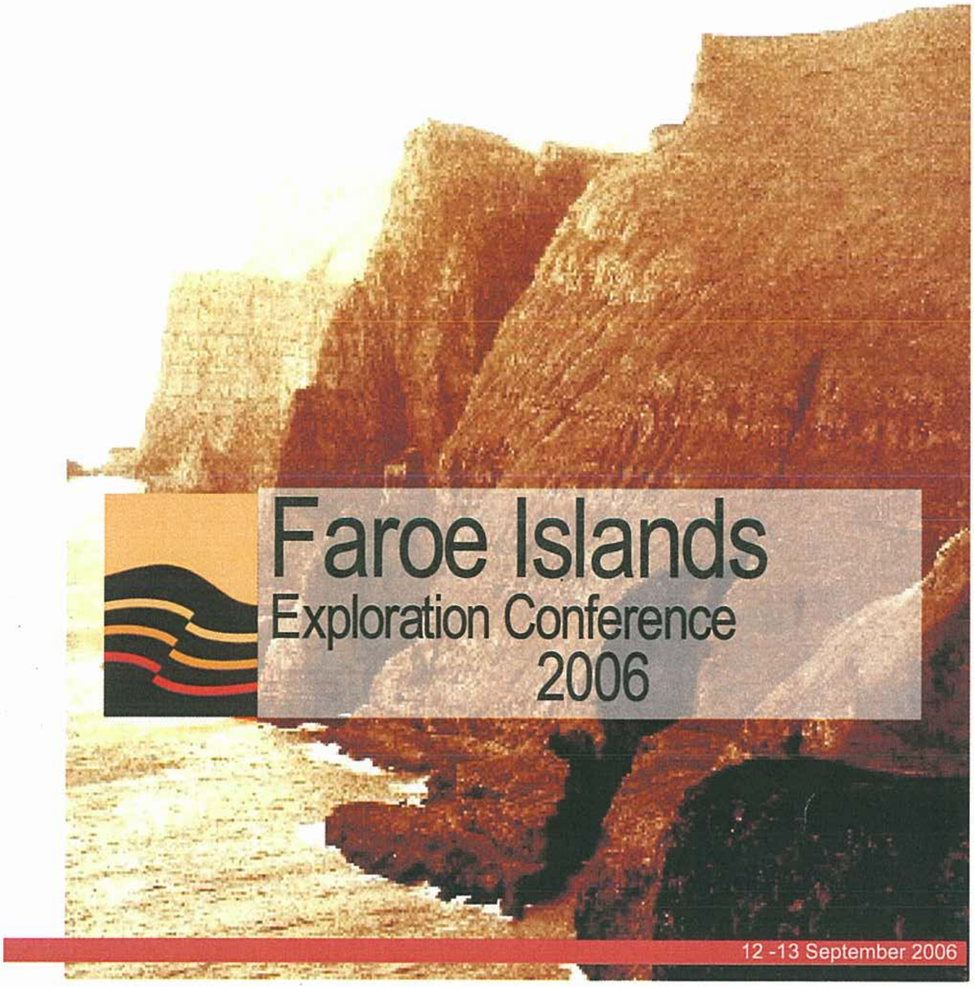

Conference Abstracts

FIEC06

BP Oral Session

Tuesday 12/9-2006

9.30 – 12.15

Patterns in pre- and syn-lava field environmental dynamics

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Studies of sedimentary successions from beneath and within major lava fields, from the Carboniferous to the Miocene, have highlighted both similarities and differences. This review focuses on the transition from pre- to syn-lava field environment and sedimentary systems, using studies of analogous examples from outside the North Atlantic Igneous Province. Contrasting these with onshore and offshore examples in the NAIP, the effect of setting, climate, structure, eruptive style and volume on the depositional and environmental system can be demonstrated.

Understanding the patterns and processes of sub-volcanic sedimentary successions and environments becomes important when potential hydrocarbon plays are defined within them. More readily apparent features, such as eruptive style and volume, can allow an insight into the likely stratigraphy and environmental dynamics of potential sub-lava reservoir successions.

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The Tertiary development of the Faroe-Shetland Basin: Intracontinental rifting or failed continental breakup?

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The Faroe-Shetland Basin, an apparent intracontinental rift basin, is co-axial with the Møre rifted margin to the north-east which formed by sea-floor spreading initiation on the Aegir ridge at ~54 Ma. Although the Faroe-Shetland Basin experienced Late Jurassic and Early Cretaceous rifting and subsequent thermal relaxation, well logging and paleoenvironment mapping indicates that the basin became emergent in the Late Paleocene, before experiencing anomalously high rates of subsidence in the Early Eocene. Flexural backstripping and decompaction to 54 Ma has been carried out on regional stratigraphic cross sections to quantify the water loaded subsidence since the basin emergence at top Paleocene times. If a depth uniform intracontinental rifting model is used, lithospheric beta factors greater than three are required to restore the post-Paleocene subsidence of the basin. However fault heave estimates indicate that there was little stretching in the upper crust of the Faroe-Shetland Basin at Paleocene and Late Cretaceous times, and substantially less than that indicated by post-Paleocene thermal subsidence assuming depth-uniform lithospheric stretching. Residual post-rift thermal subsidence from Late Jurassic and Early Cretaceous rifting, or Palaeocene mantle plume dynamic uplift cannot explain the Tertiary subsidence of the Faroe-Shetland Basin. The subsidence history of the Faroe-Shetland Basin since the Early Tertiary can be accounted for by thinning of the lithospheric mantle and lower crust beneath the Faroe-Shetland Basin, contemporaneous with continental breakup and formation of the Moere rifted margin to the north. At ~54Ma, the Faroe-Shetland Basin lay at the southern tip of the newly forming Aegir ocean ridge. Post-Palaeocene subsidence has been successfully modelled using a new model of continental lithosphere breakup and sea-floor spreading initiation in which thinning and rupture of continental lithosphere occurs due to an upwelling divergent flow field within continental lithosphere and asthenosphere. The model predicts that an ascending flow field, propagating upwards from the base of the lithosphere, first thinned the lithospheric mantle under the Faroe-Shetland Basin causing thermal uplift before thinning the lower crust, leading to rapid basin subsidence. While to the north the ascending flow field reached the surface and successfully ruptured the lithosphere giving continental breakup and sea-floor spreading initiation on the Aegir Ridge, under the Faroe-Shetland Basin the ascending flow field appears to have `died out' before reaching the surface. Upper Palaeocene basin collapse was followed by lithosphere thermal re-equilibration and thermal subsidence, which continues to the present day.

Transient rifting west of the Faroe Islands; implications for prospectivity

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The knowledge of the structural development of the Faroese Continental Shelf has been hampered by the flood basalts which cover the entire area, and thus have in the past prevented a detailed mapping of the sub basalt section.

Recent advances in sub basalt imaging, coupled with a denser grid over much of the Faroese Continental Shelf has led to a more information being retrieved which enables a better understanding of the structural geology of the Faroese Continental Shelf.

One of the enigmatic features of the Faroese Continental Shelf is trend of Munkagrunnur, Wyville-Thomson and Ymir Ridges. These features are roughly perpendicular to the dominating Caledonian trend in the region. (Boldreel and Andersen, 1993) suggested that these structural features were of compressive origin. (Lundin and Doré, 2005) did, however, suggest that a transient rift in the early Palaeocene transacted the area in which the mentioned ridges are located. Evidence for such a transient rift can be found in the density of igneous centres in the area of the suggested transient rift, and also in the timing and location of flood basalts in the region. Further support is found onshore Faroe Islands, where the fault trend in the Beinisvørð Formation on the southern most island is NW/SE, while the dominant fault trends in the overlying Malinstindur and Enni Formations over the remaining part of the Faroe Islands, have two primary trends (roughly E/W and NE/SW). The single trend in the older formation is indicative of an extensional stress regime, while the conjugate fault trends in the younger formations indicates a compressive stress regime.

Such a transient rift has implications for the prospectivity on the Faroese Continental shelf with location of the Beinisvørð Formation being controlled by this event. A rifting event has also associated uplift at the margins, which in this instance covers the Faroe Platform and the ridges in the rift area. Such uplift results in exposure of older strata, and accompanying erosion of these.

The definition of such a transient rift does also allow for a better understanding of the timing of trap formation and source rock maturity within the area affected by the rift event.

Boldreel, L. O., and Andersen, M. S., 1993, Late Paleocene to Miocene compression in the Faeroe-Rockall area, *in* Parker, J. R., ed., Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference: London, Geological Society, p. 1025-1034.

Lundin, E. R., and Doré, A. G., 2005, NE Atlantic break-up: a re-examination of the Iceland mantle plume model and the Atlantic–Arctic linkage, *in* Doré, A. G., and Vining, B. A., eds., Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference: London, The Geological Society, p. 739-754.

Gravity flow deposits and injected sands of a Selandian slope and submarine fan system - outcrop examples from the Kangerlussuaq Basin, SE Greenland

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The Kangerlussuaq Basin in southern East Greenland underwent a major change in depositional setting as a result of rift initiation at the Cretaceous–Paleogene boundary. Thick sandy deposits representing slope and basin floor fan environments are seen unconformably overlying mud-prone shelf facies. The unconformity spans the Late Maastrichtian-Selandian interval.

A broad suite of gravity flow deposits ranging from massive slope channel-fill, high and low density turbidites and remobilised sand injectites have been identified in the Paleogene succession. The thickest sandstone successions are found in the slope channels and basin floor fans respectively. However, there are marked differences in facies continuity, governed by depositional setting, and thus sandstone predictivity.

Palaeogeographic reconstructions from facies analysis and correlation of sedimentary section show that the basin bathymetry was controlled by northwest southeast oriented faults. These faults became active during the Late Cretaceous and continued to control sedimentation into the Late Paleocene –earliest Eocene volcanic phase. The Palaeogene sandprone systems were focussed at the tectonic lineament, which acted as a conduit for sediment being transported south-eastwards towards the Faroe–Shetland Basin.

This analogue study from Greenland is part of one of a number of Sindri stratigraphy projects, which have helped to improve our understanding of the sub-basaltic basins of the North Atlantic. It is hoped the work will lower the risk on existing plays and/or lead to development of new play types.

Pre-basalt Paleocene sediments from the Faroes platform

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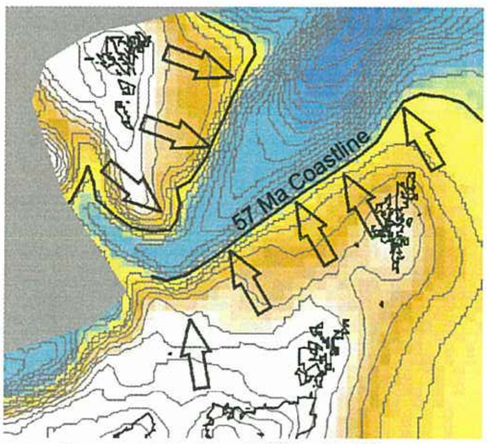
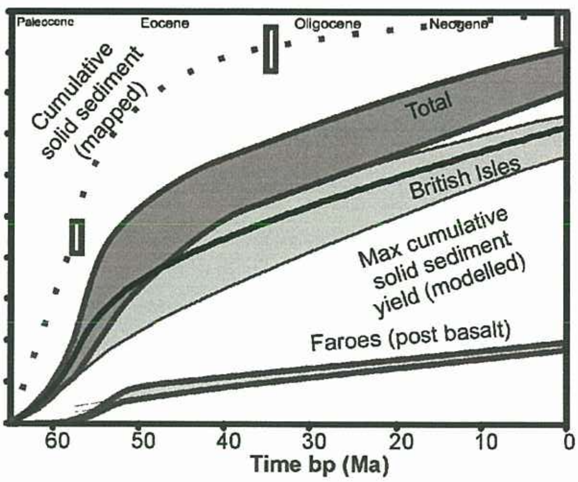
Overall during the Cenozoic, the dominant supply of coarse-grained potential reservoir sediments to the Faroe-Shetland Basin has been from the southeast. However, it has been recognised that the volume of sediments in the Basin is greater than that supplied from the British Isles' provenance area alone. Sediment has evidently been supplied from erosion of the Faroes platform lava pile since Eocene times.

New sediment volume balances also highlight the requirement for an additional component of sediment input: a Cenozoic topographic model is presented for the British Isles' and Faroe Islands' provenance areas, from which sediment supply rates are calculated. The model includes permanent uplift from igneous underplating, which is computed from gravity anomaly data, transient regional uplift, which is taken from Jones & White (2003), and a simple elevation-dependent erosion term, under isostatic balance.

Even using the British Isles' maximum Cenozoic denudation bound and an upside Eocene contribution from the Faroe Islands leaves a requirement for a pre- to syn-basalt contribution to the sediment budget from the Faroes platform or pre-basalt terrains now in East Greenland. Heavy mineral, palynological and radiometric techniques have previously offered indications of this westerly Paleocene source area. The sediment volume balance suggests that around 30% of the Paleocene sediments currently in the Faroe-Shetland Basin were sourced from such terrains.



57 Ma topography derived from Andersen et al. (2002), Jones et al. (2002), Jones & White (2003) & Smallwood (submitted).



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FIEC06

Chevron Oral Session

Tuesday 12/9-2006

13.15 – 16.30

Interlava Sedimentation – An underestimated role in the evolution of the Faroe Islands Basalt Group, Faroe Islands, NE Atlantic Ocean

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Traditionally, studies of Continental Flood Basalt provinces have focussed on the petrologies and geochemistries of the lava flows with little attention being given to interlava volcaniclastic sequences and this is no exception for the Faroe Islands Basalt Group (FIBG). The FIBG has a gross stratigraphic thickness of *ca.* 6.6 km and recent mapping has subdivided the stratigraphy into seven formations. Mapping established the newly defined Sneis Formation, a maximum 30 m thick volcaniclastic sandstone-conglomerate sequence. These rock units were deposited under mass flow conditions whereby hyperconcentrated, debris and stream flow deposits are recognised. The Sneis Formation, although widely intruded by sills, exhibits a facies variation from N to S across the Faroe Islands, implying a gross southerly transportation direction. A number of other mass flow deposits, although not on the same scale, have been observed throughout the upper 1-2 km of the FIBG.

Logging of the upper 1 km of the preserved FIBG has demonstrated an increased input of volcaniclastic material, most likely, due to a waning eruption frequency. A number of key stratigraphic marker beds have been identified; aiding correlations between lava flow sequences from the different islands. Some of these volcaniclastic sequences were deposited on laterally continuous disconformity surfaces, representing significant hiatuses in the eruption of the lava flow sequences. One such surface is recognised *ca.* 240 m above the Sneis Formation by the presence of the 2-5 m thick Argir Beds, which are well exposed and easily mapped across Sandoy to Southern Streymoy. This disconformity surface is also characterised by a change in lava flow morphology and in the NE of the Faroe Islands by a marked change in petrology. The detailed correlation between the islands using the Sneis Formation and the Argir Beds has also enabled the detection of subtle structural movements between islands not previously recognised.

This study clearly demonstrates the active role of sedimentation during the development of the FIBG, which may have acted as a transportation conduit for the eventual deposition of volcaniclastics within the Faroe-Shetland Basin. Also, a number of the volcaniclastic sequences, although not quantified, clearly have good porosities and permeabilities. One such unit is the basal Sund Bed of the Sneis Formation which has not been affected by the closely associated intrusions or by the compaction of more than 1 km thick sequence of lava flows. Consequently, these units may act as potential reservoirs within the offshore sections of the FIBG within the Faroe-Shetland Basin area.

Diagenetic effects of flood basalts on potential reservoirs

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Research by the authors is focussed on the diagenetic effects, both direct and indirect, of the emplacement of the lava, and the associated sills and dykes, in potential reservoirs. Specific interests include: the compartmentalisation of the basin by sills/dykes/lava: how does this affect fluid flow paths? Diagenesis along hot contacts: is the dramatic reduction in porosity/permeability along such contacts the result of the igneous bodies alone or do they need ground water present? Can large igneous events trigger the movement of hot fluids through the basin and to what extent does this cause alteration to sediments?

To address these issues a number of outcrop case studies have been identified within the Huab Basin in NW Namibia. Here, excellent 3 dimensional outcrop coupled with almost 100 percent exposure allows detailed sampling strategies to be employed on locations of interest. In some cases igneous dykes have acted as flow barriers to pore fluids and have therefore altered the type and degree of cementation either side of the dyke. Geochemical analysis of the cement can shed some light on the origin of the associated fluids and determine whether hot fluids have been triggered by the lava. The systematic burial of aeolian landforms by pahoehoe lava flows has preserved the original features in many of the dunes and has created ponds of lava in inter-dune areas. Suites of samples collected from the igneous contact have been analysed to assess the extent of diagenesis related, either directly or indirectly, to the lava eruption. The sandstone is shown to be well-cemented in an indurated zone (visually 1-2m wide) beside the contact but less well-cemented with distance from it. The degree of porosity change away from the contact has been measured using image analysis software on stained thin sections and the chemistry of pore-filling cement analysed using laser microsampling and spectroscopic analysis. The sediments from the Etendeka in NW Namibia provide examples of intrusion and lava contacts in an essentially dry basin setting. This allows a direct investigation of the effect of the igneous bodies on the sediments without massive overprinting due to further diagenesis caused by ground water. In the few areas where later groundwater fluids have entered the basin we are able to successfully compare the direct with indirect effects of the igneous rocks.

Intrusive and extrusive magmatism, magma flow and the role of pre-existing structure in the Flett and Judd basins.

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The Flett and Judd basins, southeast of the Faeroe Islands, are major Mesozoic and Cenozoic depositional centres that contain the distal portions of the Faeroes flood basalts and part of the Faeroe-Shetland sill complex. Although detailed work on the intrusive and extrusive magmatism has been carried out on the Faeroe Islands, the understanding of these distal and now buried portions of the system has been hampered by the limited availability of core from the subsurface and a consequent reliance on the use of seismic data. Crucial to understanding how both intrusive and extrusive magmatism developed in the distal regions is a detailed knowledge of the eruptive styles, the types of intrusions that developed, the magma flow patterns and how pre-existing basin structure influenced them. 3D seismic data from the Flett and Judd basins provides detailed data on these parameters and consequently offers the opportunity to understand how intrusive and extrusive magmatism are linked.

The data shows that the sills generally possess a concave upwards morphology produced by the development of climbing and branching magma tubes. The sills can be shown to be sourced from dykes or steep climbing portions of deeper sills that form the points of origin for the branching magma networks. This general pattern appears to be common for sills intruded into sedimentary strata with pre-existing faults resulting in only minor modifications to the morphology. Small laccoliths can also be found within the datasets with the data suggesting that they are fed by deeper sills and dykes with, in some cases, the magma also ascending deeper pre-existing faults to reach the level of laccolith emplacement. The data demonstrates that subaerial volcanic activity was predominantly from fissures, the locations of which appear to bear little relation to the underlying basin structure. Furthermore, the data provides clear evidence for fissure eruptions being fed by both dykes and sills, with the dykes also being capable of feeding contemporaneous sills. Southeast of the flood basalt, the palaeo-seabed contains a number of submarine mounds that form linear chains, with the individual mounds being elongated along the chain trend. These chains coincide with the locations of underlying dykes and/or the margins of sills. Although the possibility that such features represent hydrothermal mounds related to the underlying sills and dykes cannot be dismissed, the data suggests that they are more likely to be volcanic in origin, being accumulations of pillow lavas and hyaloclastites and fed by dykes and/or sills.

Sub-basalt mapping offshore using Vp/ Vs seismic observations.

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Sub basalt mapping poses serious problems to the exploration of hydrocarbons in many areas of the North Atlantic. Particularly in the Faroese area and in general in the northeast Atlantic basins volcanics are difficult to penetrate. A solution to this problem is to expand the active seismic apertures to offsets that permit the observation of wide angle data. This can be achieved either by applying a two-ships observation procedure or by deploying Ocean Bottom Stations to sufficiently long offsets. The advantage of the second approach is that the OBS-system is not weather sensitive and also that by coupling the receivers on the seafloor PS-converted seismic phases can be observed. In overcritical offsets S-phases penetrate also structures that the p-wave field misses.

We evaluated two different experiments; one using the two ships approach and the other based on 2- and 3-D OBS-observations. Both methods produced useful results and mapped the basalt flows and the sediments below with sufficient resolution. The approach in both cases was identical. We first evaluated the P-wave field and then by freezing the obtained geometry we computed PS-converted phases that satisfied the delayed S-wave arrivals. We used the P- and S-wavefields and obtained Vp/Vs ratios for the various lithological units of the seismic models. For the basalts we obtained a Vp/Vs ratio of 1.77 which shows that most of the basalts around the Faroe Islands are very compact and near ideally elastic. The Paleocene sediments below the basaltic flows were found to have values of 1.9 increasing to 2.1 towards the Corona Ridge. The lateral change indicates a lithological variation that could be interpreted in terms of the Sand/ Shale ratio. However, it is also possible to explain the lateral change by gas and fluid inclusions. For the Mesozoic sedimentation a value of 1.8 indicates that the lithology is consolidated and compact. In the contrary the Cenozoic sediments above the basalts have Vp/Vs ratios that progressively increase from 2.0 to 4.0 in the middle part of the Faroe-Shetland basin in the vicinity of the Corona Ridge. This observation can partly be explained by a gradual lithological change or the increase of gas and fluid inclusions. It can be shown that using converted phases one can map sub-basalt lithologies with sufficient resolution to satisfy exploration aims.

Deep crustal imaging of the Rockall continental margin by tomographic inversion of wide-angle OBS data

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and the iSIMM Team

The northern North Atlantic continental margins were formed by continental break-up in the early Tertiary accompanied by massive volcanism: flood basalts covered pre-existing sediments and a large volume of new igneous material was intruded in the lower crust. Understanding the formation and evolution of these margins and constraining the amount of igneous material added to the crust during break-up is crucial in calculations of subsidence and heat flow history, and is therefore essential for exploring the prospectivity of continental shelf and margin regions such as the Rockall and Faroes margins.

In the summer of 2002, the iSIMM project successfully acquired wide-angle seismic data across the Hatton Bank volcanic continental margin located on the western flank of Rockall Plateau. The main survey dip line traverses a range of basalt environments and crustal structure: the stretched continental crust of Hatton Basin has minor basalt cover; the continental block of Hatton Bank has increasing basalt cover with extruded lavas and emplaced sills; thick seaward-dipping reflector sequences (SDRs) of interbedded basalt and sediment are present on the continent-ocean transition beyond Hatton Bank; and the Iceland Basin exhibits thickened oceanic crust. To overcome the seismic imaging problems posed by the extruded basalts in the region, a low-frequency source and long-offset acquisition parameters were employed. The source array was designed for maximum output in the 5–20 Hz band, based on expected losses from effective Q estimates derived from Faroese basalts.

Joint wide-angle refraction and reflection tomography was used to determine a robust model of the crustal velocity structure and depth to Moho in both the dip and strike directions of the margin. The lower crust in the Continent-Ocean Transition zone exhibits elevated crustal velocities in the range of 7.0–7.4 km/s, which represent new igneous material added to the lower crust region at the time of continental break-up. Modelling accuracy was determined by applying a Monte Carlo technique to multiple different starting models for tomographic inversion so as to assess the robustness of the final models; the velocities across the dip line to are constrained to within 0.2 km/s and the depth to Moho to within ~1 km. The average lower crustal velocity increases beneath Hatton Bank towards the margin as the amount of new igneous material intruded at depth increases; the decrease in velocities away from the margin represents a wane in the mantle thermal anomaly towards oceanic crust formation over more typical mantle temperatures.

The recording of low-frequency, long-offset data has allowed the imaging of seismic velocity structure and depth to Moho beneath a volcanic continental margin, which has previously proven problematic to conventional seismic imaging techniques. The traveltime tomography technique used provided quantitative estimates of uncertainty and refined the constraint on seismic crustal velocities, particularly in the lower crust beneath the margin where structure is complicated by high velocities above a shallowing Moho. The results from the long-offset OBS data provide accurate information on seismic velocities within and below the basalts, which when used in combination with a good quality reflection profile, considerably improves seismic reflection imaging and interpretation of lithology.

Sub-basalt imaging using wide-angle and long-offset data from the Faroes Shelf

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One of the keys to imaging successfully through basalts is to tune the source and the receiver to the frequency pass-band of the sequence of basalts through which the seismic signal has to pass. Recent work measuring the seismic attenuation of basalts drilled in north Rockall Trough and in the Faroes demonstrates that stacked lava flows are highly attenuative: the effective Quality Factor is typically in the range 15–25. Synthetic seismogram modelling studies show that the attenuation is almost entirely due to scattering within the basalt sequence, due to the numerous interfaces at the tops and bases of weathered lava flows, each with high impedance contrasts. The consequence of this high attenuation is to markedly reduce the amplitude of the high-frequency component of the signal. So for successful imaging the source and receiver should be tuned to enhance the low-frequency part of the spectrum.

Another key to successful imaging is to use wide-angle arrivals, including diving waves in the crust (which are usually muted in conventional processing) and near-critical reflections which have high amplitudes (and are also usually muted). Such arrivals can be obtained either by using long streamers, with 12,000 metres now being typical, or by deploying fixed ocean bottom receivers, either in bottom cables or in stand-alone ocean bottom seismometers. An additional advantage of seafloor receivers is that they can record multi-components, and thus detect S-wave arrivals directly. An accurate velocity model is an important component to imaging weak sub-basalt arrivals, and wide-angle arrivals are key to this.

We show the application of these techniques to data from the Faroes Shelf, and illustrate the detection of sub-basalt sediments and igneous intrusions. Velocity models have been built by semblance analysis, by forward modelling of travel times, by tomographic inversion and by synthetic seismogram modelling: the aim ultimately is to refine them by waveform inversion, since the shape, amplitude and phase of the seismic arrivals carry far more information than the travel times alone.

The iSIMM project was supported by Liverpool and Cambridge Universities, Schlumberger Cambridge Research, Badley Geoscience, WesternGeco, Amerada Hess, Anadarko, BP, ConocoPhillips, Eni–UK Ltd., Statoil, Shell, the NERC and DTI. The FLARE profiles were shot by Amerada Hess Limited and its partners LASMO (ULX) Limited, Norsk Hydro a.s., DOPAS and Atlantic Petroleum.

Crustal structure of the Faroe-Shetland basin from long offset seismic data.

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J.Papoulia , Hellenic Centre for Marine Research, Mavro Lithari, Attica, Greece.
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In the mid 90´s we shot 2 long seismic lines across the Faroe-Shetland basin. We deployed 50 Ocean Bottom Seismographs (OBS) along 2 profiles in 4 km – spacing (Profile I) and 3 km - spacing along Profile II. Seismic energy was generated by 2 sleeve guns each having 60 lts volume. The guns were operated at 120 bar pressure. Shooting spacing was 125 m corresponding to 1 shot per minute at 4 nots travelling speed. Data were processed in Common OBS Gathers (COGs) and a linear moveout was applied using 6 km/s as reduction velocity. Both lines were NW-SE oriented, crossing the basin perpendicularly to its strike.

Data evaluation was accomplished in 2 steps: First we applied tau-p inversion to the COGs that allowed to obtain 1-D velocity models for each OBS position. We interpolated first order discontinuities from the 1-D velocity models and developed a 2-D velocity section for each profile by forward modeling, using the 2-point ray tracing method of Cerveny & Psencik. The results are summarized as follows:

Crustal thickness below the Shetland Islands is approximately 28 km and the crust is separated in an upper, middle and lower crust, typical for the Caledonaids. The Moho is clearly mapped as a first order discontinuity, separating a lower crust of Vp = 7 km/s from the upper mantel of Vp = 8 km/s. The same type of crust occurs again towards the Faroe Islands although the crust here is much thinner and the Moho is encountered at 20 km depth including at least 4 to 6 km sediment above the igneous crust. The crustal structure in between is dominated by a 2 layers continental crust of an upper and a lower domain. The Moho in the central part of the basin, below the Corona Ridge is only 15 km thick. Sediments on top of the crust have their maximum thickness at the southeastern part of the basin exceeding 10 km and thin to the northwest to about 6 km north of the Corona Ridge. The Mesozoic sedimentation extends over the complete basin, which is covered by Paleocene, Eocene and Oligocene series. The northwestern part of the basin is covered by basaltic flows that extend up to the Corona Ridge and separate the Oligocene – Eocene sequences from those of the Paloecene. The basalt flows have maximum thickness to the northwest (more than 1000 m) thinning towards its central part where they gradually deteriorate in thin discontinuous flows. Thickening of the igneous crust below the Corona Ridge with simultaneous thinning of the Moho indicate inversion of the tectonic regime sometime during the Mesozoic.

FIEC06

BG Group Oral Session

Wednesday 13/9-2006

9.00 – 12.15

BG GROUP

Imaging below Faroese Basalts using over/under acquisition

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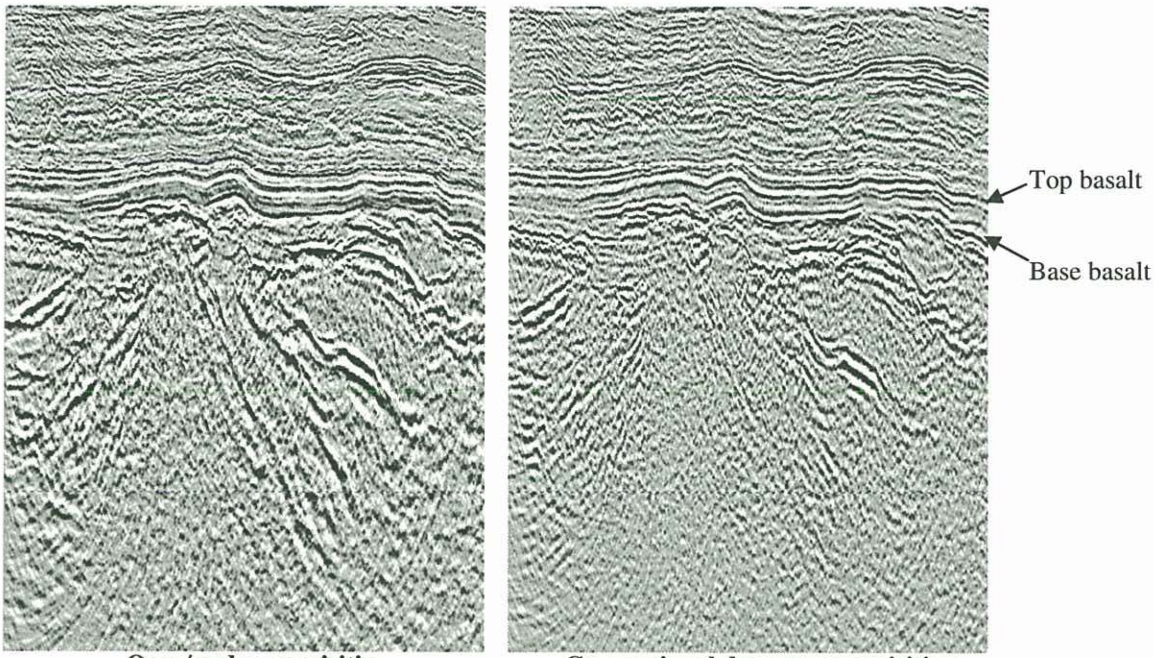
Imaging through basalt is a well-known problem that has proven difficult to solve. Potential hydrocarbon-bearing sandstone reservoirs lying beneath the basalt are a target for exploration. However, stacked basalt flows in the offshore Faroes area consist of many thin layers, and the reflection and transmission of energy within each of these layers leads to the loss of high-frequency information. Therefore, it is crucial that the input signal contain as much low-frequency energy as possible in order to counter this absorption and to produce a reliable and interpretable seismic image.

The basalt wedge extends eastwards from the Faroe Islands up to approximately the UK-Faroes border. Conventional seismic data has been acquired in this area, but was largely unsuccessful at imaging the fault blocks beneath the basalt. A multi-cable/source acquisition technique was designed to boost the low frequencies to improve reflection energy below the basalt. Over/under acquisition consists of towing pairs of cables and sources vertically above each other at different depths. In this case, the cable depths were 20.25 m and 30 m and the source depths were 12 m and 20.25 m. This arrangement and subsequent combination of sources and receivers during processing, leads to a broader signal bandwidth and higher signal-to-noise ratio dataset than conventional seismic techniques can achieve.

In 2005, approximately 3,500 km of 2D over/under data were acquired in the West of Shetlands and Faroes region. To demonstrate the superior frequency content afforded by over/under acquisition, a comparison stack simulating conventional deep-tow acquisition was also produced from the shallow source and shallow cable combination. This combination was chosen because it was considered to be the most likely conventional acquisition scenario that would be used to image beneath the basalt.

Figure 1 shows preliminary results from the survey at an early stage of processing. The results of the over/under dataset are shown to the left and the "conventional" deep tow acquisition to the right. The over/under seismic dataset shows better definition of the sub-basalt reflectors, whilst not compromising the details in the shallower data. The top basalt reflector is at approximately 3.2s, shown by the dashed line. Beneath this, the steeply dipping reflectors show a superior image on the over/under acquisition versus that of the conventional acquisition.



Over/under acquisition **Conventional deep-tow acquisition**

Figure 1. Preliminary results from the survey. The reflectors beneath the basalt layer are better defined by over/under-acquired data due to the increase in the low-frequency information contained in this dataset.

Exploring below the basalt, offshore Faroes: a case history of sub-basalt imaging.

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Discoveries in the Faroes-Shetland basin to date have been made in the areas not covered by extensive basalt flows as these flows seismically obscure the geology and structure of the underlying section. The industry has been tackling this problem for many years and it is known that high frequencies penetrate only a short way into the basalt before being scattered, generating high frequency noise. Recently, Statoil and its partners in FL006 have made a dramatic improvement in sub-basalt imaging in this problem area. The improvement comes primarily from processing the data, using careful multiple removal at all stages of the processing and removing high frequencies (dominantly noise) early in the processing to concentrate on the low frequency data. Velocity analysis must be performed as an iterative process and take into account the geological model. Deep towing the source and cable also improves the data by helping to remove the higher frequencies which generally cause noise and concentrating on the lower frequency data. Applying these processing techniques to older 2D surveys also shows significant improvement in imaging the sub-basalt structure. Data examples show that the complex sub-basalt structure can now be mapped on the improved data and sub-basalt prospects defined.

Sub Basalt Imaging beneath the Wyville Thompson Ridge

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The Wyville Thompson Ridge is large shallow basalt anticline, which is well imaged on seismic data down to the base Basalt surface. At the seabed the basalt is about 1km thick and onlapping Tertiary sediments can be seen on the flanks of the anticline. The challenge is to image primary sedimentary events and structure beneath the basalt, identified as the Rannva prospect.

The original 2D seismic data was shot in 1997, and was reprocessed early in 2005 in attempt to identify any underlying primaries. This attempt was a failure, due to the presence of poorly attenuated multiples, generated by the basalt and the sea bottom, producing interference in the zone of interest. Any possible primary structural data had low signal to noise and continuity.

Later in 2005, a two-pronged strategy was used to resolve the issues with new seismic acquisition & processing. The acquisition comprised 200km of infill 2D data with larger source, longer cable and deeper source/cable depths. The processing contractor was chosen that had regional experience in the optimisation of acquisition parameters in areas with low signal to noise events. The processing used a cascaded approach to multiple attenuation and subsequent detailed velocity analysis.

The resulting data shows the presence of events beneath the basalt that do not coincide with occurrence of predicted multiples- these are interpreted to be primary events. This analysis suggests that structural interpretation of the sub-basalt section and targeting of an exploration well is now technically possible.

The forward programme for the area will include reprocessing of the older seismic data, using the new work flow methodology, and possible acquisition of EM or magneto-telluric data. Use of these technologies in combination with analysis of gravity and magnetic data may enable Faroe Petroleum to de-risk the Rannva prospect and prepare it for exploratory drilling operations.

The Faroe Shetland Basin: A MegaSurvey Perspective

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The interpretation of the Faroe Shetland Basin (FSB) MegaSurvey was completed in two phases on a single 3D volume spanning approximately 23,500 km^2, and incorporating 32 individual seismic surveys, over part of the Faroese waters and 8 UK quadrants. MegaSurveys not only give a fascinating and invaluable view of the geology on a basinal scale, but also maintain the resolution capable of defining prospects, or field extension opportunities. They are truly a "clearer image" of the geological framework and within that the petroleum potential of the areas they cover. Even where they only partly cover an area of interest, the regional context, and detail of the structural styles provided by MegaSurveys give significant advantages over conventional regional 2D analyses.

For the FSB the initial interpretation has been restricted to key recognisable, regional, stratigraphic horizons, (calibrated to all released wells), developed across the entire dataset. It builds a robust structural and stratigraphic framework for the area illuminated. The results provide unprecedented regional coverage, and also highlight potential prospectivity in many parts of the Basin. By analogy such leads could be duplicated in adjacent areas – but ultimately the goal must be to extend the FSB MegaSurvey coverage over any prospective areas of interest. Additional 3D surveys will be coming available or be acquired in the future.

Complementary to the horizon interpretation work are suites of derived attributes. These can help to resolve the structural and stratigraphic complexity of the Faroe Shetland Basin with isochron, edge, and amplitude maps. All can be illustrated in detail through the use of ERMapper views in full 3D. The distribution of high amplitude reflection configurations, seen in a number of amplitude extractions, highlights the depositional features of the prospective clastic-rich Tertiary sections in the Flett and Foinaven sub-basins.

The Westray and Corona ridges, with their associated Mesozoic tilted fault blocks, have been the target for recent exploration activity, and the Cambo and Rosebank / Lochnagar discoveries are shown in some detail. Mapping of the deep structure has been essential to the understanding of this part of the basin, particularly in places where the overlying basalt hinders seismic imaging at depth. A number of additional structures within both UK and Faroese waters have been identified and warrant further investigation in light of these recent discoveries. Indeed, untested Mesozoic structures on the north-south trending Westray Ridge are significant targets in Faroese acreage and are potentially analogous to the Cambo structure to the south.

The FSB MegaSurvey forms a vital backdrop to assist in locating wells which can unlock the remaining petroleum potential of this part of the Atlantic Margin. This is just a starting point, and a number of further studies are proposed including added-value geological input to improve seismic calibration and the understanding of the petroleum system, potential field modelling, and further seismic attribute analyses. We fully believe that such studies, in increasing detail through time, can provide a stream of opportunities for future drilling – with a significant likelihood of success in an area that today remains essentially under-explored.

Usage of Marine FTG™ Gravity data to resolve Basalt and Sub-Basalt geology in the Faroe-Shetland Basin area.

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Full Tensor Gradiometry (FTG) or gravity gradiometry data are acquired using a multiple accelerometer instrument that measures five independent Tensor components of the gravity field. When combined they resolve a 3D gravity field to an order of magnitude greater than that of conventional gravity data. Individual components enable mapping of structural and lithological trends across the survey area, whereas the vertical Tzz component maps geological bodies.

FTG data form an integral part in exploration programmes worldwide and are routinely used on target prospecting and target delineation projects. FTG data are acquired on both sea and airborne vessels.

The data presented in this paper is a culmination of 5 individual marine surveys acquired over licensed acreage in the Faroe-Shetland basin area from 1999 to 2002. The merged data set yields comprehensive information relating to the basalt and sub-basalt geology of the region.

This paper will describe an evaluation process on the application of FTG to resolving basalt and sub-basalt geological issues in the Faroe – Shetland Basin area. The analysis employs FFT interpretation techniques to isolate causative signature arising from the sub-surface geology and 2D forward modelling to investigate the features' depth to source.

The following are identified and described:

- Deep basement of varying density and structure;
- Sub-Basalt Mesozoic and Lower Tertiary basin architecture by mapping prominent structural highs such as the East Faroes High;
- Low density sedimentary units of possible Lower Palaeocene age;
- Regional fault framework and structural control on the geological setting of target horizons.

Marine FTG™ data is a viable technology that serves to reduce exploration risk in high risk areas such as igneous provinces. The combined ability to quickly identify and delineate a structural fault framework and target geology allows the explorationist to optimise their resources when working in challenging geological environments.

Joint Inversion: the proper way to combine diverse geophysical and geological information

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In sedimentary basins, the reflection seismic technique is extremely powerful in obtaining high-resolution 3-D images from the sub surface and is by far the most important method to discover and evaluate potential hydrocarbon reservoirs. However, conventional seismic reflection technique may fail in sediments that are overlain by a basalt layer as for example in the Faroe-Shetland Trough. In this case, the reflected seismic energy is strongly scattered by the basalt layer and little or no coherent energy penetrates through to the sub-basalt layers. This missing information may be derived from gravity and magnetotelluric (MT) measurements. The high density of basalt has a relatively large impact on gravity anomalies. Also, as the basalt is transparent to electromagnetic waves due to its high resistivity, the lower electrical resistivity of the sub-basalt sediments produces a measurable effect on the MT data. Unfortunately, both gravity and MT methods are characterized by a large degree of non-uniqueness such that it is impossible to derive an unambiguous model for the sub-basalt structures, if the different data sets are processed and inverted separately. To obtain a robust result for such sub-basalt structures, which are potential undiscovered hydrocarbon reservoirs, we chose to develop an approach in which we jointly invert seismic tomography, MT and gravity data.

We tested our joint inversion technique on a 2-D model, which was developed to represent a typical geological situation of basalt structure on the European margin within the framework of the EC project "SIMBA". In this model, a basalt layer with varying thickness (400-2200 m) is introduced into horizontally layered sediments structures at a depths of about 2500 m. As input data for the joint inversion, the first arrival times of the p-waves are calculated for 4000 shot-receiver combinations using an acquisition configuration of a 12km streamer towed behind a vessel. The 2-D response of several MT stations are determined along the profile together with a gravity profile. The joint inversion problem is solved iteratively, with damping and smoothing constraints to prevent instabilities, by mapping to a common variable, in this case velocity, using rock property relationships. In this first stage we assume that these physical properties (seismic velocity, density, electrical resistivity) are linked by means of fixed relationships. Commercial drilling data from the Vøring basin located off shore between Norway and Faeroe Islands suggests that fixed relationships are adequate approximations. We show that we can recover the original model including lateral changes in basalt and sub-basalt sediment thickness, which is not possible with the individual inversions of the data sets. The result is robust and shows that the combination of non-unique data can provide strong constraint.

Application to real data is also successful. This is demonstrated using data acquired along the Flare-10 profile. Boundaries in the inverted model coincide with isolated bright reflections observed on the seismic reflection data at the presumed base-basalt and the presence of a low resistive layer beneath the basalt is confirmed.

Sub-basalt prospectivity: Learnings & Expectations

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Sub-basalt prospectivity is currently the main target in exploration of the Faroese shelf. Unfortunately these efforts are hampered by poor imaging below basalt covered regions. Recently, some progress has been made in seismic imaging by focusing on low frequencies as well as improved velocity picking and multiple attenuation. However, generally the results still remain below industry standard. Various sub-basalt well tests in the UK part of the North Atlantic Volcanic Province as well as outcrop analogues in Greenland and Scotland, offer some insights in what to expect below the thick basalt strata. Conspicuous sub-basalt 4-way-dip closures should be treated with caution as they might reveal a highly overmature sedimentary section, underlain by an igneous complex. Filtered gravity & magnetic data should be routinely integrated to avoid drilling igneous centers and subsequently lowgrade this acreage. Successful sub-basalt discoveries such as the Corrib field offshore Ireland, covered by 60 m of basalt, indicate good reservoir characteristics in Triassic Sherwood sandstone and very limited influence of sub-basalt intrusives. Generally, sub-basalt dykes and sills have limited influence on maturity and reservoir quality, unless they occur in high numbers. Onshore eastern Greenland in the Traill Ø region sill intrusions increase toward the spreading margin. In the Faroe Shetland Basin sill-dyke complexes are very evident on seismic sections near the basalt feather-edge, possibly indicating a highly intruded sub basalt section toward the COB (Continent-Ocean Boundary). Outcropping sills intruding flood basalt strata on the Faroese islands seem to corroborate this. Therefore the most prospective regions of the Faroese shelf are where flood basalts simply blanket sedimentary basins, without significant intrusives in the direct sub-surface. Potential methods might be utilized to delineate these regions. Although an increase in volcanism in sedimentary basins generally tends to increase risks, some positive effects occur as well, such as the generation of sill-induced jack-up structures, forming traps and the sealing and reservoir capacity of igneous rocks.

FIEC06

Anadarko Oral Session

Wednesday 13/9-2006

13.15 – 16.55

Anadarko
Algeria Company LLC

Post basalt prospectivity

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In the last decade or so, the Faroese sector of the Faroe-Shetland Basin, northeast Atlantic margin, has been in Oil Company's searchlight. During this time the main concentration has been on sediments which are expected to be found under the Palaeocene-Eocene flood basalts, which cover most of the Faroese Continental Shelf. Discoveries have, however, been made in the post basalt succession in UK sector of the Basin. We have therefore decided to look at the prospectivity of the post basalt sediments in the Faroese sector of the Basin.

The post basalt sediments in the Faroese area of the Faroese-Shetland Basin, are poorly understood, especially in relation to what direction they have been deposited from. Most of the literature that exists about the post basalt sediments in the Basin shows sediments being deposited from the South to Southwest (the NW British shelf area). These sediments are of siliciclastic origin and have been shown to be of a very good reservoir quality.

Our work does show that a significant amount of sedimentation has been from the Faroese Platform and Munkagrunnur Ridge. Both structures are wholly made up of basaltic material which is part of the North Atlantic Igneous Province, and any sediments from these provenance areas will therefore be of volcaniclastic composition.

We have investigated potential issues when exploring post basalt in the Faroe Shetland Basin. This includes detailed mapping of sedimentary units, and development of an understanding of the provenance area for each sedimentary unit. This enables us to distinguish between units which probably consist of siliciclastic and volcaniclastic material.

Siliciclastic material is known to have very good reservoir quality at the burial depths of the post basalt sequence. The reservoir quality of volcaniclastic sediments has been reported to deteriorate faster then in siliciclastic sediments. We will discuss this issue, and show what kind of depths we expect volcaniclastic rocks to be of useful reservoir quality in relation to the burial depths of the post basalt sequence in the Faroe Shetland Basin.

Exploration efforts East of the Faroes

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A re-evaluation effort is underway to reduce risk on existing leads East of the Faroes.
An over/under source and receiver 2D seismic survey was finalized in June 2006 and is the centrepiece of this integrated exploration effort applying regional 2D structural reconstructions, 2D and 3D basin-modelling, gravmag, sequence stratigraphy, AVO-modelling/analysis and seal studies. An overview of the work program and the approach to geological risk reduction will be given.

Enhancing the prospectivity of the Wyville Thomson Ridge

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Føroya Kolvetni (Faroe Petroleum) was awarded a licence covering part of the Wyville Thomson Ridge in the second Faroese Licensing Round over the Rannva exploration lead. The proposed work programme offered the acquisition of new 2D seismic reflection data (supplemented by the reprocessing of selected seismic profiles from pre-existing non-exclusive surveys), modelling of potential field data, and the interpretation of remotely sensed seep data obtained from the licensed blocks. This presentation summarises some of the initial results of these investigations.

Former interpretations of the Wyville Thomson Ridge as a massive pile of basaltic lavas, up to 12 km thick, effectively removed any hydrocarbon potential from the area. A basis for prospectivity was not restored until the 1990s, when gravity and magnetic data were used to invoke a geophysical model of the ridge as an inverted sedimentary basin capped by a lava carapace. While thick piles of Palaeogene volcanic rocks degrade the response of the seismic reflection method across much of the Faroese sector, early observations of deep reflectivity beneath the Wyville Thomson Ridge did provide some support for an inverted basin model. On recently acquired seismic data from the licensed acreage, a strong reflection was provisionally identified as originating from near the base of the volcanic succession. The thickness of the lava layer derived from seismic interpretation and nearby well data was then incorporated in geological cross-sections across the ridge, before using gravity modelling to help constrain the thickness of possible sub-lava sedimentary strata. This confirmed that the ridge could be modelled as an inverted basin, although the uncertainties intrinsic in the method limit the accuracy of the thickness estimates.

Seismic reflection data shot by Føroya Kolvetni in 2005 have provided improved resolution of the pre-lava succession. On the new profiles, different seismic facies can be recognised at depth, with potential faults, downlapping reflectors and truncated relationships all developed beneath the inferred base of the lavas. Encouragingly, the gross pattern of reflectivity immediately below the lavas shows some features in common with the prospective Paleocene interval elsewhere in the Faroe-Shetland Basin, while some discontinuous deeper reflectors may correspond to intrusive basic sills. Regional evidence suggests that sills are especially common near the top of the Cretaceous.

The presentation will conclude by proposing a provisional reconstruction of the structural and stratigraphic development of the Wyville Thomson Ridge that incorporates these new observations and is consistent with laboratory models of structural inversion. Other factors related to the hydrocarbon potential of the area, including source rock presence, maturity, migration and reservoir development, will be discussed. For the time being, we consider that the recognition of a potential sedimentary succession beneath relatively thin lavas, at drillable depth within what has been called the largest undrilled anticline in western Europe, significantly enhances the prospectivity of the Wyville Thomson Ridge.

The Judd Basin – what have we learned and what remains?

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Prior to drilling in the Faroese part of the Judd Basin, the Foinaven/Schiehallion play type dominated the exploration focus and the Faroese wells were all drilled on this concept.

Seismic mapping west of the Judd High and in to the Faroese area has shown a clear thickening of the Cenozoic section, but the high net to gross sand ratio of 0.6-0.7 encountered in the Faroese wells came as a surprise for most and the lack of seal presence has evolved the focus from only locating viable quality reservoir sands to also focussing on locating appropriate seal intervals.

Estimates of volumes of Paleocene clastic sediments in the Judd Basin and comparisons with calculations of denudated material from the onshore catchment area associated with the Judd Basin area has shown an excess of solids in the basin of a factor two. It could therefore be inferred that alternative provenance areas would be necessary. Heavy minerals and palynological studies have indicated a possible sediment input from East Greenland and also paleo-highs in the Faroese area (e.g. Munkagrunnur Ridge) are speculated to be a potential provenance area.

Of the four wells drilled until today only one has penetrated sequences older than the Vaila Formation displaying marginal reservoir properties for the Sullom Formation sands indicating a deeper burial (app. 1 km below present day depth) for these sands. It is noticeable that of the four wells only the well penetrating the oldest Paleocene sequences was classified as a discovery and remains unappraised at the moment.

Furthermore seismic mapping and well penetration has identified several intrusive complexes, intruding Paleocene (T31-T38) sediments and Cretaceous sediments, especially around the basalt featheredge and the effect of these are mainly considered to be an increase in the hydrothermal flux through the reservoir sands resulting in clocking of pore throats and a decrease in permeability, furthermore mobilisation of hydrocarbons in relation to hydrothermal activity is an added risk.

After the results from the Paleocene structural-stratigraphic play concepts what remains to be explored are the deeper pre-rift sequences, potentially Cretaceous and Jurassic in age, which have not yet been penetrated on the Faroese side. An example of Cretaceous reservoir sandstone with good reservoir properties was encountered in the well 204/16-1 close to the Faroese-UK border and with new encouraging results on pressure retardation maturation; the deeper older intervals could still hold promising prospects.

The Anne-Marie Prospect – Licence 005

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Licence 005 comprises parts of blocks 6004/1, 2, 3, 6, 7 and 8 in the Faroese sector of the Faroe-Shetland Basin. The licence is located over the east-west trending Westray Splay, a structural high separating the Faroe Basin in the north from the Judd Basin in the south. Tertiary basalts are present over the entire licence area. These basalts are believed to be less than 500m thick and fortunately have not significantly impaired seismic resolution.

One of the primary prospects in the licence is Anne-Marie; a low relief, four-way dip closure with Paleocene to Eocene reservoirs draping a large pre-Tertiary horst. Seismically bright, supra-basalt shelfal sandstones sealed by Eocene marine shales form the primary target. Additional drilling targets have been identified at three other levels sub-basalt. To best understand the prospectivity of the Licence 005 area and the potential of the Anne-Marie prospect, an integrated evaluation has been performed involving play assessment, 3D probabilistic basin modelling and seismic amplitude analysis and mapping. The Cambo (204/10-1) and Lochnagar (213/27-1) discoveries on the Corona Ridge are identified as potential analogues to Anne-Marie.

Palaeocene Sedimentary Models in the Sub-basalt around the Munkegrunnar – East Faroes Ridge

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Abstract

Following disappointing results of exploration drilling in the Faroese extension of the Foinaven Basin in 2001, BP reviewed their strategy in the region and identified an area of contrasting prospectivity. This prospectivity is targeted for drilling in 2007.

Initial exploration had focused on an extension of the play successfully developed in the Palaeocene Foinaven and Schehallion discoveries on the UKCS. It targeted an area where Palaeocene T50 basalts were largely absent. Significant amplitudes were identified in the Palaeocene T30 sequences and related to Direct Hydrocarbon Indications (DHI) at nearby productive fields. Following drilling, failure was attributed to absence of seal linked to increased volume of sandstone and an amplitude driven strategy without proven rock property support. Several anomalous lithologies were encountered which gave false hydrocarbon AVO signatures.

Our current area of interest has targeted intervals within the Paleocene which exhibit evidence of northwest - southeast shelf progradation. These are correlated to the T20 and T30 section and can be linked to the tectonic development of the Munkegrunnar - East Faroes Ridge intersection. The interpretation has been clarified by selective re-processing in 2005 of long offset 2D lines acquired in 2001. Correlation with the Palaeocene of the Kangerlussuaq peninsula of southwest Greenland can be made from outcrop to seismic. Contrasting models are proposed in which the relative timing of uplift of the Munkegrunnar ridge and/or volcanic activity can be assessed in the reservoir petrography, provenance and quality of the T20 and T30 section in the area of interest.

Above this section, the development of clastic reservoir in the T40-50 sequences and their relationship to the extrusive basalts will also be examined by drilling. This interval is not addressed in detail by this presentation.

Transfer Zones: The application of new geological information from the Faroe Islands applied to the offshore exploration of intra-basalt and sub-basalt hydrocarbon potential

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A recent re-evaluation of the stratigraphy of The Faroe Islands with a new understanding of the structural and sedimentological processes involved has led to its application in the offshore Faroes area. The applied model has been further refined by the use of potential field and structural modelling centred on Licence 006. The final geological model has resulted in a new concept for the emplacement and structure of the basalts in Licence 006 and was therefore interactively applied during seismic processing.

Poor sub-basalt imaging has historically been a serious impediment to hydrocarbon exploration in the Faroe-Shetland Basin. In response Statoil and its partners have in recent years made significant improvements to seismic data quality in basalt covered areas of the basin by the use of interpretative processing and the application of a geological model at the processing stage.

The resulting uplift in seismic data quality has allowed detailed and advanced studies to take place on Licence 006. This has allowed Statoil and its Licence 006 partners to commit to drilling the Brugdan Prospect in the summer of 2006. This presentation will also show how this method can be applied to other areas of the Faroe-Shetland Basin, and other volcanic basins around the world.

FIEC06

Poster Session

12/9 and 13/9 2006

The Tertiary development of the Faroe-Shetland Basin: Intracontinental rifting or failed continental breakup?

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The Faroe-Shetland Basin, an apparent intracontinental rift basin, is co-axial with the Møre rifted margin to the north-east which formed by sea-floor spreading initiation on the Aegir ridge at ~54 Ma. Although the Faroe-Shetland Basin experienced Late Jurassic and Early Cretaceous rifting and subsequent thermal relaxation, well logging and paleoenvironment mapping indicates that the basin became emergent in the Late Paleocene, before experiencing anomalously high rates of subsidence in the Early Eocene. Flexural backstripping and decompaction to 54 Ma has been carried out on regional stratigraphic cross sections to quantify the water loaded subsidence since the basin emergence at top Paleocene times. If a depth uniform intracontinental rifting model is used, lithospheric beta factors greater than three are required to restore the post-Paleocene subsidence of the basin. However fault heave estimates indicate that there was little stretching in the upper crust of the Faroe-Shetland Basin at Paleocene and Late Cretaceous times, and substantially less than that indicated by post-Paleocene thermal subsidence assuming depth-uniform lithospheric stretching. Residual post-rift thermal subsidence from Late Jurassic and Early Cretaceous rifting, or Palaeocene mantle plume dynamic uplift cannot explain the Tertiary subsidence of the Faroe-Shetland Basin. The subsidence history of the Faroe-Shetland Basin since the Early Tertiary can be accounted for by thinning of the lithospheric mantle and lower crust beneath the Faroe-Shetland Basin, contemporaneous with continental breakup and formation of the Moere rifted margin to the north. At ~54Ma, the Faroe-Shetland Basin lay at the southern tip of the newly forming Aegir ocean ridge. Post-Palaeocene subsidence has been successfully modelled using a new model of continental lithosphere breakup and sea-floor spreading initiation in which thinning and rupture of continental lithosphere occurs due to an upwelling divergent flow field within continental lithosphere and asthenosphere. The model predicts that an ascending flow field, propagating upwards from the base of the lithosphere, first thinned the lithospheric mantle under the Faroe-Shetland Basin causing thermal uplift before thinning the lower crust, leading to rapid basin subsidence. While to the north the ascending flow field reached the surface and successfully ruptured the lithosphere giving continental breakup and sea-floor spreading initiation on the Aegir Ridge, under the Faroe-Shetland Basin the ascending flow field appears to have `died out' before reaching the surface. Upper Palaeocene basin collapse was followed by lithosphere thermal re-equilibration and thermal subsidence, which continues to the present day.

The architecture, evolution and tectonic significance of transfer zones on the NE Atlantic margin: an onshore-offshore approach

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Transfer zones are prominent geological structures ("lineaments") that strike at high angles to most continental margins. These lineaments are characterised by abrupt changes in fault polarity, apparent lateral offsets of the basin bounding faults and/or anomalies in the Earth's gravitational or magnetic fields. Despite the importance of transfer zones in controlling the structural and stratigraphic architecture of many hydrocarbon basins, very little is known about the detailed geometry, kinematics or tectonic evolution of the faults and folds that define transfer structures within the sedimentary and/or volcanic overburden.

Recent mapping in the Faroe Islands by Statoil and Jarðfeingi suggests that the NW-SE trending Judd and Westray transfer zones exerted a fundamental control on the development of structural closures (faulted anticlines) on the Faroese continental shelf. Two alternative models have been put forward to explain the development of these folds: (1) sinistral strike-slip along the Judd and Westray transfer zones; and (2) wrench-dominated transtension (WDTT) controlled by reactivation of the deep-seated Judd and Westray lineaments. A critical test of these hypotheses will be to constrain the geometry, kinematics and relative timing of faulting, folding and magmatic activity in the Faroe-Shetland Basin.

Two new PhD studentships with the Reactivation Research Group at Durham University, funded by the U.K. Natural Environment Research Council and Statoil (U.K.) Ltd., will use a combined onshore-offshore approach to tackle these issues. The offshore study will constrain the geometry and growth of large-scale transfer-related faults and folds using high-resolution 3-D seismic data from the U.K. sector of the Faroe-Shetland basin. Basalt cover is thin to absent in this region, permitting detailed geometric analysis of the faults and folds associated with the Judd and Clair lineaments. Regional 2-D seismic lines will allow correlation across the basin and will enable us to compare our findings with equivalent structures that have been targeted by Statoil's drilling on the Faroes margin. A complementary study will focus on the seismic- to sub-seismic scale faults and fractures that cut – or are truncated by – volcanic and sedimentary rocks exposed onshore in the Faroe Islands. We will apply new digital mapping and laser scanning techniques developed by the Reactivation Research Group at Durham University to capture the fracture geometries, which can be compared directly with our offshore interpretations using industry-standard software packages such as Gocad™ or Petrel™. The results of these studies will provide new constraints on Statoil's exploration model of the Faroese continental shelf and will lead to better understanding of the nature and tectonic significance of transfer zones on continental margins worldwide.

Crustal structure of the Faroe Islands region from satellite gravity inversion

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A new method of inverting satellite gravity data (Sandwell & Smith, 1997), incorporating a correction for the residual Lithosphere Thermal Gravity Anomaly (LTGA) which is present in all oceanic and stretched continental lithosphere, has been used to produce maps of a maximum bound of crustal thickness. The satellite gravity dataset and an independent bathymetry dataset (GEBCO 2003) are used to derive the Mantle Residual Gravity Anomaly (MRA) which is inverted in the spectral domain assuming a simple model of lithosphere structure to produce a maximum bound of Moho depth. The MRA is corrected for the thermal gravity component by iteratively deriving and subtracting the LTGA within the inversion. The thermal model for the LTGA (McKenzie, 1978) utilises a constant break up age in continental lithosphere and magnetic isochron ages (Muller et al., 1997) in oceanic lithosphere to determine the thermal relaxation period. The continent-ocean boundary (COB) and the constant break up age in continental lithosphere are determined within the inversion scheme by making the COB location consistent with the thermal regime at the margin of interest, based on an estimate of initial magmatic oceanic crustal thickness and a critical thinning factor for decompression melting during rifting (McKenzie & Bickle 1988). Results are shown with break up age calculated for the principal periods of continental break up and changes in plate motion: the Moere margin is used to set break up age and COB position for Paleocene break up in the Norwegian Sea; The west Jan Mayen margin is used to set break up age and COB position for the Oligocene break up associated with the initiation of the Kolbeinsey ridge; possible Cretaceous break up in the southern Rockall Trough and rifting in the Faroe-Shetland basin and Northern Rockall Trough is also investigated.
This work forms part of the NERC Margins iSIMM project. iSIMM investigators are from Liverpool and Cambridge Universities, Badley Geoscience & Schlumberger Cambridge Research supported by the NERC, the DTI, Agip UK, BP, Amerada Hess Ltd, Anadarko, Conoco-Phillips, Shell, Statoil and WesternGeco. The iSIMM team comprises NJ Kusznir, RS White, AM Roberts, PAF Christie, AR Chappell, J Eccles, RJ Fletcher, D Healy, N Hurst, ZC Lunnon, CJ Parkin, AW Roberts, LK Smith, VJ Tymms & R Spitzer.

Towards a unified Cenozoic (post-basalt) stratigraphic framework for the Faroe–Shetland region

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Several stratigraphic schemes have been applied to the Cenozoic succession in the Faroe–Shetland region including sequence-stratigraphic, lithostratigraphic and seismic-stratigraphic schemes. The use of different stratigraphic procedures largely reflects the varied objectives of commercial, government and academic institutions. This presentation will highlight the results of a recent reappraisal of Cenozoic stratigraphic data compiled during the production of the joint BGS–JFS regional offshore report for the Faroe-Shetland Basin. The resultant stratigraphic scheme represents a hybrid framework that is based on the most commonly used subdivisions and nomenclature. It is hoped to formalise this scheme in the not too distant future. The key boundaries are placed within an event stratigraphic context, which is used to describe the post-basalt evolution of the region in terms of sedimentation and deformation.

Converted Shear Wave Analysis of the Faroes Margin: Further Constraint on Sub-Basalt Lithology

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A high quality combined reflection and wide angle seismic profile was acquired across the Faroes volcanic rifted continental margin as part of the integrated Seismic Imaging and Modelling of Margins (iSIMM) project. Eighty-five, 4-component ocean bottom seismometers (OBS) were deployed along the profile, from continental to oceanic crust, at 2–6 km spacing, and a coincident, reflection profile collected with a 12 km, deep-towed streamer. Both datasets were acquired using low frequency sources for effective penetration beneath the extensive flood basalts, associated with the Tertiary North Atlantic Igneous Province, that are opaque to conventional seismic reflection techniques.

Clear converted shear (S-) wave arrivals, dominantly basalt or lower crustal refractions and Moho reflections, are observed on rotated in-line geophone components of the OBS. The NNW end of the profile in the Norwegian Sea provides the highest quality wide-angle, converted S-wave data, while the thick sediments of the Faroe-Shetland trough have largely attenuated converted S-wave arrivals refracting beneath the basin. Across the Fugløy Ridge step-backs of the converted S-wave basalt-lower crustal refraction indicate that rays penetrate a sub-basalt low-velocity zone. P-S and S-P wave conversion interfaces, determined by particle motion, forward modelling of travel times and analysis of fit during travel time tomography, indicate that mode conversions occur dominantly at a near-sea-floor sedimentary interface, and at the top basalt interface. Conversions occur at both the source and receiver ends of the raypaths.

A global S-wave velocity model across the profile is produced by inverting selected arrivals for the S-wave velocity using the crustal structure determined by previous P-wave analyses. These velocities and the calculated Poisson's ratios are used to gain further insight into the lithologies and nature of the continent-ocean transition, with its lower crustal intrusions, and of the material beneath the basalt flows.

This S-wave velocity model also provides a starting point for exploring the potential for converted S-wave imaging using the higher resolution multichannel reflection data. A streamer length of 12 km allows wide angles to be recorded and there is clear evidence on the streamer data for doubly mode converted S-waves, that can be correlated back to arrivals seen on the multi-component OBS data, and which may be used for sub-basalt imaging.

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Wide Angle Velocity Structure of the Faroes North Atlantic Margin

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The margins of the North Atlantic have been of great interest to geophysicists trying to understand the breakup of the North Atlantic and the effect of the Iceland Plume. We present results from tomographic inversion and forward modelling of wide-angle travel time data from a 400km transect across the continental margin and shelf near the Faroe Islands. The deep crustal margin structure has been successfully probed and found to contain a large region of high velocity (>7km/s) material, representing heavily intruded or underplated crust.

The survey, conducted in 2002, was part of the iSIMM project, and is accompanied by high quality 12km Q-streamer data. This dataset was obtained using a large specially designed low frequency source in order to maximise seismic energy penetration through the highly attenuative basalt cover over the Faroes shelf. The two datasets have been used in conjunction with one another to interpret the structure of the transect, in particular in identifying the Moho, high velocity lower crustal layering, pronounced seaward dipping reflectors and a sub basalt velocity inversion, thought to comprise hyaloclastites and sediments.

Attention is focused on the substantial high velocity lower crustal region at the continental margin. A relatively sharp transition to normal continental crust is observed, which constrains how far into the old continental crust igneous intrusion has taken place. The results also provide constraints on the total amount of igneous material added to the crust during continental breakup. The thickened oceanic crust near the margin is indicative of high mantle temperature at the time of continental breakup.

The iSIMM project was supported by Liverpool and Cambridge Universities, Schlumberger Cambridge Research, Badley Geoscience, WesternGeco, Amerada Hess, Anadarko, BP, ConocoPhillips, Eni–UK Ltd., Statoil, Shell, the NERC and DTI. The FLARE profiles were shot by Amerada Hess Limited and its partners LASMO (ULX) Limited, Norsk Hydro a.s., DOPAS and Atlantic Petroleum.

Facies architecture of flood basalts: Implications for Sub-Basalt Imaging

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In terms of their detailed volcanology and facies architecture, Continental Flood Basalts (CFBs) and associated volcanic rifted margins reveal important information to help our understanding of their evolution. Mafic volcanism, which makes up the majority of preserved material, is characterized by flows 2-3 m to several 10s of meters thick, with ponded flows and occasional massive flow events of the order of 100 m thick. Although most of the flows are emplaced by the same mechanism as passive inflated sheets, a variety of different facies associations exist dependent on flow volumes and to some extent flow composition. The largest silicic volcanic events in CFBs are larger in volume than the largest recorded mafic events, and they are potentially more catastrophic if erupted as ignimbrite flows. The architecture of CFBs and associated volcanic rifted margins is recorded by facies types and facies associations. Facies types, such as Tabular-Classic flows, Braided-Compound flows or Hyaloclastites, represent genetically related building blocks of the volcanic stratigraphy. Facies associations, such as downlap, onlap and disconformities, relate how the volcanic facies are stacked together. Many of the facies associations occur on an intermediate to large basin wide scale and may only be revealed by detailed fieldwork, photogrammetry and 3-D geological models.

The stacking relationships of these different flood basalt facies will directly effect the ability of seismic energy to pass through the lava field. Using an intra-facies scheme it is possible to understand the rock property distribution through different types of igneous material and so gauge the impact of the different facies on the seismic signal. Using 2D and 3D synthetic models with a much more 'Geologically realistic' facies distribution, provide a much better test of how seismic energy behaves through the basalt and down into the sub-basalt regime.

The Faroes Shetland Trough Sub Basalt Stratigraphy and Plays

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The main tasks when looking for hydrocarbons beneath the extensive Faroese Basalts are: 1. To clearly image the strata beneath the basalt using advanced seismic imaging techniques; 2. Accurately date the Faroese Basalts to find out the age relationship with the best quality Lower Tertiary reservoir sandstones; 3. Gain a clear understanding of the regional geology around the Faroe Islands to better understand the source rock distribution, petroleum systems and play potential.

This presentation is a synthesis of published data, it aims to address the third point above, providing an insight into the geology and hydrocarbon potential beneath the Faroese Basalts of the Faroes Shetland Trough. The geology and exploration possibilities of the United Kingdom sector of the Faroes Shetland Trough is here sited as an analogue to the understanding of the stratigraphy and play potential beneath the extensive Faroese Basalts to the east of the Faroe Islands.

The Faroes Shetland Trough lies entirely offshore between the Faroe Islands and the Shetland Islands. This deep structure consists of northeast- southwest trending grabens and half-grabens separated by horsts and ridges. The eastern UK sector has only minor Tertiary basalt cover and has been explored since the early 1970s, hence its structure and stratigraphy are now generally well established. In contrast the Lower Tertiary and older strata of the western Faroese sector is overlain by massive thicknesses of Faroe Basalts. As a result, the underlying structure of this area is largely inferred from a compilation of gravity, magnetic and regional seismic data.

Proven plays close to the United Kingdom/Faroe Island boundary, in United Kingdom waters, suggest that similar plays may also exist in the Faroe Island sector of the trough. Two examples of these are: The Middle Eocene basin floor sandstone play in the deepwater Corona-Stremoy ridge area, established by the 214/04-1 (Tobermory), UK, gas discovery and the 213/27-01z (Lochnagar) deepwater discovery on the Corona Ridge. Lochnagar drilled a considerable thickness of basalt and tested hydrocarbons at two horizons. Regional gravity, magnetic and seismic data indicate that half grabens, ridges and highs similar to the productive eastern UK sector of the trough also exist in the Faroese sector.

Lithostratigraphic framework for the Faroe Islands Basalt Group, NE Atlantic Ocean

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The Palaeogene Faroe Islands Basalt Group (FIBG) covers an area of at least 120,000 km^2 of the NE Atlantic Ocean although only 1400 km^2 are exposed on the Faroe Islands. On the Faroe Islands, the FIBG has a stratigraphic thickness of *ca.* 6.6 km, of which 3.4 km is proven by the onshore borehole Lopra-1/1A. The FIBG is composed almost exclusively of subaerial basalt lava flows, rare pyroclastic lithologies and a variety of associated volcaniclastic strata. Since the publication of the last geological map in 1969, there have been significant advances in the understanding of the processes that occur in volcanic settings and this, associated with the developments in volcanic classification schemes, has led to our development of a revised lithostratigraphic framework for the Faroe Islands following the guidelines of the *International Subcommission on Stratigraphic Classification*. We have subdivided the FIBG into seven formations based upon the recognition of widespread disconformities and lithological changes. The base of the FIBG is composed of the *ca.* 1000 m thick Lopra Formation, a volcaniclastic strata and hyaloclastite-dominated sequence, which is overlain by the *ca.* 3300 m thick Beinisvørð Formation composed of aphyric tabular lava flows. There is a marked disconformity at this level and these lavas are overlain by the 3-15 m thick Prestfjall Formation, composed of coals, mudstones and sandstones. Volcanism resumed with the eruption of tuffs and lapillistones preserved intercalated with volcaniclastic sedimentary conglomerates and sandstones of the *ca.* 50 m thick Hvannhagi Formation. This was followed by the eruption of the *ca.* 1300 m thick compound lava flow sequence of the Malinstindur Formation. Another disconformity is recognised at the top of the Malinstindur Formation and is overlain by the 1-30 m thick Sneis Formation composed of volcaniclastic sandstones and conglomerates. The Sneis Formation is overlain by the Enni Formation, composed of interbedded compound and tabular basalt lava flows and is at least 900 m thick. The recognition of a number of distinct lava flow packages (e.g. olivine microporphyritic compound flows) and key stratigraphic marker beds (e.g. the Argir Beds) may enable future subdivisions of the stratigraphy and lead to a better understanding of the evolution of the lava field.

The Atlantic Margin Metocean Project

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Fugro has been conducting site specific ocean current measurements for over a decade in the Atlantic Margin. The focus of these measurements has been the North West Approaches, which is adjacent to the Faroes concessions and shares many common oceanographic features.

The oceanographic conditions offshore the Faroes are complex with the North Atlantic Current moving north-east in the upper water column, whilst the much colder and denser Norwegian Bottom Current flows in the opposite direction near the seabed. In addition to this, the topography and its effect on the regional water masses can lead to episodic current events which often produce the most extreme conditions. These complex oceanographic conditions can affect seismic exploration, with cross-currents (flow perpendicular to the survey line) causing streamers to 'feather' and create gaps in the survey coverage. Detailed knowledge of current conditions from preliminary desk study (downtime report) to real-time measurement of current during seismic data acquisition helps to optimise the survey execution and reduces cost.

The objective of the Atlantic Margin Metocean Project (AMMP) is to provide meteorological and oceanographic (metocean) criteria at a very early stage for drilling campaigns offshore the Faroes and Ireland. In August 1999, Fugro deployed three oceanographic moorings as part of this speculative measurement programme, south of the Faroes. The moorings each comprised a string of conventional Aanderaa recording current meters (RCM), incorporating temperature, conductivity (salinity) sensors and Teledyne RDI Acoustic Doppler Current Profilers (ADCP). The moorings were deployed in water depths ranging from 500m to just over 1000m. The locations were selected on the basis of the strategic importance to exploratory drilling and to provide information on the oceanographic processes in the region. Measurements were conducted over a year-long period and service visits conducted on a regular three month basis to recover data.

An overview of the project and the metocean criteria for seismic and drilling exploration offshore the Faroes will form the basis for discussion.