POST-DRILLING ANALYSIS OF THE NORTH FALKLAND BASIN - PART 1: TECTONO-STRATIGRAPHIC FRAMEWORK

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Six wells were drilled in the extensional North Falkland Basin in 1998. The wells encountered a Devonian to Cenozoic stratigraphy dominated by thick Mesozoic syn- and post-rift successions. Although most previously published models predicted that the succession would most likely be of marine origin, it is in fact predominantly terrestrial; marine conditions did not become established in the basin until the Late Cretaceous. The oldest rocks recorded are Devonian, and these were penetrated in only one well. The overlying succession comprises: a fluvio-lacustrine, early syn-rift interval of ?mid Jurassic to Tithonian age; a late syn-rift fluvio-lacustrine interval of Tithonian to Berriasian age; a rift-sag transitional unit of Berriasian to Valanginian age; an early post-rift lacustrine unit of Valanginian to early Aptian age; a middle post-rift, transgressive unit of Aptian to Albian age; a late post-rift, terrestrial to marine unit of Albian to early Palaeocene age; and a postuplift thermal subsidence unit of Palaeocene to Recent age.

Much of the sediment appears to have been derived from volcanic and/or metamorphic terranes, probably located to the north or NW of the basin. As well as the volcanic material which occurs in the ground mass and as lithoclasts in many of the units, some volcaniclastic rocks and minor amounts of ashfall tuffs are observed, particularly within the late syn-rift succession.

INTRODUCTION

This paper summarises the stratigraphy of the six exploration wells which were drilled in the North Falkland Basin in the period April to November 1998 (Fig. 1 and Table 1). On the basis of these wells and an extensive database of seismic reflection profiles, a new tectono-stratigraphic framework is erected to describe the evolution of the basin and provide a predictive model to aid further exploration. Changes in our understanding of the petroleum geology and remaining exploration potential of the basin resulting from this drilling campaign are discussed in Part 2 of this paper.

The regional geology and palaeogeographic evolution of the offshore Falkland Islands has been well documented (Richards and Fannin, 1994; Richards, 1995 and 1997; Lawrence and Johnson, 1995; Platt and Philip, 1995; Richards *et al*., 1996 a and b; Richards and Fannin 1997). Four Mesozoic- Cenozoic sedimentary basins surround the Falkland Islands (Fig. 1; see inset). The Falkland Plateau Basin, Malvinas Basin and South Falkland Basin lie to the east, west and south of the islands respectively, while the North Falkland Basin lies directly to the north.

The reader is referred to papers by Richards *et al*. (1996 a and b), Richards and Fannin (1997), Thomson and Underhill (1999), Bransden *et al*. (1999) and Lawrence *et al*. (1999) for differing overviews of the structural and stratigraphic setting of the North Falkland Basin, and the associated main rift zone, which was termed the North Falkland Graben by Richards and Fannin (1997). Although these papers were compiled before drilling started many, but by no means all, of the conclusions and interpretations presented in each paper remain valid following the 1998 drilling campaign. The biggest changes in understanding resulting from drilling concern the basin's stratigraphy, sedimentary geology and petroleum system mechanics.

Richards *et al*. (1996a and b) and Richards and Fannin (1997) suggested that the infill of the North Falkland Basin may be analogous to the successions observed to the west, in the San Jorge Basin of Argentina, described by Fitzgerald *et al.* (1990). The analogue has proved to be a reasonable one, since both basins appear to be dominated by fluvio-lacustrine sediments until quite late in their development. Other nearby Argentine basins, particularly the offshore Malvinas Basin and the San Julian Basin proved, after drilling, to have very little similarity to the stratigraphy observed in the North Falkland Basin. Figueredo *et al.* (1996) noted that, before drilling of the San Julian Basin, which lies just to the west of the North Falkland Basin, that it was anticipated that it also would have an infill comparable to that of the San Jorge Basin. However, drilling there proved that the succession was different in many respects, with a rift to sag transition occurring much later than in the San Jorge Basin. The San Julian Basin exhibits more in common with the stratigraphy of the Deseado Masssif which separates the Malvinas and Magellanes Basins (Figuerido *et al*., 1996), and is unlike the drilled succession in the North Falkland Basin.

The North Falkland Basin lies beneath 150 m to 2,000 m of water. It consists of a complex system of offset depocentres following two dominant structural trends (NW-SE and north-south), and displays a structural style quite different to the other offshore Falkland Islands basins. Its margins are mostly faulted (Fig. 1), and it is surrounded by a structural platform composed probably of Devonian sedimentary rocks. The geometry and tectonic evolution of the basin was documented by Richards and Fannin (1997), who noted that two major depocentres, the Western Depocentre and the Eastern Depocentre, are separated by a faulted ridge termed the Intra-Graben High. Another fault-bounded high within the Western Depocentre is here referred to as the Minke High. The Intra-Graben High appears to have been a positive feature influencing sedimentation during much of the basin's evolution. The Minke High appears to have been emergent, and the site of non-deposition, throughout the deposition of the syn-rift succession and through into the early part of the post-rift phase.

Richards *et al.* (1996 a and b), Richards and Fannin (1997), Thomson and Underhill (1999) and Bransden *et al*. (1999) noted that the infill of the North Falkland Graben could be subdivided into tectono-sedimentary units on the basis of seismic geometries. These authors recognised various rift and post-rift phases, and assigned tentative ages to their units on the basis of correlations with offshore Argentine and South African basins. Elements of each of the predicted basin-infill models appear to be confirmed by drilling.

Six wells were drilled in the North Falkland Graben in 1998; three were drilled in the Eastern Depocentre (14/5-1A, 14/10-1 and 14/24-1), two on the Intra-Graben High (14/9-1 and 14/9-2), and one on the Minke High in the Western Depocentre (14/13-1). The wells allow significant refinements to be made to the original models of the tectono-stratigraphic history of the basin.

MATERIALS AND METHODS

The collection of a full suite of downhole logs was attempted in each well, although technical problems with hole-integrity resulted in the abandonment of a some logging runs, particularly in the deeper part of Well 14/13-1. A full set of wet and dried cuttings, rotary- and percussion side-wall core samples were collected from each well, and three conventional cores were cut: two from Well 14/9-1 and one from Well 14/24-1. Biostratigraphical analyses were carried out at the well site whilst drilling, and/or at various specialist contractor's laboratories; post-drilling biostratigraphical analyses were made at two different laboratories. The results were variable, with no consistent age determinations made for different stratigraphic units by different investigators analysing palaeontological and palynological data from different wells. Thin section and XRD petrological studies were conducted by all the drilling companies, at a number of contractor's laboratories, whilst sedimentological studies were undertaken by some of these labs and by the authors. Detailed matching of mineralogy and lithology to wireline log response was undertaken by the drilling companies in order to calibrate the downhole logs. Heavy mineral analysis of one complete well (14/9-1) was undertaken by the British Geological Survey in order to determine the provenance area for the sediments, and to determine the likely contribution from the Falkland Islands themselves.

The stratigraphic correlation and subdivisions used in this paper are defined using a framework based on seismic stratigraphy and seismic geometry, established as a result of interpreting and mapping all of the speculative and proprietary data in the basin (over 20,000 km of 2D data plus over 300 km^2 of 3D data). The major bounding surfaces of the tectono-stratigraphic units defined below are based on the identification of regionally mappable unconformities and correlative unconformities observed across the basin. The mapped seismic horizons were tied to well logs and lithology, as well as to the biostratigraphy framework (where sufficient data were available), in order to define meaningful correlation units.

STRATIGRAPHY OF THE NORTH FALKLAND BASIN

Eight widely correlatable tectono-stratigraphic units are now recognised in the basin (Figs. 2 and 3). Each of the seismically-identified sequence boundaries defining the units has been tied to the downhole logs in the six wells. The eight major units can be subdivided, with the recognition of eight sub-units of basin-wide significance, but which do not coincide with changes in the tectonic regime. These sub-units are termed LC2, UC1, etc, with the abbreviations indicating relative ages, such that LC2 is Lower Cretaceous sub-unit 2 and UC1 is Upper Cretaceous sub-unit 1, etc. The sub-units form distinct sequences and/or parasequence sets in their own right, and are bounded by seisimic reflectors that separate intervals with different depositional environments, reflecting changes in the basinwards or landwards shift of facies belts, as well as changes in stacking patterns and in the nature of the seismic offlaps, downlaps or terminations observed at their boundaries. The sub-units lie within the regionally-mappable, seismically-defined tectono-stratigraphic units, and their detailed description is beyond the scope of this paper.

The eight tectono-stratigraphic units recognised are: a pre-rift sequence; an early syn-rift interval; a late syn-rift interval; a transitional unit; an early post-rift interval; a middle post-rift interval; a late post-rift interval; and a post-uplift sag unit. The eight tectono-stratigraphic units identified in the North Falkland Basin are described in turn below.

The pre-rift interval (Devonian)

The pre-rift interval was encountered only in Well 14/9-1 on the crest of the Intra-Graben High (Figs. 2 and 3), which penetrated 49 m of the unit. This cannot necessarily be considered typical of the Devonian succession elsewhere in the basin, nor of pre-rift rocks in general in the region. For example, Galeazzi (1998) noted that the pre-rift succession in the Malvinas Basin to the SW consists of low grade meta-sedimentary rocks and granites.

The unit lies beneath a prominent, high-amplitude reflector some 0.38 s TWT below the crest of the Intra-Graben High, and appears to form the buried core of the high. The reflector can be mapped into deeper parts of the basin, where it is interpreted to represent the base of the Mesozoic sedimentary succession. The top of the unit is picked at a downwards increase in bulk density and a decrease in interval transit time (Fig. 2), as well as at a downwards change in dip direction from 180° to about 50°. It is defined by the downwards transition from Jurassic or indeterminate Mesozoic rocks to Devonian sedimentary or metasedimentary rocks.

Lithology

The only thin section sample shows a moderately well sorted silty mudstone with subrounded to subangular grains, a weak to moderate compaction fabric and some evidence of low angle laminations defined by accumulations of silt sized grains. The detrital mineralogy is dominated by illitic clays, with abundant carbonaceous material, and more minor amounts of monocrystalline quartz, muscovite, biotite and chlorite.

Palynology

Some unidentifiable and poorly preserved spores of terrestrial origin were recorded, together with a single Palaeozoic marine algal specimen.. All the palynological material is in a post-mature state of thermal alteration.

Depositional environment

The palynoflora is dominated by miospores of terrestrial origin suggesting a lacustrine or fluviolacustrine depositional environment, but the occurrence of a single marine alga may indicate at least intermittent marine conditions.

Age

Although only sparse, poorly preserved microfossils have been recovered from this unit, the occurrence of *Emphanisporites* spp and *Perotrilites microbaculatius* suggest a Devonian age.

The early syn-rift sequence (? Mid-Jurassic to ?Tithonian)

This unit was encountered in both Wells 14/9-1 and 14/9-2, drilled respectively on the crest of the Intra-Graben High and in a near-crestal location on its eastern flank, and also in Well 14/5-1A near the centre of the Eastern Depocentre. It is absent at the 14/13-1 locality (Fig. 2), having pinched out westwards onto the Minke High within the Western Depocentre (Fig. 3). The unit lies below TD in Wells 14/10-1 and 14/24-1.

This unit is the lowermost wedging seismic package above Palaeozoic basement. Its top is defined by a high-amplitude seismic marker in the Eastern Depocentre which separates the early and late syn-rift seismic units (Fig. 4). The reflector is not easily identifiable over the crest of the Intra- Graben High, but is recognisable on its eastern flank as an onlap surface.

In both Wells 14/9-1 and 14/5-1A the top of the unit is picked at the base of a relatively low gamma interval which coincides with the top of an interval with a gradual downwards decrease in interval transit time (Fig. 2). The top of the unit corresponds to a downwards decrease in miospore abundance and degree of preservation in the Well 14/9-1. Sidewall core samples from both 14/9-1 and 14/5-1A indicate that kaolinite is virtually absent in this sequence, while illite forms a more pervasive clay phase than in younger units.

Lithology

The sequence varies laterally between Wells 14/9-1, 14/9-2 and 14/5-1A. In Wells 14/9-1 and 14/9–2 drilled on the Intra-Graben High, the unit is dominated by conglomerates, conglomeratic sandstones, sandstones and tuffs with minor quartzites and interbedded claystone. In Well 14/5-1A near the middle of the Eastern Depocentre, the unit comprises mostly silty claystone, with sandstones up to 5m thick. The claystones are silty to very silty, medium brown to white in colour, soft, sticky and plastic. In the lowest part of the sequence at Well 14/5-1A, the claystones contain more tuffaceous material. The sandstones are feldspathic, fine to medium grained, sub-angular to sub-rounded, moderately well sorted, with white calcareous coatings to grains giving a frosted appearance.

Palynology

Palynomorph recovery is significantly poorer in this unit than in the overlying units. Sparse, poorly preserved miospores are characteristic of the unit in the finer grained sediments of the 14/5-1A well. The miospore *Cyclusphaera psilata* is sparsely recorded here, and may be caved. Species recovered include frequent inaperture pollens, rarer, bisaccate pollen, and some pteridophyte spores.

Depositional Environment

The unit was probably deposited in a fluvial or fluvio-lacustrine setting, possibly with alluvial fans shedding sediment into the basin from the marginal faults (Fig. 5). The Intra-Graben High was probably a slight topographic ridge at the time, and is developed to the west of the tilt-fulcrum of the early syn-rift phase in the Eastern Depocentre, which was structurally deepest adjacent to the eastern bounding fault of the basin. This region may have been the locus of fluvial sedimentation at the time, prior to the avulsion of fluvial channels preferentially towards the developing low area adjacent to the eastern bounding fault of the basin. Alternatively, the developing Intra-Graben High may have been the shoreline area of a fluvial/lacustrine depositional environment, and thus received coarser sediment than the central parts of the Eastern Depocentre. The finer grained, claystone dominated succession found in the more centrally located 14/5-1A well possibly represents lacustrine and intermittent fluvial deposition closer to the deepest part of the evolving rift.

Age

Although all taxa recovered are generally long-ranging, they suggest an age no older than Middle Jurassic. Different biostratigraphers examined different sample preparations in several wells, and consequently it has been interpreted in some wells as ranging from Middle to Upper Jurassic, but in others as ranging up to as young as possibly Valanginian. Given the probable age of the overlying sequence, it is most likely that the sequence ranges in age from ?Middle Jurassic to Tithonian (Fig. 6), although its top may be slightly younger. A seismic sequence with a similar geometry and position near the base of the rift section was identified by Figuerido *et al*. (1996) in the nearby San Julian Basin, but was interpreted by them as being of Permian age.

The late syn-rift unit (Tithonian to Berriasian)

This unit was encountered in all wells except 14/13-1, from where it is absent due to pinchout towards the Minke High in the Western Depocentre (Figs. 2 and 3). The unit forms the late syn-rift phase of basin infill, and comprises a wedge-shaped seismic package displaying some onlap of reflectors onto the tilted top surface of the early syn-rift sequence (Fig. 4). Figure 2 shows that the top of the unit is generally marked by a downwards decrease in interval transit time, a downwards decrease in Compensated Neutron Log porosity values, and a downwards increase in gamma-ray values.

Lithology

Lithofacies types vary according to the palaeogeographic position of the wells. In Well 14/9-1 located on the crest of the Intra-Graben High, the sequence comprises a lower conglomerate interval and an upper claystone interval. The conglomerate is pale green to brownish grey, with a clay matrix in places. Side-wall core samples from near the base of the conglomerate consist almost entirely of cryptocrystalline silica glass and microcrystalline quartz. The overlying claystone interval is light to medium grey, pale brown and brownish grey.

Well 14/5-1A, located nearer the middle of the Eastern Depocentre, encountered a claystone dominated succession with thin sandstone beds, which had a total thickness of about 120 m. The sequence in Well

14/24-1 in the southern part of the basin is dominated by tuffaceous claystones. These are pale to dark grey/green, moderately hard, with some relict granular texture and occasionally visible crystals. Most of these tuffs represent reworked volcanic material deposited by sedimentary processes. Minor amounts of matrix- and clast-supported conglomerates and current rippled sandstones are also present, as is the localised development of rootlet structures. Similar reworked tuffaceous sedimentary rocks have been described by Figuerido *et al*. (1996) from the rift succession in the nearby San Julian Basin, although Galeazzi (1998) described a sequence dominated more by volcaniclastic and rhyolitic rocks (the so-called Tobifera volcanics) from the Malvinas Basin.

Palynology

In Well 14/9-1 the unit has a rich to moderately rich, non-marine palynomorph assemblage. In Well 14/5-1A, the palynofloral assemblage contains the fresh to brackish water alga *Celyphus rallus,* and *Botryococcus*. Kerogen is dominated by abundant, pyritised amorphous organic matter, with subordinate structured inertinite and vitrinite phytoclasts. In Well 14/24-1, the unit is dominated by miospores, particularly gymnosperm pollen, while non-marine to brackish water algae are also common.

Depositional Environment

In common with the underlying sequence, the late syn-rift interval was probably deposited in a fluvio-lacustrine environment. The coarser grained sedimentary rocks found at the base of the sequence along the crest of the Intra-Graben High probably represent, as in the underlying unit, lacustrine shoreline deposits fringing a more permanent lake, before the establishment of more pervasive lacustrine conditions at this location (as seen in the overlying units).

The succession in Well 14/5-1A near the middle of the Eastern Depocentre has a mixed sandstone/claystone basal unit of probable lacustrine and lacustrine ?turbidite origin, but becomes less sand-rich upwards, possibly reflecting the establishment of a more permanent lake system towards the end of the late syn-rift period. In Well 14/24-1 in the southern part of the Eastern Depocentre, the lacustrine claystones are largely tuffaceous. These were probably deposited in a low energy lake, with some infrequent high energy depositional events indicated by the presence of matrix- and clastsupported conglomerates and current-rippled sandstones. The localised presence of ?early diagenetic mottling and ?roots may indicate the development of incipient soil profiles at the lake margin or in a waterlogged, marshy setting. Less tuffaceous claystones overlie the tuff-dominated succession in Well 14/24-1, and may represent the re-establishment of permanent lacustrine deposition, coupled with a decrease in the availability of volcanic material, as a result of drowning of a local source area as lacustrine conditions expanded. Lambiase (1990) demonstrated that syn-rift successions in continental basins tend to be dominated by semi-permanent lakes in their central parts.

Age

This sequence has been variously assigned (by different biostratigraphers working on different wells), as Tithonian to Valanginian, Valanginian to Barremian, or Tithonian to Berriasian. Most of the taxa recovered are long-ranging, but they are comparable to other late Jurassic to Berriasian assemblages known from the Springhill Formation of Argentina and Chile. This unit is probably of Tithonian to Berriasian age (Fig. 6), although it is possible that its top lies within the Valanginian.

The rift to sag transition (?Berriasian to ?Valanginian)

This unit can be identified in all wells except 14/13-1; it pinches out onto the flanks of the Minke High within the Western Depocentre (Figs. 2 and 3). It has a lensoid profile (Fig.3), indicating that it may represent the first phase of sag-infill of the basin. The top of the unit is defined as the base of a series of high amplitude reflections (Fig. 4), and in most wells by a downwards decrease in interval transit time, a downwards decrease in gamma values, a downwards decrease in Compensated Neutron Log porosity values and a slight downwards decrease in bulk densities (Fig. 2).

Lithology

This unit is generally claystone dominated. Thus, in Well 14/5-1A near the centre of the Eastern Depocentre, the unit comprises an organic-rich claystone which is medium to dark greyish brown, firm to moderately hard, blocky to sub-fissile, micromicaceous, silty in part, generally clean and homogenous, and increasingly indurated with depth. Traces of well sorted, kaolinitic sandstones are recorded at some levels. Well 14/9-1 shows the only variation to the dominant claystone lithology; here, as well as tuffaceous claystones, the unit comprises weathered conglomerates which are poorly sorted, very coarse to granular, and contain angular to subrounded lithic clasts.

Palynology

The unit is not separately identifiable as a distinct palynological unit in any of the wells. It appears to contain similar assemblages to the overlying early post-rift succession, being dominated by fresh to brackish water alga and non-marine miospores. *Depositional Environment* As in the underlying units, the crestal Well 14/9-1 possibly represents a shoreline depositional environment fringing a lake. The claystone-dominated successions in the other Eastern Depocentre wells (including Well 14/9-2 on the flank of the ridge) may represent sites of more permanent lacustrine deposition.

Age

This unit is relatively thin, and difficult to differentiate biostratigraphically from the overlying claystone succession of the early post-rift sequence. The most likely age range for this unit is probably Berriasian to Valanginian (Fig. 6).

The early post-rift unit (Valanginian to ?Aptian)

The early post-rift unit is probably present in all six wells, although the lowermost part is present only in the Eastern Depocentre and on the eastern flanks of the Intra-Graben High (Figs. 2 and 3). The early post-rift succession represents the more widespread development of a saucer shaped seismic package developed above the syn-rift wedges and the transitional unit. The top of the unit is picked at a seismic reflector which defines the top of a lowstand seismic package developed in front of an axial, Lower Cretaceous delta (Figs. 2 and 3) identified originally by Richards and Fannin, 1997). The top of the unit is marked by a downwards increase in gamma ray log response and a significant downwards increase in interval transit time and bulk density (Fig. 2).

The early post-rift unit is sub-divided into three seismic or sequence stratigraphic units of subregional significance (Fig. 2). Unit LC2 at the base of the succession is characterised by an interval of high amplitude, sub-parallel reflectors, and is observed on seismic sections to pass northwards into the oldest deltaic foreset deposits recognised in the Eastern Depocentre. The overlying unit LC3 is more seismically transparent over much of the basin, and in the northern part of the Eastern Depocentre contains the main, progradational part of the Lower Cretaceous axial delta that infilled the basin from the north. The topmost sub-unit, LC4, is present only locally within the Eastern Depocentre, directly to the south of the foresets of the axial delta, and is interpreted to represent a relative low-stand period following maximum delta progradation into the basin.

Lithology

The early post-rift succession is dominated by massive claystones with minor sandstones, siltstones and interbedded dolomite. However, a sandier succession is present where a series of deltas (prograding predominantly from the north, but also with minor progradational lobes from both the western and eastern margins of the basin) comprise much of the LC2 and LC3 sub-units of the sequence in the northern parts of the basin (Fig. 2).

The claystones which dominate the succession are grey to brown coloured, soft to firm, amorphous or blocky to sub-fissile, slightly calcareous, rarely pyritic, carbonaceous, and occasionally micromicaceous, with rare plant remains. Interbedded with it are buff coloured, soft to firm, amorphous to sub-blocky, silty and carbonaceous dolomite beds, up to 2 m thick (which cause the high seismic reflectivity of the unit), and also rarer, silty sandstones.

Well 14/5-1A, the northernmost well in the Eastern Depocentre, penetrated the axial deltaic system draining from the north. Near the top of this deltaic interval, presumed topset deposits comprise interbedded argillaceous sandstones and claystones. The argillaceous sandstones are very fine grained and moderately well sorted, with detrital components comprising abundant mono-and polycrystalline quartz grains, K-feldspar and volcanic and metamorphic rock fragments. The topset claystones are dark brown, with abundant flakey (woody?) particles, locally abundant silt grains, and scattered, small, golden brown phosphate grains. Beneath these seismically imaged topsets, the dipping foreset interval comprises claystones interbedded with sand, sandstone, silty or sandy claystones and rare dolomite. The presumed foreset sands and sandstones are translucent to orange green, with mixed lithic fragments, including volcanics, cherts and quartzites. They are fine to very coarse grained, poorly sorted and angular to sub-rounded. The sands have occasional white kaolinitic coatings to grains, and are rarely cemented. Lithic clasts within the sandstones include trachytic and rhyolitic volcanics, and the dominant quartz grains generally have a thin veneer of microcrystalline quartz. The seismically imaged, flat-lying bottomset interval comprises claystone and silty claystone with thin sands and dolomite stringers that produce high amplitude seismic reflections.

Palynology

The succession is dominated by the fresh- to brackish-water alga *Botryococcus*, *Celyphus rallus* and rarer *Pediastrum*.

Depositional Environment

The predominantly claystone lithologies of this succession were deposited in a lacustrine setting, as indicated by the general absence of salt-water indicators in the palynological assemblages. A similar lacustrine setting was reported for the D129 succession in the nearby San Jorge Basin (Fitzgerald *et al*., 1990), although Galeazzi (1998) reported that generally similar claystones in an early post-rift setting in the Malvinas Basin to the SW are of marine origin.

The presence of interbedded dolomites within the predominant lacustrine claystone lithology may suggest possible drying phases, with evaporite deposition in relatively shallow water areas. Alternatively, the organic carbonate-rich layers may represent deposition in a relatively deep lake during climatic dry periods, and the carbon-rich rocks represent deposition during wetter periods (c.f. Collinson, 1978). Thin coals (recorded in Well 14/24-1) support the hypothesis of relatively shallow water lakes, although waters may have been shallow only around the lake margins, of which the well 14/24-1 site is an example. However, sinuousoidal reflectors defining deltaic build-up within the northern part of the lake (see below) are up to about 500m high, suggesting that lake depths were of this order of magnitude in the northern part of the Eastern Depocentre.

The occurrence of fish remains and ostracods in places attests to the fact that the lake was probably oxygenated, at least in the upper parts of the water column. However, total organic carbon values averaging 5%, and oil yield values (determined by Rock-Eval: see Part 2) up to 74.5 kg HC/tonne of rock in well 14/10-1 suggest the development of anoxic bottom conditions. In present day East African lakes, the highest TOC values are recorded in lakes that are either permanently stratified or are only episodically overturned (Talbot, 1988). However, TOC values of 1.4% to 4% have been recorded in lakes that are only occasionally stratified (Talbot, 1988). Katz (1990) showed that the highest organic concentrations, and the highest hydrocarbon generating potentials, are found in East African lakes of intermediate water depth (50 to 400m), possibly because of the better phytoplankton production in such lakes as compared to deeper, permanently-stratified water bodies.

It is relatively unusual for large lake systems to be recorded within post-rift rather than syn-rift settings, although the broadly age equivalent D-129 Formation lacustrine claystone of the San Jorge Basin (Eastern Argentina) also occurs in an early post-rift setting (cf. Fitzgerald *et al*., 1990). By contrast, all the modern lakes in the East African Rift Valley are syn-rift systems. Lambiase (1990), in a review of ancient rift-basin lakes worldwide, suggested that the topography required for the development of a large lake occurs only in the early phase of rift evolution, although lacustrine sedimentation can occur at any stage in the evolution of a rift system. It is probable that the early postrift lacustrine deposits are a remnant of more localised lake deposition that first became established during the late syn-rift phase of the basin's evolution.

Delta progradation from the north (which began during deposition of sub-unit LC2 and continued throughout deposition of sub-unit LC3) resulted in the development of a significant axial delta system within the Eastern Depocentre. The source area for the delta is uncertain, although petrographic and heavy mineral analyses (see below) on side-wall core and cuttings samples suggest that it was derived by unroofing of a metamorphic and granitic terrane, probably located to the north. However, no detailed provenance-typing studies have yet been conducted. In Well 14/5-1A a range of deltaic environments and associated sedimentary rocks are preserved in seismically imaged intervals interpreted as topsets (1,750m to 1,780m below rig floor) and foresets (1,780m to 2,008m) in a 258 m thick section sitting above generally fine grained deposits interpreted as bottomsets of lacustrine/prodelta origin (2,008m to 2,274m). The foresets dip at approximately 5°, which contributed to predrilling prognoses that they were composed predominantly of sand-grade material.

Although the delta succession in Well 14/5-1A is relatively sand-rich, it is possible that much sand-grade material was carried further offshore, into the deeper-water lake areas by sediment-laden underflows, producing density-flow deposits within the lake. Such density deposits have not yet been encountered by wells in the basin, but mounding visible along some seismic reflections within the early post-rift unit by indicate the sites of such sand deposition. Progradation of the axial deltas ceased, probably during the Valanginian to early Barremian, when an apparent relative lake level fall led to the development of lowstand deposits (sub-unit LC4) located distally to the delta front in the deeper parts of the basin (Figs. 2 and 7).

Age

As with the other stratigraphic units of the North Falkland Basin, the early post-rift succession has been dated differently in different wells. In some wells it has been assigned to the Valanginian to Barremian, whereas in others a Valanginian to Aptian or even Albian age has been assigned. The differences in age ranges possibly result, at least in part, from the generally long-ranging ages of the dominant non-marine taxa. In Well 14/5-1A, miospores typical of the Aptian to early Albian in Antarctica and Australia, including *Inaperturopollenites elegans*, *Trilites tberculiformis* and *Cyatheacidites annulatus* are observed near the top of the sequence, whilst the freshwater alga Celyphus rallus, which is characteristic of the Barremian, is recorded from near the middle of the sequence. The base of the sequence is hereby taken to lie within the Valanginian, whilst its top is assigned to the Aptian (Fig. 6), although it may range slightly younger, up into the Albian.

The middle post-rift unit (Aptian to Albian)

This unit is recognised in all six wells (Figs. 2 and 3). No distinct log breaks are observed at the top of the unit, and lithologies are generally similar above and below. However, its top corresponds with a downwards transition from sedimentary rocks bearing marine or marginal marine palynomorphs, to rocks with predominantly non-marine forms.

Three sub-units are identified within the middle post-rift succession (Fig. 2). The lowest sub-unit, LC5, overlies the low-stand deposits of sub-unit LC4 at the top of the early post-rift sequence, and is interpreted as a transgressive systems tract before the renewal of fluvial deposition over the delta surface. The overlying sub-unit (LC6) is significantly coarser-grained than sub-unit LC5, and probably therefore represents a low-stand systems tract development (a basinwards shift of facies). A thin, uncored transgressive systems tract must cap sub-unit LC6, as the succeeding unit (LC7) represents the development of highstand systems tract fluvial sedimentation that continued throughout the remainder of the middle post-rift interval.

Lithology

The succession comprises sandstones, conglomerates, claystones and minor coals. Nearly half of sequence stratigraphic sub-unit LC5 at the base of the succession was cored in Well 14/9-1. This cored interval predominantly comprises fining upwards cycles about 0.5 to 1.5 m thick, with sharp, erosively-based, coarse-grained or granule-rich sandstones fining up to fine- or very fine-grained sandstone, and in one case up to siltstone. Carbonaceous wisps and laminae in places in the sandstones define both wave and current ripples, which are occasionally disrupted by bioturbation; although some indistinct, possibly vertical burrow forms are present, no definitive types can be identified. Muddier and siltier facies are sharply interbedded with the sandstones, and range in thickness from a few centimetres to about 70 cm thick. The siltstones are lenticular bedded, with intense bioturbation of the sandy lenses in places, and the development of some small, vertical burrows near the tops and bases of some beds. Some small (cm scale) gutters are present at the bases of current rippled sand lenses in the lenticular bedded units.

The overlying sequence stratigraphic sub-unit LC6 was also partially cored in the Well 14/9-1. The cored interval comprises very fine to medium grained, fining upwards sandstones in beds up to about one metre thick. Rootlets and small, vertical burrow structures are observed in places, and the sandstone is often disprupted by bioturbation. The detrital mineralogy of the cored interval is dominated by fragments of devitrified acidic lavas, with more minor components of claystones, sandstones, granites and sparse schists and quartz. Sub-unit LC6 is not cored in Wells 14/5-1A, 14/9-2 and 14/10-1, where it appears to be significantly coarser grained, with a number of conglomeratic horizons identified in side-wall core samples. A side-wall core sample from a conglomeratic bed in Well 14/5-1A shows clasts of K-feldspar-rich volcanic rocks, devitrified volcanic glass, granite and metamorphic rocks in a matrix of very coarse grained sandstone. Sub-unit LC7, which forms the remainder of the middle post-rift succession comprises interbedded sandstones, conglomerates, claystones, tuffaceous claystones, siltstones and minor limestone, dolomite and coal beds.

Palynology

Sub-units LC5 and LC6 contain humic vitrinite debris and miospores, with locally high concentrations of vitrinite and low concentrations of inertinite and amorphous kerogens. Sub-unit LC7 contains marginal to non-marine palynoflora, with some vitrinitic debris and *Botryococcus* algae. A diverse, pteridophyte spore assemblage was recorded from Well 14/13-1, suggesting a humid, temperate palaeoclimate and non-marine conditions. Well 14/5-1A encountered rare marine dinocysts within this interval, although they are significantly less common than in the overlying L/UC1 unit, and the organic material is dominated by carbonised woody matter.

Depositional Environment

The absence of widespread marine palynological indicators generally precludes a fully marine setting, suggesting that the depositional environment may have been a marginal lake area or a lacustrine lagoon. Common bioturbation, coupled with some evidence of vertical burrows, suggests that the near surface sediment was well oxygenated. The occurrence of carbonaceous laminae and chips indicate that there was abundant vegetation in the hinterland.

The fining-upwards sandstones that dominate the cored interval in sub-unit LC5 indicate high energy traction deposition of sand in either small, confined streams, or more widespread, unconfined flows, that scoured into a muddy substrate, probably in a shallow water environment. Large-scale cross-bedding is generally absent, suggesting that the channels and/or sheetfloods were of relatively minor size. The sandstones may represent deposition in a range of fluvial, crevasse splay, storm sheet and other nearshore to lagoonal settings. Although not cored, the conglomerates in sub-unit LC6 are interpreted as representing coarse-grained fluvial deposits; they are recorded in the same sub-unit as small-scale fining upwards sandstones with rootlets and burrows, interpreted as representing deposition in a vegetated fluvial floodplain. The thin coals recorded in well 14/24-1 support the hypothesis of deposition more or less at lake level in a marginal, waterlogged setting, suggesting that similar conditions were widespread across the Eastern Depocentre at this time.

Age

A wide range of ages has been proposed for this sequence in the six wells. In some wells it has been assigned a Valanginian to Albian age, in others a Barremian to Albian age, and in others an Aptian to Cenomanian age. As with the older units, the general absence of marine dinocysts and the long-ranging nature of the dominant miospores hinders accurate age determination. In Well 14/9-1 a marked influx of *Classopollis* spp near the very top of the unit suggests an age no younger than early Albian, whilst the presence of Callialasporites trilobatus a few tens of metres below the top suggests a probable Aptian age. In Well 14/9-1 the presence of the miospore *Classopollis turbatus*, in association with *Cyclusphaera psilata* near the top of the sequence suggests an Aptian to early Albian age. This unit is therefore assigned a probable Aptian to Albian age (Fig. 6).

The late post-rift succession (Albian to early Palaeocene)

This interval is present in all six wells, and represents continued overstepping of the basin margins which had begun during deposition of the underlying succession. Continued inundation of the basin margins was partly facilitated by relative lake-level rise, with the first development of significant marine incursion into the basin. The sequence therefore represents a combined transgressive and marine highstand systems tract.

Sub-units L/UC1 and UC1 are separated by a regionally mappable seismic reflector, but and can be differentiated on the basis of their palynological content. Sub-unit L/UC1 is of apparent marginalmarine origin, whereas sub-unit UC1 is of fully-marine character.

The top of the succession is picked at a seismic event that marks a significant unconformity recognisable throughout the basin. There are insufficient logs and samples to characterise the top of this unit adequately, since in most of the six wells the first sample retrieval occurred only just above or below this major unconformity.

Lithology

The succession can either be sand-dominated (with interbedded claystones), or claystone dominated with interbedded sands, depending on the precise location. The sands are occasionally sphaerosideritic.

Palynology

Sub-unit L/UC1 yielded very few microfossils, but caved dinocysts are abundant at some levels, in a palynofloral assemblage dominated by miospores with occasional, probably *in situ* dinocysts. The dinocyst *Palaeoperidinium cretaceum,* and the agglutinating benthonic foraminiferid *Spiroplectammina praelonga* are present, together with rarer examples of other dinocysts, suggesting a marginal marine setting, probably partially restricted.

Sub-unit UC1 contains a diverse marine microfauna, dominated by a range of dinocysts, calcareous benthonic and agglutinating foraminiferids with more minor radiolaria and sponge spicules. Low numbers of planktonic foraninifera are also present. The amount of terrigenous, humic debris is variable throughout the unit, but it is more common in the lower parts of the sequence. The fresh to brackish water alga *Botryococcus* is also present in places within the lower parts of the unit.

Depositional Environment

Within sub-unit L/UC1, the presence of sphaerosiderite indicates the possibile development of waterlogged soils, and this, together with the palynological data, suggests a terrestrial to marginal marine environment. The restricted marine character of the dinocysts and foraminifera suggest possible lagoonal conditions, and may have developed only periodically. By contrast, the overlying sub-unit UC1 was deposited in a more pervasive marine environment, developed as relative sea levels rose. Although there are indicators in the palynofacies for an open-marine setting, the presence of some agglutinating foraminiferids suggests the possibility of at least locally restricted conditions. The intermittent presence of humic debris and *Botryococcus* suggests that terrestrial run-off was important at times, possibly in a near-coastal setting.

Age

The range of ages proposed for this unit in the various wells is less than that observed for the underlying units: the sequence is assigned to the Albian to Maastrichtian or Danian in most wells. No palynomorphs characteristic of the Turonian to Santonian periods are present in any of the wells except Well 14/5-1A, where the first downhole occurrences of the dinocysts *Surculosphaeridium longifurcatum*, *Odontochitina porfera* and *Cleistosphaeridium huguoniotti* are respectively taken to indicate a Coniacian age, a Coniacian to Albian age and a Coniacian age. The presence of abundant *Manumiella* spp in Well 14/9-1 near the top of the sequence supports an early Palaeocene age for the top of the interval. This tectono-stratigraphic interval probably spans the Albian to early Palaeocene (Fig. 6). The middle and late post-rift successions together possibly equate more or less with Megasequence 3 described from the Malvinas Basin by Galeazzi (1990). He suggests that the base of Megasequence 3 in the Malvinas Basin is defined by an unconformity at 112 ma (Aptian) and that the top of the succession may be marked by an unconformity at 68 ma (Maastrichtian).

Early Palaeocene uplift

Two potential phases of uplift have been invoked for the North Falkland Graben. Lawrence and Johnson (1995) and Thomson and Underhill (1999) proposed mid-Cretaceous uplift leading to deltaic progradation, followed by Tertiary inversion of the basin. Richards *et al*. (1996 a and b), invoked comparisons with the Malvinas and Magallanes Basins of Argentiana and the various South African offshore basins, and suggested that there was evidence only for Palaeogene uplift of the entire region. However, they acknowledged that there could be evidence for a Cenomanian unconformity (significantly younger than deltaic progradation) similar to that observed in the Falkland Plateau Basin and Malvinas Basin.

The age data now available from the six wells in the basin indicate that there are a number of regional or sub-regional unconformities (Fig. 6); the two most significant of these span the late Cenomanian to Santonian and much of the Maastrichtian. Plots of Vitrinite Reflectance (VR) versus depth from Well 14/9-1 show a surface intercept value of 0.27%, indicating that some 800m of Cretaceous-Cenozoic section is missing over the crest of the Intra-Graben High. However, surface intercept values for VR observed in the other wells range from 0 in Well 14/5-1A in the centre of the basin to almost 4% in Well 14/24-1. This range of values probably indicates that there has been differential uplift and/or erosion and/or non-deposition in different parts of the basin, probably as a result of local tectonic readjustments over individual fault blocks.

Post-uplift sag subsidence (Palaeocene-Recent)

This unit was penetrated in all six wells, but was neither sampled nor fully logged in any of them. The top of this unit is seabed.

Lithology

The unit consists of massive claystones which are medium to dark brown, locally chocolate brown, soft to moderately hard, non-calcareous and generally very silty. Interbedded with these are minor, very fine to fine grained sandstones.

Palynology

Microfossils from this unit are more or less restricted to samples from near sea bed, as there were very few returns to any of the rigs during penetration of the sequence. The samples from the seabed and 36" hole in well 14/13-1 contained a rich and diverse assemblage of planktonic and calcareous benthonic foraminiferids, sponge remains, radiolaria and dinocysts. The samples from the 24" hole in Well 14/13-1 also yielded a rich microfauna and flora, with a different composition to the overlying samples. This fauna was dominated by fairly diverse, calcareous benthonic foraminifera with, rarely, planktonic foraminifera, while the flora is dominated by marine microplankton, principally dinocysts.

Depositional Environment

Deposition probably followed early Palaeocene uplift of the basin, and commenced with the northwards progradation of a major deltaic wedge into a fully marine basin.

Age

This unit ranges in age from Palaeocene to Recent.

PROVENANCE OF ALL UNITS

Before drilling commenced it was assumed that much of the sediment infilling the basin was derived from the area of the present-day Falkland Islands, or from the Devonian platform surrounding the basin, while the Lower Cretaceous deltas were thought to have been sourced from areas to the west and NW (Richards and Fannin,1997). Analysis of lithoclasts, detrital mineralogy and particularly, the heavy minerals suggests that all the sediments encountered to date may in fact have been derived from a mixed volcanic, regionally metamorphosed and perhaps granitic terrane, probably located to the north or NW of the basin. Much of the kaolinite that fills pore throats in the middle post-rift sandstones may have been derived from the breakdown of feldspars weathered from a granitic terrane. The precise location of the source region has not been established, and no heavy mineral typing studies have yet been conducted to compare the North Falkland Basin successions with any onshore outcrops in Argentina or South Africa.

The lowermost part of the early syn-rift succession in Well 14/9-1 contains Devonian clasts, and therefore appears to have been eroded from Devonian sedimentary rocks. However, the remainder of the Mesozoic section in this well contains distinctive, dark brown rutiles which indicate that the source area was mineralogically different from the Devonian rocks that form the bulk of the Falkland Islands, as these contain mostly yellow to red rutiles (analyses conducted by R.W.O'B. Knox, pers. comm., 1998). Apatite, anatase, topaz, calcic amphiboles, garnet, monazite and zircon are commonly found throughout the succession in Well 14/9-1, and indicate derivation from a range of igneous, metamorphic or sedimentary rocks. The predominant monocrystalline quartz found as lithoclasts indicates, in addition, a possible volcanic source. The tuffs, tuffaceous claystones and other volcaniclastic rocks in Well 14/24-1 (the most southerly of the wells drilled so far) display a variety of lithologies, whilst the variable degrees of rounding in some sections indicates derivation from a variety of sources with different distances of transportation and/or variable time spent by grains in different depositional environments.

In summary, the provenance area was therefore not the Falkland Islands, but probably a progressively unroofed granitic intrusion and associated metasomatized and volcanic rocks somewhere, possibly to the north or northwest (RWO'B Knox, pers. Comm., 1998).

CONCLUSIONS

Stratigraphic correlation in the basin

The infill of the northern part of the North Falkland Basin can be modelled using a tectonostratigraphic approach, tying the wells to the regional seismic database. Biostratigraphic information is, at present, not sufficietly refined to allow the erection of a regional, sequence stratigraphic framework based on palynological and palaeontological data alone. Lithostratigraphic subdivisions, which are adequate to describe the stratigraphy in individual wells, are not particularly useful when correlating between wells because of the lateral lithological variation observed within units.

The tectono-stratigraphic framework

Eight tectono-stratigraphic units (and eight sub-units) are recognised in the basin. These are:

Unit	**Sub-units**	**Probable age**
Post-uplift	sag	Cenozoic
Late post-rift	L/UC1 and UC1	Albian-Palaeogene
Middle post-rift	LC5, LC6 and LC7	Aptian-Albian
Early post-rift	LC2, LC3 and LC4	Valanginian-Aptian
Rift-sag transition		Berriasian-Valanginian
Late syn-rift		Tithonian-Berriasian
Early syn-rift		Jurassic-Tithonian
Pre-rift		Devonian

The basin was the site of fluvio-lacustrine deposition throughout the early and late-syn rift periods, and a more permanent lake became established during the transitional phase towards post-rift subsidence. The early post-rift phase was tectonically quiescent, and saw the progradation of several deltaic systems (dominated by a southwards prograding axial delta in the Eastern Depocentre) into a large lake system. A relative lake level fall at the end of the early post-rift phase was followed by deposition in a fluvial and lacustrine lagoonal setting, before the establishment of highstand fluvial sedimentation throughout the remainder of the middle post-rift phase. The late post-rift phase, from the late Albian or Cenomanian to the early Palaeogene, saw the establishment firstly of marginal-marine conditions and then of fully-marine conditions (in the Campanian), as a marine connection was established into the basin. By contrast, marine conditions became established earlier (late Jurassic) in the Malvinas Basin (Galeazzi, 1998) and later (Cenozoic) in the San Jorge Basin to the NW (Fitzgerald *et al*., 1990), suggesting that the regional development of marine conditions spread from the south or SE. Regional uplift in the Palaeogene (see Richards *et al*. (1996a) for a discussion of the Late Cretaceous/Early Cenozoic uplift in offshore Argentine and Falkland Islands basins) was followed by thermal sag, and marine/deltaic deposition occurred through the remainder of the Cenozoic.

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See Part 2 of this paper for acknowledgements.

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Figures

1. Structural outline of North Falkland Basin, showing locations of the six wells drilled in 1998.
2. Log correlation of the eight tectono-stratigraphic sequences and the associated sub-units in all six wells. Gamma Ray Log scale on each well is from 0 to 150 API, sonic log scale is from 140 to 40 microsecs/ft. The Late Jurassic to Early Cretaceous lacustrine claystone that forms the primary source rock interval in the basin is shaded grey. See Figure 1 for location of wells.
3. Composite SW-NE cross section based on interpretations of seven intersecting seismic lines (four oriented E-W and three oriented N-S) traversing the North Falkland Basin. The section illustrates the relationships between the tectono-stratigraphic units in three of the wells. Vertical scale in milliseconds of two-way travel time (TWT). See Figure 1 for location.
4. Part of E-W seismic line across the Eastern Depocentre, illustrating the relationship between the early syn-rift, late syn-rift, transitional unit, early post-rift and middle post-rift units. Data reproduced courtesy of Spectrum Energy and Information Technology Ltd. PR = pre-rift; ES-R = early syn-rift; LS-R = late syn-rift; TU = transitional unit; EP-R = early post-rift; MP-R = middle post-rift; LP-R = late post-rift; P-US = post-uplift sag. See Figure 1 for location.
5. Cartoon of depositional setting of the early syn-rift sequence (mid Jurassic to Tithonian) in the northern part of the North Falkland Basin. Note that the Minke High was probably exposed, whereas the Intra-Grabenal-High was probably the site of fluvial deposition.
6. Sequence stratigraphic representation of well correlation in the North Falkland Basin.
7. Cartoon of depositional setting of the LC4 sub-unit of the early post-rift sequence (Barremian to Aptian) in the northern part of the North Falkland Basin. Note that the Intra-Grabenal-High was probably at least partially emergent at this time.

Tables

Table 1. Statistics for the six wells drilled in the North Falkland Basin in 1998.

Figure 1 Structural outline of North Falkland Basin, showing locations of the six wells drilled in 1998.

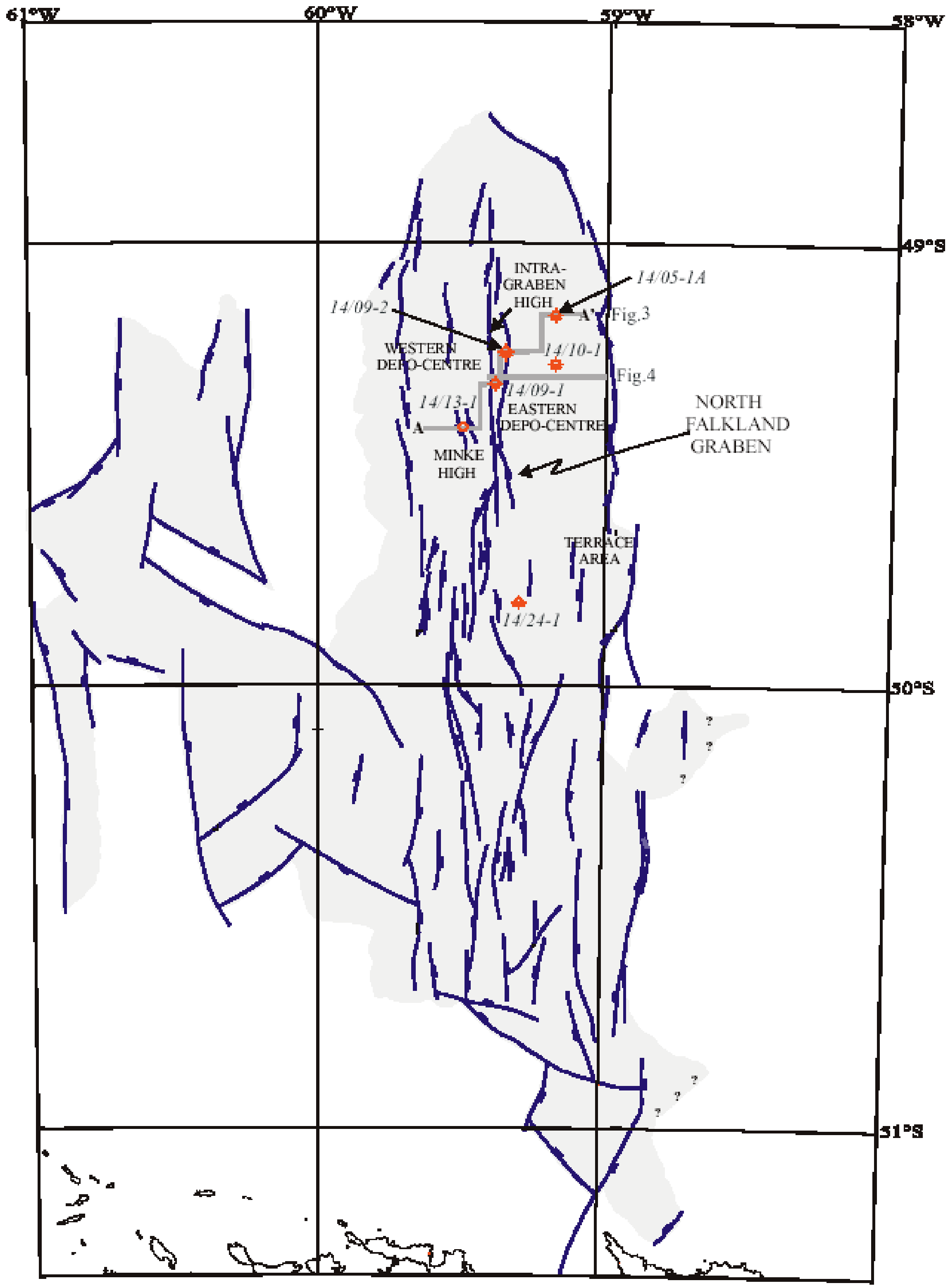

Figure 2 Log correlation of the eight tectono-stratigraphic sequences and the associated sub-units in all six wells. Gamma Ray Log scale on each well is from 0 to 150 API, sonic log scale is from 140 to 40 microsecs/ft. The Late Jurassic to Early Cretaceous lacustrine claystone that forms the primary source rock interval in the basin is shaded grey. See Figure 1 for location of wells.

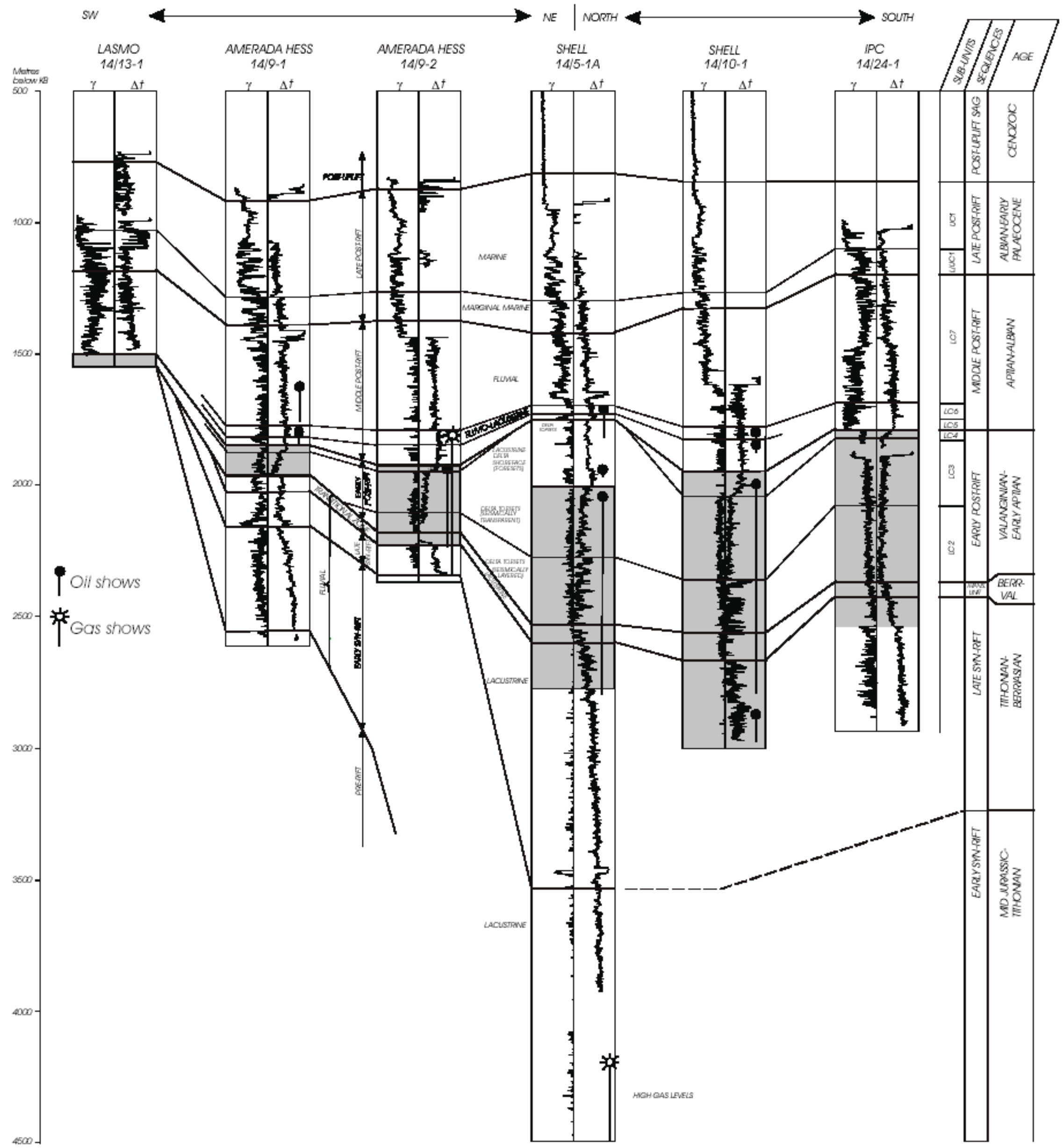

Figure 3 Composite SW-NE cross section based on interpretations of seven intersecting seismic lines (four oriented E-W and three oriented N-S) traversing the North Falkland Basin. The section illustrates the relationships between the tectono-stratigraphic units in three of the wells. Vertical scale in milliseconds of two-way travel time (TWT). See Figure 1 for location.

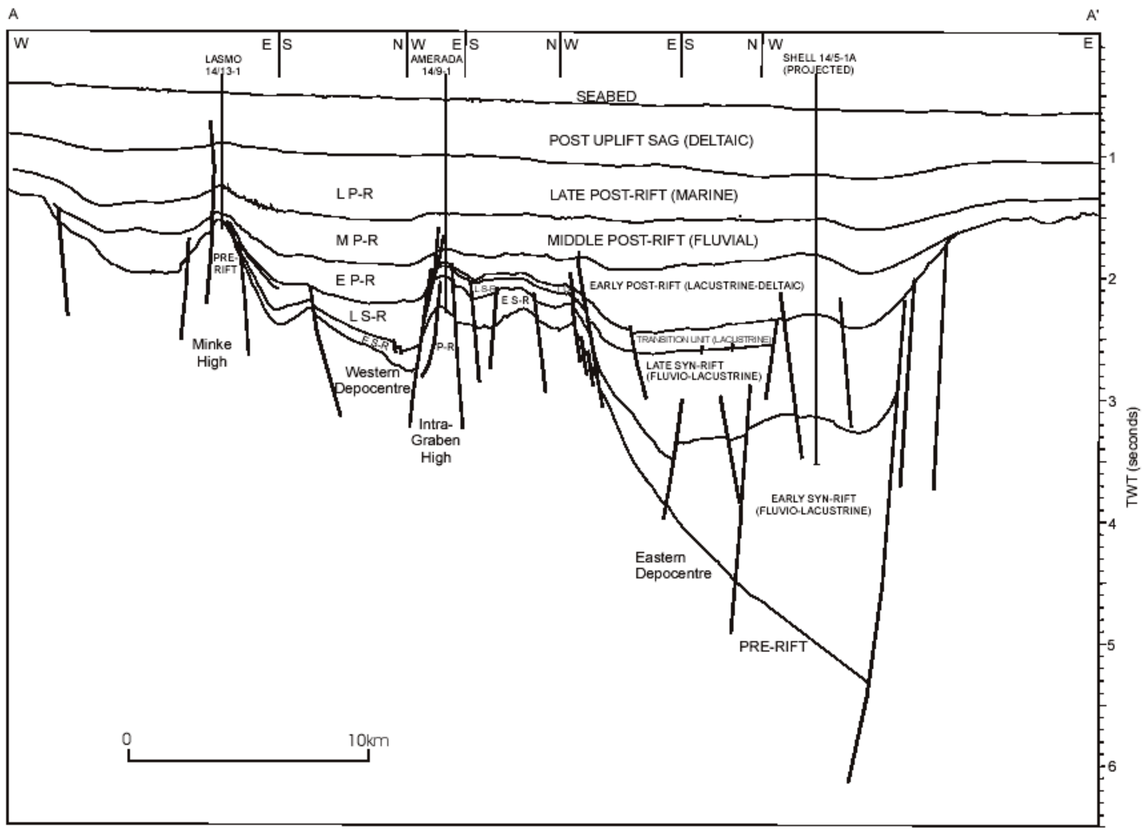

Figure 4 Part of E-W seismic line across the Eastern Depocentre, illustrating the relationship between the early syn-rift, late syn-rift, transitional unit, early post-rift and middle post-rift units. Data reproduced courtesy of Spectrum Energy and Information Technology Ltd. PR = pre-rift; ES-R = early syn-rift; LS-R = late syn-rift; TU = transitional unit; EP-R = early post-rift; MP-R = middle post-rift; LP-R = late post-rift; P-US = post-uplift sag. See Figure 1 for location.

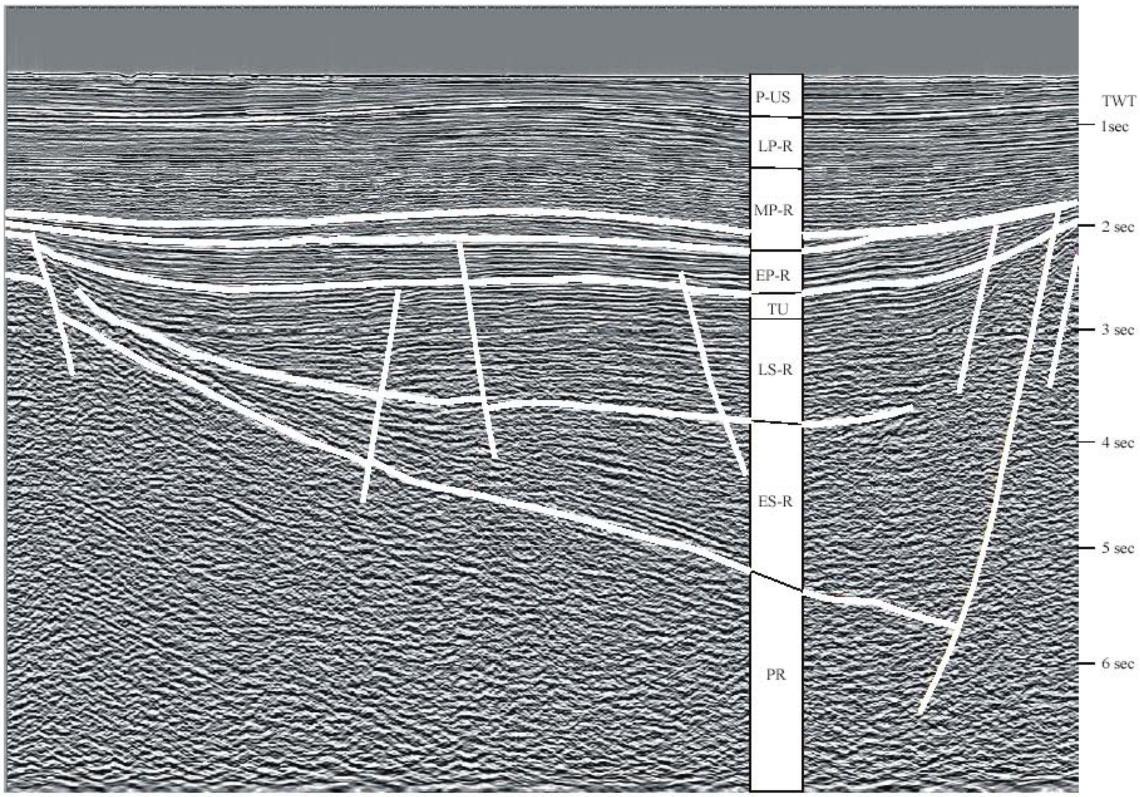

Figure 5 Cartoon of depositional setting of the early syn-rift sequence (mid Jurassic to Tithonian) in the northern part of the North Falkland Basin. Note that the Minke High was probably exposed, whereas the Intra-Grabenal-High was probably the site of fluvial deposition.

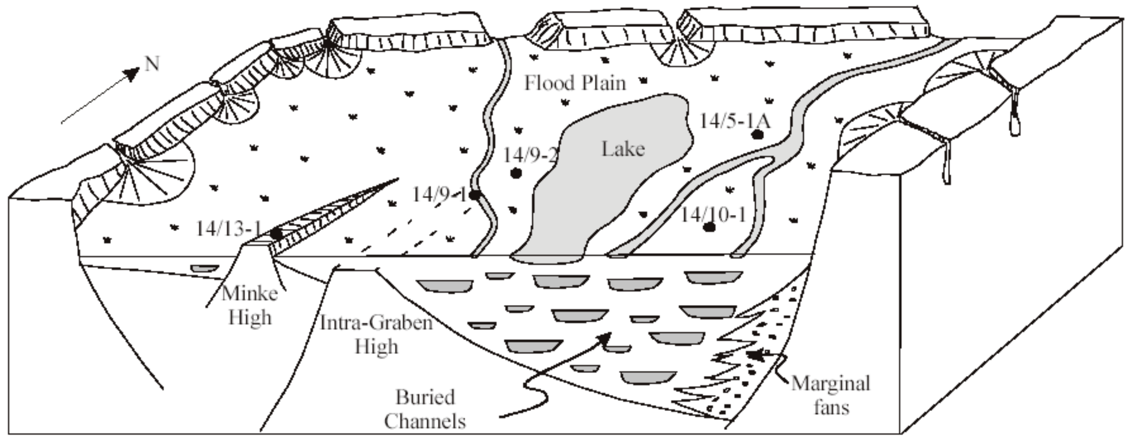

Figure 6 Sequence stratigraphic representation of well correlation in the North Falkland Basin.

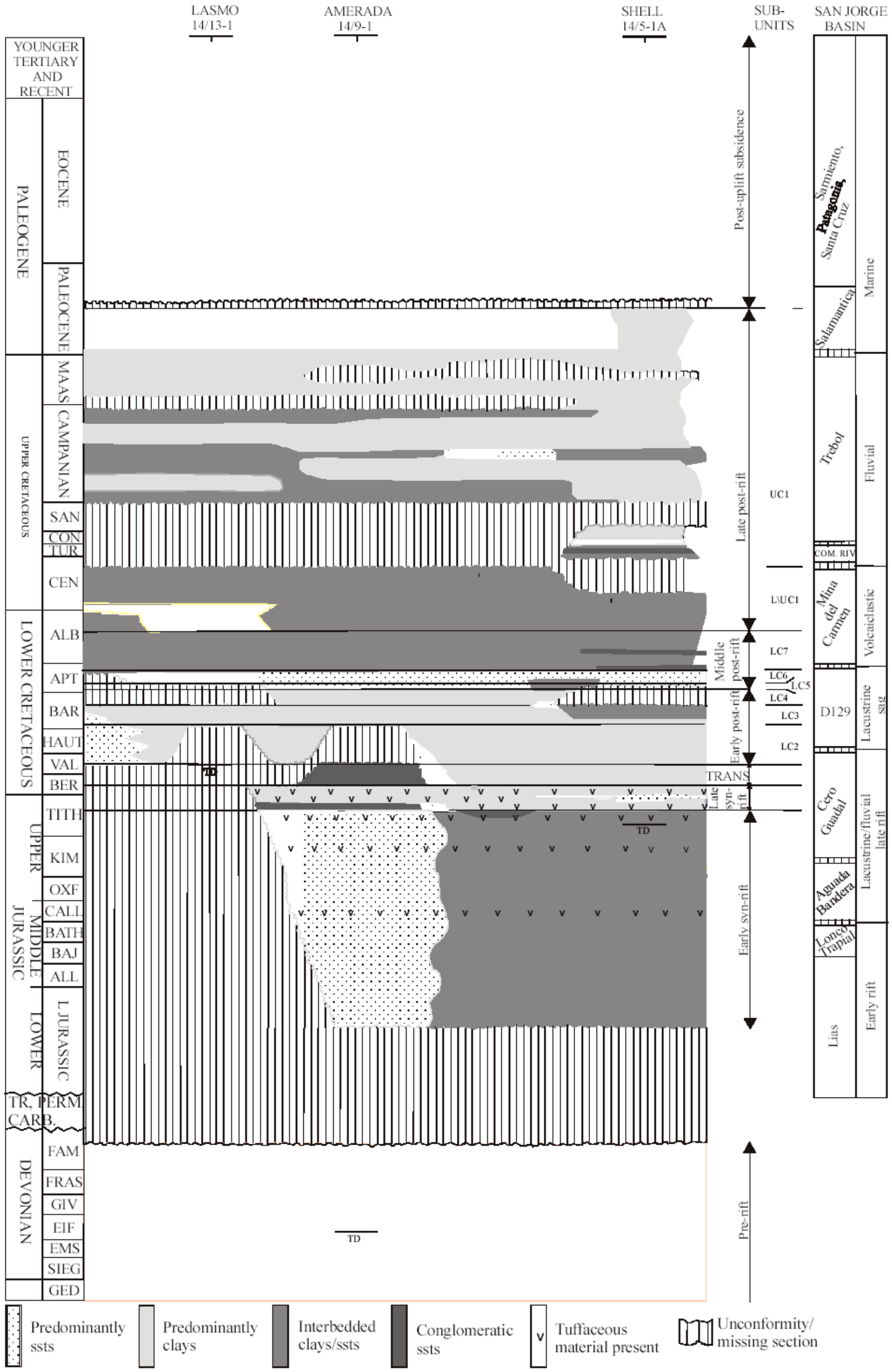

Figure 7 Cartoon of depositional setting of the LC4 sub-unit of the early post-rift sequence (Barremian to Aptian) in the northern part of the North Falkland Basin. Note that the Intra-Grabenal-High was probably at least partially emergent at this time.

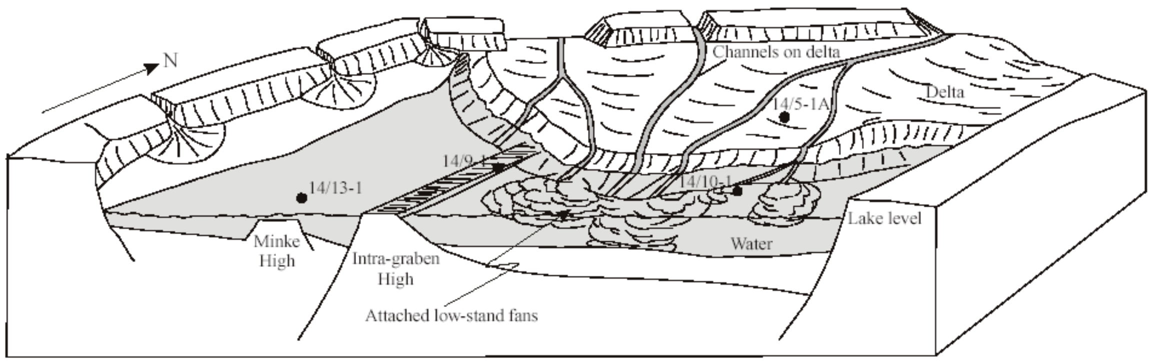

Table 1. Statistics for the six wells drilled in the North Falkland Basin in 1998.

Well	**Operator**	**Spud date**	**Status**	**TD depth (m)**
14/09-1	Amerada	27/04/98	P&A oil shows	2615
14/13-1	Lasmo	06/06/98	P&A dry hole	1550
14/05-1A	Shell	05/07/98	P&A oil & gas shows	4525
14/24-1	IPC	16/09/98	P&A oil shows	2939
14/09-2	Amerada	13/10/98	P&A oil shows	2370
14/10-1	Shell	01/11/98	P&A oil & gas shows	3005