Paper published in Journal of Aquatic Research 2002
Special Publication on the Falklands Environment

Overview of petroleum geology, oil exploration and associated environmental protection around the Falkland Islands

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Keywords: Falklands
Geology
FOSA
Oil
Exploration
Environment

Abstract

The Falkland Islands offshore exploration area contains several Mesozoic basins with the potential for oil development. Exploration of all of these basins is at a very early stage. The only area to have undergone exploratory drilling so far is the North Falkland Basin, where six wells were drilled in 1998. These wells proved the presence of a rich organic source-rock, which has probably generated significant quantities of oil. However, all six wells targeted a limited number of exploration concepts, and none found commercial quantities of hydrocarbons. Post-drilling analysis of the well data suggests that commercial quantities of oil may be found in other parts of the basin.

The exploration to date has been conducted in tandem with an extensive and detailed environmental assessment of the region, funded largely by the oil companies and the Falkland Islands Government. The natural environment of the Falklands is important as a resource as well providing an unspoilt habitat. Detailed legislation and planning was put in place before exploration started in order to protect the environment.

Introduction

The Falkland Islands' offshore exploration area extends to over 400,000 km^2, and in terms of oil exploration, is one of the last remaining under-explored regions of the earth. This paper reviews the geology and oil potential of the area, and sets in context the environmental investigations that were conducted both in the preparatory phase and during the initial campaign of drilling for hydrocarbons in the North Falkland Basin, which lies to the north of the Islands.

Although the North Falkland Basin is the only area to have undergone exploratory drilling so far, geological and environmental research related to exploration has also begun to be focussed on the area of the Malvinas Basin, to the SW of the Islands. Here, in co-operation with Argentina, it is planned to offer further exploration licences for future drilling. A desk-top study off all available published environmental data pertinent to the region has already been undertaken jointly by the British Geological Survey (BGS) on behalf of the FIG and the Argentine Foreign Ministry. Both governments are also planning the first of a series of research cruises to acquire further data.

History of exploration

Exploration around the Falkland Islands started in the late 1970's, with the acquisition of a regional speculative seismic dataset by two different oil service companies. These data were not used to start exploration drilling at the time because the FIG was not then ready to offer drilling licences. The Argentine invasion of the Islands in 1982 curtailed further exploration. The BGS was contracted by the FIG to identify and promote exploration opportunities in 1992. Following an initial investigation which revealed the presence of several Mesozoic basins (Fig. 1), more seismic surveying followed. Although attempts were subsequently made to licence areas all around the Islands based on these new data, the only exploration interest at the time of the first licensing round in 1996 lay in the North Falkland Basin, an elongate rift basin (Fig. 2) located under relatively shallow water. The other basins to the south and east of the Islands present a more difficult technological challenge, and although possibly have good potential for oil production, lie under water depths often of several thousand metres.

Against all predictions, a drilling campaign comprising seven firm and a number of contingent wells was committed by the oil companies when they bid for North Falkland Basin licences in 1996. These wells were all planned for the first five-year term of the new licences. Six of these wells have been drilled to date: two by Shell and partners, two by Amerada Hess and partners, one by Lasmo and partners and one by Lundin Oil and partners (Fig. 2). The planning process for these six wells included the acquisition of an extensive network of seismic data to infill the existing speculative data that had been acquired by others before licensing began, and also the acquisition of a series of detailed, high-resolution surveys around 16 potential well sites. Further seismic data has since been acquired to the south of the southernmost well, over the portion of the North Falkland Basin closest to the Islands.

Several more wells may be drilled in the North Falkland Basin in the remaining years of the first phase of the licences, but meanwhile, reviews and analyses of existing datasets are being made by all of the oil companies. All of the existing licensees are marketing the exploration potential of the area to other companies, and are hopeful of achieving farm-in deals to boost exploration there and to fund further drilling.

The geological and geophysical data derived from the six wells are just a small sub-set of the information derived from the drilling campaign. Significant amounts of environmental surveying and associated new research was undertaken before any of the wells were started, and this surveying continued throughout the drilling phase, producing abundant environmental data. These environmental data have been analysed over the last few years, as can be seen from the other papers in this dedicated volume, and the collection of data continues through organisations such as Falklands Conservation.

How the environmental risk was managed before and during exploration in the North Falkland Basin

Before drilling licences were awarded in the North Falkland Basin, the Falkland Islands Government commissioned (from Brown and Root Ltd.) a reconnaissance survey of the coastline and near-shore benthic areas, in order to monitor any effects of future oil exploration activity on the local wildlife in the inshore zone. Using these data as a starting point, applications for exploration licences were judged partly on the basis of the applicant's understanding of the natural environment, and on the measures and further work that they would undertake to protect the environment from any potentially damaging effects of exploration. It was made clear to all applicants for drilling licences that environmental concerns were a priority for the FIG, and that the natural environment provided the Islands main income in the form of revenues from fisheries licences. As such, it was deemed imperative to ensure the highest standards of environmental research, analysis and protection, before drilling was allowed to start.

Because of the financial dependency the Islands have on their marine resources, the FIG placed quite severe restrictions on the nature and timing of exploration activity in certain regions of the North Falkland Basin. For example, no seismic acquisition is allowed in areas of high *Illex* squid concentrations during the fishing season, and there is also a restriction on shooting seismic within 12 miles of the coast because of the presence of squid-breeding areas in the inshore kelp.

There is no documented evidence that seismic surveying has a detrimental effect on the behaviour of squid, but even so, in order to ensure that the oil industry was not implicated if there were statistically meaningful dips in the squid catches during exploration operations, each operator was subject to the same strict regulations. These regulations did adversely affect some of the oil companies, restricting their operational phases considerably at times, with an attendant cost implication. In order to help ensure the protection of the fishing resource through the application of up to date research knowledge, several of the oil companies commissioned a report from ERT Ltd. to assess the effects of seismic acquisition on the environment.

All the local non-governmental organisations with an interest in the Falklands' natural environment were appraised at all stages of the planning process for exploration, and a Government-NGO liaison group (termed FENTAG, for Falklands Environmental Task Group) was set up to disseminate information in the early satges of exploration. When more detailed and extensive exploration activity started, FENTAG was dissolved, and the Falkland Islands Exploration and Production Environmental Forum (FIEPEF) was established, with permanent seats for the interested pressure groups and the oil companies, in order to report on environmental work in progress. FIEPEF still meets at least once every year, despite the present hiatus in the drilling campaign. In addition to FIEPEF, the FIG established an Environmental Committee, chaired by a local politician, to deal with all Island environment issues: this committee also has NGO representation.

Much of the environmental work during the last exploration phase was financed by a contractural grouping of the oil companies (termed FOSA, for Falklands Offshore Sharing Agreement). FOSA played a significant role in acquiring and interpreting environmental data in the region. The combined effort of their surveys was to some extent extended by peer pressure (despite the costs), and inevitably led to an enhanced environmental model for the region. 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.

An important part of the exploration drilling planning was the preparation of an Environmental Impact Assessment relevant to the first exploration wells (six of which have already been drilled) in the North Falkland Basin. This assessment, commissioned from ERT Ltd. by FOSA, was published in the Falkland Islands Gazette for comment, as well as being scientifically reviewed by the Natural Environment Research Council on behalf of the Falklands Government. Recommendations for change made by NERC and members of the public/NGOs were incorporated into the document before it was

accepted by the Government and the Environmental Forum. Further EIAs, conducted by the relevant oil companies, will be a necessary requirement of the planning process for drilling in other parts of the Falklands offshore area.

As part of the general environmental planning for oil exploration, the FIG established a new national oil spill contingency plan to complement the oil spill plan devised by FOSA. Both of these plans were drawn up by Oil Spill Research Ltd., and training in implementation of the plan was carried out locally. However, it was recognised that any perceived major environmental threat from oil spills, particularly to the north of the Islands, derived more from fishing fleets or passing tankers than from exploratory work.

One environmental aspect that the FIG legislated for in detail concerned the health and safety of the workforce and the offshore installations. It was considered that safe working practices, whilst intrinsically valuable, also usually result in the creation of a safe and pollution-free environment. Consequently, it was incumbent on the operators to ensure that the offshore rig used to drill the first six wells satisfied the UK's Health and Safety Executive both with regard to the worthiness of the rig and to the standards of the safety management system (SMS) in place to deal with incidents offshore. Ensuring an adequate SMS is in place will be an important part of the vetting process for any new rig that works in the area in future.

How FOSA worked

The FOSA operation was a unique sharing operation that was developed specifically to aid Falklands exploration. FOSA undertook all of the logistics and support work to facilitate a multi-well drilling campaign for and on behalf of the oil companies. The FOSA operation had many benefits, both for the oil companies concerned and the Falkland Islands Government, and it is therefore worth outlining its main components, in addition to the environmental surveying benefits described above.

FOSA was established as an umbrella organisation led by a steering committee composed of each operating company. Each company also took direct responsibility (answering to the steering committee) for one or more aspects of the FOSA agreement. In all, there were seven areas covered by the agreement: drilling services (managed by Amerada Hess); the 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).

Realising the socio-economic advantages to be won by sharing a single rig, supply base, aviation link, site survey facility and operations/logging staff in a remote region like the Falklands, FOSA contracted all the required services for a minimum six well drilling campaign on this basis. This approach resulted in a calculated saving of over £24m for each operator. It also provided each of them with a larger pool of expertise than they could provide 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.

However, the FIG also derived significant advantages from the FOSA agreement. 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.

The geological information learnt from drilling

The North Falkland Basin 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. 2), and it is surrounded by a structural platform composed probably of Devonian sedimentary rocks. Two major depocentres, the Western Depocentre and the Eastern Depocentre, are separated by a faulted ridge termed the Intra-Graben High. The Intra-Graben High appears to have been a positive feature influencing sedimentation during much of the basin's evolution.

Eight widely correlatable tectono-stratigraphic units are recognised in the basin. Each of the seismically-identified sequence boundaries defining the units can be tied to the downhole logs in the six wells. The eight tectono-stratigraphic units thus recognised are: a pre-rift sequence of Devonian age; an early syn-rift interval of Jurassic to Tithonian age; a late syn-rift interval of Tithonian to Berriasian age; a transitional unit probably of Berriasian to Valanginian age; an early post-rift interval of Valanginian

to Aptian age; a middle post-rift interval of Aptian to Albian age; a late post-rift interval of Albian to Palaeogene age; and a post-uplift sag unit that spans the remainder of the Cenozoic (Richards and Hillier, Part 1, in press).

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 was followed by thermal sag, and marine/deltaic deposition occurred through the remainder of the Cenozoic.

Although no commercial accumulations of oil were found, live oil flowed to surface in one well, and shows were seen in another four. Significant amounts of gas were also released while drilling in parts of the syn-rift succession. Despite the lack of commercial success, post-drilling analysis suggests that the early post-rift lacustrine claystone encountered in all six wells may be a richly-productive source rock. The generation of oil from these claystones starts at around 2,700m below sea level, and peak generation will occur in source rocks buried to greater than 3,000m below sea level (Richards and Hillier, Part 2, in press). The main oil-prone source rocks have not yet been penetrated in a setting deeper than the 3,000m peak oil generation threshold, although they are more deeply buried in the central, undrilled parts of the basin.

Up to 60 billion barrels of oil may have been generated in the basin (Richards and Hillier, Part 2, in press). This figure is based on the source rock pyrolysis data obtained from the wells, and assumes a 400m thick mature interval at the base of the early post-rift source-rock succession, extending over an area of 40km by 40km. However, even when the calculations are based on much more conservative figures for the thickness and extent of the mature source and the richness and generative potential of the kerogens, significant amounts of expulsion are also calculated. For example, a 200m thick mature zone, over an area of 35km by 12km, may have expelled over 11.5 billion barrels of oil, even at oil yields of 8 kg HC/tonne, which are towards the low end of those observed by rock-eval pyrolysis for this basin.

All six exploration wells encountered reservoir rocks. These reservoirs range in age from Upper Jurassic to Upper Cretaceous. Some significant sandstone intervals have been recorded. For example, Shell well 14/5-1A encountered a total of 390 m of net reservoir with an average porosity of 13%, whilst Shell well 14/10-1 had a total of 84 m of net sandstones, with porosities averaging 27.5%.

An understanding of migration pathways and seals may partly explain why only limited quantities of oil have been found so far, and may also 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 (that were the principal targets of the drilling campaign) lying above the source/seal might be possible where traps lie close to penetrative faults which provide a migration pathway up from the main kitchen area.

Discussion

The FOSA agreement, and the consequent use of a single rig to drill each hole on a back to back basis did have one draw-back: there was no time available for analysis of well results before the next well had

to be spudded. 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 has identified several other play concepts that might have been better options for drilling.

Lateral and down-section migration (because of the poor vertical migration routes provided by the normally-pressured early post-rift claystone) 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. Such targets have not yet been adequately tested, and include: Jurassic to earliest Cretaceous fan sandstones, deposited during the syn-rift phase, along the margins of the basin in situations analogous to the Brae complex in the South Viking Graben; early Cretaceous sandstone-dominated deltaic bodies that prograded into the basin from the marginal areas during the early post-rift phase, and that may be may be sand-rich and closer to migration pathways, particularly those associated with the basin margin faults; 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 post-rift phase; numerous closed highs in several discrete, deep sub-basins in the southern parts of the North Falkland Basin, where the stratigraphy may be different to that encountered in the six wells; and fan sands with associated channels developed within the lacustrine source rock succession itself.

In summary, one of the richest source rock intervals anywhere in the world has been encountered in the North Falkland Basin, capable of generating up to 70 kg HC/tonne of rock, and it may have expelled up to 60 billion barrels of oil. Some thick (approximately 100 metre) sandstones have been encountered above the main source rock interval, with porosities ranging up to about 30%, but these are not on the optimum migration pathways. Very few thick sandstones with good reservoir properties have yet been encountered in the syn-rift succession beneath the main source rock interval, but few of the wells have penetrated this section.

Exploration opportunities in the North Falkland Basin are available either through farm-ins to existing licences (with the advantage of significant data access in most cases), or through the new open-door licensing policy to be pursued by the Falkland Islands Government. However, any new drilling activity either in the North Falkland Basin or elsewhere around the Islands will require the submission of new Environmental Impact Assessments, and therefore the continuation of the environmental monitoring programme that has already begun.

Acreage in the so-called Special Co-operation Area (SCA) to the SW of the Islands (Fig. 3) will also be licensed at a future date, after further research has been conducted to establish the baselines for environmental impact due to oil exploration. Unlike the situation in the North Falkland Basin (where the activity was over 100 km from shore and situated where prevailing currents would probably have carried pollutants away from the Islands), current directions are such that any pollutants resulting from exploration or development activity to the SW of the Islands would probably be driven towards the shore. It is therefore important that the risks are fully catalogued in advance of any such activity in the SCA, and that the necessary plans are made to deal with any emergencies before exploration begins.

Acknowledgments

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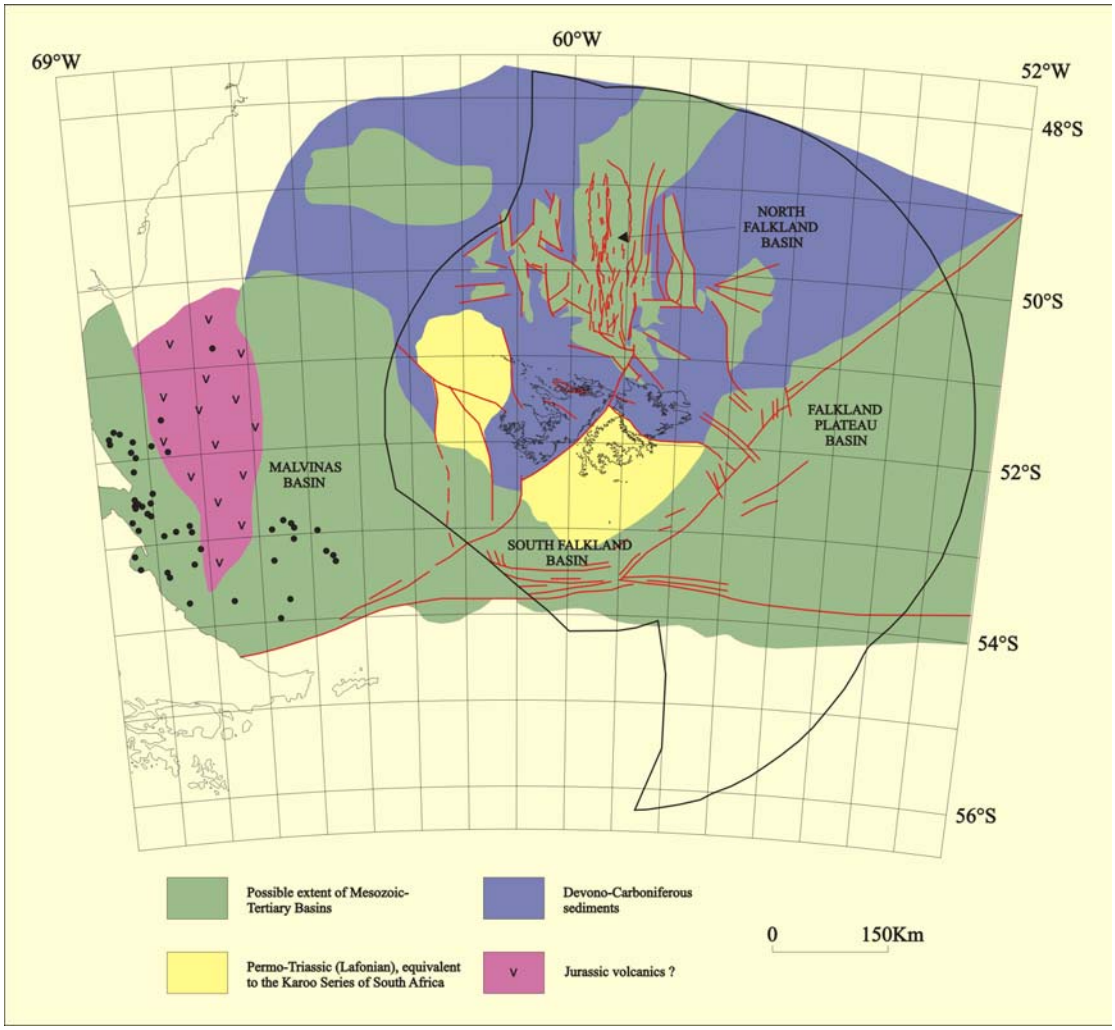
Figure captions

1 The location of Mesozoic-Cenozoic basins around the Falkland Islands.
2 Outline geological map of the North Falkland Basin, with leased areas and wells drilled during 1998.
3 Location of the Special Co-operation Area.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NORTH FALKLAND BASIN
FALKLAND PLATEAU BASIN
MALVINAS BASIN
SOUTH FALKLAND BASIN
Possible extent of Mesozoic-Tertiary Basins
Devono-Carboniferous sediments
Permo-Triassic (Lafonian), equivalent to the Karoo Series of South Africa
Jurassic volcanics ?
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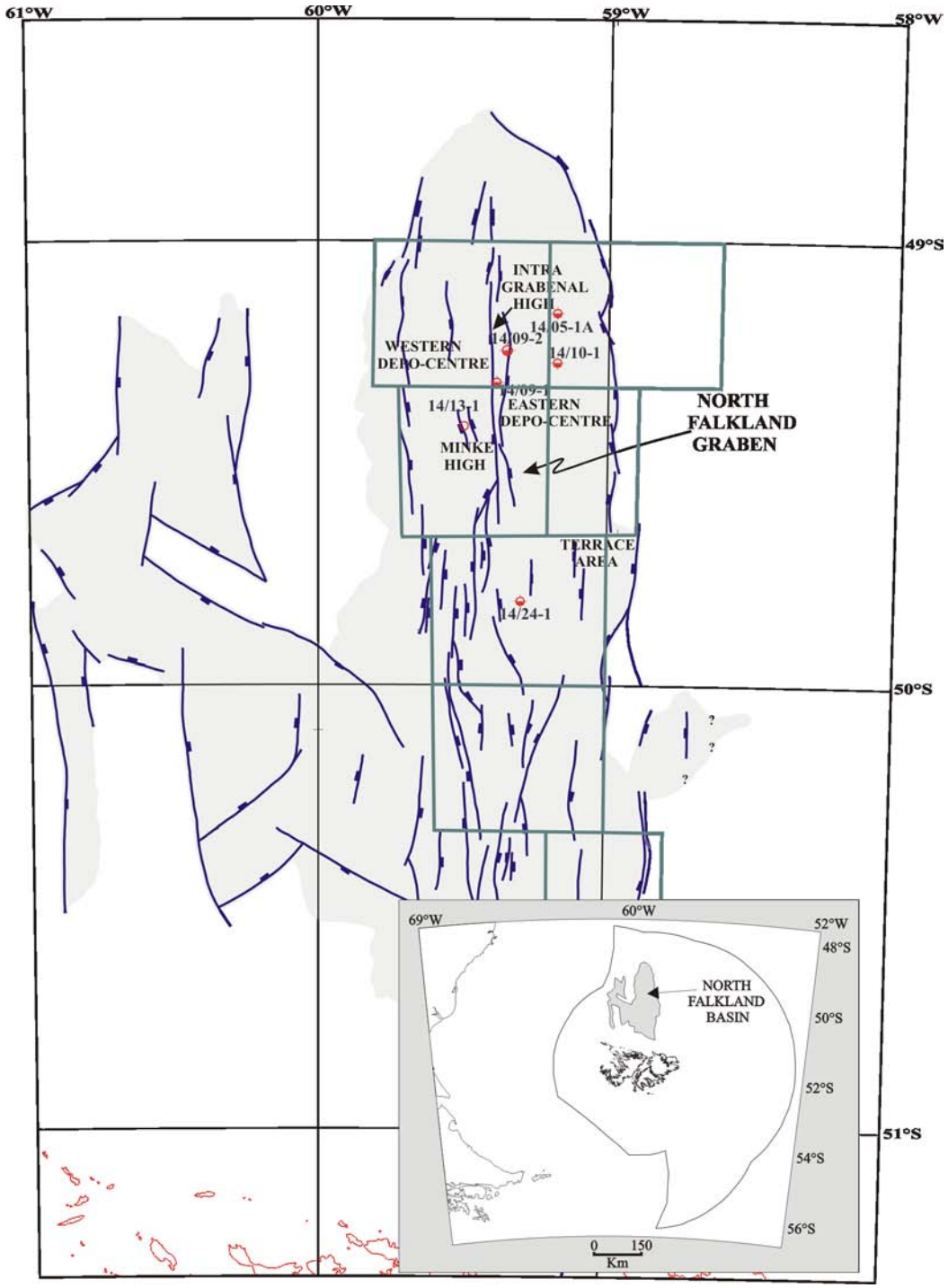
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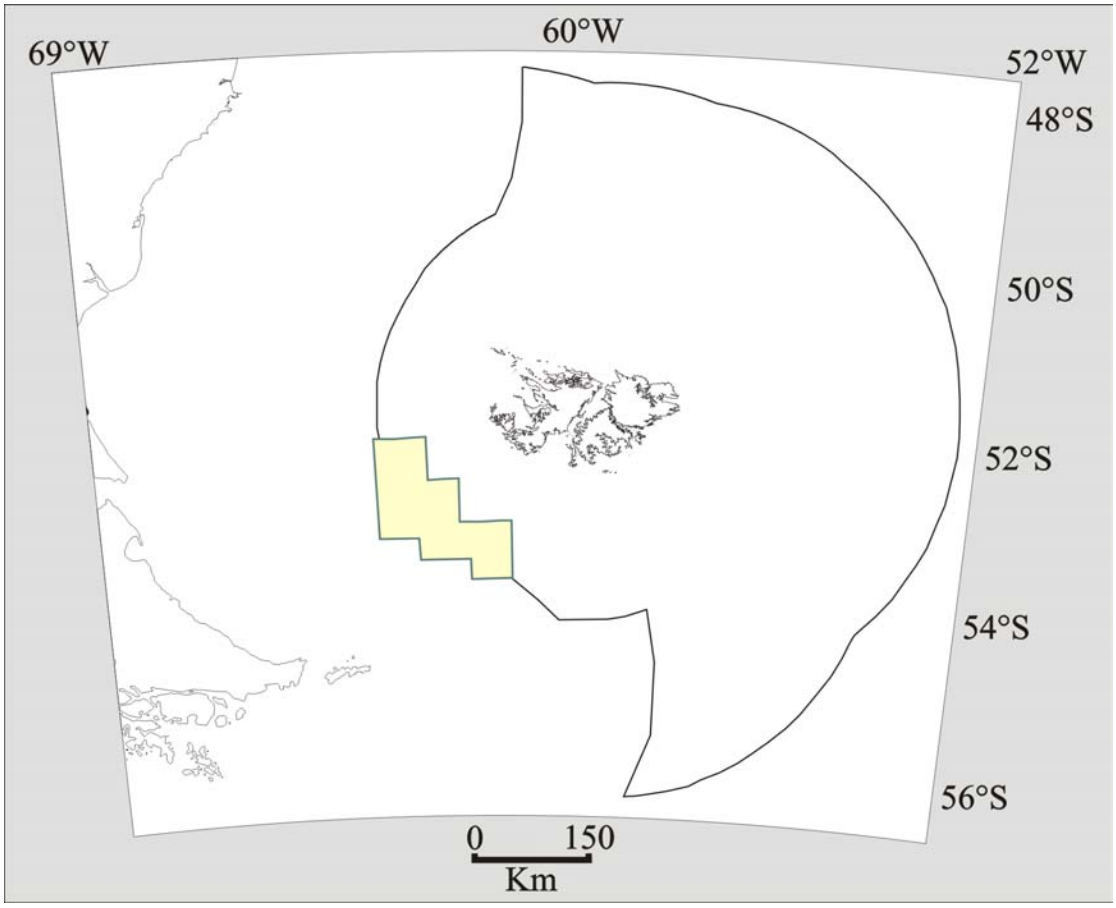
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