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# **Falkland Islands: past exploration strategies and remaining potential in under-explored deepwater basins**

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## **Abstract**

The Falkland Islands are surrounded by four major sedimentary basins (the Falkland Plateau Basin to the east, the South Falkland Basin to the south, the Malvinas Basin to the west, and the North Falkland Basin to the north). The basins underwent complex rifting from the ?Triassic through Valanginian, during fragmentation of Gondwanaland, before being subjected to Cretaceous thermal sag and Cenozoic uplift coincident with Andean compression and the development of overthrusting along the plate boundary to the south.

Only the North Falkland Basin has been drilled, with six wells spudded back to back by four operators who formed a unique alliance in 1998 to undertake all of the logistics and support work to facilitate a multi-well drilling campaign. Drilling took place in water depths between 250 and 460 metres. Five of the six wells had oil shows, mostly in post-rift sandstones located immediately above the main source rock interval. Live oil was recovered at the surface from one of the Shell wells; significant levels of gas were also recorded in some wells. Although none of the wells encountered commercially viable accumulations, it is possible that up to 60 billion barrels of hydrocarbons could have been expelled in the basin. Post-mortem analyses of the petroleum system have revealed why the wells were non-commercial, and have pointed the way to future commercial success.

As well as the remaining potential of the North Falkland Basin, the other large, deepwater to ultra-deepwater basins around the Islands are under-explored, and are covered only by reconnaissance seismic data. Oxfordian to Aptian claystones encountered in DSDP boreholes indicate a potentially prolific hydrocarbon yield from Type II kerogens. Modelling suggests that the source rocks are possibly mature for oil generation at about 3,000 metres below sea bed, and numerous play types can be predicted on the basis of the existing seismic data and by correlation with analogous basins.

The paper will highlight the entire basin potential of the offshore Falklands region (petroleum systems, sequence stratigraphy, tectonic evolution, etc), evaluate the pros and cons of the unique exploration sharing strategies adopted so far, and outline the E & P challenges posed by the particularly sensitive environmental concerns in the region.

## **Introduction**

The Falkland Islands' offshore exploration area extends to over 400,000 km<sup>2</sup>, and contains four Mesozoic sedimentary basins (Fig. 1). Following a competitive licensing round in 1996, 14 oil companies took seven concessions in the North Falkland Basin, and drilled six wildcat wells within the distinctive half graben that forms the main axis of the basin. The other basins surrounding the Islands are undrilled. All four basins offer unique exploration opportunities and challenges. The remoteness of the area and deep water nature of some of the basins mean that the exploration costs

may be relatively high, but there is potential for large economic rewards

The sealife surrounding the Falkland Islands is diverse, unique and unspoilt. Because of the environmental sensitivities of the region, it has been necessary to develop strict environmental controls on exploration activity. However, oil companies operating in the region to date have contributed significantly to the understanding of the marine environment, and demonstrated that exploration can be conducted safely in such sensitive areas if the explorers, regulators and stakeholders work in concert.

This paper provides a geological framework for the four basins, outlines the nature of the petroleum systems in each of them, and examines the unique exploration strategies that have been adopted in the area to date.

## **History of exploration**

### **Academic seismic data**

Seismic profiles were first shot across the area by the Lamont-Doherty Geological Observatory in the late 1950s. This was followed, in the 1970s, by a range of mostly academic studies, culminating in the drilling of three DSDP boreholes on the Maurice Ewing Bank, several hundred kilometres east of the Islands in 1974; these boreholes proved the existence of potential oil source rocks in the area.

### **Speculative seismic data**

Several generations of multi-channel, speculative seismic data have been acquired across the region. In 1977-78 two regional seismic surveys were shot by Western Geophysical and GSI; together these comprise some 21,652 km of data. Between 1993 and 1995 Geco-Prakla and Spectrum acquired regional reconnaissance speculative seismic data south and north of the Islands respectively, with a combined total of 15,558 km of data. Spectrum subsequently acquired infill speculative seismic data over their original reconnaissance grid to the north of the Islands; this infill survey comprises 3,650 km of data. In 1997 Spectrum also acquired a grid of seismic data over the so-called Special Co-operation Area (spanning the putative median line between the Falklands and Argentina), infilling the original regional reconnaissance grid laid down by Geco-Prakla. Lundin Oil acquired 1,250 km of seismic data over the unlicensed area immediately north of the North Falkland Basin licensed areas in early 2001.

### **Wells in Argentine waters adjacent to the Falklands**

In the eighties and early nineties, 17 wells were drilled in the adjacent Argentine waters of the Malvinas Basin; 13 of the wells were drilled by Exxon, three by Occidental Argentina and one by YPF. The geology of these wells has been summarised by Galeazzi (1998). None of them yielded commercial quantities of hydrocarbons, but five had

encouraging shows of oil and gas in an under-charged Lower Cretaceous reservoir; the best flow rates were from the Calamar x-1 well, which flowed about 3,200 barrels of 37° API oil per day. A well drilled in late 1994 in the San Julian Basin to the northwest of the Islands is reported to have had oil shows within a 300 m thick reservoir interval.

### **Award of Falklands Production Licences**

In 1996, seven Production Licences were awarded for acreage in the North Falkland Basin directly north of the Islands (Fig. 2). The seven licences initially covered some 12,800 square kilometres of the North Falkland Basin, an area equivalent to 48 UK North Sea blocks; parts of the acreage have since been relinquished (Fig. 2). The operators of the seven licensed areas in the North Falkland Basin agreed to an exploration programme encompassing over 7,500 km of seismic, a large exploration 3D seismic programme across the boundary of licences A and B, and the drilling of six or seven commitment wells. All of this work was committed for Phase 1 of the licences. Seismic acquisition subsequently started in 1997; the drilling operations (discussed below) commenced in April 1998, finishing in November 1998.

### **Wells drilled in the 1998 drilling campaign in North Falkland Basin**

Six wells were drilled in the North Falkland Basin during 1998 (Fig. 3). The 1998 drilling campaign was a great success, and the technical challenges of drilling in Falklands waters were proved to be far less severe than anticipated. The six wells were drilled over an eight month period, using a shared rig on a back to back basis.

Five of the six wells drilled had oil shows, mostly found within post-rift sandstones located immediately above the main source rock interval. Live oil was recovered at surface from one of the Shell wells: the oil has an API gravity of 27°, and was expelled from a mature source rock. Significant levels of gas were also recorded in some wells. Although none of the wells encountered commercially viable accumulations, sufficient was learnt about the basin and its petroleum systems to anticipate success in future operations.

### **The innovative drilling strategy adopted to explore the North Falkland Basin**

An innovative exploration strategy, whereby all operations across several licences were conducted under a single umbrella agreement, was adopted for the 1998 drilling campaign in the North Falkland Basin. The four groups that had committed to early drilling combined to form a unique operation company called FOSA (standing for the Falklands Offshore Sharing Agreement), which undertook all of the logistics and support work to facilitate a multi-well drilling campaign.

FOSA was managed through a steering committee composed of members from each operating company. Each company also took direct responsibility (answering to the steering committee) for managing one or more of the

operational sub-committees set up by FOSA. There were seven such sub-committees, responsible for: drilling services (managed by Amerada Hess); operations base and supplies (managed by Lasmo); health and safety issues, aviation and site survey work (all managed by Shell); environmental work (managed by Lasmo); and finance/tax (managed by Amerada and Lasmo).

As with any innovative strategy for reducing exploration costs and impact, there were inevitably advantages to be gained and disadvantages to be endured. Overall, the FOSA model worked well, with significant cost reductions, expanded environmental studies and minimal socio-economic disruption to a small community. The agreement benefited the oil companies concerned and the Falkland Islands Government. However, there were disadvantages associated with the rapid exploratory drilling. The main advantages and disadvantages of the FOSA system are outlined below.

### **Advantages**

The FOSA agreement led to a rapid exploration effort in the North Falkland Basin after the award of licences. Led by operators Shell, Amerada, Lasmo and IPC/Lundin Oil, the 14 companies quickly acquired extensive seismic databases. Fast-track drilling followed, with the first well spudding in April 1998, just 18 months after the award of licences. Given the remoteness of the region, and the absence of proprietary data at the beginning, this was a remarkably quick start to the exploration campaign.

FOSA determined that the greatest economic advantage for the drilling campaign lay in sharing a single rig, supply base, aviation link, site survey facility and operations/logging staff, and therefore contracted all the required services for a minimum six well drilling campaign on this basis. The main advantages that this agreement afforded the companies were a financial saving of over \$36million each, a larger pool of expertise than could be provided in-house, greater flexibility than if they were each mounting a single or two well drilling operation, a reduced manpower requirement, and a unified voice on many issues. It also gave the companies enhanced bargaining power when dealing with suppliers.

Aviation links were effected through the use of a shared helicopter charter, and through the use of a chartered Boeing 747 for crew changes between the UK and the Falklands, thereby overcoming the difficulty of limited seat availability on the scheduled flights to the islands. The companies shared the charter of a single site survey vessel to investigate all potential drilling sites for the first round of exploration: this reduced mobilisation costs significantly. By agreeing to share (virtually) all exploration and engineering data before commissioning a rig, FOSA were able to contract one set of engineers, well loggers, and other essential contract personnel, who worked through the entire

drilling campaign (with appropriate shore-leave). Each operating company supplied the drilling managers from their own staffs, and they were responsible directly for their own wells. The sharing of data and engineering expertise obviated the need for crew changes at the start and finish of each well, and also relaxed the pressure on accommodation both at the forward supply base and in Stanley, the capital of the Falklands, which has a population of only 1,500.

By sharing operational capacity and establishing a single forward supply base, FOSA were able to ensure that sufficient equipment and disposable assets were available in the Falklands throughout the drilling campaign. Therefore, there were always sufficient pipe sections, casing shoes, mud supplies, etc, to maintain more or less constant rig use, which would have been difficult from several single supply bases. The socio-economic and environmental impact of setting up just one supply base was minimal, especially compared to the potential situation had several been established, with one operation for each well.

The FOSA advantages were not restricted to the operators, with the Falkland Islands Government also benefiting from the agreement in many ways. The Falklands is a very small community (just over 2,000 people), and there were pre-drilling concerns that a multi-rig scenario, with separate supply bases, might impact adversely on local employment. The single FOSA supply base had a minimal operational/manpower impact on the community. However, the biggest advantage to the community was probably in terms of the amount of environmental protection and associated monitoring that was conducted by FOSA. The combined effort was to some extent extended by peer pressure (despite the costs), and inevitably led to a significantly enhanced environmental model than if the companies had managed individual environmental projects. This was an important aspect for the Government, which had legislated fully to ensure the highest standards of environmental protection and awareness in this unspoilt haven, where the coasts teem with sea-life and sea-birds.

### **Disadvantages**

The FOSA agreement did, however, have one major draw-back. Because the operators were sharing a single rig, with the clock continuously ticking and a daily rental rate near the peak of the market, there was no time available for analysis of well results before the next well had to be spudded. This problem was compounded by the fact that the drill sites had been chosen at least six months in advance, in order for the necessary site survey works to be undertaken using a single survey vessel drafted in from the UK. Although most of the operators surveyed several possible sites, each was chosen on the basis of pre-drilling knowledge, and there was no chance to pick completely new locations, with new play concepts, based on the results of the wells as they were drilled. Consequently, only a small number of play types

were actually tested, and extensive post-drilling analysis (conducted slowly and with the benefit of hindsight) has identified several other play concepts that would have been better options for drilling. The results of the post-mortem analyses are summarised below in the section on the geology and prospectivity of the North Falkland Basin.

### **The environment and associated exploration sensitivities**

#### **Climate**

The climate of the Falkland Islands is similar to that of Scotland. The Islands are at about 52°S, and are therefore at a similar latitude south as London and Calgary are north. Falkland winters tend not to be as severe as found in some parts of the UK, but they are longer. Summers are not quite as warm as the UK, but the Islands enjoy more hours of sunshine than London.

The climate is characterised by a temperature range from 21°C (70°F) in January to -3.4°C (26°F) in July. Mean temperatures are about 4.8°C (40°F) in winter and 9.6°C (49°F) in summer. Offshore sea surface temperatures range from around 6°C (42°F) in July/August to 13°C (56°F) in February. Rainfall is evenly distributed throughout the year, averaging 625 mm (24 inches) per annum in Stanley to as little as 310 mm (12 inches) per annum in the southwest of the Islands. The prevailing wind direction (70% of the time) is from a broad arc spanning the SSW to NNW. For at least 60% of the time the winds are less than Force 5 (17 knots) in intensity. Force 8+ gales (>34 knots) and storms account for only 5% to 8.5% of winds in the nine months September to May, but for 12% of all winds in the June through August winter months.

Most waves (67%) also originate from a broad arc to the SSW through NNW of the Islands. Wave heights exceeding four metres occur only for 14% of the time during most of the year, except during the winter months of June to August when their frequency rises to around 24%. Waves exceeding six metres high occur for only 2% of the year except from June through August when their occurrence increases to 4.9%. A strong westerly current is experienced on the southern shores of the Islands during and after south and southeasterly gales. To the north of the Islands, the "Falklands Current" has a mean velocity of about 0.5 knots towards the northeast, but strong currents can be expected at times due to the unsettled and stormy characteristics of the region. To the southwest and east of the Islands, the "Southern Ocean Current" has a mean velocity of about 0.5 to 1 knot towards the north and northeast. There are twice daily tides around the Islands, ranging from 0.3 to 3.5 metres above local datum.

There is no pack or floating ice as the area is 850 miles (1365 Km) north of the Antarctic circle. There are rare incidents of ice-bergs passing close to the eastern margin of the offshore exploration zone, but the risk from bergs within the area of initial exploration interest is considered to be negligible.

A statistical analysis of seismic surveys shot around the Islands between 1992 and 1998 suggests that the offshore climate favours exploration for most months of the year, and indicate that the annual average shooting downtime due to weather is just over 19%. The months with the highest weather related downtime are July (35%), August (60%) and September (32%). The most productive months are December (with 11% downtime), January (7% downtime) and February (with no recorded downtime).

### **Environmental impact assessments before drilling**

Before drilling operations were started, licence holders conducted a full Environmental Impact Assessment (EIA) to determine the possible adverse effects on the environment as a result of operations. These EIAs were reviewed by the Government and its specialist advisors, and were made available to local non-governmental environmental organisations. Licensees took account of the findings of the reviews, and made changes considered appropriate by the Government. The EIA contained a plan for minimising any potential environmental threat perceived as a result of planned operations, as well as a strategy for dealing with any adverse effect on the environment caused by the operations. The first six wells drilled in the North Falkland Basin in 1998 were covered by a single EIA, prepared by FOSA.

### **The local Environmental Forum**

An environment forum including oil company representatives, Falkland Islands Government officials, local non-governmental organisations and Island stake holders was established before the first exploration drilling began in 1998. The Forum meets annually during periods of reduced drilling activity offshore, but meets as required when drilling is scheduled. The resultant close co-operation between explorers, regulators and all interested parties ensured that the highest standards of environmental protection were maintained throughout the initial exploration campaign in the North Falkland Basin.

Oil exploration companies spent nearly \$2million on environment data acquisition at the time of the first drilling campaign in the North Falkland Basin between 1997 and 1999. This expenditure included obtaining metocean data, as well as funding a seabirds and cetaceans at sea study; this study has continued after the initial drilling campaign through funding provided by the Falkland Islands Government, in order to provide up to three years of data. The environmental management model used by the Falkland Islands is one which could be adopted in other environmentally sensitive exploration areas worldwide.

### **Exploration Geology**

The Falkland Islands lie at the western end of the Falkland Plateau. The regional geology of the area has been

described by Richards *et al.* (1996), who summarised the various hypotheses relating to the plate tectonic evolution of the region and discussed many of the early studies of the area. The Islands are surrounded by four major sedimentary basins: the Falkland Plateau Basin to the east, the South Falkland Basin to the south, the Malvinas Basin to the west, and the North Falkland Basin to the north (Fig. 1). The four basins appear to have extended initially as Triassic through earliest Cretaceous rifts associated with the break-up of Gondwanaland. A Valanginian end to rifting was followed by thermal sag. There is evidence of Cenozoic uplift, possibly coincident with Andean compression and the development of overthrusting along the plate boundary to the south of the Islands resulting from opening of the Scotia Sea.

### **The "southern" basins - Malvinas Basin, South Falkland Basin and Falkland Plateau Basin**

This area includes the zone of Special Co-operation to the southwest of the Falkland Islands (Fig. 2). No parts of these basins in Falklands waters have yet been awarded as Production Licence areas, and no commercial wells have been drilled within the Falkland Islands Designated Area in any of them. However, the DSDP boreholes on the Maurice Ewing Bank to the east, and about 60 commercial boreholes drilled in Argentine waters in the Malvinas and Magallanes basins to the west provide information on petroleum potential. Estimates of other petroleum factors can be made by comparing the basins with the Bredasdorp, Pletmos and Southern Outeniqua basins off Southern Africa, because the two areas may have shared a similar tectono-sedimentary history until the separation of the eastern and western portions of Gondwana in the Early Cretaceous.

#### *Source rocks*

Oxfordian to Aptian claystones encountered in DSDP boreholes 330 and 511 on the Maurice Ewing Bank to the east of the Falklands contain terrestrial and aquatic organic matter, with up to 6% TOC, and a potential hydrocarbon yield of around 25 kg/ton of rock from Type II kerogens. Thermal subsidence modelling suggests that the source rocks are possibly mature for oil generation at about 3,000m below sea bed, over a wide area of the Falkland Plateau Basin and Malvinas Basin (Fig. 4). Generation of oil here may have started in the Campanian, about 81 million years ago. Within the South Falkland Basin the same source rocks may be oil mature at a depth of either 11,100 ft below sea bed or 8,500 ft below sea bed depending on whether a low or high heat flow is computed during the main rift phase of the basin. Maturity levels of the main Upper Jurassic to Lower Cretaceous source interval within the South Falkland Basin may have increased gradually during the Cretaceous, with oil generation starting at around 98 to 102 million years ago. Similarly aged source rocks within the Malvinas Basin may be mature for oil at a depth of around 11,000 ft below sea bed, with oil generation possibly starting at 40 million years ago (*i.e.* in the mid Eocene).

Drilling in the Argentine sector near the axis of the Malvinas Basin has been only partly successful, due largely

to the unpredictable nature of the reservoir target in the area. However, some of the wells, particularly the more northerly, may have been dry because of their distance from the site of mature source rocks to the south and east.

#### *Reservoir rocks*

Permo-Triassic, Mesozoic and Cenozoic sediments occur beneath or within all three basins, and each interval could contain potential reservoir rocks. The only Mesozoic clastics of possible reservoir quality proven thus far in the Falkland Plateau Basin are of probable Oxfordian age, and were penetrated in DSDP borehole 330, where the Oxfordian succession commences with a clean, beach sand deposit marking the Late Jurassic marine transgression over a swampy terrestrial environment.

The Lower Cretaceous Springhill Formation forms the main reservoir interval in the Argentine part of the Malvinas Basin, and may extend eastwards into the South Falkland Basin. It is a fluvial and transgressive sandstone that was deposited over the eroded basement topography. Proximal sediments derived from the Devonian-Carboniferous Falklands Platform area may substantially improve reservoir quality locally at the Lower Cretaceous level. Albian to Cenomanian sandstones are also present in the western part of the Malvinas Basin, and isolated developments of these sandstones draped over basement highs or Jurassic tilted fault blocks may be found in the Falkland Islands Designated Area. The Palaeocene glauconitic sandstones recorded in the Argentine Ciclon 1 well in the southern Malvinas Basin were probably deposited during a shallow marine transgression, and may therefore occur over large parts of the basin. Similarly, transgressive sandstone may have developed at several horizons throughout the Mesozoic and Cenozoic. Reservoir intervals may also be found in lowstand systems-tract wedges, similar to those which form reservoir intervals in the offshore Southern Africa basins.

#### *Seals*

All of the sandstone reservoirs in these basins are likely to be capped by thick argillaceous sequences and may therefore be adequately sealed. Major intra-basinal faults which terminate upwards within the Jurassic interval are unlikely to provide vertical breaches of younger sealing horizons. The low-stand fan wedges developed near the eastern limit of the Falkland Islands Designated Area are likely to be encased in pelagic mudstones, and these may form adequate sealing horizons.

#### *Play types*

Potential "play" types for these basins include:

- (1) large-scale wedges of low stand fan deposits, particularly in the Falkland Plateau Basin;
- (2) localised sandstone wedges associated with the basin margin faults;

- (3) tilted fault-block traps at Jurassic level;
- (4) intra-basinal mounds of low-stand fan origin at Cretaceous level, particularly within the Falkland Plateau Basin;
- (5) sub-thrust sheet structures along the southern margin of the South Falkland Basin;
- (6) folded Cretaceous sandstones deformed by, or draped over, east-west orientated strike-slip faults and associated flower structures in the South Falkland Basin;
- (7) the pinchout of Lower Cretaceous Springhill Formation equivalent sandstones;
- (8) stratigraphic wedge-outs or lateral facies change of Albian to Cenomanian sandstones developed over intra-basinal structural highs or palaeo-slope breaks within the Malvinas Basin;
- (9) fractured Jurassic volcanic rocks overlain and sealed by Cretaceous or Cenozoic mudstones around the margins of the Malvinas Basin; and
- (10) probable Permo-Triassic rocks in structural traps beneath a seal of either Jurassic volcanic rocks or Cretaceous-Cenozoic mudstones in any of the basins.

### **The North Falkland Basin**

The North Falkland Basin comprises two main structural elements: a N-S trending graben termed the North Falkland Graben, and a set of subsidiary basins to the west of the graben, also controlled by N-S trending extensional faults, but constrained by NW-SE oriented reactivated Palaeozoic thrust sheets. The North Falkland Graben is subdivided, in its northern part, into western and eastern depocentres, separated by a pervasive, N-S trending intra-graben high (Fig. 5). The graben is about 50 km wide at its northern end, and about 30 km wide near its southern margin, just 36 km or so north of the Islands; it is about 230 km long as presently mapped, but may extend further to the northeast.

Of the six wells drilled in 1998 (Fig. 5), three were 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.

Eight widely correlatable tectono-stratigraphic units are now recognised in the basin (Fig. 6). Each of the seismically-identified sequence boundaries defining the units has been tied to the downhole logs in the six wells. 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 detail by Richards and

Hillier (2000).

### *Source rocks*

Extensive analyses have been conducted on all claystones in all six wells. The claystone-dominated early post-rift succession is the main source rock interval of the North Falkland Basin. The organic matter in this claystone dominated interval is predominantly Type I kerogens, comprised mainly of alginite or lamalginite. Minor amounts of organic matter derived from terrestrial plants are also present. The algae are composed primarily of small unicellular types, with some larger *Botryococcus*, and indicate deposition in a lacustrine environment. The greyish brown lacustrine source rocks developed within the late syn-rift to early post-rift sections are lithologically similar to the Upper Permian lacustrine source rocks of the southern Junggar Basin of NW China, which are ranked amongst the richest petroleum source rocks in the world.

Modelling the timing of oil generation is imprecise, as it is difficult to define exactly when the peak heat-flow was reached in the basin: it may have been either from about 150 to 125 million years ago (during Jurassic to Valanginian rifting), or around 90 million years ago (during the post-rift phase), when the crustal temperature in the region may have increased due to opening of the South Atlantic. A regional unconformity has been recognised in the Turonian at about 90 million years ago, and may represent a phase of regional uplift and crustal thinning, and could therefore be associated with increased heat-flow at that time.

A number of basin subsidence models with varying heat-flows were calculated for the basin, but a model based on a peak heat-flow of around  $80 \text{ mW/m}^2$  at 90 ma (Fig. 7) closely matched the observed VR, temperature and geochemical data, and indicated that oil generation took place from the early post-rift source rock during the late Cretaceous, between 70 and 100 million years ago. This model suggested that at a depth of around 3,000m below sea level, over 50% of the organic material was converted to oil. A second subsidence model based on an earlier heat-flow peak (around 125 million years ago) produced peak oil generation around present day, but suggested that there was only about 2% conversion of organic matter, which is not consistent with the maturation analyses carried out on the source rocks themselves. A third subsidence model, with a heat-flow peak at around 112 million years ago, but with an estimated depth to source rock interval at 3,400m below sea level (which it may be in deeper, undrilled parts of the basin), predicted about 35% organic matter conversion to oil, but with maximum expulsion in the Aptian.

Subsidence modelling of the (relatively lean) deeper potential source rocks of mid Jurassic to Berriasian age within the early and late syn-rift successions suggested that they are currently post-mature, but have possibly been a (marginal) source, mostly for gas. They probably reached peak generation in the early Cretaceous, with most of the

hydrocarbons expelled by about 90 million years ago (in the Cenomanian to Turonian).

#### *Shows and oil types*

Oil, or oil and gas shows were encountered in five of the six wells, but the only hydrocarbons that flowed to surface were waxy oils (27° API) from Well 14/10-1. The shows were recorded from reservoir rocks at various levels, and also while drilling through the late syn-rift to early post-rift source rock interval, apparently seeping directly from the source.

Gas shows observed during drilling ranged from part of one percent, to in excess of 32% in the early syn-rift sequence in Well 14/5-1A. Gas types were often confined to C1, sometimes with minor amounts of C2 and C3, although high levels of C2 to C5 were recorded at times. Gas shows in the stratigraphically higher sandstones are generally less voluminous.

#### *Reservoir rocks*

All six exploration wells encountered potential reservoir rocks, ranging in age from Late Jurassic to Late Cretaceous. Lower Cretaceous potential reservoirs were most commonly encountered, particularly within the early and middle post-rift units. Some significant sandstone intervals have been encountered. For example, Well 14/5-1A encountered a total of 390 m of net reservoir (deltaic and fluvial sandstones) with an average porosity of 13%; while Well 14/10-1 had a total of 84 m of net sandstones, with porosities averaging 27.5%. However, location of good quality reservoir sandstones, particularly in the syn-rift section beneath the source rock remains the primary objective of future drilling campaigns.

#### *Seals*

An understanding of migration pathways and seals may provide the key to predicting the presence of hydrocarbon accumulations in the North Falkland Basin. The most effective top seal is probably provided by the early post-rift source rock itself, just as the Kimmeridge Clay Formation acts as both source and regional seal in the central and northern North Sea. The uppermost 600m or so of the early post-rift claystone interval is above the oil generation window in the central parts of the Eastern Depocentre. Headspace gas analyses suggest that there has been no vertical migration of gas through this claystone, pointing to its viability as an effective seal.

The main source rock interval (the Valanginian to early Aptian, early post-rift sequence) is represented on seismic sections by a Low Velocity Zone (LVZ), and before drilling this was thought to represent an overpressured zone. However, no overpressures were recorded in the basin during drilling, and the LVZ represents an extremely organic rich interval with low density values.

Since the claystones are not overpressured, the fluid-flow system beneath the claystones is not confined, and hydrocarbons are therefore more likely to have migrated laterally down-section, along migration channels provided by sandstones within or just below the claystones. This type of migration would tend to favour the accumulation of oil either near the basin margin in marginally-attached fans, in tilted fault blocks stratigraphically beneath the claystone blanket, or in syn-rift reservoirs along features such as the Intra-Graben High. Analyses of the oils recovered at the surface and observed as shows tend to confirm the hypothesis of preferential downwards migration. Only oil shows were observed in apparently under-charged sandstones above the main early post-rift source interval, whereas live oil was recovered from beneath the early post-rift source rock in Well 14/10-1.

It therefore seems probable that the main source rock interval provides an efficient vertical barrier to migration, and possibly explains why only small amounts of oil were able to migrate from the mature, basal parts of the source rock interval up into the middle post-rift transgressive and fluvial sandstones penetrated in all six wells. However, vertical migration into the middle post-rift sandstones might be possible where traps lie close to penetrative faults which provide a migration pathway down into the main kitchen area in the Eastern Depocentre, particularly adjacent to the basin margins. Lateral migration, beneath the claystones, and then into sub-source rock tilted fault blocks, fans attached to the eastern margin, or syn-rift sandstones in places along the Intra-Grabenal-High, are possibly the most efficient migration pathways in the basin. Large volumes of oil have possibly been generated in the basin, but there are only relatively minor shows in post-rift traps, whilst syn-rift traps have not been adequately tested.

#### *Play Types*

A variety of play types were planned to be targeted by the 1998 drilling campaign, but post-well analyses indicate that only three play types were actually partially tested. These tested plays were the early post-rift deltas, the middle post-rift transgressive and fluvial sandstones, and the syn-rift succession in the core of the Intra-Graben High. Untested plays include Jurassic to earliest Cretaceous fan sandstones deposited during the syn-rift phase, early Cretaceous deltaic bodies that prograded into the basin from marginal areas during the early post-rift, shoreline and/or transgressive sandstones of Aptian to Albian age that may have been deposited along the margins of the basin during the initial overstepping of the flanks in the middle post-rift phase, and other closed highs, particularly at syn-rift level, in the undrilled, southern part of the North Falkland Basin.

#### *Summary of North Falkland Basin prospectivity*

Good quality source rocks, reservoirs, seals and traps have all been identified in the North Falkland Basin. Although oil was recovered at surface in small quantities, the structures and primary reservoir targets drilled by the six

wells did not contain commercially viable accumulations of hydrocarbons. However, all of the elements of a working petroleum system are present in the basin, suggesting that further drilling, planned using information such as that derived from this post-well analysis, could lead to better commercial results.

The present day geothermal gradient for the basin has been established as approximately 44°C/km. Calculations of the probable depth of burial required at the present day geothermal gradient to place oil-prone claystones within the oil generation window indicate that the early generation of oil starts at around 2,700m below sea level, and that peak generation will occur in source rocks buried to greater than 3,000m below sea level.

The main oil-prone source rock intervals are provided by early post-rift lacustrine claystones of Valanginian to early Aptian age, although there is also some source potential in the deeper, older units. The Valanginian to early Aptian (early post-rift) claystones have not yet been penetrated in a setting deeper than the 3,000m peak oil generation threshold. However they, as well as older source rocks, are more deeply buried in undrilled parts of the basin (Fig. 8). The mature source rock has probably expelled over 60 billion barrels of oil.

The six wells were drilled in quick succession, using a single rig, on pre-planned locations that had been site-surveyed several months earlier. Although some scope for testing different play types had been built into the exploration programme by all the drilling companies, each had picked the largest, most easily defined structure to test in their own acreage. These structures all relied on a primary reservoir being located in early or middle post-rift sandstones situated within or above the early post-rift sequence that was correctly predicted to be the main source interval in the basin. However, because the wells were drilled back to back, with little time available to analyse the information obtained from previous wells, there was only very limited opportunity for the companies to refocus wells to target different play concepts. Consequently, all six wells were focused primarily on targeting sandstones that lie on probably the least effective migration pathway in the basin, and all found under-charged reservoirs.

An understanding of migration pathways and seals may provide the key to predicting the presence of hydrocarbon accumulations in the basin. The most effective and viable top seal within the basin is probably provided by the main source rock interval itself. The uppermost 600 metres or so of the source rock is above the oil generation window in the central parts of the basin. The entire source interval is normally pressured, although it has an anomalously low velocity due to its high organic content. Since the claystones are not overpressured, there are only ineffective vertical migration pathways through it, and hydrocarbons will therefore more likely have migrated laterally down-section, along the higher permeability, more horizontal migration channels provided by sandstones within or just below the claystones. However, vertical migration into the post-rift sandstones lying above the source/seal (that were the

principal targets of the drilling campaign) might be possible where traps lie close to penetrative faults which provide a migration pathway down into the main kitchen area. Lateral and down-section migration would tend to favour the accumulation of oil either near the basin margin, or in tilted fault blocks and stratigraphic traps beneath the claystone blanket (as in the Brent Province of the North Sea). Such targets have not yet been adequately tested.

### **New opportunities**

New exploration opportunities are available through farm-ins to existing licences (in the North Falkland Basin) and also through the issue of new Production Licences over any currently unlicensed acreage. New licences are available by application to the Government at the end of each month, and have initial exploration periods of three or five years, depending on the type and amount of data that will be collected in the initial phase: entry to a second exploration phase of three years requires a drilling commitment. A "Discovery Area" can be identified at anytime, and such an area can be held for 5 years to allow time for appraisal drilling and/or development planning. Once a development plan has been approved, exploitation can take place over a 35 year period.

Farm-ins to existing licences in the North Falkland Basin are actively encouraged by the Government, whose aim is to secure an injection of new exploration money into the region to kick-start a new drilling campaign. As noted above, there are many potentially exciting targets and play types in the basin that were not explored during the first six well drilling campaign, and substantial possible reserves have been identified in places. However, most current licence holders in the North Falkland Basin are small, relatively cash-poor companies without sufficient funds to mount drilling campaigns in their own right.

### **Conclusions**

Exploration of Falklands waters is in its infancy, and the four major basins surrounding the Islands are under-explored. A limited drilling campaign in the North Falkland Basin produced encouraging results, confirming the presence of an active petroleum system, with live oil recovered at surface. However, post-mortem analyses of drilling results indicate that the wells were not optimally sited with regard to migration routes in the basin. An active petroleum system has been demonstrated in the southern basins by drilling in Argentine waters and by DSDP boreholes drilled many miles to the east. However, no commercial drilling has been undertaken in the southern Falklands basins.

A unique cost and facilities sharing agreement was devised for the initial exploration phase of the North Falkland Basin. It had benefits both to the oil companies and government, and is a model that could be followed elsewhere to reduce exploration costs.

New exploration opportunities are available in all of the basins. Farm-ins to existing licences in the North

Falkland Basin would provide extensive datasets and readily defined drilling targets. New licences offered through the government's open-door policy would allow the early acquisition of exploration acreage in presently undrilled basins.

### **Acknowledgements**

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### **Figures**

- 1 Outline sketch of the offshore geology of the region.
- 2 Location of existing and relinquished Production Licences and the Special Co-operation Area (SCA).
- 3 Location of wells and proprietary seismic data in the licensed areas of the North Falkland Basin.
- 4 Distribution of mature source rocks in the offshore region.
- 5 Shaded two-way-time map to the base of the early post-rift succession, illustrating the main structural features of the North Falkland Basin. Structurally deeper areas are shaded yellow; structurally shallower areas are shaded dark blue; the major regional fault pattern is shown in grey.
- 6 Correlation of tectono-stratigraphic packages identified in the six North Falkland Basin wells (after Richards and Hillier, 2000).
- 7 Subsidence patterns and probable heat flow in the North Falkland Basin, and the modelled curves for the generation (solid line) and expulsion (dashed line) of oil from the early post-rift lacustrine source rock.

- 8 Map illustrating the area over which the lower part of the lacustrine source rock interval is mature in the Eastern Depocentre of the North Falkland Basin, relative to the positions of the six wells in the basin.

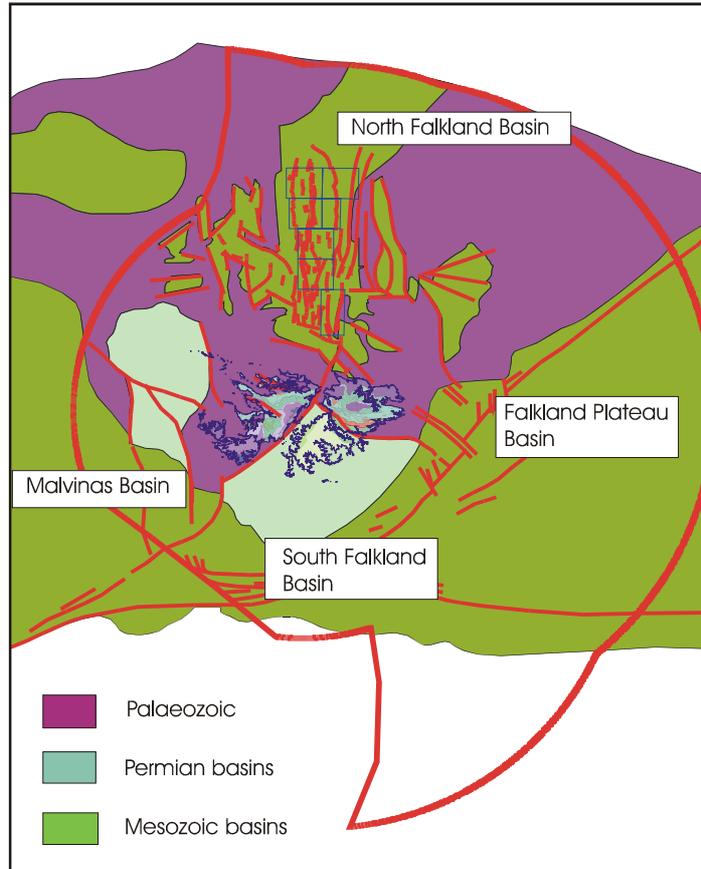


Figure 1

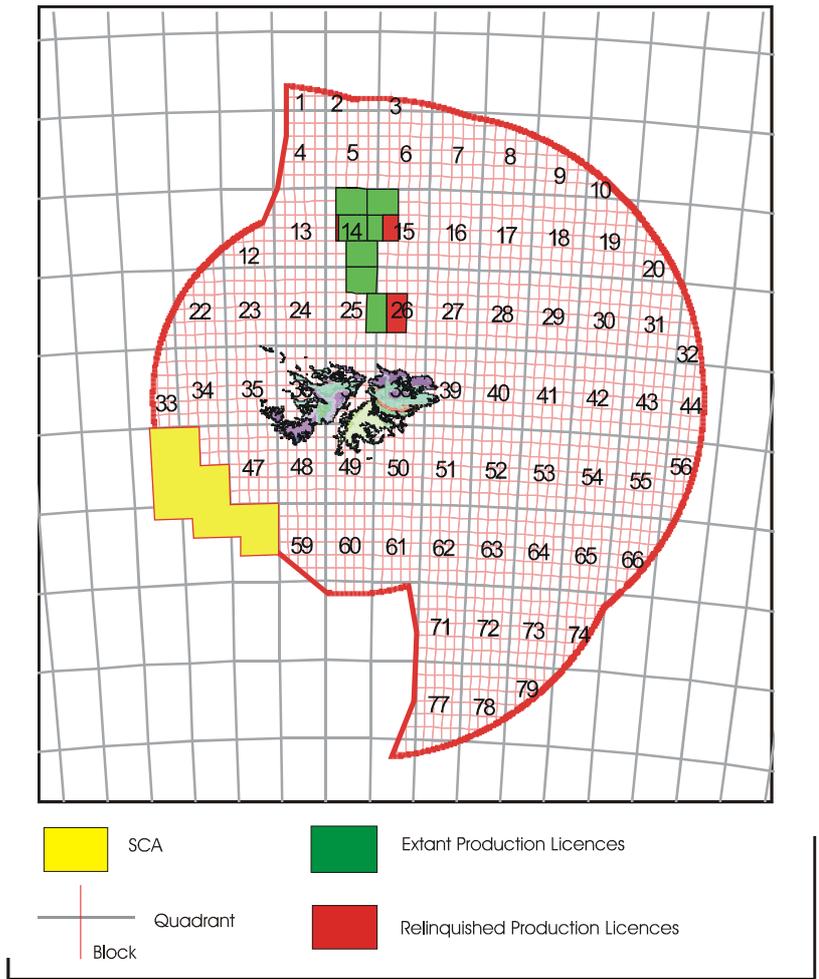


Figure 2

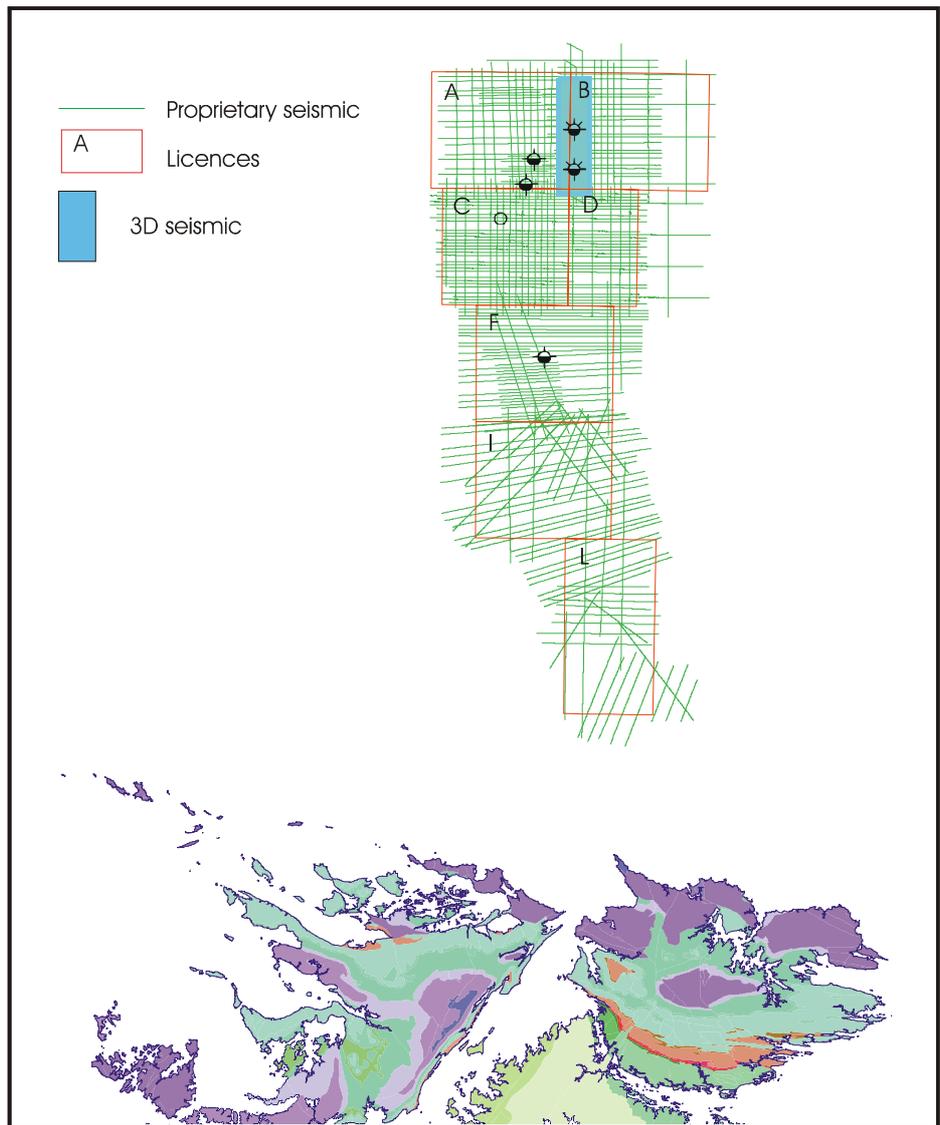


Figure 3

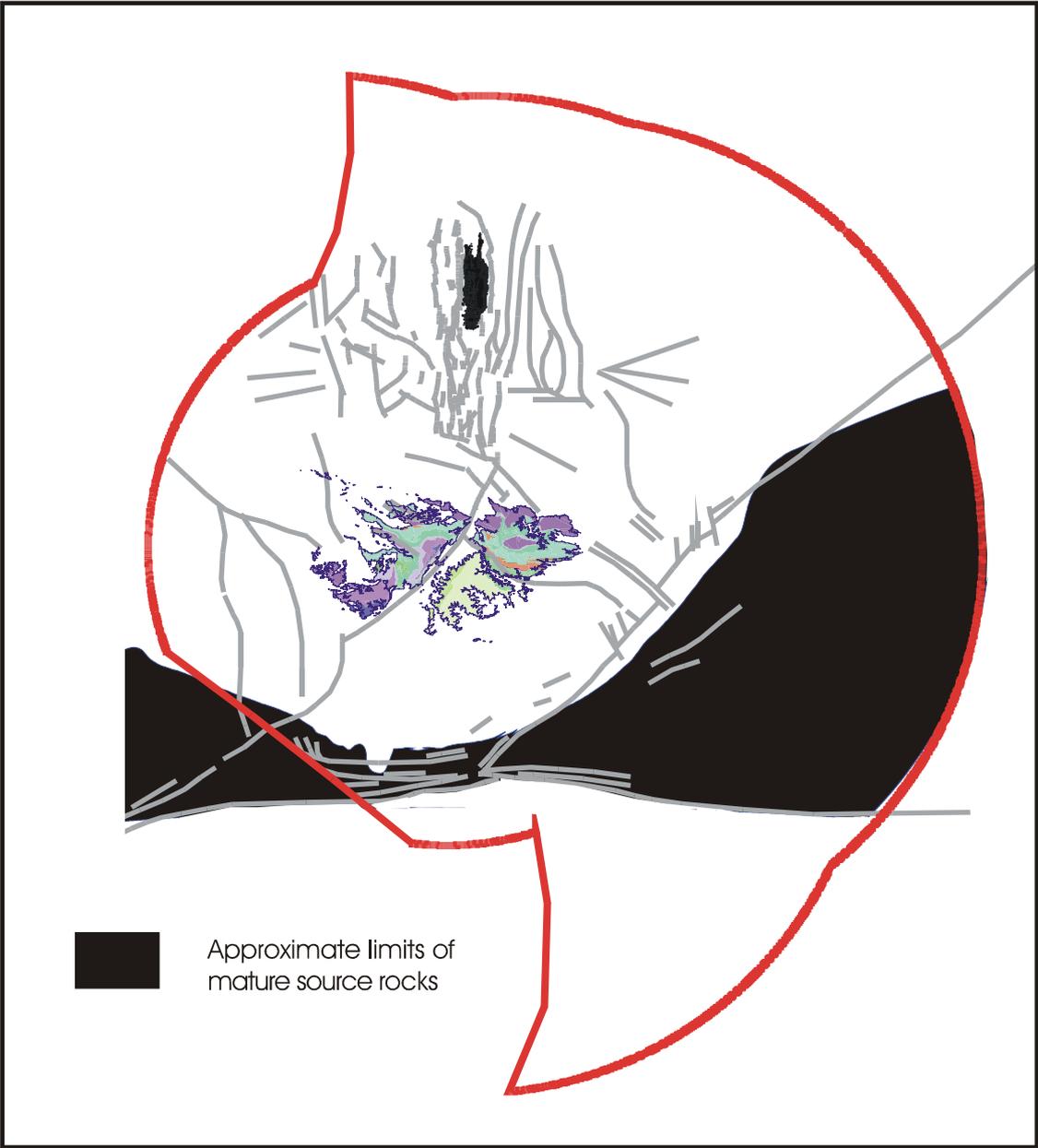


Figure 4

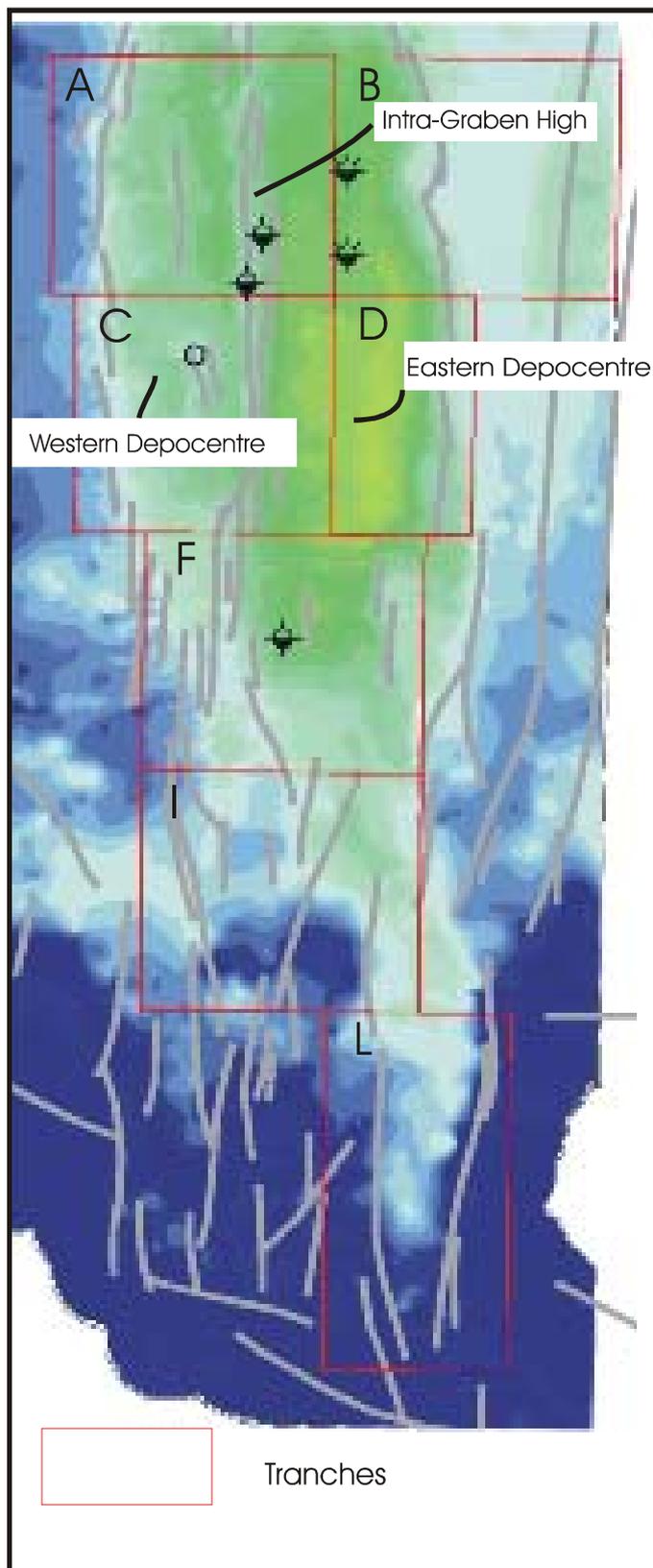


Figure 5

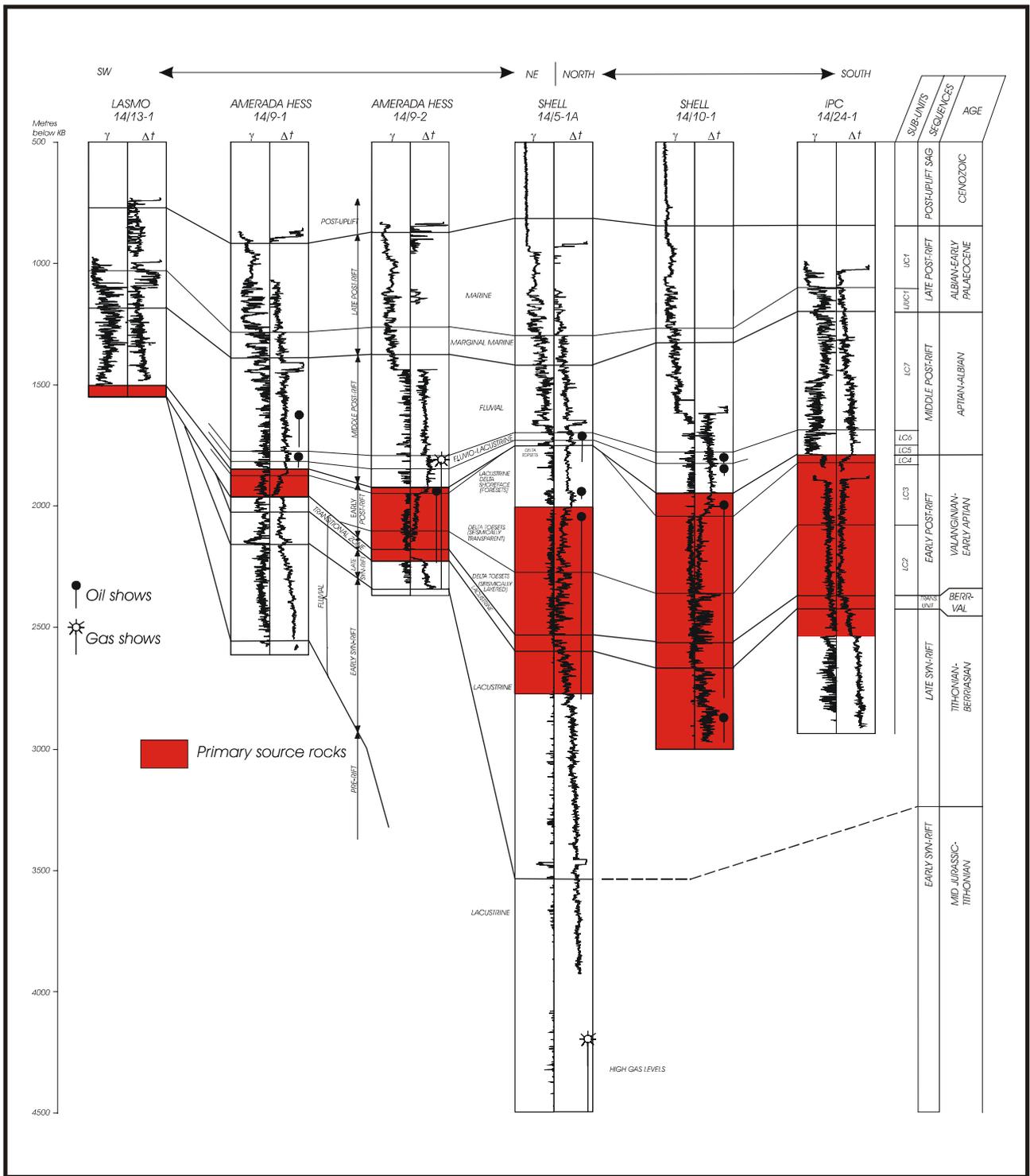


Figure 6

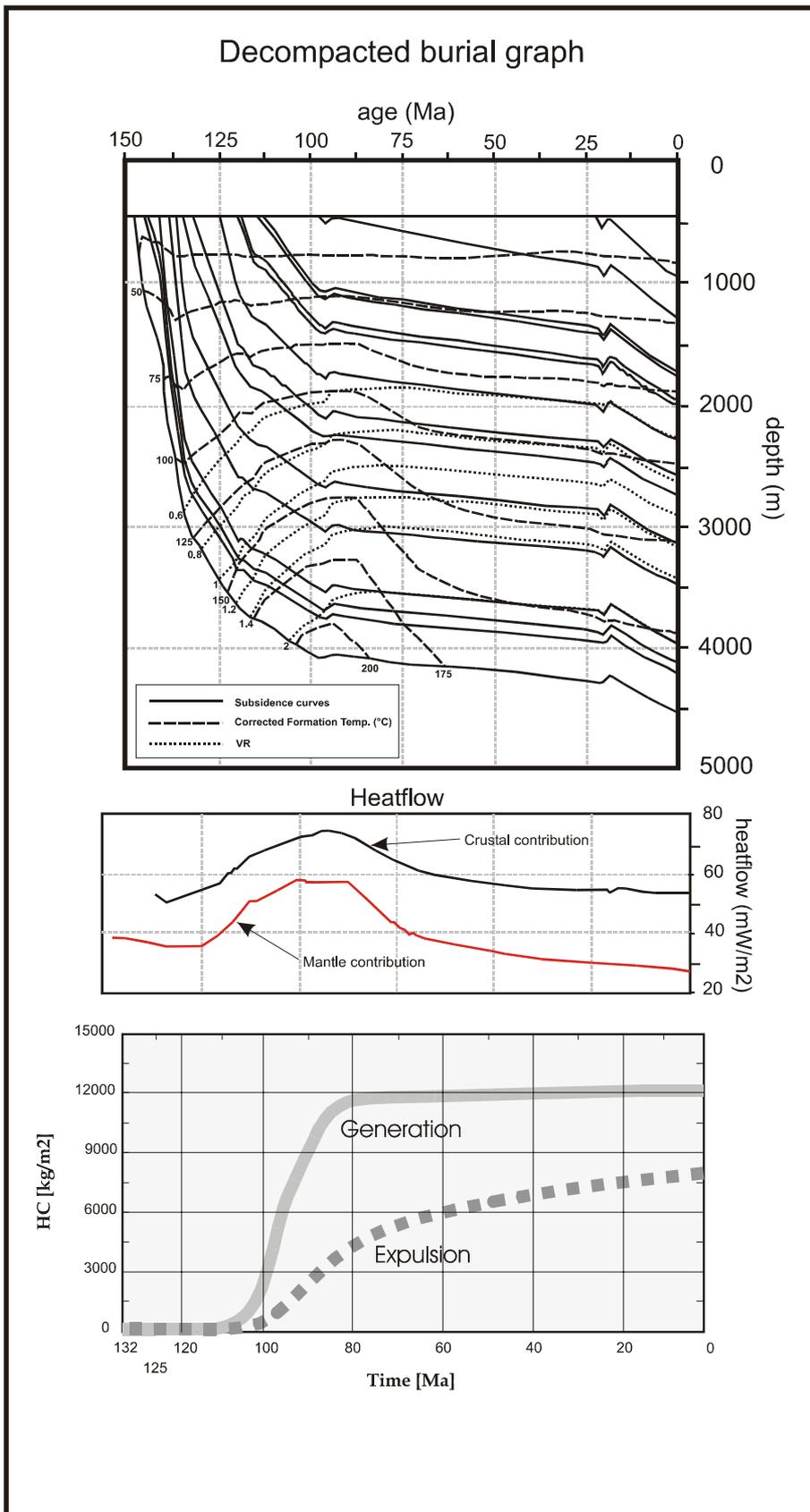


Figure 7

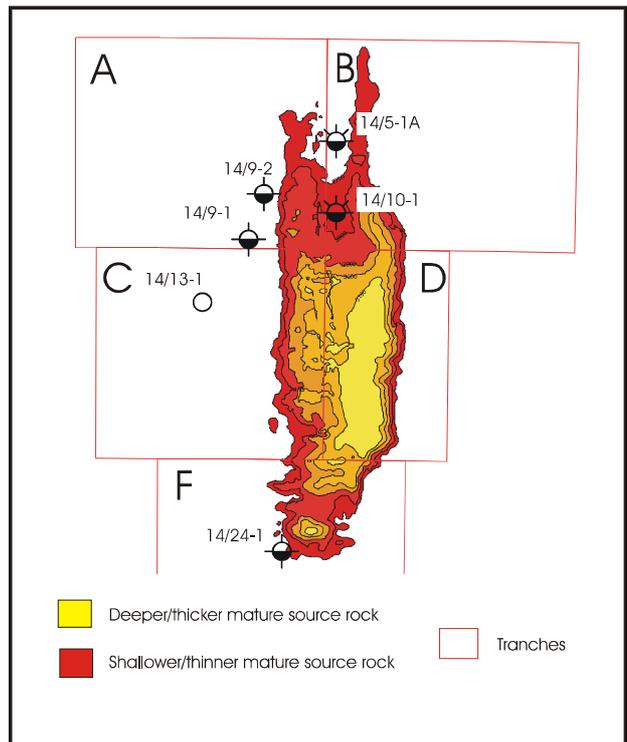


Figure 8