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Abstract Volume

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4th Faroe Island Exploration Conference – 1 - 2 May 2012

Oral Presentations

Abstracts

Tuesday 1 May 2012

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Late Paleocene oblique rifting in the Kangerlussuaq Basin (southern East Greenland)

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During fieldwork in 2009-2010 in southern East Greenland, structural analysis of major faults was carried out to better understand the tectonic setting of the Kangerlussuaq Basin and the structural significance of major NW-SE trending faults analogue to the transfer zones described in the Faroes-Shetland area. In the Kangerlussuaq region the Lower Cretaceous–Paleocene sedimentary succession reaches almost 1 km in thickness and comprises sediments of the Kangerlussuaq Group overlain by the Tertiary basalts of the Blosseville Group.

The study shows four stages evolution for the basin:

- Late Cretaceous-Early Paleocene rift;
- Late Paleocene volcanic rift;
- Early Eocene oceanic rift;
- Late Eocene-Early Oligocene basin inversion and uplift.

Fault-slip data collected along major fault systems document two episodes of strike-slip faulting in the Late Paleocene and Late Eocene-Early Oligocene. In particular, left-lateral and dip-oblique movements along N60ºE trending Late Paleocene rift faults, NE-SW oriented maximum horizontal stress derived from inversion of fault-slip data, NE migration of volcanic centres and the development of en-echelon magmatic segments (macrodikes complex) can be interpreted as evidence for oblique rifting (corresponding to the volcanic rift) leading to the final breakup around 55 Ma. Moreover, the prominent NW-SE Nansen Fjord and Kangerlussuaq Fjord Faults are inferred to be right-lateral faults from geological evidence and coeval with the left-lateral movements along main rift faults (Sødalengletscher Fault). Finally, the overall rift geometry, kinematics of faults, trend of dike intrusions and paleostress orientation are the expression of a left-lateral ENE-WSW oriented fracture zone linking the South East Greenland and the Norwegian Sea line of breakup.

Provenance of sediments in the Faroe-Shetland basin: Characterisation of source components in Southeast Greenland

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This study is a continuation of previous SINDRI-funded projects, with the aim of investigating the provenance of sediments in the Faroe-Shetland basin. In previous studies, U-Pb ages of detrital zircons in representative samples from drill core in the Faroese sector of the Faroe-Shetland basin have been analysed with LA-ICP-MS. In this study, stream sediment and till samples from southern East and South-East Greenland have been analysed to assess this area as a source region. The samples were collected primarily along the coast, from Kangerlussuaq in the north to Timmiarmiut in the south, a stretch of 800 km.

The age pattern changes from north to south commensurate with ages of the basement rocks, with an overall dominate age range from 2900-2700 Ma. Most samples do not contain Proterozoic zircons except two samples collected in the Palaeoproterozoic Ammassalik Intrusive Complex that yield age patterns dominated by 1950-1900 Ma zircons, in good agreement with the intrusion age.

As such, the overall age pattern for Southeast and East Greenland is markedly different from that of the samples from the drill core in the Faroese sector making it unlikely that this part of Greenland was the source for this segment of the Faroe-Shetland basin.

In previous SINDRI-studies, it has been suggested that the sediment of the Faroese sector was sourced from the UK margin. An alternative source exists in central East and North-East Greenland where suitable-aged source rocks are known to occur. This potential source appears more compatible with pollen records and sediment transport directions.

In-situ geochemical characterization of experimentally generated partial melts: modelling crustal contamination beneath the Faroe Islands

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Understanding partial melting of ancient gneiss terranes is crucial when considering crustal contamination of volcanic systems such as the Faroe Islands, as these rocks are unlikely to melt completely at magmatic temperatures (900-1200 °C) and crustal pressures (<500 MPa). Variations in the bulk composition of the protolith, magma temperature, pressure (depth) and the composition of any fluids present will produce a variety of partial melt compositions. This may range from partial melts enriched in incompatible elements to more complete melts, nearing the bulk chemistry of the parent gneiss.

We have used piston cylinder experiments to simulate partial melting in a suite of 12 gneisses from NW Scotland and Eastern Greenland at magma chamber temperatures and pressures (P = 200 MPa, T = 975 °C). These gneisses form the basement to much of the North Atlantic Igneous Province, where crustal contamination is frequently identified. However, the actual compositions of the crustal partial melts are poorly constrained. Partial melts were produced in all 12 experiments. The experimental melts were quenched to glass in-situ, making them suitable for microanalysis; including electron microprobe spot analyses, energy-dispersive x-ray spectroscopy (EDX) mapping and in-situ Sr and Pb isotope analyses.

This novel petrological, experimental and in-situ geochemical approach allows the quantification of partial melting processes in a volcanic context, providing accurate geochemical end-members for modelling crustal contamination with unprecedented precision. Our whole rock and mineral data will also form part of a detailed crustal dataset for sedimentary provenance studies in the North Atlantic region.

Records of magma-crust interaction as constraints on the sub-basalt basement beneath the Faroe Islands

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The Faroe Islands Basalt Group is ~6 km thick and is underlain by ~38 km continental crust, as estimated by geophysical surveys[1]. The exact nature of these continental rocks is unknown, though previous studies have presumed an Archean basement, probably overlain by sediments related to the pre-volcanic rifting. Potential onshore equivalents of the basement rocks can be found in Scotland and East Greenland.
In this study, we employ multiple geobarometric models coupled with Sr, and He isotope signatures to decipher crustal influences in the Faroe basalts. This approach allows us to construct "virtual geochemical boreholes" through the basalts into the underlying crustal basement.
In-situ analyses of plagioclase exhibit a range of measured 87Sr/86Sr signatures between 0.70331 - 0.70498. Helium isotopes from olivine and pyroxene separates record both primitive as well as highly crustal values. Anorthite contents in plagioclase are separated into two populations: An62-72 and An80-90, suggesting two main levels of fractionation. The majority of the analysed rocks record shallow depths of fractionation (<10 km) corresponding with the upper part of the basement rocks plus intrabasaltic storage. This, coupled with helium isotope signatures with significant crustal input, indicate a scenario with widespread melting and assimilation of the underlying continental crust. The wide range of Sr and He isotope signatures, indicate a complex plumbing system with variable degrees and depth levels of assimilation.
We present a preliminary virtual geochemical borehole through the basalts, attempting to identify the general lithostratigraphy of the sub-basaltic basement.

Reference:
[1] Richardson et al 1999, Petrol. Geosci. 5, 161-172.

Seismic mapping, crustal modelling and rock sampling of Faroe Bank and Bill Bailey Bank, the North Atlantic Igneous Province: evidence of prolonged volcanism, inversion and deep erosion

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Seismic mapping shows that basaltic lava flows flooded the present continental margin south-west of the Faroe Islands in a 300 km wide belt at the time of breakup between Europe and Greenland. A reconstruction of the original top of the basalt from shallow seismic reflections combined with other seismic data indicate that the volcanic succession was originally about 6 km thick on Bill Bailey Bank, 50 km from the line of breakup, but that it decreases in thickness eastward to about 0.5-1 km on the Wyville-Thomson Ridge south of the Faroes. The volcanic strata form open folds with amplitudes of up to 6-7 km. The culminations are associated with gravity minima, which are best modelled by light cores of sediment. Most folds are approximately at right angle to the line of opening and were probably formed mainly during compression in early to late Eocene time. The deformed plateau was subsequently eroded to a depth of 3-4 km at the culmination of the large folds forming Bill Bailey Bank and Faroe Bank, respectively. The sediments that covered the lower flanks of the banks to the NE towards the Iceland Basin were also partially removed, indicating that this low area was above sea level for a long period of time while close to the proto-Atlantic rift. Because of sediment starvation and strong bottom currents the eroded volcanics are widely exposed in elevated areas allowing dredging and shallow rock drilling of the lava plateau to a stratigraphic depth of about 3 km. Magnetic reversals modelled at shallow depth suggest that lavas belonging to the North Atlantic Igneous Province (NAIP) pre-breakup phase 1 (56-61 Ma) are exposed centrally on both banks and this is supported by ^{40}Ar-^{39}Ar dating and rock chemistry. On both banks about 2 km of syn-breakup lava from NAIP phase 2 have been recovered with a mean age of 55 Ma, coeval with the middle and upper basalt formations in the Faroes and the Main Basalts in East Greenland. Post-breakup basalts with an age of ~49-53 Ma have been sampled at three locations on Faroe Bank and one on Bill Bailey Bank, and seem to be of regional extent. They have a maximum thickness of 0.5-1 km on the banks, but may be thicker in the adjacent basins.

3D Seismic Mapping of Magmatic Intrusive Bodies in the Faroe-Shetland Basin

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The sedimentary section of the Faroe-Shetland Basin is strongly influenced by the magmatic events of the North Atlantic Tertiary Igneous Province. The western part of the basin is covered by extrusive volcanic lava whereas numerous magmatic sills known as the Faroe-Shetland Sill Complex are prominent in central and eastern part. The sill complex has primarily been intruded into the Upper Cretaceous and Palaeogene sedimentary succession.
With new high quality and high resolution 3D seismic, acquired in 2008 and 2009, it is possible to perform detailed interpretations of sill morphology and their internal structures. In the study area a large complex 6,3 x 5,0 km was mapped in detail. The mapped complex is displayed on 2D map views, and 3D figures are constructed from converted horizons. Based on the detailed interpretation it is possible to analyse morphology and flow patterns and determine a spatial connections between individual intrusions. It is concluded that the intrusions in the mapped complex are connected in a larger intrusive system, and hence emplaced from one intrusive event.
Finally a new emplacement mechanism the 'bullet-hole' emplacement hypothesis is introduced, which is suggested as an emplacement mechanism for *cup-shaped* sills.
A hydrothermal vent created on the seafloor directly as a consequence of the intrusive event by explosive eruptions of gasses, liquids and sediments, is used to determine the age of the intrusive system, by using well ties and biostratigraphic markers.

Seismic volcano-stratigraphic characteristics of the Jan Mayen Micro-Continent area and the possible distribution of volcanic intrusion complexes and hydrothermal vents.

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Improved seismic and recent seafloor sample data have added a new view on the inner structures of the Jan Mayen Ridge (JMR) and its seismic stratigraphic mapping approach. This study is part of an ongoing hydrocarbon exploration study conducted in preparation and follow up of the second Icelandic Petroleum Exploration License Round in 2011-2012. During the generating of the structural model it was essential to identify igneous complexes and features as part of a volcano-stratigraphic seismic characterization that resulted in the re-assessment of the seaward dipping, sill- and dyke, and hydrothermal vent complexes within the different segments of the JMR. These igneous features can be grouped and the first of which relate to the breakup of the Vøring and Møre Basins from the East-Greenland margin during the continental rifting during the Paleocene to Eocene and the forming of the Aegir Ridge system along the eastern flanks of the JMR. Secondly, the identification of JMR typical versus transitional crust and sets of sill and dyke intrusions added to the understanding of the rifting transition from the Aegir ridge to form the Kolbeinsey Ridge that separated the JMR from the East Greenland main land. Indications are present that show a gradual transition with possible failed rifting attempts during the early Middle Eocene, and during the transition between Late Eocene and Early Oligocene along the southeastern and southern flanks of the JMR. Thirdly, a series of intrusions were observed that probably relate to the rifting and separation of the western flank of the JMR from the main land.

Volcanic stratigraphy from ditch cutting analysis

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Ditch cuttings from wells penetrating flood basalt sequences provide the most commonly available lithological data from which an assessment of the volcanic stratigraphy at a specific location can be made. Many advances in recent years have been made in regards the geophysical response of volcanic facies from down-hole tools however, a similar development in regards to ditch cutting analysis and classification is not apparent. We propose a fresh approach in an attempt to quantify some of the accuracy issues commonly attributed to cuttings. The approach presented comprises a simple analysis workflow and non-genetic classification system that aims to encompass broadly the expected lithologies found in a flood basalt volcanic succession. From this classification system a simplified log output can be produced and subsequently interpreted. The major benefits include a simplistic transparent approach, easily integrated into the real time drilling workflow along with a visual output again easily integrated with well logs and any other stratigraphically constrained information. A move towards a unified approach is required before regional comparisons and synthesis can be undertaken with confidence.

"Facies modelling of the Erlend Volcanic Complex and hyaloclastite distribution within the northern sector of the Faroe Shetland basin from seismic reflection data."

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The Erlend volcanic complex is situated offshore within the Faroe Shetland basin to the NE of the Shetland Islands. The complex is Palaeocene in age and located in the northern sector of Quads 208 and 209. It was first identified from its gravity and magnetic anomaly in 1977. In this study we have identified and mapped the volcanic facies found within the Erlend volcanic complex. Fully migrated, 2D reflection seismic survey lines are interpreted over the area with six wells available to tie into the seismic. Three wells (209/4-1A, 209/3-1 and 209/9-1), penetrated the Erlend volcanic sequence.

Volcanostratigraphy was used to identify different packages within the volcanic sequence. Previously published work was then tied into the well locations, this used log responses and biostratigraphy to identify the individual units. These were then compared to the different packages identified using volcanostratigraphy and a close correlation was found. Using this information it was possible to map out the lateral extent and thickness of the individual units that make up the Erlend volcanic sequence.

Hyaloclastite have been identified from well 209/4-1A within the Erlend volcanic complex and from the Tobermoray well 214/4-1. This, when combined with the classic prograding lava delta facies that has been observed in both Greenland and Antarctica, allowed for the identification and the lateral extent of this facies to be mapped out using reflection seismic profiles.

Geophysical aspects of basalt geology and identification of intrabasaltic horizons

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The Faroe Islands Basalt Group, part of the North Atlantic Igneous Province, attains a stratigraphic thickness of more than 6.6 km. The stratigraphic sequence is previously described by surface mapping and logging of three deep onshore wells. This work addresses geophysical aspects of the basalt geology and aims to extend the geological information onto conventional marine seismic data in the Faroes area. The work is based on zero offset VSP and surface seismic data acquired at Glyvursnes in 2003 as part SeiFaBa project and on the resent reprocessing of the OF94/95 data by TGS. Well logs from the Lopra, Vestmanna and Glyvursnes are also used.

Although individual basalt flows have the common property of a high-velocity massive core and a low-velocity porous crust, the difference in configuration of flow thicknesses and interbedded sedimentary beds leads to that the three major basalt formations (Enni, Malinstindur and Beinisvørð Fm) have quite different geophysical properties. The reflection series for the Malinstindur Fm, located between Enni and Beinisvørð Fm has low amplitudes for scales relevant for seismic signals while the Enni and Beinisvørð Fm have high-amplitudes.

The base of Malinstindur and Enni Fm (A- and C-horizon respectively) are identified on the seismic data acquired at Glyvursnes. While the A-horizon with confidence can be tied to TGS-OF94 profiles to the north-east of the Faroes area the identification of the C-horizon is more difficult. By extrapolating the onshore mapping of the C-horizon onto the profiles the Malinstindur Fm is found to be ~1100 m thick just south of the northern islands, the same thickness as has previously been found at Glyvursnes, while ~15 km north-east of Fugloy the indications are that it thins significantly to an estimated thickness of ~500 m .

The identification of the A-horizon on conventional marine seismic data opens up a whole new mean for geological interpretation of the Faroes area. In the quest for solving the sub-basalt imaging problem it is of importance to realize that basalt is not just basalt with some general properties. Different configurations of flow thicknesses and interbedded sedimentary beds lead to quite different properties when regarding velocity, anisotropy, attenuation and scattering. Distinguishing between types of basalt formations is most likely of importance for the quality of seismic processing.

The use of de-tuned airgun arrays for improved imaging through high impedance structures

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In many exploration provinces potential hydrocarbon bearing formations are located beneath thick layers of basalts, carbonate rocks or salt. These structures present several challenges to seismic reflection imaging:

- The interfaces between the strata above and below these layers are high acoustic impedance boundaries that reflect a good percentage of the down-going and/or up-going seismic energy.
- These layers can be highly absorptive, attenuating high and mid frequencies and only passing low frequencies.
- In salt provinces, as well as absorbing seismic energy, the generally complex formations require sophisticated 3D techniques to effectively image potential hydrocarbon traps.

A standard seismic airgun array emits energy in a typical bandwidth of 7-100 Hz. Experience shows that the higher end of the normal seismic bandwidth is most affected by the high impedance contrasts, and therefore most vulnerable to scattering and attenuation, manifested as higher noise in the seismic dataset. This suggests that during data acquisition the bandwidth of the seismic acquisition system should be tuned to optimise the signal-to-noise at the low frequency end of the signal spectrum.

A test was conducted offshore West Africa to evaluate techniques to optimise seismic reflection data within narrow low frequency bands through the use of a low frequency source, deep towed solid streamers, and long offsets.

These techniques proved effective, and should be applicable in many areas where the primary exploration targets are deep in the rock section and/or are overlain by high impedance low-pass salt, basalt, or carbonate structures.

Broadband acquisition – new possibilities for intra- and sub-basalt exploration

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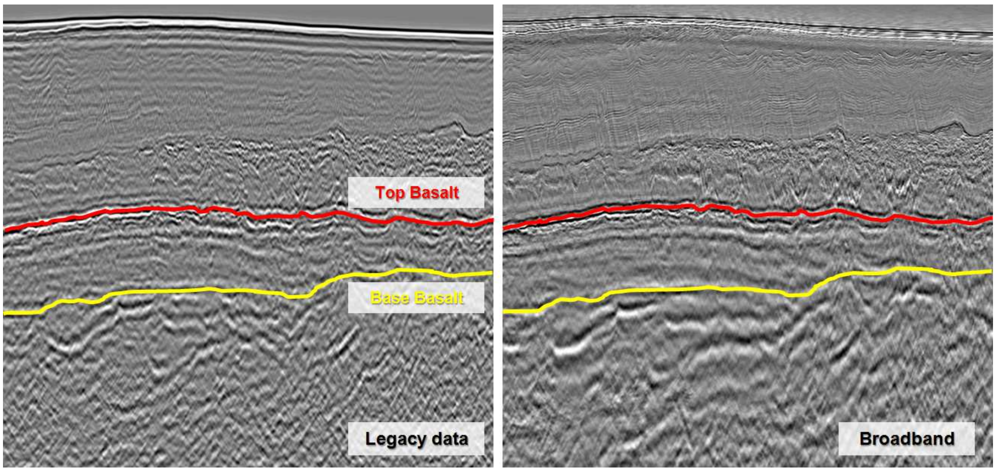
Recent developments in towed streamer seismic acquisition, leading to much broader bandwidth, have sparked interest in challenging imaging environments around the world. The thick volcanic deposits of the Faroe Shetland Basin are one such challenge, which obscures the deeper underlying sediments. The basalts scatters the seismic energy and generates severe multiples which in turn overwhelms the weak sub-basalt target reflectors. The most common approach has been to hone in on the low frequencies and image only using a very narrow bandwidth, typically 5-35Hz or less. This was achieved by towing conventional sources and streamers deep – albeit compromising both spatial and temporal resolution. With the advent of new de-ghosted source- and streamer-technology available today, this compromise is no longer needed. In this paper we compare 2D data acquired using broadband acquisition technology to conventional deep tow data previously acquired in the same locations over basalt in the Faroe Shetland Basin. Four single 2D lines were acquired using a time and depth distributed source recorded with a dual-sensor streamer allowing both receiver- and source-side deghosting. The different lines cover a range of basalt facies and thicknesses. The resulting data is free of any surface ghosts resulting in an ultra large bandwidth of 2-220Hz. Comparisons to legacy data shows the benefit of broadband signal processing allowing optimal imaging conditions for all frequency ranges. This in turn opens up new ways of processing seismic data and revealing geology.



Comparison of legacy deep towed conventional data (left) to new broadband seismic data(right). The broadband data can image both high and low frequencies at the same time without any compromise.

Enhanced low frequency signal processing for sub-basalt imaging on the Faroese Continental Shelf

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Sub-basalt seismic imaging continues to provide a challenge on the Faroese Continental Shelf. The key to providing improved sub-basalt images with conventionally acquired 2D marine data is to retain and enhance as much low frequency energy as possible. Two key signal processing steps are described.

a) Spectral Enhancement: Low Frequency Boost

At the beginning of data processing, after conversion to zero-phase, the recorded source wavelet is manipulated in order to enhance the signal at the low frequency end of the amplitude spectrum. The low frequency components of the wavelet are edited and shaped to generate a target wavelet and appropriate zero-phase matching operators – one operator for each vintage of seismic acquisition. This apparent spectral shaping is in alignment with some key findings made in an evaluation on the spectral output of marine airgun arrays.

b) Multi-domain Noise Attenuation

As the boosting operator does not discriminate between signal and noise, the poor signal-to-noise ratio common at low frequencies is not improved after applying the operator However, by choosing to apply the operator at the beginning of processing this enables a full suite of noise attenuating processes to be performed in all of the available 'time-offset' domains, and for all of the signal enhancing components in the processing sequence to work on the boosted low frequency data. Optimum improvements to the signal-to-noise ratio at low frequencies can therefore be expected. We are able to demonstrate consistent improvements to the imaging quality through the reprocessing of 2D seismic covering the Faroese Continental Shelf.

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Understanding the onset of flood volcanism at rifted margins: sedimentary environments, sediment/lava interaction and volcaniclastics

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A key part of continental flood basalts and associated volcanic rifted margins is the onset of flood volcanism and the start of the large igneous province (LIP) formation. As we aim to unravel volcanic margins from a LIP evolution and from a petroleum exploration perspective, detailed field studies of flood basalt provinces, offshore sampling and improved imaging, all allow the characterisation of detailed volcanic facies and facies architecture. Where we can study the basal contacts of the LIPs we can relate this information to the sedimentary basins they erupt onto and intrude into.

Onset volcanism is characterised by flows 2-3 m to several 10s of meters thick, with ponded flows and examples of sediment interlayers of various styles. A variety of different lava facies and facies associations exist dependent on many factors including; flow volumes, distance from source, type of source, environment of eruption and flow composition. Importantly, the onset of volcanism in a number of examples from LIPs worldwide show a significant component of volcaniclastics. In many examples these volcaniclastics can be used to show that wet environments and/or significant water bodies, including seaways, that were around at the start of flood volcanism, and sometimes upwards into the volcanic pile. The presence of such volcaniclastics at the onset of flood volcanism help us to constrain the types of environments around and also the limits to uplift models associated with LIP emplacement theories.

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Using earthquake seismology to image volcanic rifted margins: constraining flood basalts, marine sediments and upper/lower crustal magmatic intrusions beneath the Main Ethiopian Rift

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Recent studies in Ethiopia show that the Cenozoic northern Main Ethiopian Rift (NMER) has developed in a Neo-Proterozoic lithospheric framework modified by a Tertiary plume. A 400 km long profile of 91 broadband seismic stations across the NMER has provided a P-S-wave receiver function section that provided evidence for syn-rift deposits that exist over a ~110 km wide region beneath which strain was accommodated during the early stages of rifting.

Major variations in crustal thickness and seismic properties along the profile divide the crust into four distinct regions: i) a NW rift flank where mafic middle and lower crustal rocks are overlain by a felsic upper crust and a high P wave velocity lowest crustal layer may consist of frozen gabbroic sills and some partial melt; ii) a rift with a ~34.5 km thick crust, thinned with a strong likelihood of partially molten rocks and where high velocity and density anomalies and the presence of a Moho ‘‘hole’’ in the receiver function profile constrain the limits of a well-developed crustal magma system; iii) the southeast rift flank consisting of a thick, felsic to intermediate composition crust (ave. crustal thickness of 39 km); iv) a 35 km wide zone marking the transition from intruded and thinned (by ~5 km) crust beneath the rift to the southeastern rift flank.

Although magma injection appears to have replaced mechanical failure as the main strain accommodation mechanism within the NMER, the presence of pre- and syn-rift magmatism may have controlled the location and development of the NMER in the vicinity of the profile.

Møre Basin
Sub-Basalt Exploration in a Regional Context

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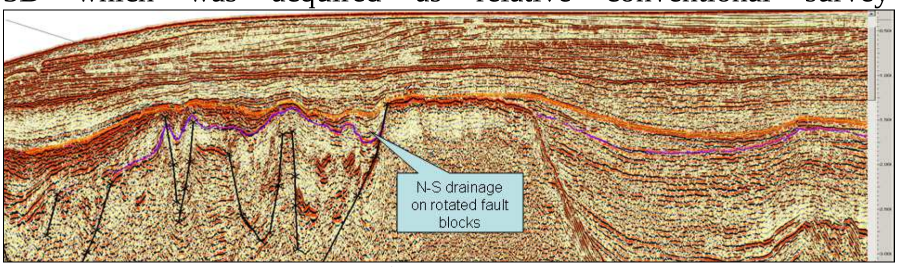
Basalt cover creates challenges for the understanding of the regional setting and tectonics in the Faroe, West of Shetland (WoS) and Møre areas. During our work on the Norwegian Tulipan discovery, we proposed a depositional model excluding Greenland as a source for a Danian sand in the WoS region an assumption which may be strengthened by observation on Lagavullin.
Fugro Multi Client Services have a large regional 2D database in the Basalt areas, and with improved seismic processing it is possible to make an interpretation to create the necessary regional frame work.
The presentation attempt to compare the conjugate East Greenland with the Møre Margin, and to predict the depth to Jurassic source rocks in the basalt covered areas. However, the critical factor west of Shetland and in Faroe waters has not been source and maturity, but the presence of reservoirs.
The discovery well 6302/6-1 (Tulipan) identified a good reservoir potential in the outer part of the Møre Basin. Alternative depositional models and provenance for the "Tulipan" sand and also the implications on sand distribution, will be discussed. Both Greenland and the Shetland platform are candidates as provenance areas. The seismic examples used will illustrate why we believe Shetland is a likely source.
Both Greenland and the Shetland platform are candidates as provenance areas, and seismic examples we will be used to illustrate why we believe that Shetland is a likely source.
Paleocene rifting, prior to the break up, gave large structural closures under the Møre Basalt. These structures have a good trap potential for the Danien sand. We will show some of the structures on seismic.
The play potential gave motivation for a multi client 3D in the area. Preliminary results from this 3D which was acquired as relative conventional survey are very promising for



Seismic line (WE) crossing the Shetland platform, showing channels that could act a depositional drainage routes

We believe that our work will have implications for the regional depositional model for the whole Faroe, WoS, Møre area.

Igneous Reservoirs – An Overview

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Continued price rises in oil and gas will drive exploration to assess the economic viability of unconventional basement reservoirs. Basement reservoir lithologies include metamorphics, intrusives (especially granitic plutons) and volcanics. The main focus of the presentation will be the characterization of various volcanic reservoirs, and the associated issues concerning their exploration and development. Currently producing volcanic reservoirs from the Cretaceous Campos basin of Brazil, the Jurassic from Argentina, the Palaeocene Deccan Traps of India, and the Miocene volcanics from Japan and Thailand.

Many basement reservoirs are highly competent lithologies, and with little matrix porosity rely upon the development of secondary porosity to create commercially viable reservoirs. Volcanic rocks can develop significant primary poroperm if they are rapidly quenched after eruption. Moreover, the primary composition of the original volcanic material (in particular the silica content) is of major importance because this is the main control on lava viscosity and thus in part determines how susceptible the rocks will be to later tectonism (faulting and fracturing). Volatile content also exerts a major control on poroperm development since it affects the degree of vesiculation and vug development. High porosity is often associated with such gas escape structures, although they commonly lack significant permeability. Development of secondary fractures and faults are often needed to provide sufficient permeability for subsequent reservoir development, although in some examples primary cooling joints can also contribute significantly to overall reservoir connectivity.

Secondary porosity can be subdivided into two broad categories:

1. Tectonic porosity related to joint, fracture and fault development across various scales.
2. Dissolution porosity created by an extensive range of process from deuteric crystal dissolution within weathering and fault damage zones, to the later effects of hydrothermal circulation and subsequent alteration.

Use of Micro-Focus X-ray Computed Tomography to Visualise and Quantify the Porosity and Permeability of Volcanic Reservoir Rocks

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Development of unconventional volcanic reservoirs relies upon understanding the contributors to their porosity and permeability. Volcanics typically have high porosities but low permeabilities, with secondary fractures ultimately controlling reservoir permeability. Production rates from the Padra oil field, India (where the Tertiary Deccan Trap basalts are reservoirs) show characteristic production patterns of many volcanics, with initial high production rates rapidly declining to uneconomic levels over short-timescales. This pattern is consistent with fracture controlled permeability systems. Deviation from this production trend to a more stable recovery occurs when there is a secondary mechanism contributing to connectivity.

Primary porosity in igneous reservoirs is dominated by vesicular porosity, which is controlled by both the original chemistry of the magma, and the eruption style. Specifically, the volatile and silica content are important to the ability of magma to degas and develop substantial vesicles. Results from micro-focus X-ray computed tomography (μCT) of a suite of variably altered South American volcanic rocks reveal vesicle densities greater then 10% show significantly high permeabilities due to the development of inter-vesicular micro-fractures. These tensile micro-fractures are formed when the pressure exertion by the gas or fluid phases within the vesicles exceeds equilibrium and fractures. Such features are prevalent within lava flow tops, where high vesicle densities (average of 40% for South American samples) form a connected system by this mechanism.

The Kettla Member
An overview from the Faroe-Shetland Basin

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The Kettla Member, sometimes referred to as the Kettla or the Andrew tuff, is a geographically wide spread volcaniclastic horizon in the Faroe Shetland Basin. The member has a characteristically low GR response at approximately 25-30 API Units which correlates well throughout the Basin. It is believed to pass northwards, eastwards and southwards into mudstones (Knox et al. 1997).
The source of the Kettla Member is still unproven and this study aims to get a better idea of its provenance areas in order to establish the sedimentary pathways during the early stages of volcanism in the area.
Through literature research, data from composite logs and reports from drillings in quadrants 6004 and 6005 (Judd Basin) from the Faroe area and composite logs from quadrants 204 (Judd Basin), 205, 206 and 214 (Flett Sub-Basin) from the UK area, preliminary results can now be presented.
Focus has primarily been on the Kettla Members thickness variation throughout the Faroe Shetland Basin but also on its composition and the reworked stage of the material.
The preliminary results show that the member is thickest in quadrant 6004 in the Faroe area and in quadrant 205 in the UK area. The thickness of the member in Well 6004/12-1z is 89 meters and consists of varies volcaniclastic lithologies, e.g. coarse and poorly-sorted volcaniclastic sandstones and siltstones. In Well 6004/17-1 the thickness of the Kettla Member is 68.5 meters and comprised of e.g. coarse and well-rounded volcanic sand. In Well 205/9-1 the thickness of the Kettla Member is 56 meters and also comprised of e.g. coarse-grained, pepply tuffaceous sandstones in the lower section. Additionally a “Lower Tuff” has been identified in the two wells 6004/12-1z and 6005/17-1 where the thickness of the “Lower Tuff” is 53 meters and 66.5 meters, respectively. These “tuffs” also share comparable low GR log characteristics and are overall, compositionally similar to the Kettla Member indicating they possible originate from similar sources as the Kettla Member deposits. The three wells above contain coarse material (high energy facies) from an apparently proximal source most likely in the vicinity of the three wells.

Reference: Knox, R W O’B, Holloway, S. Kirby, G A, and Bailey, H E. 1997. *Stratigraphic Nomenclature of the UK North West Margin. 2. Early Palaeogene lilthostratigraphy and sequence stratigraphy*. British Geological Survey, Nottingham.

Volcanism and Exploration in the West of Shetland

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Since the first licence award in the 19th round, DONG E&P have participated in 11 exploration wells in the Faroes and UK part of the West of Shetland Basin and 12 appraisal wells. 8 of the exploration wells have resulted in discoveries - with 6 commercial discoveries in the UK part. Due to this attractive track record, DONG E&P is keen to progress with an ambitious exploration programme in the region and take the lead role as Operator in selected areas. The last decade saw the emergence of large seismic mega-surveys and new well data from released or proprietary wells. This wealth of new data can only lead to a better understanding of the volcanic system in the area.

The first part of the talk will focus on the numerous Paleocene volcanic features identified using regional 3D seismic data in the West of Shetland. These features challenge the accepted understanding that the Faroes-West of Shetland volcanic system is sourced exclusively from the North-West. The second part of the talk will focus on magmatic intrusions and their potential role on hydrocarbon migration through an integrated study of seismic and well data in the Flett Basin.

Several consortiums and projects are leading the study of the West of Shetland volcanic system, resulting in numerous publications and proprietary reports. In order to make the most out of the large quantity of new high quality data in the area, the effort to and collaboration needs be pursued.

Statoil in the Atlantic Margin: From Exploration through Appraisal to Development

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Statoil's activities in the Atlantic Margin cover the full spectrum from true frontier exploration to appraisal and development.
From north to south, in northeast Greenland, Statoil are involved in the Kanumas Group (Statoil, BP, Chevron, ExxonMobil, JOGMEC, Shell and Nunaoil) where frontier exploration is in its emergence. The First Licensing Round, with operatorships exclusive these companies closes in December 2012.
In the Barents Sea Statoil has had production from Snøhvit since 2007, but recent exploration has discovered two excellent finds, Skrugard and Havis with accumulated resources around 500 mmboe and appraisal drilling has already started. These two discoveries demonstrate the reward for perseverance in a moderately explored basin.
Exploration in the Vøring and Møre Basins has not been as successful as the prolific neighbouring Haltenbanken Province but the Luva gas field in Vøring has been given development approval and the giant Ormen Lange gas Field in Møre has been on stream since 2007.
Our activities in the Faroe-Shetland Basin include production at Schiehallion and potential development at Rosebank but in 2012 our key activity is the Brugdan 2 well. This, our third well and Faroes eighth, should spud in July. Although Brugdan 1 successfully drilled through over 2.5km of volcanic rocks, into sediments beneath, the well was terminated in the Paleocene Lamba Formation when the BHA became stuck and a fish could not be retrieved. As a consequence the Vaila Formation play, similar to the Foinaven – Schiehallion play remains to be tested in the Faroe Islands.

The Wyville-Thomson Ridge – The continuing quest to explore the largest undrilled anticline in North West Europe

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The Wyville-Thomson Ridge (WTR) is a 25km wide and 200 km long, WNW-ESE aligned bathymetric ridge that sits in both Faroese and UK waters. Seismic data shows the ridge to comprise a large anticlinal fold, with coaxial reverse faults along its flanks. Paleocene basalts are thought to sub crop the sea bed capping and potentially sealing the structure, whilst early Paleocene and pre-Tertiary clastic sediments are anticipated to form the main reservoir and source components.

Imaging of the base basalt reflector and with it the calculation of the overlaying basalt thickness is therefore of critical importance. A Marine Magneto-Telluric (MMT) survey was acquired by WesternGeco in Oct 2010 to directly detect the highly resistive basalt, and to provide an accurate estimate of its spatial thickness variation. The MMT results were mixed, as acquisition related noise problems hindered the subsequent processing. However the MMT data can be shown to be well fit by a model consistent with that derived from seismic and gravity data (i.e. a thin basalt cap) but with the additional presence of a resistive region at depth beneath the ridge axis. There are also concerns with the slightly eleveated resistivity response below the basalt which may indicate an elarged volcanaclastic section rather than that of a cleaner sand. This observation is something that is now directly supported by an increasing number of wells that have drilled sub-basalt targets in the West of Shetland.

Overall, whilst the MMT supports a thin basalt cap, it also poses serious questions as to the quality of the pre-basalt section. None the less, the fact still remains that the WTR structure is capable of holding many tens of billions of barrels of hydrocarbons, and for this reason it still remains a potentially high reward prospect.

Structural control on the distribution of Eocene progradional units and deep water fans in the NW Faroe-Shetland Basin – implications for hydrocarbon exploration

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In this study the post-basalt strata in the Faroese area have been investigated based on interpretation of 2D and 3D reflection seismic data. The post-basalt package is divided into 5 units which have led to the constructions of 6 structural maps and 5 thickness maps in TWTT. Within the 5 units 12 prograding and basin floor fans (sub-units) have been identified. Based on the interpretation of the seismic profiles and maps it is possible to obtain an overview during time of the location of depocentres and input direction of sub-units as the results of an interplay between uplift, subsidence and compression.

During Cenozoic time sediment input directions and placement of depocentre varies. During Eocene time the influx mostly is from south and southwest where the depocentre is in the central part of the basin. During Oligocene to Pliocene time the sediment input direction is from north and northwest and the depocenter has moved in a westward direction closer to the Faroe Platform area.

However, the actual distribution of sediments appears to be controlled by re-activation of older, Mesozoic, structural elements controlling the sediment path way and restricting the depositional areas. Different elements being re-activated at different times causing considerable structural complexity. Understanding older, Mesozoic, structural elements control on sedimentation is a potential tool understanding deviations from "normal" thermal subsidence and for predicting the prospectivity in post-rift succession in the Faroe-Shetland Basin.

Exploration in the Faroes: Challenges for a smaller company

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Exploring for oil and gas in the Faroe Islands comes with unique challenges for all oil companies. Harsh met-ocean conditions, water depth, basalt thickness, lack of infrastructure, lack of data and lack of significant success all increase the challenge when compared to drilling in the North Sea. For smaller companies, where capital is very tight, this is further increased by high costs and long time-frames for drilling, appraisal and development activities. However, this has the potential to be offset by increased size of the prize in Frontier areas.

In this talk, we compare the experience of exploring and drilling exploration wells in the UKCS to that of the Faroes. Comparisons of costs, timeframes, strategies that have to be employed and the risks that have to be mitigated will be demonstrated using recent examples form Atlantic Petroleum's portfolio.

An opportunity and a discovery on the Faroese Continental Shelf

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The Faroese Continental Shelf is a frontier area in hydrocarbon exploration terms, with the first well drilled 11 years ago and to date only seven wells are drilled. Discoveries have been made, but none of them obviously commercial. There is however, still interest from the exploration community, partly because the high impact opportunities that are identified, and partly because of recent successes near the Faroes-UK boundary.

The driving force for exploration on the Faroese Continental Shelf are the large traps, that in a best case scenario can contain several billions barrels of oil equivalents. One such example is the Ymir Ridge southwest of the Faroe Islands. This lead does capture the concept of high risk high reward, with the reward being in a very conservative case billions of barrels, while the risks include lack of knowledge of the presence and maturity of the source rock and presence and quality of reservoir. Exploration to date has, however, yielded some interesting results. The most notable is the Marjun Discovery. Well 6004/16-1Z struck light oil at a total depth of 4058.8 m at a waterdepth of 974.5 m. The well penetrated an extended hydrocarbon bearing column. The reservoir quality did indicate that the maximum burial was about 1 km more than present day depth, which had led to a lower porosity compared to what was expected at its current dept. Permeability was also low, which was linked to an expected warm water circulation associated with the intrusion of basaltic sills. The reservoir parameters coupled with problems regarding understanding of the trapping mechanism resulted in the discovery being relinquished.

New analyses of data from the discovery well, indicates that the permeability is better than the initial results showed, up to 100 mD in places. The n/g is about 50%, with average porosity of 10,9% and the average permeability is 8,2 mD. This analyses also suggests that the well did not reach the OWC. These numbers combined with a Pmean about 300 Mbbl's STOIIP, and the fact that the discovery well found light oil does suggest that it is time to take a closer look at this discovery.

Poster Presentations

Abstracts

The posters will be on display throughout the whole of the conference

Lava geochemistry as a potential aid to predictive stratigraphy offshore

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Geochemical analyses of the volcanics within the onshore successions of the North Atlantic Igneous Province (NAIP) are widespread and comprise high quality analyses commonly covering the complete stratigraphy of a given area. Within the volcanic pile of the Faroe Islands, situated centrally in the NAIP, distinct geochemical trends along with geochemical 'events' are observed which can in some cases be correlated to other onshore volcanic sequences of the NAIP. Using the geochemical stratigraphy observed on the Faroe Islands as an index section for the NAIP volcanics in the Faroe-Shetland Basin we propose the viability of attaining geochemical data sets of sufficient quality as to allow improved stratigraphic resolution and correlation within the offshore setting. The integration of geochemical volcanic stratigraphy data with the already well constrained biostratigraphic framework for the Palaeogene evolution of the Faroe-Shetland Basin may provide a highly valuable line of evidence not yet readily available to prospective hydrocarbon exploration targets to the S and E of the Faroe Islands.

Faroe Islands Passive Seismic Experiment (FIPSE) data characteristics and preliminary results

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The Faroe Islands Passive Seismic Experiment (FIPSE) is a 2-year (May 2011-2013) SIndri-funded project that will collect global teleseismic earthquake and other passive seismic data to image variations in crustal layer thickness and velocity beneath the Faroe Islands. Initially using the receiver function method, we will focus on imaging: i) the uppermost ~10 km to investigate basement thickness variations and identify P-to-S converted energy that adds constraints to basalt thickness and the presence of sediments beneath the basalt; and ii) imaging the Moho discontinuity to provide three-dimensional variations in crustal thickness and bulk velocity, together with the identification and classification of high-velocity lower crustal layers.
Twelve Güralp CMG-ESPD broadband (60 sec – 50 Hz) seismometers were installed across the Faroe Islands in June 2011 and will continue to record passive seismic data continuously until October 2012. Thus far, the data from the period June 2011 to February 2012 have been downloaded and analysed. In addition to a review of the data characteristics, we present preliminary results in the form of crustal thickness variations and identification of the major acoustic impedance boundaries in the uppermost 10 km of the Faroese crust.

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Improved understanding of basaltic terrains using regional seismic investigations

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The Natural Environment Research Council's (NERC) Geophysical Equipment Facility (GEF) provides equipment suitable for onshore and offshore based geophysical research. All equipment is available free-of-charge to institutions engaged in research within the NERC remit. The 2 seismic nodes of GEF are: (1) SEIS-UK, based within the University of Leicester which maintains a pool of onshore seismic instrumentation for both active and passive sources; (2) OBIF at the Universities of Durham and Southampton which supports offshore seismics and EM.
SEIS-UK has provided instrumentation for a number of projects in the Faroes and similar basaltic terrains. For example, receiver function analysis by Cambridge University of data from a previous deployment of 45 seismometers around the Glyvursnes-1 well indicated a crustal thickness of 29-30 km and the presence of a high velocity lower crust (Harland and White, 2003). Currently, SEIS-UK is supporting 12 broadband sensors deployed by Leeds University throughout the Faroes aimed at delineating detailed crustal structure, thickness and velocity variation.
Other relevant SEIS-UK projects include: Understanding the development of the Afar rift, magmatic emplacement in central Iceland, basin structure and development in central Europe and uplift mechanisms and controls in Norway. A number of combined onshore-offshore experiments have been supported including a large (150 station/ 6,500 shots) tomographic imaging study of Tenerife. Data from a number of experiments have also subsequently been used in noise interferometry studies.

Geochemistry of basalts from the Continental Margin North of the Faroe Islands results from wells 336 and 337 from DSDP leg 38

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The new geochemical data described in this paper are from the Deep Sea Drilling Project (DSDP) leg 38, sites 336 (northern slope of the Faroe-Iceland Ridge) and 337 (eastern shoulder of the Ægir Ridge), respectively (Figur. 1). Core samples of the basaltic lava sequence from both sites were analyzed for major and trace elements and Sr, Nd and high precision Pb isotopic composition.
The geological settings for these two sites are very contrasting. The Faroe-Iceland Ridge (FIR) is characterized as the bathymetric expression of the time transgressive "hotspot track" formed symmetrically with respect to Iceland and consists of anomalously thick (ca. 30km) oceanic crust. Together with the more classical spreading ridge setting at the Ægir Ridge these data give an opportunity to estimate the various mantle sources feeding the lavas in this submarine region. Initial K-Ar dating of the basalts yielded ages from 18-24 Ma for site 337 and 40-43 Ma [1].
The existence of continental crust beneath the Faroe Islands has also been evidenced geochemically by high $^{86}Sr/^{87}Sr$ values (0,7100 – 0,7163), enrichment in *incompatible elements* in the High-Si lavas [2] and further addressed by using the late dykes and lavas onshore Faroe Island [3, 4] and the High-Ti lava types [4].
The new isotope data from sites 336 and 337 indicate that a similar source component for both sites, which is markedly different than what is seen in the Iceland, Faroe Island and Jan Mayen basalts. Furthermore, the data also show similarities with Øræfajøkull on Iceland. These trends are explained as a mixing with a local enriched component, reflecting the addition of small amounts (0,5%) of pelagic sediments [5], and as a EM2 type component [6]. This indicates a larger lateral extent of this mantle component.
Crustal contamination could explain some of the variations seen in the 336, samples 12 and 13. These are enriched in LILE elements, have relatively high $^{86}Sr/^{87}Sr$ ratios, SiO_2.

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"The northern Faroe Platform: Transition from plateau basalt to oceanic crust illustrated by conventional reflection seismic data"

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2D reflection seismic profiles north of the Faroe Islands have been used for seismic interpretation, using seismic volcanostratigraphy with main emphasis on Seaward Dipping Reflectors (SDRs). SDRs are found all over the world at passive volcanic margins, and several models have been put forward as to how these SDRs were formed.

There is a general agreement among the models suggested that the area containing SDRs consists of four zones which are: *Zone I* – Outer SDRs; *Zone II* – Outer High; *Zone III* – Inner SDRs and *Zone IV* – Landward Flows. All four zones have been observed on the seismic profiles used in this study and it can be concluded that the SDRs have a south to north trend; which is consistent with previous work done.

The interpretation gives an indication of where the continental oceanic transition zone lies and how it ties in with the magnetic anomalies in the area.

Lithology and composition of the basement offshore Faroe Islands

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Boreholes south of the Faroe Islands and exposures on the Shetland Islands provide samples of sub-basalt basement. We characterise the lithologies and composition of these basement samples (n=38), in order to provide an understanding of occurrence and origin of the offshore Faroese basement. Petrographic descriptions of basement samples are presented, along with major and trace element geochemistry and preliminary Pb isotope data to characterise and identify geochemical tools for discrimination between basement types.
The basement samples can be divided into five groups; metasediments, granites to granodiorites, schist, gneiss and amphibolite. Protoliths of metamorphic lithologies vary from sandstone to pelagic sediments with minor carbonate components. The granites to granodiorites are peraluminous, heterogeneous, especially in LILE compositions and show distinctly high La/Th and Sr/La ratios. The amphibolite basement sample has low LILE and conspicuously high Ca content. The schists and gneisses have uniform trace element compositions with high contents of LILE, whereas the metasedimentary rocks have highly variable trace element compositions. Preliminary Pb isotope data for the granites and granodiorites display low $^{206}Pb/^{204}Pb$ of 14.1 to 17.1, and slightly positive Δ8/4.
Systematic characterisation of available basement lithologies from drill cores will help to unravel the source of the continental crust and potential provenance of overlying sediments as well as the distribution of the sub-Faroe Island basement. Geochemical mapping of the sub-basalt crust will facilitate calibration of end-member compositions that are involved in magma-crust interaction. This will help connect the magmatic records to distinct basement lithologies.

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Source rocks, oils and gases in the Faroes - West of Shetland Region; a new study supporting an improved petroleum systems interpretation.

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This study is based on a high quality unified data set of newly analysed flowed oils, proxy oils extracted from cores and cuttings and source rocks. The work programme has included full geochemical characterisation including high resolution biomarker studies on oils, proxy oils and source rocks. The study database comprises: 32 flowed oils from 28 wells, 330 rock samples reviewed and where feasible, analysed for hydrocarbons or source potential and 45 gas analyses. All chemical work has been carried out in the APT AS laboratories in Kjeller, Norway. Kerogen maturity and description work has been undertaken in-house on around 65 samples. Large amounts of legacy geochemical and maturity data have been accessed

The results have been incorporated into a new petroleum systems framework. Key deliverables are:

- A new comprehensive stratigraphic review and database created for around 165 wells;
- Comprehensive and consistent new analyses;
- GIS database;
- Evaluation of the basin history especially the Tertiary history of subsidence and uplift;
- Creation of a new present day geothermal database for ca. 160 wells;
- Thermal modelling using the Genesis programme for numerous calibration and pseudo wells identified from the seismic maps in undrilled locations utilising 4 TWT surface maps derived from the PGS Mega Merge data set.

The study has addressed:

- Characterisation of source rocks and which sources have generated the oils and shows encountered so far.
- The limits of variation in the fluids found have been established.
- The generation temperatures of the fluids found to date.
- The polyphase history of migration, emplacement and degradation and controls on these processes.
- The present and past heat flow history of the basin and consequences for maturation and preservation of hydrocarbons.
- The controls on basin subsidence and inversion.
- Modern thermal conditions in the depocentres and the implications for the current viability of the petroleum system.

The Future

- There is much still to learn about this under-explored petroleum province;
- Incorporation of the results of this study may well have significant impact on realising future petroleum potential of the area.

This study has been sponsored and actively assisted by BP including access to pre-existing reports, samples, logs and reports. Additional support has been provided by PGS who have allowed the project to utilise 2 way time surface data from the MegaMerge™ dataset. This assistance is gratefully acknowledged.