsidence. Thick, composite sands, shales and interbedded lignites are interpreted as shallow-marine to coastal-plain sediments deposited during the Lower Tertiary. The basinal equivalents of these marginal sediments are thinner sequences of probable turbidite sands and shales deposited in base-of-slope and basinal fans (Rockow, 1981).

The *Forties* (Thomas *et al.*, 1974; Walmsley, 1975; Carman and Young, 1981) and *Montrose* fields (Fowler, 1975) are both interpreted as Palaeocene fans. Resedimentation from the shelf to the deeper (150-900 m) basin was either via slope canyons or by movement across an actively prograding delta. The *Frigg, NE Frigg* and *Odin* fields have also been interpreted as fans, with an initial fan development in the Palaeocene and the main fan being of Eocene age. A main feeder channel, suprafan area, mid-fan channels and lower-fan lobes have been interpreted from seismic evidence (Sambet, pers. comm. 1978), and from sand body geometry, electric logs and sediment types (Heritier *et al.*, 1979). However, there is growing evidence from

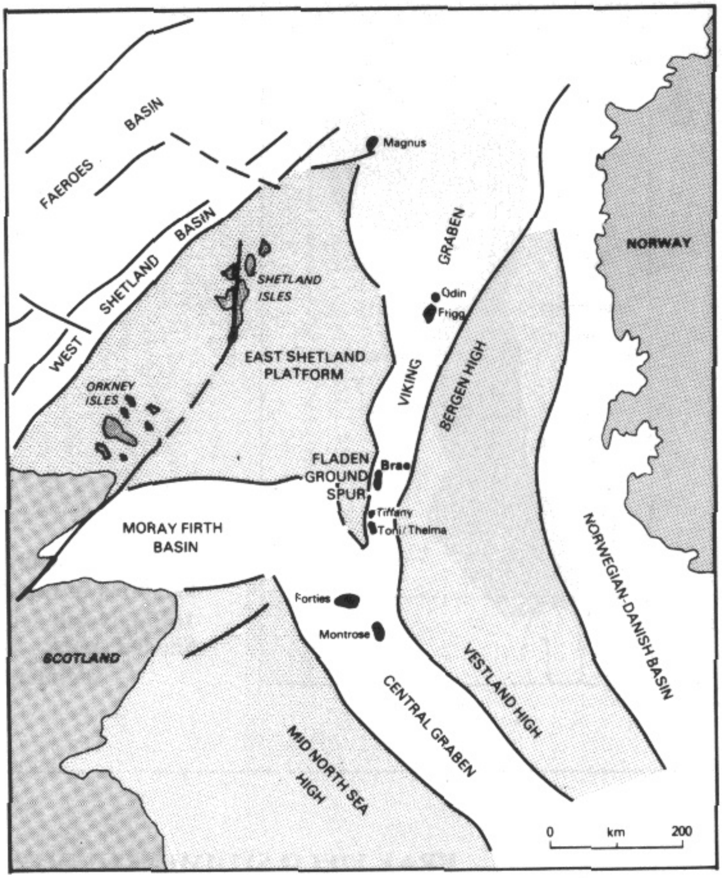


Fig. 3. Tectonic framework of the central and northern North Sea showing locations of oil and gas fields (black) mentioned in text.

micropalaeontological data and seismic reconstructions that the water depth during fan deposition was never very great, although continued basin subsidence led to thick sediment accumulation.

Middle and Upper Jurassic sands also provide a variety of important hydrocarbon reservoirs in the North Sea (Finstad and Selley, 1975, 1977). Many of these sands were deposited nearshore; others are best explained as submarine fan sands and gravels that were deposited close to an active fault-controlled basin margin (Surlyk, pers. comm., 1980), or to an active submarine fault scarp (Selley, 1976). The *Magnus* field in the north (De'Ath and Schuyleman, 1981) and *Brae, South Brae, Tiffany, Toni* and *Thelma* fields east of the Fladen Ground Spur can be interpreted as submarine fans (Fig. 3).

However, Harms *et al.*, (1981) present an alternative model for the southern part of the *Brae* field, in which the conglomerate and sandstone are interpreted as mainly subaerial deposits of coalescing "fan-deltas" with laterally adjacent "fringing marine foresets". This model is currently accepted by the Operator.

It is clearly important to derive the correct sedimentary model for these valuable North Sea reservoirs. One reason for the controversy over the fan interpretation of both Tertiary and Jurassic North Sea sands may lie in the common association of submarine fan with "deep" water. "Shallow-water", small-basin fans are significantly different from the deep-ocean basin type. They are probably more common in the geological record, and present the most appropriate model for the North Sea hydrocarbon-bearing fans.

The remainder of this paper discusses the sedimentology of the *Brae* field and interprets the sequence in terms of overlapping submarine fans, closely analogous to the shallow-basin, tectonically-controlled fan model E discussed above.

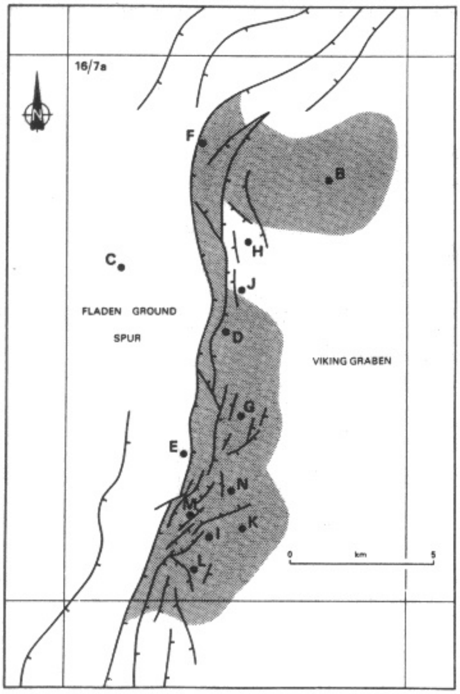


Fig. 4. Structural framework and well locations of the *Brae* field, license block 16/7a, North Sea, UK Continental Shelf. Shaded parts indicate areas of thick sediment accumulation.

BRAE FIELD SEDIMENTOLOGY

Tectonic setting and stratigraphy

The *Brae* oilfield is an Upper Jurassic (mainly Kimmeridgian to Volgian) reservoir developed on the western margin of the South Viking Graben adjacent to the fault escarpment at the edge of the Fladen Ground Spur (Fig. 4) (Harms *et al.,* 1981). An intense phase of tectonic activity in the Late Jurassic caused up-lift and erosion of the Fladen Ground Spur and resulted in deposition of coarse clastic sediments along the faulted margins of the South Viking Graben. It is this intimate relationship between tectonics and sedimentation that is the unique factor contributing to the complexity of the *Brae* field and related plays. In the *Brae* area the graben margin is defined by a north-to-NE trending normal fault zone which juxtaposes Upper Jurassic reservoir against impermeable Devonian sandstone and conglomerates. The fault zone is several kms wide comprising a series of en échelon faults that dip at about 60-80° eastwards, and became progressively younger to the west. These bring Late-Jurassic shales, Lower-Cretaceous marls and younger strata into direct onlapping contact with presumed Devonian basement. The fault blocks appear to be antithetically rotated so that the deepest part of the downthrown fault block is adjacent to the platform. Subsequent sediment fill and minor tectonism has resulted in a series of gentle anticlines parallel to the margin that now form the important structural hydrocarbon trap (Harms *et al.,* 1981).

Although seismic sections provide the general structural setting, their resolution below the base Cretaceous unconformity is, as yet, insufficient to allow seismic facies analysis. However, 13 wells have now been drilled on the 16/7a block and about 2,500 m of core have been recovered (Fig. 5). This core material, together with electric log and dipmeter data, provides the basis of the sedimentological interpretation outlined below.

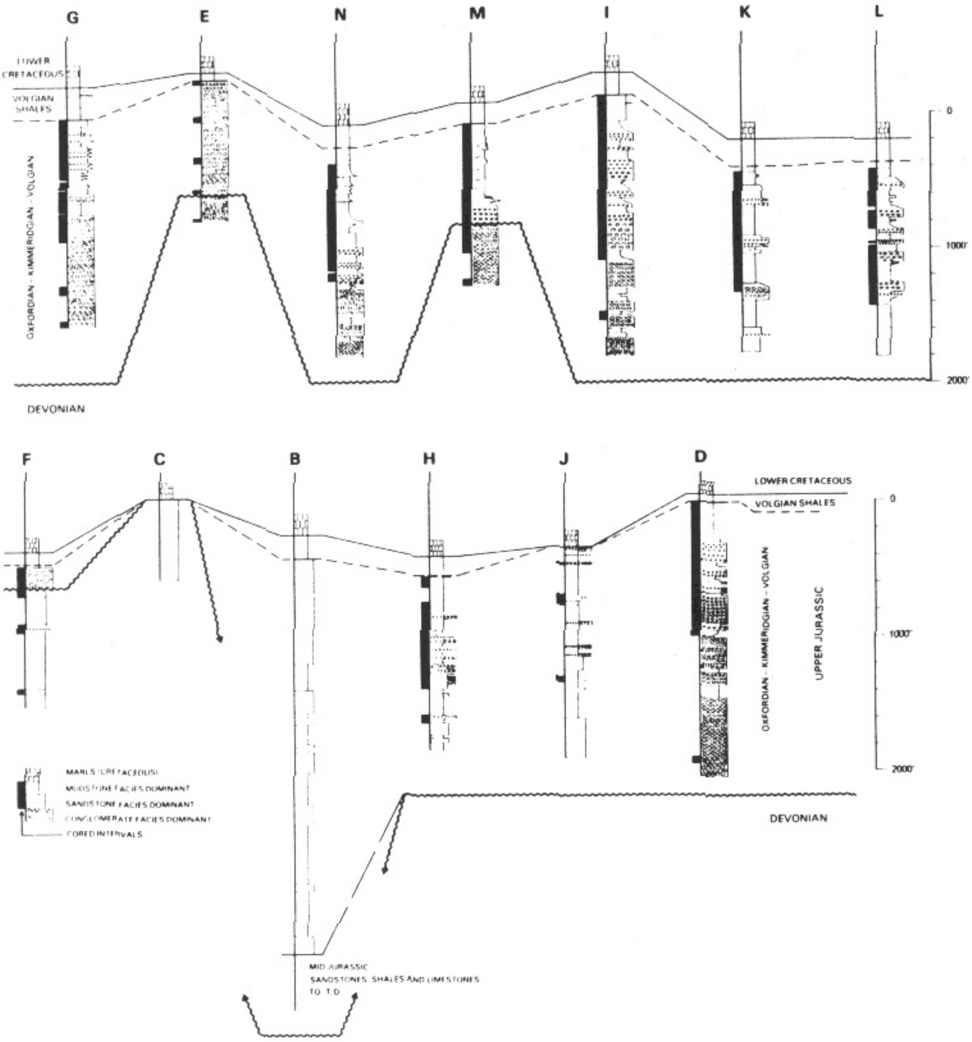


Fig. 5. ***Brae*** **field summary well logs showing stratigraphic relationships and cored intervals.**

Sediment facies

Three main facies groups can be identified in the *Brae* cores: mudstones, sandstones and conglomerates. A "slump" facies can occur in any of these three, but appears most commonly within the mudstone group.

(1) *Mudstone group* (Fig. 6)

This group comprises interbedded dark grey mudstones and light grey sandstones (known informally as "tiger-stripe" facies). The mudstone is silty and micaceous with comminuted carbonaceous plant debris that is commonly pyritised. Pyrite framboids up to 2 cm in diameter are also noted. Marine microplankton, terrestrial spores and pollen and rare marine macrofossils (ammonites, belemnites, bivalve fragments) provide evidence of age and marine environment. The sandstone is fine- to very-fine grained, argillaceous and carbonaceous, and occurs as laminae (1-10 mm thick) or thin beds commonly 1-2 cm thick and rarely up to 10 or 15 cm. Thin concentrations of plant debris occur very rarely in wells G and L.

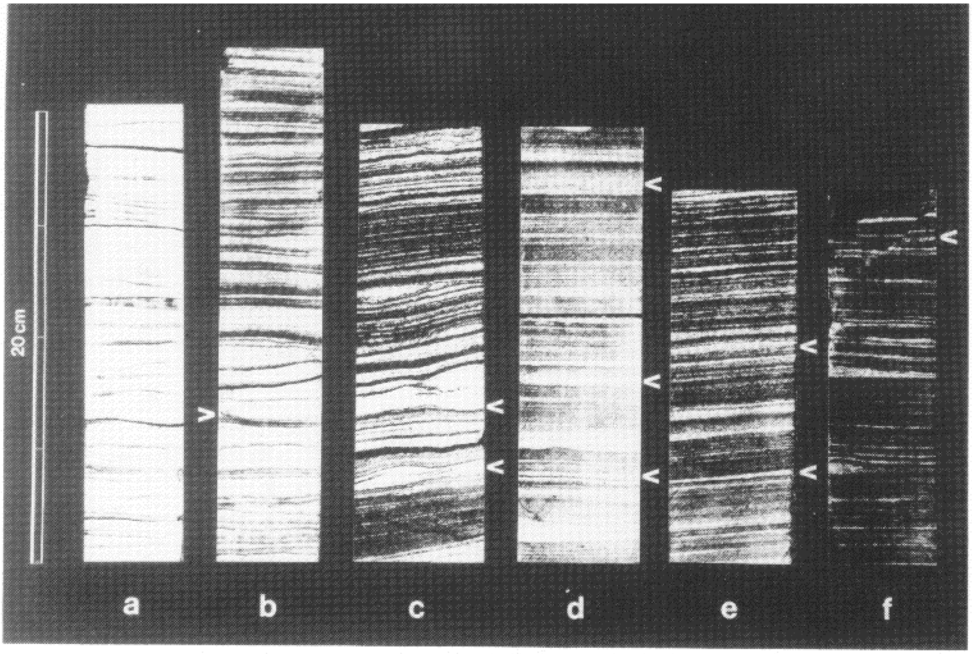


Fig. 6. Representative core photographs of mudstone group Facies (1) to (5): (a) Facies 5. Note lenticularity of sandstone layers and basal scouring; (b) Facies 5/4. Note internal lamination, basal scouring and mud-injection structure *(arrow)*; (c) Facies 4/3. Note asymmetrical fading ripple *(arrow)* and loaded base to thick sandstone layer *(arrow)*; (d) Facies 3. Note very low-amplitude long-wavelength ripples *(arrows)*, and normal grading in some laminae; (e) Facies 3. Note grading in thin lamina *(arrow)* and set of about three climbing low-amplitude ripples *(arrow)*; (f) Facies 2/1. Note synsedimentary micro-fault *(arrow)*.

Although porosities in the sandstones can be up to 10%, very low average permeabilities render this facies group of negligible importance as a reservoir.

The mudstone group can be divided into five facies on the basis of micro-structures and the sandstone/mudstone ratio (SS/MD). These facies are entirely gradational, from dominantly mudstone to dominantly sandstone.

Facies (1): dominantly mudstone, SS/MD 20/80; very-thin, parallel sandstone laminae, gradational and sharp boundaries, rare normal grading; also rare thin sandstone beds.

Facies (2): SS/MD between 30/70 and 40/60; thin, parallel sandstone laminae, very low-amplitude long-wavelength ripples; gradational and sharp boundaries, some grading; also rare thin sandstone beds.

Facies (3): SS/MD 50/50; thin, parallel sandstone laminae, very low-amplitude long-wavelength ripples, rarely lenticular, gradational and sharp boundaries, some grading and loaded or scoured bases; rare thin sandstone beds.

Facies (4): SS/MD between 60/40 and 70/30; thin- to thick-parallel sandstone laminae, lenticular laminae common, fading-ripple lamination (Stow and Shanmugan, 1980) at the tops of thick laminae and thin sandstone beds, gradational and sharp boundaries, grading, internal parallel and cross-lamination, loading and scouring, mudstone rip-ups and injection structures; alternatively, abundant closely-spaced thin- to thick-parallel sandstone laminae.

Facies (5): dominantly sandstone, SS/MD 80/20; mainly thick-parallel sandstone laminae and thin sandstone beds, often abundant lenticular to flaser bedding, fading-ripple lamination, internal parallel and cross-lamination, grading, loading and scouring, mudstone rip-ups and injection structures, gradational and sharp boundaries; some sandstone beds up to 10 cm thick.

Interesting dipmeter patterns are observed in the mudstone facies, although dipmeter analysis in such a structurally complex field is, of course, hazardous. Structural dip appears to vary between 2°-10° mostly towards the east, NE or SE, although westerly dips are also inferred. Removal of the structural dip component is complex as fault movement was occurring during sedimentation. However, some remaining dip variation is probably sedimentary in origin. Within the dominantly mudstone sequence between 3,725-3,850 m in well H (Fig. 7), the dip decreases upwards (red motif) from a maximum of 18° (average 13°) to a minimum of 4° (average 6°) without significant change in the easterly azimuth over 125 m of section. This is concomitant with a gradual upward coarsening as revealed by the sonic and gamma ray logs as well as by core analysis. On a smaller scale, the dips oscillate by 2°-4° over 3-10 m intervals, showing both upward increasing (blue) and upward decreasing (red) dip motifs. There are similar oscillations in the gamma ray log and in the facies themselves, but it has not yet been possible to correlate these exactly.

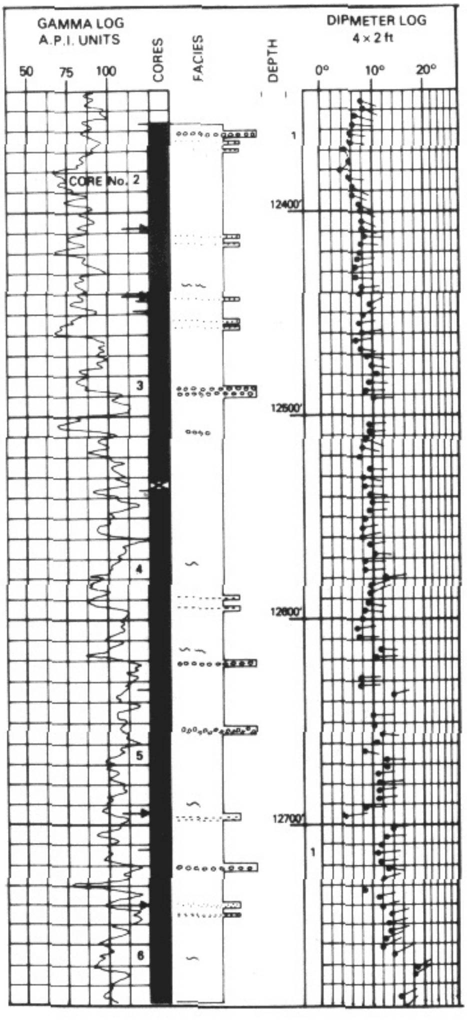


Fig. 7. Dipmeter pattern and gamma-log motif for part of dominantly-mudstone sequence in well H. Note upward decrease in easterly dips, as well as dip oscillation, concomitant with decrease in gamma-log response.

In the I, K and N wells, similar thick 25-75 m mudstone sequences show an overall dip increase of about 10° (blue motifs). These may be associated with either one or two fining-upwards or coarsening-upwards cycles. The slight oscillation of dips is again present but not so pronounced as in well H.

(2) *Sandstone group* (Fig. 8)

The sandstones are quartzitic (including polycrystalline quartz and chert) with minor to trace amounts of feldspar, muscovite and heavy minerals. Carbonaceous plant debris (sometimes pyritised) and mudstone fragments are common. Shell debris (clams, echinoids, sponges, cephalopods, benthonic forams) and glauconite are particularly common in wells D, G and H, but are very rare in the cleaner sandstone of wells I, K, L, M and N. The sandstones are fine- to coarse-grained and become pebbly in parts. They can be massive, parallel and less commonly cross-laminated, and graded with sharp load-cast bases and gradational tops passing up into thin mudstone partings. Secondary silica cementation is common with minor authigenic illite, but calcite cementation is very patchily distributed, being most common in the shell-rich sandstones and much rarer in the cleaner sandstones. Average porosities and permeabilities are generally good in the clean massive sandstones, except where calcite cementation has reduced reservoir quality.

Two sandstone facies are recognized on the basis of bed thickness and internal structure:

Facies (6): thin bedded (2-10 cm), with common mudstone partings; internal parallel and cross-lamination and grading common, also massive.

Facies (7): medium- to thick-bedded (> 10 cm, 20-40 cm probably common); mostly appears massive, may have some internal parallel lamination and grading to pebbly sandstone.

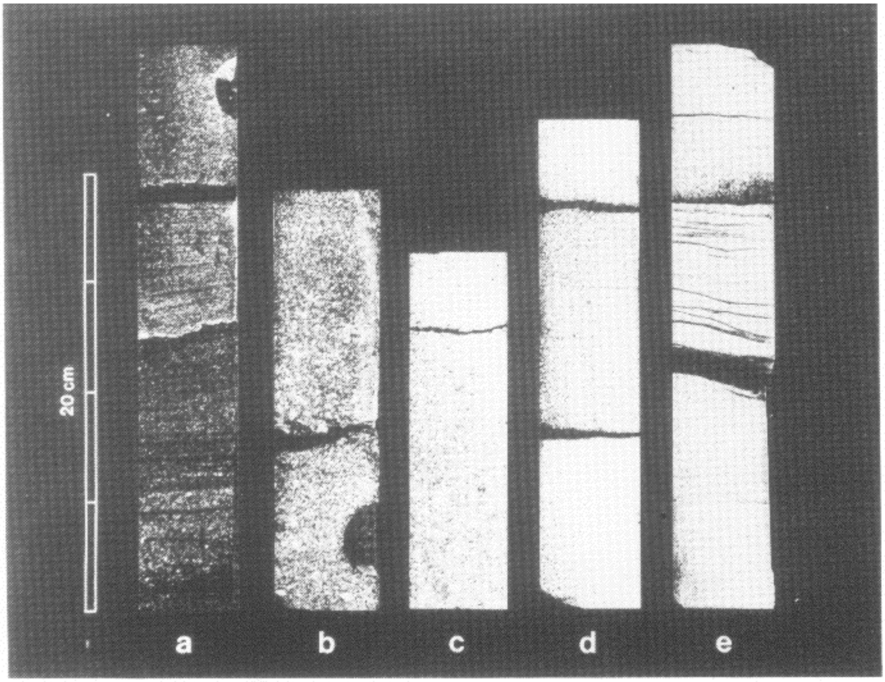


Fig. 8. Representative core photographs of sandstone group Facies (6) and (7): (a) Facies 6. Parallel-laminated, normally-graded sandstone; (b) and (c) Facies 7. Normally-graded, pebbly sandstone-sandstone; (d) Facies 7. Massive sandstone; (e) Facies 6. Thin-bedded sandstone with grading, lamination and thin mudstone partings.

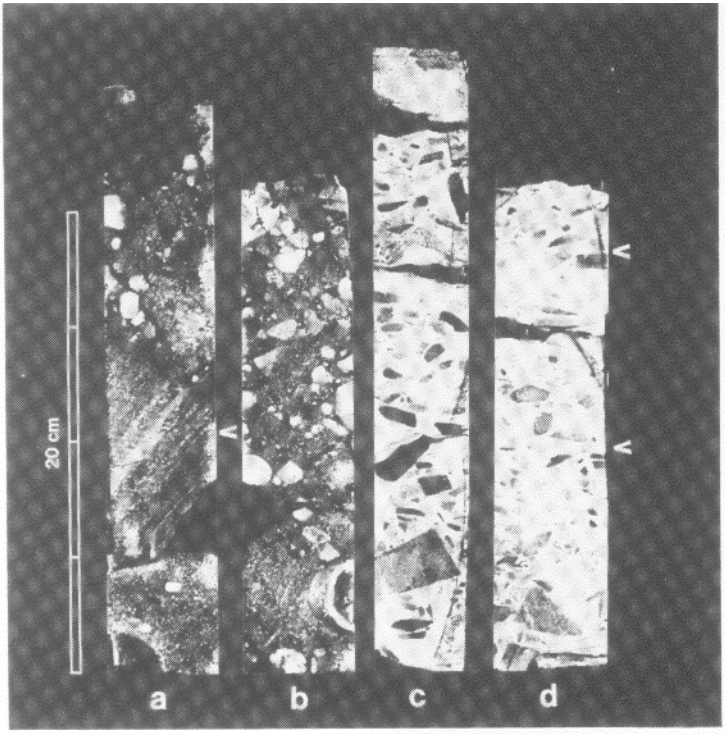


Fig. 9. Representative core photographs of conglomerate group facies (8) and (9): (a) Facies 9. Clast-supported "massive" conglomerate, pebbles over 10 cm in diameter *(arrow)*; (b) Facies 9. Matrix-supported "massive" conglomerate with rounded pebbles; (c) Facies 8. Matrix-supported (?) graded conglomerate (or breccia) with angular pebbles; (d) Facies 8. Matrix-supported conglomerate (breccia); note crude stratification, clast alignment parallel to bedding *(arrow)* and possible imbrication *(arrow)*.

Dipmeter patterns in the sandstones are less clearly defined than those in the mudstones. Both red and blue motifs are common, showing an often irregular 5°-15° change over 3-10 m. These changes do not appear to match consistently with facies changes observed in the cores or on the logs. Larger-scale patterns were not noted.

(3) *Conglomerate group* (Fig. 9)

The conglomerate group comprises a wide variety of rock types including breccias, pebbly sandstones, pebbly mudstones and (?) tectonic breccia. The clast composition is dominated by tight, feldspathic, fine-grained Devonian sandstones which make up between 60-95% of the clasts. In some wells (notably I and K) there are 20-30% quartz pebbles, other clasts include dark grey (?Jurassic) mudstones, dolomite, shell fragments and carbonaceous plant debris. The matrix is in most cases a medium- to very-coarse sandstone similar in composition to facies (6) and (7), and is only glauconitic and shelly in the northern wells. In wells B, D, E, F and L, the topmost conglomerate unit has a muddy matrix and in well H there are numerous pebbly mudstone units, up to 2 m thick, through the mudstone-dominated sequence.

Clast size is very variable; maximum sizes are mostly 20-40 cm although boulders up to 150 cm are present. In general, the larger clasts (10-30 cm) are subangular while the smaller clasts (2-5 cm) are more rounded. However, rounded boulders are found and, particularly in well D, there are angular small pebble breccias. With such

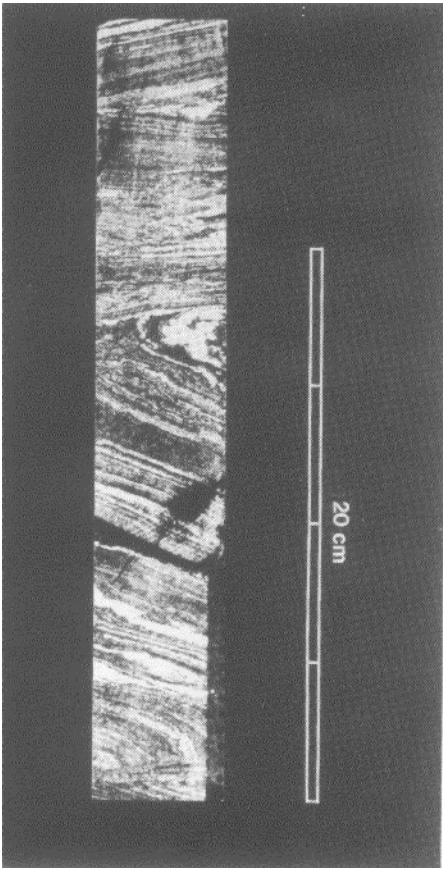


Fig. 10. Core photograph of slump zone (Facies 10) in laminated mudstone.

coarse-grained sediments, internal structures and individual bed thicknesses are very difficult to determine in 10-15 cm diameter cores. Both clast-supported and matrix-supported conglomerates occur, the latter perhaps more commonly, and both often appear massive. Normal grading over 0.5-2.0 m is present and, rarely, probable reverse grading at the base of units. There may be a crude parallel stratification, clast alignment parallel to bedding and, rarely, some clast imbrication. Calcite and dolomite-filled fractures are common, especially in wells E and F where a tectonic overprint, including mylonitisation, has destroyed original structures. Porosity and permeability in the sandstone matrix is variable and moderately good, except where destroyed by calcite cement.

A number of conglomerate facies could be recognized in the *Brae* wells, but, due to the difficulties in dealing with this group of rocks in narrow core sections, only two facies are distinguished here.

Facies (8): graded conglomerate-pebbly sandstone, stratified or non-stratified; occurs as distinct beds 20 cm-2 m thick.
Facies (9): massive conglomerates, matrix and clast-supported, bedding not distinct.

Both facies commonly show random “bag o’ nails” dipmeter patterns, and a blocky log character.

(4) *Facies (10): slumped beds* (Fig. 10)

Features indicative of synsedimentary slumping are common in all the facies described above. They include slightly convoluted, contorted and overturned laminae and beds, small-scale normal faults, steeply-inclined laminae, and chaotic mudstone/sandstone mixes. Conglomerate units are sometimes separated by thin slumped mudstone horizons. Where the slump features occur over more than about 50 cm of section they are described here as a separate facies.

Facies distribution

Sediment facies in eight of the fully-cored *Brae* wells have been carefully logged (Fig. 11). About 45% of the section is made up of the mudstone-group facies, (1) to (5), 20% comprises the sandstone facies (6) and (7), and 35% the conglomerate facies (8) and (9). Sequential facies transition matrices have been compiled for each well, and a composite matrix for the eight wells is shown in Fig. 12. The most common transitions are 6-5, 5-4, and 4-3 followed by the reverse of these, 5-6, 4-5 and 3-4, which together comprise about 50% of the observed transitions. The next most common are 7-6, 8-7, 6-7 and 7-8 making up a further 20%.

On a small scale, each facies tends to be associated with only one or two other similar facies in repetitive sequences. On a medium scale (5-20 m), both fining/thinning-upwards and coarsening/thickening-upwards sequences are noted with, perhaps, a slight dominance of the former. On a large scale (50-150 m), between three and six fining upwards megasequences are present in most of the *Brae* wells (Figs 5 and 11). On the basin-fill scale (300-600 m), there is an overall fining upwards sequence from Devonian basement through coarse Jurassic (Oxfordian) breccias and conglomerates to progressively-finer grained sandstone and mudstone facies (mostly Kimmeridgian) which are finally overlain by a Volgian black shale sequence.

The basin-fill sequence is the only one that can be correlated with certainty between wells. Even the megasequences seem to vary in number and in facies between closely-spaced wells (Fig. 5), so that precise correlation is not possible. This lack of correlation is due to marked lateral facies variation over short distances in an east-west direction at right angles to the boundary fault zone (e.g., well I to well K; well E to G), and in a north-south direction parallel to the fault zone (e.g. well I to M, well D to J to H). Marked compositional differences between the northern more shelly and glauconite-rich facies and the southern wells have been noted earlier. Wells C, E and F are on higher fault blocks or on the platform proper and are

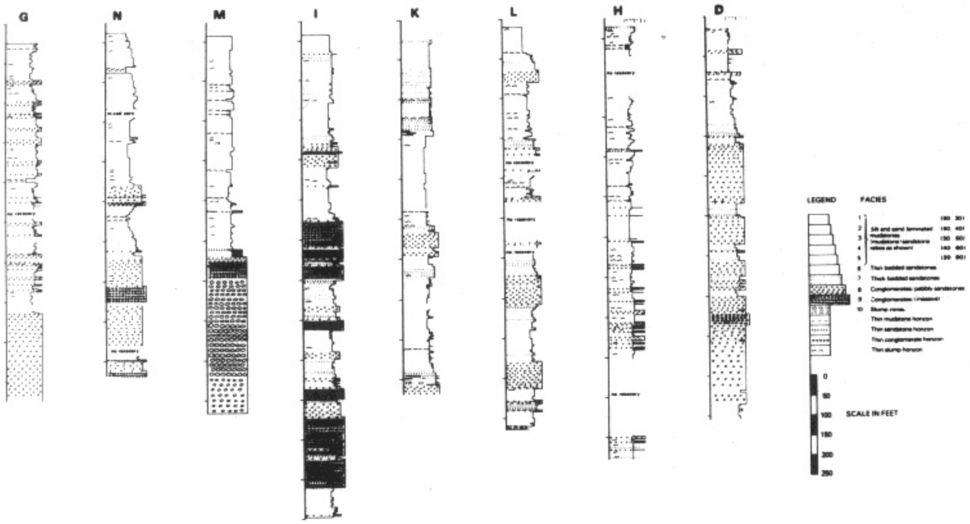


Fig. 11. ***Brae*** **field core logs for eight of the extensively-cored wells.**

FACIES	1	2	3	4	5	6	7	8	9	10	TOTALS
1		2								1	3
2	2		27	8	1	2		2		8	50
3	2	28		66	6	4	2	22		10	140
4		6	75		49	17	3	14	1	6	171
5		2	6	67		52	6	19	2	1	155
6		2	5	12	70		23	17	1	3	133
7				3	9	38		20	5	1	76
8		4	15	8	13	19	42		5	3	109
9					1		3	14			18
10		4	10	11	4	5		1			35
											890

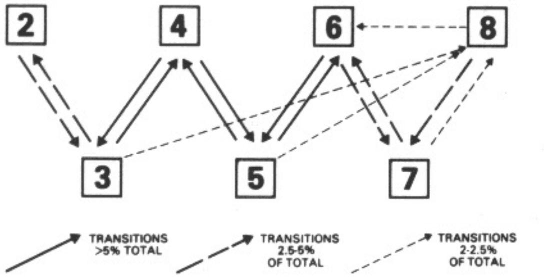


Fig. 12. Composite facies transition matrix showing nearly 900 facies-transitions in the eight extensively-cored wells. The six most common transitions are 4-3, 6-5, 5-4, 3-4, 4-5 and 5-6, accounting for nearly 45% of the total.

composed almost entirely of highly-fractured and faulted conglomeratic sequences over Devonian basement.

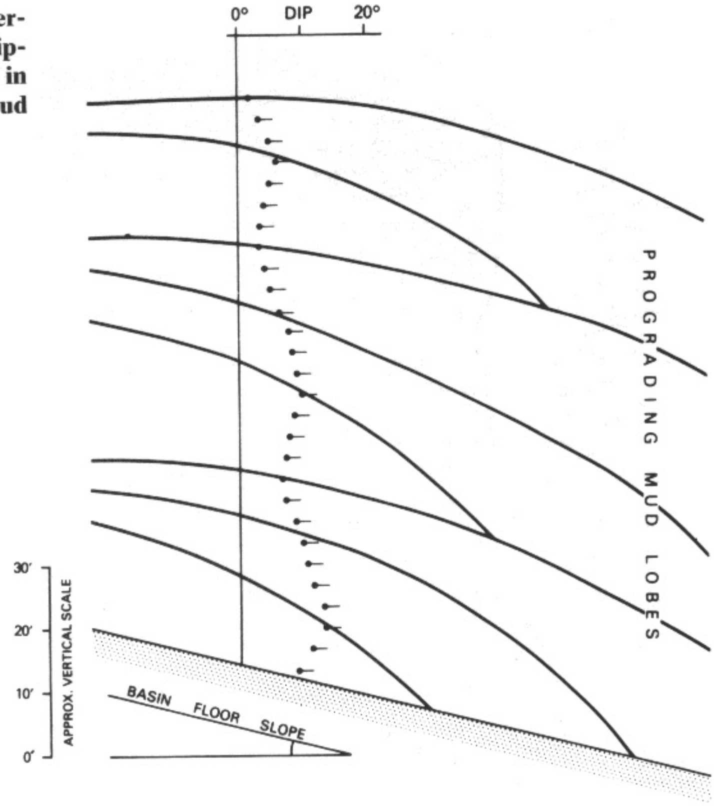
Facies interpretation

The range of small-scale sedimentary structures observed in the mudstone group facies is very similar to those described for fine-grained turbidites by Stow and Shanmugam (1980). Each of the facies (1) to (5) is composed of one or more of their ‘ideal’ turbidite divisions (T_0-T_8) in repetitive sequence. Thus, the thin-parallel sandstone laminae and low-amplitude ripples of facies (3) represent repeated T_2-T_3 units, the thicker-parallel and lenticular laminae and fading ripples cross lamination of facies (4) are made up of repeated T_0-T_4 units, and so on. Glaister and Hopkins (1974), Mutti (1977) and Piper (1978) also interpret such structures as resulting from fine-grained turbidity current deposition. Facies (5) was deposited in the most ‘proximal’ levee or channel-mouth setting and facies (1) in the most ‘distal’ inter-channel, inter-fan or basinal position.

The dipmeter patterns and the small-scale fining and coarsening-upwards sequences noted in the cores and logs are important indicators of the nature of turbidite mudstone deposition. The overall coarsening-up sequence associated with an oscillating red dipmeter motif in well H, for example, can be interpreted in terms of prograding mud lobes (Fig. 13).

The sandstones and conglomerates (facies 6-9) are closely comparable with the coarse-clastic resedimented facies described by Walker (1967, 1975, 1978), Walker and Mutti (1973) and Surlyk (1978) among others. They are mostly very ‘proximal’ deposits in the fan setting and are not readily described by the classic Bouma (1962) turbidite sequence. The coarse breccias with occasional very large angular clasts are interpreted as rock-fall avalanches at the base of the fault scarp. The mud-supported

Fig. 13. Schematic interpretation of mudstone dipmeter motif (e.g. Fig. 8) in terms of prograding mud lobes.



conglomerates and pebbly mudstones are probable debris flows. The sandy matrix-supported and clast-supported conglomerates, the pebbly sandstones and massive sandstones can all be interpreted as the result of grain flow-liquefied flow-turbidity flow deposition (Middleton and Hampton, 1976; Lowe, 1976a, b).

The slump facies (10) and the common slump structures throughout the well sections are indicative of deposition on a slope with periodic tectonic activity and/or rapid sediment build-up. The major fractures, particularly common in the thick conglomerate sequences, attest to fault proximity and activity both during and immediately following deposition.

Environmental setting

There is a mixed pelagic and shallow water benthonic fauna and flora in most of the cores examined which is clearly marine. There is also a very strong terrestrial influence including spores, pollen, woody debris and rare drifted-coaly horizons. Parts of the lowermost conglomerates and breccias, particularly in the high fault-block wells C, E and F and perhaps in some of the other wells, may have been deposited subaerially as alluvial fans on a Devonian terrain feeding directly into the sea. During the remaining Upper Jurassic sedimentation, the water depth was probably never very deep. Some of the sandstone ripples in facies (5) and (6) may be wave-induced (Harms *et al.*, 1981) but, for the most part, deposition occurred below wave base in relatively-quiet water. There is no large-scale cross-bedding, little or no bioturbation, no oxidation of carbonaceous detritus and there are thick sequences of undisturbed parallel-laminated mudstones.

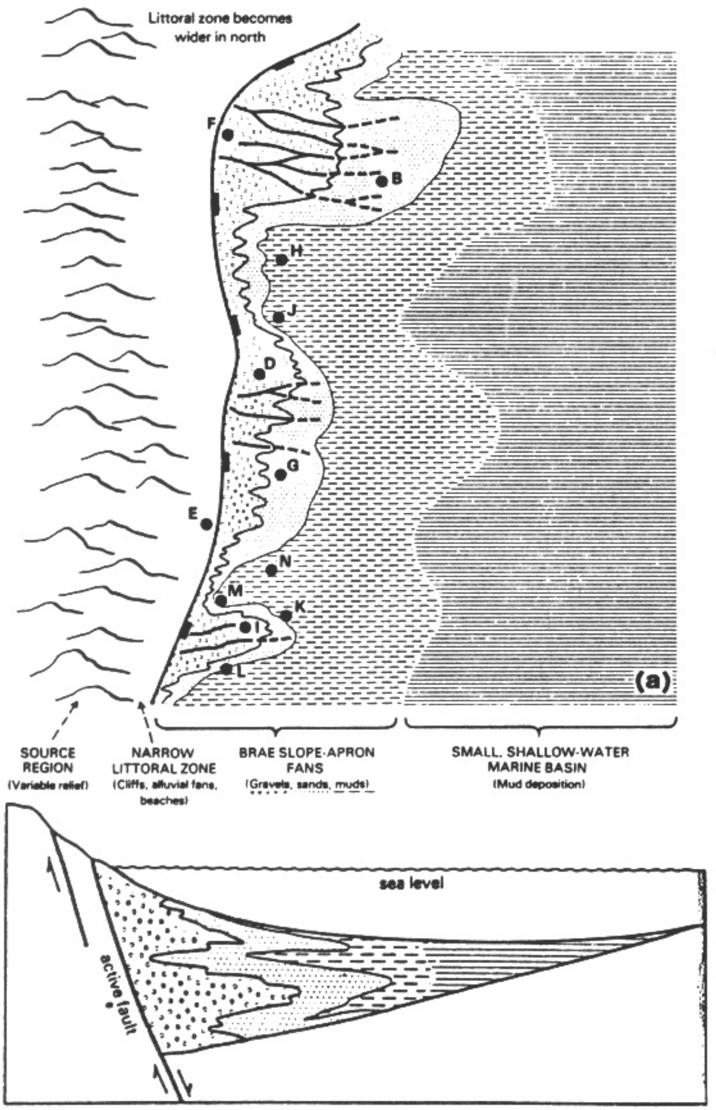


Fig. 14. ***Brae*** **field submarine fans model: (a) plan view of** ***Brae*** **field showing main boundary fault and well locations. Schematic distribution of main facies groups shown by ornament. Solid and dashed lines indicate probable distribution of submarine-braided channel network; (b) cross-section showing schematic basin-fill sequence. Vertical facies megasequences related to periodic fault activity.**

These features, together with the complex lateral and vertical distribution of facies, the fining-upwards megasequences and the repeated interdigitation of coarse-grained and fine-grained sediment gravity flow deposits are best explained by a fault-controlled, small-fan model.

‘Brae’ fans model (Fig. 14)

(a) Wells B through N were drilled through at least three small overlapping submarine fans that form a complex sediment apron along the faulted scarp margin.

(b) The fans are small, perhaps extending up to 5-10 km from the fault scarp, and were deposited for the most part below wave base in a shallow basin.

(c) The main control on fan development has been tectonic. Coarse-clastic sedimentation began with major fault movement and antithetic basin subsidence in the Oxfordian. Several episodes of fault movement and basin fill occurred through the Kimmeridgian and resulted in up to six fining-upwards megasequences. Faulting was not uniform in time or location along the margin, so that megasequences are not readily correlated between wells. A general decrease in fault activity and/or sediment supply through the Late Jurassic led to an overall fining-upwards basin fill that culminated in the Volgian black-shale transgression.

(d) Individual megasequences are composed of both fining-upwards and coarsening-upwards sequences that are related to channel, lobe, interchannel and interfan deposition.

(e) A base of fault-scarp, breccia-conglomerate facies association was deposited as rockfall avalanches. An inner-fan channel and lobe conglomerate-sandstone association resulted from grain flow-liquefied flow-turbidity flow processes. Channel-mouth massive sandstones-pebbly sandstones were similarly deposited. A mudstone-facies association was deposited by turbidity currents in interchannel, interfan, outer-fan and basinal settings, the facies type being closely related to position on the fan.

(f) Quantitatively, each of the ten facies identified is relatively-equally represented. There is a complex interdigitation of these facies and very marked lateral and vertical facies changes.

(g) The source of sediment was mainly Devonian sediments subaerially exposed on Fladen Ground Spur to the west. At times, alluvial fans may have fed directly into the sea, although mostly there was a narrow littoral zone in which pebbles were rounded and sands sorted. Muds and plant debris were supplied to the coast by rivers. The coastal zone became wider to the north and more shelly debris and glauconite was resedimented downslope. Still further north, well B (not cored) and well A (250 m core, location not shown) comprise more mature dominantly-sandy sequences, indicating a relatively-wide sandy shelf zone and lack of very coarse sediment supply to the slope.

Reservoir characteristics

There are three major interrelated controls on porosity and permeability in the *Brae* reservoir: diagenesis, facies distribution and fault distribution. The diagenetic history has involved several stages:

(a) mechanical compaction, clay alteration and expansion, seriticization;
(b) irregular calcite cementation, in some wells, destroys porosity, replaces k-feldspar, mica and clays, prevents further diagenesis and even some compaction;
(c) silica cementation, mainly quartz overgrowths (over a broad time span);
(d) solution of k-feldspar, some calcite and clays (late stage);
(e) partial infill of solution porosity and original porosity by kaolinite, illite, quartz and rarely dolomite; silica cementation tends to increase with depth.

The highest porosity-permeability values are found in the massive sandstones and in the sandy matrix of conglomerates. The average values for the conglomerates as a facies are lower as the clasts are non-porous. The fine-sandstone layers of the mudstone-group facies have fair porosities but permeabilities are very low due to the mudstone laminae. Mudstone-supported conglomerates also have very poor reservoir quality. The calcite cementation is controlled largely by the original content of shelly debris in the sediment, and is therefore more severe in the northern group of wells. It is not clear what has controlled the solution of k-feldspar and the other minerals.

In highly-fractured sections close to faults (e.g. wells C, E and F) the porosities are very low due to cementation by calcite, dolomite and minor barite.

CONCLUSIONS AND IMPLICATIONS

In view of the importance of submarine fans as hydrocarbon reservoir and source rocks it has seemed pertinent to review the sedimentary-fan models that have been developed over the past 15 years. There have been many descriptions of fans, both modern and ancient, and the five best-documented models have been summarised. These vary significantly in detail, and it is important to know which model, if any, is appropriate for a particular area or field, although certain aspects of each of the models have wider application.

A different approach is to evaluate the various controls that operate to determine the type of fan developed. The most important controls are: type and amount of sediment supplied, tectonic setting and sea-level changes. An attempt is made to relate these controls to the fan models. Most present-day fans that have been studied are oceanic; more work is required on modern examples of shallow, small-basin fans which are particularly relevant to hydrocarbon exploration.

North Sea hydrocarbon-bearing fans of both Jurassic and Tertiary age would fit into this latter category. The *Brae* oilfield is an Upper Jurassic reservoir developed on the western faulted margin of the North Sea central rift system. A detailed sedimentological study has been carried out using electric logs, dipmeter logs and 2,500 m of core. The *Brae* field comprises at least three small overlapping submarine fans that form a complex sediment apron along the faulted scarp margin, and that were deposited by a variety of gravity-flow processes in a shallow basin below wave base. The main control on fan development has been tectonic. Periodic fault activity resulted in up to six fining-upwards megasequences within the overall fining-upwards basin fill. There has been a large but intermittent supply of coarse detritus (sands, gravels and boulders) across a narrow littoral zone and down a steep slope. Short, sediment-laden rivers supplied large amounts of mud and plant debris, and a complex interdigitation of coarse- and fine-grained facies has resulted.

The *Brae* fans appear most closely analogous to the Jurassic fans of East Greenland (Surlyk, 1978) although there are several differences in detail. They are an important example of the fault-controlled, shallow small-basin fan. It is also important to derive an accurate model of reservoir characteristics. In the case of the *Brae* field, there have been three controls on porosity and permeability: diagenesis, facies and fault distribution. Reservoir quality varies from good to very poor. The pattern of reservoir character is expected to vary markedly along the fault margin; a clear understanding of the controls is essential if successful exploration and development of both structural and, perhaps, stratigraphic traps is to continue successfully.

Acknowledgements

The work for this paper was carried out while the authors were employed by the British National Oil Corporation. We acknowledge the co-operation of the *Brae* field operator, Marathon, and partners, Bow Valley, British National Oil Corporation, Kaiser Canadian, Kerr McGee, Louisiana Land and Exploration, Saga and Siebens Oil and Gas, in granting permission for the publication of this paper. We should also like to record our thanks to various colleagues within BNOC, in particular Dr M. F. Ridd, Mr M. J. Fisher and Dr A. J. Parsley, for their advice and encouragement during this study. The manuscript has been critically read by Mr M. Curry, who is thanked for his helpful comments.

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