Magnetostratigraphy and Depositional Sequence Analysis of Triassic fluvial sediments: UK Central North Sea

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ABSTRACT

The stratigraphy and depositional history of the Triassic of the UK Central North Sea has been studied using a combination of litho and magnetostratigraphic techniques. Depositional sequences and facies cycle wedges represent major phases of alluvial plain/lacustine progradation and retrogradation. Three main sequence sets, named TRI, TR2 and TR3 are recognised in which the peak retrogradation boundaries are identffied at the high gamma apex on upward-fining profiles,

In order to test the chronostratigraphic significance of the lake margin flooding surfaces a detailed magnetostratigraphic study of the TR2/TR3 boundary has been undertaken in five wells from the Mamock, Drake, Fiddich and Skua fields. The results indicate that significant improvements can be made to these correlation schemes which are based on lithofacies stacking patterns interpreted from core and wireline log responses. The results indicate that the TR2/TR3 approximates closely to a chronostratigraphic boundary, at least on a field wide scale.

Key Words: Triassic, Fluvial Central Graben, Sequence, North Sea

RESUMEN

Se realiza el estudio de la Estratigrafía e historia deposicional del Triásico Británico de la cuenca Central del Mar del Norte utilizando una combinación de técnicas lito y magnetoestra-tigráficas. Las secuencias deposicionales

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y los ciclos de prismas de facies, representan episodios mayores de progradación y retrogradación asociados a los depósitos de llanura de inundación/lacustres. El momento de máxima retrogradación de las tres secuencias principales, denominadas TR1, TR2 y TR3, se establece como el valor máximo del gamma ray de los perfiles granodecrecientes de las diagrafías.

Con el objeto de verificar el significado cronoestratigráfico de las superficies de inundación asociadas a los márgenes lacustres, se realizó un estudio magnetoestratigráfico del límite TR2/TR3 en cinco sondeos realizados en los campos Marnock, Drake, Fiddich y Skua. Los resultados mejoran significativamente las correlaciones litoestratigráficas establecidas a partir de testigos y diagrafías. Los resultados indican que el límite TR2/TR3 se aproxima mucho a una isocrona, al menos a escala del Campo.

Palabras clave: Triásico, Fluvial, Graben Central, Secuencias, Mar del Norte.

INTRODUCTION

In order to provide more insight into the stratigraphy and depositional history of the Triassic of the Central North Sea, GAPS Geological Consultants (1992a,b) undertook a regional review based upon more than 100 wells from the UK and Norwegian sectors of the North Sea and based on detailed logging and interpretation of 2400 metres of core. In the study, the stratigraphic approach was based on the recognition of «depositional sequences» and facies cycle wedges, within the Triassic section. These depositional sequences represent major phases of alluvial plain progradation and retrogradation, in response to relative changes in base level (Figure 1). «Sequence boundaries» are placed at points of maximum retrogradation, representing periods of basinwide expansion/deposition of a mud-dominated floodplain-lake margin facies and the regional «shaling-out» of the depositional systems. On wireline logs, phases of retrogradation are defined by pronounced upward-fining profiles on the gamma ray and for the purposes of consistent correlation the boundary in each case has usually been placed on the high gamma apex of the profile. Through a process of well to well correlation and facies analysis, a regional correlation of depositional sequences was established.

Results of the correlation work indicated that the Triassic in the UK Central North Sea area could be subdivided into three main sequence sets (termed TRI, TR2, TR3). Further subdivision of TR2 and TR3 into correlatable lower order sequences was also achieved (Figure 2).

During the early Triassic (i.e. Sequence TRI) much of the Central North Sea area was dominated by lacustline sedimentation, characterised by the de-

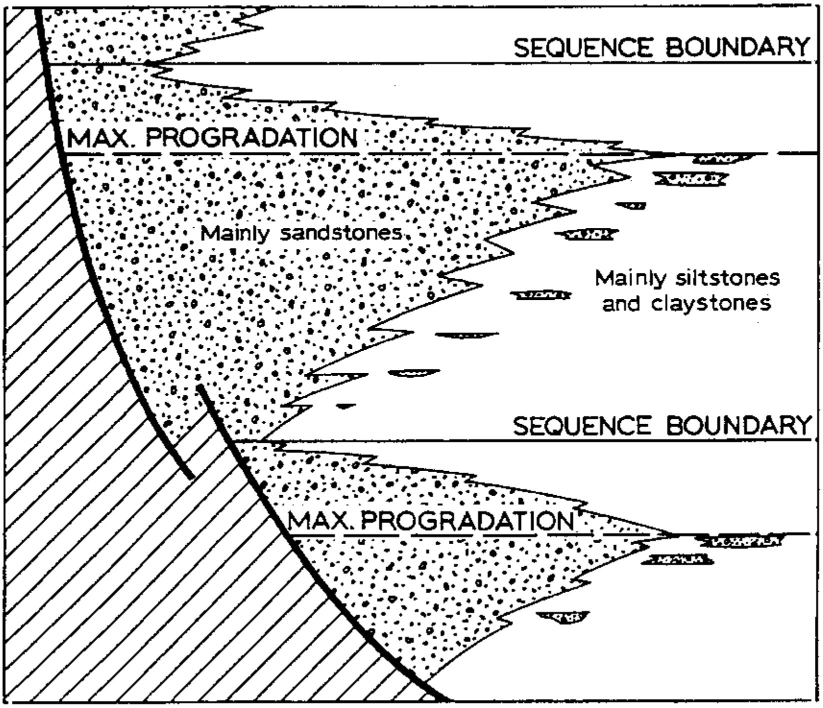


Fig. 1.—Conceptual diagram illustrating some of the principles surroundingTriassic sequence stratigraphy (modified from Steel and Ryseth, 1990). Sequence boundaries are picked at the level of retrogradation

Fig. 1.—Modelo diagramático en el que se ilustran algunos elementos del análisis estratigráfico secuencial del Triásico (modificado de Steel y Ryseth, 1990). Los límites de las secuencias se definen en el nivel de retrogradación máximo.

position of syndepositionally reddened mudstones. In contrast, for the remainder of the Triassic (i.e. Sequences TR2 and TR3) sand-dominated facies were prevalent. Facies analysis (GAPS, 1992a,b) has shown how the lacustrine sedimentation was followed by the basinwide progradation of an alluvial system dominated by braided streams and sheetfloods. These were deposited in an alluvial plain setting, downslope from basin margin alluvial fans. Discrimination of the alluvial plain into an upper (proximal) and lower (distal) component is also possible and in general the downslope change from the upper to lower alluvial plain is accompanied by a decrease in channelisation and an increase in sheetflooding (Figure 3).

Core sedimentology reveals the braided streams to be generally of an ephemeral nature. Individual channel units are generally thin but frequently incomplete due to the tendency for them to be of a stacked, mutually erosive

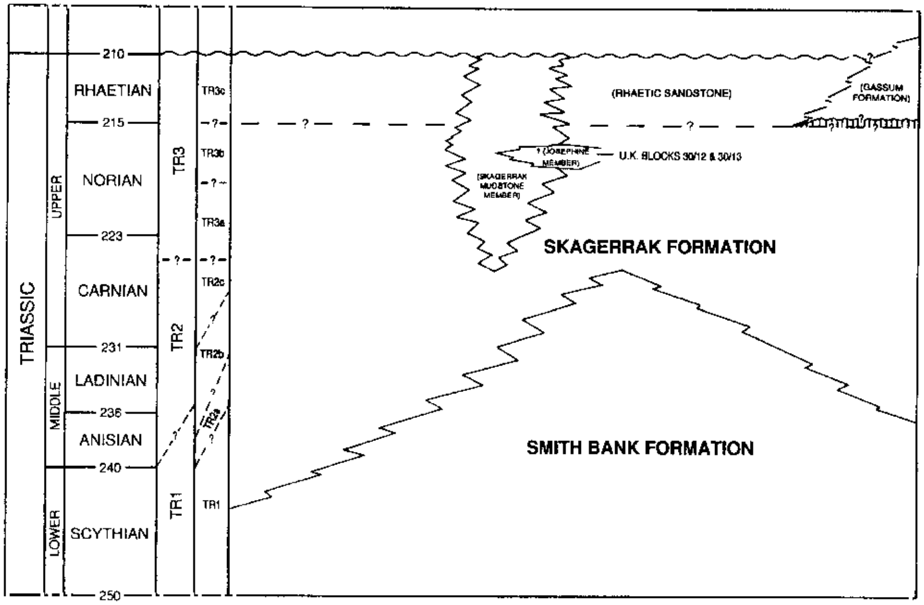


Fig. 2.—Relationship of unpublished TR sequence scheme used in this study to the Lithostratigraphy and Chronostratigraphy of the Triassic in the Central North Sea.
Fig. 2.—Relación del esquema de secuencias TR utilizado en este trabajo con la Litoestratigrafía y Cronoestratigrafía del Triásico en el Mar del Norte.

nature. However, well developed braided systems do occur and are particularly characteristic of Sequence TR3 in UK Quadrant 22. Furthermore, mapping of environmental facies indicates that during the Triassic, the fluvial systems were predominantly fed from a northeastern hinterland. Consequently, and as predicted by the regional depositional models, braided channels become increasingly dominant and coarser grained in this direction. This is evidenced throughout the Triassic section in Well 22/5b-5 for example where deposition occurred predominantly within a proximal alluvial plain setting.

Interbedded and interdigitating with braided stream deposits are finer grained sheetflood deposits, their presence indicating the presence of fluctuating discharge rates during deposition of the fluvial systems. Two main types of sheetflood are recognised in core: i) massive/ homogenised sheetfloods of mass flow origin, or ii) structured sheetfloods dominated by upper flow regime plane bed lamination.

The dynamic nature of the braided fluvial systems meant that overbank/abandonment fines were generally poorly preserved and laterally impersistent within the alluvial plain. Where preserved they are generally of a thinly interbedded nature and commonly show incipient pedogenic features.

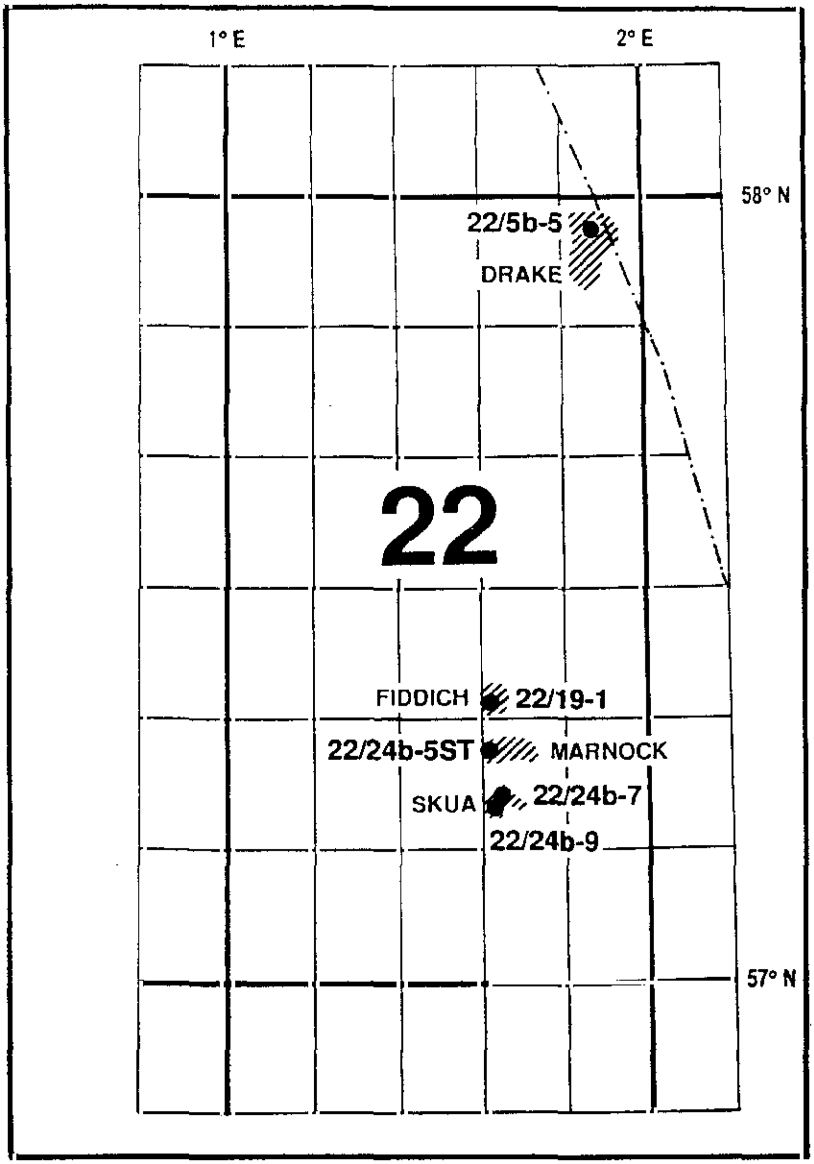


Fig. 3.—Well location map
Fig. 3.—Localización de los sondeos.

However, more substantial thicknesses of floodplain-lake margin fines do characterise the retrogradational phases that mark the end of each sequence/subsequence in TR2 and TR3. In particular, over 100 feet of ?lake margin mudstones may be present at the top of TR2, up to the contact with TR3.

The apparent basinwide cyclicity of Triassic sedimentation indicated that the allocyclic mechanisms affecting the relative rise and fall of base level on a basinwide scale were in operation. Although the precise nature of the allocyclic control is still unclear, the model if correct, gives confidence to the hypothesis that the depositional sequences are time equivalent. Furthermore it also suggests the high gamma ray bounding surfaces to depositional sequences are «isochronous», representing the basinwide expansion/deposition of floodplain-lake margin facies during a period of retrogradation and relative base level rise.

To test the hypothesis that the lake margin flooding surfaces are chronostratigraphically significant we applied a magnetostratigraphic approach to one specific lake margin flooding surface at the boundary between TR2 and TR3 over which there was available core material. This was undertaken in 5 wells (22/5b-5, 22/19-1, 22/24b-5 ST, 22/24b-7 and 22/24b-9) from the Central North Sea (Figure 3). The objectives of the study were as follows

* Describe the basic palaeomagnetic properties of the Triassic rocks with the aim of distinguishing primary and secondary components of magnetization.

* Establish a Triassic reference stratigraphy of normal and reversed magnetic polarity for use in locally correlating cores from development wells.

* Test the magnetostratigraphy against the facies based sequence stratigraphy and review the lateral facies variations.

BACKGROUND TO THE STUDY

Magnetostratigraphy, in which periods of normal and reversed polarity of the Earth's magnetic field are recorded in sedimentary successions, is potentially a very valuable technique for subsurface correlation of continental sequences like the Triassic. It is used routinely in the Ocean Drilling Project (ODP) on Cenozoic marine sediments and in recent years a large number of land-based studies have extended the magnetostratigraphies back into the early Mesozoic and even the Palaeozoic. However, the technique has not yet been developed for use by the petroleum industry and there are few reported studies of subsurface correlation or dating based on magnetostratigraphy.

In the subsurface-Triassic there are a number of potential problems in applying magnetostratigraphy, the most important of these is the absence of a well-constrained Triassic polarity stratigraphy (Rey *et al.* 1993) However, there have been considerable recent advances in this area and Figure 4 shows a Triassic chronomagnetostratigraphy reproduced from Gradstein *et al* 1994. An earlier Triassic magnetostratigraphy was been presented by Molina-Garza *et al* (1991) but this differs significantly from the Gradstein et al. *(op. cit.)* particularly in the chronological ages assigned to Triassic Stage boundaries. Comparisons between the two are thus very difficult.

The main features of the published Triassic magnetostratigraphy are a series of relatively rapid reversals in the Upper Scythian-Lower Anisian interval generally reversed polarity dominated. Longer periods of normal and reversed polarity dominate the late Triassic. The lithological thickness of individual magnetozones varies according to the duration of the geomagnetic polafity and the rate of sediment accumulation (higher sediment accumulation rates thickened the magnetozones).

In the UK Central North Sea the spatial and temporal relationship between the Skagerrak (sandy) and Smith Bank (silty) Formations of the Triassic remains poorly understood. In particular, the lack of chronostratigraphic control means that it is difficult to reconstruct the evolution of the Triassic basin, which in turn makes the distribution of reservoir sands difficult to predict. The application of magnetostratigraphy within the confines of existing Triassic stratigraphic schemes should therefore not only serve to constrain and improve the latter but also help to improve the understanding of the Triassic as a whole.

GEOLOGICAL SETTING

Deposition throughout the Triassic within the Central North Sea area took place within a continental basin setting. Palaeoclimate was predominantly semi-arid, although at times punctuated by more humid conditions. The early configuration of the Central Graben, which dominates the area, is believed to have been established during Permian-Triassic rifting. During the Triassic, sediment entered the graben from various sources, the most important of which was the northeastern hinterland of the Fenno-Scandian Shield. Other localised sediment sources may have included the Fladen Ground Spur, the Western Platform and the Mid-North Sea High.

Throughout the Triassic, movement of the underlying Zechstein salt exerted a strong control on depositional patterns. Thick accumulations or «pods» of Triassic sediment were deposited within areas of active salt withdrawal whereas thinning of the sedimentary section often occurred over salt highs or «walls», although secondary dissolution across salt wall crests resulted in the development of localized, secondary synforms. The geometry and configuration of the synforms generated by salt withdrawal and dissolution strongly influenced the direction of fluvial drainage, generally being axial to the graben.

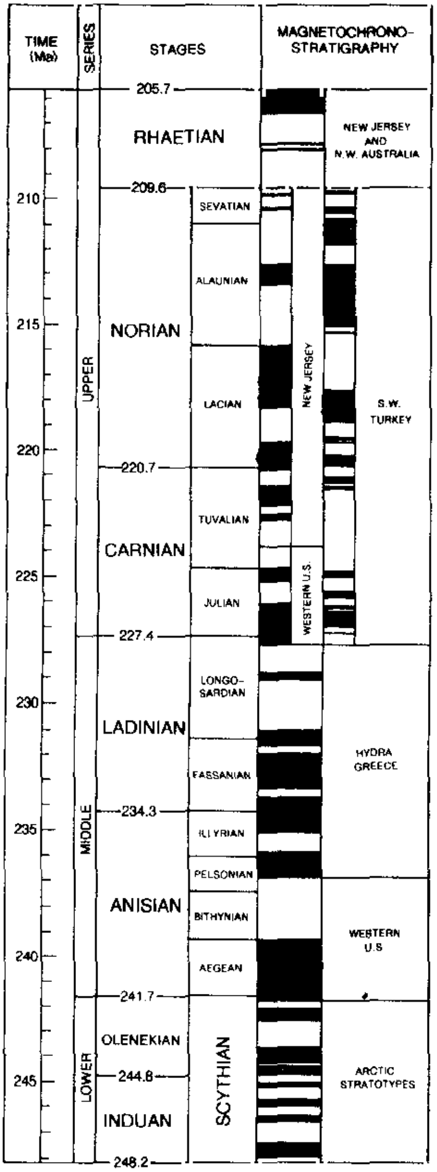


Fig. 4.—GPTS for the Triassic (after Gradstein et al. 1994). The central North Sea section compares closely with the Anisian

Fig. 4.—Escala temporal de Polaridad Magnética para el Triásico (basada en Gradstein *et al.* 1994). La sección de la cuenca Central del Mar del Norte es comparable con el Anisiense.

In the wells included in this study, four (22/19-1, 22/24b-5ST, 22/24b-7 and 22/24b-9) are located within the Mamock Field area to the east of the Forties-Montrose High. Seismic evidence (Smith *et al.*, 1993) has shown that the Triassic section within each of the wells was deposited within «pods» or sites of salt withdrawal that were essentially continuous in their development throughout the Triassic. Consequently, thick accumulations of Triassic sediment (in excess of 1500 ft) were deposited at these well sites. In addition, the general geometry of the salt walls meant that a broad N/S-oriented conduit for fluvial drainage was established from the early Triassic onwards for this area.

Preservation of the Triassic section in this area has been complicated by the subsequent effects of salt movement, pod inversion, Early-Middle Jurassic regional uplift and Late Jurassic rifting. As a result, variable erosion of the Triassic section has occurred in the Marnock Field area. Non-deposition/erosion of the Jurassic section is also clearly evidenced by the fact that in each of the «Marnock» wells the Triassic is unconformably overlain by Cretaceous sediments.

Considerably less information is currently available regarding the structural/halokinetic influence on Triassic deposition and preservation in Well 22/5b-5 (Drake Field). This well is located to the southwest of the Ling Graben which may to have formed a major axis for sediment transport into the Central North Sea during the Triassic (GAPS, 1992a,b). The thickness of the Triassic section in this well again suggests that «pod» development may have occurred. Uplift and rifting during the Jurassic resulted in the development of a series of faulted terraces to the northwest of the Jaeren High along which the Drake Field (including Well 22/5b-5) is located. Partial erosion at the top of the Triassic section is again evidenced in 22/5b-5 and other nearby wells although unlike the Mamock area, the Triassic here is unconformably overlain by Jurassic sediments.

PALAEOMAGNETISM

Measurements of the weak permanent Natural Remanent Magnetisation (NRM) of sedimentary rocks show that they are capable of recording ambient geomagnetic field changes. The present-day NRM recorded in sedimentary rocks can be the result of several components of magnetization. The components can be classified into two main groups: primary and secondary. Primary components of magnetization comprise detrital remanent magnetization (DRM), acquired during deposition through rotation of magnetic minerals, and post-depositional remanent magnetization (PDRM), acquired shortly after deposition through rotation of magnetic minerals during compaction and dewatering. Secondary components of magnetization comprise chemical remanent magnetization (CRM), which is acquired during diagenesis, including the authigenesis and alteration of iron oxyhydroxides, resulting from geochemical and thermal effects respectively. A third component of magnetization, termed partial thermal viscous remanent magnetization (PTVRM) relates to the present-day Earth field component and can be used to reorientate cores. In addition, other secondary components of magnetization may be acquired during drilling of the core or plugging of the samples, especially if the samples come into contact with strong magnetic fields or ferrous materials.

SAMPLING AND MEASUREMENT

Cores from five wells: 22/5b-5, 22/19-1, 22/24b-5ST, 22/24b-7 and 22/24b-9 totalling 2083ft were sampled at approximately 6 feet intervals and preferentially in finer grained units, where the magnetic minerals are hydrodynamically more suitable for post-depositional rotation and primary iron oxides and oxides are more abundant (total of 317 sample locations). The slabbed surface of the core was marked with an orientation line (Figure 5). Two plugs were then drilled exactly normal to the slabbed surface at each sample location, each then being trimmed with a brass blade to produce 3 or 4 «palaeomagnetic specimens» of 2.2 cm length and 2.54 cm diameter. All the palaeomagnetic measurements were then made relative to the orientation line and corrected so that the magnetic inclinations were relative to bedding. Since the cores were unorientated all the declination values are arbitrary. Measurements of initial Natural Remanent Magnetisation (NRM) were made on all samples while saturation remanence and initial susceptibility were measured on one sample from each location. Thermal demagnetization analysis were also carried out on one sample from each sampling location. Fifty two samples were also selected for measurements of isothermal remanent magnetization and reflected fight microscopy was performed on selected samples in order to determine the magnetic mineralogy.

As the NRM represents the resultant magnetization of the rock, a key aim of palaeomagnetic analysis is to distinguish between primary and secondary components of magnetization. Two basic methods are employed, alternating field (AF) and partial thermal demagnetization. In continental red beds lithofacies, thermal demagnetization is considered the most appropriate because of the high coercivity of the main magnetic mineral, haematite ($Fe_2 0_3$). The specimens are heated in a stepwise fashion (usually 50^0 intervals) and allowed to cool in magnetic «field free» space. The susceptibility and NRM are remeasured after each step and the results plotted so that directional and intensity changes may be analysed. The plots include a stereographic projection which shows declination relative to the orientation line and inclination relative to

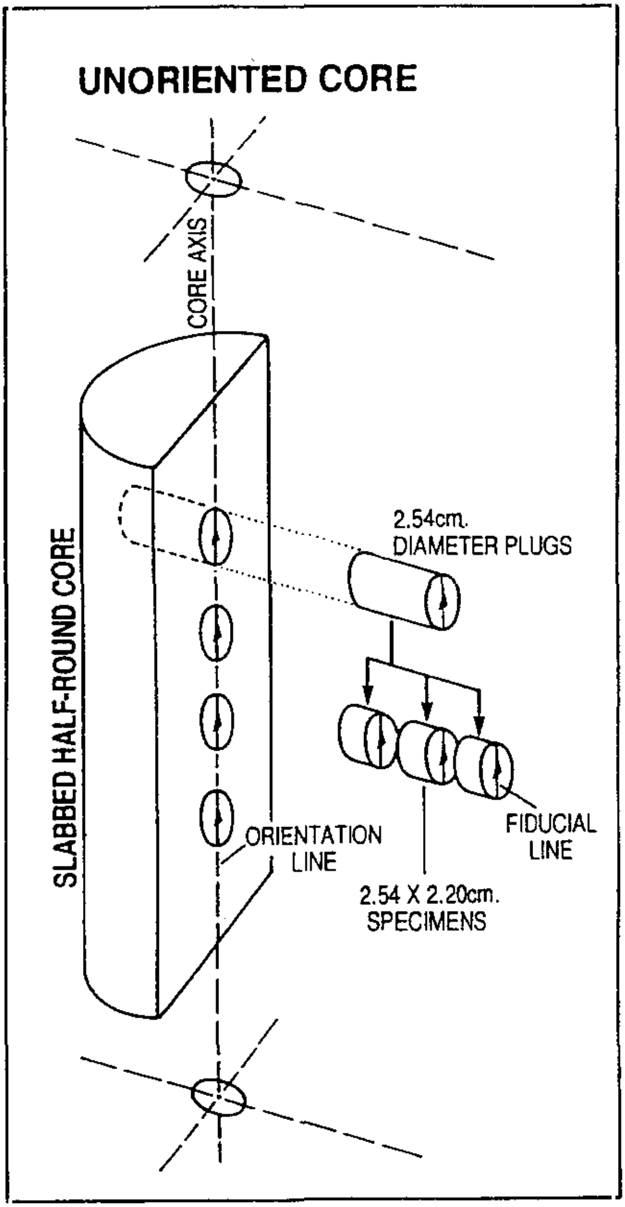
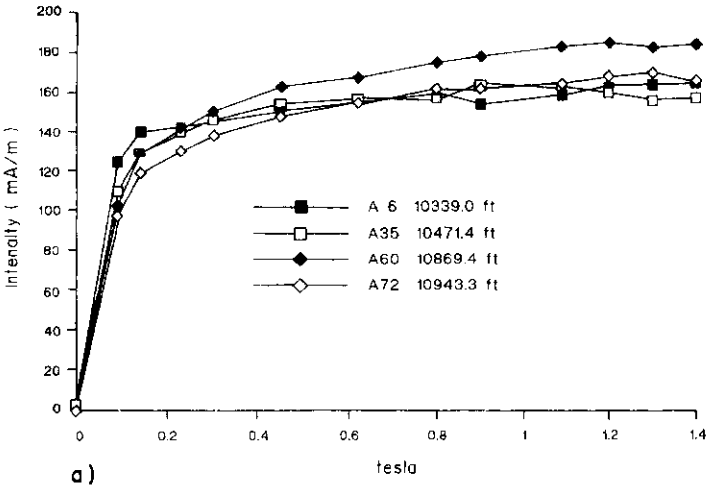


Fig. 5.—Method of Palaeomagnetic sampling of unorientated core. (reproduced from Rey 1992).

Fig. 5.—Método de muestreo paleomagnético en testigos no orientados (reproducido de Rey 1992).



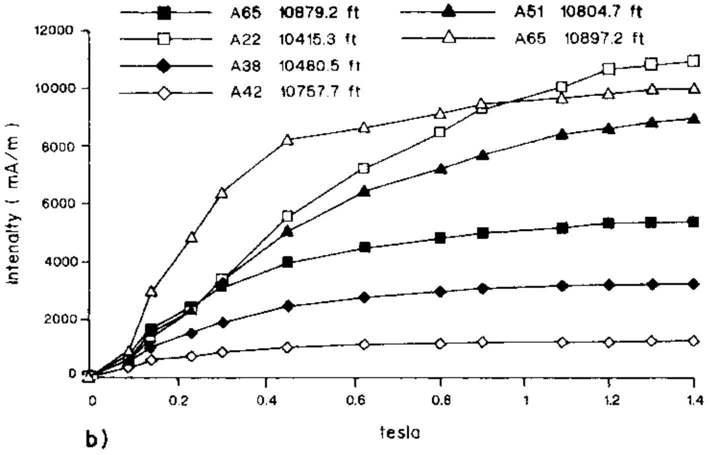
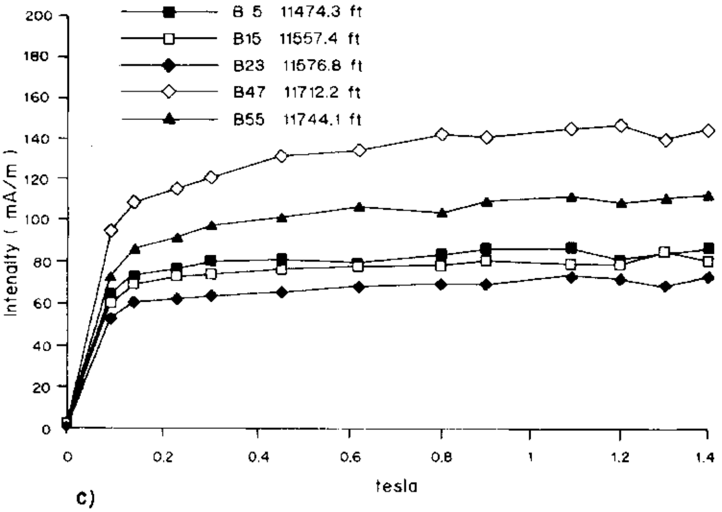


Fig. 6a.—Isothermal Remanent Magnetization diagram for well 22/5b-5 displaying magnetite-dominated samples,

Fig. 6a.—Diagrama de Imanación Remanente Isotérmica para el sondeo 22/5b-5. Las muestras están dominadas por Magnetita.

Fig. 6b.—Isothermal Remanent Magnetization diagram for Well 22/5b-5 displaying haematite-dominated samples.

Fig. 6b.—Diagrama de Imanación Remanente Isotérmica para el sondeo 22/5b-5. Las muestras están dominadas por Hematita.



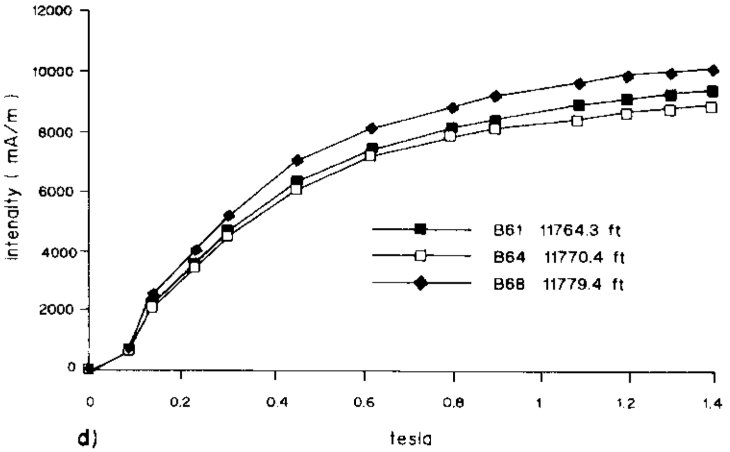


Fig. 6c.—Isothermal Remanent Magnetization diagram for Well 22/19-1 displaying magnetite-dominated samples.
Fig. 6c.—Diagrama de Imanación Remanente Isotérmica para el sondeo 22/19-1. Las muestras están dominadas por Magnetita.

Fig. 6d.—Isothermal Remanent Magnetization diagram for Well 22/19-1 displaying haematite-dominated samples
Fig. 6d.—Diagrama de Imanación Remanente Isotérmica para el sondeo 22/19-1. Las muestras están dominadas por Hematita.

the palaeohorizontal (bedding), a normalized plot of intensity decay versus temperature and an orthogonal (vector) plot. The latter is most useful in distinguishing primary and secondary magnetizations because individual components plot as straight fine segments.

Typical Triassic inclinations for the Central North Sea area plot between $20\text{-}50^0$, the range in values reflecting the relatively rapid northward movement of the UK/North Sea area during the Triassic (Johnson, 1993, Johnson *et al.*, 1995). Secondary components overprinting the primary Triassic inclinations are in the order of $50\text{-}70^0$ for Tertiary or Recent magnetizations induced during diagenesis and oil residence. Viscous components induced by the drilling process plot steeply ($>75^0$). The use of orthogonal diagrams during the interpretation stage enables distinction between the diiferent types of magnetisations from their inclination characteristics. Once the primary components of magnetization have been recognized they can be plotted up onto the core to reveal which parts of the section were deposited during periods of normal magnetic polarity and those deposited during periods of reversed magnetic polarity. Components with positive inclination are judged to be of normal polarity and those with negative inclination of reversed polarity. Characteristic patterns of normal and reversed polarity may then allow well-to-well correlation of core material.

MAGNETIC MINERALOGY

The magnetic mineralogy of the specimens was determined by bulk rock magnetic measurement together with reflected light microscopy. Curves showing the acquisition of isothermal remanence are shown in Fig. 6. The results indicate a wide range of behaviour but in general there is a marked contrast in behaviour in sediments of different colours. The red units show much higher values of saturation remanence (SIRM) (up to 10,000 mA/m) and show no sign of complete saturation. This is consistent with the presence of relatively large amounts of haematite. Drab units have much lower SIRM's (up to 180 mA/m) and approach saturation values at fields of less than 0.2Tesla (Fig. 6). In reflected fight microscopy there are also marked differences in the two types of units.

Red units show abundant coarse grained (specular) and fine grained (pigmentary) haematite. Specularite grains are typically 80-100 mm in diameter and comprise haematite and haematite with ilmenite exsolution lamellae.(Fig. 7) A common grain type are phylloslicates (biotites) partially to completely replaced by haematite (Turner and Archer 1977). The specular grains are smaller than the associated siliciclastic particles and may show a «floating grain» texture. This texture clearly shows that these detrital grains were capable of post-depositional rotation within the fixed framework of coarser grains and could thus generate a PDRM, as described previously.

In contrast, the drab units have little or no visible haematite. Titanium oxides are abundant as an authigenic component but no magnetic oxides have been positively identified in these specimens. The IRM curves and petrographic evidence indicate that drab units may have been strongly leached by aggressive reducing fluids. The difference in magnetic mineral character may be due to the fact that the IRM's reflect magnetite or other relatively magnetically soft minerals which are present within rock fragments and were thus protected from leaching. Although the drab colouration can be attributed to acidic fluids associated with oil emplacement we have not observed directly under the microscope any authigenic oxides or sulphides formed as a result of this process.

Fig. 8 shows normalized intensity decay curves and changes of intitial susceptibility with respect to temperature. The intensity decay curves allow some assessment to be made of the magnetic grain size variations within the specimens. Specimens with relatively large amounts of specularite are characterized by unblocking temperature spectra which are thermally discrete . Pigmentary-haematite dominated specimens, on the other hand have unblocking temperature spectra which are thermally distributed; these specimens are more susceptible to secondary remagnetization although in general different components of magnetization can be easily separated by vectorial analysis (see late section).

RESULTS AND INTERPRETATION

Four types of magnetization have been defined on the basis of directional and intensity changes during partial thermal demagnetization.

Type I: Comprising a single component of magnetization with moderate inclination of +/-20^0-50^0 Such components generally have thermally discrete blocking temperature spectra. Type I magnetizations are interpreted as Triassic PDRM's or DRM's carried by specularite.

Type II: Comprising two components with a low unblocking temperature component superimposed on a Type I magnetization. The secondary component has variable orientation and may be drilling or plugging induced. In Type II magnetizations the break in the unblocking temperature spectra is very sharp and the two components are easily distinguished.

Type III: Magnetizations consisting mainly of a steeply inclined low temperature component superimposed on a weak higher temperature component with shallower inclination. The inclination of the primary component is difficult to distinguish because of chemical changes at higher temperature although its polarity can be determined by extrapolating reliable high temperature results to the origin (theoretical point at which no magnetization exists). In most cases iron mineral transformation occurs before complete demagnetization of the sample.

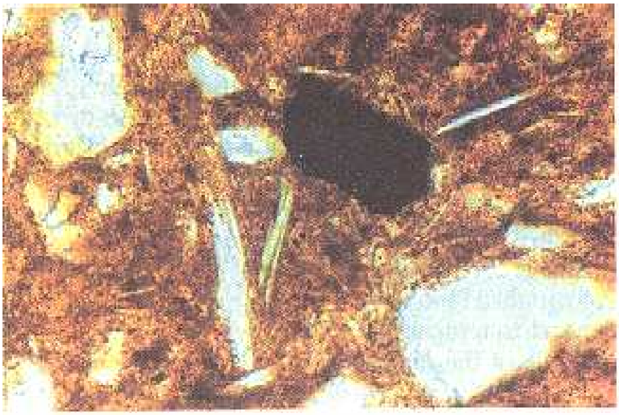


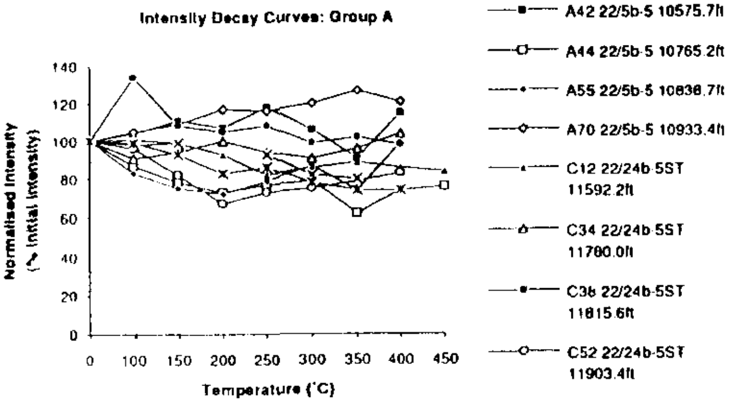
Fig. 7a.—Detrital haematite as seen in transmitted light (Sample: C47, Well 22/24b-5ST,Core Depth 11882.3ft)
Fig. 7a.—Hematita detrítica en luz transmitida (Muestra C47, sondeo 22/24b-5ST. Profundidad: 11882,3 pies)

Fig. 7b.—Detrital haematite with large exsolution discs of ilmentita. (Sample:A17, Well 22/5b-5, Core depth: 10398.0 ft)
Fig. 7b.—Hematita detrítica en la que se observan discos de exolución de ilmenita (Muestra A17, sondeo22/5b-5. Profundidad: 10398,0 pies)

Fig. 7c.—Martite grain with a typical triangular alteration pattern formed.by the alteration of magnetite or maghemite to haematite. (Sample: C47, Well 22/24b-5ST, Core Depth 11882.3ft)
Fig. 7c.—Grano de Martita con la típica textura de alteración triangular deformada durante la alteración de Magnetita o Maghemita a Hematita (Muestra C47, sondeo 22/24b-5ST. Profundidad: 11882.3 pies)

Fig. 7d.—Detrital phyllosilicate which has been extensively replaced by haematite prior to final deposition due to its overall rounded apperence. (Sample A8, Well 22/5b-5 Core depth 10362.0ft)
Fig. 7d.—Filosilicato detrítico reemplazado extensivamente por Hematita con anterioridad a su sedimentación debido a su forma redondeada (Muestra A8, sondeo 22/5b-5. Profundidad: 10362.0 pies)

8a: Representative intensity decay curves for Group A demagnetisation.



8b: Representative intensity decay curves for Group B demagnetisation.

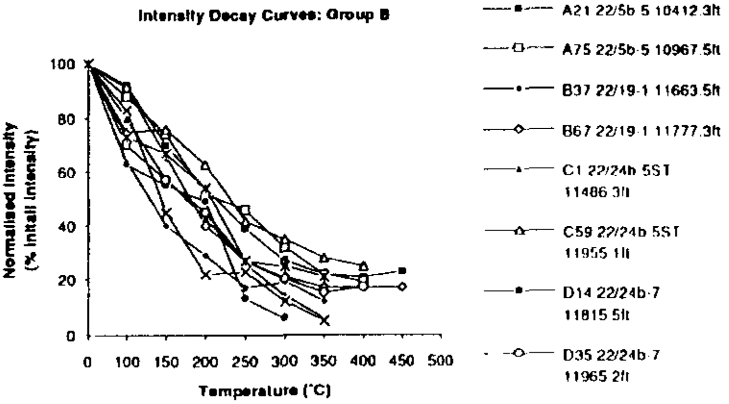


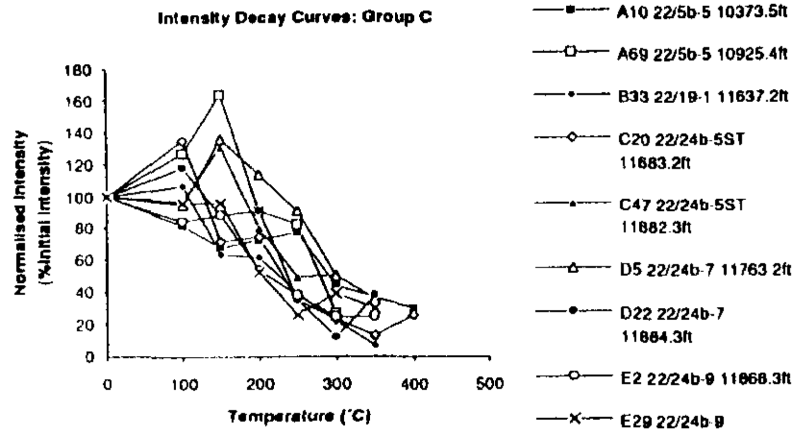
Fig. 8.—Representative Intensity Decay Curves and susceptibility variations during thermal demagnetization

Fig. 8.—Curvas típicas de disminución de la Intensidad y de los Cambios de Susceptibilidad, durante la desimanción térmica.

Type IV: Magnetization consisting of a single low unblocking temperature component. Generally Type IV magnetizations have positive, very steep inclinations which lie near the ambient geomagnetic inclination. These are interpreted as viscous remanences. Components which lie near to the vertical are thought to have been influenced by drilling.

Representative results of the partial thermal demagnetization are shown in Figures 9 to 12.. Fig. 9 shows typical Type I magnetizations. In both these cases over 75% of the original remanence remains after heating to 500^0 C and

8c: **Representative intensity decay curves for Group C demagnetisation.**



8d: **Representative normalised susceptibility variations during demagnetisation.**

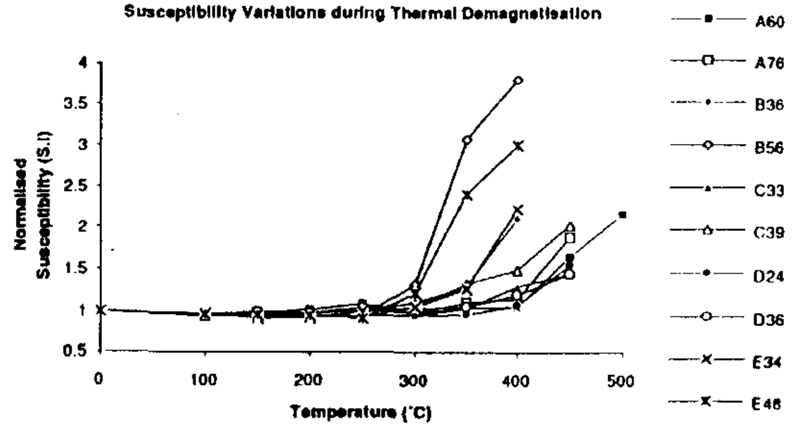


Fig. 8.—Representative Intensity Decay Curves and susceptibility variations during thermal demagnetization

Fig. 8.—Curvas típicas de disminución de la Intensidad y de los Cambios de Susceptibilidad, durante la desimanción térmica.

there is no indication of any significant low temperature component. Above 500^0 C there are substantial changes in NRM intensity and initial susceptibility which indicate chemical changes during the laboratory heating. In 9a the positive inclination includes normal polarity whilst 9b is of reversed polarity

Fig. 10 shows a typical Type II magnetization. In this case there is a marked unblocking temperature at 100^0 C. The direction of the component removed is Dec: 284 °; Inc:+17 °. Such a shallow inclination relative to bedding indicates that this secondary magnetization may have been induced during the plugging process. The high temperature component in this case I has Dec: 148 ° and Inc: +50 °. This component which ranges to 450 °C is interpreted as a Triassic normal magnetization.

A Type III magnetization is illustrated in Fig. 11. In this case the secondary components dominate the NRM but there is a significant amount of primary remanence left which, although difficult to define precisely can generally be used to determine the polarity of the primary magnetization.

Type IV magnetizations are characterized by unblocking temperature spectra in which over 80% of the remanence is lost by heating to 200 °C. Fig. 12 shows a typical Type IV magnetization in which the NRM is dominated by a single steep normal component. Such components are considered to reside in the pigmentary haematite and lie close to the local geomagnetic inclination. They are thus interpreted to be viscous in origin.

Types I, II and III have been utilized to generate the Triassic magnetic reversal stratigraphies for the cores. No attempt has been made to use Type IV magnetizations in the magnetostratigraphic analysis.

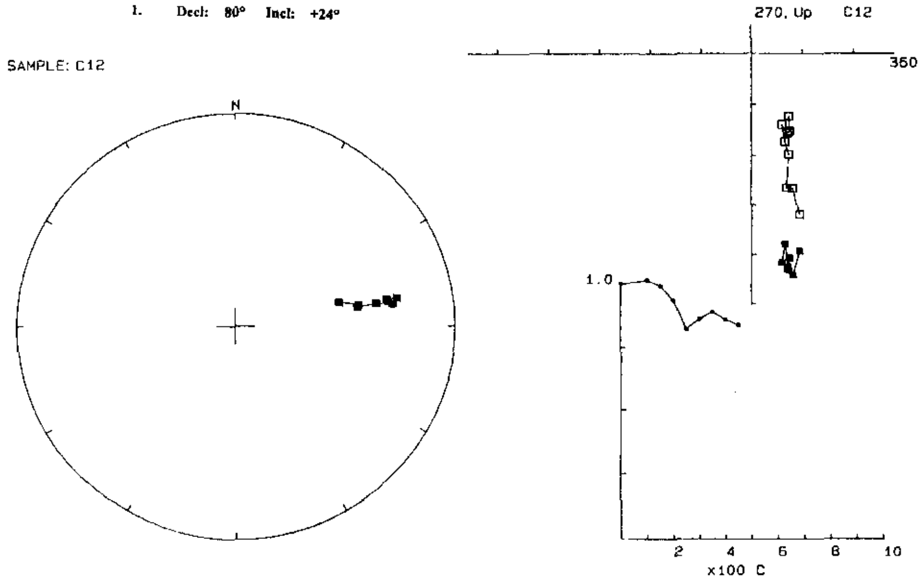


Fig. 9a.—Representative sample of Type I magnetization (C 12 at 11592.2ft from Well 22/24b-5 ST)

Fig. 9a.—Típica muestra en la que se observa una magnetización de Tipo I (C12 a 11592,2 pies. Sondeo 22/24b-5ST)

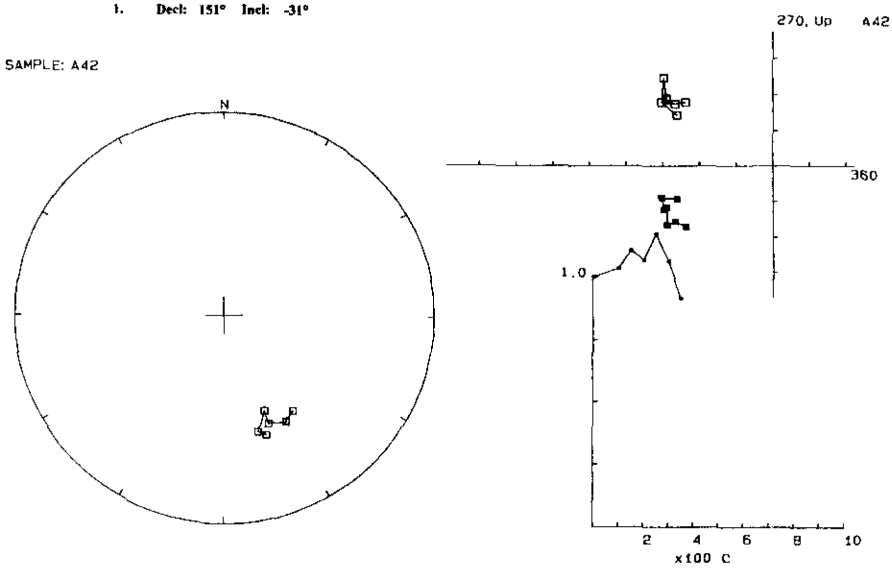


Fig. 9b.—Representative sample of Type I magnetization (A42 at 10757.7 ft from Well 22/5b-5)
Fig. 9b.—Típica muestra en la que se observa una magnetización de Tipo I (A42 a 10757,7 pies. Sondeo 22/5b-5)

MAGNETOSTRATIGRAPHY

Directional components extracted by principal component analysis of Type I and Type II magnetizations in conjunction with polarity determinations from Type III magnetizations were used to generate a magnetostratigraphy for each well. The magneto-polarities are conventionally shown with normal polarity zones in black and reverse polarity zones as white segments. Single sample locations which show opposite polarity are marked as half segments on the magnetopolarity column (Figure 13).

Well 22/5b-5 shows a well defined magnetostratigraphy based mainly on Type I and II magnetizations. Four zones of normal polarity and four zones of reversed polarity have been defined. The magnetostratigraphy for Well 22/5b-5 can be considered well constrained because the samples produced consistent Type I and Type II magnetization results. This is due to the nature of the sampled lithologies which are generally red and fine grained and contain primary magnetic minerals.

Well 22/19-1 is dominated by normal polarity magnetizations but there are a number of apparently short-lived reversals. The magnetostratigraphy interpreted for the cored interval of this well is less reliable than well 22/5b-5 due to remagnetizations observed in the samples from the middle section of the cored interval. However, Triassic inclinations extracted in the uppermost and lowermost sections of the core are well constrained.

Four zones of normal and four zones of reversed polarity are also observed in Well 22/24b5 ST. NRM results for Well 22/24b-5 ST suggest that the majority of samples from this well have suffered remagnetizations of recent or Tertiary age. This has been supported by the generally poor, quality of the demagnetization data and resulting unreliability of the interpreted magnetostratigraphy. The poor quality of the data may be a result of reduction of primary haematite to magnetite, and remagnetization in the ambient magnetic field, during the residence of a palaeo-oil column. The oil staining found through the majority of the cored interval is evidence for this theory. The abundance of the more insoluble titanium oxides would suggest oil emplacement has resulted in the dissolution of ferric oxides carrying primary remanence.

Well 22/24b-7 displays a predominantly normal polarity magnetization

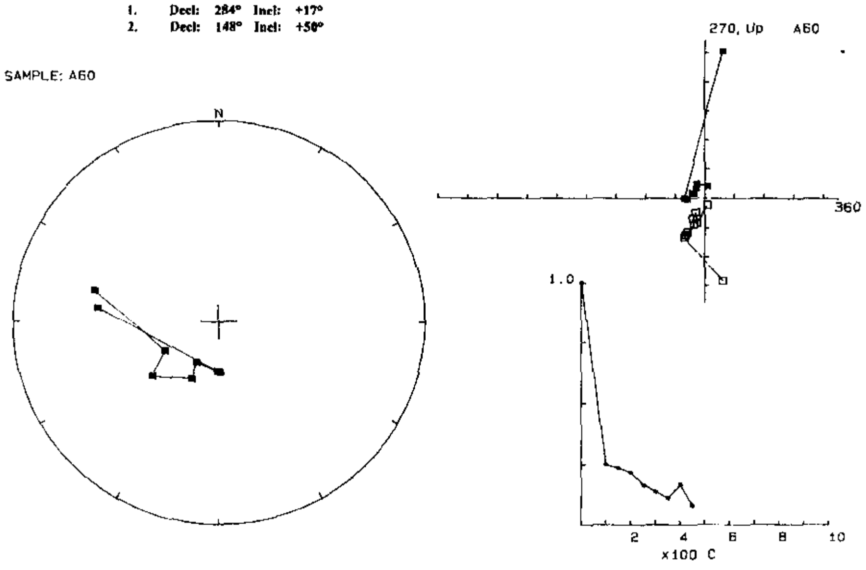


Fig. 10.—Representative sample of Type II magnetization (A60 at 10869.4 ft from Well 22/5b-5)

Fig. 10.—Típica muestra en la que se observa una magnetización de Tipo II (A60 a 10869,4 pies. Sondeo 22/5b-5

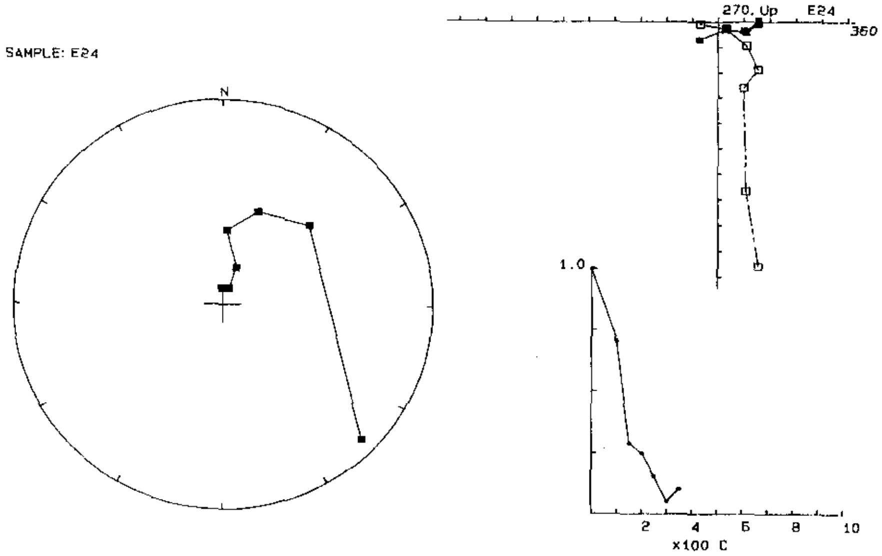


Fig. 11.—Representative sample of Type III magnetization (E24 at 12043.2 ft from Well 22/24b-9)

Fig. 11.—Típica muestra en la que se observa una magnetización de TipoIII (E24 a 12043,2 pies. Sondeo 22/24b-9)

comprising of two thick normal zones and one thin reversed polarity zone. The normal polarity events are characterized by Type I and II magnetizations while the reversed polarity event is defined by less reliable Type III magnetizations.

The cored interval in Well 22/24b-9 is similar to that of Well 22/24b-7 with two zones of normal polarity and one zone of reversed polarity.

In general terms the magnetostratigraphy of the cored intervals can be said to be of mixed polarity. The chron boundaries are reasonably well defined but because of the remagnetization in drab coloured units and those dominated by pigmentary haematite some of the thicker normal polarity events must be considered to have less reliability.

COMPARISON OF DEPOSITIONAL SEQUENCE CORRELATION AND MAGNETOSTRATIGRAPHY RESULTS

Figure 13 illustrates how the depositional sequences within the study wells compare with the magnetostratigraphies of the cored intervals within

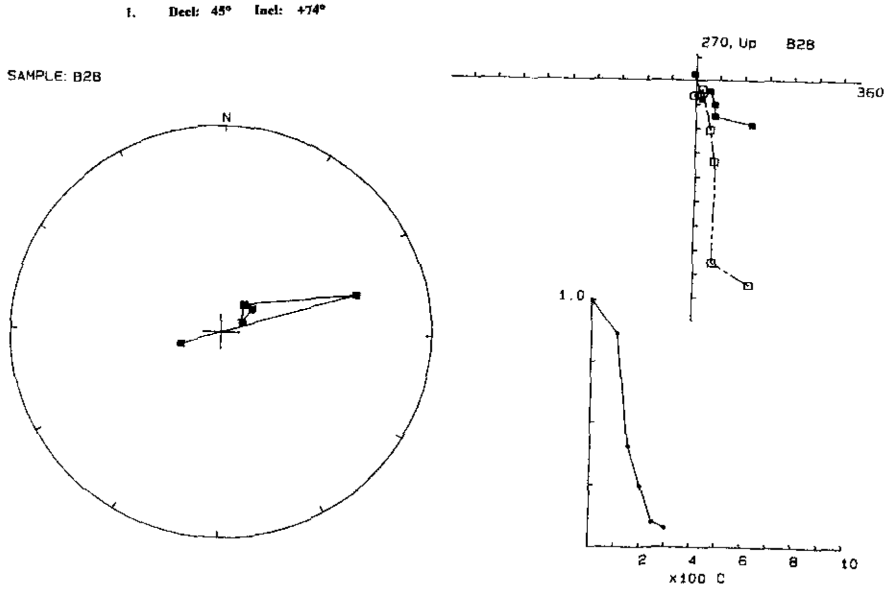


Fig. 12.—Representative sample of Type IV magnetization (B28 at 11613.0 ft from Well 22/19-1)
Fig. 12.—Típica muestra en la que se observa una magnetización de Tipo IV (B28 a 11613,0 pies. Sondeo 22/19-1)

each of the wells. The main observations to be drawn from the comparison are as follows:

* In Well 22/24b-5ST the boundary between TR2 and TR3 is accompanied by two, short period reversed polarity zones (sub-chrons): one on the boundary and one just below the boundary.

* In Well 22/24b-7 a short period reversed zone occurs at a similar position beneath the boundary pick as in Well 22/24b-5 ST, although no reversal has been picked up on the boundary itself

* Thin reversed zones are present just above the TR2/3 boundary in Wells 22/5b-5 and 22/19-1. A reversal in Subsequence TR3a from 22/19-1 correlates with one in the TR3 a interval from 22/24b-5 ST.

The magnetostratigraphy of the cored interval in Well 22/24b-9 differs from that encountered in the two nearest Wells (22/24b-5ST and 22/24b-7). The magnetozonation of the cored interval from 22/24b-9 does not correlate, however, with the zones from the lower cored section in 22/5b-5, which were originally interpreted to be from a stratigraphically equivalent section (Subsequence TR2b).

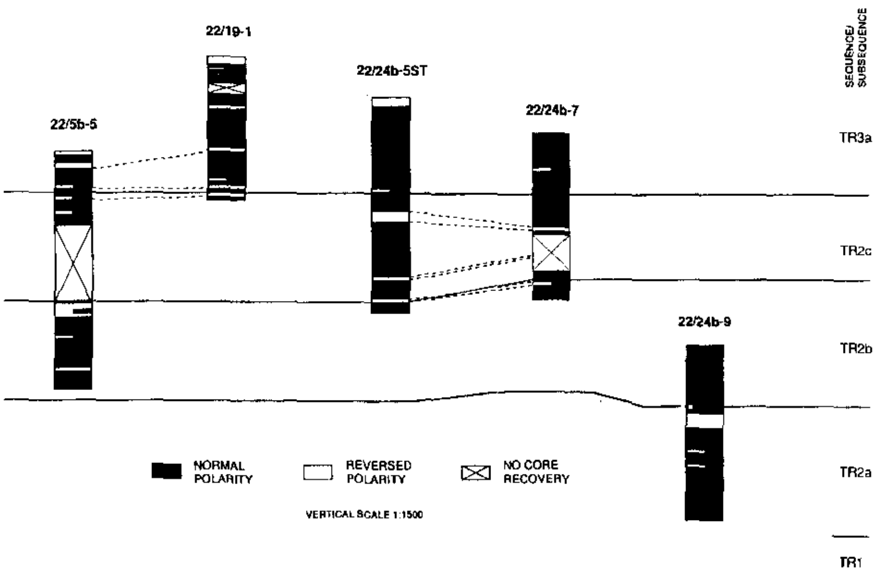


Fig. 13.—Magnetostratigraphy correlation using GAPS stratigraphic subdivision.
Fig. 13.—Correlación magnetoestratigráfica utilizando la subdivisión estratigráfica de GAPS.

DISCUSSION

From the above the following points can be made:

1. The hypothesis that TR2/TR3 boundary is of chronostratigraphical significance is, in part, supported by the magnetostratigraphic correlation of Wells 22/24b-5ST and 22/24b-7.

2. Similar short period double reversal zones similar to that found in association with the TR2/3 boundary in 22/24b-5ST are also found in cores from 22/5b-5 and 22/191. However, in both these wells the reversals occur above the interpreted TR2/3 boundary. Two possible explanations for this can be offered:

a) the boundary «lake margin flooding surface» between TR2 and TR3 is older in wells 22/19-1 and 22/5b-5 than in 22/24b-5ST and 22/24b-7

or b) the interpreted TR2/3 boundary in wells 22/19-1 and 22/5b-5, and therefore the overall depositional sequence subdivision, is not compatible with that interpreted for 22/24b-5ST and 22/24b-7.

3. The apparently older nature of the TR2/3 boundary offered in Scenario 2a above is inconsistent with the regional depositional model which predicts the progressive retreat of the alluvial system away from the basin centre (i.e. north/northeastwards through Quadrant 22) during depositional sequence retrogradation/relative base level rise. The possibility that the TR2/3

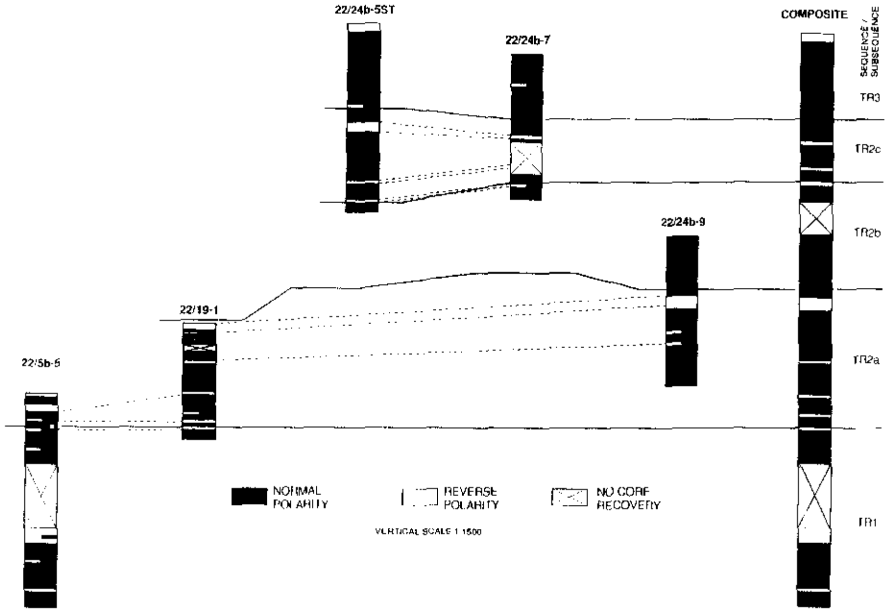


Fig. 14.—Magnetostratigraphy correlation using revised GAPS stratigraphic subdivision.
Fig. 14.—Correlación magnetoestratigráfica utilizando la subdivisión estratigráfica de GAPS revisada.

depositional sequences defined in both 22/5b-5 and 22/19-1 are different to those in 22/24b-5ST and 22/24b-7 must therefore be considered. This explanation is further supported by the fact that the TR2b magnetozonations from Wells 22/5b-5 and 22/24b-9 show little similarity (see Figure 13).

If the above is true, then an alternative correlation to the facies based scheme must be sought. In this respect, the most logical correlation is to make the TR2/3 boundary in 22/19-1 and 22/5b-5 equivalent to the TRI/2 boundary in Wells 22/24b5ST, 22/24b-7 and 22/24b-9 (see Figure 14). In this scenario, magnetostratigraphies in 22/19-1 in particular should equate with those found from the cored interval taken from ubsequence TR2a in well 22/24b-9 (the stratigraphic subdivision of this well appears to be well constrained by wireline log correlation with nearby wells 22/24b-5 ST and 22/24b-7).

4. Inspection of Figure 14 reveals good correlation between the magnetozonations in 22/19-1 and 22/24b-9 at the TR2a level. Reversed magnetozones correlate as do two half block reversals determined by single sample locations beneath. It can therefore be argued that the original subdivision of Well 22/19-1 was miscorrelated by a factor of one major depositional sequence and indeed the wireline log data do not contradict this interpretation. In ad-

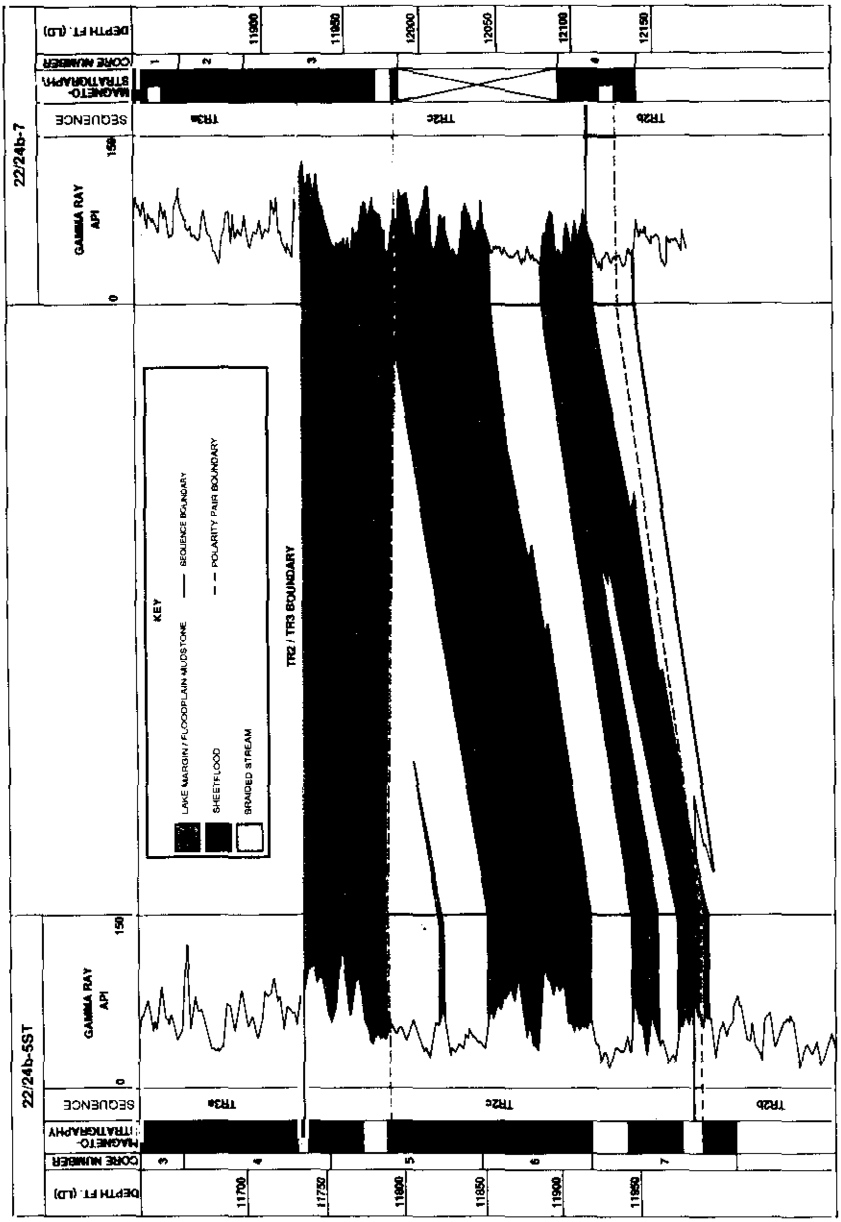


Fig. 15.—Magnetostratigraphically constrained lateral facies relationship between Wells 22/24b-5ST and 22/24b-7 for subsequences TR2c and TR2b (top).

Fig. 15.—Relación lateral de facies entre los sondeos 22/24b-5ST y 22/24b-7 para las subsecuencias TR2c y TR2b (arriba), acotada magnetoestratigraficamente.

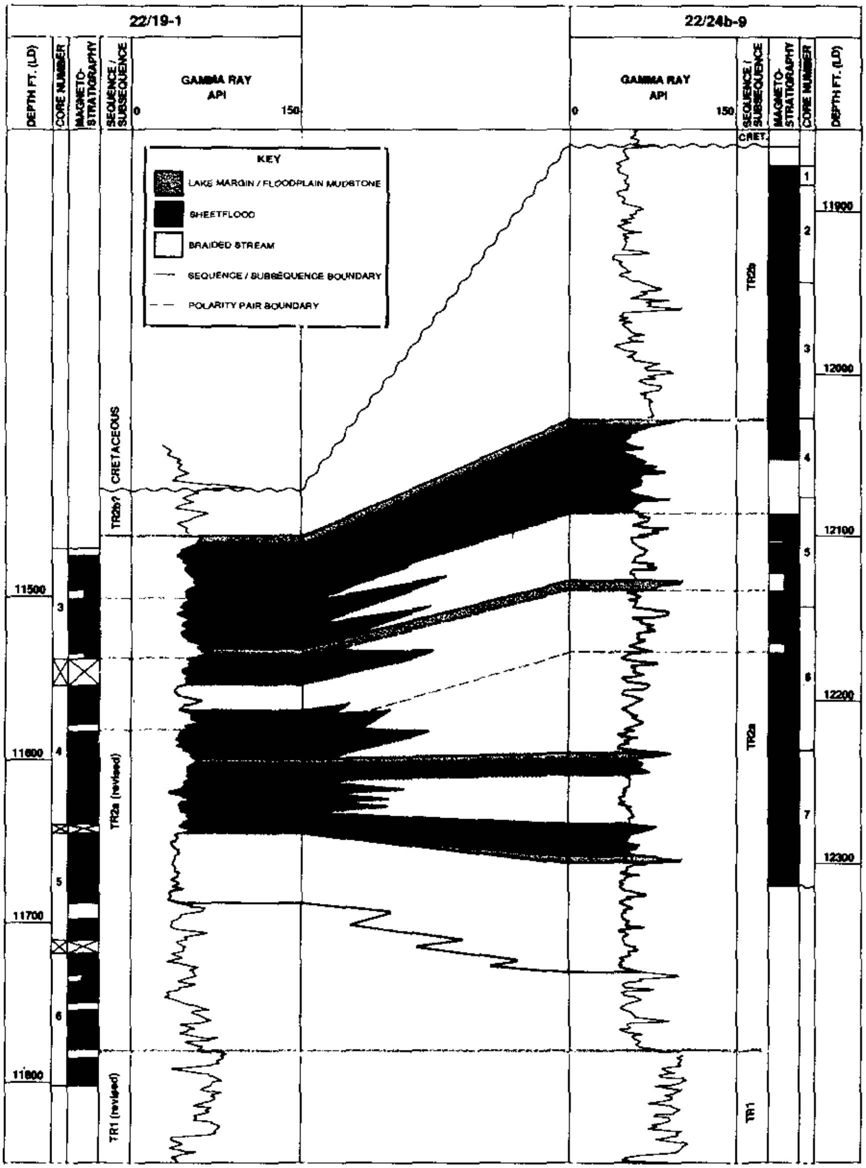


Fig. 16.—Magnetostratigraphically constrained lateral facies relationship between Wells 22/19-1 and 22/24b-9 for subsequences TR2a. (NB: TR2a subdivision for Well 22/19-1 is based on revised well stratigraphy.)

Fig. 16.—Relación lateral de facies entre los sondeos 22/19-1 y 22/24b-9 para las subsecuencias TR2a , acotada magnetoestratigraficamente. (Nota: la subdivisión del sondeo 22/19-1 se basa en una estratigrafía revisada de dicho sondeo).

dition, given the good correlation between the magnetostratigraphies of Well 22/19-1 and the upper cored interval of Well 22/5b-5, it is also proposed that the sequence subdivision of the latter well be adjusted in the same way.

5. Using the correlation proposed above (i.e. with revised stratigraphies for Wells 22/5b-5 and 22/19-1), a composite magnetostratigraphy can be derived for the TRI, TR2 and TR3 sequences, Figure 14) The rapid reversal stratigraphy observed in the composite magnetostratigraphy for the TR2a/2b section in this study does compare well with the published GPTS for the Anisian to Ladian section (Molina-Garza *et al.*, 1994)

IMPLICATIONS OF THE MAGNETOSTRATIGRAPHIC RESULTS FOR SEDIMENTOLOGY AND RESERVOIR ARCHITECTURE

By integrating the sedimentological interpretations, the sequence stratigraphy and the magnetostratigraphic results it is possible to model the lateral and vertical variation in facies (particularly reservoir heterogeneity and sand body interconnectivity) at a relatively local scale. Although this exercise is limited in its extent within the context of this study, it nevertheless illustrates how the technique can be used to improve definition of reservoir architecture and thus has important implications for potential Triassic field appraisal and development strategies in the Central North Sea province.

Given the limitations of the dataset used in this study, two different well-to-well correlations have been used to demonstrate the potential of the technique:

a) Wells 22/24b-5ST and 22/24b-7 for Subsequence TR2c (up to the TR2/3 boundary) (Figure 15)

and b) Wells 22/19-1 and 22/24b-9 for Subsequence TR2b (Figure 16). (N.B. This correlation assumes the revised stratigraphic subdivision of 22/19-1; see Figure 14).

For both correlations the environmental facies interpretation has been derived from the core sedimentology previously interpreted for each well. The final correlation and facies/reservoir architecture presented is as well constrained as possible by wireline log correlation and magnetostratigraphic results.

Both correlations illustrate how considerable vertical and lateral variation in facies can be modelled over relatively short distances within the magnetostratigraphically constrained subsequences. Of particular note is the way that braided channel sandbodies tend to be laterally constrained within the section. This obviously has important implications for both mapping and predicting the distribution of channel fairways which from previous investigation have been proven to be of best reservoir potential. Sheetflooding events in contrast are generally revealed to be laterally persistent although in certain sections the correlations show how they can be interpreted as laterally equivalent «overbank» facies to braided channels. The latter point is important as the lateral variation in time-equivalent facies while determine the precise internal architecture of a potential reservoir interval. In this respect the ability to place magnetostratigraphic isochrons through the sedimentary section is crucial.

The lateral persistence and chronostratigraphic significance of mudstone horizons within any sequence/subsequence can also be investigated in this way enabling the testing of the depositional sequence model. The association of a reversal event with a correlatable mudstone in Subsequence TR2a in wells 22/19-1 (11550 ft) and 22/24b-9 (12137 ft) illustrates this point well, giving extra confidence to the depositional sequence model as well as revealing the lateral persistence of the mudstone (at least at the local scale). In contrast, the comparison of the palaeomagnetic signature of the mudstone used to pick the TR2b/2c boundary in wells 22/24b-5ST and 22/24b-7 reveals a distinctive discrepancy in polarities, with a reversal event in the mudstone in 22/24b-5ST equating with a reversal event in a channel sand below the mudstone in 22/24b-7. Some minor diachroneity of the mudstone at the local scale is therefore indicated in this case.

Other information which may be gleaned from the magnetostratigraphic technique include details on sedimentation rates, although in this study the correlations suggest relatively uniform thicknesses for each depositional sequence/subsequence in each of the study wells. Nonetheless the technique may provide extremely useful information in areas of variable salt withdrawal and pod development where there can be marked lateral thickness variation of the preserved sediment over a given time interval.

CONCLUSIONS

The main conclusions to arise from this study of the Triassic in the Central Graben of the North Sea are:

* It is possible to recognize palaeomagnetic reversals and construct magnetostratigraphies for all the cored intervals from the five wells.

* Using the magnetostratigraphies generated for each well, it is possible to test, constrain and refine previously established stratigraphic schemes and correlations, the approach is particularly useful in the Triassic in the Central North Sea where poor biostratigraphic control limits the confidence of the original stratigraphy.

* A basis for a reference magnetostratigraphy for part of the Triassic using periods of normal and reversed polarity has been constructed.

* On a local scale, it is possible to apply the magnetostratigraphies along with the facies based stratigraphic scheme to further facilitate Triassic field appraisal and development.

ACKNOWLEDGEMENTS

This paper is dedicated to Amparo. She showed us the beauty of Spain.

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