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THE NATURE OF THE BRENT DELTA, NORTH SEA : A CORE WORKSHOP

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1. INTRODUCTION

Since 1984 the Hydrocarbons Research Group of the British Geological Survey has run 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 BGS/D.En core store in Edinburgh. This workshop will provide the opportunity to examine the sediments of The Brent Group, the principal hydrocarbon reservoir in the northern North Sea. "Hands-on" examination of the core is encouraged, as is full discussion of the concepts and ideas presented at the workshop.

The sequences illustrated all lie within the East Shetland Basin (Fig 1). To the west lies the East Shetland Plataform, where Tertiary strata rest on Devonian or older rocks, and to the east lies the NNE-SSW trending trough of the Viking Graben with its thick Mesozoic-Tertiary fill. Both N-S and NE-SW faults cut the Jurassic in the East Shetland Basin. They are normal faults which bound a number of tilted blocks whose geometry has a crucial influence on the location of hydrocarbon traps.

The most pronounced growth on these faults occurred during the late Jurassic but there is evidence of limited synsedimentary movement accompanying Brent Group deposition. This is shown by broad thickness variations in individual formations but is also seen on a smaller scale by bed thickness changes between closely spaced wells in some producing fields (Hallet 1981).

The formally defined five-fold lithostratigraphic subdivision of the Brent Group proposed by Deegan and Scull (1977) is listed below and compared with the original descriptive scheme of Bowen (1975).

Deegan and Scull (1977)	Bowen (1975)	
Tarbert Formation	Upper Brent Sand Member	
Ness Formation	Middle Brent Sand Member	
Etive Formation		(Massive Sand
		(
Rannoch Formation	Lower Brent	(Micaceous Sand
	Sand Member	(
Broom Formation		(Basal Sand

The Brent Group is enclosed by the dark marine shales of the Dunlin Group (Lower Jurassic) below and of the Humber Group (mostly Middle-Upper Jurassic) above. The lower boundary appears to be generally conformable (but see Hay, 1978) whereas the nature of the upper is more variable in character, largely depending on structural position. An unconformity between Humber and Brent Group strata is especially common towards the crests of fault-bounded blocks. The Tarbert Formation is often removed completely from such locations.

The lithostratigraphic boundaries within the Brent Group are considered to be at least in part diachronous in the context of a prograding clastic wedge. However, the resolution of the presently available biostratigraphy, based largely on palynological studies, is too coarse to allow detailed analysis of age relationships. Indeed the Brent Group as a whole can at best only be assigned an Aalenian to Bajocian or earliest Bathonian age.

Most workers accept a hypothesis of Brent deltaic progradation from south to north down a palaeoslope orientated along the axis of the Mesozoic Viking Graben, but with sediment derivation ultimately from basement terrains to the west and east of the Viking Graben. Within this generally northwards prograding system a number of specific depositional environments can be differentiated, each correlatable with a lithostratigraphic subdivision of the group. Note however that there is only a partial concensus concerning the interpretation of depositional environment within the Brent Group (Brown _et al._ in press).

2. DATA SET FOR WORKSHOP

Approximately 2,500 feet of core, taken from all five of the Brent Group formations will be displayed at the workshop. The core is taken from 11 wells and represents sequences fairly typical of the Brent Group as a whole. These cores have been taken from a number of oilfields including N.W. Hutton, Thistle, Murchison, Lyell, N.W. Alwyn and Dunlin. Petrophysical logs and core logs through the displayed well sections are provided as text figures.

It is intended that the workshop be organised as a series of short talks introducing various aspects of Brent Group geology, each followed by a more informal core examination session. The sequence will be examined from the base upwards, and the depositional style and evolution of the delta through its progradational and retreat phases will be evaluated in detail.

3. THE BROOM FORMATION FAN DELTA

3.1 The Broom Formation is the basal unit the Brent Group and has been interpreted in a number of ways including offshore sheet sand, gravity flow deposit and beach sequence. It is a mostly coarse grained, poorly sorted and often bioturbated surbarkose. It forms an easterly tapering wedge away from the fault bounded margin of the East Shetland Basin and also thickens across certain intra basin faults (Fig. 2). This thickness pattern is markedly different to that observed in other Brent Group units and this, together with its generally unusual lithological character and the fact that it is separated from the rest of the Brent Group by low energy, marine offshore muds in places, suggests it is a genetically distinct depositional system from the remainder of the group.

Interpretation of the Broom depositional environment is aided by its locally intimate stratigraphic relationship with the better understood (overlying) Rannoch Formation. As will be shown later, Rannoch is a storm-dominated shoreface deposit that records the initial progradation of the Brent deltaic sequences into the East Shetland Basin. Rannoch usually overlies Broom but in places the two depositional systems interfered to produce interbedding. The nature of the Broom Formation (and its association with Rannoch) is described below from different parts of the basin.

3.2 The North Alwyn Area

In well 3/9-2 (Fig. 3) facies typical of the Broom Formation are interbedded with Rannoch-type hummocky cross stratified, cross laminated and parallel laminated silty sandstone (Plate 1). Broom in this area comprises medium to coarse grained, ripple laminated sandstones and sharp based, matrix supported pebbly sandstones with evidence of low angle laminae and convex up parting surfaces. This heterolithic sequence is interbedded with and passes up into typical Rannoch facies.

3.3 The Lyell area

In well 3/1-2 (Fig. 3) the Broom Formation comprises a lower unit of medium grained, wispy laminated sandstones and siltstones, and an upper unit of thinly interbedded, sharp-based, hummocky cross stratified sandstones and siltstones (Plate 2). It is overlain by fine grained sandstones with hummocky cross stratification which separate typical Broom facies from very fine grained micaceous sands typical of Rannoch.

3.4 The NW Hutton area

Well 211/27-4a is an example of a complete sequence through the Broom Formation near the centre of the basin (Fig. 4). The basal boundary with the underlying Dunlin Group is transitional, with some interbedding of Dunlin - type siltstone and sandy mustone to muddy sandstone with floating sand grains and granules in bands, lenses and pods (Plate 3). Transitionally overlying these basal beds is a sequence dominated by fine to medium sandstones with scattered coarse grains and vague, planar cross bedding in sets 3 to 4 feet thick. The top of the formation in this well is dominated by interbeds of the previous lithologies plus a heterolithic development of micaceous siltstone to very fine sandstone with lenses and bands of dark mudstone (Plate 4). This heterolithic sequence defines an interbedded Broom Formation/Rannoch Formation transition zone.

3.5 Dunlin area

Well 211/24-2 in the Dunlin oilfield area displays a typical sequence at the feather-edge of the Broom depositional system. Broom is very thin in this area (Fig. 2) and consists of coarse, oolitic sandstones and thin laminae and pods of coarse sandstone (Plate 5). It occurs at the transition between the offshore silty mudstones of the Dunlin Group and the fissile, micaceous siltstones of the lower part of Rannoch (pro-delta deposits developed in front of the northwards prograding Brent delta system).

3.6 Interpretation

Only a preliminary interpretation of the Broom Formation is offered because the sequence is the subject of present research by the authors and J M Dean (also of the Hydrocarbon Group). The Broom Formation prograded across the East Sheltand Basin from the west, probably as a fan delta system. At least around the periphery of the easterly tapering wedge, deposition was influenced by storm waves in a shallow marine environment. By association, the interbedding of Broom facies with shoreface storm deposits of the northwards prograding Rannoch Formation (basal Brent delta progradation) in the Alwyn area indicates Broom deposition locally in a shoreface environment. The character of the Broom Formation in the Lyelll area suggest storm reworking of the Broom sands.

The occurrence of thin Broom sands in the low energy mud deposits in the Dunlin oilfield area can be explained by storm or rip-current transport of the coarser sediment into the offshore area. Because of the progressive northwards progradation of the delta, Broom is associated with finer grained, more distal, pro-delta sediments in the north than in the south of the basin (Richards et al 1987).

4. PROGRADING BARRIER COAST - THE RANNOCH AND ETIVE FORMATIONS

4.1 Six cored sequences are displayed through the marine progradational part of the deltaic system. Within these six cores a range of environments can be discerned, from offshore areas influenced by intermittent storms, through storm dominated shoreface sequences up to a barrier complex cut by (?)tidal channels. Each of the six wells is described below and the significance of the sequence recorded at each site is discussed.

An isopach map of this marine progradational phase of the Brent delta (Fig. 5) shows that the sequence thickens considerably northwards, with a marked NW-SE trending thick accummulation in the north east of the basin.

4.2. Wells 211/27-10 and 211/27-4a

These two wells illustrate two facets of the prograding barrier coast: (a) the nature of shoreface to offshore construction where delta progradation occurred as a single phase; (b) the nature of the barrier bar deposits and erosion of the barrier by a (?) tidal inlet channel.

4.2.1 Shoreface to offshore sequence

Four major facies are recognised in the shoreface to offshore sequence in these two wells.

4.2.2 Facies 1: heterolithic beds.

This association of interbedded sandstones, siltstones and claystones is restricted to the base of the Rannoch Formation (Fig. 6). Its main component is a micaceous, dark grey, argillaceous siltstone with well developed, even, parallel lamination emphasised by mica alignment. Low angle scours locally truncate this fabric. These scours are filled by laminated siltstones whose laminae are concordant with the erosion surfaces. Biogenic reworking is common. Usually bioturbation produces a locally chaotic framework making the identification of individual forms difficult. However, examples of *Planolites* and ?*Phycodes* burrows can be recognised.

Other minor lithological components of this facies occur in beds less than 15 cm thick and include less micaceous siltstone with wavy clay laminae, dark grey silty claystones and very fine micaceous sandstones. The sandstones resemble those of facies 2, especially in their distinctive parallel lamination. In one sandstone bed the laminae pass up into symmetrical ripples.

The base of the facies is rapidly gradational with the underlying medium to coarse grained, muddy sandstones of the Broom Formation. Thinly developed in the NW Hutton area, these basal Rannoch Formation argillaceous beds become thicker in the north of the East Shetland Basin.

4.2.3. Facies 2: laminated and hummocky cross stratified micaceous sandstone

This facies is pale grey to buff coloured, very fine to fine grained micaceous subarkose with distinctive bipartite lamination. The lamination is produced by alternating layers of clean sand and micaceous, carbonaceous sand on a scale of 2-3 mm.

Laminae are even and parallel or in low angle (less than 10°) wedge-shaped cross laminated sets. In the cross-sets laminae parallel subjacent truncation surfaces with no evidence of downlapping foresets. Occasionally the laminae are slightly divergent within one set, some are convex-up (Plate 6) and in places laminae fill low angle, smooth-bottomed scours or 'swales' concordantly. Laminae occasionally show thinning and fining upward trends in packages a few laminae thick. In some places laminae become undulose upward, sometimes grading into symmetrical wave ripples.

Individual beds generally have sharp boundaries and beds are often stacked or amalgamated ranging in thickness from 0.2 to 1.37 m. Where amalgamation has not occurred and more complete sedimentation units are developed and preserved, the tops of beds are rippled or more frequently, bioturbated (Plate 7). Bioturbation often partially or completely destroys rippled horizons. Many burrow forms can be recognised, including *Planolites*, *Scoyenia*, *Teichichnus*, *Terebellina*, *Tigillites* and *Skolithos*. These bioturbated horizons are often truncated by younger laminated beds or by beds of facies 3 or 4.

4.2.4 Facies 3: indistinctly laminated micaceous sandstone

Visually distinct from facies 2 but often grading into it, this facies is also a very fine to fine grained micaceous subarkose. It is characterised by a lower concentration of micas along laminations, producing much less of a banded appearance than facies 2. The indistinct laminations define structures similar to those in facies 2, including even, parallel lamination and wedge-shaped cross-lamination. Boundaries with both facies 2 and 4 range from gradational to erosive. The facies represents a lithological and also a likely genetic transition between facies 2 and 4. Burrow structures are rare, but Scoyenia and Planolites have been identified.

4.2.5 Facies 4: structureless sandstone

This facies is lithologically similar to facies 2 and 3 but generally lacks a micaceous laminar fabric. Micas are dispersed throughout the sediment, but rare examples of isolated mica-rich laminations are observed. Burrow structures are similar to those in facies 3. The structureless nature of this facies is probably a primary depositional feature rather than the result of secondary destructuring by bioturbation or water escape, because of the presence of undeformed, micaceous laminae in places. The facies grades into facies 3 and is sometimes difficult to distinguish from it.

4.2.6 Facies relationships

Facies 1 consistently occurs only at the base of the Rannoch Formation. The other three facies are intimately interbedded, but with facies 2 tending to occur predominantly in the lower part of the formation and facies 3 and 4 in the upper part. Facies 2 is dominant in well 211/27-4a but the uppermost beds of the formation have probably been removed by erosion in this well.

4.2.7 Interpretation

These 4 facies form part of an overall upward coarsening sequence. The heterolithic, muddy unit at the base passes up through the micaceous sandstones, up to the barrier top deposits of the overlying formation. The key to the interpretation of this offshore to shoreface sequence is facies 2, which displays many features consistent with hummocky cross - stratification (Richards and Brown 1986). These features include: wedge shaped cross laminations; fanning laminations; convex-up laminations; thinning and fining upwards laminae packages; concordant drape over scours; abundance of mica and plant remains along laminations; random dip orientation of laminae; bioturbation at top of beds; ?wave rippling at tops of beds; erosive bases and amalgamated beds.

HCS is now commonly considered to be formed by storm waves in a lower shoreface environment below fair weather wave base (eg Dott and Bourgeois 1982; Tunbridge 1983). The storm waves remove sediment from near the top of the shoreface and re-deposit it seaward out of sediment-laden suspension clouds under conditions of intense oscillatory shear (eg Kumar and Sanders 1976).

As the oscillatory shear forces wane towards the end of the storm event symmetrical oscillation ripples form on the tops of beds. This type of rippled top to beds is relatively infrequent in facies 2 because the tops of most beds are eroded and amalgamated with younger beds. Ripples may also have formed in places but been destroyed by subsequent bioturbation (cf. Hamblyn et al. 1979). Ripples may also have been unable to form at some horizons because high levels of mica in the sediment inhibits the formation of avalanche faces (Collinson and Thompson 1982). The presence of bioturbated tops to some beds suggests that there were periods of "fair weather" colonisation between at least some of the storm events, indicating that energy levels were not constant (cf. Tunbridge 1983). Amalgamation of many beds in facies 2 possibly suggests that the storms were frequent (cf. Duke 1985) and therfore fair weather periods may have been relatively short.

Since facies 1, 3 and 4 occur in close vertical proximity to facies 2 storm sands, often with gradational boundaries, all are considered to have formed in closely related environments on a storm-influenced coast.

Facies 1 at the base of the sequence is very similar in lithology and primary sedimentary structure to upper offshore sediments described elsewhere from storm dominated shelf sequences (eg Brenchley and Newell 1982; McCubbin 1983; Tunbridge 1983). The thin, laminated sandstones recorded within facies 1 are similar to those in facies 2 and probably represent distal equivalents of the facies 2 (shoreface) deposits carried into the offshore zone by the more severe storms.

Facies 3 and 4 are more difficult to interpret because they exhibit few sedimentary structures directly visible in cores. That they form a continuum of process with facies 2 is demonstrated by the gradational nature of many of the boundaries between the three facies. The lower frequency of laminations in facies 3 and 4 than in facies 2 possibly suggest deposition under conditions of less effective oscillatory shear. That is, the two facies may represent lower energy or less severe storm conditions than facies 2 deposits. Brenchley and Newell (1982) described similarly structured sediments associated with classical HCS, and attributed their origin to lower energy storms. Facies 3 and 4 predominantly occur above facies 2, probably in an upper shoreface setting.

4.2.8 Barrier and tidal inlet sequences.

In wells 211/27-4a and 10 markedly different facies are preserved above the hummocky cross stratified shoreface deposits. The sequence in well 10 is more typical of this sequence as a whole. The base of the inferred barrier sequence in well 10 is erosively sharp on top of the shoreface deposits and, at it's top is bioturbated and then rooted, and overlain directly by coal, suggesting possibly an element of subaerial deposition, at least towards the top. Although grain size variations within this presumed barrier sequence are difficult to observe in hand specimen, detailed laboratory grain size analysis reveals that the sequence coarsens upwards, a feature mimicked by the gamma ray log profile (Fig. 6).

By contrast, a barrier sequence is difficult to differentiate in well 4A (Fig. 6), making the sequence rather anomalous. In this well the hummocky cross stratified shoreface sequence is overlain erosively by fine sandstone with steeply inclined muddy laminations and succeeded in turn by a fine sandstone with abundant scattered dark mud clasts and then by a sandstone-mudstone interbedded sequence (Plate 8) in which the beds have a marginal marine signature based on palynofacies analysis. One interpretation of the inclined mud layers in this sequence is that they are mud drapes on foresets of a tidally influenced migrating sand body in an area where the prograding barrier was breached. Alternatively the steep mud layers may represent rotational slump blocks derived from the margins of a barrier breaching distributary or tidal channel. The overlying sandstone with clasts suggests either fragmental bank collapse or rip-up of mud clasts from the lagoonal sequence developed behind the protective barrier (Brown et al. in prep.).

4.3 Wells 211/19-4, 211/18-22 and 211/18-21

These three wells lie near the northern margin of the system and illustrate aspects of barrier coast progradation not preserved in wells to the south (Brown and Richards 1987).

These wells lie near the northern limit of Brent delta progradation and in the area of maximum thickness of the Rannoch-Etive sequence (Fig. 5). The interbedded sandstones, shales and coals of the Ness Formation thin out here, with the consequent increase in sand-shale ratio in the reservoir section and improved vertical continuity of reservoir sand.

The Rannoch Formation, resting on a thin distal development of the Broom Formation which in well 211/19-4 (Fig. 7) is an oolitic sandstone, consists of lenticular bedded, burrowed, silty mudstone grading up to laminated and hummocky cross-stratified micaceous sandstone (see also well 211/18-22, Fig. 8 and 211/18-21, Fig. 9). This sequence, interpreted as a prograding, offshore to shoreface succession, is broadly comparable to the Rannoch Formation further south in, for example, the NW Hutton area. In the northern wells the basal argillaceous sub-unit is thicker and finer grained towards its base.

The Rannoch sandstones are again interpreted as high-energy, storm-dominated deposits, with an alternation of laminated and bioturbated deposits near the base of the sand sequence recording alternating storm and fairweather processes. In the overlying Rannoch Formation sandstones there are no good examples of medium scale, angle of repose cross-stratification. There is therefore a distinct dearth of physical sedimentary structures recording fairweather shoreface processes; it remains difficult to identify an upper shoreface deposit.

The overlying quartz-dominant, mica-poor sandstones, with stacked upward-fining grain size profiles are assigned to the Etive Formation. They have been interpreted as distributary channel sandstones in the Murchison Field (UK Block 211/19) by Parry et al. (1981). The sands here are fairly well sorted, medium to very fine grained, and have at best an indistinct sub-horizontal to gently inclined lamination. These parameters make a distributary channel-fill hypothesis less than wholly conclusive although clearly reasonable given the local setting. The channel sandstones rest directly on high energy shoreface deposits.

In well 211/18-22 (Fig. 8) parallel laminated micaceous sandstone, similar to Rannoch Formation sandstone, occurs within a stacked upward-fining sandstone succession. A first hypothesis suggests deposition following the landward shift of a wave-dominated shoreface environment during a period of temporary transgression.

The succession above the stacked channel sands is variable in this northern portion of the Brent delta. In 211/19-4 a sequence of interbedded delta plain deposits is present which record, in addition to distributary channel fills, overbank processes and wave-reworking of lagoons/bays. In 211/18-22 (Fig. 8) this is only represented by very thin beds of fine sediment between channel sands.

Comparison of gamma-ray logs shows that the stacked channel sands in 211/19-4 have a less ratty character than the stacked channel sands in 211/18-22. This results from the presence of thin overbank/abandonment deposits between the sands in 211/18-22 as well as the presence of rather micaceous laminae within the usually indistinct stratification of the 211/18-22 succession. In contrast, a sequence of exclusively channel sand with an even gamma-ray log response occurs in 211/18-21 (Fig. 9).

In every case the uppermost unit of the Brent Group is a transgressive sandstone sequence. This contains facies comparable again to the sandstones of the Rannoch Formation. It is suggested that the transgressive sandstones represent a return to wave-dominated shoreface conditions following coastline retreat.

4.4 Well 3/1-2

This well (Fig. 10) illustrates an aspect of the Rannoch Formation shoreface sequence not seen in the other wells exhibited. In this well the shoreface sequence above the Broom fan delta deposit consists of two distinct units: a lower, fine grained, vaguely structured division; and an upper division more akin to typical Rannoch sediments as observed elsewhere in the basin. Whilst it is generally coarser and less well structured than typical Rannock Formation facies, the lower unit contains similar types of sedimentary structures to the overlying more typical unit, and HCS has been recorded at one level.

At the base of the upper part of the sequence a number of thin units of laminated sand passing up to bioturbated silty sand can be seen. These repetitive sequences record evidence of a number of storm plus fair weather couplets and are overlain by amalgamated beds of silty sandstone displaying evidence of hummocky cross stratification.

5. BACK BARRIER AND DELTA PLAIN - THE NESS FORMATION

5.1 These deposits are illustrated by means of well 211/27-10 from the N W Hutton field (Fig. 11). Back barrier deposits throughout the UK East Shetland Basin (Fig. 12) consist in varying proportions of interbedded sandstones, siltstones, mudstones and coals, with both upward-coarsening and upward-fining grain size trends and, among the mudstones, massive beds with rootlets and heterolithic beds with silt to very fine sand streaks and small lenses. Ripple cross-laminated lenses in the heterolithic facies record both unidirectional flow and, commonly, wave reworking. Occasional gutter casts are found and interpreted as storm scours (cf. Kreisa 1981).

A prominent argillaceous unit (Mid Ness Shale) up to 18 m (60 ft) thick has been correlated over an area of 2,100 km^2 (Eynon 1981; Budding and Inglin 1981) and is interpreted as a lagoonal deposit. Palynofacies evidence indicates that salinity varied within this lagoon and sedimentary structures show that at times the bottom was influenced by waves. The thick argillaceous sequence 24.5 m (80 ft) above the base of the Ness Formation in 211/27-10 is probably this laterally extensive unit. With northwards progradation of a conformable Rannoch to Ness sequence, the Mid Ness Shale should appear lower in the Ness Formation succession towards the north.

6. TRANSGRESSIVE DEPOSITS - THE TARBERT FORMATION

6.1 Transgressive sandstones overlie the progradational deltaic sediments in many places in the basin and locally form important hydrocarbon reservoirs. Core sequences through these transgressive sediments are presented in order to document some of the vertical and lateral variation within the transgressive system.

Most of the transgressive sequences are composed of vertically stacked, upwards fining units with sharp, erosive bases overlain by thin beds of coarse sand or granule grade material. These erosion surfaces overlain by coarse lag deposits are found both at the bottom of the transgressive sequence and also within it (eg. well 3/9-2, Fig. 13) and are interpreted as shoreface erosion or ravinement surfaces. The basal one in each sequence represents the initial migration of the transgressive shoreface across the area as rate of sea-level rise outpaced the rate of local sediment accumulation. Ravinement surfaces above the basal one are attributed to repeated shoreface erosion during successive transgressive events between regressive depositional phases.

In many places the basal shoreface erosion unit directly overlies blocky siltstones with rootlets, deposited in a terrestrial environment (well 3/2-2, Fig. 13) and the coarse lag deposit therefore represents the first indication of marine transgression of the area. However, it is also possible to detect evidence of a brackish transgression in places. For example, in well 211/27-10 bioturbated, lenticular bedded mudstone with marine palynomorphs succeeds an in situ coal and is in turn succeeded by coarse sand (Fig. 11).

In the southern part of the basin, beyond the limits of progradation of "delta top" sediments, transgressive sands rest directly on barrier bar sediments of the underlying marine progradational phase eg well 211/18-21 (Fig. 9). In this well as in many others, the transgressive sands display many features identical to those in the progradational shoreface sequence below and examples of hummocky cross stratification and storm/fair weather couplets are common.

7. CONCLUSIONS

The lithological character, distribution, thickness patterns and the presence of a low energy, marine mud separating it from the deltaic sediments of the Brent Group proper suggest that the Broom Formation is a genetically distinct depositional system from the remainder of the Brent Group. There is, however, some interference between the two depositional systems, as recorded in well 3/9-2 where the two sequences interbed and presumably shared similar depositional processes dominated by storm sedimentation.

Progradation within the regressive phase of Brent Group deposition occurred by migration of a storm-influenced barrier coast towards the north-east. Marine mudstones at the base of the regressive sequence thicken to the north-east and coastal plain sediments thin and are eventually lost in this direction.

Sequences through the NW-SE trending locus of maximum marine progradational thickness in the north-east lie close to the limit of progradation where the balance between sediment supply and the background rise in eustatic sea-level during the early-mid-Jurassic (Hallam 1983) lead to the available "space" created by subsidence being filled by nearshore deposits marking a halt to significant progradation.

The prograding sequence can be interpreted as a storm-wave dominated delta with barrier protected coastal plain lagoons of varying salinity, distributary channels feeding minor mouth bars, and vegetated flats. A widespread mud basin developed for a time (Mid Ness Shale environment) with sand supply diverted elsewhere.

First signs of transgression, when presumably eustatic rise finally overtook the regression driven largely by sediment supply, can locally be seen in the "delta-top" succession (brackish transgression). Multiple pulses of transgression and accompanying shoreface erosion are recorded in the Tarbert Formation.

The Brent Group deltaic sediments in the UK sector of the northern North Sea form part of a much wider paralic development. Wave-dominated in the classification of Galloway (1975) but with the record of submarine deltaic sedimentation dominated by storms, the regressive phase of the Brent Group in the UK sector can be compared broadly to the type IV delta configuration of Coleman and Wright (1975, Fig. 10) on the basis of likely net sand distribution at time of maximum northward extent.

Deposition occurred at about 45°N (Smith et al. 1980) probably under subtropical, humid conditions in the non-glacial and therefore more equable Jurassic climatic regime. Marine connections with a Boreal and Central Atlantic ocean are likely to have existed (Hallam 1983). Following the reasoning of Duke (1985), the hummocky cross stratification present in the Brent Group, which formed on a broadly north facing coast, was probably the result of intense winter storms.

8. DISCUSSION

The Brent Group has been compared to a number of modern deltas by different authors. Budding and Inglin (1981) compared it to both the Niger and Grijalva Deltas, Johnson and Stewart (1985) to the Nile Delta and Moiola et al. (1985) to the Lafourche lobe of the Mississippi Delta. A comprehensive analysis of similarities, and contrasts with the Brent delta is beyond the scope of this paper but a brief comment on each in turn is instructive.

The Niger Delta, exposed all year round to high energy marine processes and locally to a meso-tidal range, has a barrier complex protecting extensive vegetated intertidal swamps cut by numerous tidal creeks (Allen 1964, 1970; Oomkens 1974). Fluvial influence is subordinate to tidal influence on the present lower delta plain and substantial lagoons are restricted to the extreme western margin. Minor mouth bars building into lagoons or lakes, so common in the Ness depositional environment, are rarely reported. However fluvial influence has left a greater mark on parts of the earlier Holocene record of deltaic sedimentation (Oomkens 1974). Allen (1970) indicates that in a prograding sequence the present lower delta plain sediments would have an erosive relationship with the underlying barrier deposits due to the downcutting of migrating tidal creeks. The composite nature of the barrier complex sand bodies described by Weber (1971) in the subsurface record of the Niger system and indeed the gamma ray log patterns he figures look attractive analogues for the marine progradational sequence. However the setting of the present Niger Delta with respect to a large ocean basin, the remaining difficulty in proving substantial tidal influence in the Brent delta, and the apparent contrasts in the importance of upward coarsening sequences in lower delta plain settings prevents too close comparison.

The Grijalva Delta on the east coast of Mexico is influenced by high but seasonally varying, wave energy in a microtidal setting. The present delta is characterised by a broad beach ridge system seaward of an alluvial floodplain (Psuty 1965). Drainage on the lower delta plain is channelled through a small number of active distributaries which breach the beach ridges and debouche at the coast. The absence of a barrier-lagoon complex and little or no tidal influence on deposition precludes close comparison with the Brent delta although progradation through migration of an essentially linear coast may be applicable locally.

Johnson and Stewart (1985) compared the Brent Group to the Nile Delta, dominated by moderate wave processes and with insignificant tidal influence. The aridity of the lower delta plain, the absence in the present configuration of minor delta construction in back barrier lagoons and perhaps also the limited breaching of the barrier by distributary channels only, contrast with the likely character of the Brent delta. The two deltas seem however to have been similar in geographic extent (Johnson and Stewart 1985).

Another Mediterranean delta influenced by moderate wave energy and insignificant astronomical tides, is that of the Rhône. Fluvial-wave interaction has produced a barrier coast with rather subdued mouth bars in front of the small number of distributary channels which breach the coastal barrier (Oomkens 1970). Progradation at present is by beach ridge accretion mostly adjacent to the mouth of one distributary, the Grand Rhône, but with some barrier accretion away from river mouths by marine processes (Kruit 1955). As well as the absence of well developed minor mouth bars in the back barrier lagoons of the present Rhône Delta, it has a very gradual upward coarsening, interbedded sand and mud sequence in the record of offshore transition to barrier coast progradation. The high energy, storm influence on the submarine part of the Brent Delta has left a rather abrupt upward termination of mud grade sediment in the record of progradation.

Finally Moiola et al. (1985) in a study of the Statfjord Field compared the Brent Group with the Lafourche lobe of the Mississippi Delta. The present Lafourche lobe is characterised by an inactive, fluvially-constructed lobe subsiding and being transgressed by a barrier island arc with back-barrier lagoon (Penland and Suter 1983). This stage in the evolution of the Lafourche lobe may give useful clues to the processes involved locally in the deposition of the transgressive deposits of the Brent sequence but the active, prograding mode of the Lafourche lobe is not considered to be an appropriate analogue for the Brent Group in the U.K. sector of the northern North Sea.

Features of the modern delta can be abstracted and compared usefully with the Brent Group but none are really substantially close analogues. Inconsistencies arise from differences in regional setting and in regional or local patterns of deposition. A more critical documentation of comparisons and contrasts is required before the use of such analogues has real value. However the authors accept that no one modern delta will fully demonstrate the combination of features observed in the Brent depositional system.

9. ACKNOWLEDGEMENTS

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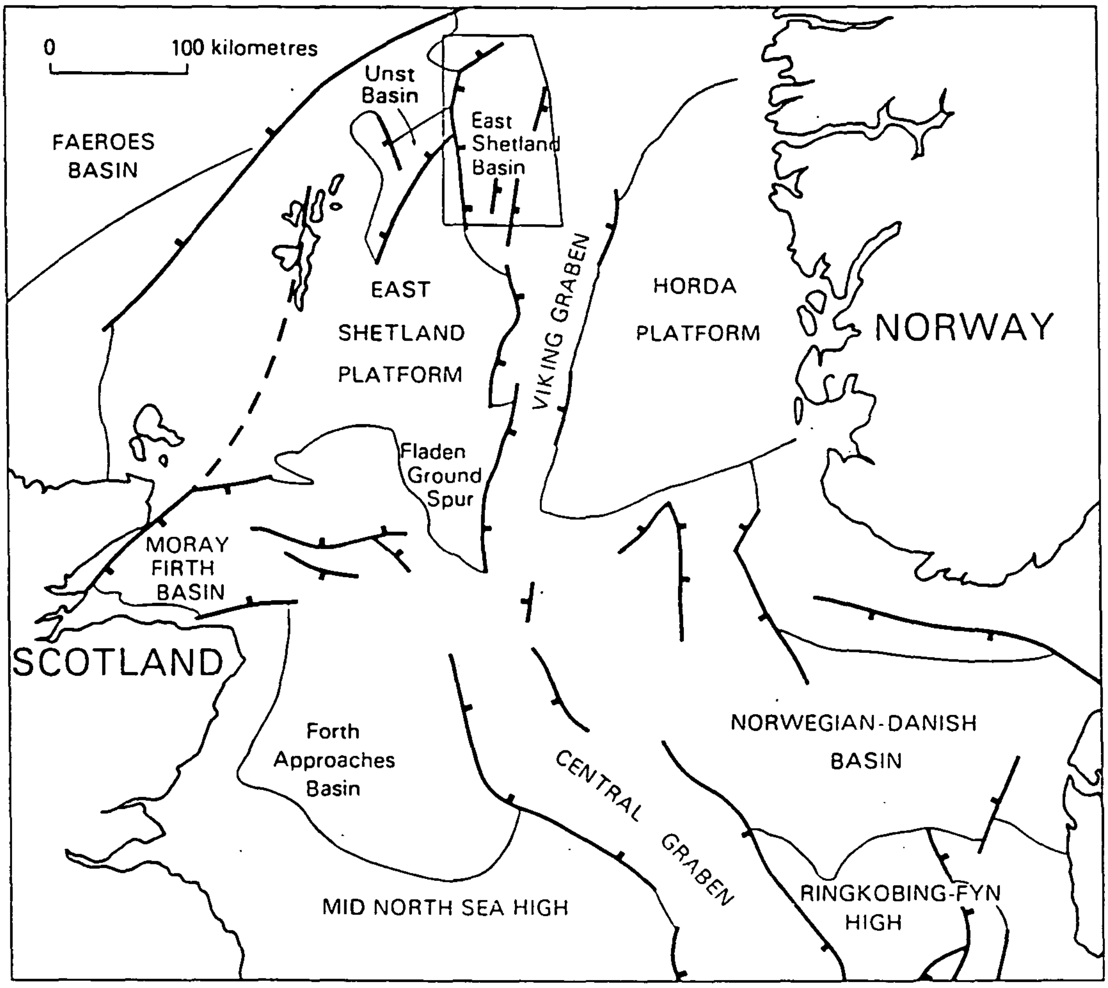


FIG.1 LOCATION MAP OF EAST SHETLAND BASIN

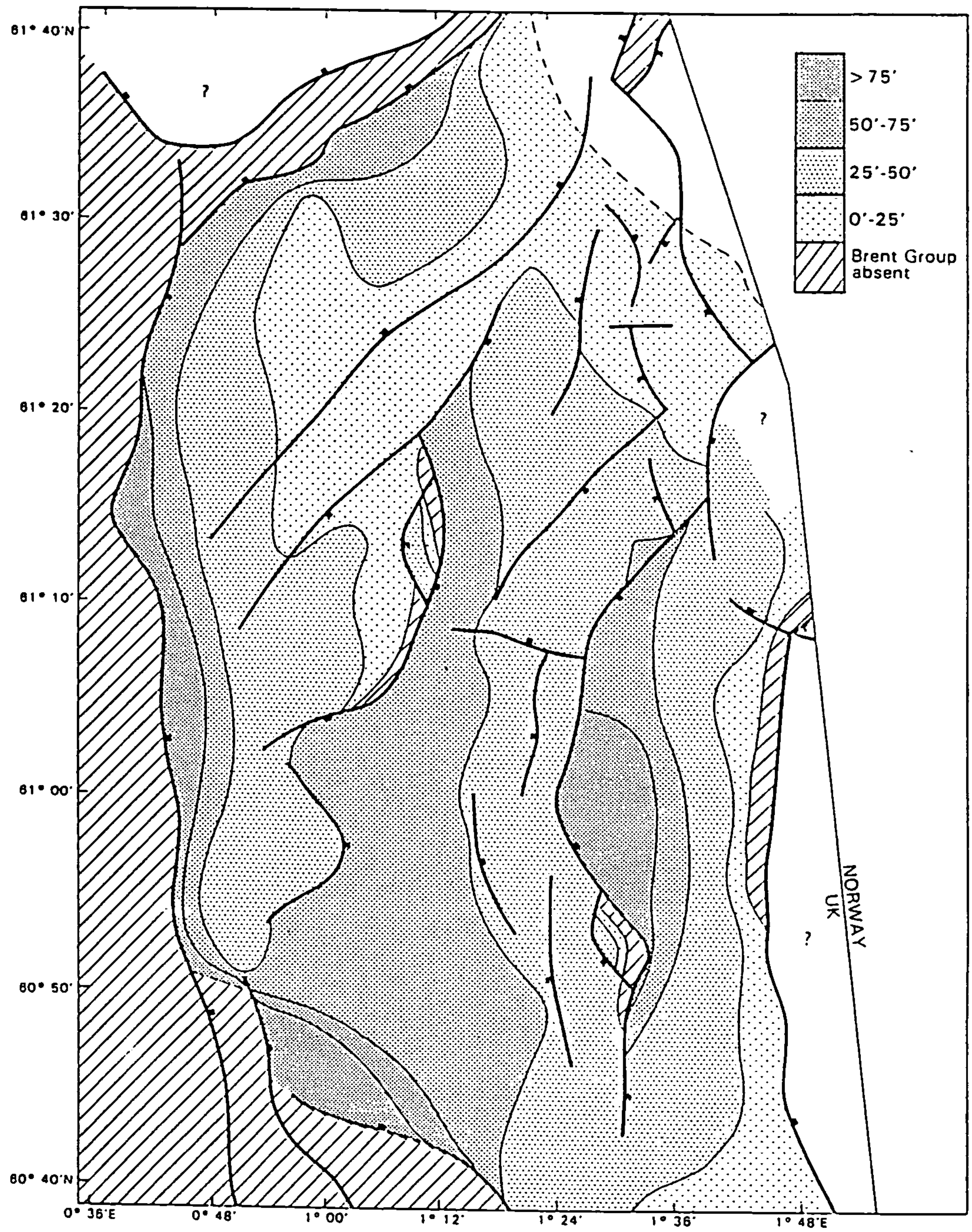


FIG.2 ISOPACH MAP OF BROOM FM.

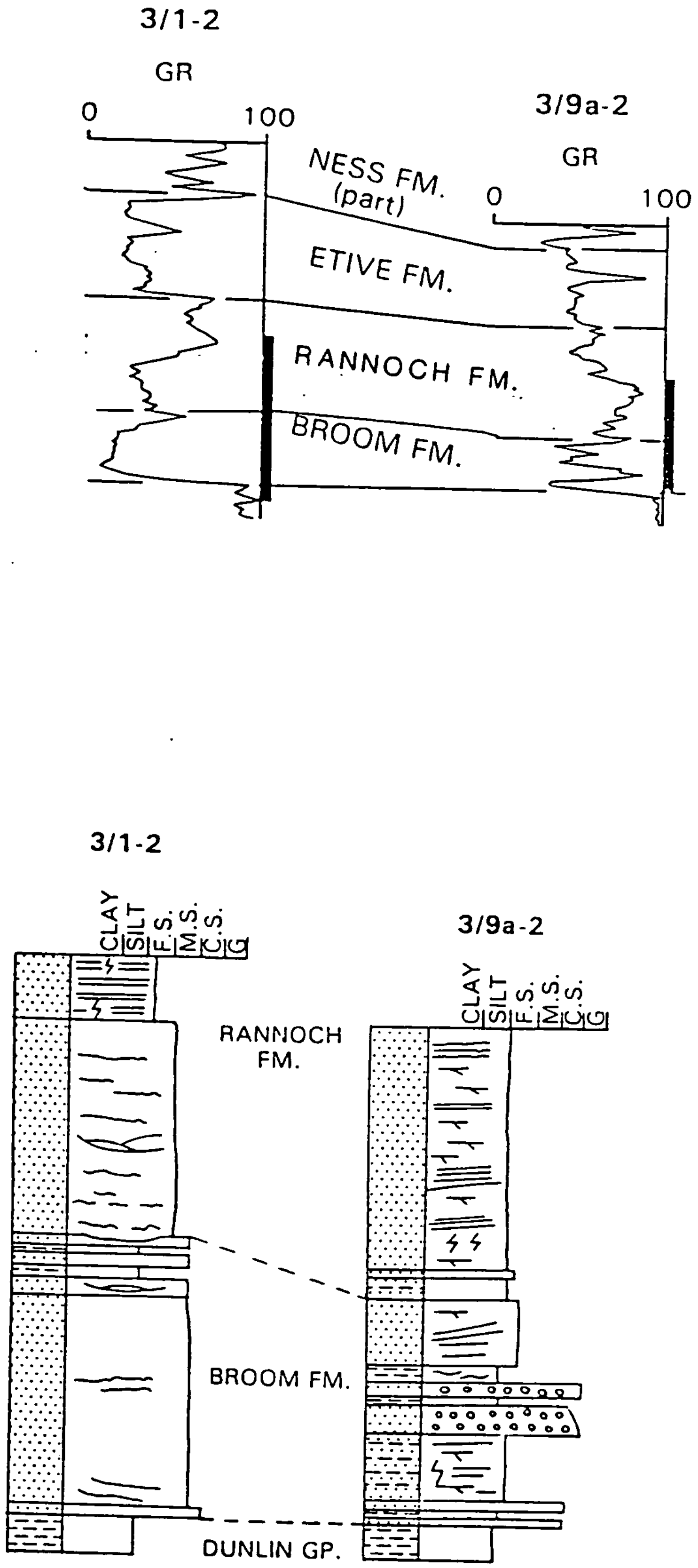


FIG.3 CORE AND GAMMA RAY LOGS OF BROOM AND RANNOCH FORMATIONS

211/27-4a

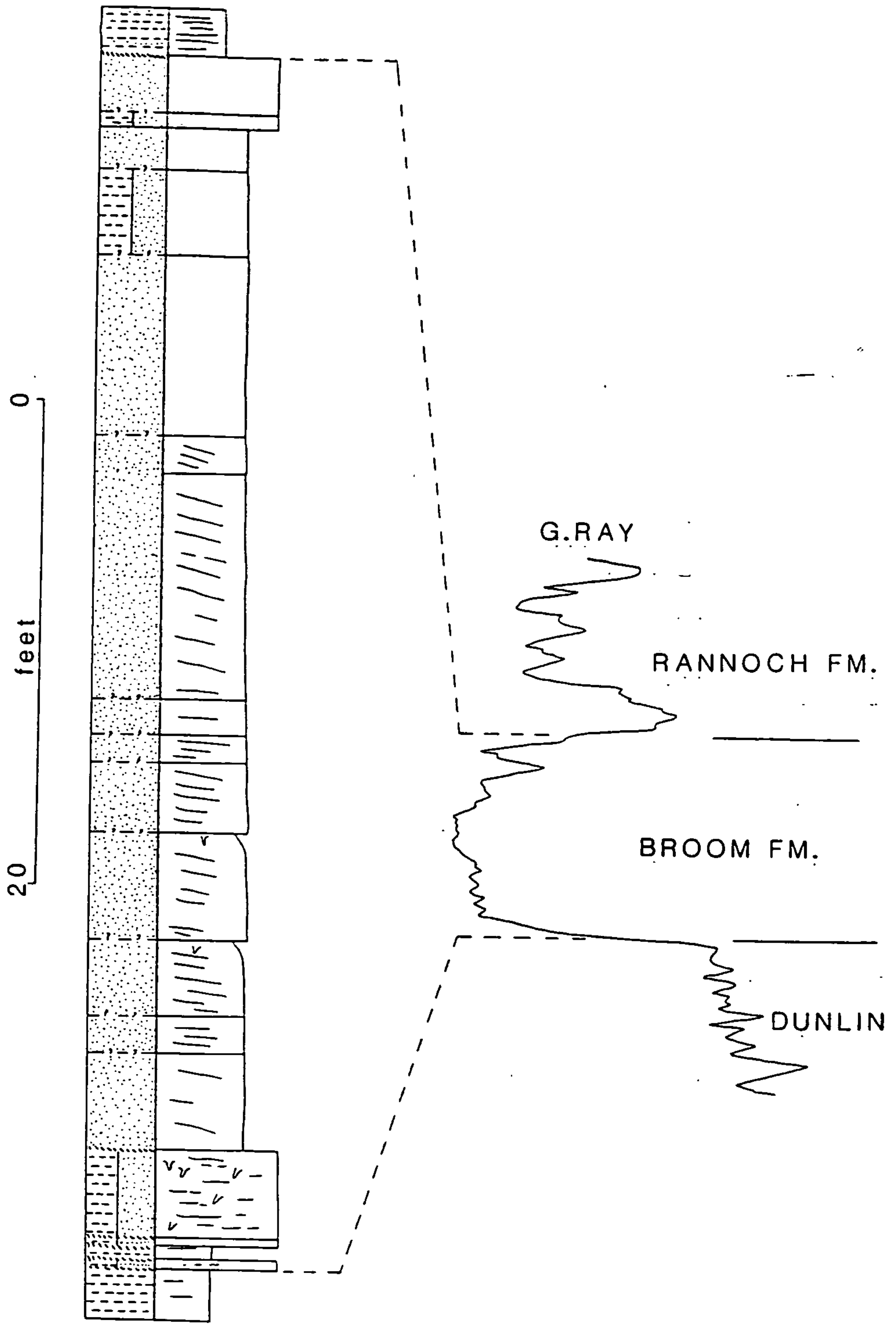


FIG.4 CORE AND GAMMA RAY LOGS OF BROOM FM.,WELL 211/27-4a

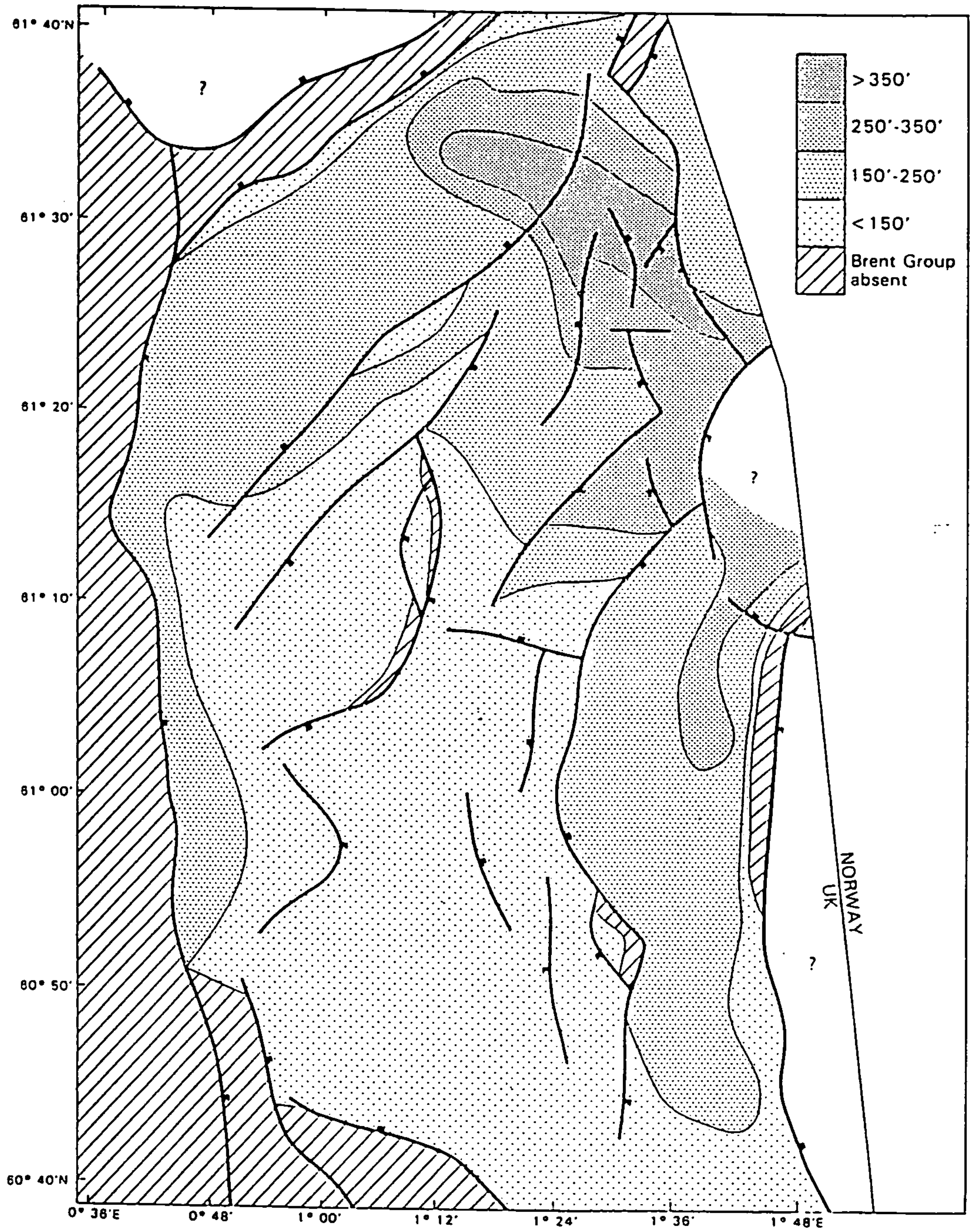


FIG.5 ISOPACH MAP OF RANNOCH PLUS ETIVE FORMATIONS

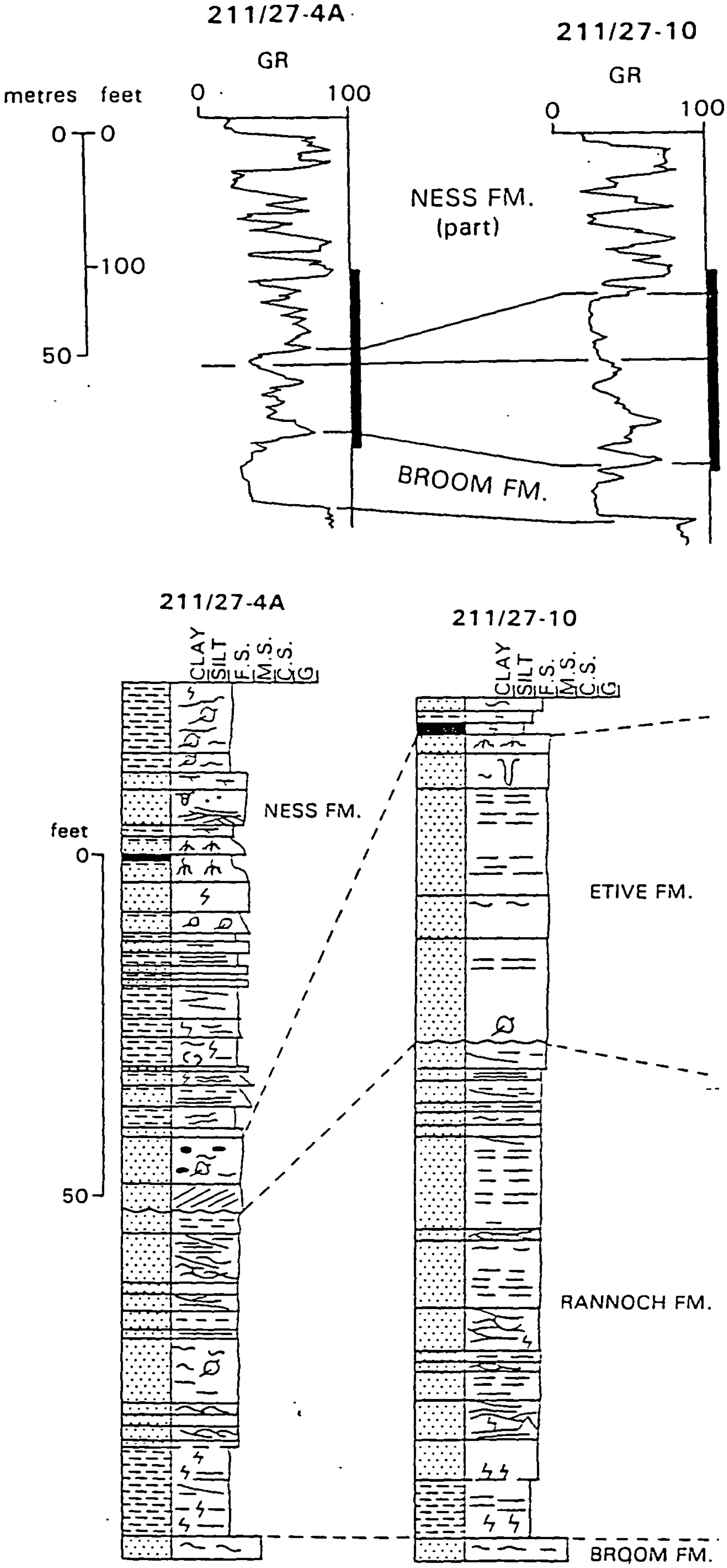


FIG.6 CORE AND GAMMA RAY LOGS OF RANNOCH AND ETIVE FORMATIONS

UK 211/19 – 4 (CONOCO)

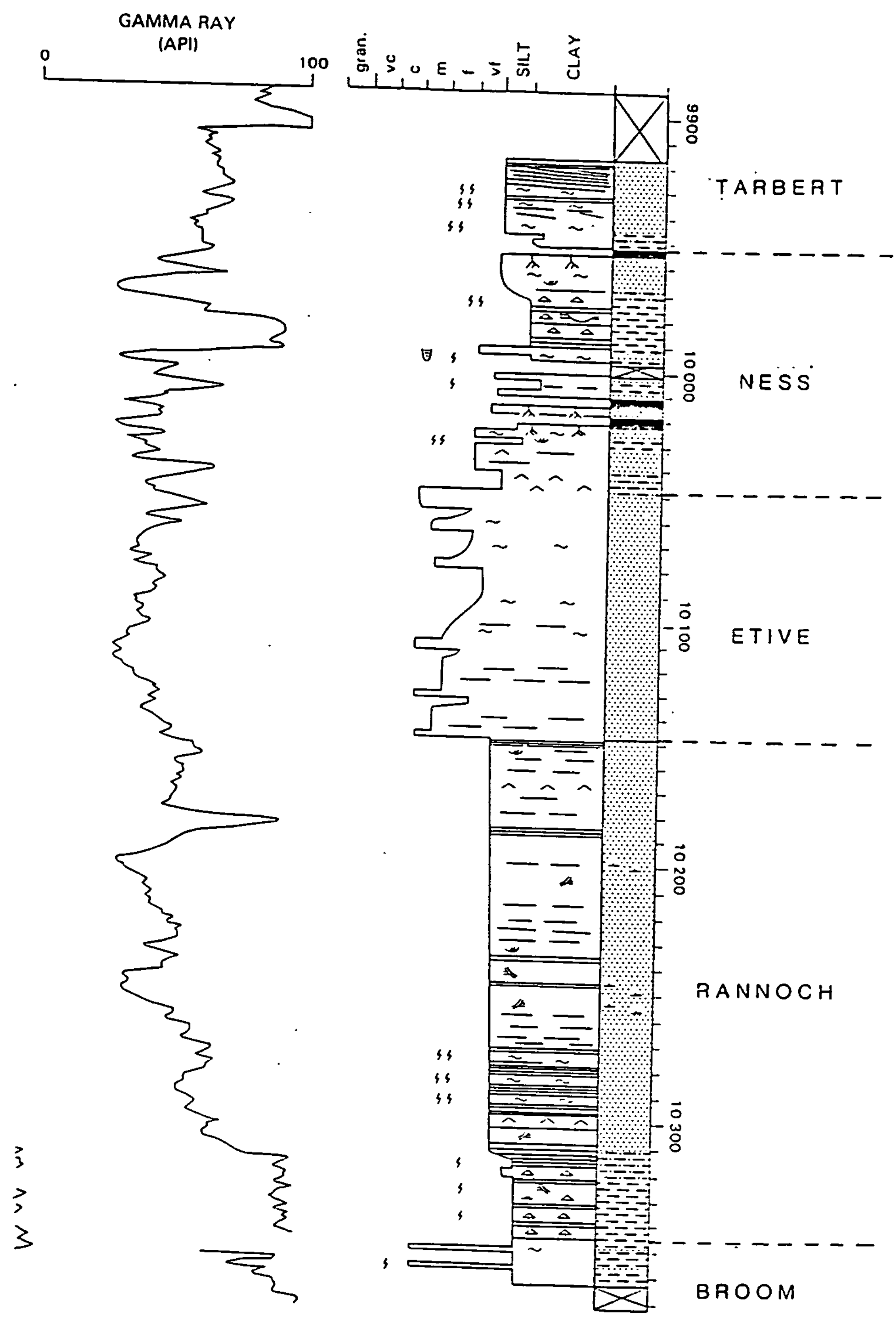


FIG.7 CORE AND GAMMA RAY LOG OF RANNOCH TO TARBERT SEQUENCE IN WELL 211/19-4

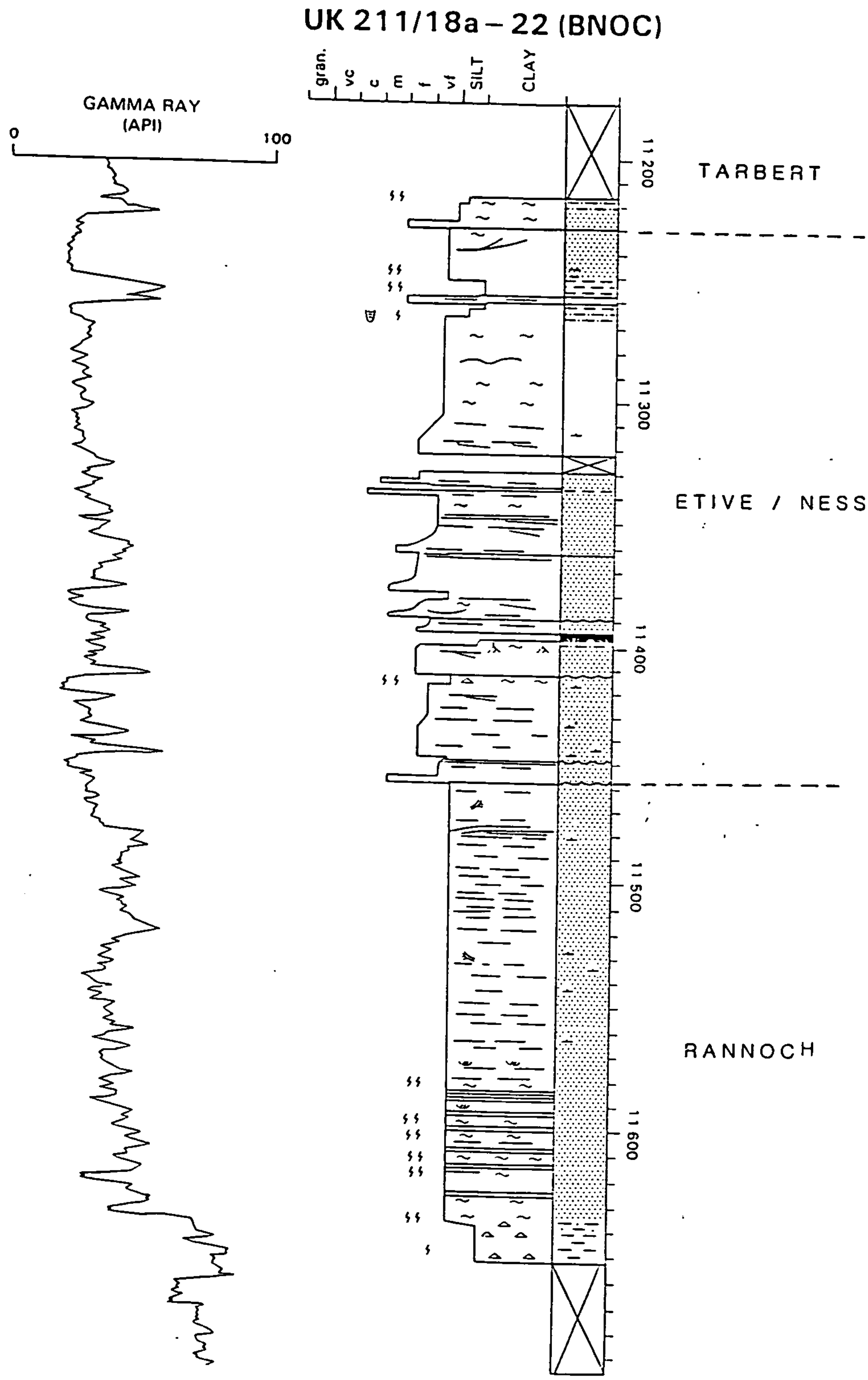


FIG.8 CORE AND GAMMA RAY LOG
OF RANNOCH TO TARBERT IN WELL 211/18a-22

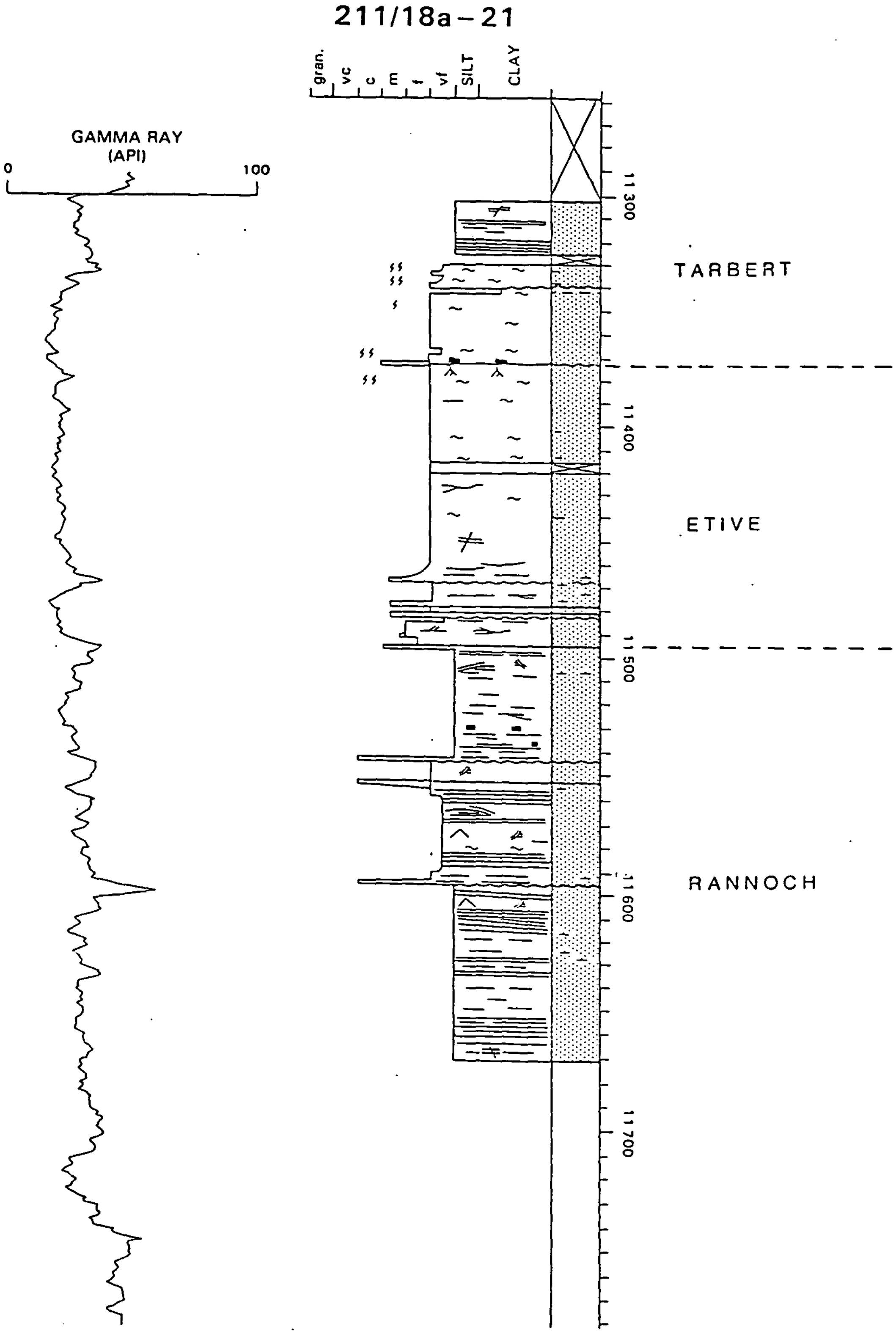


FIG.9 CORE AND GAMMA RAY LOG OF RANNOCH TO TARBERT IN WELL 211/18a-21

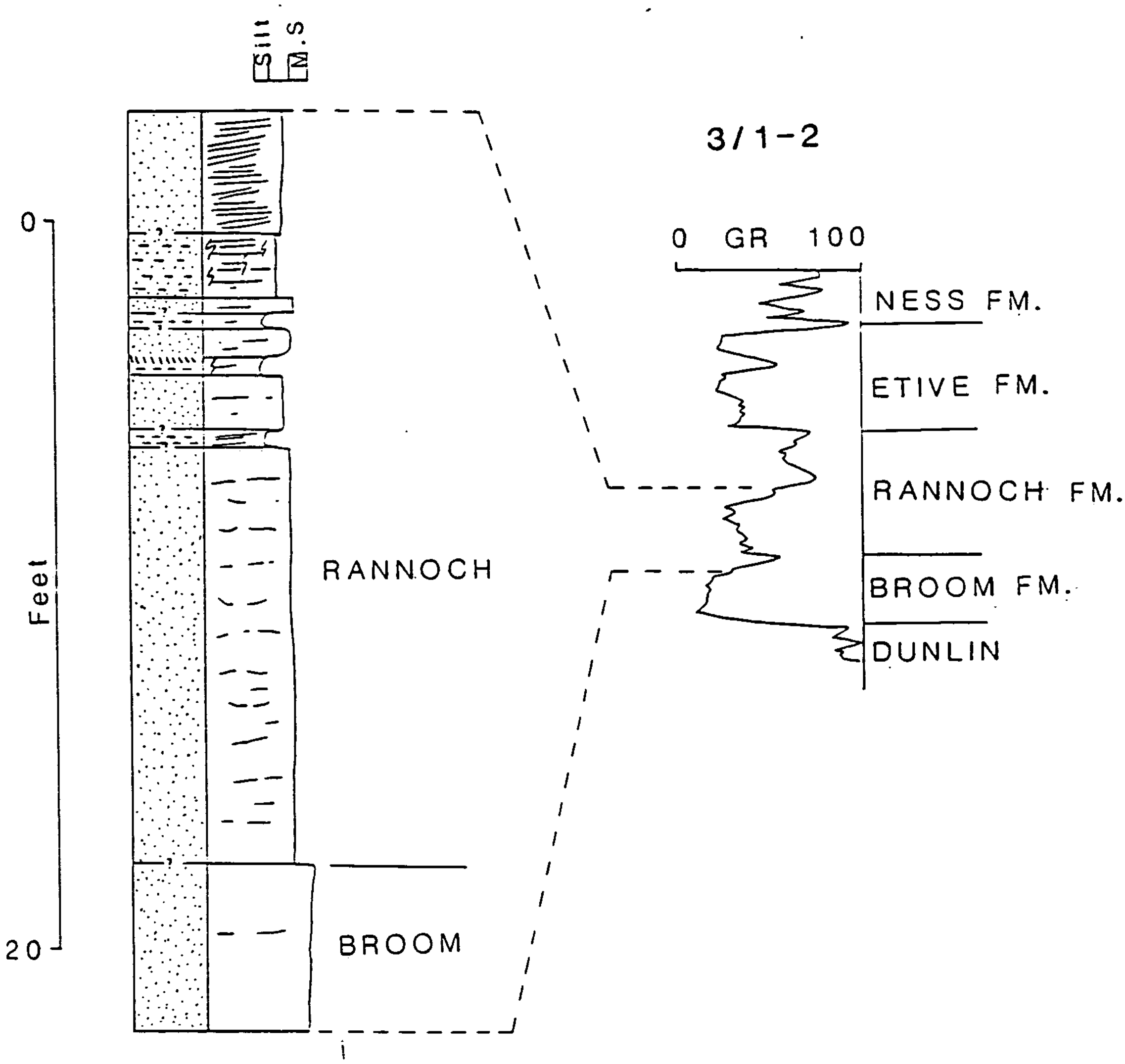


FIG.10 CORE AND GAMMA RAY LOG OF RANNOCH FM.,WELL 3/1-2

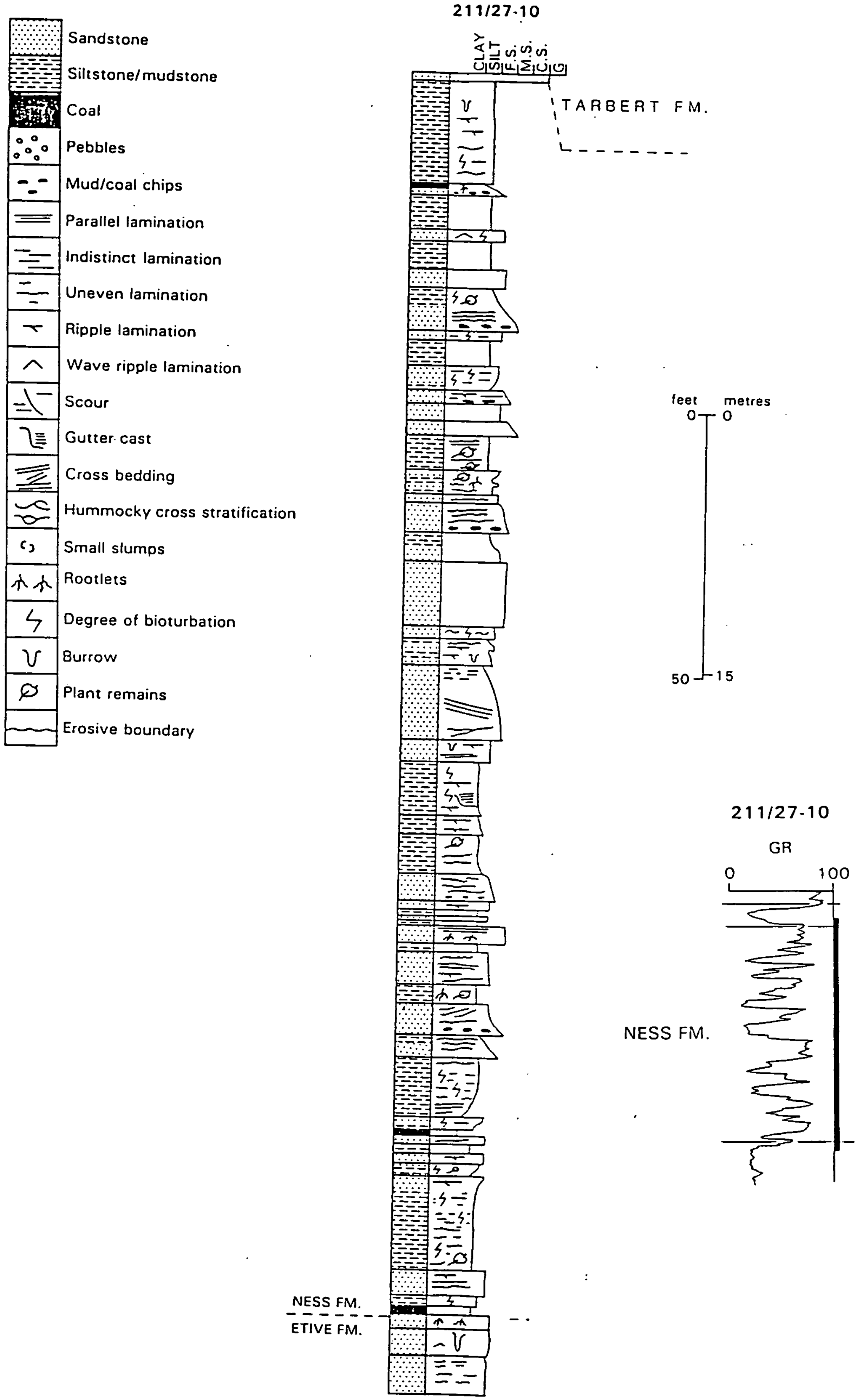


FIG.11 CORE AND GAMMA RAY LOG OF NESS FM.,WELL 211/27-10

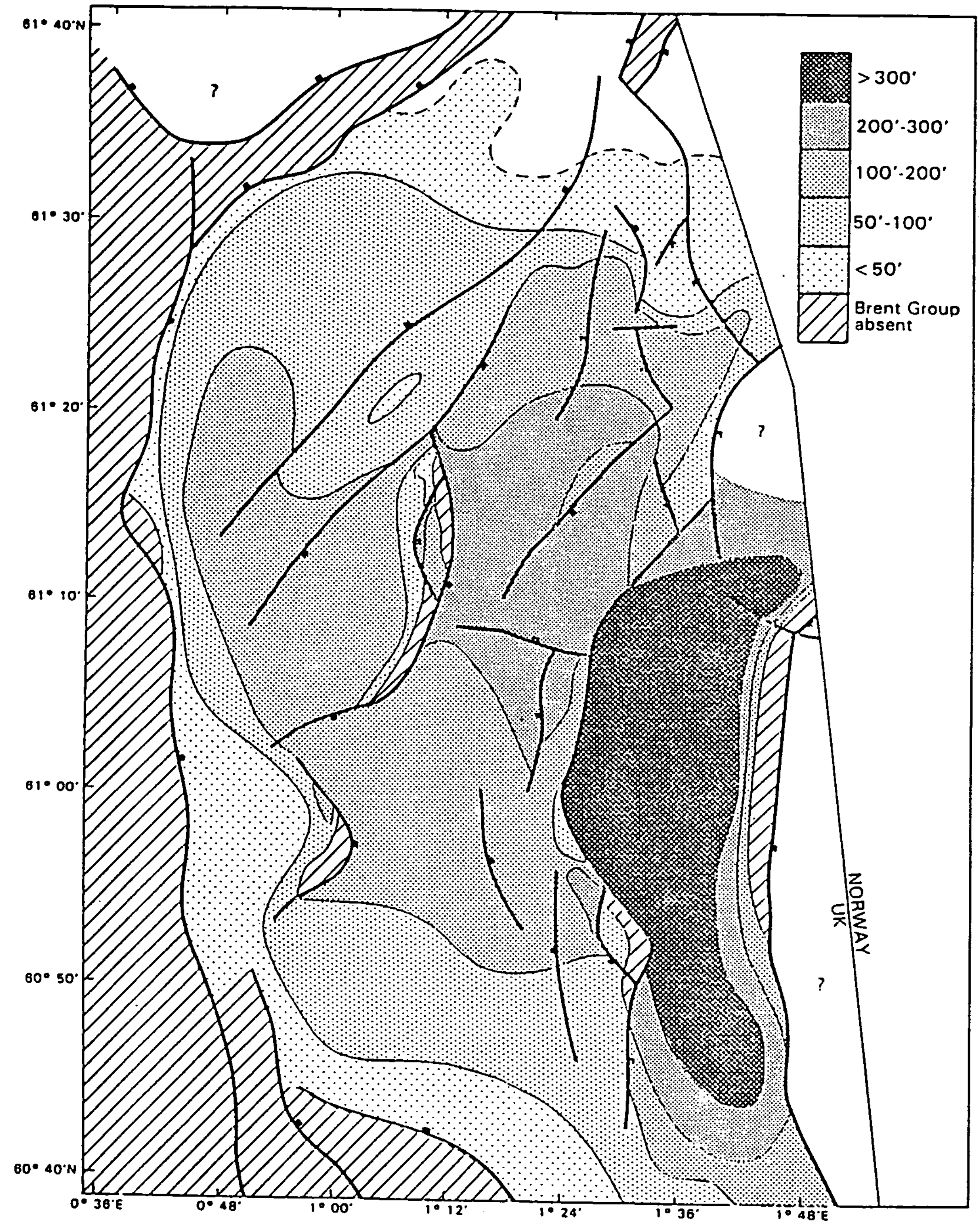


FIG.12 ISOPACH MAP OF THE NESS FM.

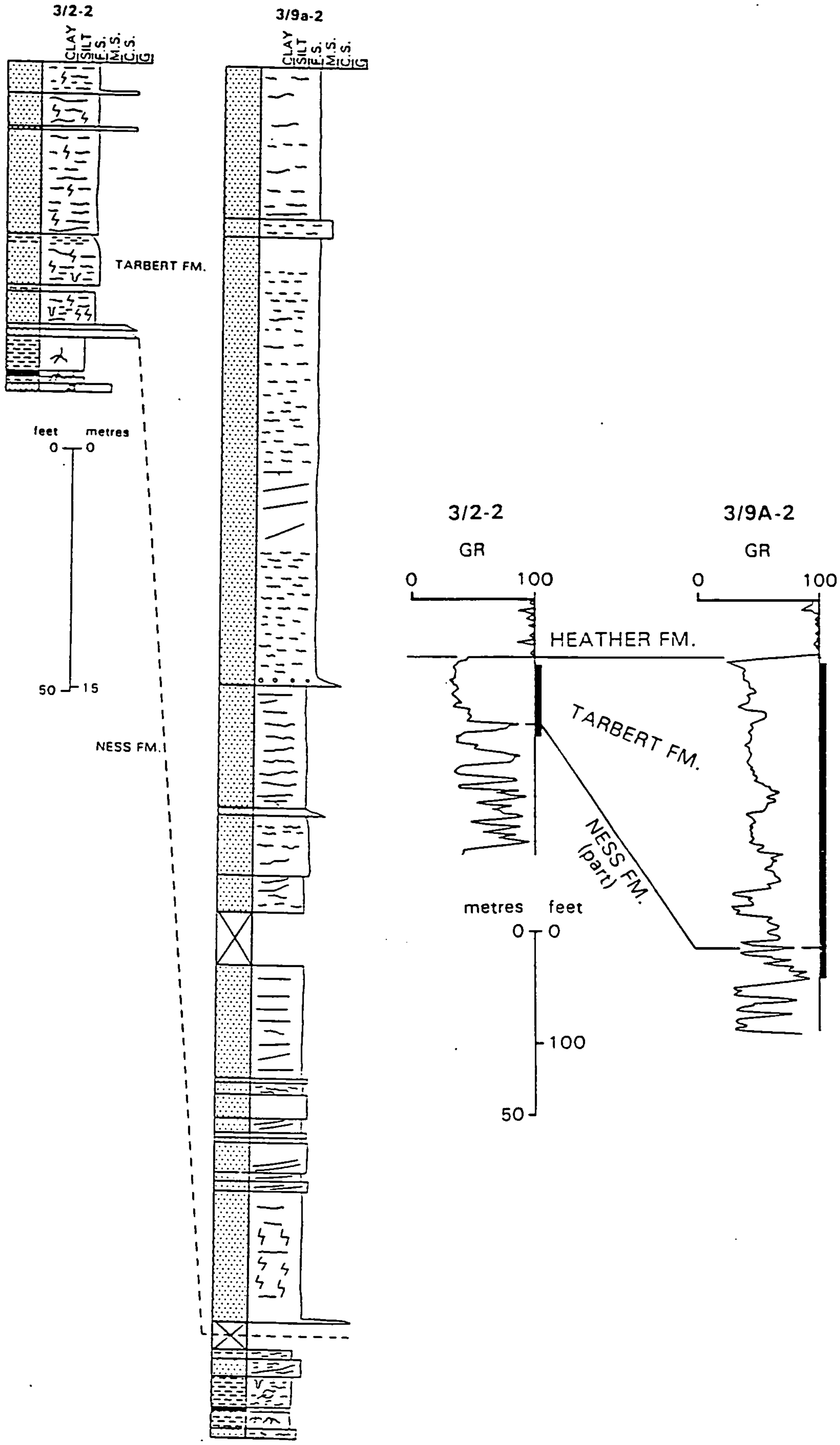


FIG.13 CORE AND GAMMA RAY LOGS OF THE TARBERT FM.

EXPLANATION OF PLATES

Plate 1 Pebbly sandstones and coarse sandstones of the Broom Formation interbedded with Rannoch-type hummocky cross stratified, cross laminated and parallel laminated silty sandstone. Well 3/9-2.

Plate 2 Upper unit of Broom Formation in well 3/1-2.

Plate 3 Basal Broom Formation sequence in well 211/27-4a.

Plate 4 Top of Broom Formation in well 211/27-4a.

Plate 5 Thin Broom Formation sandstones interbedded with Dunlin Group and Rannoch Formation sediments in the 211/24-2 well.

Plate 6 Convex-up laminae in the Rannoch Formation.

Plate 7 Bioturbated top to laminated bed in the Rannoch Formation.

Plate 8 Anomalous Etive Formation in well 211/27-4a. Note the steeply inclined mud draped laminae and the scattered mud chips.

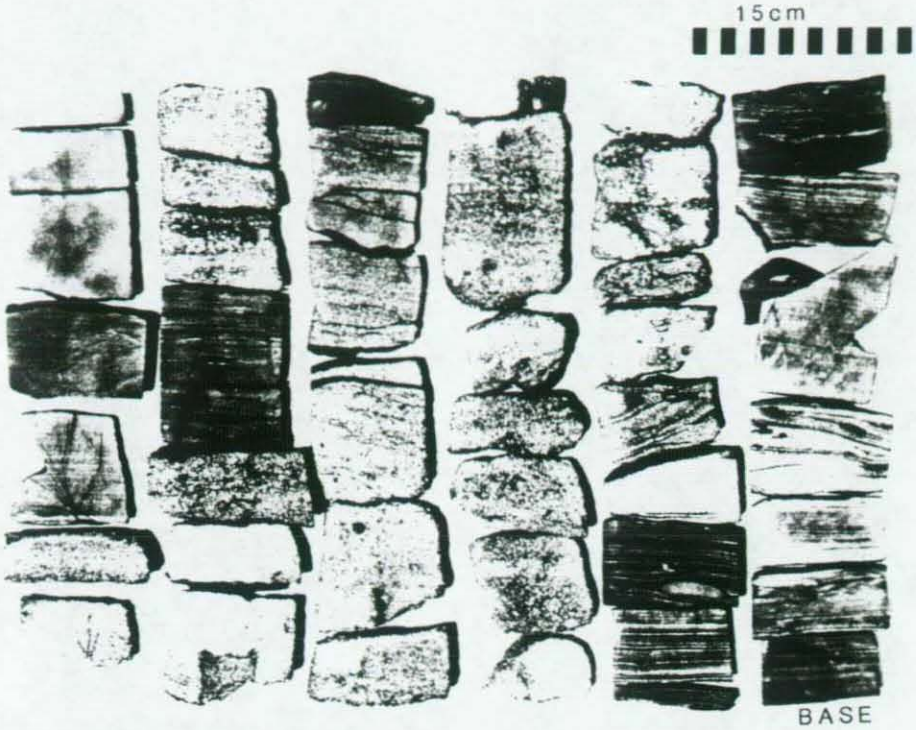
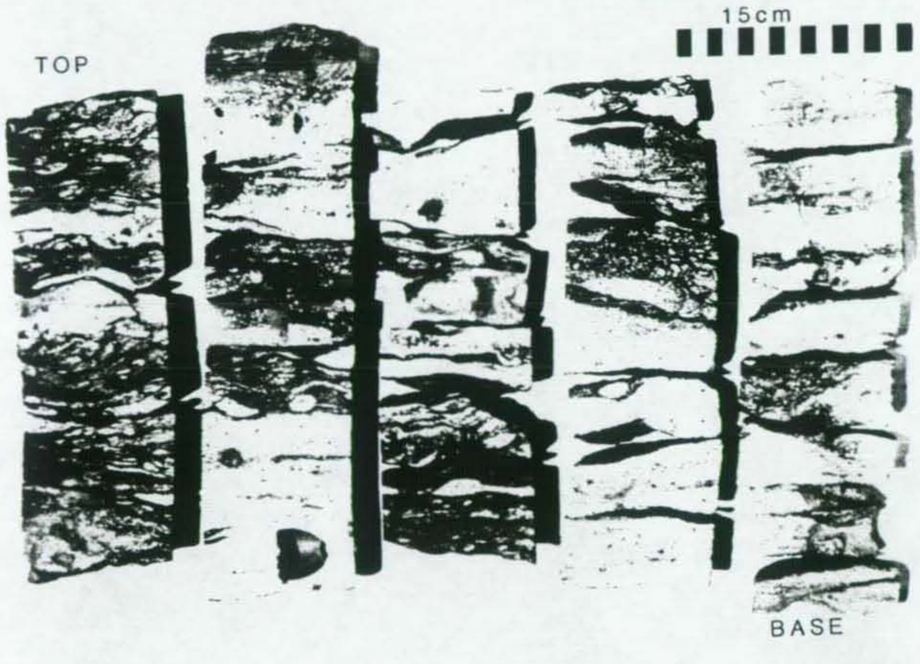


PLATE
1



PLATE
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PLATE
3

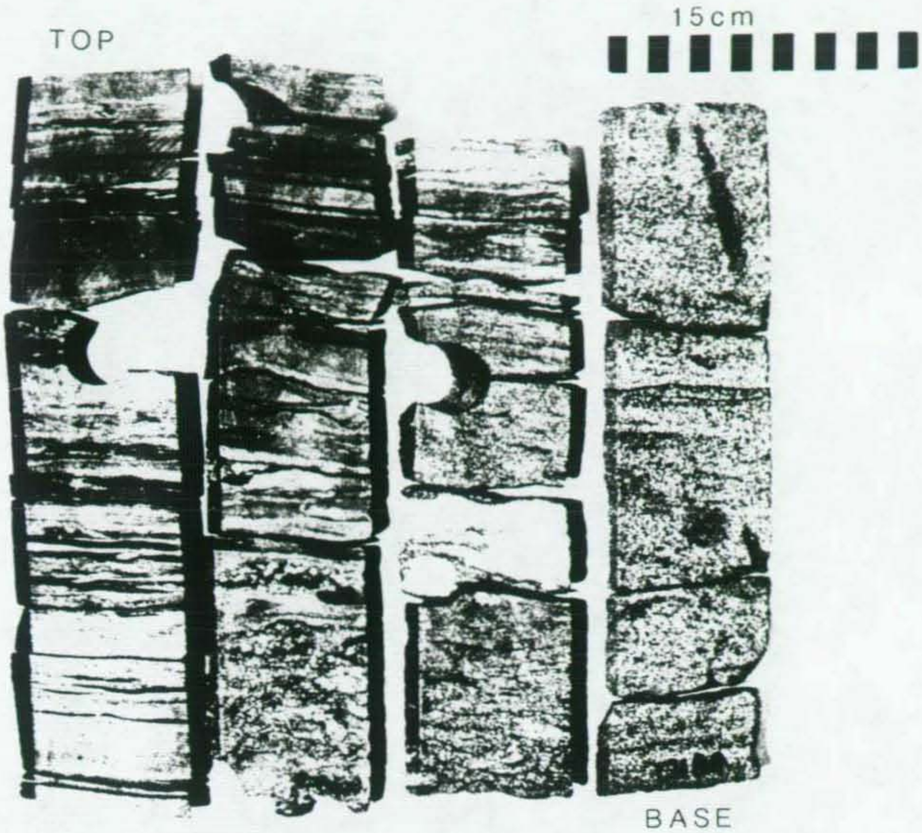


PLATE 4

PLATE 5

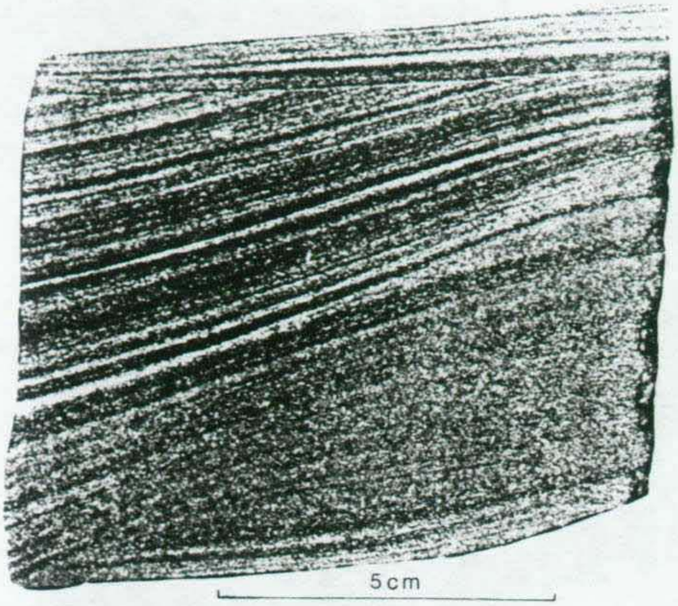
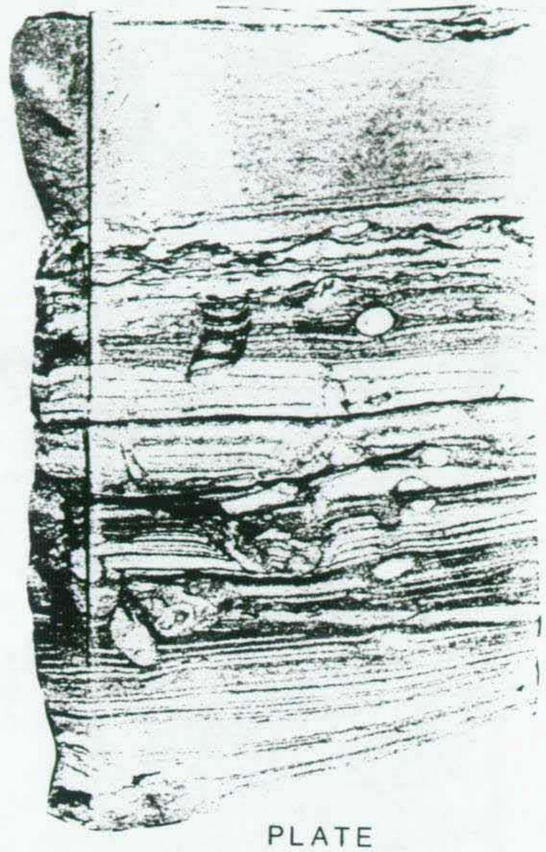


PLATE
6



PLATE
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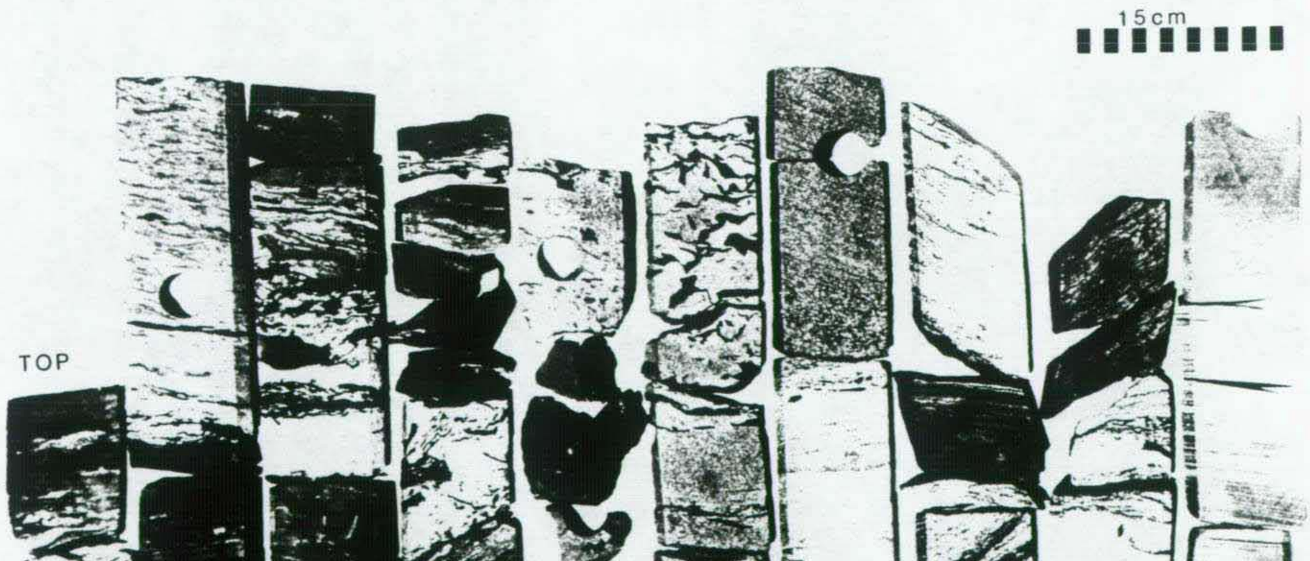

PLATE
8