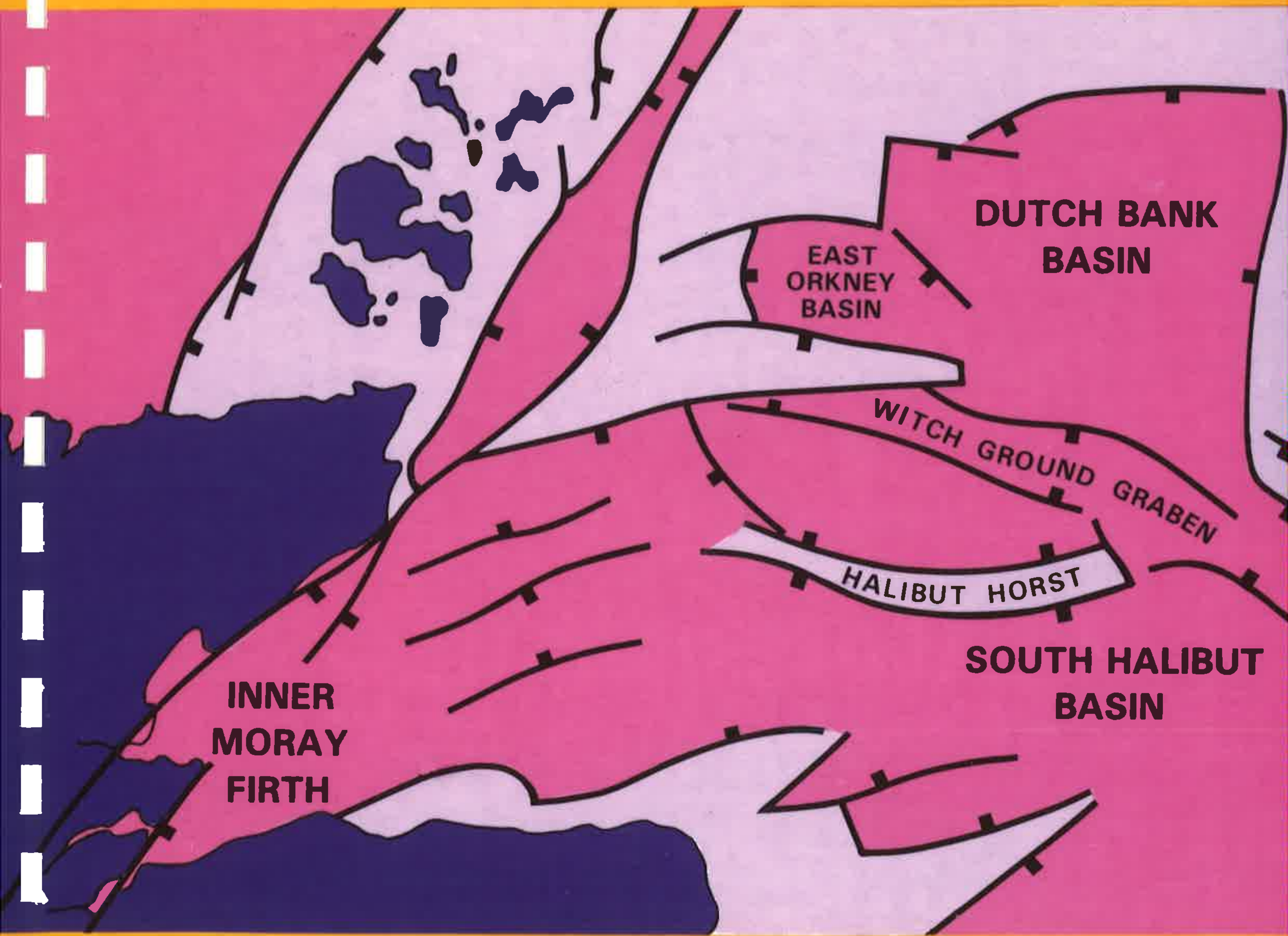
BRITISH GEOLOGICAL SURVEY

HYDROCARBONS RESEARCH PROGRAMME

Stratigraphic Evolution and Reservoir Sedimentology, Moray Firth Basin: a core workshop.



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Stratigraphic evolution and reservoir sedimentology, Moray Firth Basin : a core workshop

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1. INTRODUCTION

Since 1984 the Hydrocarbons Research Programme of the British Geological Survey has presented a series of core workshops to illustrate the reservoir rocks of the UK North Sea. These workshops have made extensive use of the unique archive of North Sea core material stored at the Department of Energy/BGS core store in Edinburgh. This workshop, the first of the series to be run in conjunction with the Petroleum Exploration Society of Great Britain, provides the opportunity to examine the reservoir rocks of the Moray Firth area.

The Moray Firth Basin, consisting of a number of grabens and half-grabens, has proved to be highly petroliferous. Hydrocarbon reservoir rocks occur at a wide range of stratigraphic horizons ; in this workshop reservoirs from Devonian, Carboniferous, Permian, Middle and Upper Jurassic, and Lower Cretaceous intervals will be illustrated and discussed. In addition, the facies distribution of Triassic strata will be examined. The stratigraphic and structural context in which the reservoir rocks are developed will be considered and an outline account of the evolution of the Moray Firth Basin will be presented.

The wells used in the workshop are illustrated in this document by the inclusion of appropriate down-hole logs and synoptic core descriptions.

The following sequences are illustrated:

Old Red Sandstone	Lower ORS	12/27-1	(Figure 3.1)
	Lower ORS	13/19-1	(Figure 3.2)
	Middle ORS	13/24-1	(Figure 3.4)
	Upper ORS	21/1-6	(Figures 3.5 to 3.8)
	Upper ORS	21/1-8	(Figure 3.9)
Carboniferous	'Coal-bearing strata'	14/19-6	(Figure 4.2)
Permian	Halibut Bank Fm	20/2-2	(Figure 5.2)
	Turbot Bank Fm	14/19-C26	(Figure 5.3)
	Kupferschiefer Fm	14/19-C26	(Figure 5.3)
Triassic	Smith Bank Fm	20/10-1	(Figure 6.1)
	'Skaggerak' Fm	14/19-3	(Figures 6.2 and 6.3)

Jurassic	Beatrice Fm	11/30a-8	(Figures 7.3 and 7.4)
	Alness Spiculite Unit	12/22-2	(Figures 7.5 and 7.6)
	Piper Fm	15/16-12	(Figures 7.7 and 7.8)
	Sgiath Fm and Claymore Sandstone Mbr	14/19-3	(Figures 7.9 and 7.10)
	Ettrick Sandstone Mbr	20/2-1	(Figures 7.11 and 7.12)
	Intra-Kimmeridge Clay Fm sandstones	13/27-1A	(Figures 7.13 and 7.14)
Lower Cretaceous	Scapa Sandstone Mbr	14/19-15	(Figures 8.2 and 8.3)
	Bosun sands	16/27-3	(Figures 8.6 and 8.7)
	Aptian/Albian sands	21/2-6	(Figures 8.9 and 8.10)

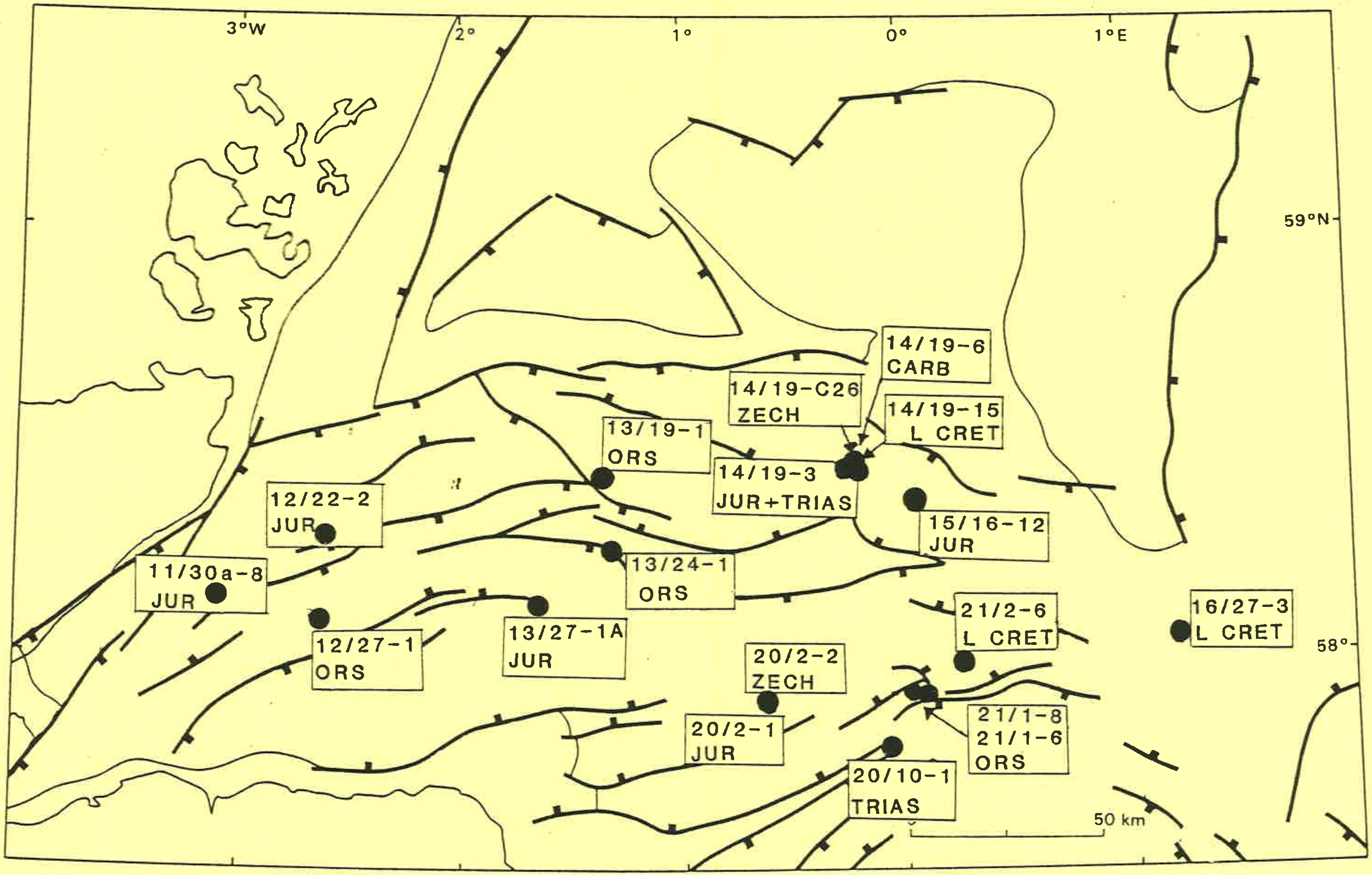


Fig 1.1 Map showing the location of the figured wells

2. REGIONAL SETTING AND INTERNAL STRUCTURE OF THE BASIN

2.1 Regional setting

The Moray Firth Basin is a complexly polygenetic sedimentary basin whose origins and development have a critical control on the habitat of hydrocarbons. Once thought of simply as the westerly-projecting arm of a North Sea trilete graben system, now perhaps only the NW-SE trending Witch Ground Graben, lying in the eastern part of the Moray Firth area, can make any claim to satisfy this description. The merit in persisting with this trilete grabens hypothesis is the subject of some debate; structure maps of the central North Sea area commonly show the Witch Ground Graben as a north-westwards continuation of the Central Graben.

2.2 Internal stuctural patterns

There is a strong contrast in structural trend within the the Moray Firth Basin, with a dominant NE-SW alignment of faults in the west, reflecting the Caledonian inheritance of the major structures, and an NW-SE trend in the east (Figure 2.1). The latter trend can probably be related to extensional stresses applied to the central North Sea area during phases in its early to mid-Mesozoic history.

The deep structure of the Moray Firth also exhibits a marked east to west contrast. In the east, beneath the the Witch Ground Graben there is evidence of lithospheric thinning (Christie and Sclater, 1980), accomplished during extension. In the west however, Donato and Tully (1981) report little or no thinning. Barr (1985) argues that the extension which produced the Mesozoic basins of the Inner Moray Firth occured above a mid-crustal detachment surface.

The western area has, in contrast to the Outer Moray Firth and indeed to the Viking Graben and most of the Central Graben, suffered uplift and erosion during the the Tertiary. McQuillin *et al.* (1982) estimate the amount of uplift at 1000m, resulting in Lower Cretaceous and older strata cropping at sea-bed over the Inner Moray Firth.

2.3 Structural nomenclature

The structural nomenclature to be used throughout this text is shown in

Figure 2.1. The first order subdivision of the Moray Firth area into an Inner and Outer basin is made along the Little Halibut Fault, the western end of the Halibut Horst, and along the margin of a buried granite beneath the Buchan Graben. Marginal basins lie within the East Shetland Platform area to the north.

2.4 Outline of tectonic evolution

Following consolidation of the Caledonian orogen, probably c.410 Ma, intra-montane DEVONIAN basins developed. The early Devonian basins were probably small and isolated but sedimentation became more widespread with time. There is some debate as to the tectonic control on the formation of these Devonian basins, either as pull-apart basins in a major NE-SW strike-slip zone, parallel to the Caledonian structural grain (Zeigler, 1982; the "sinistral megashear hypothesis" described by Norton *et al.*, 1987), or in a regional extensional setting, with the major stress direction transverse to the Caledonian grain (Dewey, 1982; the "extensional collapse hypothesis" favoured by Norton *et al.*, 1987. See also Watson, 1985).

Evidence of CARBONIFEROUS geology is scarce, mainly coming from the occurrence of Viséan-Namurian strata in the Outer Moray Firth. In the UK area to the south, Leeder (1982) describes a fragmentation of the crust, on the incipient Hercynian foreland, during a period of extension. The offshore evidence from the Moray Firth indicates that the rifting and basin development may have continued farther north. The effects of Hercynian compression, well known as far north as the Midland Valley, may be seen in the Moray Firth area from the absence of Westphalian strata below the base Permian unconformity.

The PERMIAN saw more widespread subsidence and preservation of strata in the Moray Firth area, in a basin initially separated from the North Permian Basin by a NE-SW high along trend from the onshore Highland Boundary Fault (Glennie, 1986). There are conflicting views as to when rifting began in the Central Graben; in the Permian according to Glennie (1986), in the Triassic according to Zeigler (1982). In the Moray Firth area the evidence points to a later date, but the evidence is largely negative; although deposited in a Moray Firth Basin there is no conclusive evidence of Permian facies or original thickness changes associated with faults. The evidence of fault control on TRIASSIC subsidence is also less than clear-cut, especially in the western part of the basin. A number of authors have referred to Triassic rifting, notably Frostick *et al.* (1988) in their paper on the Triassic of the Moray Firth. An examination of thickness data from wells and seismic in the Inner basin, however, indicates that the Triassic sediments form a geometrically tabular package of strata, and therefore not significantly affected by differential fault-controlled subsidence (see Barr 1985).

Interpreting the origin of the Inner Moray Firth Basin, McQuillin *et al.* (1982) envisage 8 km of dextral transcurrent movement along the Great Glen Fault during the Mesozoic and Tertiary, but mostly during the Jurassic. This movement has been transferred to intra-basinal faults, allowing the Inner Moray Firth half-grabens and grabens to develop through extension.

The early JURASSIC development of the Moray Firth Basin can only now be charted in the west, where Lower Jurassic strata are found in the Great Glen Sub-basin and the Smith Bank Graben. There is no conclusive evidence of Lower Jurassic beds farther east. The Lower and Middle Jurassic strata in the Inner Moray Firth were deposited in a relatively simple basin, uplifted at times in the east when the fill was subject to erosion. This basin configuration persisted until the mid-Oxfordian when, as shown by a change from an essentially tabular sediment package up to a strongly wedge-shaped one in the Inner Moray Firth, the influence of a small number of marginal and intra-basinal faults on subsidence and sedimentation increased. A series of major half-grabens developed.

In the Outer Moray Firth, Middle Jurassic strata rest unconformably on Triassic or older rocks. The formation of this unconformity surface is rather poorly understood. Basic volcanism characterised the Outer Moray Firth and adjacent areas to the east and south-east during the mid-Jurassic. This has been associated with a rifting phase which also led to regional uplift (updoming) of the central North Sea. The estimates for the amount of uplift vary from 3000m (Zeigler, 1982) to 60m (Kent, 1982)! The Middle Jurassic is overlain by mid to late Oxfordian strata in the Outer Moray Firth area, at an unconformity. The time interval represented by this unconformity may have been over-estimated in the past; Howitt *et al.* (1975) dated the Middle Jurassic volcanics as Bajocian-Bathonian but recent dates published by Ritchie *et al.* (1988) indicate a Callovian age. (The implications of this for the chronology of rifting and uplift phases in the North Sea needs to be considered. For example, it suggests that the volcanism post-dates the deposition of the Brent Group in the Viking Graben which was related by Eynon (1981) to the development of a contemporaneous upwarp in the central North Sea.)

By the mid to late Oxfordian there was shallow marine to paralic sedimentation throughout the Moray Firth area. Fault control on sediment thickness and facies became a major factor in the Kimmeridgian and persisted through the remainder of the Jurassic period. There is evidence that the fault influence waned for a time during the Ryazanian as "hot" shales blanketed the area and the influx of sands was reduced.

There is no simple, single basin event marking the end of the Jurassic, although the termination of Kimmeridge Clay Formation organic shales (of Oxfordian to Ryazanian age) may be due to a synchronous and widespread basin-flushing event (Rawson and Riley, 1982). Normal faulting continued to affect the subsidence of the early CRETACEOUS basin which developed for a time with a similar structural configuration to the late Jurassic basin. Probably from the Barremian onwards, the style of basin development changed, with less contemporary fault influence on sedimentation in evidence.

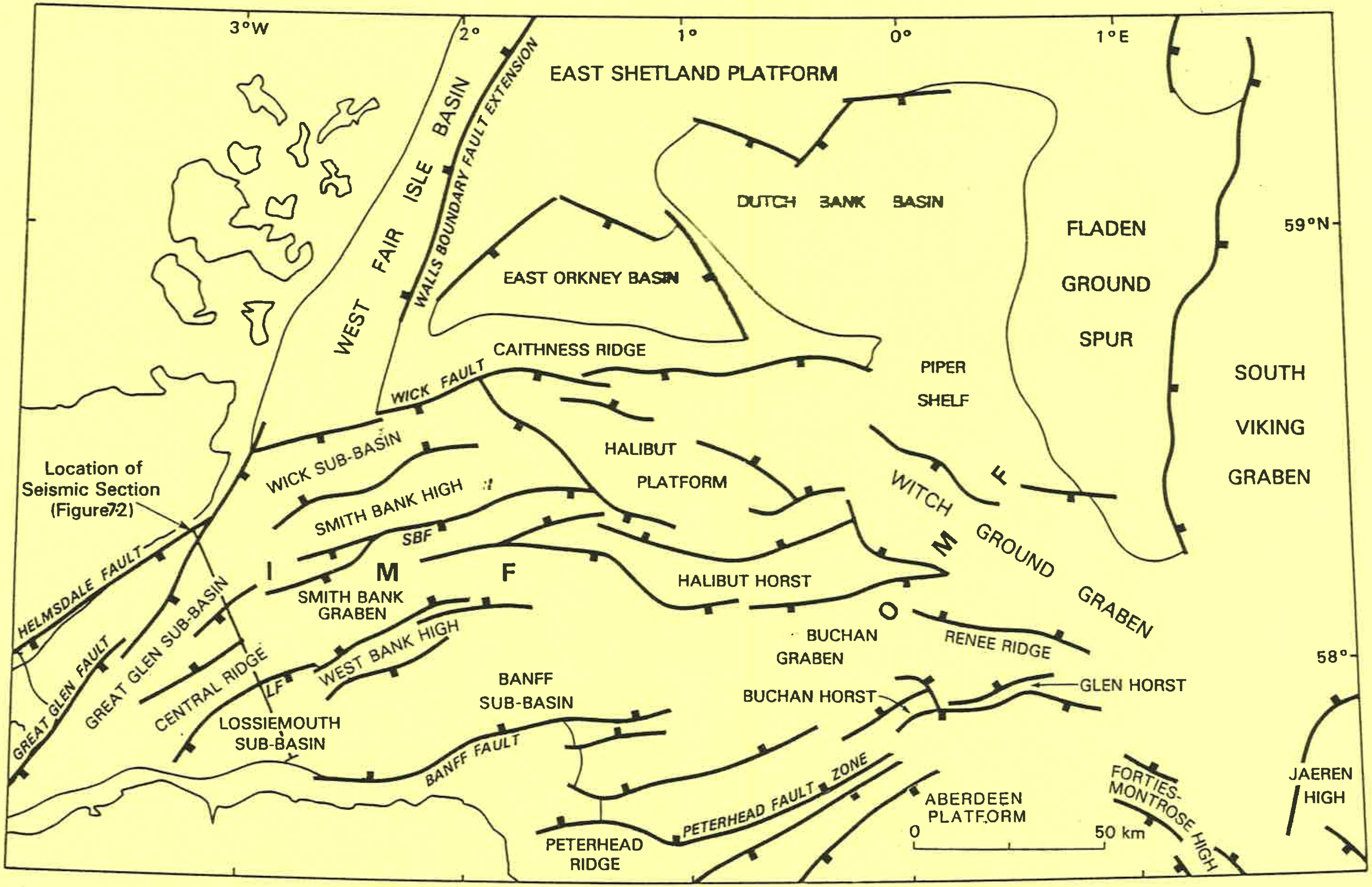


Fig 2.1 Generalised structure map of the Moray Firth area
(IMF – Inner Moray Firth, OMF – Outer Moray Firth)

3. DEVONIAN (OLD RED SANDSTONE)

Deposits of the Orcadian Basin are exposed onshore along the south coast of the Moray Firth, in Caithness, Sutherland, Banffshire, Orkney and Shetland. They have also been sampled at-sea bed, and in over 25 commercial boreholes offshore. The basin is now regarded as being of entirely continental origin, although some form of connection, possibly a river, may have linked the Orcadian lake with the mid-Devonian sea in the Central Graben area south of the Outer Moray Firth (Mykura, 1983).

Simple reconstructions of the geometry and extent of the Orcadian Basin suggest that its western margin lay along the coast of the Moray Firth and its eastern margin was in Western Norway (Zeigler, 1982). The western margin of the basin parallels the Great Glen Fault complex and its position may have been controlled by faults (Watson, 1985). Watson has also postulated that the position of the southern margin of the basin, which appears to cross-cut the structural grain, may also be defined by a deep fracture. Over 16,000 feet (5000 m) of ORS sediment was deposited in the Orcadian Basin as a result of the collapse of the overthickened crust of the Caledonian mountain chain, with the formation of localised half grabens within the basin area controlled by extensional reactivation along easterly dipping Caledonian thrusts (Astin, 1985; McClay *et al.*, 1986).

Although a division into Lower, Middle or Upper ORS can be made in some wells offshore, a large number of sequences remain undifferentiated because of their predominantly arenaceous nature and a consequent lack of fossil material.

3.1 Lower Old Red Sandstone

Lower ORS sequences onshore around the margins of the Orcadian Basin consist of associations of lenticular conglomerates, fine grained sandstones and, locally, high proportions of siltstones and mudstones. These sediments were probably deposited in isolated, mainly playa lake basins fringed by active fault scarps. A rare, Lower ORS fluvial sequence is preserved in the Turriff Basin at New Aberdour.

Lower Old Red Sandstone rocks have been recognised in a number of wells offshore, including 12/27-1 (Figure 3.1) and 13/19-1 (Figure 3.2). These

Lower ORS sections comprise a similar argillaceous dominated lithology. Drilled sequences are up to 3202 feet (976 m) thick and are predominantly grey to reddish brown siltstones and claystones with minor greyish brown, very fine grained, silty, calcareous sandstones.

The Lower ORS sections recognised offshore have yielded sporomorphs which confirm an early Devonian age. These sporomorph assemblages include examples of *Emphanisporites annulatus*, *E. robustus*, *E. rotatus*, *Calamospora* sp., *Retusotriletes* sp., *R. simplex* and *Apiculiretusispora* sp.

The fine grained nature of the sediments, the relative abundance of terrestrially derived miospores, and the lack of marine micro-organisms suggests deposition in fairly low energy, non-marine environments. Comparisons with onshore sections suggests that deposition occurred in intermontaine lacustrine environments. These lakes were probably formed in fairly small, isolated basins (Figure 3.3a) like those onshore (Richards, 1985a; Watson, 1985).

Some Lower ORS siltstone sequences are overlain by sandstone dominated units of undifferentiated Lower ORS or Middle ORS type. Comparisons can be drawn with the Lower ORS sections at Mealfuavonie, west of Loch Ness (Mykura and Owens 1983) and also with the Middle ORS in Ross and Cromarty. A more precise age date is not possible because the sandy sequences have proved to be non-fossiliferous.

3.2 Middle Old Red Sandstone

Middle Old Red Sandstone outcrops onshore are developed mainly in lacustrine and aeolian facies in the northern parts of the outcrop and in a mainly fluvial facies in the south (Mykura, 1983; Astin, 1985). The lacustrine facies are probably the best known of these sediments, and give rise to the popular term, Orcadian lake (Figure 3.3b), to describe the mid-Devonian Orcadian Basin. They occur in sequences up to 13,000 feet (4 km) thick, and some horizons are fish-bearing.

Although a relatively large number of interbedded sandstone and siltstone sequences of ORS affinity occur in the Moray Firth, unequivocal palynological identification of Middle ORS strata has only been made in a small number of wells. Well 13/22-1 contains a Middle ORS section comprising interbedded, varicoloured siltstones, silty mudstones and sandstones which are sometimes medium to coarse-grained or gravelly. Sporomorph assemblages in the upper parts of this well section are similar to that from the Eday Group flagstones, and an assemblage like that from the middle part of the section is found in the Lower Caithness Flagstone Group and the Achanarras Limestone onshore (c.f. Richardson, 1964). Middle ORS has also been recorded in well 13/24-1 (Figure 3.4), but the sequence there is very different to that seen in the 13/22-1 well.

3.3 **Upper Old Red Sandstone**

Upper Old Red Sandstone outcrops onshore have been attributed to the late Devonian on the basis of fossil fish content. Additional evidence of an Upper Devonian age is available at Hoy, where the sandstones overlie lavas dated as 370 Ma by Halliday *et al.* (1977). The lacustrine Orcadian Basin had become largely infilled by sands by the end of the Mid-Devonian. Deposition of the Upper ORS occurred in fluvial, wadi and playa lake environments in a desert setting (Figure 3.3c).

Although Upper Old Red Sandstone occurs in the coastal belt bordering the Moray Firth, none has been proven in the inner parts of the offshore basin. This is possibly because of a phase of post-mid Devonian uplift and erosion prior to renewed deposition in the Permo-Triassic. Deegan and Scull (1977) did suggest that a thick red bed sequence overlying a volcanic unit in well 12/23-1 may be of Upper ORS affinity by correlation with the Hoy succession (Orkney). However, a recent age analysis of the lavas underlying these red beds in the well has shown that the sandstones are more likely to be of Rotliegend age (see sections 4 and 5.1).

Upper Old Red Sandstone has been recorded in the outer parts of the Moray Firth, for example in the Buchan Oilfield, where late Devonian to early Carboniferous ages have been assigned to the ORS succession (Hill and Smith, 1979; Richards, 1985b). The Buchan sequence is up to 2215 feet (675 m) thick, and comprises mostly fining upwards sheetflood and channel deposits (Figures 3.5 to 3.9).

Figure 3.1 Composite and core log for the Lower Old Red Sandstone of well 12/27-1(Burmah).

Regional Setting

Well 12/27-1 is situated in the Smith Bank Graben area of the Inner Moray Firth Basin. The area was the site of an isolated, intermontaine basin during the early Devonian.

Well Stratigraphy

Old Red Sandstone strata in this well occur at a depth of 7693 ft (235 m), below a thick sequence of reddish sandstones referred to the Permian. The sequence is entirely of Lower ORS aspect and has a drilled thickness of 3200 ft (975 m). Lithology is predominantly siltstones. Patches and laminae of microcrystalline or micritic dolomite occur frequently. Symmetrical, wave-type ripples occur in places. Soft sediment deformation is common.

Depositional Environment

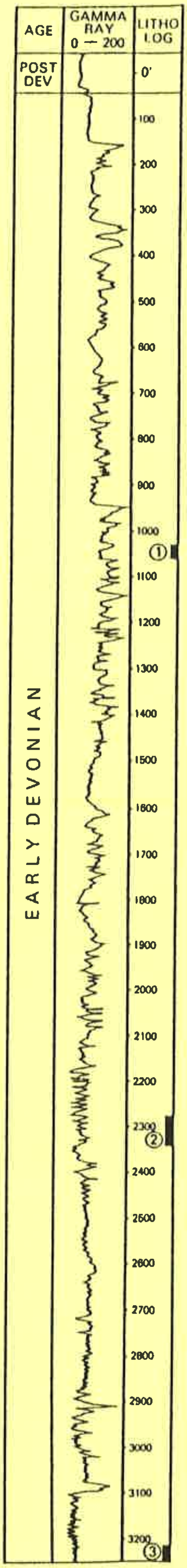
The fine grain size indicates low energy depositional conditions, and presence of terrestrial sporomorphs suggests deposition in a lacustrine setting. Symmetrical wave ripples suggest that the lakes were fairly shallow, and that bottom waters were subjected to agitation, probably by wind-driven waves. The considerable thickness of sediment suggests that the lake was long-lived.

Isolated lake basins such as this may have formed at intervals throughoutthe Caledonian mountain chain, their location possibly controlled by the distribution of major faults.

Reservoir Characteristics

These argillaceous sediments have no reservoir potential. Their source potential remains to be investigated, although spores recovered from the sequence are usually carbonised.

12/27-1 (BURMAH)



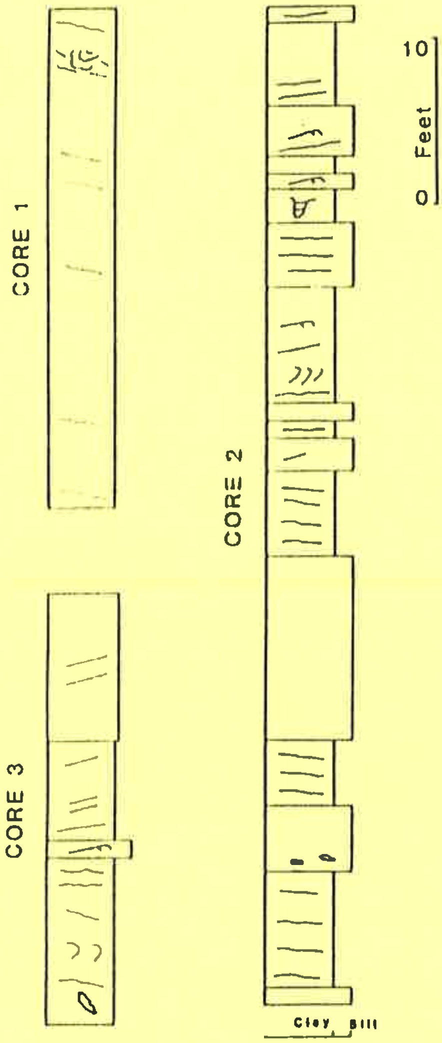


Fig. 3.1

Figure 3.2 Composite log for the Lower Old Red Sandstone of well 13/19-1 (Mobil).

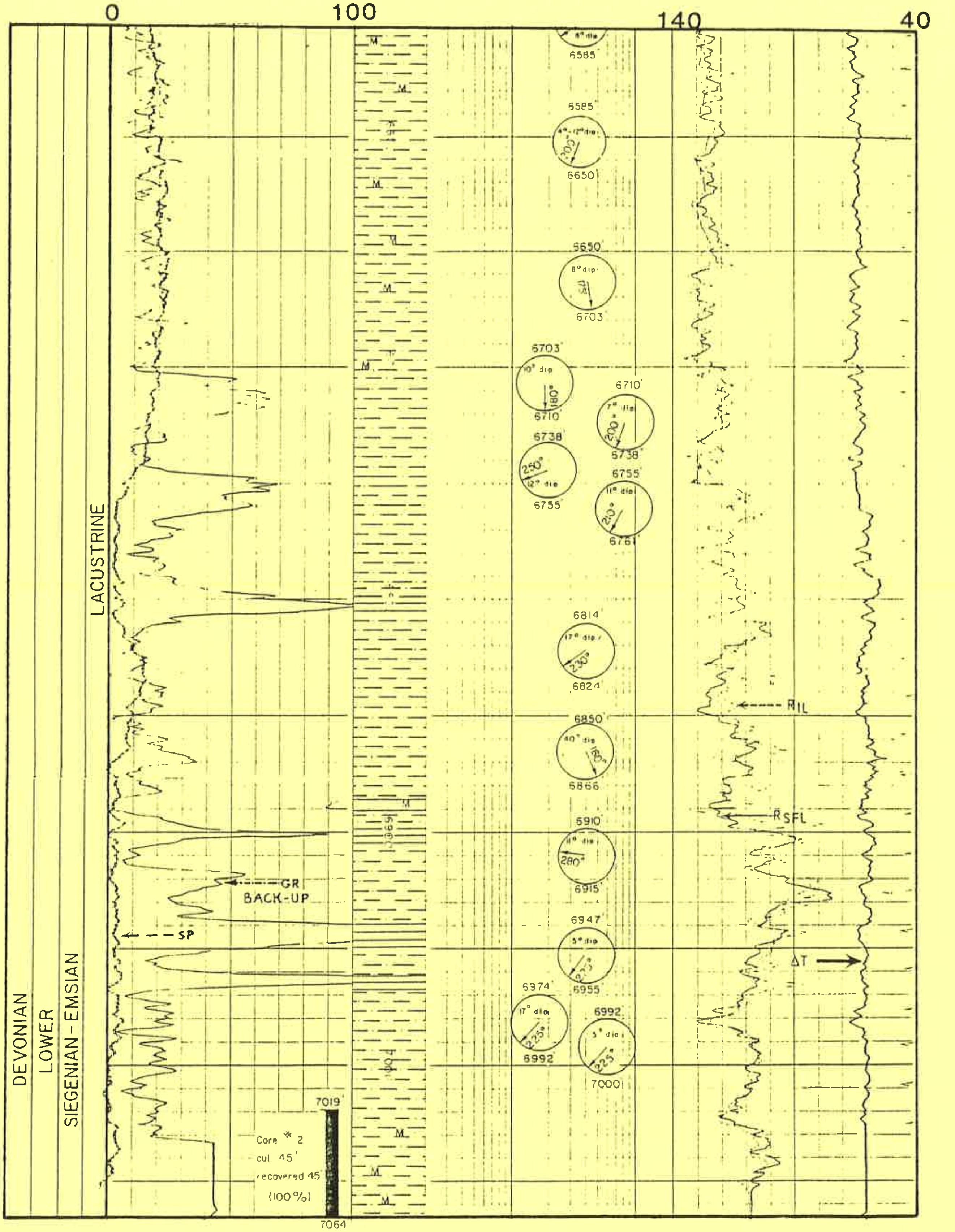
Regional Setting

Well 13/19-1 is situated on the Halibut Platform. The area was the site of an intermontaine lake basin during lower Old Red Sandstone times.

Well Stratigraphy

Lower ORS strata in this well are very similar to that from well 12/27-1, comprising mostly mid grey siltstones with some coarser silt bands. A few metres of this core is displayed for comparison with the 12/27-1 well.

13/19-1 (MOBIL)



DEPTH SCALE : FEET

Fig. 3.2

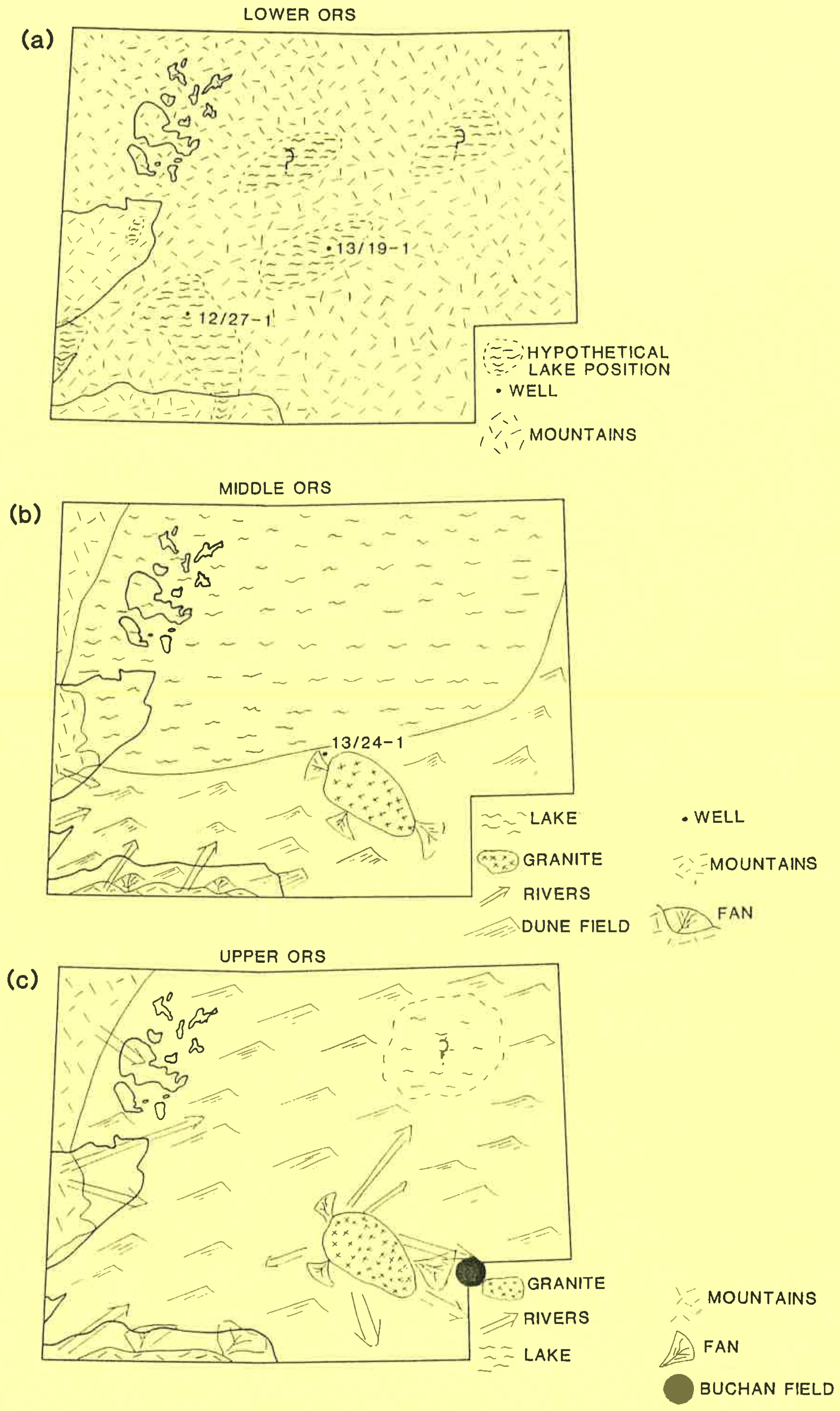


Fig. 3.3 Cartoon of Old Red Sandstone palaeogeographies

Figure 3.4 Composite log for the Middle Old Red Sandstone of well 13/24-1 (Amoco).

Regional Setting

Well 13/24-1 is located in the Smith Bank Graben, immediately south of the Halibut Horst. During mid-Devonian times the area was near the southern margin of the Orcadian lake, and the site was occasionally transgressed during phases of lake expansion. A large, Caledonian granite lies 5 km to the south east, and this granite was being eroded during the Devonian.

Well Stratigraphy

Old Red Sandstone strata are encountered at a depth of 6313 feet (1925 m) and comprise mostly fine to coarse sandstones and conglomerates, with thin beds of grey green claystone and siltstone.

The exhibited core material comprises 18 feet of mid grey coloured conglomerate from near the base of the drilled sequence. The core is mostly fragmented. Clasts are up to several centimetres across, and include pieces of white and pink, coarsely crystalline granite, phyllite and, rarely, gneiss. Epidote is common. Hydrothermal veining is common.

Depositional Environment

These Old Red Sandstone sediments were deposited in an alluvial setting fringing the Orcadian lake. The granite debris was probably being eroded from the 428 ±32 Ma old granite a few kilometres to the south east. The Dalradian-type metamorphic clasts were probably derived from basement in the vicinity of the granite.

Reservoir Characteristics

Traces of methane were recorded in the well, which was plugged and abandoned.

13/24-1 (AMOCO)

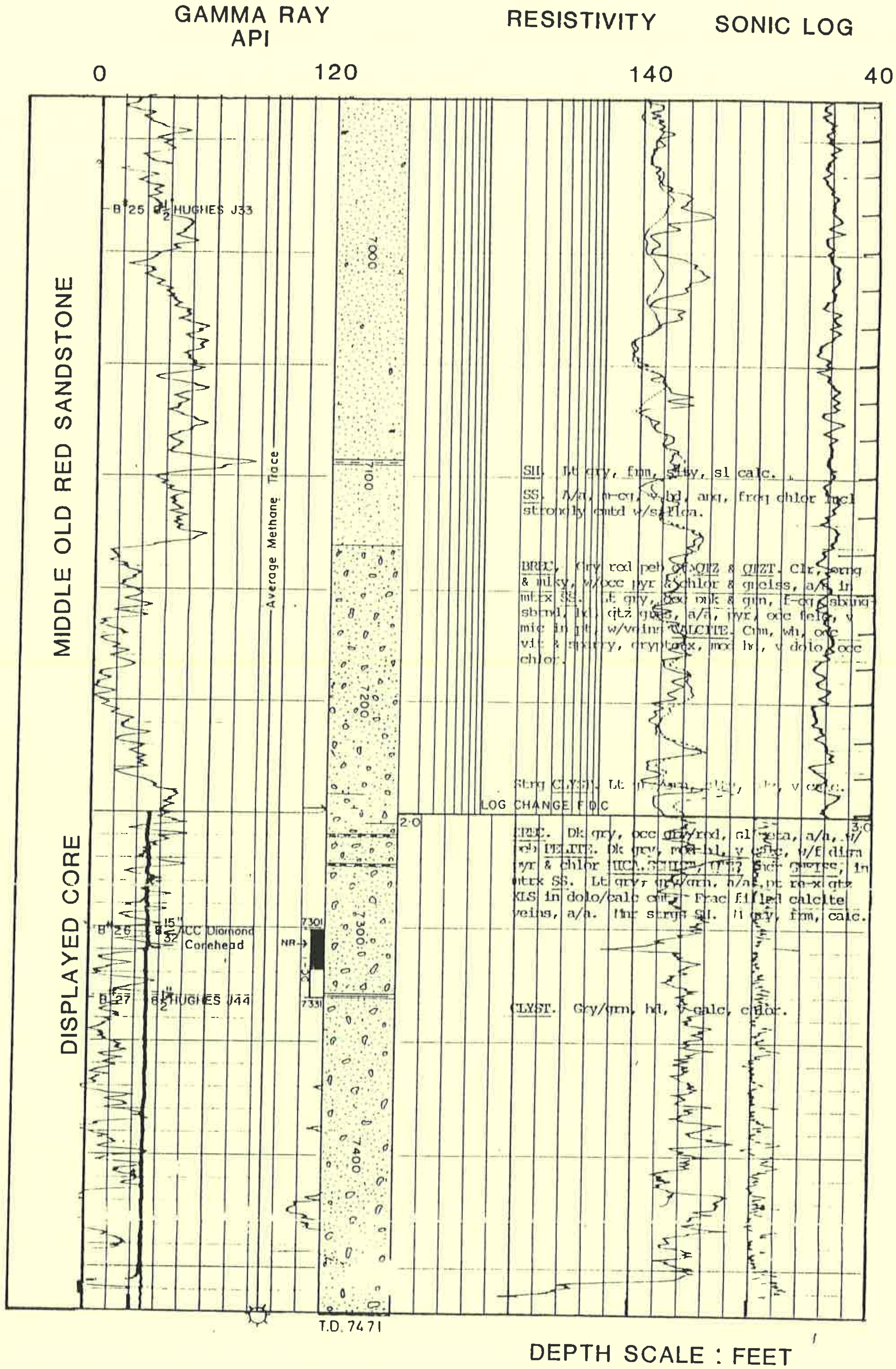


Fig. 3.4

Figures 3.5 and 3.6 Composite and core logs for the Upper Old Red Sandstone of well 21/1-6 (BP), Buchan Oilfield.

Regional Setting

This well is from the Buchan Field, which produces oil from an Upper Old Red Sandstone reservoir.

Well Stratigraphy

Upper ORS strata of Famennian to Visean age occur below Lower Cretaceous mudstones at a depth of 8806 feet (2685 m). The sequence is in excess of 2214 feet (675 M) thick.

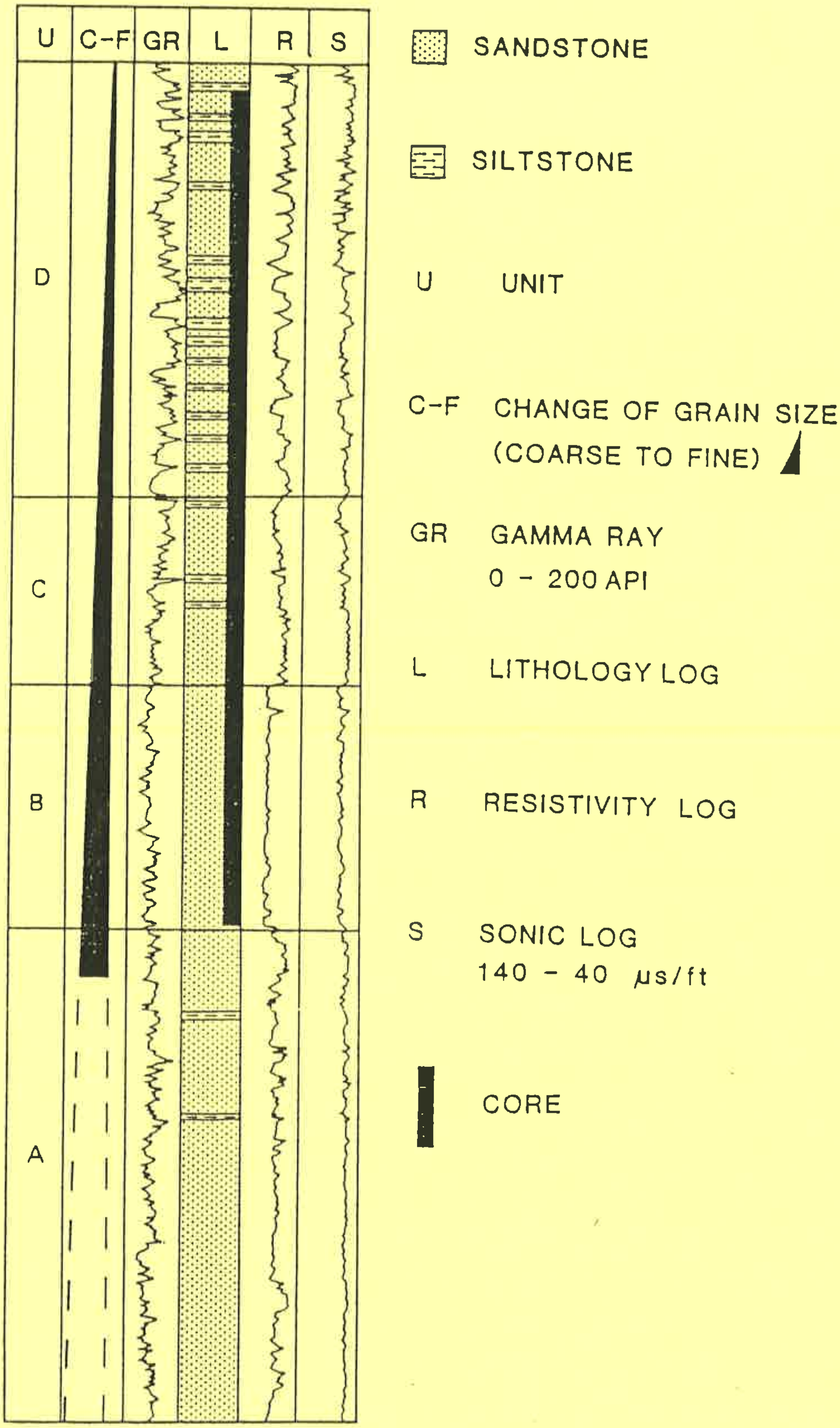
Four lithostratigraphic units are recognised in the sequence. The lower ones are dominated by sandstones with minor siltstones, and the amount of siltstone increases upwards through each unit.

The core log opposite (3051 m-3061 m) is from the sandstone dominated unit B of Richards (1985) from near the base of the sequence. The sands in this unit are arranged in fining up cycles, some of which have an amalgamated thickness of up to 10 m. The sandstones are very fine to fine grained, subarkosic, moderately well sorted and micaceous.

Depositional Environment

The sands were probably deposited predominantly from bed load in fluvial channels and as sheetfloods. The channels have produced sheet-like sandstone bodies.

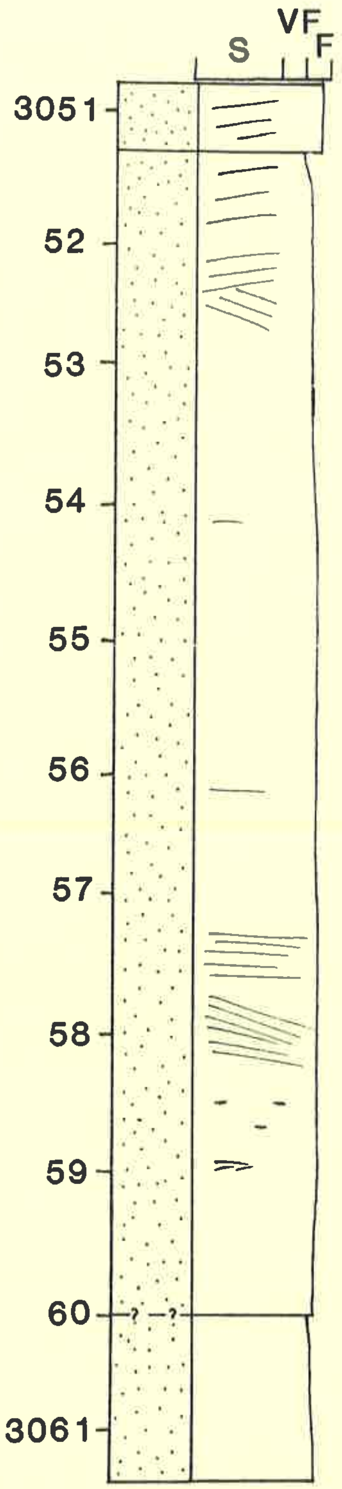
21/1-6 (BP)



THE SEQUENCE SHOWN IS 165m THICK

NOTE THE SUBDIVISION INTO FOUR UNITS

Fig. 3.5



21/1-6 UNIT B OF UPPER ORS

Typical sequence of amalgamated sandstones

DEPTH SCALE : METRES

Fig. 3.6

Figure 3.7 Core logs for the Upper Old Red Sandstone (Unit C) of well 21/1-6 (BP), Buchan Oilfield.

Regional Setting

This well is from the Buchan Field, which produces oil from an Upper Old Red Sandstone reservoir.

Well Stratigraphy

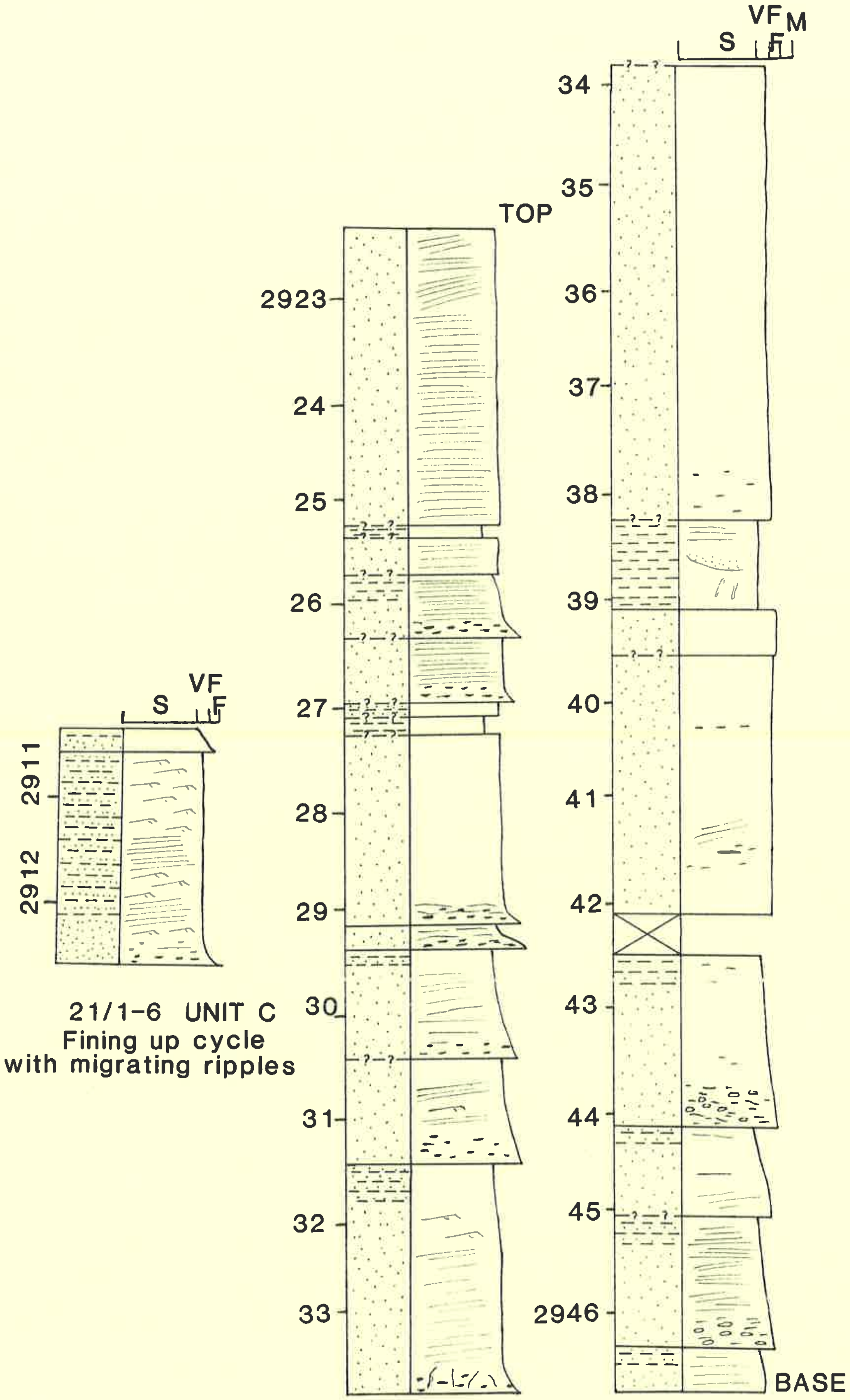
Richards (1985) identified four lithostratigraphic units within the Famennian to Visean Upper ORS sequence here. These are termed A to D from the base upwards. These units display an upward increase in the amount of siltstone horizons and associated cornstones.

The core logs opposite (2910.5 m-2912.5 m and 2922.5 m-2946.5 m) are from Unit C, near the middle of the succession. This unit contains more siltstone horizons than the previous core from Unit B, but less cornstones than the next core (following page) from Unit D.

About 67% of the beds in Unit C have fining up profiles, although 90% of the unit is composed of sandstone. These fining up cycles, occasionally starting with mud chip conglomerates, are exhibited in the cores. Sedimentary structures recognised in the fining up cycles include planar laminae, planar cross bedding, asymmetrical ripples and migrating ripples.

Depositional Environment

About 23% of the fining up cycles in Unit B are probably channel deposits, and 32% waning-flow sheetflood deposits. The remaining cycles are ambiguous and represent either channels or sheetfloods. Larger areas of the floodplain were preserved between channel belts in this unit than in the underlying Unit B.



21/1-6 UNIT C
Fining up cycle
with migrating ripples

21/1-6 UNIT C
Typical fining up cycles

DEPTH SCALE :METRES

Fig. 3.7

Figure 3.8 Core logs for the Upper Old Red Sandstone of wells 21/1-6 (BP) and 21/1-8 (BP), Buchan Oilfield.

Regional Setting

These wells are from the Buchan Field, which produces oil from an Upper Old Red Sandstone reservoir.

Well Stratigraphy

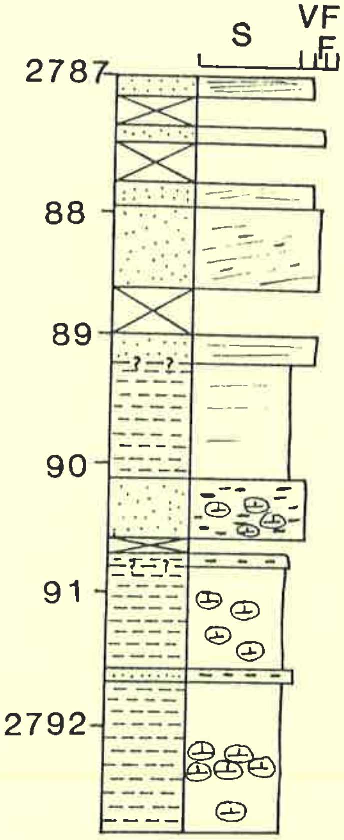
Richards (1985) identified four lithostratigraphic units within the Famennian to Visean Upper ORS sequence here. These are termed A to D from the base upwards. Unit D at the top displays more siltstone beds and cornstone horizons than the three lower units.

The cores exhibited here show various aspects of the Unit D succession. Two fining up cycles (up to 8 m thick) are displayed, showing the typical arrangement of lithologies in the unit, with fining up cycles having mud chip conglomerate bases, passing up to cross bedded and rippled sands and eventually to cornstone bearing siltstone.

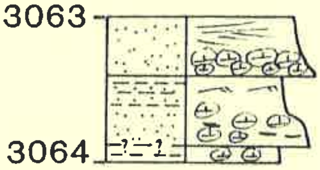
The three shorter lengths of core display varieties of cornstone horizon. Some are in situ, and some are cornstone conglomerates formed as a result of erosion of cornstone bearing siltstone beds.

Depositional Environment

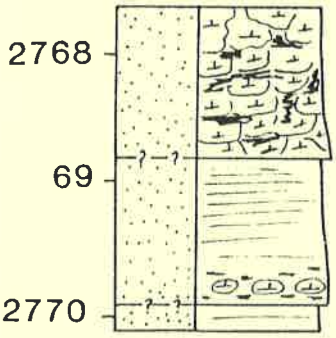
Most of the fining up cycles in this unit were deposited in channels. About 25% of cycles can be attributed to sheetfloods on the basis of vertical thickness. Floodplain environments were more stable during deposition of this unit than earlier units, and soil processes formed extensive cornstone horizons. These were sometimes ripped up and destroyed by sheetfloods.



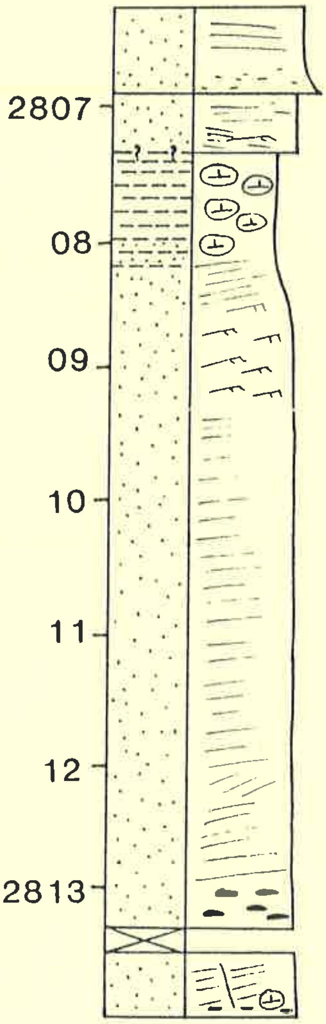
21/1-6
UPPER ORS UNIT D
Silts with crnstones
and rolled cornstones



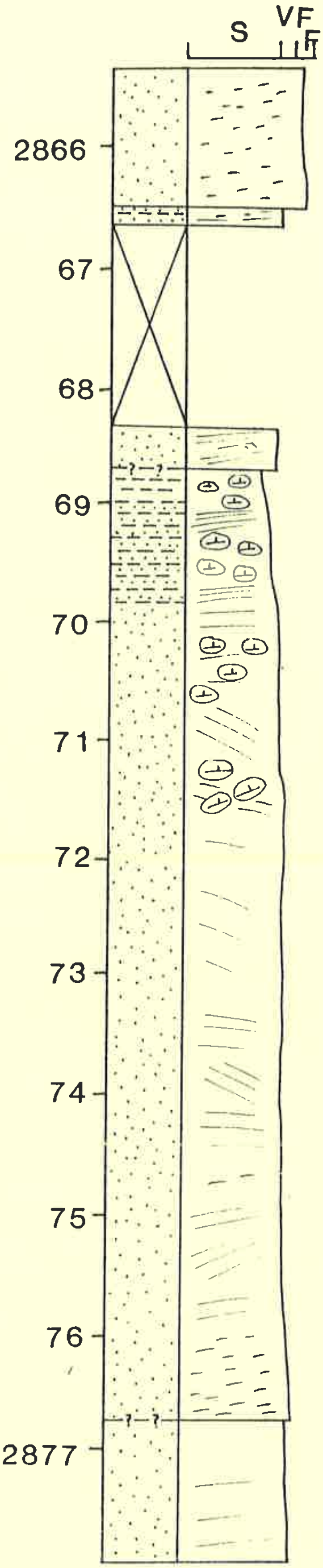
21/1-8
UPPER ORS
Rolled cornstones



21/1-6
UPPER ORS UNIT D
Cornstone conglomerate?



21/1-6
UPPER ORS UNIT D
Fining up cycle to cornstones



21/1-6
UPPER ORS UNIT D
Fining up cycle to cornstones

Fig. 3.8

Figure 3.9 Composite log for the Upper Old Red Sandstone of well 21/1-8 (BP), Buchan Oilfield.

Regional Setting

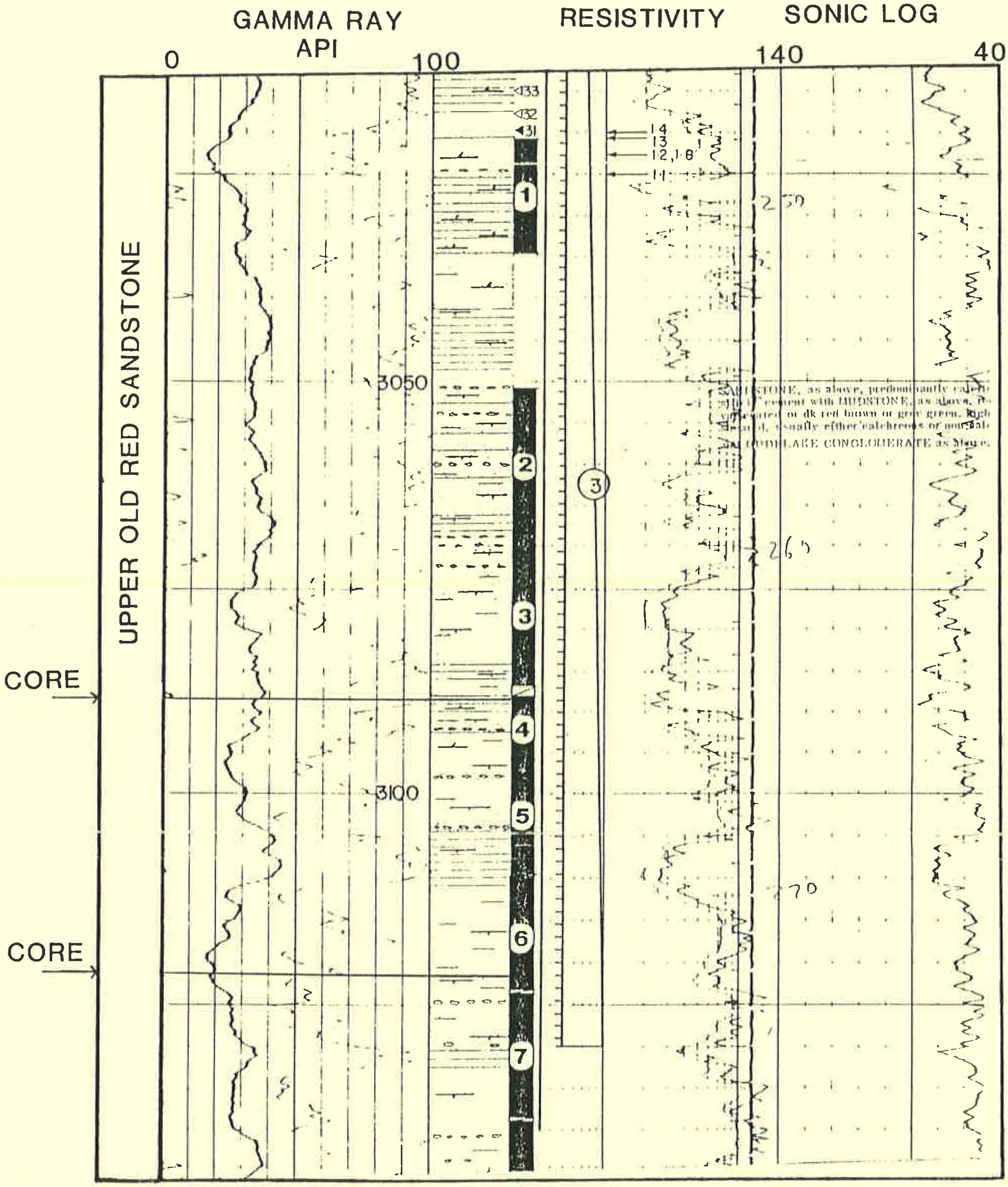
This well is from the Buchan Field, which produces oil from an Upper Old Red Sandstone reservoir.

Reservoir Characteristics

Core logs illustrating depositional features of the Upper ORS sediments of the Buchan Field have been presented on previous pages. Two short cores (3121.7 m-3122.2 m and 3087 m-3088.3 m) are exhibited here to demonstrate the nature of the fractures from which the field produces. Many of the fractures in the reservoir are not preserved in cores because of the fragmented nature of the reservoir, which yields small pieces of rubble on coring.

Oil staining of some sandstones demonstrates a degree of inter-granular porosity as well as the fracture porosity.

21/1-8 (BP)



DEPTH SCALE : METRES

Fig. 3.9

4. CARBONIFEROUS

Although not present onshore in the Moray Firth area, Carboniferous rocks have been penetrated offshore. Two types of sequence are recognised offshore: a) coal-bearing facies, and b) volcanics. Coal-bearing successions occur in the Witch Ground Graben and the Peterhead Ridge and may also be present over much of the Aberdeen Platform (Figure 4.1). Most information comes from the Claymore Oilfield, the Piper Shelf and other highs within the Witch Ground Graben although these sediments are probably also present in the deeper parts of the graben. However they are absent from the Galley Oilfield within the Witch Ground Graben and may also be absent from other prominent highs within the graben. The occurrences in the Moray Firth area connect via the Forth Approaches Graben with the Midland Valley of Scotland. This is supported by comparison of the Moray Firth lithologies with the Limestone Coal Group of the Midland Valley.

No wells in the Moray Firth area completely penetrate the coal-bearing succession. The maximum thickness drilled is 2346 feet (715 m) in the Claymore area, but a total sequence thickness of 4977 feet (1517 m) is suggested. The succession has everywhere been truncated by post-Carboniferous erosion so present thicknesses cannot be reliably related to depositional thicknesses. Even thicker sequences may be expected in the deeper parts of the graben.

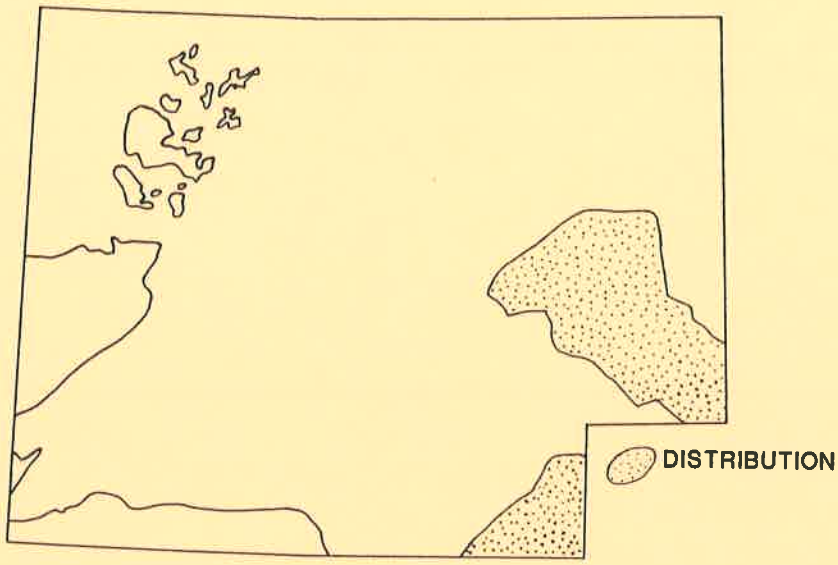
The facies association consists of thinly bedded sandstones, siltstones, shales and coals (Figure 4.2). The sandstones are white to grey, quartzose, fine to coarse grained, often micaceous, locally carbonaceous, and occasionally haematite mottled. The sandstone units are up to 65 feet (20 m) thick and are developed both as components of fining-upwards and coarsening-upwards cycles. In a typical cyclical development the sandstones fine upwards to siltstones and shales, which are normally dark grey or black and highly carbonaceous. The top of a cycle is characterised by a coal band, usually overlain by a carbonaceous shale. These cycles are usually less than 100 feet (30 m) thick, but can be much more complex than that described.

Coal-rank, deduced from vitrinite reflectance studies, is in the range of high-volatile bituminous coal, but is likely to be of higher rank off structure in the deeper parts of the basin.

Some sections have been dated palynologically, where the rich miospore assemblages are diagnostic of the Viséan, (Asbian and Brigantian stages) and Namurian.

Lithological assemblages, geophysical log characteristics and limited core information suggest that deposition took place in an extensive paralic environment on a prograding delta. Possible fluvial channels, interdistributary bay and swamp deposits have been recognised.

Well 12/23-1 in the Inner Moray Firth Basin penetrated a 190 feet (58 m) thick volcanic unit, comprising mainly olivine basalt and devitrified basalt lavas overlain by volcanic ashes with a minor interbedded basalt flow. A core from near the base has been described as an analcite-rich alkali olivine basalt. A ^{40}Ar-^{39}Ar age determination of 340 Ma suggests a minimum age within the Viséan.



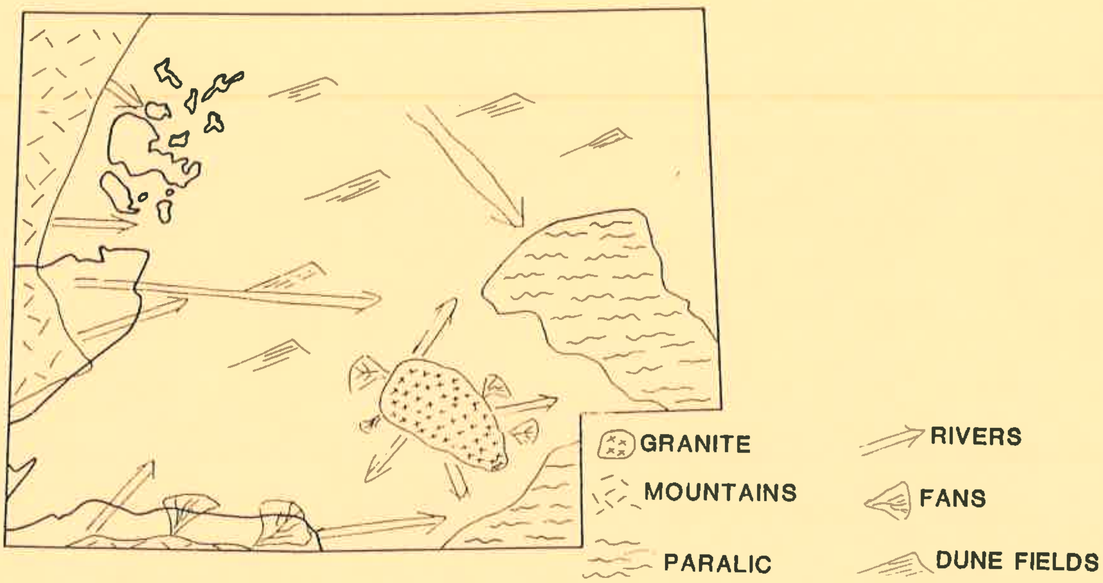


Fig. 4.1 Distribution of coal-bearing Carboniferous strata and generalised palaeogeography

Figure 4.2 Composite log for the Carboniferous of well 14/19-6A (Occidental), Claymore Oilfield.

Regional Setting

Well 14/19-6A is situated in the Claymore Field area. The area was the site of paralic and deltaic deposition during the Dinantian.

Well Stratigraphy

Carboniferous strata occur unconformably below Zechstein deposits at a depth of 9110 feet (2777 m), and their drilled thickness is 1182 feet (360 m). The sequence is dated as Visean (latest Dinantian) and comprises an interbedded sequence of sandstones, siltstones, shales, coals and minor limestones and volcanics. A few short cores through the sequence are exhibited to demonstrate the nature of some of the sandstone and siltstone beds.

This coal bearing sequence is similar to the Lower Carboniferous succession of east Fife

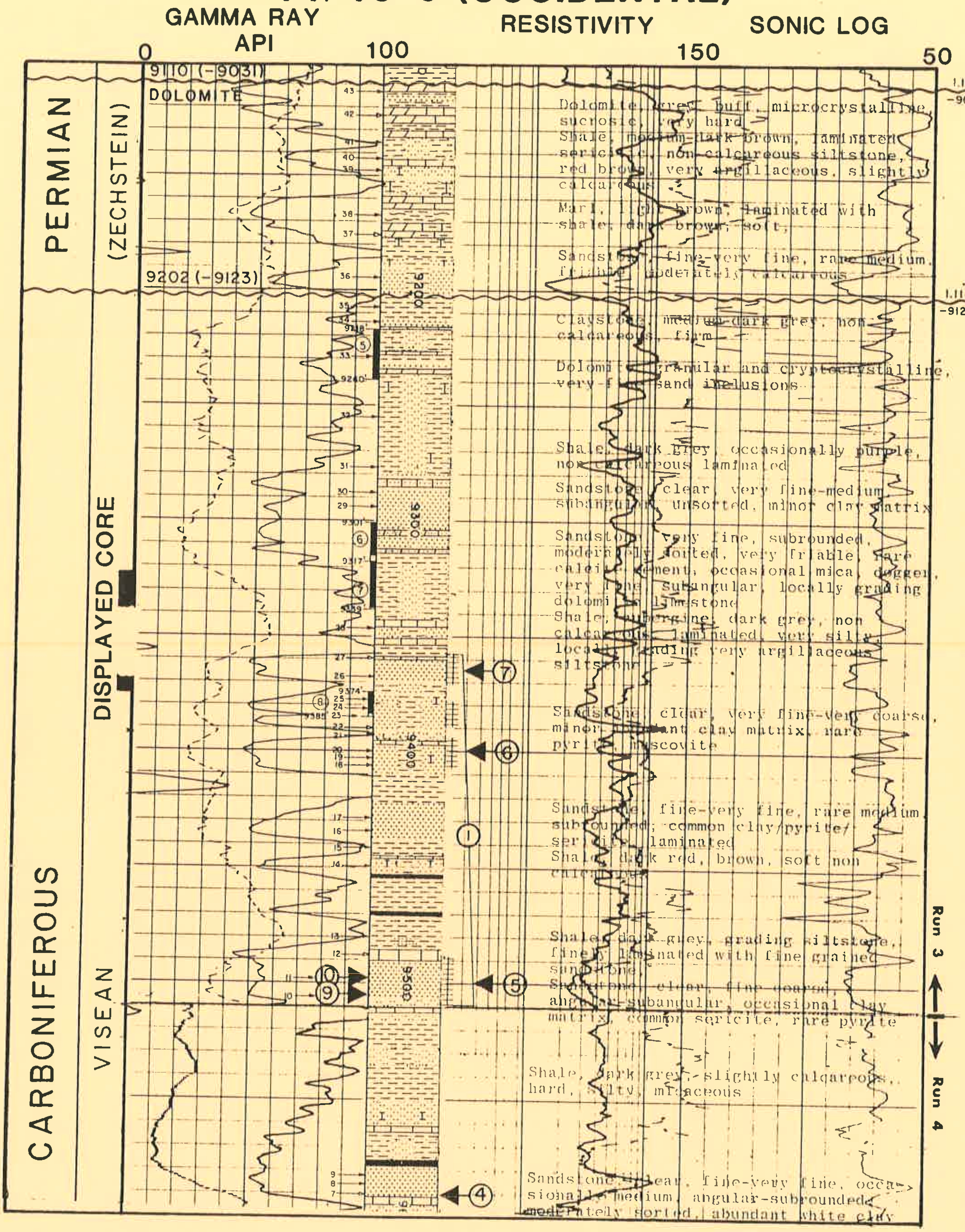
Depositional Environment

Deposition probably took place in an extensive paralic environment influenced by deltas. Log responses and facies analysis suggests the presence of fluvial channels, interdistributary bay and swamp environments. The depositional basin probably passed laterally to a river and aeolian dominated plain over which Upper Old Red Sandstones like those that form the reservoir in the Buchan Field were being deposited.

Reservoir Characteristics

The coals and shales within this Carboniferous succession have source rock potential. Sandstones are of good reservoir potential where uncemented, and in places have porosities of up to 20%.

14/19-6 (OCCIDENTAL)



DEPTH SCALE : FEET

Fig. 4.2

5. PERMIAN

5.1 Lower Permian - Rotliegend

A limited number of penetrations and poor dating of the red-bed sequences have restricted study of the Rotliegend in the Moray Firth. The identification of probable Rotliegend strata rests solely on their stratigraphic position and lithology.

Two distinct areas of Rotliegend deposition are recognised (Glennie 1986): the Moray Firth Basin and part of the Northern Permian Basin. These areas are at present separated by the Halibut Horst and South Halibut granite, where Permian strata may have been deposited but subsequently removed by erosion. This distribution differs markedly from that of the Carboniferous, emphasizing the effect of intervening Variscan uplift and erosion. The early Permian sediments represent the first deposits of the Moray Firth Basin.

In the inner area of the Moray Firth Basin, the Rotliegend unit is 1640-2300 feet (500-700m) thick. Thinning is indicated to the southwest, and also eastwards where this is accompanied by a change in facies. In Quadrant 20, on the margins of the North Permian Basin, 400 feet (120m) of Rotliegend is present. Rotliegend beds are generally not considered to be represented in the onshore Moray Firth outcrops (Peacock *et al.* 1968). Whether or not the lower part of the aeolian Hopeman Sandstone Formation represents a Weissliegend equivalent at the top of the Rotliegend is open to debate (see Glennie and Butler 1983 and Clemmensen 1987).

Three main facies associations are present (Figure 5.1a): (1) very fine to fine-grained, well-sorted red-brown sandstones characterise the Inner Moray Firth succession, although dark red-brown non-calcareous claystone beds up to 6 feet (2m) thick are frequent and these occasionally contain traces of anhydrite. (2) In the central Moray Firth (for example well 13/18-1) a tripartite division is recognised: a basal fine-grained sandstone (207 feet, 63m) is overlain by a siltstone/claystone unit (213 feet, 65m) and then a sandstone with interbedded siltstones and claystones (505 feet, 154m). (3) The Fraserburgh Formation, as defined in the type well (21/11-1) just outside the area (Deegan and Scull 1977), is limited to the southeastern part of the area. It consists of grey to red-brown dolomitic shales with thin dolomitic and micaceous sandstone stringers; the latter contain anhydrite nodules.

Two of the four classic Rotliegend facies (Glennie 1986) can be recognised in the Moray Firth area, however these should be treated with some caution in view of the lack of core information. In the inner Moray Firth fine-grained and well-sorted sandstones are interpreted as aeolian dune sands, while the finer-grained and locally anhydritic beds of the central and southeast areas were probably deposited in a sabkha environment. Fluvial facies may be present as indicated by the coarser components of some sandstones, but bedded lacustrine halite has yet to be demonstrated in this basin.

5.2 **Upper Permian - Zechstein**

The beginning of the late Permian is marked by a rapid marine transgression with the widespread deposition of the Kupfershiefer. During late Permian times most of the Moray Firth area was a shallow marine embayment lying to the northwest of the Northern Salt Basin. This platform-basin configuration was controlled by the easterly extension of the NE-SW Highland Boundary Fault (Threlfall, 1981). A carbonate-sulphate platform model can be applied to the majority of the area, whilst a deeper hypersaline basin lay to the southeast and a clastic rim surrounded the area.

Thicknesses of Zechstein strata vary considerably, largely reflecting the facies present. In general the Zechstein is 160-500 feet (50-150m) thick, with carbonate sequences thinner than those dominated by evaporites. The thickest preserved Zechstein shelf sequences occur in the Dutch Bank Basin (over 750 feet, 230m) and where thick salts are present on the Aberdeen Shelf Zechstein thicknesses can reach 3000 feet (1000m). Although the Zechstein is now absent from some intra-basin highs, it is likely that it was originally deposited and subsequently eroded from these areas. The presence of anhydrite in Upper Jurassic conglomerates in the south Viking Graben suggests that deposition continued over the Fladen Ground Spur at least.

Four main lithofacies are recognised in the Zechstein of the Moray Firth area (Figure 5.1b): (1) clastic, (2) carbonate, (3) anhydrite and (4) halite. The type sequence has been divided into an upper predomiantly anhydritic Turbot Bank Formation, a lower dolomitic and shaley Halibut Bank Formation which in turn rests on the Kupferschiefer Formation (Deegan and Scull 1977). However thin carbonate and thicker anhydrite formations are more commonly found separately.

The Halibut Bank Formation consists of hard light brown to grey dolomite with a microcrystalline, sucrosic, vuggy, laminated or brecciated texture. Carbonate boundstones, packestones and grainstones have been described, including an isolated occurrence of oolites in well 12/23-1. At Ettrick Oilfield a dolomite, considered to be of algal origin, is interpreted as an organic buildup facies, probably forming patch mounds (Figure 5.2; Amiri-Garroussi and Taylor 1987). The minor amounts of interbedded mudrocks are commonly anhydritic.

Core from Claymore Oilfield includes a 30 foot (9m) thick mud-matrix dolomite breccia (Figure 5.3). which is thought to have been deposited as a non-turbid slurry or debris flow rather than by solution collapse (Clark 1986).

In two areas, the Dutch Bank Basin and southeast of the Halibut Horst, the Zechstein is dominated by the anhydritic Turbot Bank Formation (Figure 5.1b). The anhydrite has a chicken-wire, displacive texture in core (Figure 5.2) and is frequently interbedded with minor amounts of mudstone, dolomite and sandstone. The number of anhydrite beds increases with total thickness, and there is locally evidence for mudstone-dolomite-anhydrite shallowing-up cycles.

Sequences dominated by clastics are found in the west and north, and significant beds of sandstone occur in some wells elsewhere. Onshore, the Hopeman Sandstone Formation (probably a late Permian deposit) contains evidence for complex star dunes and NNE Trade Winds (Clemmensen 1987). At Beatrice Oilfield a grey to reddish-brown shale with dolomite and limestone stringers is thought to represent the Zechstein. South of the Wick Fault white to reddish orange sandstones and subordinate reddish brown claystones and siltstones, which pass up into siltstones, are also assigned to the Zechstein, based on the presence of a highly radioactive basal shale and striate bisaccate pollen. These clastic sequences probably represent aeolian and fluviatile deposition on the margins of the Zechstein Sea, with occasional influxes extending further into the areas of sabkha and carbonate deposition.

Over the Aberdeen Platform thick basinal evaporites are preserved in a series of salt pillows. Over 3000 feet (1000m) comprising four evaporitic cycles are present, containing potassium and magnesium salts and anhydrite in addition to the dominant halite.

Correlation of the Moray Firth succession with the classic 5-cycle division of the Zechstein elsewhere in the North Sea has proved difficult. Most, if not all, of the succession probably represents a marginal facies of the first cycle (Z1) of the southern basin, however one or more of the later cycles could be represented in sabkha or lagoonal facies in the thick Turbot Bank sequences (Taylor 1981). In the southeast the thick basinal sequences may represent cycles Z1 to Z4 (Deegan and Scull 1977).

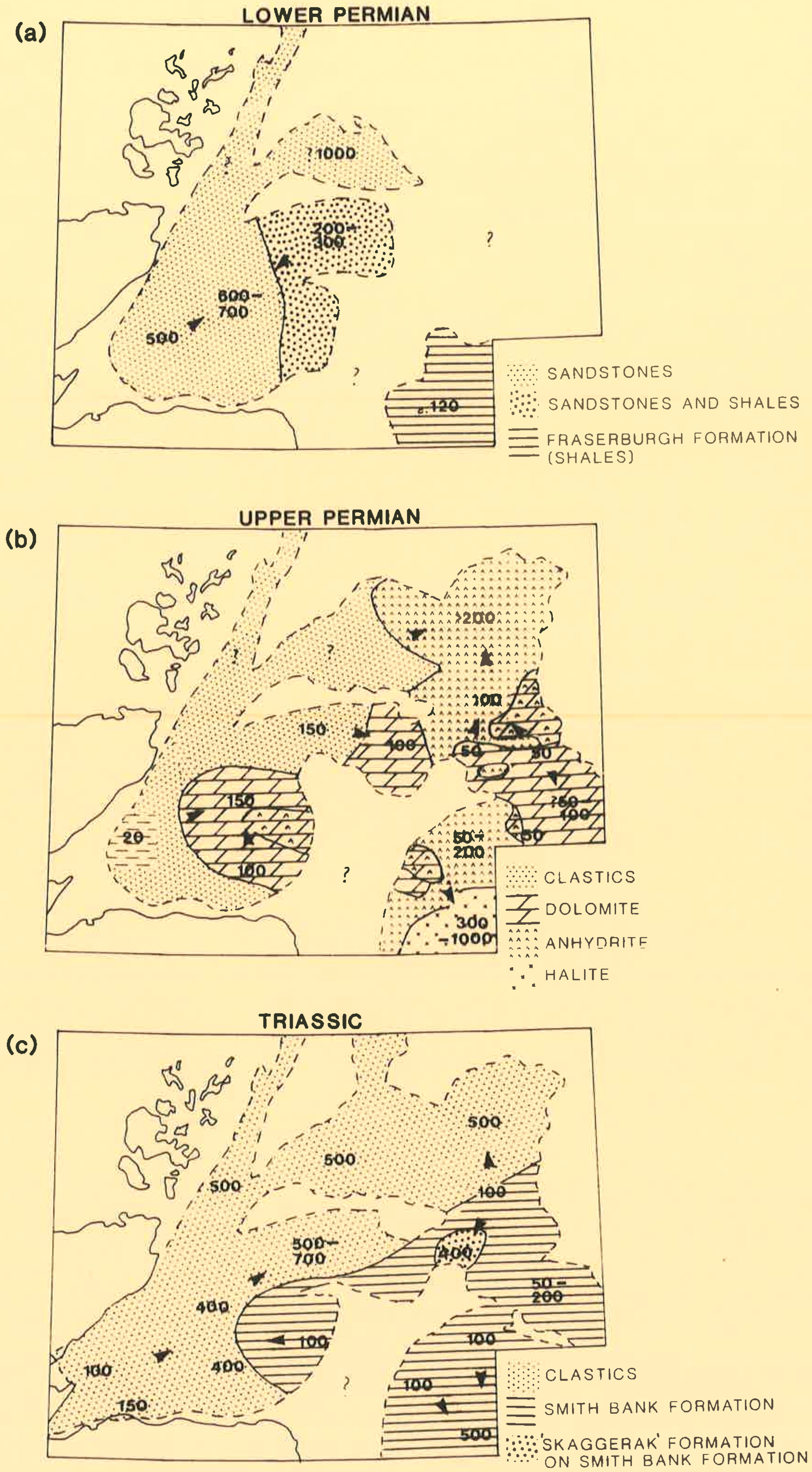


Fig. 5.1 Isopach and facies maps for the Rotliegend, Zechstein and Triassic

Figure 5.2 Composite Log for the Turbot Bank Formation (Zechstein) of well 20/2-2 (Britoil), Ettrick Oilfield

Regional Setting

Well 20/2-2 is located on the southeast of the carbonate-sulphate platform which covered most of the Moray Firth Basin during Zechstein times. Immediately to the east lies the northern North Sea salt basin.

Well Statigraphy

The Zechstein is 734 feet (224m) thick in the well and is divided into two formations. The Halibut Bank Formation (486 feet, 148m) is composed predominantly of dolomite with interbedded dark claystones at the base and a 30 foot (9m) thick fine to coarse-grained sandstone unit near the top. The dolomites are microcrystalline and argillaceous at the top becoming more coarsely crystalline with depth.

The overlying Turbot Bank Formation (248 feet, 76m) is dominated by massive anhydrite. However a 43 foot (13m) thick dolomite towards the base contains two lithofacies: a dolomite grainstone/boundstone of possible algal origin overlain by a lithoclastic dolomite grainstone/ wackestone.

The majority of the displayed core consists of the lower grainstone/ boundstone facies. It is a light tan-grey to brown (oil-stained), extremely fine to very finely crystalline dolomite with nodules of brownish-grey anhydrite. The dolomites are composed chiefly of elongate, tapering, non-encrusting tubular structures 3-4mm wide and 10-15mm long. Parallel tubes are sometimes stacked in layers, but they show no evidence of branching or internal partitions. In thin section the tubes reveal a lamellar wall structure and a central canal, which is commonly filled by finely crystalline dolomite or with anhydrite. An algal origin for these structures is favoured with some similarity with the narrower *Calcinema permiana* found in the southern North Sea Basin.

The lithoclastic dolimite facies found at the top of the displayed core has a similar colour and crystal size to that of the dolomite below but it contains sub-rounded lithoclasts and some tubular forms.

Depositional Environment

The overall environmental setting is that of a shallow-marine carbonate-sulphate platform. The two lithofacies have been described in terms of organic (?algal) patch-mounds and laterally shifting inter-mound channels.

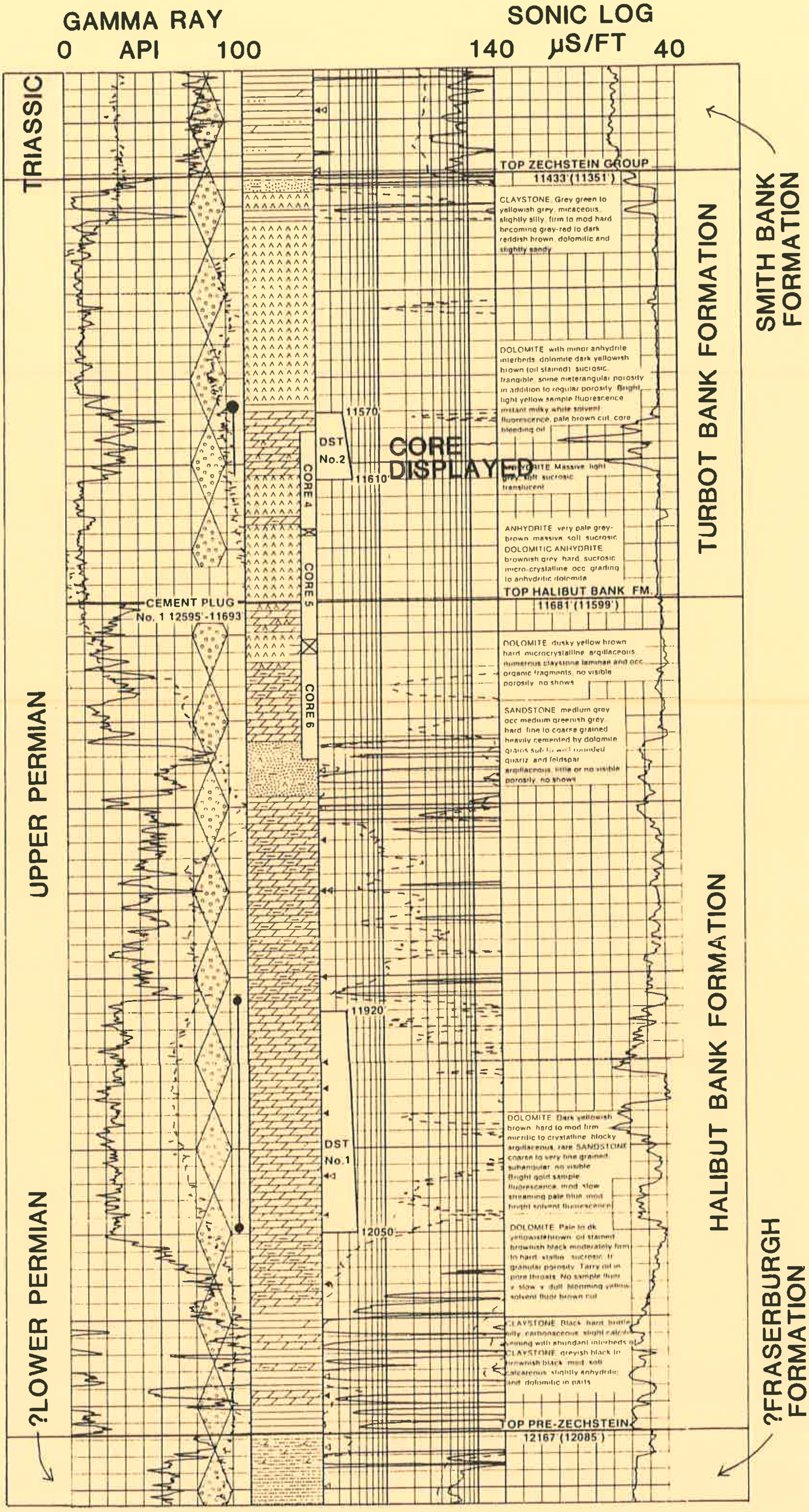
Reservoir Characteristics

Dolomite core from the Turbot Bank Formation has porosities ranging from 7-22% and the core is extensively oil-stained. This porosity is vuggy, intercrystalline, mouldic and intergranular. Porosity is largely generated by leaching, of which there have been at least two periods (a vadose episode followed by a later and deeper episode). Nodular and void-filling anhydrite reduces porosity but in general porosity is protected from later cementation by the migration of oil into the reservoir.

Reference

The description and interpretation of this section is based extensively on the paper by Amiri-Garroussi and Taylor (1987).

20/2-2 (BRITOIL)



DEPTH SCALE: FEET

Fig. 5.2

Figure 5.3 Composite Log for the Halibut Bank Formation (Zechstein) of well 14/19-C26 (Occidental), Claymore Oilfield

Regional Setting

Well 14/19-C26 is located within the carbonate-sulphate platform which characterises the Zechstein of the Moray Firth area. The well tests the central fault block of the Claymore oilfiled.

Well Stratigraphy

The Zechstein in well 14/19-C26 is classified as Halibut Bank Formation with a 100 foot (30m) vertical thickness (note: the well is deviated at an angle of 45 degrees through this unit). In this central area of the field thicknesses range up to 191 feet (58m) with dolomite and dark grey shales the main lithologies. Downdip, the maximum recorded thickness is 305 feet (93m), where extensive anhydrite development (Turbot Bank Formation) is encountered (Maher and Harker 1987).

A 30 foot (9m) thick brecciated carbonate mudstone occurs in the middle of the Zechstein. The clasts of this breccia, which are suspended in a mud matrix, vary in size from coarse grained to cobble grade and are in various degrees of consolidation. The carbonate and sandstone clasts are invariably rounded or subrounded whereas some mudstone clasts are tabular. The orientation of clasts is chaotic, but there are rare cases of imbrication of large clasts and there are signs of bedding, particularly fining-upwards units, in the finer-grained interbeds. Compaction has resulted in local pressure solution, brittle fracture of clasts and streaking-out of unconsolidated clasts.

At the base of the succession a 3 foot (1m) thick dark grey laminated silty shale represents the Kupferschiefer Formation. It has a gamma log response of about 200 API units corresponding to a concentration of Uranium. Broken surfaces also reveal a finely disseminated brass-yellow sulphide which may be chalcopyrite.

Depositional Environment

The overall environmental setting is that of a shallow-marine carbonate-sulphate platform. Evidence from the displayed core suggests that the breccia was formed by debris flow processes in contrast to the more widespread type of Zechstein breccia formed by solution collapse. The chaotic nature of the breccia, the fact it is matrix supported and the presence of various lithologies are all critical features. The preservation of fragile clasts and some sharp clast corners is consistent with a non-turbulent slurry. Similar debris flows described in northeast England were possibly initiated by synsedimentary fault reactivation (Kaldi 1980).

The Kupfershiefer Formation is a sapropelic shale deposited under anoxic conditions below wave-base.

Reservoirs Characteristics

Reservoir quality of the Halibut Bank Formation at Claymore is exceptionally variable; porosties range from 2-19% and permeabilities from 2-899mD. Porosity types include vugs, fractures and intergranular and were probably formed by fresh water leaching of replacive anhydrite in the crestal location prior to the deposition of the Triassic. However the enhancement of porosity is localised. In the downthrown areas the carbonates have escaped exposure and the interbedded evaporites are largely preserved (Clark 1986; Maher and Harker 1987). Reservoir characteristics of the brecciated mudstone are poor compared to those of collapse breccias (as found at Auk and Argyll Oilfields in the central North Sea). Some of the intraclasts are oil-stained vuggy dolomite, but overall the rock is considered to be a non-reservoir facies.

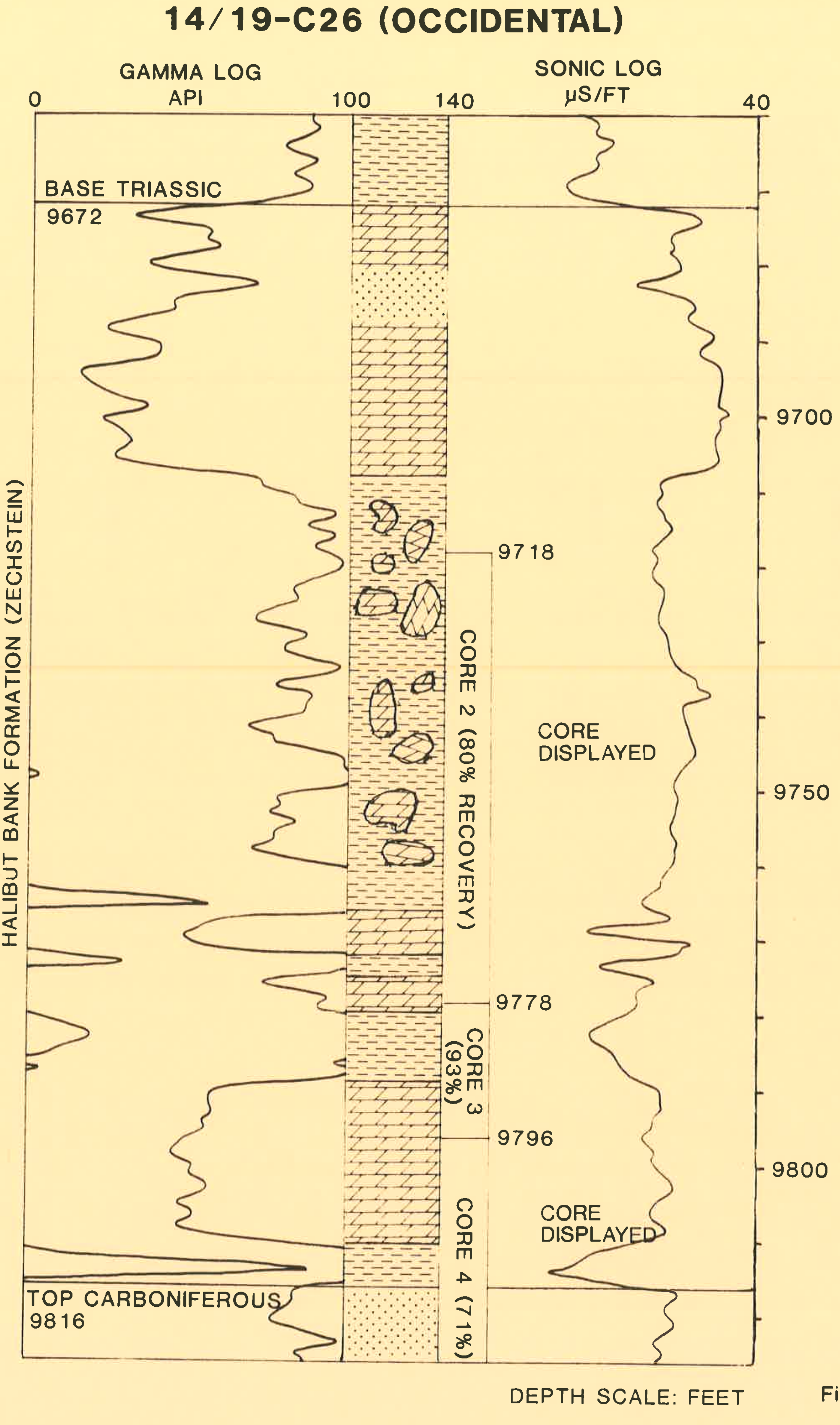

14/19-C26 (OCCIDENTAL)
GAMMA LOG
API
0
100
140
SONIC LOG
µS/FT
40
BASE TRIASSIC
9672
HALIBUT BANK FORMATION (ZECHSTEIN)
9718
CORE 2 (80% RECOVERY)
CORE DISPLAYED
9778
CORE 3 (93%)
9796
CORE 4 (71%)
CORE DISPLAYED
TOP CARBONIFEROUS
9816
9700
9750
9800
DEPTH SCALE: FEET

Fig. 5.3

6. TRIASSIC

Outcrops and quarries in the vicinity of Elgin expose a 353 feet (108m) composite thickness of Triassic clastics resting on Old Red Sandstone. The section is divided into the Burghead and Lossiemouth Sandstone Formations (Warrington *et al.* 1980).

Offshore the Triassic is thickest in the Inner Moray Firth and the marginal basins where it is usually greater than 1500 feet (500m) thick and reaches a maximum of 2529 feet (771m) south of the Wick Fault (Figure 5.1c). Only in the west is the Triassic conformably overlain by Lower Jurassic strata; elsewhere the upper part has been eroded by varying amounts, especially on tilt block highs.

The extent to which synsedimentary faulting controls thicknesses is probably minimal and localized, unlike other areas of the North Sea (e.g. Jakobsson *et al.* 1980). Evidence from the marginal basins, where the seismic resolution of the shallow Triassic is greatest, suggests that whilst gross thicknesses increase towards the bounding faults, internal bed thickness remains constant. This together with the lack of facies changes in the vicinity of faults is evidence that the faulting is post-Triassic, preserving down-faulted pockets of a formerly more extensive Triassic cover. No evidence has been found to corroborate the use of an East African rift model for the Inner Moray Firth Triassic (Frostick *et al.* 1988).

In the Inner Moray Firth the Triassic consists of a lower predominantly sandy unit and an upper unit comprising interbedded fine-grained sandstones, siltstones and claystones. The sandstones vary from grey, brown to orange-red and are fine to coarse grained. Thin beds of reddish-brown claystones with traces of anhydrite are particularly numerous in the upper unit. Correlation with the onshore sequence is problematical, although the lower unit may be the lateral equivalent to the Burghead Sandstone Formation, with the upper unit tentatively interpreted as the basinward equivalent of the Lossiemouth Sandstone Formation (Frostick *et al.* 1988). In the depocentre south of the Wick Fault fine-grained sandstone and siltstones are interbedded with coarser units, and the upper half comprises a large-scale coarsening-upwards unit. The thick arenaceous successions in the Inner Moray Firth and marginal basins form part of a rim of aeolian and more proximal fluviatile sedimentation separating the basin from the surrounding uplands.

Throughout the Inner Moray Firth the Triassic is capped by the Cherty Rock which is 35-40 feet (11-12m) thick. Locally it consists of microcrystalline silica that includes scattered sand grains. However more typically the deposit is tan-coloured micritic limestone with chert inclusons and relics of concretionary layering. The Cherty Rock is believed to be a dolomitised calcrete, originating as an extensive soil horizon on a semi-arid floodplain (Peacock *et al.* 1968). It suggests a period of tectonic quiesence to allow its formation, and also a landscape of subdued relief.

Red-brown argillaceous sequences, belonging to the Smith Bank Formation are the most widespread deposits of the Triassic in the Outer Moray Firth area (Figure 6.1). Although generally monotonous they are frequently silty with not uncommon thin sandstones and local traces of anhydrite and dolomite. The red-brown colour is characteristic but this is locally reduced to a light greenish-grey in spots or broad zones. Sedimentary structures are not common but small-scale trough cross-bedding and ripple cross-lamination are present in the fine-grained sandstones and thin fining-upwards cycles also occur. Lithologically these red mudstones have been equated with the Bunter Shale Formation of the southern North Sea (Brennand 1975).

During the Triassic the outer Moray Firth formed part of an extensive, featureless continental plain dominated by the red mudstone facies which also occupied the Central North Sea for most of Triassic time. Some of these mudstones and siltstones are thought to represent the distal deposits of ephemeral streams derived from the surrounding uplands. The remaining argillites, associated with anhydrite, are thought to be the deposits of extensive, shallow playa lakes in a semi-arid environment. In the southeast sedimentation was controlled by salt movement which was triggered during the Triassic. The mudstones accumulated mainly in the lows between developing pillows.

In a limited area around Claymore Oil Field a 300-1000 feet (100-300m) thick micaceous sandstone unit overlies the red claystones of the Smith Bank Formation (Figures 6.2 and 6.3). A new name is required for these sandstones, although they are informally termed 'Skaggerak' Formation based on similarities with that formation in the eastern Central North Sea (Maher and Harker 1987). These fining-upwards cycles are of fluvial origin probably representing a localised influx of fine sediment in braided streams from the flanks of a proto-Halibut Horst in latest Triassic times; there is possibly some control on sedimentation by faulting.

Figure 6.1 Composite Log for the Smith Bank Formation (Triassic) of well 20/10-1 (B.P.)

Regional Setting

Well 20/10-1 is located to the southeast of the Peterhead Ridge in an area which, although included here in the Moray Firth area, also has similarities and links with the central North Sea area.

Well Stratigraphy

A thickness of 358 feet (109m) of Smith Bank Formation is proven in this well, but the base of the unit is not reached. A terminal core records red-brown, mottled grey-green mudstone, which is hard, dolomitic, micaceous and silty. Veins of colourless crystalline anhydrite are present in the core, and thin beds of microcrystalline dolomite are also found higher in the well where the beds become predominantly grey-green in colour.

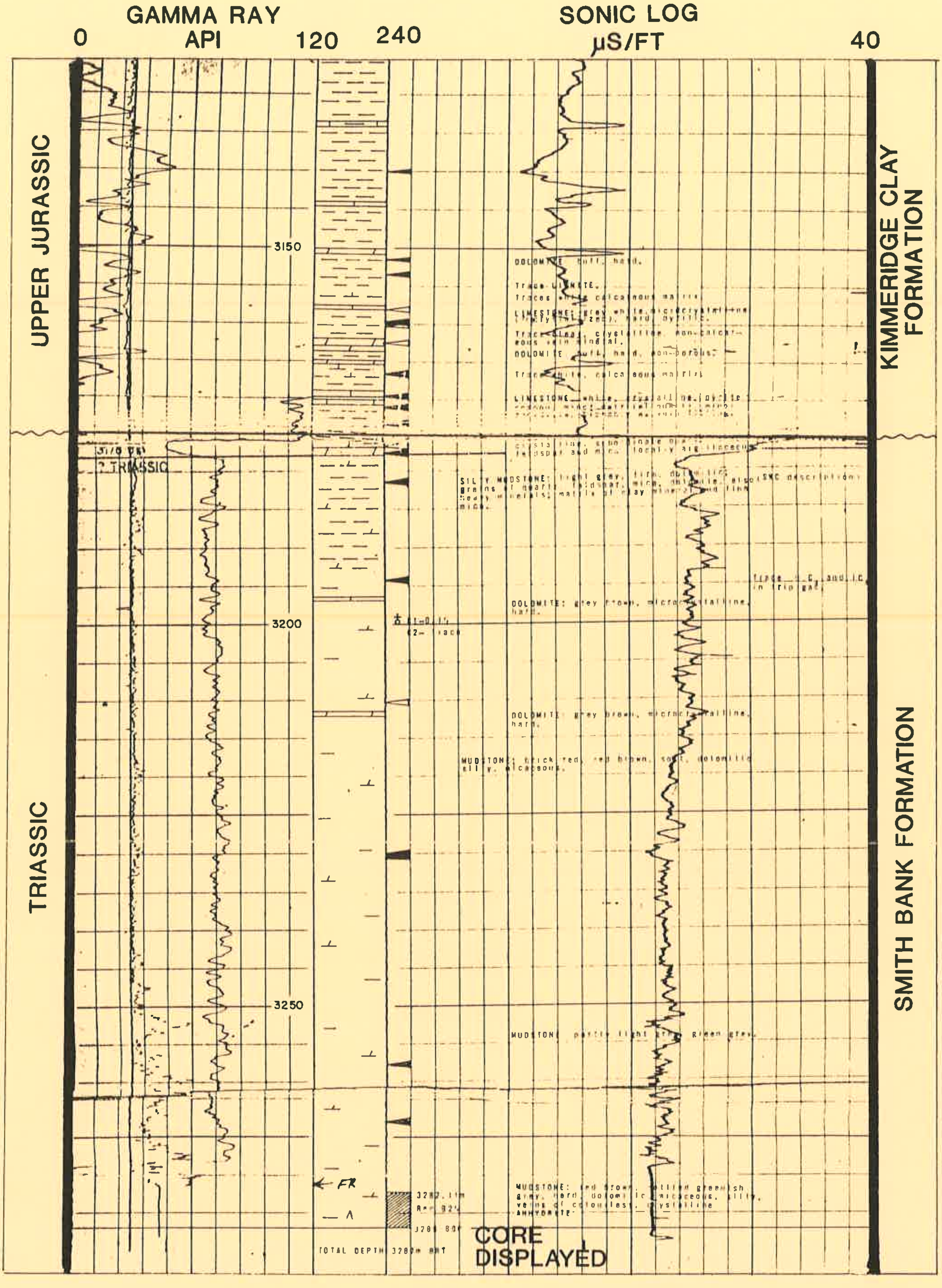
Depositional Environment

This part of the Moray Firth area forms the northern limit of an extensive, low-relief, continental plain dominated by red mudstone facies which occupied the central North Sea for most of Triassic times. Distal deposits of ephemeral streams may be present elsewhere, but the presence of anhydrite suggests an environment including shallow, playa lakes.

Reservoir Characteristics

The predominantly argillaceous lithologies of this formation are not considered to have reservoir potential.

20/10-1 (BP)



DEPTH SCALE: METRES

Fig. 6.1

Figures 6.2 and 6.3 Composite and core logs for the 'Skaggerak' Formation (Triassic) of well 14/19-3 (Occidental), Claymore oilfield

Regional Setting

Well 14/19-3 is located on the Claymore structure which lies between the Witch Ground Graben and the Halibut Horst.

Well Stratigraphy

Red claystones and siltstones (Smith Bank Formation), 615 feet (187m) thick, are overlain in this well by 372 feet (113m) of miceceous shaley sandstone ('Skagerrak Formation equivalent'). The sandstones of the upper unit are characteristically high micaceous with a kaolinitic matrix and although mainly red at the base, but increasingly mottled grey-green at the top. Sedimentary faults are common. Typically the sandstones are arranged in fining-upwards cycles which contain the following elements: (a) an erosive base, (b) a mud pebble conglomerate of green and red clasts, occasionally imbricated, (c) fine to medium grained sandstones, with planar laminations and high angle and trough cross-bedding, (d) fine to very fine grained sandstones with planar laminations and ripple cross-bedding.

Depositional Environment

Evidence from the cored interval suggets that the environment was non-marine and fluviatile. A low sinuosity, braided stream environment has also been suggested due to the relative lack of fine-grained sediment. The unit represents a localised influx of sediment off the flanks of a proto-Halibut Horst in latest Triassic times; there is possibly some control on sedimentation by faulting.

Reservoir Characteristics

The micaeous sandstones have moderate to good porosities (10-22%), but permeabilities are negigible (0.1-1.0 mD) due to the sericitic and kaolinitic matrix.

14/19-3 (OCCIDENTAL)

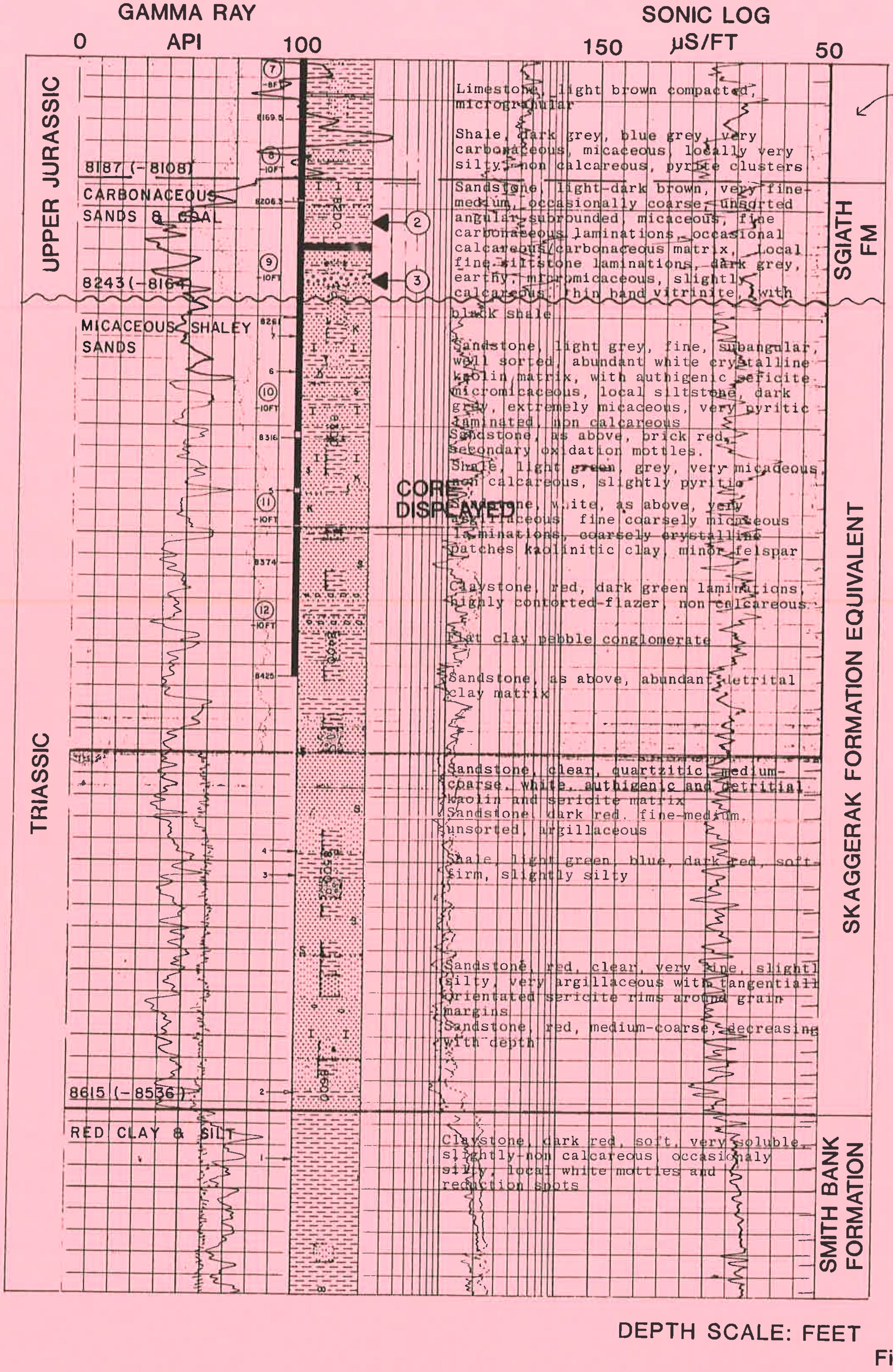


Fig. 6.2

14/19-3 (OCCIDENTAL)

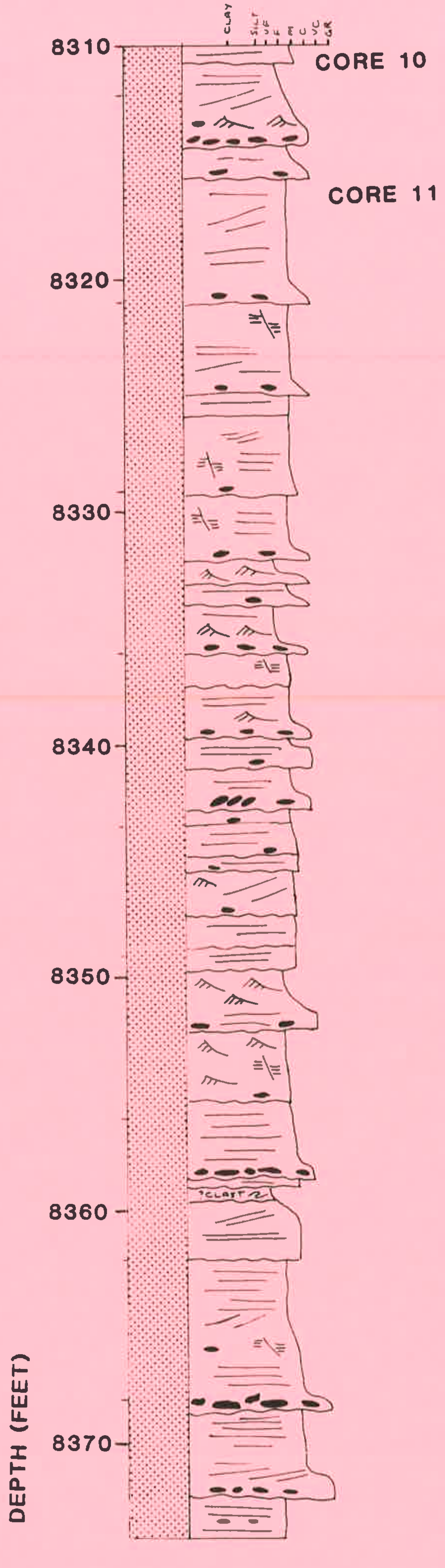


Fig. 6.3

7. JURASSIC

The Jurassic is the most important stratigraphic interval, from an economic viewpoint, in the Moray Firth Basin. As well as having a number of productive reservoir units within it, it also provides the principal hydrocarbon source rock in the basin, the Kimmeridge Clay Formation, and a subsiduary local source in the Middle Jurassic of the Inner Moray Firth area. The main reservoir rocks are (1) the Callovian shallow marine sands found in the Inner basin and productive in the Beatrice Field (Block 11/30), (2) the Upper Oxfordian to Lower Kimmeridgian marginal marine sands (Piper Formation) widely developed in the Outer basin and productive in e.g. the Tartan Field (Block 15/16), and (3) marine gravity flow sands of Kimmeridgian to Volgian age, found as cones within the Kimmeridge Clay Formation shales, usually in the proximity of faults, and productive e.g. in the Claymore (Block 14/19) and Ettrick fields (Block 20/2).

Additional reservoir potential occurs in the minor sands of the Lower Jurassic, restricted to the west of the Moray Firth, which contribute slightly to the pay zone in the Beatrice Field, in the upward-coarsening and interbedded sands of the Middle Jurassic paralic sequence in the Inner basin which are also present in the Beatrice pay zone, and in the Oxfordian spiculitic sands found principally across the southern part of Quadrant 12. The spiculitic sands have yet to yield commercial hydrocarbons; there are doubts as to whether the porosity/permeability characteristics of this unit are sufficiently good for it to act as a viable reservoir.

7.1 Onshore sucession

Onshore outcrop provides a useful window on the subsurface development of the Jurassic in the Inner Moray Firth. The Lower-Middle Jurassic can be interpreted broadly as a transgressive-regressive-transgressive sequence on the evidence of sedimentary facies, with the early Jurassic and Callovian the dominantly transgressive and marine intervals. Shallow marine, stable shelf sedimentation continued in a marine environment from the Callovian until the late Oxfordian, followed by reactivation of the Helmsdale Fault and the deposition of the Helmsdale Boulder Beds and related sediments by submarine sediment gravity flows during the Kimmeridgian and Volgian.

This history of events is also recorded offshore, from the Jurassic succession of the Inner Moray Firth.

7.2 Distribution

Jurassic strata are thickest within the major grabens in the UK sector of the North Sea but deposition did encroach onto marginal platforms in places, notably to the west of the Central Graben. Whatever the extent of Jurassic deposition across the present structurally higher platforms and ridges which define the Moray Firth basins, little has been preserved; the present limits of Jurassic distribution in the area are largely structurally controlled, depositional pinch-outs can rarely be identified with any confidence.

The present northern limit of Jurassic rocks coincides with the Helmsdale Fault and the southern edge of the Caithness Ridge (see structural map, Figure 2.1). Farther east, Jurassic strata extend into the Dutch Bank Basin bounded by the East Shetland Platform. The Jurassic thins rather gradually to the east against the Fladen Ground Spur, a narrow southward projection of the East Shetland Platform. The southern limits of the Jurassic distribution in the Moray Firth area are formed presently by the Grampian High and Peterhead Ridge, but with the possibility of a veneer of Jurassic preserved over parts of the adjacent Peterhead Shelf.

Sequences of Jurassic strata up to c.12,000 feet (3.6 km) thick are present in the offshore area of the Inner Moray Firth. In the Outer area, where the mid-Jurassic volcanic centre is located, there is in addition at least 5 000-6 500 feet (1.5 to 2 km) of lavas and associated volcaniclastic sediment.

7.3 Stratigraphic framework

The Jurassic succession is most stratigraphically complete in the Great Glen Sub-basin. Pre-Callovian strata are progressively lost beneath an unconformity eastwards across the Inner Moray Firth (see Figure 7.1). There is a belt, which includes the Halibut Platform and the area to the south of the Halibut Horst, where mid to late Oxfordian strata rest directly on pre-Jurassic rocks. Erosion over a broad central North Sea upwarp removed any Lower Jurassic strata from the Outer Moray Firth. Mid-Jurassic volcanics and volcaniclastics rest directly on Triassic or older strata in this area.

The Lower to Middle Jurassic strata have therefore a discontinuous distribution in the the Moray Firth. The oldest Jurassic strata to be found throughout the Moray Firth area are of mid to late Oxfordian age.

In the Inner Moray Firth, Upper Jurassic strata rest with little or no stratigraphic break on the Middle Jurassic. To the east, Middle to Upper Oxfordian strata rest on Middle Jurassic, the age of the Middle Jurassic variously reported as Bajocian to Bathonian, or Callovian (see Howitt *et al.*, 1975; Ritchie *et al.*, 1988).

In the east, heterolithic Oxfordian strata, deposited in a coastal plain to lagoonal environment, record a brackish transgression across the top Middle Jurassic surface. Assigned to the Sgiath Formation by Harker *et al.* (1987), these deposits are overlain by a marine shale (I Shale of Maher, 1980; the basal beds of the Piper Formation according to Harker *et al.*, 1987).

The Piper Formation is dominantly of sand and represents shallow marine deposition, perhaps related to the growth of a delta (see Harker *et al.*, 1987). Piper sands pass laterally to marine shales both to the north and south of the Halibut Horst, and are equivalent in age to the marine shales found above the spiculitic sands in the Inner Moray Firth, indeed equivalent to the basal part of the wedge-shaped seismic package reported earlier from the interpretation of seismic data in the Inner basin.

The post-Piper, Kimmeridgian to late Ryazanian succession is broadly similar in all the sub-basins where it is present in the Moray Firth area. Dark grey to black, organic rich shales, usually with a high gamma ray log response, are ubiquitous. The shale successions are locally interrupted by wedges or cones of coarse clastics, associated with normal faults active during sedimentation. The Halibut Horst seems to have been one important source of sediment for these cones, the sediments being carried into the adjacent marine basins by gravity flows.

The top of the Kimmeridge Clay Formation throughout the Moray Firth Basin is taken at a sharp upward decrease in gamma ray and sonic log response. In stratigraphically complete sections the boundary occurs in the *stenomphalus* zone of the late Ryazanian. On some intra-basinal highs, the Kimmeridge Clay Formation is overlain unconformably by strata of the Cromer Knoll Group (Lower Cretaceous).

7.4 **Reservoir Rocks**

The following reservoir units are illustrated in this workshop:

1) the Callovian sandstones of the Beatrice Formation (Andrews and Brown, 1987), from well 11/30a-8 (Figures 7.3 and 7.4);

2) the Oxfordian spiculitic sandstones of the Alness Spiculite Unit (Andrews and Brown, 1987), from well 12/22-2 (Figures 7.5 and 7.6).

3) the Oxfordian to Kimmeridgian sandstones of the Piper Formation, from well 15/16-12 (Figures 7.7 and 7.8). A core through the underlying Sgiath Formation (Harker *et al.*, 1987), from well 14/19-3 is also figured (Figures 7.9 and 7.10).

4) the Kimmeridgian to Volgian sandstones from within the Kimmeridge Clay Formation, including the Claymore Sandstone Member from well 14/19-3 (Figures 7.9 and 7.10), the Ettrick Sandstone Member from well 20/2-1 (Figures 7.11 and 7.12), and a short core from an Upper Jurassic sandstone sequence in well 13/27-1A (Figures 7.13; 7.14).

7.4.1 The Beatrice Formation

This sandstone formation is of Callovian age and is the main reservoir in the Beatrice Field. It is widely developed over the Inner Moray Firth Basin; it thins out to the east and is absent notably from the eastern part of the Wick Sub-basin. Thicknesses vary from less than 10 feet (3m) up to 100 ft (30m), increasing towards the Helmsdale Fault. The Formation consists of a series of coarsening-up cycles, with five recorded in the best developed sequences. Shelly claystones, bioturbated siltstones, and cross-bedded or massive, fine to medium grained sandstones are present. A shallow marine shelf environment of deposition is envisaged.

In the Beatrice area the Formation has been divided into two units, the A and B Sands (see the correlation chart, Figure 7.1). The boundary is taken at the base of a thin shale. The lower, B Unit is progressively lost to the east by onlap onto a pre-Callovian unconformity surface.

For well and core logs through the Beatrice Formation see Figures 7.3 and 7.4.

7.4.2 The Alness Spiculite Unit

This unit of very fine to fine grained sandstone dominated by up to 50% *Rhaxella* sponge spicules is of mid-Oxfordian age. It is best developed in the area of Quadrant 12SE and is known to pass laterally to dark marine shales with traces of sponge remains (Uppat Formation), towards the Beatrice Field. The unit reaches up to 130 feet (40m) thick locally. It has a gradational base, coarsening-up from Uppat Formation shales, and a sharp top. The upper boundary correlates with an important seismic marker in the Inner Moray Firth, the Intra-Oxfordian Event of Figure 7.2. Migrating spiculitic sand shoals on a shallow marine shelf are envisaged as the depositional environment.

For well and core logs through the Alness Spiculite see Figures 7.5 and 7.6.

7.4.3 The Sgiath and Piper Formations

This important hydrocarbon reservoir unit is widely developed over the Witch Ground Graben area and adjacent shelves. It thins onto the Fladen Ground Spur and passes laterally into dark marine shales to the west, both to the north and south of the Halibut Horst (see Turner *et al.* 1984; Boote and Gustav, 1987). The Formation consists predominantly of medium to coarse grained sandstones, interbedded with minor dark mudstones. It was deposited during the late Oxfordian to Kimmeridgian, in a shallow marine shelf to shoreface environment. The Formation is characterised by a repetition of sandstones, with upward-decreasing gamma ray log signatures, alternating with thin mudstones. The mudstone seams probably represent transgressive horizons in a stacked transgressive-regressive sequence.

The base of the Piper Formation, first defined by Deegan and Scull (1977), was discussed by Harker *et al.* (1987), who established a new formation between the Piper Formation and the underlying base Upper Jurassic Unconformity in the Outer Moray Firth. This new unit, the Sgiath Formation, is of Oxfordian age, up to c. 200 feet (60 m) thick, and consists carbonaceous shales, and coals. It was deposited in a marginal marine to coastal plain environment. It represents a brackish transgression across the Outer Moray Firth and is equivalent in age to open marine sediments in the Inner Moray Firth. Harker *et al.* (1987) place the base of the Piper Formation at the base of a thin marine shale dated as latest Oxfordian (*pseudocordata* zone).

For well and core logs through the Sgiath and Piper Formations see Figures 7.7 to 7.10.

7.4.4 Intra-Kimmeridge Clay Formation sands

Kimmeridgian to Volgian, less commonly Ryazanian, sands occur throughout the Moray Firth Basin bounded by and passing laterally to the marine, organic-rich shales of the Kimmeridge Clay Formation. These sands have been found to be highly prospective in the Outer Moray Firth, along the margins of the Witch Ground Graben (e.g. in the Claymore, Galley and south Piper areas), and in the Buchan Graben (Ettrick area). The sands are usually fine grained and intimately associated with marine, organic shales. They represent the deposits of gravity flow processes and probably form laterally restricted cones of reservoir facies within the predominantly argillaceous basin fill.

For well and core logs from the late Jurassic sand reservoirs of the Claymore, Galley and Ettrick fields see Figures 7.9 to 7.14.

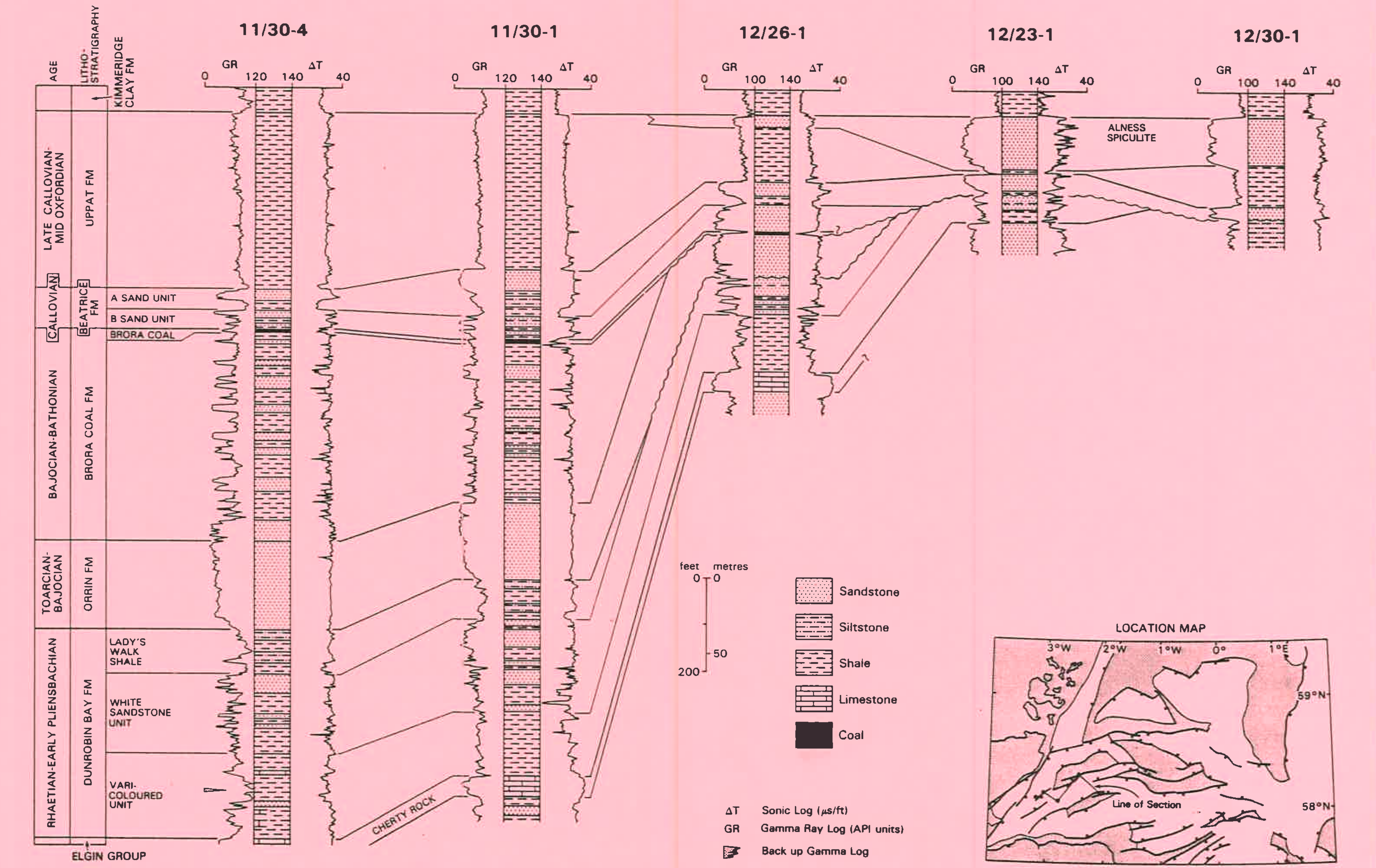


Fig. 7.1 Correlation of Rhaetian to mid-Oxfordian strata across the Inner Moray Firth Basin

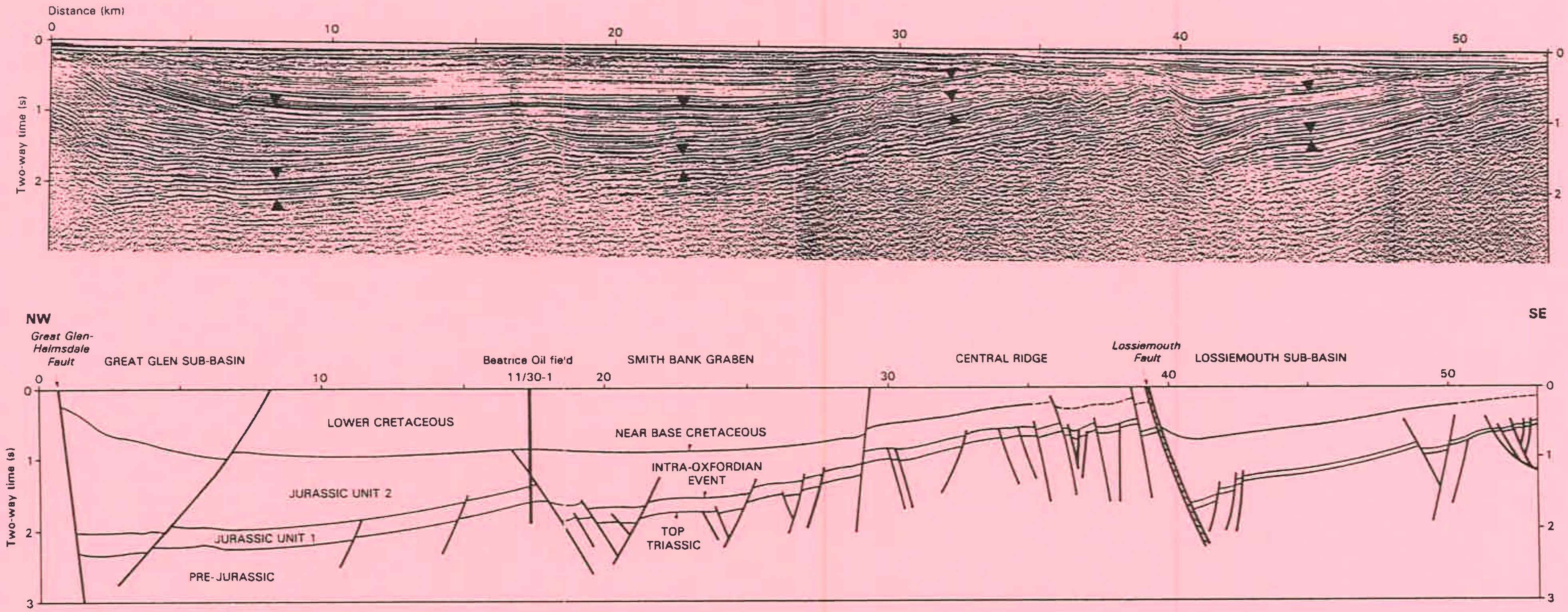


Fig. 7.2 Illustrative seismic cross-section across the Inner Moray Firth Basin

Figure 7.3 Composite log for the Beatrice Formation of well 11/30A-8 (Britoil), Beatrice Oilfield.

Regional setting

This well is located at the south-eastern end of the Beatrice Oilfield. The field is situated on the north-westerly dipping slope of a large Jurassic half graben, the Great Glen Sub-basin. The Beatrice structure has a NE-SW trend, parallel to the main tectonic elements in the Inner Moray Firth.

Well stratigraphy

The principal reservoir sands, lying between 6873 and 6987ft. are Callovian in age. They overlie Callovian sands and shales which in turn rest on the Brora Coal marker bed, of (?)Bathonian age. The pay zone in the Beatrice Field extends from the top of the Callovian sands down to thin sands interbedded with shales of early Jurassic age, below the base of the log figured here.

The Callovian sequence can be divided into three reservoir zones, an upper, A Sand, a Mid Shale, and a B Sand, as shown.

The A Sand is overlain abruptly by dark marine shales of the Uppat Formation.

Depositional environment

The Callovian sequence is open marine in character, probably representing deposition in a shallow shelf environment. A number of upward-coarsening sequences can be identified in the B Sand and there is an overall upward-coarsening into the A Sand. Migrating shelf sand bodies can be proposed as a first order interpretation of depositional environment.

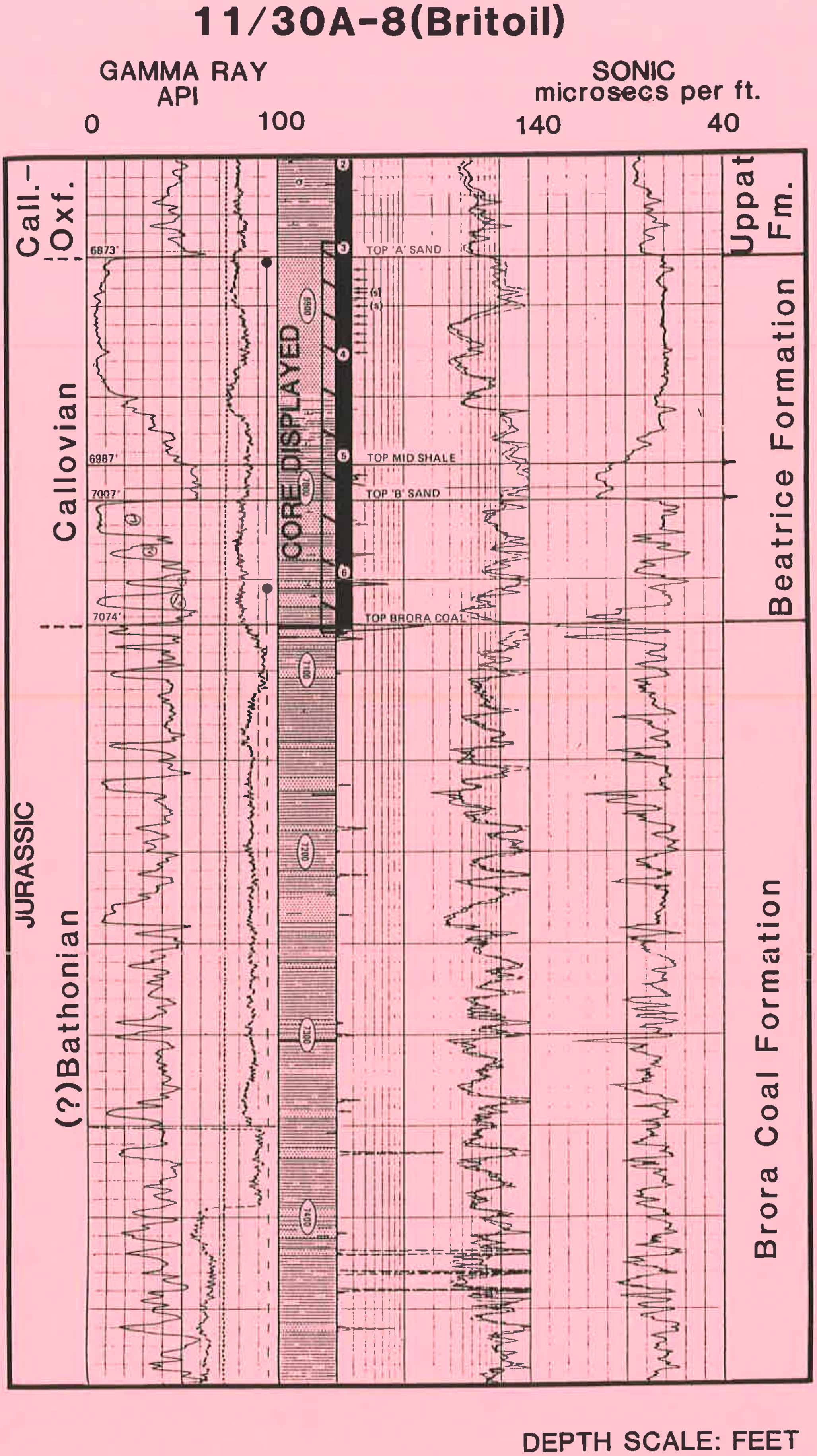

11/30A-8(Britoil)
GAMMA RAY
API
0
100
SONIC
microsecs per ft.
140
40
Call.-
Oxf.
Callovian
JURASSIC
(?)Bathonian
6873'
6987'
7007'
7074'
CORE DISPLAYED
TOP 'A' SAND
TOP MID SHALE
TOP 'B' SAND
TOP BRORA COAL
Uppat
Fm.
Beatrice Formation
Brora Coal Formation
DEPTH SCALE: FEET

Fig. 7.3

Figure 7.4 Core log for the Brora Coal, Beatrice and basal Uppat formations of well 11/30A-8 (Britoil), Beatrice Oilfield.

The core displayed spans the interval between the Brora Coal Formation, of interbedded sandstones and shales, and the dark shales of the Uppat Formation. It includes the sandstones of the Beatrice Formation, the principal reservoir of the Beatrice Field.

At the base of the core is the Brora Coal overlying a sandstone with root traces. The overlying sandstones interbedded with shales exhibit small-scale upward-fining and more commonly upward-coarsening sequences. Bioturbation is common and there are localised concentrations of shell debris. At c.7005ft. the sand/shale sequence is overlain by a thick argillaceous unit which contains a belemnite shell at its base.

The upper sandstone, above 6950ft. has a coarsening-upwards base. It is fine to medium grained, oil stained, and appears rather structureless. The sandstone is succeeded by shale of the Uppat Formation. The upper boundary of the sandstone is marked by burrowing and a shelly siltstone.

The upper sand, the "A Sand" in the local reservoir zonation scheme, has the best reservoir characteristics; permeabilities of several Darcies are recorded.

Fig. 7.4

11/30A-8(Britoil)

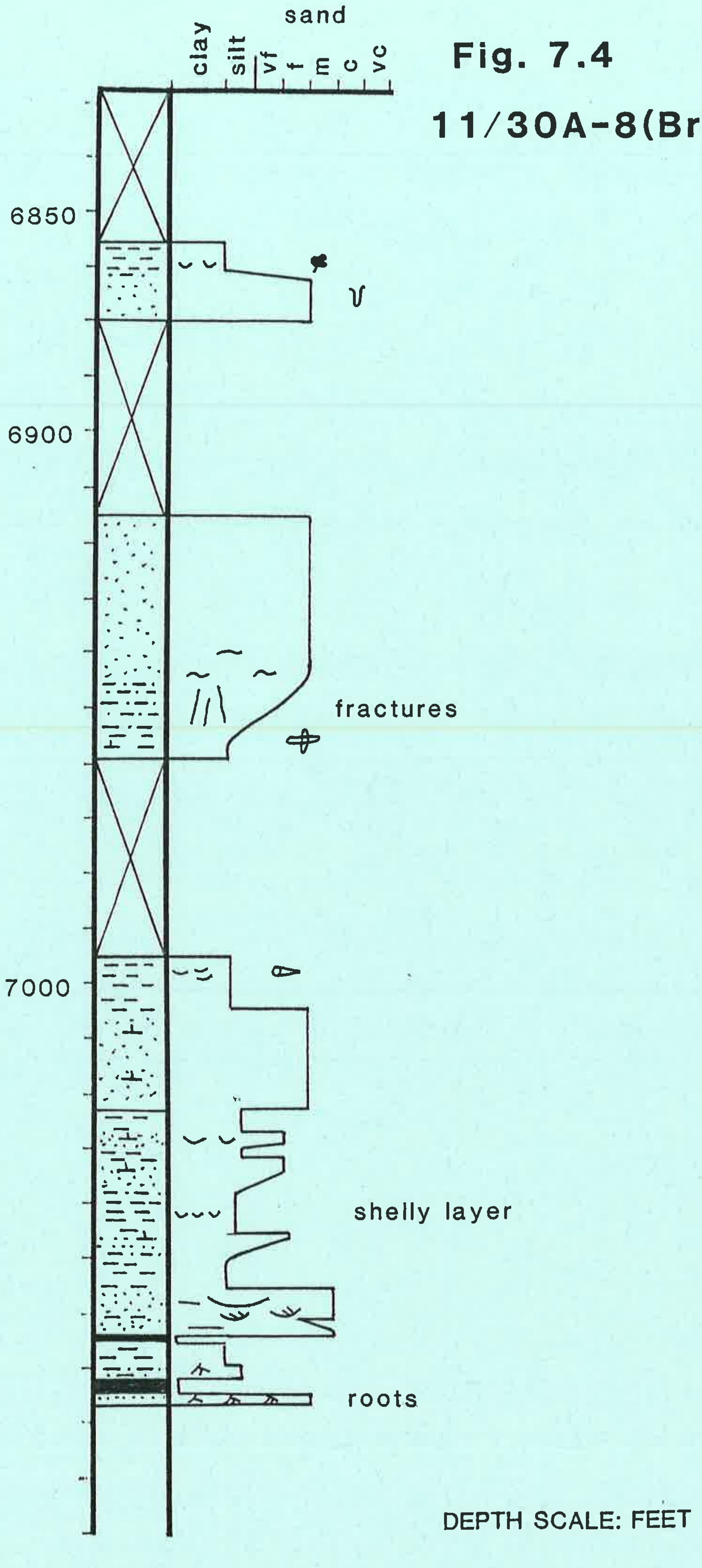


Figure 7.5 Composite log for the Alness Spiculite Unit (Oxfordian) of well 12/22-2 (Arco).

Regional setting

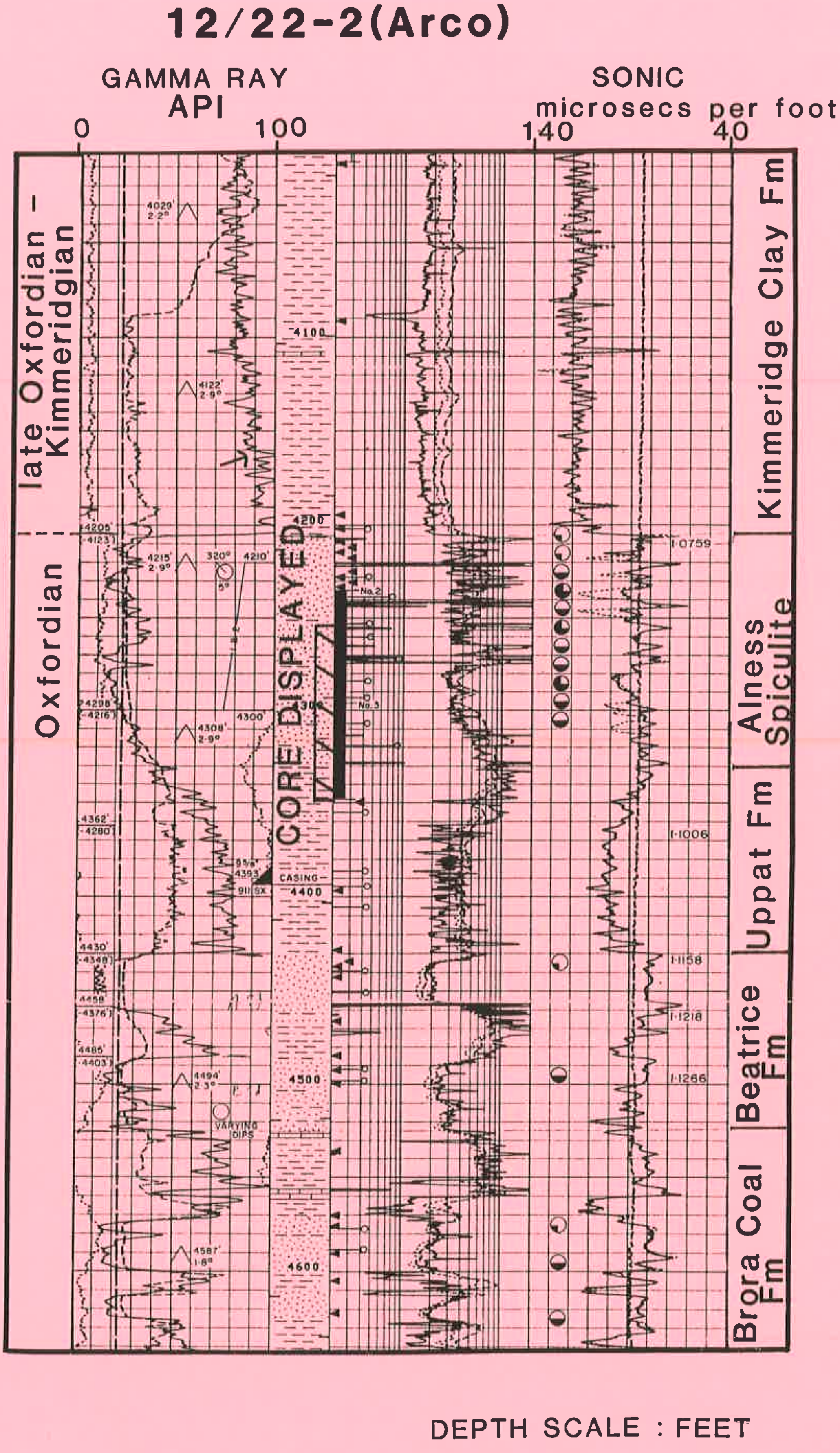
Well 12/22-2 is located near the margin of the Smith Bank High, a NE-SW trending horst in the Inner Moray Firth which separates the Wick Sub-Basin from the Smith Bank Graben.

Well stratigraphy

The Callovian sequence is comparable to that in the Beatrice Field to the south-east. The Alness Spiculite Unit is a localised development and shales out before the Beatrice Field. It is best developed in Quadrant 12SE. The Spiculite is abruptly overlain by dark shales; the Spiculite is probably mid-Oxfordian in age, the shales are probably late Oxfordian or younger. The boundary correlates with a widely correlatable seismic event in the Inner Moray Firth, termed the Intra-Oxfordian Event By Andrews and Brown (1987).

Depositional environment

The Alness Spiculite is a marine deposit composed predominantly of spicules of the sponge Rhaxella. It is developed in a coarsening-upwards sequence recording progradation on a marine shelf. The late Oxfordian to Kimmeridgian shales above are marine, laterally equivalent to the Piper Formation in the Outer Moray Firth. It is tempting to equate the shale-on-spiculite boundary here with the base of the I-Shale transgressive deposits at the base of the Piper Formation farther east.



12/22-2(Arco)
GAMMA RAY
API
0
100
SONIC
microsecs per foot
140
40
late Oxfordian – Kimmeridgian
Oxfordian
Kimmeridge Clay Fm
Alness Spiculite
Uppat Fm
Beatrice Fm
Brora Coal Fm
CORE DISPLAYED
4100
4200
4300
4400
4500
4600
CASING
DEPTH SCALE : FEET

Fig. 7.5

Figure 7.6 Core log for the Alness Spiculite Unit of well 12/22-2 (Arco).

The core extends across the upward-coarsening sequence above the mudstones of the Uppat Formation. The upward-coarsening silts and sands belong to the Alness Spiculite Unit. The lower, more argillaceous strata in the core are silty and bioturbated. Bioturbation remains characteristic of the overlying siltstones and very fine sandstones. Both siltstones and sandstones are commonly calcareous.

Above c.4290ft. the sandstones have a more massive appearance and have a patchy oil stain; there is a patchily developed calcareous cement. The slight increase in gamma ray log response above 4264ft. corresponds to a slight increase in argillaceous material in the form of discontinuous, irregular laminae.

The dominant component of the sandstones, and a significant contributor to the silty deposits in the lower half of the core, is in the form of spicules from the siliceous sponge Rhaxella.

The permeability of the sandstones is variable. Patches of tight silica-cemented and calcite-cemented sandstone are common. Best permeability is c.40 mD.

Fig. 7.6

12/22-2 (Arco)

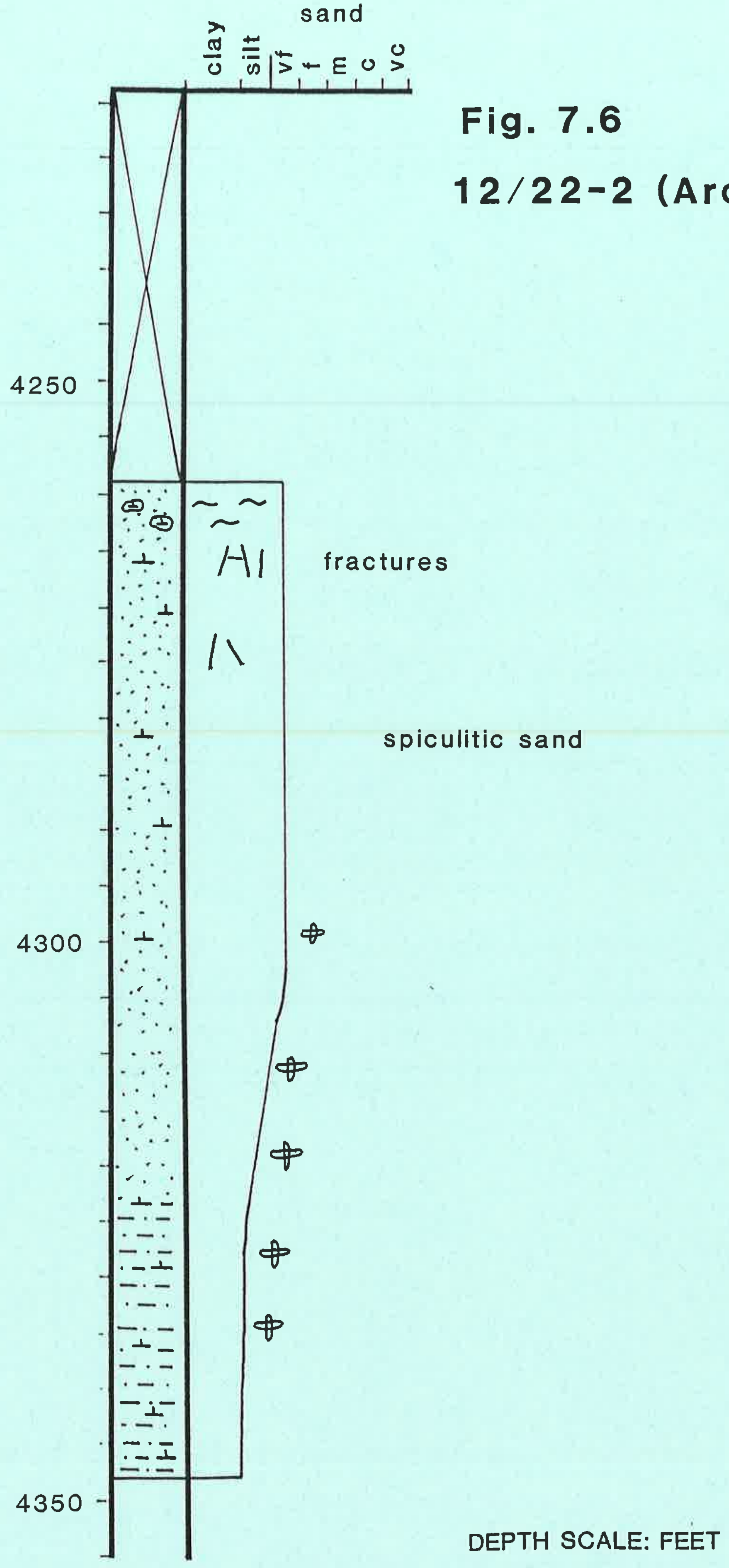


Figure 7.7 Composite log for the Piper Formation of well 15/16-12 (Texaco), Tartan Oilfield.

Regional setting

The Tartan Field lies within the Witch Ground Graben, on a structure with a broadly E-W trend. The reservoir is the Piper Formation, a widely distributed unit in the Outer Moray Firth area.

Well stratigraphy

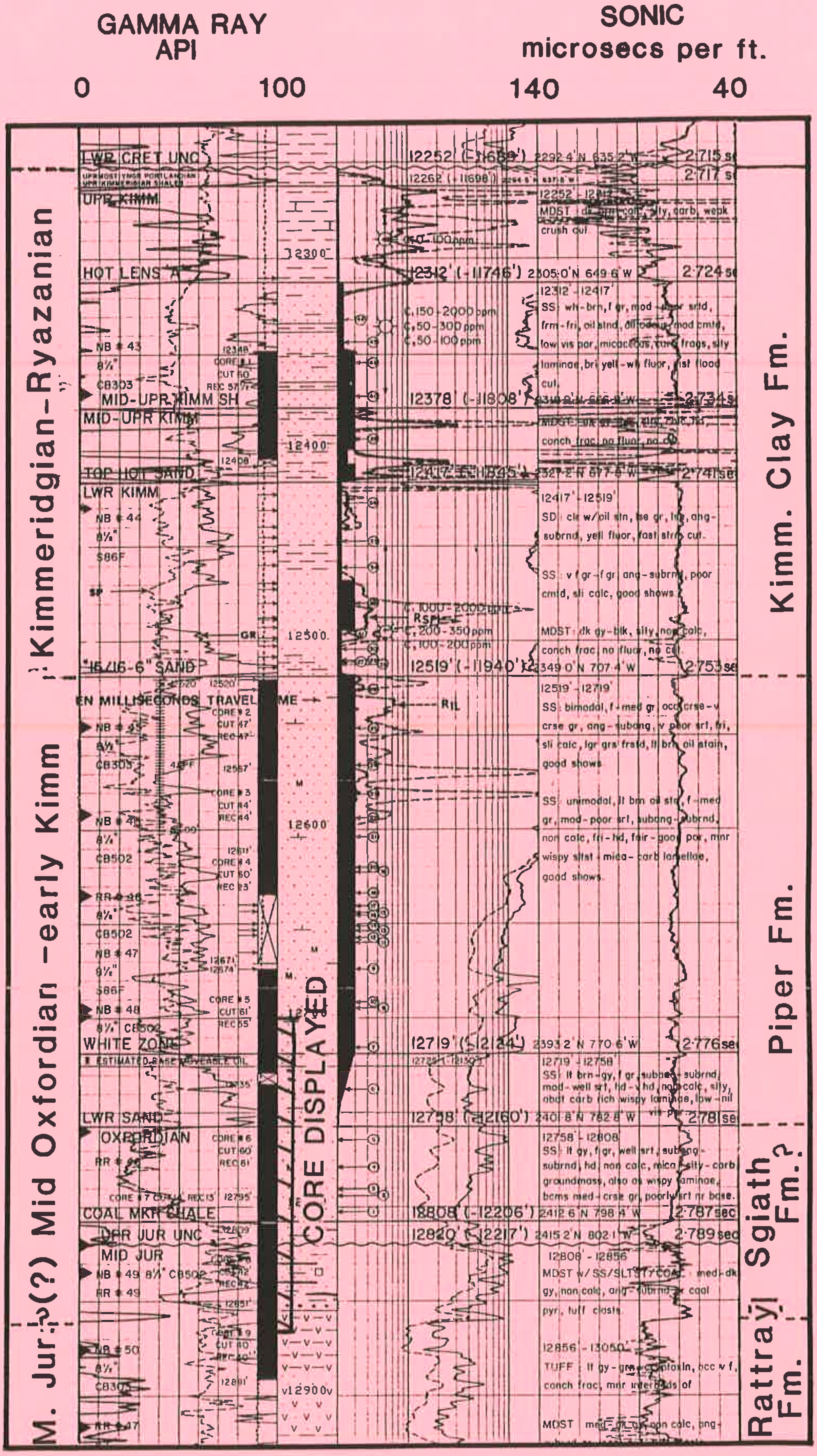
Middle Jurassic volcanics are overlain by a thin Sgiath Formation which is overlain in turn by the Piper Formation at 12820ft. The Piper Formation is succeeded by the Kimmeridge Clay Formation which contains thin interbedded sands.

Depositional environment

The Piper Formation is probably entirely marine in origin. Environments of deposition ranging from shallow shelf to deltaic have been suggested. Locally a shallow shelf environment is favoured.

The Kimmeridge Clay is also marine but deposited in a less energetic, probably deeper environment. The interbedded sands are gravity flow deposits, broadly equivalent in age and origin to the main Jurassic reservoir sands in the Claymore Oilfield.

15/16-12(Texaco)



DEPTH SCALE: FEET

Fig. 7.7

Figure 7.8 Core log for the Piper formations of well 15/16-12 (Texaco), Tartan Oilfield.

The core displayed spans the boundary between the Rattray Formation (Middle Jurassic) and the Upper Jurassic Sgiath Formation. It also extends upwards into the Piper Formation, the reservoir in this well located in the Tartan Oilfield.

The Rattray Formation consists of tuffs and subordinate coarse breccia or agglomerate beds. It is overlain abruptly by a fine grained, rather muddy and carbonaceous sandstone with rootlet structures and much evidence of soft sediment deformation, probably due to root penetration. This fines-up to a grey siltstone and in turn to a dark grey silty mudstone. The lower sands and silts are probably part of the Sgiath Formation; the dark shales are probably equivalent to the I-Shale in the Piper area, marking the base of the Piper Formation.

There is a pronounced upward-coarsening sequence above 12835 ft. but above c.12812 ft. the trend is for thin upward-fining sequences, some rather subtle in character. The example at 12780 ft. is the most obvious; it has fine to medium sandstone passing up to burrowed silty mudstone.

The upper sandstone unit in the core displayed from the Piper Formation has a transitional base, with burrows in evidence. Calcareous bands occur locally in the sandstone interval, as do thin coarse grained sand units, interrupting the otherwise rather uniform grain size profile. Towards the top of the cored interval some wispy mud laminae are found.

Permeability reaches 1 Darcy in the best Piper sands in this well.

Fig. 7.8

15/16-12(Texaco)

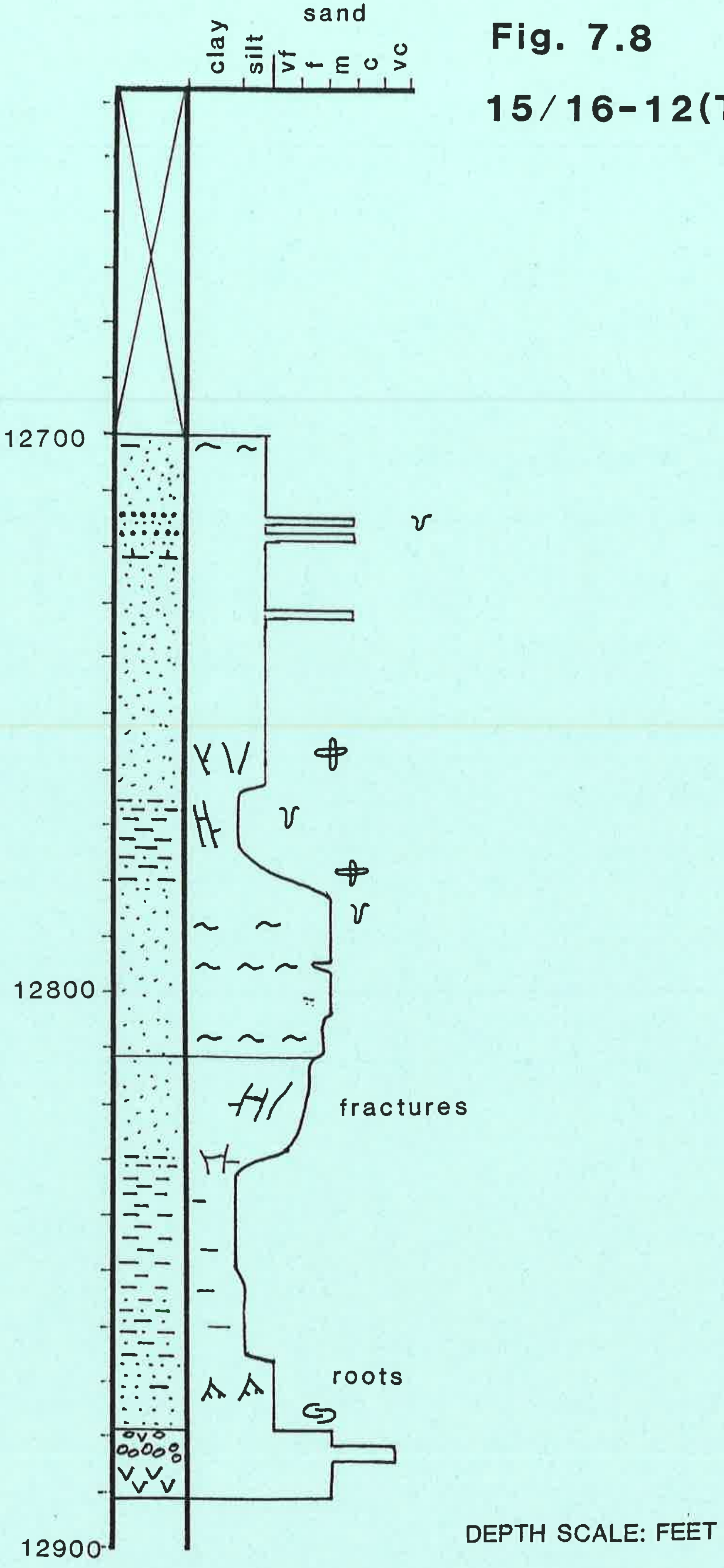


Figure 7.9 Composite log of the Sgiath Formation to Claymore Sandstone Member of Well 14/19-3 (OXY), Claymore Oilfield.

Regional setting

This well is located on a fault-bounded terrace north of the Halibut Horst, on the margin of the Witch Ground Graben. It lies just to the west of the limit of sand deposition during the late Oxfordian to Kimmeridgian (Piper Formation times) in the Witch Ground Graben area. Sands, presumably shed from the adjacent Halibut Horst in the late Kimmeridgian to Volgian, occur over the terrace.

Well stratigraphy

Probable Triassic strata are overlain by sands with minor coal of the Sgiath Formation, at 8243ft. The overlying shales have been interpreted as a lateral age equivalent of the Piper Formation by Harker et al (1987). The sandstones above the "Piper shales" belong to the Claymore Sandstone Member of the Kimmeridge Clay Formation, the Jurassic reservoir in the Claymore Oilfield.

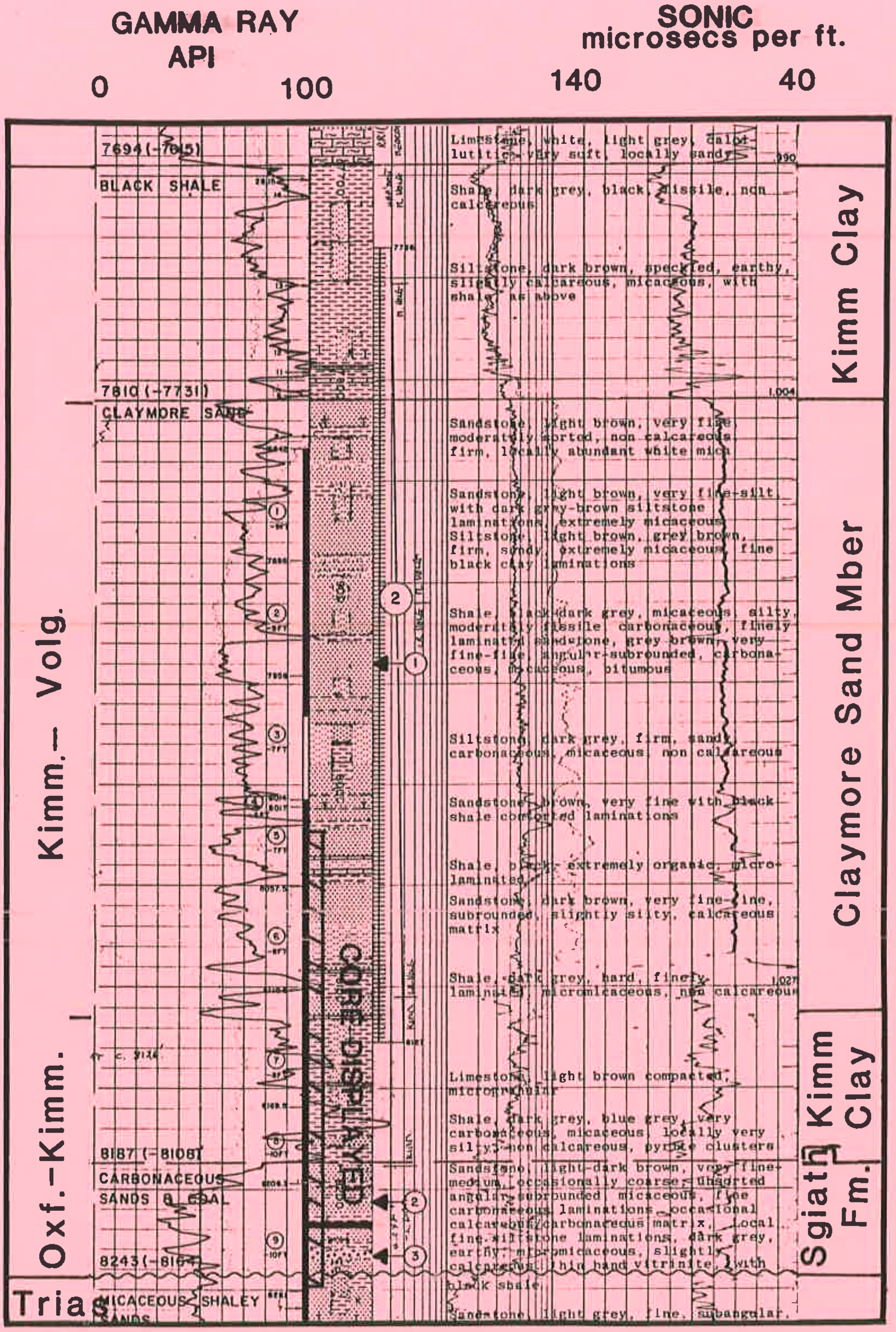
The Piper equivalent shales are similar in age to the basal part of the Kimmeridge Clay Formation over the northern North Sea. The Claymore Sand Member is late Kimmeridgian to early Volgian in Block 14/19.

Depositional environment

The basal Jurassic deposits, the Sgiath Formation, represent the product of a mid- to late Oxfordian transgression over the Outer Moray Firth area. Deposition occurred in a paralic environment, including coal-forming swamps on a coastal plain.

The sequence above is wholly marine; the Claymore sandstones are submarine gravity flow deposits forming rather localised cones of relatively coarse clastic sediment encased in the argillaceous facies of the Kimmeridge Clay Formation.

14/19-3 (Oxy)



DEPTH SCALE: FEET

Fig. 7.9

Figure 7.10 Core log for the Sgiath Formation and Claystone Sandstone Member of well 14/19-3 (Occidental), Claymore Oilfield.

The core displayed extends from (?)Triassic very fine grained, micaceous sands at the base, through the late Jurassic Sgiath Formation and shales laterally equivalent to the Piper Formation, up to the sandstones of the Claymore Member of the Kimmeridge Clay Formation, the principal reservoir in this well from the Claymore Oilfield. There is a sharp and erosive base to the Sgiath Formation preserved in this core. Thin coarsening-up sand and shale sequences, along with some thin sharp-based sands and with thin in situ coals, occur in the Sgiath Formation. There is a transitional boundary with the overlying dark shales. The siltstone at the transition and the superjacent mudstone both contain belemnite remains.

The thick mudstone below c.8126ft. has traces of shell debris locally. It is succeeded, possibly at an abrupt contact, by very fine grained sandstone. The sequence up to 8020ft. is dominated by sandstone with only thin intervals of dark mudstone, often rich in cardonaceous scraps. The sandstone, part of the Claymore Member, is oil stained. It is characterised by fractures in this core, and evidence of small-scale faulting is present.

Fig. 7.10
14/19-3(Oxy)

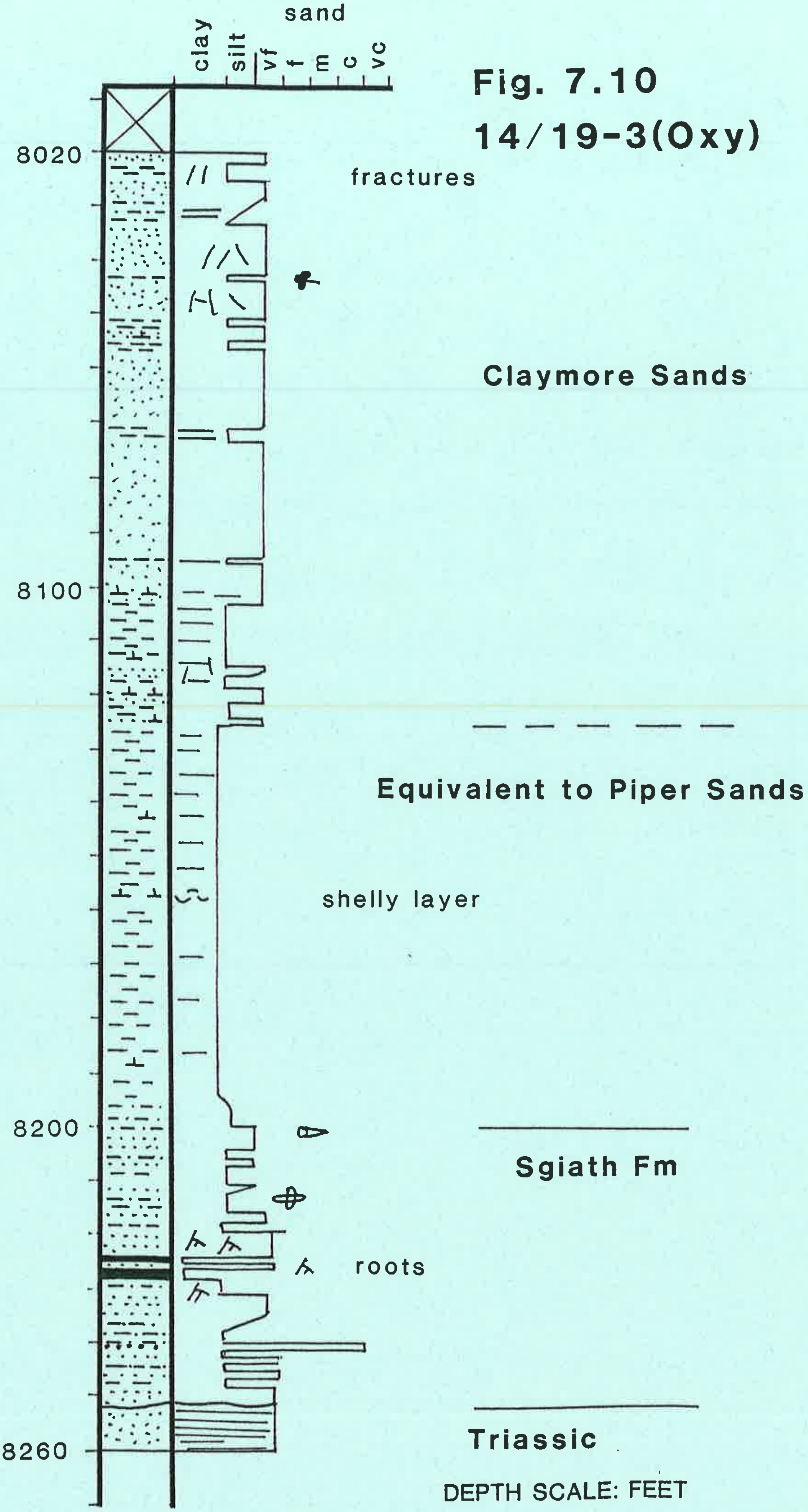


Figure 7.11 Composite log for intra-Kimmeridge Clay Formation sandstones ("Ettrick Sand Member") of well 20/2-1 (BNOC), Ettrick Oilfield.

Regional setting

This well, the discovery well for the Ettrick Field, penetrates 2200ft. of Humber Group (Upper Jurassic to Ryazanian) strata in the area of the Buchan Graben, south of the Halibut Horst. The well location lies to the west of the limit of Piper Formation sand distribution.

Well stratigraphy

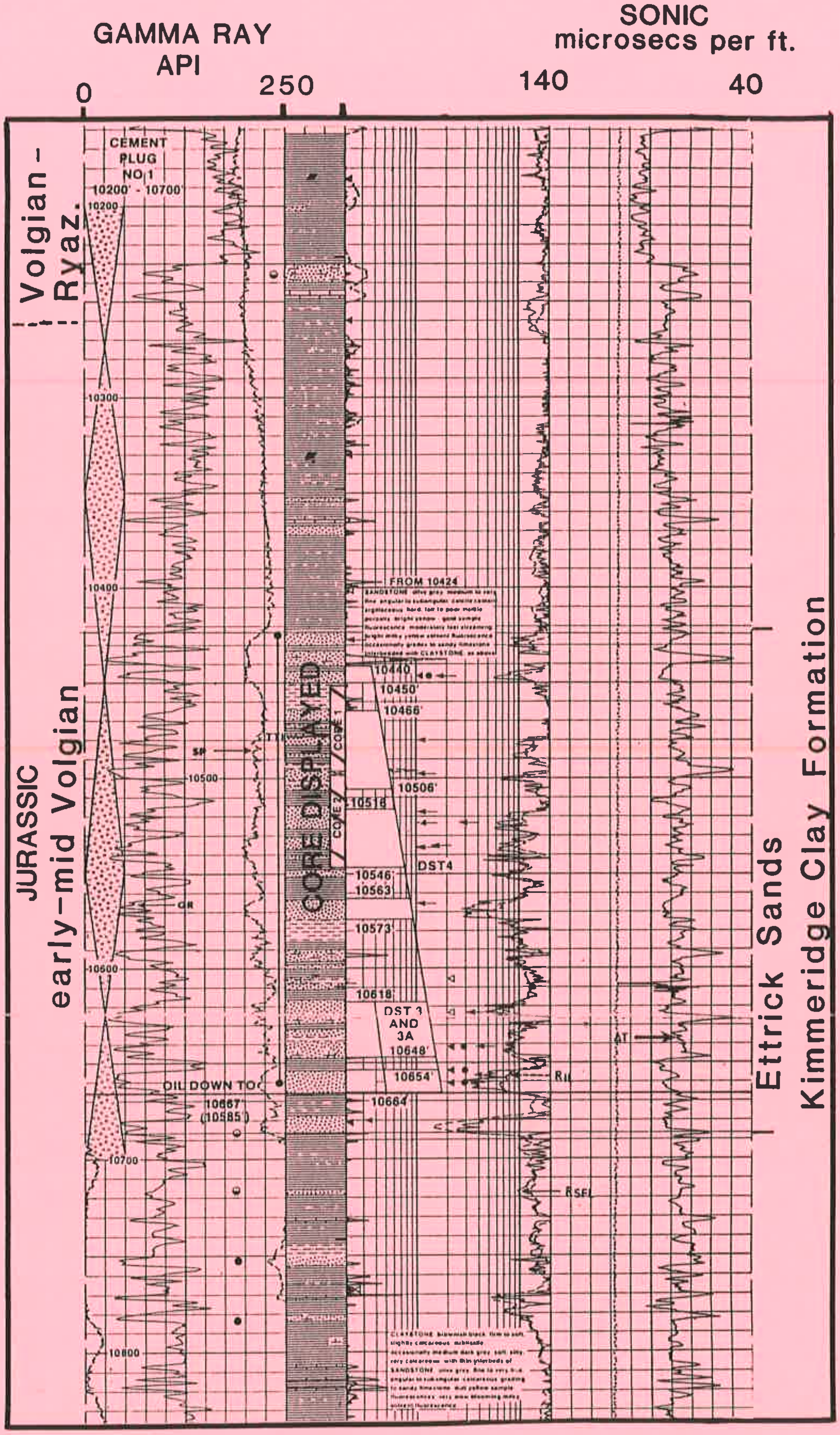
The thick Jurassic succession rests unconformably on Triassic claystones. The basal Jurassic beds are probably Oxfordian to early Kimmeridgian in age; they consist of shales, but with a thin coal seam present c.20ft above the unconformity. The sand:shale ratio in the Humber Group is low; sands are concentrated only in the interval shown in the section of log figured here.

The reservoir sands are (?)early to mid-Volgian in age, similar in age to the Claymore Sand Member in well 14/19-3, located to the north of the Halibut Horst.

Depositional Environment

The late Jurassic sands are submarine gravity flow deposits shed into a basin whose background sedimentation was the "hot" shale facies of the Kimmeridge Clay Formation.

20/2-1 (BNOC)



DEPTH SCALE: FEET

Fig. 7.11

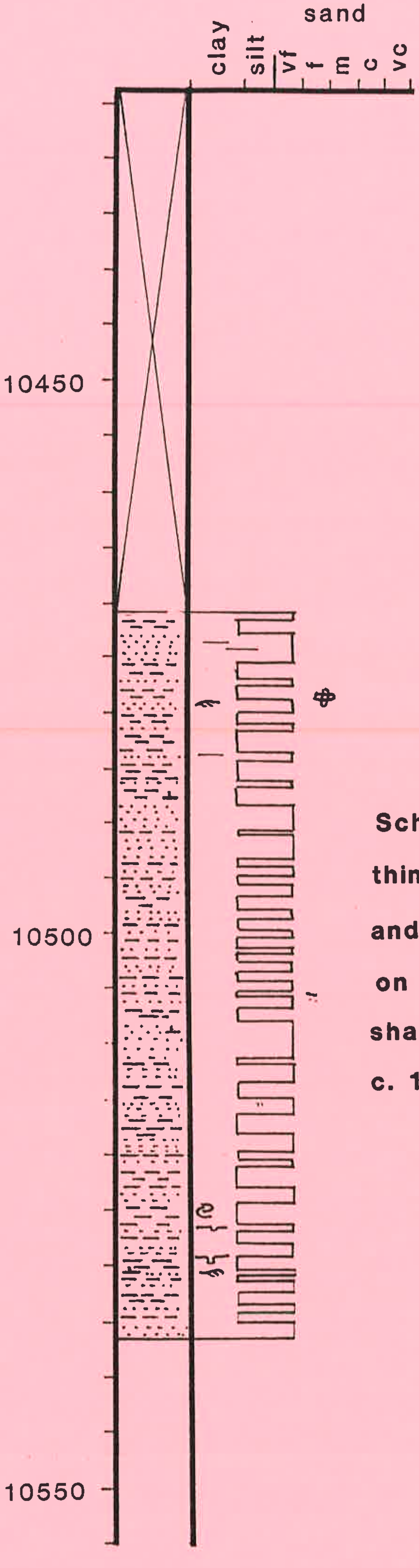
Figure 7.12 Core log for intra-Kimmeridge Clay Formation sandstone ("Ettrick Member") of well 20/2-1 (BNOC), Ettrick Oilfield.

This core shows an interbedded sandstone and shale sequence from within the Kimmeridge Clay Formation in the Ettrick Oilfield. Very fine sand to silt beds, on a scale of often less than 2ins, alternate with shale bands; upward transitions from laminated sand, to ripple cross-laminated sand, to shale are present. Thicker sand units, forming the effective reservoir in the the Ettrick Field, have sharp bases, are fine-grained, are mostly structureless, and have transitional upper boundaries with superjacent shales.

Permeabilities of up to 800 mD have been recorded, but with the thin sandstones having a permeability of usually less than 400 mD.

Fig. 7.12

20/2-1(BNOC)



Schematic representation of thinly interbedded shales and very fine sandstones on scale of c.2ins and sharp based sandstones c. 1-5ft thick.

DEPTH SCALE: FEET

Figure 7.13 Composite log for intra-Kimmeridge Clay Formation sandstones of well 13/27-1A (Amoco)

Regional setting

The well is located between the Halibut Horst and the Banff Basin to the south, just on the upthrown side of the NE-SW trending Bosies Bank Fault.

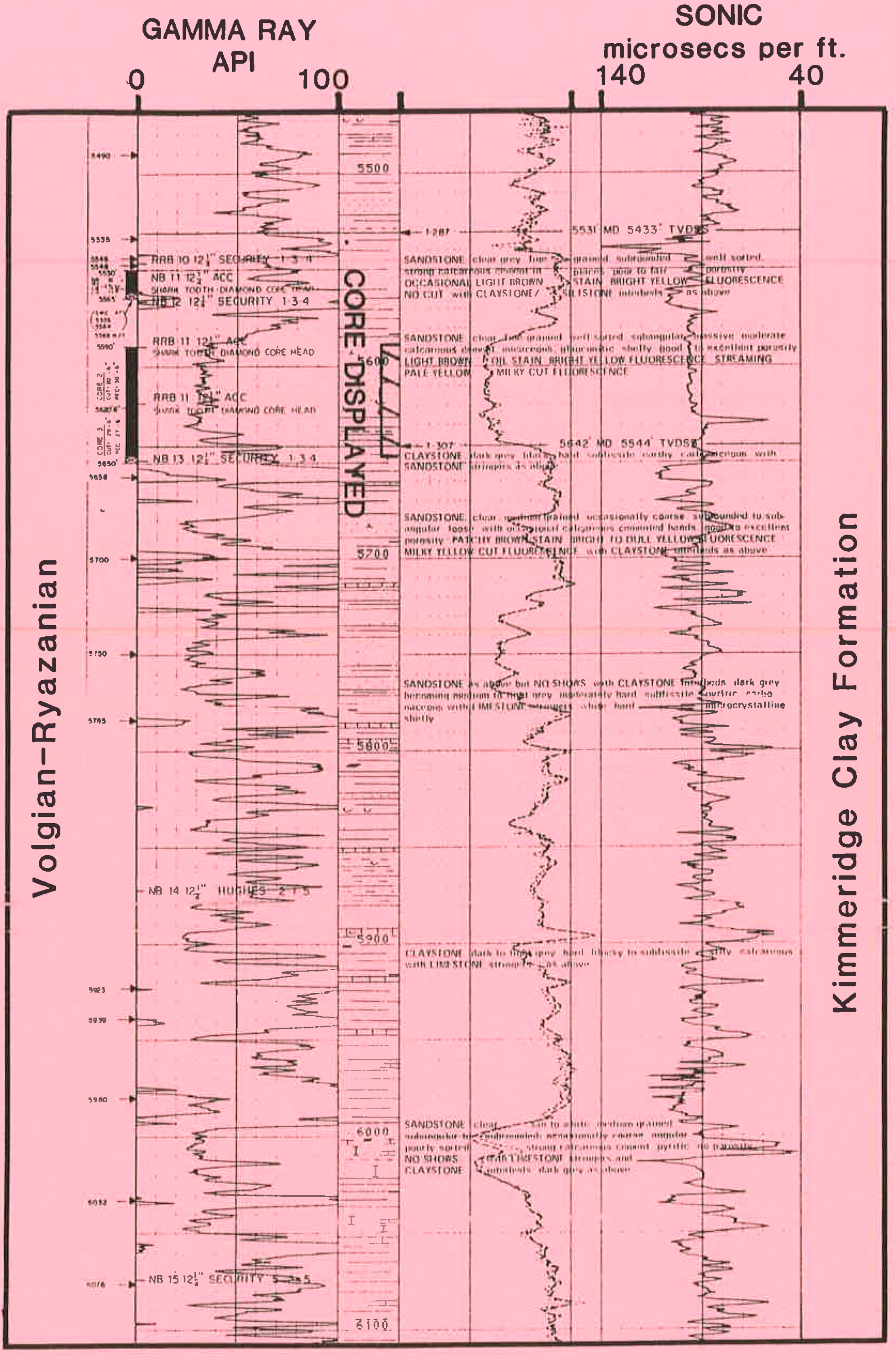
Well stratigraphy

The Jurassic in this well, with the Alness Spiculite Unit (Oxfordian) at the base, rests unconformably on Triassic claystone. Some 1650ft of Jurassic strata are present. Above the Spiculite, the Jurassic succession consists of c.600ft of dark shales overlain by thinly interbedded sandstones and shales, as shown on the log section figured here. The strata illustrated are mid-Volgian to Ryazanian in age.

Depositional environment

On the basis of limited core evidence and regional considerations it is probably that the sandstones are submarine gravity flow deposits transported into an environment whose background sedimentation was typical "hot" shale facies of the Kimmeridge Clay Formation. The main sand in the log, above 5626ft. may represent a submarine channel deposit given its abrupt base and transitional top.

13/27-1(Amoco)



DEPTH SCALE: FEET

Fig. 7.13

Figure 7.14 Core log for intra-Kimmeridge Clay Formation sandstone of well 13/27-1A (Amoco).

This short core illustrates the character of sandstones found in a sequence of interbedded sandstones and shales within the Kimmeridge Clay Formation of the Moray Firth Basin, south of of the Halibut Horst. Thinly interbedded shale and subordinate very fine to fine sandstone are succeded by fine sandstone which is mostly structureless, has traces of cross-lamination and ripple lamination, and at c.5603ft. a thin interval in which coarse quartzose sand grains and carbonaceous scraps "float" in a fine sand matrix. The gamma ray log response of the main sand unit displayed in the core indicates an upward-fining grain size profile.

The permeability of the main sand unit reaches c.1 Darcy in places.

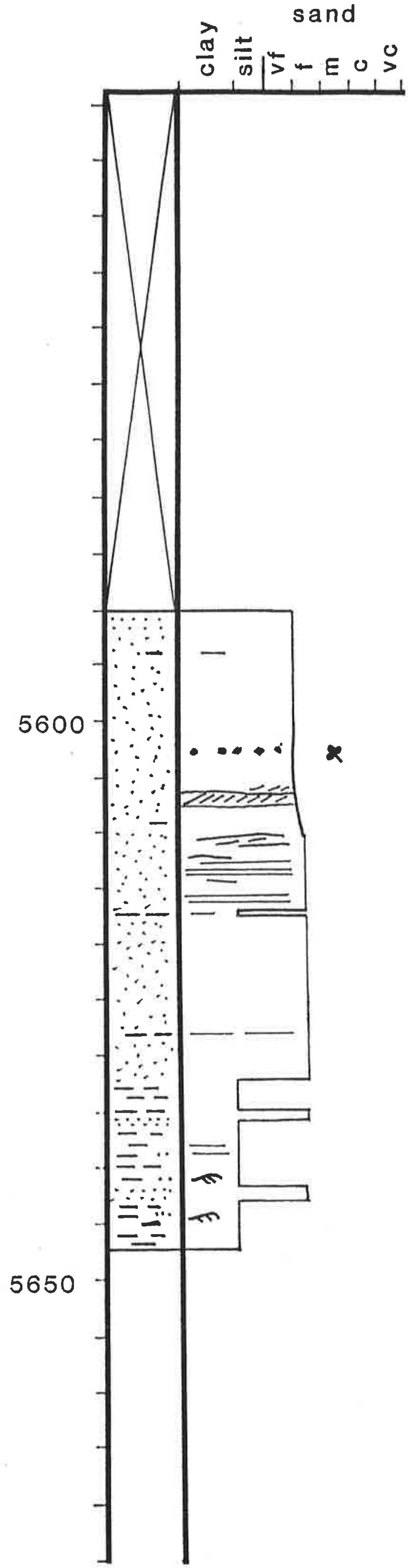


Fig. 7.14

13/27-1(Amoco)

DEPTH SCALE: FEET

8. LOWER CRETACEOUS

Lower Cretaceous sediments occur widely offshore but are absent on land around the Moray Firth. The Lower Cretaceous of the Moray Firth is largely synonymous with the Cromer Knoll Group which ranges in age from Upper Ryazanian to the Albian/Cenomanian boundary (the Lower to Middle Ryazanian is represented by Humber Group sediments). In the Outer Moray Firth it is possible to divide the Cromer Knoll Group into the Valhall, Sola, and Rodby Formations; this becomes very difficult within the inner basin. Figure 8.1 shows the thickness variation of the Lower Cretaceous strata of the Moray Firth.

The two dominant factors which controlled Cromer Knoll Group sedimentation in the Moray Firth were relative sea-level changes and tectonic activity. Normal faulting continued from the Jurassic into the early Cretaceous and reached a maximum during the late Ryazanian and Valanginian, with a later phase during the Aptian-Albian (Hesjadal and Hamar, 1983). The tectonic events during the Lower Cretaceous controlled the deposition of the sands in the Inner and Outer basins, the distribution of which is shown in Figure 8.2.

There was an overall rise in global sea-level during the Cretaceous but subsidiary transgressive and regressive phases are also recognisable within the area, beginning with the *stenomphalus* zone transgression in the Ryazanian. This causes the change from Kimmeridge Clay Formation black shale deposition to calcareous mudstone and limestone deposition and reflects a major environmental change, from the anaerobic conditions present at the sediment/water interface in the late Jurassic to the well oxygenated bottom conditions which developed during the early Cretaceous. There was an associated change in the microfaunal assemblages from a predominantly agglutinated foraminiferal assemblage in the black shale facies to one dominated by benthonic hyaline foraminifera in the Valhall Formation mudstones. Well 14/19-15 illustrates the Kimmeridge Clay Formation/Cromer Knoll Group boundary (Figure 8.3 and 8.4).

8.1 Valhall Formation

The Valhall Formation (Upper Ryazanian-Barremian) consists predominantly of calcareous mudstones and marls. The basal part of the Formation comprises interbedded limestones and marls. The sediments are conformable with the underlying Humber Group shales in the deeper part of the basin, but over some intra-basinal highs the base is unconformable and in places strata progressively onlap older Mesozoic and pre-Mesozoic sequences.

During this period large thicknesses of clastics were shed into the basin from the Halibut Horst area and off the crests of other uplifted fault blocks. These sediments range in age from Upper Ryazanian to Barremian, and have been termed the Scapa Sandstone Member by Harker *et al.* (1987) where they occur in Quadrant 14, north of the Halibut Horst (Figures 8.2 and 8.5). The Scapa sandstones are interpreted as having been deposited from turbidity currents by Boote and Gustav (1987). The interbedded mudstones contain a predominantly planktonic palynological assemblage, indicative of deposition in a normal marine environment. They are finely laminated with thin sandstones and siltstones, which were probably deposited by distal turbidity currents.

A unit consisting of calcareous siltstones and sandstones lies beneath the Scapa Sandstone Member and also thickens towards the Halibut Horst (Figure 8.5). Burrows are common in these sediments suggesting a relatively low sedimentation rate.

Deposition of the fans ceased rapidly with no apparent fining upward of the sequence. Other similar aged fan deposits are present in Blocks 14/20 and 15/16.

8.2 **Sola Formation**

The sediments above the Valhall Formation are termed the Sola Formation (after Hesjedal and Hamar, 1983). They range in age from Lower Aptian to Lower Albian, and consist of non-calcareous dark grey, organic rich claystones with thin limestone and siltstone beds; in places sandstones dominate the sequence. There is however an increase in calcareous content of the claystone towards the top of the formation. The Sola Formation sediments are more organic rich than the Valhall Formation shales and are believed to have been deposited in a more restricted marine setting than the Valhall deposits (Hesjedal and Hamar, 1983). The microfauna is typified by agglutinating foraminifera, such as *Glomospira* and *Recurvoides*. This restricted marine environment is related to a mid-Aptian orogenic phase by Hesjedal and Hamar (1983), which resulted in basin isolation. Fault blocks were reactivated and sands were eroded from local horsts and upland areas (such as the Fladen Ground Spur) into the Witch Ground Graben. Different oil companies working in the area have referred to these sands as the Bosun, Kopervik and Aasgard Formations. The term Bosun sands is prefered (largely on the grounds of historical precedence).

The Bosun sands (see well 16/27-3, Figures 8.6 and 8.7) typically consist of interbedded sandstones and mudstones which are interpreted as having been deposited by turbidity and debris flow currents in a submarine fan environment. In the Witch Ground Graben the Bosun sands can be divided into four units (Figure 8.8). There is a basal unit which is restricted to an area around blocks 16/27 and 16/28. This is overlain by a more widespread unit consisting of fining upward (50 feet, 15 m thick) sandstone/mudstone sequences. This is in turn overlain by a correlatable mudstone unit which reflects a phase of fan abandonment. The youngest unit consists of a series of 10-20 feet (3-6 m) thick sandstone/mudstone sequences. These fining upward sequences are interpreted as being the deposits of submarine fan channel systems.

Tectonic activity gradually decreased and sea level gradually rose during the Aptian-Albian, explaining the fining upward nature of the Formation.

There is an Aptian-Albian sand body south of the Renee Ridge in Block 21/2. This consists of an arenaceous sequence divided by a predominantly argillaceous unit (Figure 8.9). The sandstones are quite distinct from those in the Witch Ground Graben (Figure 8.10).

8.3 **Rodby Formation**

The Rodby Formation (Middle Albian to Upper Albian) overlies the Sola Formation and is typified by grey to red/brown sandy marls and calcareous shales. There is a gradual upward increase in carbonate content, ultimately leading to the deposition of the hemi-pelagic carbonates of the Chalk Group. The deposition of the Rodby Formation is associated with a major transgressive event, which is reflected in a change in the foraminiferal population, with planktonic forms largely succeeding the agglutinating forms in the Sola Formation.

8.4 Inner Moray Firth

In the Inner Moray Firth the Cromer Knoll Group has a high sandstone content. The thickness of the sands in common with the sequence as a whole increases towards the north-east adjacent to the Halibut Platform. There is a strong tectonic control on sedimentation with growth particularly marked along the Halibut and Smith Bank faults. The sandstones are lithologically varied and range from fine to coarse grained, and occasionally conglomeratic, with rare beds of lignite. In the south of the inner basin the sediments are predominantly argillaceous with a sandy basal section (Upper Ryazanian to Valanginian). The overlying claystones are black to dark grey, locally silty and contain shell fragments. The nature of the lithologies and the high concentration of spores suggests deposition in an inner shelf and paralic environment with a shoreline close to the present day northern limit of Cretaceous rocks. Rodby Formation sediments are recognised where they have not been removed by Tertiary erosion. The depositional regime prevalent in the outer basin therefore spread to the inner basin in mid-Albian times.

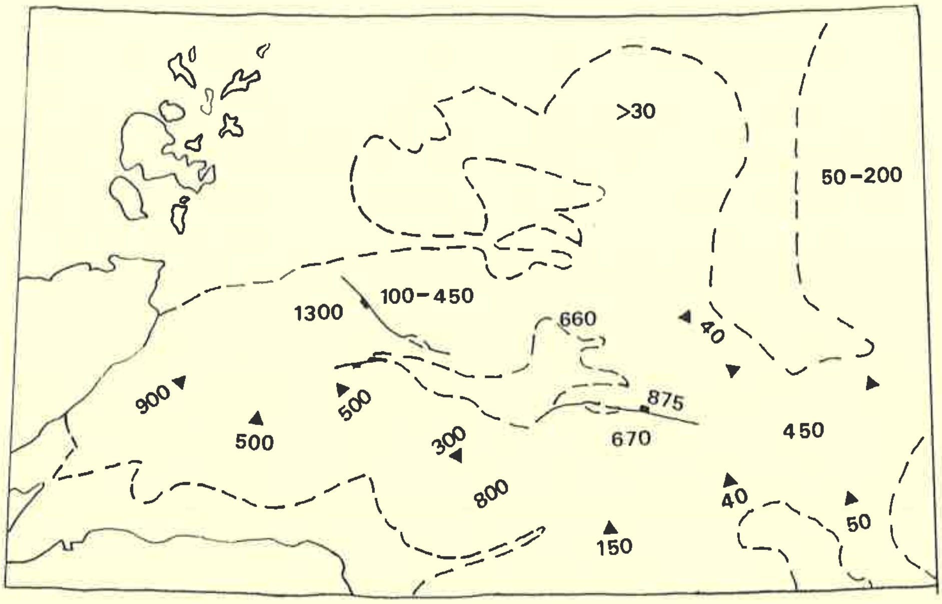


Fig. 8.1 Lower Cretaceous Isopach Map (metres)

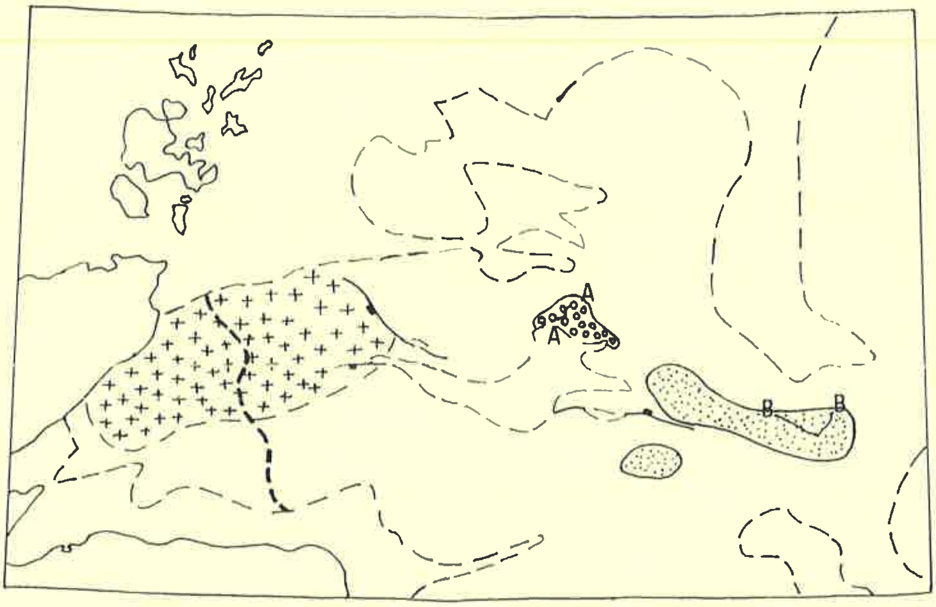


Fig. 8.2 Lower Cretaceous Sand Distribution

Inner Moray Firth sands
Ryazanian -Barremian sands (Scapa type)
Aptian-Albian sands (Bosun type)

A — A Scapa correlation
B — B Bosun correlation

Lower Cretaceous subcrop

Figures 8.3 and 8.4 Composite and core logs for the Scapa Sandstone Member (Lower Cretaceous) of well 14/19-15 (Occidental), Scapa Oilfield

Regional Setting

Well 14/19-15 is drilled north of the Halibut Horst and penetrates a sequence of Lower Cretaceous sandstones restricted to block 14/19.

Well Stratigraphy

The Lower Cretaceous sequence is 1026ft thick in well 14/19-15. The Scapa Sandstone Member has been dated as Valanginian to Hauterivian in age. Underlying the Scapa sandstone is a unit ("basal unit") of Upper Ryazanian to Lower Valanginian calcite cemented sandstone. Which is both extensivelly fluidized and burrowed.

The Scapa sandstones are fine to medium grained with scattered mudstone and shale clasts, shell debris and plant fragments. The sandstone beds frequently fine upwards to fine grained sandstones and silty mudstones. The sandstones display a primary calcite mud matrix and in places are strongly cemented.

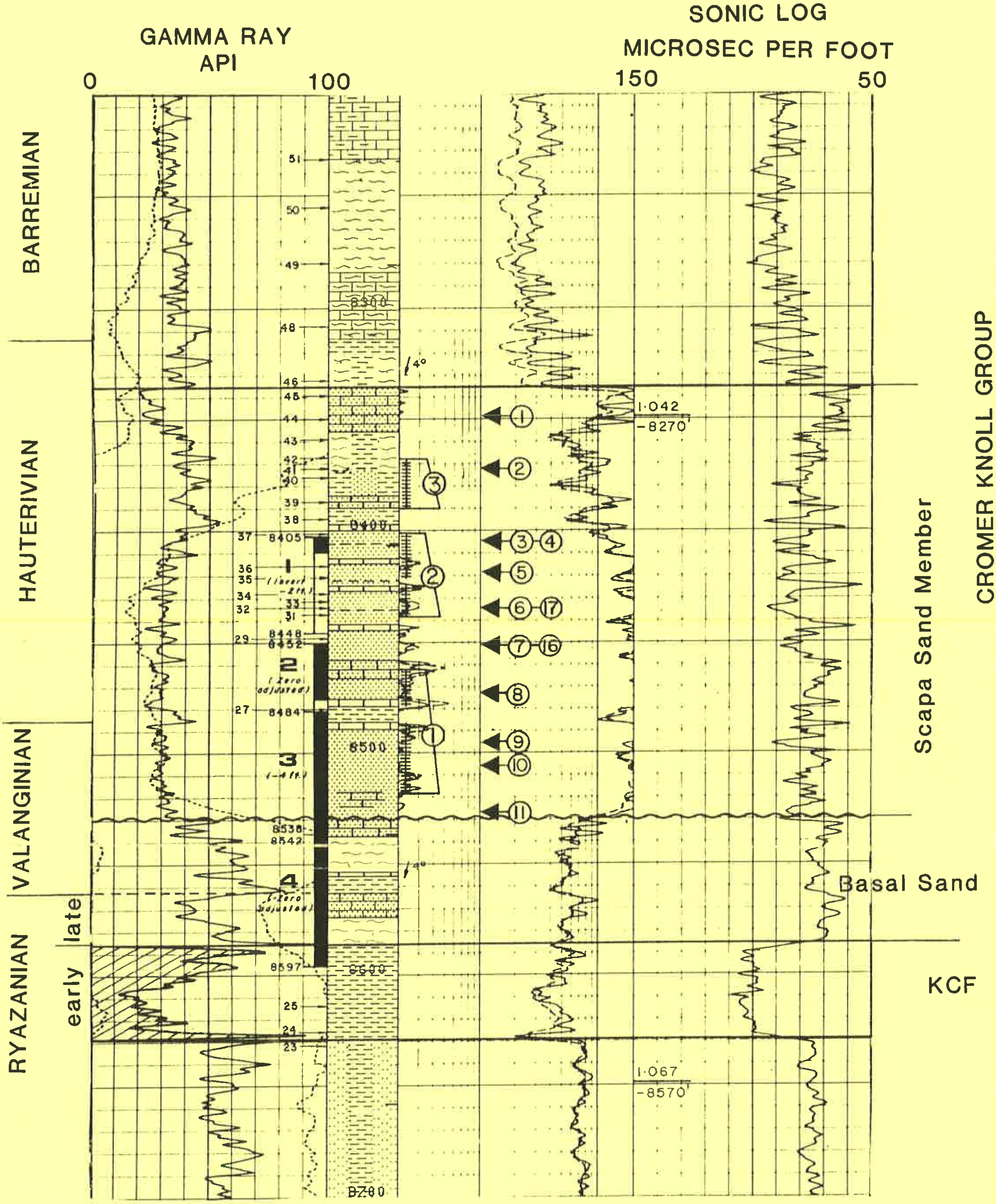
Depositional Environment

The depositional environment of the Scapa sandstones is in general a submarine fan, with the sequence thickening quite markedly towards the Halibut Horst fault. The sandstone deposits are suggestive of deposition by turbidity and debris flow currents. The burrowed nature of the basal unit indicates that sedimentation rates were lower during this period.

Reservoir Characteristics

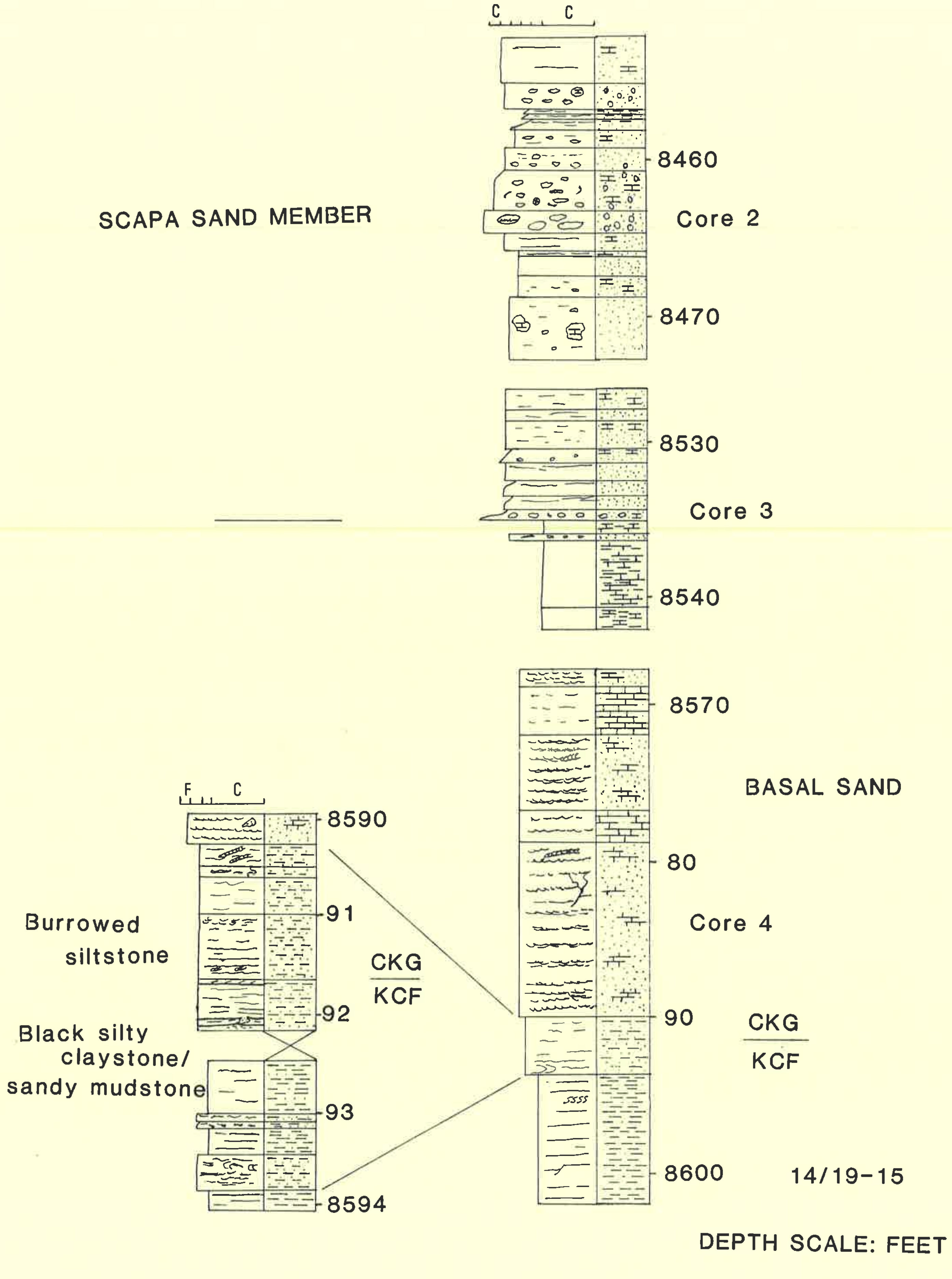
The sandstones range between being clean and uncemented with porosities of up to 30% and tightly cemented sandstones with nil porosity. Most samples lie close to these two extremes.

14/19-15 (OCCIDENTAL)



DEPTH SCALE:Feet

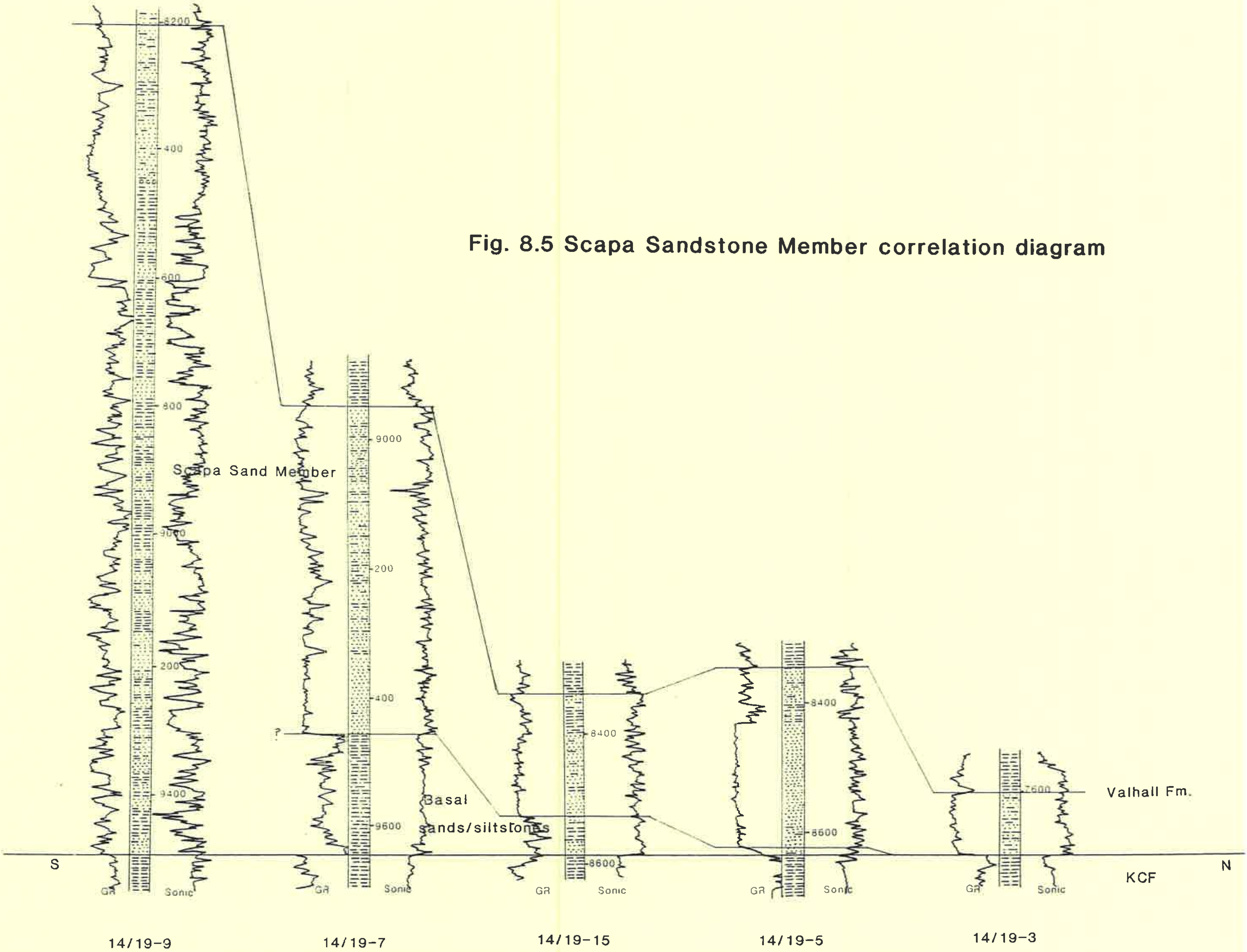
Fig. 8.3



C C
SCAPA SAND MEMBER
8460
Core 2
8470
8530
Core 3
8540
8570
BASAL SAND
F C
8590
80
91
Core 4
Burrowed siltstone
CKG
KCF
92
90
Black silty claystone/ sandy mudstone
CKG
KCF
93
8600
14/19-15
8594
DEPTH SCALE: FEET

Fig. 8.4

Fig. 8.5 Scapa Sandstone Member correlation diagram



Figures 8.6 and 8.7 Composite and core logs for the Bosun Sand (Lower Cretaceous) of well 16/27-3 (Phillips), Bosun Condensate Field

Regional Setting

Well 16/27-3 is located in the Witch Ground Graben, south of the Fladen Ground Spur.

Well Stratigraphy

The Lower Cretaceous is 1818ft thick in this well and can be divided into the Valhall and Sola Formations. The Valhall Formation is 865ft thick and the overlying Sola Formation 924ft thick. The Bosun sands lie within the Sola Formation and are directly overlain a thin (29ft) Rodby Formation.

The Bosun deposits typically consist of interbedded sandstones and mudstones. The Bosun sequence fines upwards as a whole and the individual sandstone/mudstone units thin towards the top of the sequence. The basal unit is typified by an extensivel y fluidized, poorly sorted, argillaceous sandstone with abundant mudstone and shale clasts. The overlying unit commonly contains a better sorted and cleaner sandstone which is horizontally laminated and frequently fines upwards. The sandstones are interbedded with dark-grey to black mudstones, shales and silty mudstones, and thin beds of a sandy, pebbly mudstone.

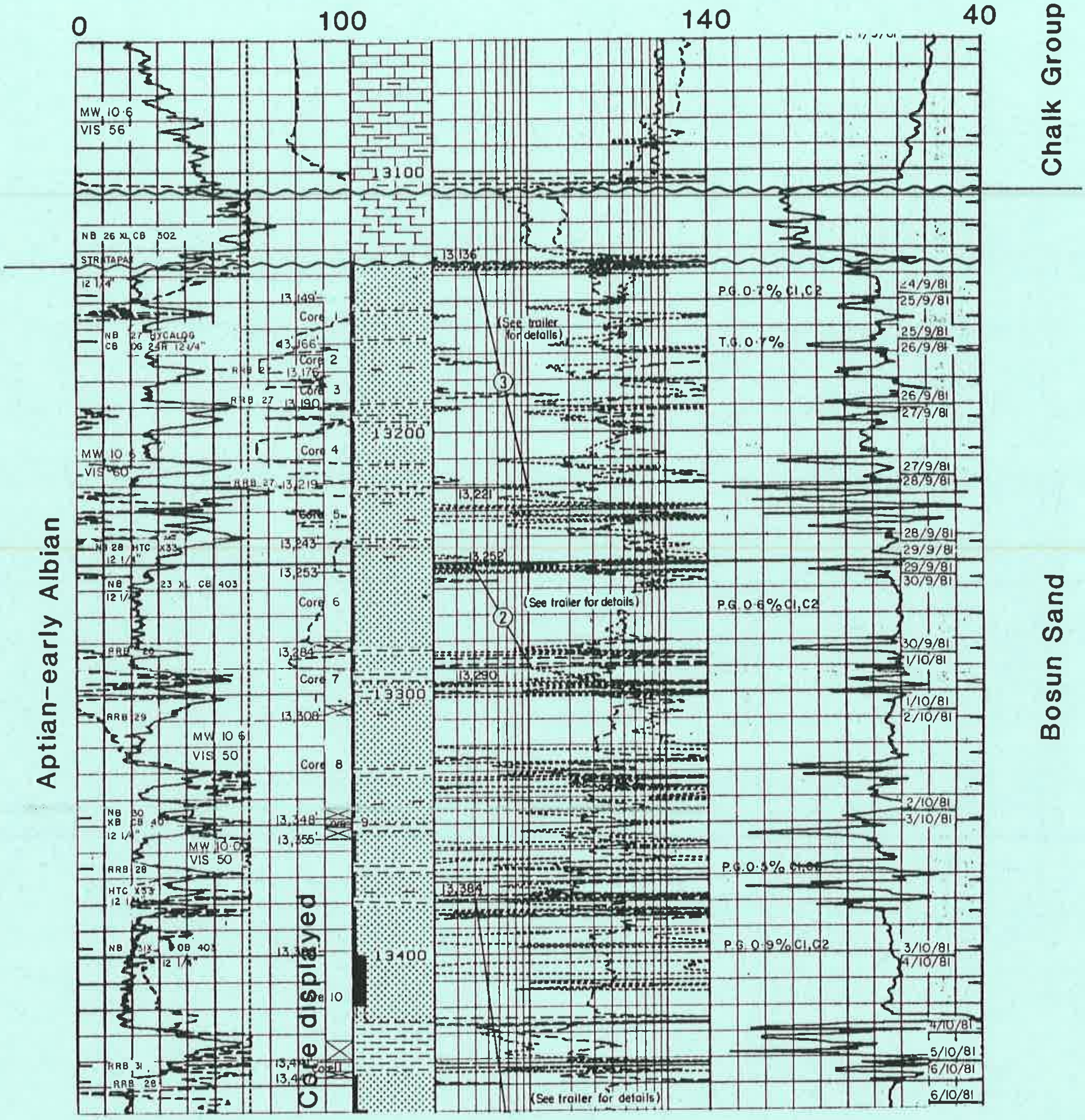
Depositional Environment

The overall depositional setting is of a submarine fan system. The basal unit sandstones are interpreted as having been deposited by a mud supported debris flow. The fluidized nature of these sandstones may reflect both their rapid deposition and a tectonically active environment. The sands of the upper unit are interpreted as having been deposited by turbidity and debris flow currents. The pebbly mudstone facies is thought to be the result of mud flows, with sand deposition triggering a rapid flow of sediment.

Reservoir Characteristics

The basal unit sandstones have porosities in the range of 2-11%, while the permeability is nowhere greater than 1mD. This reflects the poor sorting and high argillaceous content of these sandstones. The typical sandstones of the upper unit have porosities of 10-20% and permeabilities of 1 to 100mD.

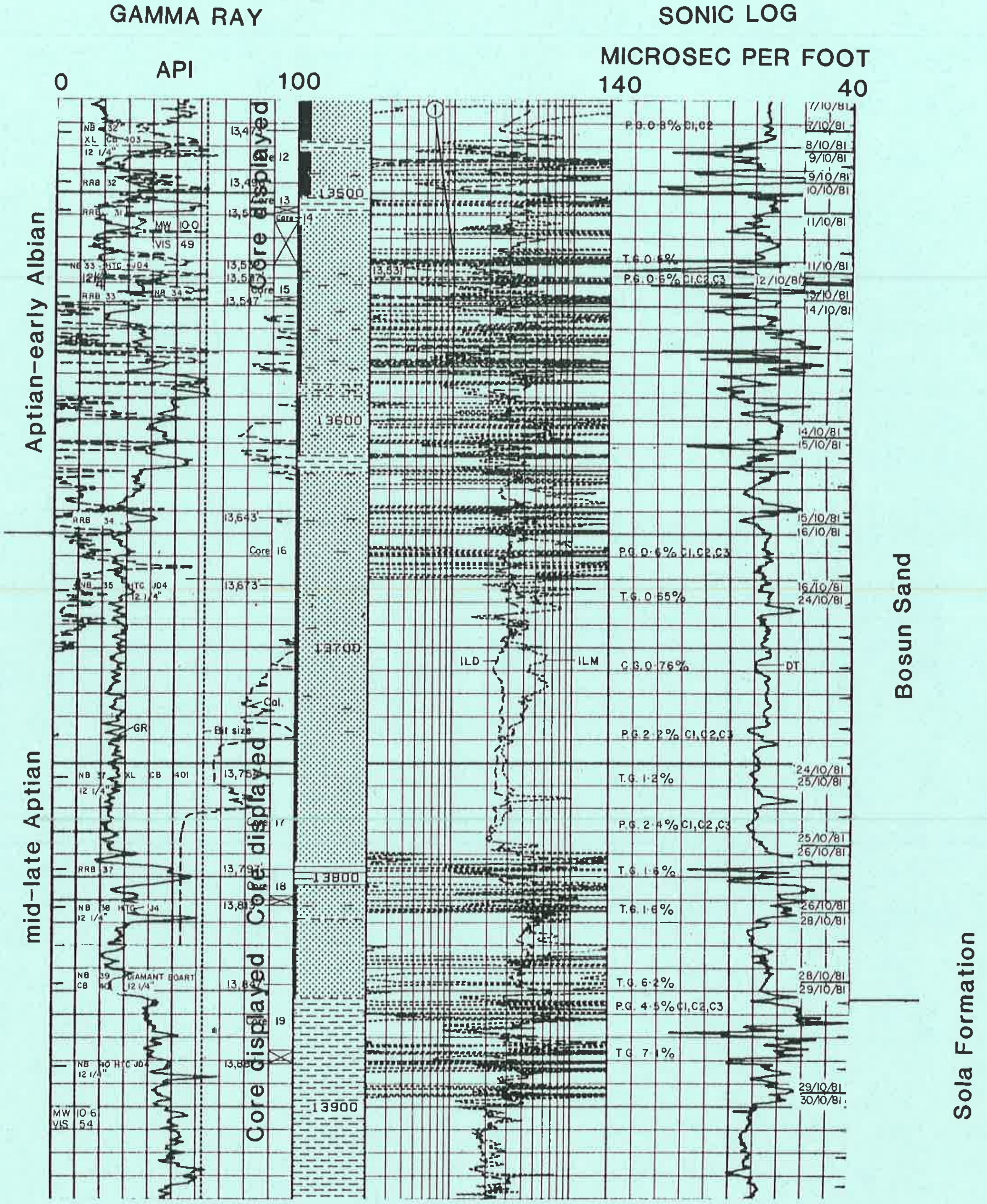
16/27-3 (PHILLIPS)



DEPTH SCALE: FEET

Fig. 8.6

16/27-3 (PHILLIPS)



DEPTH SCALE: FEET

Fig 8.6 (cont.)

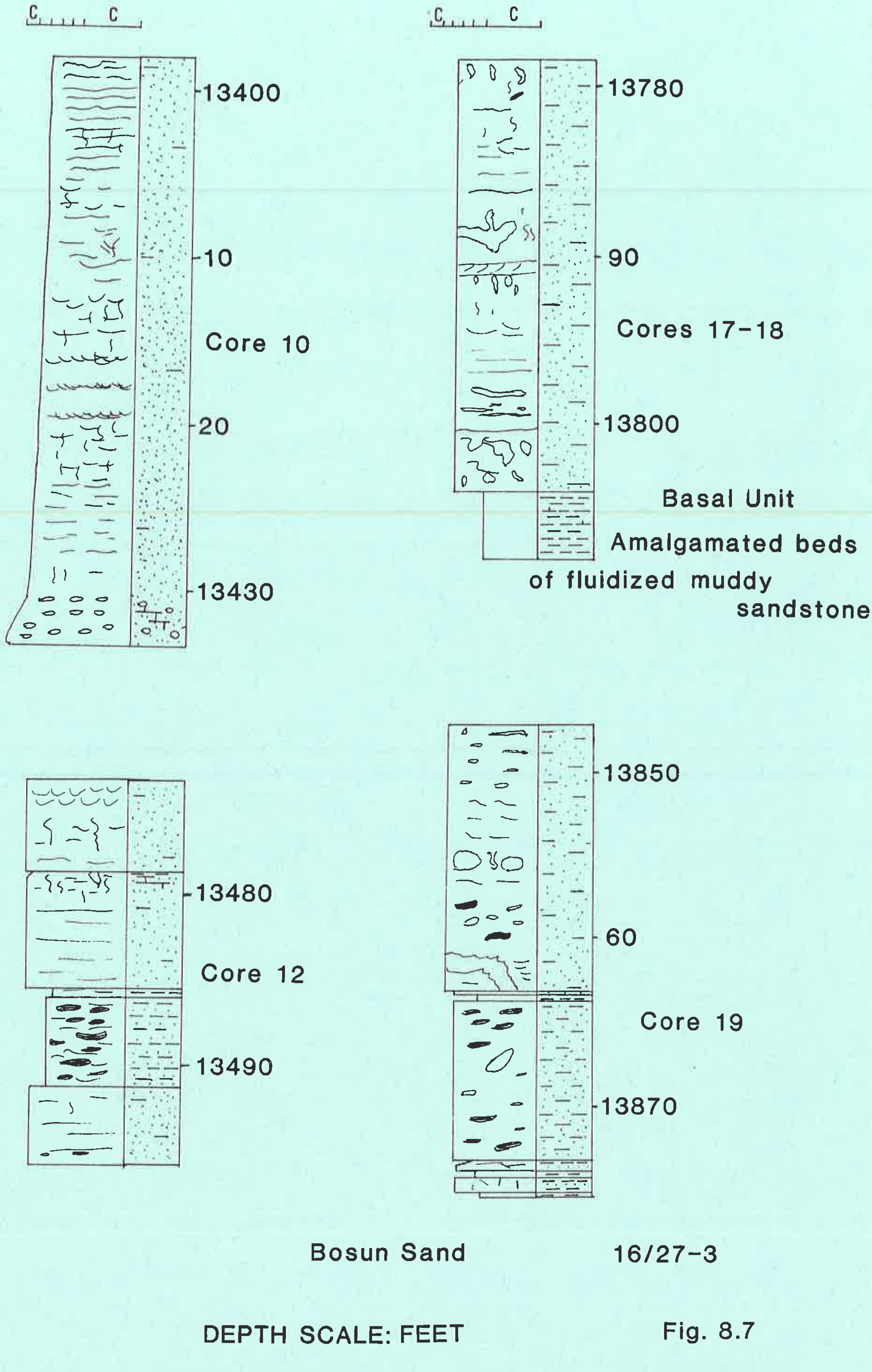

C C
13400
10
Core 10
20
13430
C C
13780
90
Cores 17-18
13800
Basal Unit
Amalgamated beds
of fluidized muddy
sandstone
13480
Core 12
13490
13850
60
Core 19
13870
Bosun Sand
16/27-3
DEPTH SCALE: FEET

Fig. 8.7

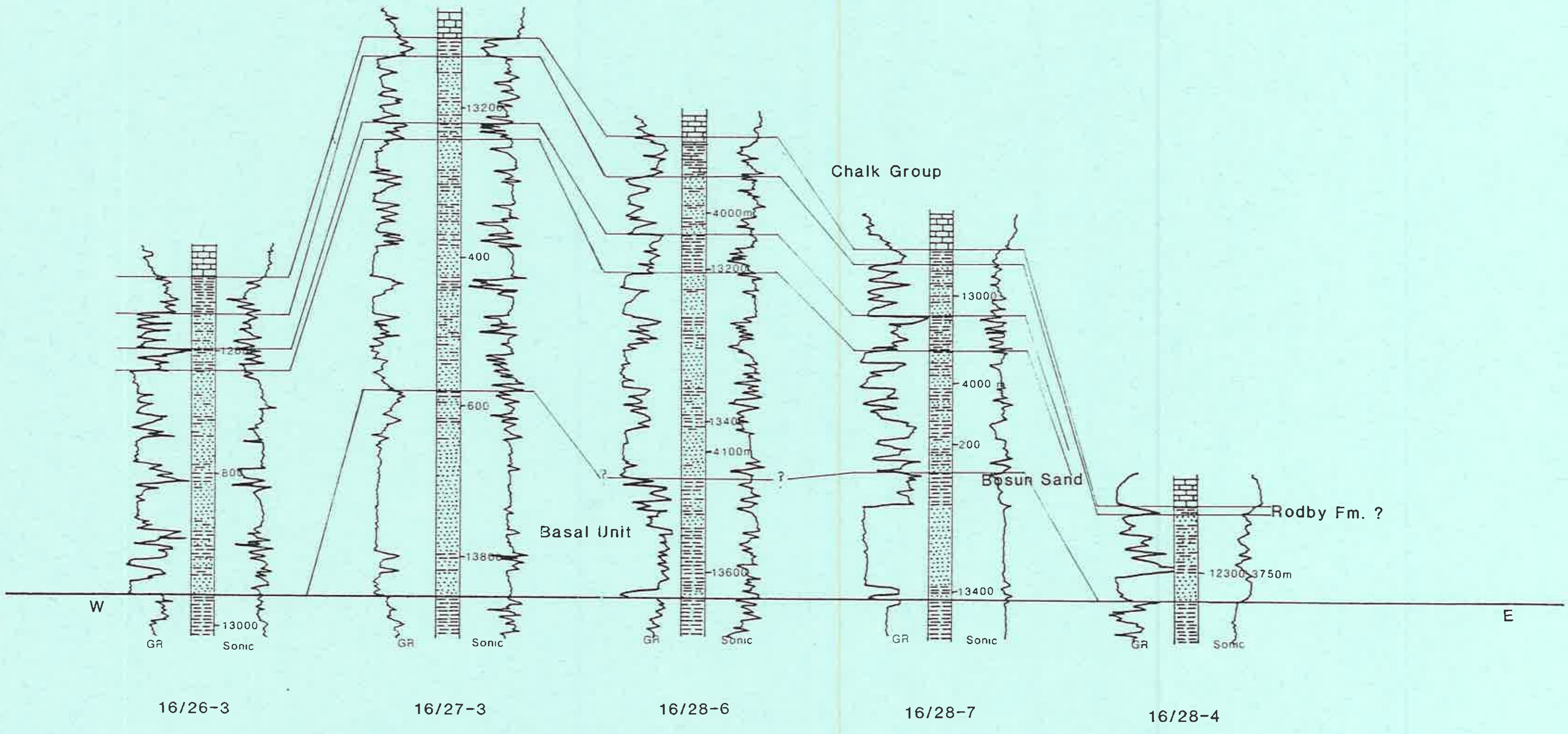


Fig. 8.8 Bosun Sand correlation diagram

Figures 8.9 and 8.10 Composite and Core logs for the Aptian/Albian Sand (Lower Cretaceous) of well 21/2-6 (Zapata)

Regional Setting

21/2-6 is located south of the Renee Ridge. The well is drilled through part of an Aptian/Albian sand sequence which is essentially restricted to block 21/2, just north of the Glen Horst.

Well Stratigraphy

The well does not penetrate beneath the Barremian. The Aptian/Albian sandstone body totals 373ft in thickness and is overlain by 350ft of Albian aged claystone.

The sandstones are divided by a predominantly argillaceous unit. The sandstones are quartzitic, poorly sorted but clean, fine to coarse grained, with small shale clasts. They are structureless to poorly laminated with rare water escape structures.

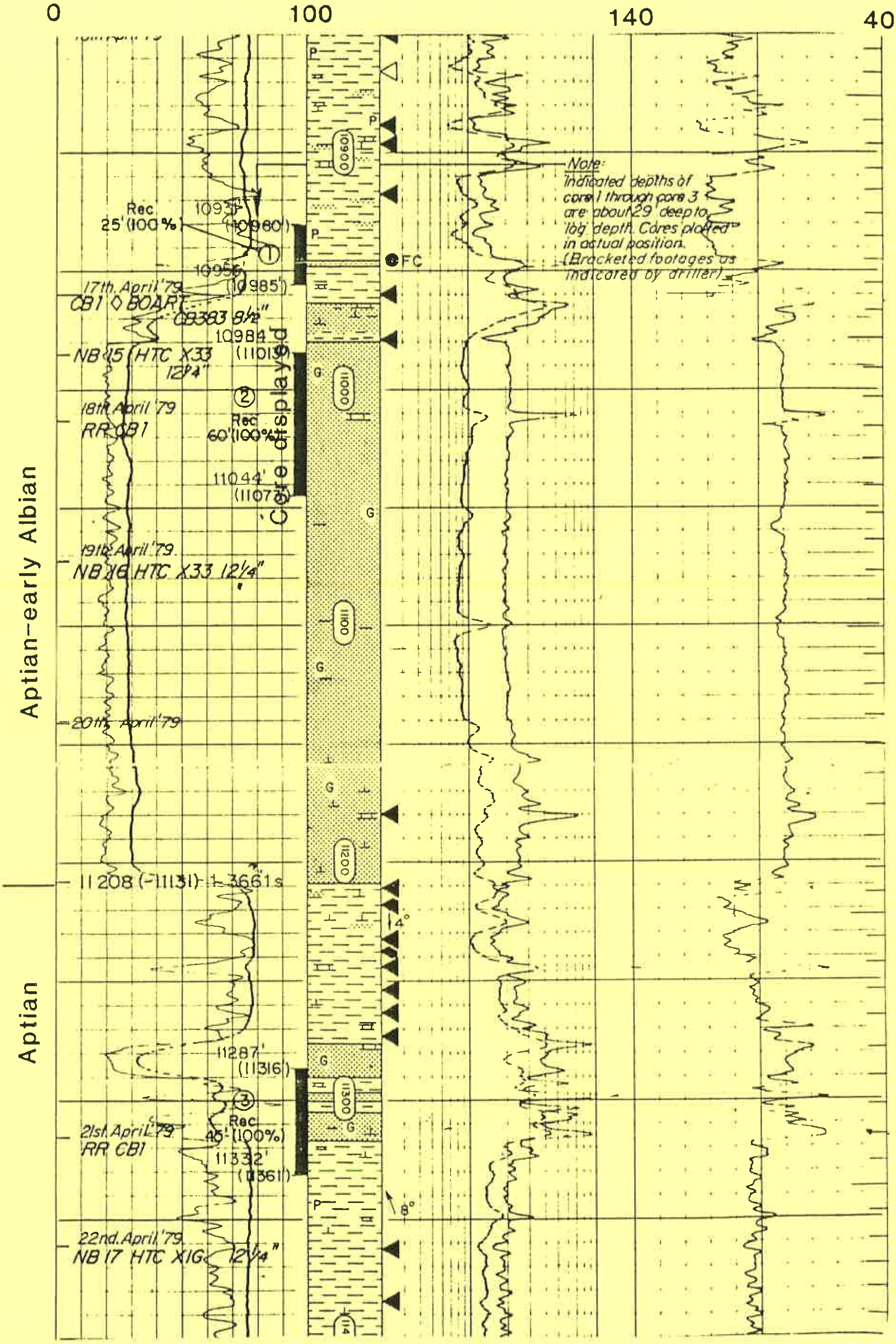
Depositional Environment

The sandstones are believed to be of mass flow origin possibly turbiditic or debris flows, deposited in a submarine environment.

Reservoir Characteristics

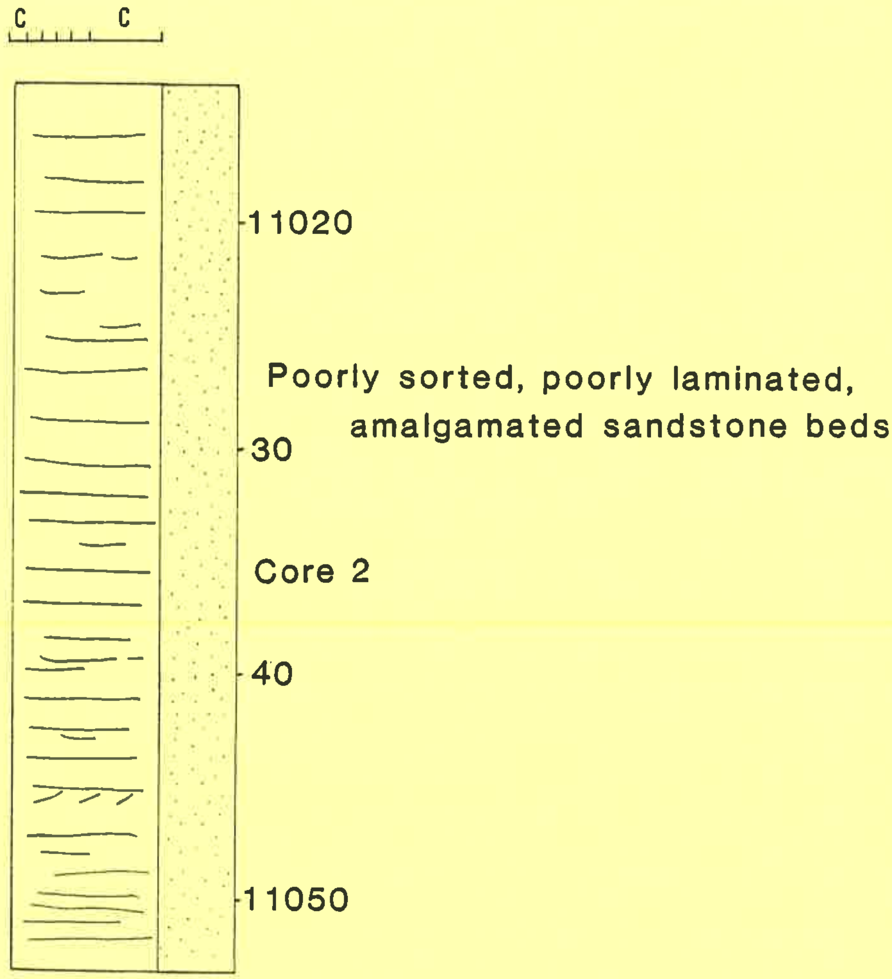
The sandstones have good to moderate visible, intergranular porosity. Where calcite cemented the sands are tight.

21/2-6 (ZAPATA)



DEPTH SCALE: FEET

Fig. 8.9



Aptian/Albian Sand

21/2-6

Fig. 8.10

9. REFERENCES

Amiri-Garroussi, K. and Taylor, J.C.M. 1987. Complex diagenesis in Zechstein dolomites of the Ettrick Oil Field. *In*: Brooks, J. and Glennie, K.W. (eds) *Petroleum Geology of North West Europe*. Graham and Trotman. pp. 577-589.

Andrews, I.J. and Brown, S. 1987. Stratigraphic evolution of the Jurassic, Moray Firth. *In*: Brooks, J. and Glennie, K.W. (eds) *Petroleum Geology of North West Europe*. Graham and Trotman. pp. 785-795.

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

Barr, D. 1985. 3-D Palinspastic restoration of normal faults in the Inner Moray Firth: implications for extensional basin development. *Earth and Planetary Science Letters* 75, 191-203.

Boote, D.R.D. and Gustav, S.H. 1987. Evolving depositional systems within an active rift, Witch Ground Graben, North Sea. *In*: Brooks, J. and Glennie, K.W. (eds) *Petroleum Geology of North West Europe*. Graham and Trotman. pp. 819-833.

Brennand, T.P. 1975. The Triassic of the North Sea. *In*: Woodland, A.W. (ed) *Petroleum and the continental shelf of North-west Europe*. Vol 1 (Geology). Applied Science Publishers, London. pp. 295-311.

Christie, P.A.F. and Sclater, J.G. 1980. An extensional origin for the Buchan and Witchground Graben in the North Sea. *Nature* 283, 729-732.

Clark, D.N. 1986. The distribution of porosity in Zechstein carbonates. *In*: Brooks, J., Goff, J.C. and van Hoorn, B. (eds) *Habitat of Palaeozoic Gas in N.W. Europe*. Special Publication of the Geological Society, London No. 23, 121-149.

Clemmensen, L.B. 1987. Complex star dunes and associated aeolian bedforms, Hopeman Sandstone (Permo-Triassic), Moray Firth Basin, Scotland. *In*: Frostick, L.E. and Reid, I. (eds) *Desert Sediments: Ancient and Modern*. Special Publication of the Geological Society, London. No. 35, 213-231.

Deegan, C.E. and Scull, B.J. (compilers) 1977. A standard lithostratigraphic nomenclature for the central and northern North Sea. *Institute of Geological Sciences Report* 77/25; Norwegian Petroleum Directorate Bulletin 1.

Dewey, J.F. 1982. Plate tectonics and the evolution of the British Isles. *Journal of the Geological Society of London* 139, 371-412.

Donato, J.A. and Tully, M.C. 1981. A regional interpretation of North Sea gravity data. *In*: Illing, L.V. and Hobson, G.D. (eds) *Petroleum Geology of the Continental Shelf of North-West Europe*, pp. 65-75.

Eynon, G. 1981. Basin development and sedimentation in the Middle Jurassic of the northern North Sea. *In*: Illing, L.V. and Hobson, G.D. (eds) *Petroleum Geology of the Continental Shelf of North-West Europe*, pp. 196-204.

Frostick, L., Reid, I., Jarvis, J. and Eardley, H. 1988. Triassic sediments of the Inner Moray Firth, Scotland: early rift deposits. *Journal of the Geological Society, London* 145, 235-248.

Glennie, K.W. (ed) 1986. Introduction to the Petroleum Geology of the North Sea. Second edition. Blackwell, Oxford.

Glennie, K.W. and Buller, A.T. 1983. The Permian Weissliegend of NW Europe: the partial deformation of aeolian dune sands caused by the Zechstein transgression. *Sedimenatry Geology* 35, 43-81.

Halliday, A.N., McAlpine, A. and Mitchell, J.G. 1977. The age of the Hoy Lavas, Orkney. *Scottish Journal of Geology* 13, 43-52.

Harker, S.D., Gustav, S.H. and Riley, L.A. 1987. Triassic to Cenomanian stratigraphy of the Witch Ground Graben. *In*: Brooks, J. and Glennie, K.W. (eds) *Petroleum Geology of North West Europe.* Graham and Trotman. pp. 809-818.

Hesjedal, A. and Hamar, G.P. 1983. Lower Cretaceous stratigraphy and tectoncs of the south-southeastern Norwegian offshore. *In*:

Kaasschieter, J.P.H. and Reijers, T.J.A. (eds) *Petroleum geology of the southeastern North Sea and the adjacent onshore areas.* Geologie en Mijnbouw, special edition, 62, 135-144.

Hill, P.J. and Smith, G. 1979. Geological aspects of the drilling of Buchan Field. Offshore Europe 79 Conference, *Society of Petroleum Engineers*, 8153.1-8153.7.

Howitt, F., Aston, E.R. and Jacque, M. 1975. The occurrence of Jurassic volcanics in the North Sea. *In*: Woodland, A.W. (ed) *Petroleum and the continental shelf of North-west Europe.* Vol 1 (Geology). Applied Science Publishers, London. pp.

Jakobsson, K.H., Hamar, G.P., Ormaasen, D.E. and Skarpnes, O. 1980. Triassic facies in the North Sea north of the central highs. *In*: Hardman, R.F.P. (ed) *The sedimentation of the North Sea reservoir rocks.* Norwegian Petroleum Society Conference, Geilo.

Kaldi, J. 1980. The origin of nodular structures in the Lower Megnesian Limestone (Permian) of Yorkshire, England. *Contributions to Sedimentology* 9, 45-60.

Kent, P. 1982. In discussion of Ziegler, P.A. 1982. Faulting and graben formation in western and central Europe. *Philosophical Transactions of the Royal Society of London* 305A, *143.*

Leeder, M.R. 1982. Upper Palaeozoic basins of the British Isles - Caledonian inheritance versus Hercynian plate margin processes. *Journal of the Geological Society of London* 139, 497-491.

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

McQuillin, R., Donato, J.A. and Tulstrup, J. 1982. Development of basins in the Inner Moray Firth and the North Sea by crustal extension and dextral displacement of the Great Glen Fault. *Earth and Planetary Science Letters* 60, 127-139.

Maher, C.E. 1980. Piper Oil Field. In: Halbouty, M.T. (ed) Giant Oil and

Gas Fields of the Decade 1968-1978. *American Association of Petroleum Geologists Memoir* 30, 131-172.

Maher, C.E. and Harker, S.D. 1987. Claymore Oil Field. *In*: Brooks, J. and Glennie, K.W. (eds) *Petroleum Geology of North West Europe.* Graham and Trotman. pp. 835-845.

Mykura, W. 1983. Old Red Sandstone. In: Craig, G.Y. (ed) *Geology of Scotland.* Scottish Academic Press. pp. 205-251.

Mykura, W. and Owens, B. 1983. The Old Red Sandstone of the Mealfuarvonie Outlier, west of Loch Ness, Inverness-shire. *Report of the Institute of Geological Sciences* 83/7.

Norton, M.G., McClay, K.R. and Way, N.A. 1987. Tectonic evolution of Devonian basins in northern Scotland and southern Norway. *Norsk Geologisk Tidsskrift* 67, 323-338.

Peacock, J.D., Berridge, N.G., Harris, A.L. and May, F. 1968. The Geology of the Elgin District. *Memoir of the Geological Survey, Scotland.*

Rawson, P.F. and Riley, L.A. 1982. Latest Jurassic - Early Cretaceous events and the "Late Cimmerian Unconformity" in the North Sea area. *American Association of Petroleum Geologists Bulletin* 66, 2628-2648.

Richards, P.C. 1985a. A Lower Old Red Sandstone lake in the offshore Orcadian Basin. *Scottish Journal of Geology* 21, 381-383.

Richards, P.C. 1985b. Upper Old Red Sandstone sedimentation in the Buchan Oilfield, North Sea. *Scottish Journal of Geology* 21, 227-237.

Richardson, J.B. 1964. Middle Old Red Sandstone spore assemlages from the Orcadian Basin, north east Scotland. *Palaeontology* 7, 559-605.

Ritchie, J.D., Swallow, J.L., Mitchell, J.G. and Morton, A.C. 1988. Jurassic ages from intrusives and extrusives within the Forties igneous province. *Scottish Journal of Geology* 24, 81-88.

Taylor, J.C.M. 1981. Zechstein facies and petroleum prospects in the central and northern North Sea. *In*: Illing, L.V. and Hobson, G.D. (eds) *Petroleum Geology of the Continental Shelf of North-West Europe*. pp. 176-185.

Threlfall, W.F. 1981. Structural framework of the central and northern North Sea. *In:* Illing, L.V. and Hobson, G.D. (eds) *Petroleum Geology of the Continental Shelf of North-West Europe*. pp. 98-103.

Turner, C.C., Richards, P.C., Swallow, J.L. and Grimshaw, S.P. 1984. Upper Jurassic stratigraphy and sedimentary facies in the central Outer Moray Firth Basin, North Sea. *Marine and Petroleum Geology* 1, 105-116.

Warrington, G. *et al.* 1980. A correlation of Triassic rocks in the British Isles. *Geological Society of London Special Report* No. 13.

Watson, J. 1985. Northern Scotland as an Atlantic-North Sea divide. *Journal of the Geological Society London* 142, 221-243.

Ziegler, P.A. 1982. Geological Atlas of Western and Central Europe. *Shell Int. Petrol. Maats. B.V.*, distributed by Elsevier, Amsterdam.