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Conference Abstracts

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The Kangerlussuaq Basin, SE Greenland - Stratigraphy and depositional evolution of a sub-basaltic basin. Results from a SINDRI project

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The Cretaceous–Paleogene succession of the Kangerlussuaq Basin in southern East Greenland was studied as part of the SINDRI research theme: "Future Exploration Issues Programme of the Faroese Continental Shelf" established by the Faroese Ministry of Petroleum and financed by the partners of the SINDRI Group.

The basin exposes an approximately 1 km thick sedimentary succession below Paleogene flood basalts. The sediments are of Late Barremian to Early Eocene age and were deposited on the western margin of a seaway running between Greenland and the Faroes/UK. Plate reconstructions of the North Atlantic region thus indicate the former proximity of Greenland to the Faroe Islands and the Kangerlussuaq Basin probably constitutes the most important regional field analogue with regards to biostratigraphy, sequence stratigraphy and general basin evolution.

The sedimentary succession records a long history of basin evolution starting with marine transgression of the crystalline basement in the Early Cretaceous (latest Barremian), shallow marine deposition into the Late Cretaceous, rifting and deep marine deposition in the latest Cretaceous to early Paleocene, rapid uplift and fluvial erosion in the Late Paleocene and onset of volcanism in the latest Paleocene to Early Eocene.

Palynological event stratigraphy correlated with ammonite and bivalves datings indicate presence of major unconformities (sequence boundaries) in the Santonian–Early Campanian, Late Maastrichtian–Early Paleocene and mid-Paleocene. These unconformities are thought to be related to falls in relative sea-level and possibly be used to predict times of sediment input from the west to the Faroe-Shetland region. The stratigraphy study and the SINDRI field work in southern East Greenland have been linked to other SINDRI studies including studies on potential source rocks and sediment provenance.

The Greenland analogue studies should help improve our understanding of sub-basaltic basins found along the margins of the North Atlantic and may eventually lower the risk on existing plays and/or lead to the discovery of new plays in deep offshore areas.

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Biostratigraphy zonation (palynology) for the Upper Cretaceous – Lower Palaeogene based on the sedimentary succession in Kangerlussuaq, southern East Greenland

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Data gathered in the ongoing Sindri stratigraphy project have shown that the Upper Cretaceous – Lower Palaeogene succession of the northern North Atlantic still presents problems for biostratigraphic correlation. The main reasons for the apparent correlation problems are the extensive erosion occurring at the K/T boundary at basin margins, poor preservation of palynomorphs due to intense thermal heating by Palaeogene intrusions and extensive reworking of Upper Cretaceous strata. The study aims to investigate the correlation problems for the Upper Cretaceous – Lower Palaeogene succession in the northern North Atlantic (West and East Greenland – Faroes – UK) based on biostratgraphic framework established in onshore sections. This is accomplished by analysis of a large number of mudstones and macrofossils from the Kangerlussuaq Basin in southern East Greenland. The results of the study are important for dating and correlation of the new wells drilled in Faroese waters and for predicting volcanic influence on basin evolution and reservoir properties in the Early Paleocene.

Based on new sampling of a number of key sections across the K/T boundary in the Kangerlussuaq Basin a revised palyno-stratigraphy based on events is proposed for the Upper Cretaceous – Lower Palaeogene succession. The results are in good agreement with the collected macrofossils and indicate that strata of Turonian, Coniacian, Maastrichtian, Late Danian and Selandian age are found in the basin. The Santonian, Campanian and the uppermost Maastrichtian, however appears to be unrepresented and like most places around the Northern North Atlantic the K/T boundary is represented by a major unconformity.

Chemostratigraphy and chemical characteristics of Cretaceous-Paleocene-Eocene sandstones and mudstones in the Kangerlussuaq area, East Greenland, and in the Faroe-Shetland basin

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A total of 440 samples representing Cretaceous, Paleocene and Eocene clastic sediments have been analysed for 10 major elements, 33 trace elements and loss on ignition. Of these, 269 samples represent washed and dried cuttings from wells in the Faroe-Shetland Basin, whereas 171 samples represent rocks collected in the Kangerlussuaq area in East Greenland. The approach of analysing a very high number of samples for a very high number of elements with very high sensitivity allows for a novel interpretation of the geology in the potential reservoirs. Conventional provenance analysis is focussed on analysis of heavy minerals which only constitute a small fraction of the sediments, whereas bulk rock geochemical analysis allows evaluation and interpretation of the effects of the complete mineralogical composition of the sediment. Accordingly, the effects of e.g. feldspars and clay minerals, as well as heavy minerals such as zircon, can be evaluated. Further, carbonate cementation and redox conditions in the depositional environment can be investigated.

In general, it is found that the sedimentary units have distinctive geochemical characteristics. Common sources can be detected for different units as well as internally within units, both vertically and laterally. To achieve this, no single or few parameters can be used but it is necessary to consider the complete dataset. The advantage is that it is possible to generate and interpret such large datasets at fairly low cost due to the new analytical techniques now available. There is no evidence for a common source shared by the sediments from the Kangerlussuaq and the Faroe-Shetland areas. This is in line with the findings of the zircon dating provenance study reported by Frei et al. (this conference).

Sediments containing a component of reworked volcanic material can be recognised geochemically by high Ti/Al, Nb/Zr and Eu/Ce ratios. In the Kangerlussuaq area, this effect is seen in the Kulhøje and Willow Pass Members and partly in the Schjelderup Mb. However, it has also been possible to trace the effect of the remote volcanic activity in the basin on the Ti/Al ratio in the mudstones in the Faroe-Shetland basin: this ratio increases gradually with time during the opening of the North Atlantic Ocean. A similar effect is seen in the Yb/La ratios that increase with time, reflecting an increasing volcanic input and decreasing continental character of the mud component.

Sands containing high proportions of heavy minerals such as zircon can be recognised on their high Zr/Al and low Nb/Zr ratios. This is the case for some but not all of the sands in the Fairy Tale Valley Mb in the Kangerlussuaq area. Further, the relationship beween eg. U and Zr is characteristic of a sediment with high heavy mineral content. As heavy minerals are concentrated in beach placers this may have implications for the interpretation of the depositional environment. In the Fairy Tale Valley Mb of the Kangerlussuaq area, there is a lateral variation in the source of the mudstones, seen as variation in eg. the Ti/Al and the K/Al ratios among the different profiles sampled.
In the Faroe-Shetland basin, large variations in source among the different units have been found. One example is the Vaila Fm in well 205/9-1, which due to high Eu/Ce ratios can be separated from the other units. In the Vaila Fm, certain parts contain dolomite cement (3 to 8 wt %), whereas parts of the Sullom Fm and one sample from the Maastrictian "Formation E" contain calcite cement. This can be seen by combining information about the Ca, Mg, Al and volatile contents.

Geochemistry of Hydrocarbons in the Cretaceous-Tertiary of the Kangerlussuaq Basin, SE Greenland: Implications for plays offshore Faroe Islands

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Lower Cretaceous sandstones sampled from the Kangerlussuaq Basin, SE Greenland, contain a large number of hydrocarbon-filled fluid inclusions indicating that hydrocarbon generation and migration has occurred within the basin. Hydrocarbon fluid inclusions were found in bituminous sandstones of the Watkins Fjord Formation at five widely spaced localities. They are also found in injected sandstones at one locality. The hydrocarbon fluid inclusions can be divided into those with green fluorescence and those with predominantly blue fluorescence. The two populations represent oils at different temperatures and stages of diagenetic evolution. The green-fluorescing hydrocarbon inclusions are one-phase (liquid-filled) at room temperature indicating that they were entrapped at low temperatures (<~50°C). These inclusions only occur within trails in detrital quartz grains that predate quartz and calcite cementation. The blue-fluorescing hydrocarbon fluid inclusions are two-phase (liquid and vapour filled) at room temperature and were entrapped at temperatures of 100-180°C. These inclusions occur within trails that cut quartz and calcite cements, indicating that they were entrapped after cementation.

Rock-Eval screening analysis (80 mudstone and 9 sandstones of Late Aptian to Late Paleocene/earliest Eocene ages) reveals that most of the succession is of post-oil window/gas condensate maturity and generally contains a low total organic content (TOC). This reflects the deep burial and the strong volcanic influence on the basin during Late Paleocene/earliest Eocene times. The occurrence of mid-Albian estuarine/marine mudstones (Suunigajik Member) with high TOC values (up to 14%) at several localities across the basin, however, suggests that this member may once have formed a potential source rock. Biomarker analyses on selected mudstone samples suggest the presence of organic material from both marine and terrestrial sources at different levels of thermal maturity.

Biomarker and molecular marker data from oil extracted from pores and hydrocarbon-filled fluid inclusions reveal that the oil is predominantly of late to post-oil window thermal maturity. The thermal maturity indicates the presence of an exhumed palaeo-gas condensate play in the Kangerlussuaq Basin. The high temperature that these samples have been exposed to has removed, or altered most of the biomarkers that would normally be used for the purposes of oil-oil and oil-source correlation. Despite this, the presence of selected molecular markers suggests a compositional similarity between the majority of the hydrocarbon fluid inclusion-bearing sandstones and the mid-Albian mudstones of the Suunigajik Member. Therefore, it is probable that the organic matter in this mudstone and the petroleum in the hydrocarbon fluid inclusion-bearing sandstones are genetically related.

These data are encouraging for exploration of sub-Paleocene plays offshore Faroe Islands, especially where the thermal history was not severe.

Petroleum Systems in the Greater Faroese Region: An Oil - Source Correlation Study

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In order to provide geochemical data and interpretational input to further understand the Faroe - Shetland hydrocarbon system, a joint organic-geochemical research project under the auspices of the Sindri Group was initiated in 2005. The source rock analyses / data included comprise those from both 1) source rock units within the area from wells and shallow boreholes drilled in the UK sector and 2) source rock units around the margins of the area, from wells and onshore outcrops both in Scotland/ the northernmost North Sea and East Greenland. The migrated hydrocarbon analyses / data comprise 1) those from shows and oils in wells of UK- and Faroe sector wells, 2) from samples onshore the Faroe Islands and 3) from offshore seeps in the Faroe-Shetland Basin. The data thus gathered has been collated in two 'databases' as one of the main aims of the program. The data from GC, GC-MS (SIR) of saturated and aromatic fractions, GC-MS-MS (age-related biomarkers), bulk C isotope and porphyrin analyses has been used to correlate between the samples of source rocks and migrated hydrocarbons. Maturity data in the form of vitrinite reflectance data, SCI and biomarker maturity parameters have also been included in the interpretations of the petroleum system. The source rock units included range from being highly immature to at least peak oil mature.

Source rock units of Devonian to Cretaceous age have been included in the study, with the bulk of the analyses however being of Upper Jurassic-Lower Cretaceous age (i.e. representing the KCF or its equivalents). This is a reflection of several factors, the most important being a) that this formation has the most consistently high source potential in the region, and b) due to 'sampling bias', at least for the wells, since the bulk of the known hydrocarbon-bearing reservoirs are relatively shallow in the Faroe-Shetland region, and there is a paucity of wells that penetrate below the M.Jurassic. The abundance of U.Jurassic samples however does allow better possibilities of studying facies variations within the KCF. Regarding source potential in general, apart from the KCF, good source rock potential is shown by units of Lower and Middle Jurassic, Carboniferous and Devonian ages on the eastern Atlantic margin, and by units of these ages plus Permian and Triassic units in East Greenland. No higher Cretaceous units, as e.g. have been identified to the north east along strike, offshore Norway in the Møre Basin, appear to have any significant source potential in the study area.

In terms of bulk composition, the migrated hydrocarbons of the study vary from condensate range hydrocarbons through to heavy oils, and with variable degrees of biodegradation. In order for comparison, a selection of progressively degraded oils from the northernmost N.Sea (Gullfaks) has been included. For sourcing comparisons, apart from the latter, a selection of oils/shows was also included from the Moray Firth area, which are by now generally accepted to have been at least partly sourced by a non-KCF (?Devonian) source with lacustrine character. Wherever possible, the detrimental effects of any artefact hydrocarbons (from drill mud systems) present have been taken into account in looking at the migrated hydrocarbons.

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Constraints on provenance of Paleocene-Eocene sandstones in the Faroe-Shetland Basin from high-resolution detrital zircon stratigraphy

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One of the most important questions for hydrocarbon exploration in the Faroe region is the understanding of sediment dispersal patterns and depositional systems in the Faroe-Shetland Basin prior to continental break up in the Late Paleocene to Eocene. A powerful tool for tackling these questions is detrital zircon analysis. Detrital zircon analyses uses the interpreted provenance of zircon (usually derived from the age information recorded in zircon) to unravel the geological history of sedimentary basins and their surrounding areas. Here, we present the results of a study that investigated the systematics of detrital zircon age distributions in sandstones from East Greenland and the UK sector of the Faroe-Shetland Basin with hitherto unprecedented detail (Frei et al., 2005). In total, we have analysed the ^{207}Pb-^{206}Pb ages of 4347 detrital zircons by means of LA-Q-ICP-MS (Frei et al., 2005). Detrital zircons were separated and analysed from 25 samples from East Greenland (2321 zircons), and 20 samples from wells in the UK sector of the Faroe-Shetland Basin (1832 zircons).

The observed detrital zircon age distributions in samples from the Kangerlussuaq Basin unequivocally demonstrate that the sedimentary successions are derived from two distinct sources, the first being Archaean basement situated to the south and southwest, and the second being younger, Proterozoic rocks situated to the north and northeast. Furthermore, the zircon age distributions allow tight constraints to be placed on the timing of changes in sediment supply, to validate the stratigraphic correlations drawn from litho- and sequence stratigraphy, and to exclude large-scale local reworking of sedimentary units in the Kangerlussuaq Basin. However, the most important feature of the zircon age distributions in sandstones from the Kangerlussuaq Basin is the general presence of a characteristic Middle Archaean age component. In marked contrast, this distinctive age component is almost completely absent from detrital zircon age distributions in samples from wells in the UK sector of the Faroe-Shetland Basin.

This difference in detrital zircon age signatures allows distinction between a western, Greenlandic source and an eastern, predominantly UK margin source. The influence from a western source (Greenland) has not been proved in the examined stratigraphic intervals of wells from the UK sector of the Faroe-Shetland Basin. However, the structure of the Faroe-Shetland Basin suggests that the western, Greenlandic source might be much more important for the deeper, central parts of the basin towards the Faroes area.

References:

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A cost-saving technique for high precision U-Pb age dating of detrital zircons

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Analysis of the crystallisation ages of detrital zircon grains in clastic sediments is a powerful tool in sedimentary provenance studies. Zircon is very resistant to physical and chemical alteration, and U-Pb dating of detrital zircons can therefore yield the age of their sources, even after metamorphism and deformation. Previous studies have demonstrated that accurate and precise U-Pb ages of > 100 zircon grains in a sample are sufficient to detect all major sedimentary source components with statistical confidence. Achieving these large numbers of individual analysis needed in provenance studies by isotope dilution thermal ionisation mass spectrometry (ID-TIMS; the currently most precise and accurate zircon U-Pb age dating technique) is prohibitively expensive. Therefore, U-Pb age dating of detrital zircons is generally the domain of ion microprobe techniques (SHRIMP or SIMS), where relatively rapid *in situ* analysis can be achieved. The major limitations of these techniques are sample throughput (about 75 zircon age dates per 24 hours), the very high purchasing and operating costs of the equipment and the need for highly specialised personnel, resulting in high cost. These high costs usually impose uncomfortable restrictions on the number of samples that can be analysed in a provenance study.

The potential of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for rapid *in situ* U-Pb geochronology was already realised in the early to mid 1990s. The viability of LA-ICP-MS for U-Pb dating of detrital zircons was recently demonstrated by Košler et al. (2002) and Frei et al. (2005). Here, we present a technique for U-Pb dating of detrital zircons by laser ablation magnetic sectorfield inductively coupled plasma mass spectrometry (LA-SF-ICP-MS). This technique takes advantage of recent advances in laser technology and the introduction of magnetic sectorfield ICP-MS instruments (SF-ICP-MS). Based on a ThermoFinnigan Element2 magnetic sectorfield ICP-MS combined with a New Wave UP 213 laser ablation system, these techniques allows U-Pb dating of detrital zircon grains with precision, accuracy and spatial resolution comparable to SHRIMP or SIMS. Because an individual analysis is carried out in less than 2 minutes and all data is acquired in pre-set mode with only minimal operator presence, the sample throughput is an order of magnitude higher (> 700 analysis per 24 hours) compared to SHRIMP or SIMS. Furthermore, LA-SF-ICP-MS uses simpler and more robust equipment and the purchasing and operating costs are only a fraction of the costs of SHRIMP and SIMS. We therefore conclude that U-Pb dating by LA-SF-ICP-MS is the cost-saving technique of the future for advanced provenance studies using geochronology of detrital zircons.

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Impact of sill emplacement on sandstones in the Northern Atlantic region

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The Faroe-Shetland Basin sedimentary successions have been extensively intruded by sills. The affect of sill emplacement in potential sandstone reservoirs is generally under-investigated and the magnitude of the impact, especially in porosity and permeability, is unknown. Previous studies indicate a degradation of porosity and permeability as a result of fluid-rock interaction associated with diagenesis, contact thermal effects and hydrothermal activity.
The current study on contact-sandstones from East Greenland (Trail Ø) and Scotland (Skye) revealed that the impact magnitude on sandstones highly depends on (1) the temperature of sill during the intrusion; (2) detrital composition and thickness of the sandstone and (3) the scale of the fluid-rock interaction. The temperature of the sill during intrusion and temperatures reached in the adjacent sandstone can be determined using vitrinite reflectance. Vitrinite reflectance measurements from East Greenland indicate sill temperatures ~1000°C (5.9%Ro) while the Scotland samples indicate temperatures ~500°C (2.85%Ro). The detrital composition of both sample sets comprises mainly quartz with minor feldspar and clay. However, the East Greenland samples are thin turbiditic sandstones (Cretaceous) within thick mudstone units, while the Scotland samples are lagoonal sandstones (Jurassic) partly interlayered with thin limestones. Both sample areas were buried up to ~600m before sill emplacement and show early diagenetic features such as clay coating, feldspar dissolution and pyrite precipitation. The scale of fluid circulation during sill emplacement probably varied immensely between the different sample areas. The study shows that the East Greenland sandstones experienced major mechanical and chemical compaction, large scale fracturing and fluid-rock interaction leading to a diagenetic assemblage of laumontite, sphene, pseudomorphs after cordierite and major albitization. The contact-sandstones in East Greenland with maximum burial depth of 600m represent a diagenetic parasequence typically found in rocks buried up to 7000m and temperatures above 200°C. The Scotland samples also experienced major mechanical compaction but diagenetic alteration is limited to enhanced quartz overgrowth and calcite cementation near limestone stringers.
The data presented here show a wide spectrum of temperature-dependent diagenetic mineralogy but inevitably resulting in primary porosity and permeability loss. However, the biggest impact on porosity and permeability of contact-sandstones is mechanical compaction. Samples of unaffected sandstones in far proximity to the contact have porosities of 25-30% (permeability ~200mD) while contact-sandstones have porosities of 3-7% (permeability ~0.3mD). The contact zone of the sill intrusion varies from a few centimetres up to several metres depending on the detrital mineralogy, fluid-rock interaction and temperature of sill during the intrusion. Finally, a general prediction of the impact on reservoir quality of sandstones outside a contact zone can not be made as this is strongly dependent on the properties of the contact-sandstone.

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The potential of legacy data and constrained models to determine optimum acquisition parameter for sub-basalt exploration.

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Introduction

Exploration of the Faroes shelf for hydrocarbons has been ongoing for over 30 years. It was soon evident that seismic reflection methods perfected in the North Sea and elsewhere were not going to provide a complete image of the basin structures in areas were there is a layer of extrusive basalt. In an attempt to obtain more robust information about the sediment sequences beneath the basalt layer ever more exotic and expensive acquisition methods were tested. At the same time ever more ambitious processing and inversion methods were developed. Despite this onslaught of technology a robust image of the sub-basalt sedimentary structure remained elusive. This SINDRI funded project had two principal aims:

1) to rigorously test existing data to identify causes of poor imaging and recommend optimum acquisition methods;
2) through using constrained models identify best practice for data processing and inversion. Also quantify uncertainty in the methods and impact on risk.

Results

Seismic reflection – as is well known, we confirm the use of sources rich in low frequencies, however, we note a caviat that this reduces resolution and, for the case of refraction data, increases the uncertainty in the velocity model (see below). The principal issues for processing was the suppression of multiple energy, the use of appropriate deconvolution operators that retain the low frequency energy but compress the effective wavelet and exploiting longer offset data (typically <12km).

Seismic refraction – this is widely used to provide an independent velocity map. However, the method is not best suited to quantifying low velocity layers sandwiched between higher velocity basalt and basement. By using the Metropolis method we show that provided there is sufficient frequency content to enable accurate and unique phase identification then tomography can recover useful information about the whole model including the low velocity layer. Care must be taken to fully understand the selected tomography code as model parameterisation has a stong effect on the final result.

Potential field – on their own potential methods provide no unique solutions, but combined with some additional information then these data can be used to identify possible sedimentary basins. As more data is collected and parameters are constrained better then potential field data can become a significant constraint on feasible models.

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Joint inversion: the way forward

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We have developed a joint inversion strategy for combining seismic refraction, gravity and MT. These data types are ideally suited for this purpose as they have similar resolutions also they measure three quantities (velocity, density and resistivity) that can be related through rock physics. For sub-basalt exploration the three methods complement each other so that a unique constrained model can be obtained. The seismic data gives a robust model for the supra-basalt sediments; whilst the gravity field is dominated by the bathymetry, the high density basalt and basement features; and the MT is sensitive to the conductivity in both the supra- and sub-basalt sediments. The method has been developed with 3-D capability though current tests only use 2-D synthetic and real data. The results show that the method is both robust and converges quickly to the optimum result. However, there are issues which need to be explored to fully test the algorithm and improve its performance.

The raw gravity field is complex and contains information on both regional and local structure. To date we have used satellite gravity measurements which, because of the distance, does not adequately resolve small scale features and also requires the definition of a compensation layer to remove regional effects. To address this problem we will integrate Full Tensor Gravity (FTG) measurements that can be used to compute the full gravity field but in particular are sensitive to shallow lateral density variations of the subsurface, because of their higher spatial resolution. Furthermore FTG data is less effected by chosen compensation depth in the model.

In addition to the first arrival times we will use velocity information from reflection data in our joint inversion scheme. Such information will increase the resolution of the velocity field in the supra-basalt layers where first arrival tomography can only provide limited constraints. This improvement in the velocity model will aid estimation of the other physical parameters in the sediments. We will test both stereo-tomography and a CRS-stack based tomography which has been developed to obtain the subsurface velocities from pre-stack seismic data. An advantage of these two methods, in contrast to other approaches, is that only locally coherent events are considered so that interfaces need not to be defined and, accordingly, time-consuming picking along continuous events is not required. This also will allow disjoint reflections occasionally observed sub-basalt to provide extra constraint to the inversion scheme deeper in the model.

Lastly, we will develop a multi-threaded Metropolis algorithm so we can test the accuracy and resolution of the model caused by errors in picking data and uncertainty in the relationships in the physical properties. By initiating a number of parallel random walks, the time taken to fully explore the local parameter space is significantly reduced.

We think that an implementation of such methods in our joint-inversion algorithm will supply very important additional information for the sub-basalt problem. By improving the definition of the supra-basalt structure, and by including extra information in the basalt and sub-basalt regions. Also the formal mapping of errors from the data space to the model space will help build confidence in the final models.

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Effect of burial on in situ properties of flood basalt successions in the Faroe-Shetland Region

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Early Cenozoic flood basalts are found throughout most of the Faroe-Shetland region. We have investigated burial related variation of logged properties using data from eight exploration wells where the flood basalts apparently are at their maximum burial depth. The basalt successions represent basalts buried to depths varying from ca. 1100 to 3500 m. In addition, burial related variations of logged properties have been studied in the Lopra-1/1A well drilled into the Lower Basalt Series, Faeroe Islands. The basalt in this well represents the depth interval 200-2489 m below sea-level. Overall neutron porosity decreases with depth while seismic P-wave velocity and density increase. In the Lopra-1/1A well, also seismic S-wave velocity is recorded and increases with depth. Using all data from the eight offshore wells, crude trends are established representing porosity reduction and seismic velocity and density increase as functions of burial depth. The variation around the general trend is large and related to lithology[1]. Trends specific to the individual lithologies are thus better suited for predicting property changes with depth.

Overall porosity reduction, velocity and density increase with depth is also observed in the Lopra-1/1A well. The trend from Lopra-1/1A is offset towards lower porosities and higher velocities and densities relatively to the offshore wells. However, Lopra-1/1A is not at its maximum burial depth. It is thus suggested that the depth dependent change of the porosity related properties is mainly due to porosity reduction during burial and that the offset of the trends observed in Lopra-1/1A is caused by denudation of the basalt succession at Lopra.

This study was funded by the Sindri Group (oil companies with exploration licences in the Faroese sector).

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[1] Andersen, M.S. & Boldreel, L.O. and the SeiFaBa group, 2006. Lithological analysis of wireline logs through flood basalts in 8 explorations wells in the Faroe-Shetland Region, **This volume**.

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Integration of wire-line log and core data from Glyvursnes-1 and Vestmanna-1, Faroe Islands

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The Glyvursnes-1 and Vestmanna-1 boreholes form part of the Sindri project called 'SeiFaBa', which purpose was to examine the seismic properties of basalts by combining seismic experiments carried out around the two boreholes with studies of wire-line logs and cores. Results from the latter studies are presented here. The 700-m Glyvursnes-1 borehole was drilled in 2002 at the tip of the flat Glyvursnes peninsula near Tórshavn with wire-line coring technique (recovery >99.9%). The 3-inch diameter borehole was located such that it could serve as a focal point of seismic experiments at both land and sea. The 660-m Vestmanna-1 well was drilled in 1980 with the same technique 30 km farther north as part of the Faroes Deep Drilling Project. It was reamed (cleaned) in 2002 removing thick deposits of tufa to a final depth of 590 m. After drilling, both holes were wire-line logged with eight different slim-hole tools including optical televiewer, caliper, formation density, dual neutron porosity, focussed electric, full-wave sonic, spectral gamma and temperature/ conductivity. The logs were run one by one mounted with a gamma-ray unit for depth correlation.

Glyvursnes-1 starts in the lower part of the Upper Basalt Formation (UBF) and extends 345 m into the 1.4 km thick Middle Basalt Formation (MBF). The formation boundary is characterised by a 0.78-m tuffaceous bed overlain by a 9-m low-Ti basalt flow forming part of the so-called C-horizon. The old Vestmanna-1 borehole begins in MBF and extends 100 m into the Lower Basalt Formation (LBF) separated by a 0.7-m bed of basaltic conglomerate belonging to the coal-bearing formation (A-horizon). MBF is dominated by thin-bedded compound flows. These are mainly olivine-phyric in Vestmanna-1, but plagioclase-phyric in Glyvursnes-1. Tuffaceous beds are rare. UBF in Glyvursnes-1 is likewise dominated by plagioclase-phyric compound flows, but flow-units are generally thicker and tuffaceous beds (<6 m) more abundant.

The Glyvursnes and Vestmanna cores have been divided into >2000 units of massive, vesicular and brecciated lava, chilled lava skin and sediment beds. The wire-line logs were carefully depth-shifted to fit the detailed core descriptions. Sixty core samples from Glyvursnes-1 were selected for rock chemistry and 38 samples from both boreholes for measurements of bulk density, porosity, permeability, Vp and Vs (up to 300 kb confined pressure, dry or brine saturated). The two-receiver full-wave sonic log was processed several times at two service companies and GEUS to obtain Vp and Vs. The final results show excellent correlation with the velocities measured in GEUS Corelab. The density logs, on the other hand, show systematic differences from core data because of poor calibration and have been adjusted accordingly.

Measured physical properties show clear correlation with lithology. Examples are shown of the log response of the different volcanic lithologies and mean values are given. The prime parameter is porosity. Porosity measured by the neutron porosity tool is systematically higher than the gas porosity measured on cores. The reason is that the neutron tool measures the hydrogen content of the formation, which is assumed to be contained in free water. However, some water is bound in secondary minerals of the volcanic matrix. The degree of alteration of the rocks is therefore the second most important parameter. The matrix water have been either analysed or estimated from loss of ignition and subtracted from the neutron porosity to give true porosity. This results in a fine correlation with Vp and suggests that Vp can be used as a proxy for true porosity.

Rock physics analysis of sonic velocities in basalts from Faroese and Icelandic wells

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We have analysed the acoustic properties of basalts based on sonic log data from three Faroese and three Icelandic boreholes and ultrasonic laboratory measurements on 43 1.5" core samples from the three Faroese boreholes. The Faroese boreholes are Lopra-1/1A (LP-1), Vestmanna-1 (VM-1) and Glyvursnes-1 (GL-1) that penetrate the Palaeogene basalts of the Lower, Middle and Upper Basalt Formations (UBF, MBF and LBF) and these rocks are mainly subaerial flood basalts apart from hyaloclastites below c. 2.5 km depth in the LP-1 well. The Icelandic wells penetrate volcanic rocks of Plio-Pleistocene age and cover a mixed environment: HH-1 (95% hyaloclastites), LA-10 (45% submarine and 45% subaerial basalts) and LL-3 (95% subaerial basalts).

We find a tight correlation between sonic Vp and He-porosity based on core data irrespective of basalt facies and well (only data for sediment samples deviate). The core data also reveal a well-defined relation between Vp and Vs, which is to be expected from rocks of broadly similar composition. However, there is a significant scatter in plots of Vp versus density and this scatter is related to the range of grain (matrix) densities from 2.7 to 3.1 g/ccm. Low grain densities represent altered samples with high content of light minerals such as zeolite and clay.

We can distinguish two main Vp-density trends for flood basalts based on the log data: (1) a trend of relatively low Vp compared to density (the UBF in the GL-1 well; the flood basalts in the LL-3 well), and (2) a trend of relatively high Vp compared to density (the LBF in the LP-1 well). The properties of the MBF are transitional between the two trends. The GL-1 data from this interval represents both the high and the low trend, whereas the VM-1 data represent a very high trend. However, towards the base of VM-1, we observe a 'reversal' of the Vp-density trend within the thin sequence of the LBF penetrated by the well. The analysis of the Vp-density relation for the core data shows that the outlying samples towards low densities are characterized by low grain density. Hence the relatively high Vp-density trend defined for the log data in these wells for the MBF also must be characterized by low grain densities. This means that the low Vp-density trend represents basalt with unaltered matrix with high grain density and the high trend represents altered basalt with a low grain density.

The transition from the low Vp-density trend of fresh basalts to the high trend of altered basalts within the MBF occurs concurrently with an increase of the sonic velocity and density with depth even though there is no increase in the flow thickness. This shows that the transition from fresh to altered basalt is accompanied by an increase in velocity and density and thus probably also by net influx of mass leading to higher densities (growth of zeolites). This means that data points along a high Vp-density trend represents samples with relatively high velocity compared to density, because filling of the pore space with zeolites and clay increases velocity and only changes density of low-porosity basalts slightly.

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Lithological analysis of wireline logs through flood basalts in 8 explorations wells in the Faroe-Shetland Region

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Basaltic successions of various thicknesses and characters have been penetrated in a number of exploration wells in the British sector of the Faroe-Shetland Channel and around the Northeast Rockall Basin. The wireline logs through basaltic successions in eight released wells were selected for a systematic study of the log-response of basaltic rocks in this region.

We propose a simple classification scheme of basaltic rocks, which is based on the log data from these wells and the well site descriptions of cuttings and sidewall cores.

All of the basaltic successions in the studied wells can be sub-divided into five major classes, *simple lava beds*, *compound lava units*, *volcaniclastic units*, *hyaloclastic units*, and *hypabysal intrusive units* characterized by distinct log responses. Further characterisation of the individual basaltic unit is easily carried out using a small number of *response components*, which mostly reflect the porosity distribution within the units

The response components used in this study are selected in such a way that they as far as possible can be considered diagnostic of typical lava morphological features of basaltic eruptives. In the studied wells, the classification and characterisation of log responses allowed a description of the eruptive style and the environment of lava emplacement, which is in good agreement with descriptions based on palynological and petrological investigations of the successions. Examples illustrating the use of log response components in basaltic rocks will be presented.

Wireline logs, as well as any other investigation of borehole data, provide data along one dimension only. However, the log response may frequently be related to general (or local/regional) lava morphologic facies, especially if supported by studies of cuttings from crucial intervals. In addition to environmental parameters, the wireline logs provide in situ measurements of physical properties. Elaborate models for forward and inverse studies of 3D distribution of physical properties in basaltic successions should thus as far as possible be linked to interpretation on wireline logs, which provide a basis for a feasible lateral extrapolation of the physical properties in the vicinity of the well.

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SINDRI

Phase converted reflections in the Glyvursnes 2003 surface seismic experiment

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Phase conversions within basalt successions pose a special problem in sub-basalt imaging, which is not well studied. In the surface seismic data recorded during the Glyvursnes 2003 seismic experiment detailed analysis of stacking velocities and of phase polarity in 3-component receiver gathers reveal that reflections converted within basalt successions are identified. Offset dependent amplitude variations may also contribute to the identification of converted reflections.

Simple parallel-layered elastic models representing the succession investigated by the Glyvursnes 2003 seismic experiment were constructed using well logs and geometric information from the seismic data.

The events identified in the simulated full elastic seismic data of the elastic models do not conform completely with events in the recorded data. To some extent, this may reflect variable lateral continuity within the basalt succession.

Phase converted reflections from a surface within the basalt succession is generally of low amplitude compared to the primary P-wave reflection, and they are generally removed/attenuated during standard processing of seismic data, that is when seismic velocities increase with depth, and velocities are picked properly. However, the stacking velocities of the phase converted reflections lies somewhere between the P-wave velocity and 0.7 times the P-wave velocity. Sub-basaltic sediments are likely to have velocities in the same range, and although the interbasaltic conversion are weak compared to interbasaltic p-wave reflections the amplitudes are significant compared to expected reflections from sediment interfaces. It is thus likely that phase converted reflections from the lower part of a basalt succession may be confused with reflections from a sediment succession.

SINDRI

Seismic velocities, anisotropy and attenuation of Faroe Islands basalts

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Borehole data, vertical seismic profiles, near-offset and wide-angle seismic reflection data have been used to investigate the velocities, anisotropic and attenuation properties of seismic waves in layered basalts on the Faroe Islands. We present the first results from studies at Vestmanna harbour, where the 660 m Vestmanna-1 borehole penetrates the lower 550 m of homogeneous "pahoheoe" lavas of the Middle Basalt Formation (MBF) and into the 10–30 m thick, "aa" lava type flows of the Lower Basalt formations (LBF). We have correlated the ultrasonic-scale velocity measurements from the borehole with the seismic-scale velocities and reflection images derived from VSP and surface data.

Sesismic data were acquired from a 3-component sensor in the borehole and from a 120-channel 3-component Geometrics geophone array extending away from the borehole on basalt outcrop. We recorded a vertical seismic profile (VSP), six offset VSPs (OVSP) with borehole sensors at 50 m depth intervals, and six wide-angle (WA) profiles into the borehole receovers and the land array (LAND). Using the phase-slowness method on the first arrivals on OVSP and WA data we find that the observed anisotropy from the layered basalts is less than 0.5%, even smaller than the value of 1% derived by theoretical calculation from the layered structure. The geometry of the borehole (WA, VSP, OVSP) plus land acquisition allows rays to be recorded over a wide range of illumination angles: the P wave velocity model calculated from the first arrivals by an isotropic ray tracing code shows average velocities of 5200–5800 m/s with an overall increase with depth. The observed travel-times from borehole and wide-angle P-wave data match well with those predicted from the borehole logging measurements.

Reflection profiles from our data show a strong and continuous intra-basalt reflector at 600 m depth: This does not correlate exactly with the MBF-LBF boundary but is produced by a 30 m thick basalt flow ~40 m deeper. Synthetic seimogram modelling confirms that 10–30 m thick basalt layers of the LBF are capable of producing strong reflections from individual layers, whereas the thin (average < 2 m) layers of the MBF produce reflectivity from the interference effect of multiple thin layers, as reported by Smallwood *et al.* (1998) from the basalt sequence in eastern Iceland.

Measured values of apparent Quality Factor (Q) are ~30, similar to values elsewhere in basaltic sequences (Maresh & White, 2005). We demonstrate that the most likely cause of the low values of Q is a combination of 1D scattering by the layered basalt sequence and intrinsic attenuation due to seismic wave induced fluid flow within pores and micro-cracks.

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Sindri Poster Session

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A cost-saving technique for high precision U-Pb age dating of detrital zircons

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Analysis of the crystallisation ages of detrital zircon grains in clastic sediments is a powerful tool in sedimentary provenance studies. Zircon is very resistant to physical and chemical alteration, and U-Pb dating of detrital zircons can therefore yield the age of their sources, even after metamorphism and deformation. Previous studies have demonstrated that accurate and precise U-Pb ages of > 100 zircon grains in a sample are sufficient to detect all major sedimentary source components with statistical confidence. Achieving these large numbers of individual analysis needed in provenance studies by isotope dilution thermal ionisation mass spectrometry (ID-TIMS; the currently most precise and accurate zircon U-Pb age dating technique) is prohibitively expensive. Therefore, U-Pb age dating of detrital zircons is generally the domain of ion microprobe techniques (SHRIMP or SIMS), where relatively rapid *in situ* analysis can be achieved. The major limitations of these techniques are sample throughput (about 75 zircon age dates per 24 hours), the very high purchasing and operating costs of the equipment and the need for highly specialised personnel, resulting in high cost. These high costs usually impose uncomfortable restrictions on the number of samples that can be analysed in a provenance study.

The potential of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for rapid *in situ* U-Pb geochronology was already realised in the early to mid 1990s. The viability of LA-ICP-MS for U-Pb dating of detrital zircons was recently demonstrated by Košler et al. (2002) and Frei et al. (2005). Here, we present a technique for U-Pb dating of detrital zircons by laser ablation magnetic sectorfield inductively coupled plasma mass spectrometry (LA-SF-ICP-MS). This technique takes advantage of recent advances in laser technology and the introduction of magnetic sectorfield ICP-MS instruments (SF-ICP-MS). Based on a ThermoFinnigan Element2 magnetic sectorfield ICP-MS combined with a New Wave UP 213 laser ablation system, these techniques allows U-Pb dating of detrital zircon grains with precision, accuracy and spatial resolution comparable to SHRIMP or SIMS. Because an individual analysis is carried out in less than 2 minutes and all data is acquired in pre-set mode with only minimal operator presence, the sample throughput is an order of magnitude higher (> 700 analysis per 24 hours) compared to SHRIMP or SIMS. Furthermore, LA-SF-ICP-MS uses simpler and more robust equipment and the purchasing and operating costs are only a fraction of the costs of SHRIMP and SIMS. We therefore conclude that U-Pb dating by LA-SF-ICP-MS is the cost-saving technique of the future for advanced provenance studies using geochronology of detrital zircons.

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Constraints on provenance of Paleocene-Eocene sandstones in the Faroe-Shetland Basin from high-resolution detrital zircon stratigraphy

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One of the most important questions for hydrocarbon exploration in the Faroe region is the understanding of sediment dispersal patterns and depositional systems in the Faroe-Shetland Basin prior to continental break up in the Late Paleocene to Eocene. A powerful tool for tackling these questions is detrital zircon analysis. Detrital zircon analyses uses the interpreted provenance of zircon (usually derived from the age information recorded in zircon) to unravel the geological history of sedimentary basins and their surrounding areas. Here, we present the results of a study that investigated the systematics of detrital zircon age distributions in sandstones from East Greenland and the UK sector of the Faroe-Shetland Basin with hitherto unprecedented detail (Frei et al., 2005). In total, we have analysed the ^{207}Pb-^{206}Pb ages of 4347 detrital zircons by means of LA-Q-ICP-MS (Frei et al., 2005). Detrital zircons were separated and analysed from 25 samples from East Greenland (2321 zircons), and 20 samples from wells in the UK sector of the Faroe-Shetland Basin (1832 zircons).

The observed detrital zircon age distributions in samples from the Kangerlussuaq Basin unequivocally demonstrate that the sedimentary successions are derived from two distinct sources, the first being Archaean basement situated to the south and southwest, and the second being younger, Proterozoic rocks situated to the north and northeast. Furthermore, the zircon age distributions allow tight constraints to be placed on the timing of changes in sediment supply, to validate the stratigraphic correlations drawn from litho- and sequence stratigraphy, and to exclude large-scale local reworking of sedimentary units in the Kangerlussuaq Basin. However, the most important feature of the zircon age distributions in sandstones from the Kangerlussuaq Basin is the general presence of a characteristic Middle Archaean age component. In marked contrast, this distinctive age component is almost completely absent from detrital zircon age distributions in samples from wells in the UK sector of the Faroe-Shetland Basin.

This difference in detrital zircon age signatures allows distinction between a western, Greenlandic source and an eastern, predominantly UK margin source. The influence from a western source (Greenland) has not been proved in the examined stratigraphic intervals of wells from the UK sector of the Faroe-Shetland Basin. However, the structure of the Faroe-Shetland Basin suggests that the western, Greenlandic source might be much more important for the deeper, central parts of the basin towards the Faroes area.

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Quantifying and investigating null space in refraction data

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Seismic exploration in the Shetland-Faroe Basin area has increased in recent years. Mesozoic and Tertiary sedimentary sequences fill this basin and comprise a potential hydrocarbon reservoir. Close to the Faroe Shelf these sedimentary sequences are covered by Paleocene-Eocene basaltic lavas.

The high impedance contrast between basalt and sediments and the scattering caused by rugged interfaces leads to a lack of coherence in the seismic signal. Internal characteristics (heterogeneity) of the basalt can also cause scattering in the wave field resulting in a low quality seismic reflection image in the sub-basalt zone.

Synthetic simulations have been carried out using a model which contains a thin basalt layer (< 1 km) with rugged interfaces. The choice of a thin layer for the basalt is justified because it represents the best geological setting for exploration and exploitation natural resources for the industry. In addition, in the case of Shetland-Faroe Basin, the area where the basalt thins is closer to the centre of the basin where geology is well known and can be extrapolated to infer properties of sub-basalt structures. The main aim of these simulations has been to check if it is possible to recover the original model using seismic tomography techniques. Tomographic inversions have been carried out considering both: reflected and refracted phases for those synthetic data. The resulting model fits the original one above the basalt layer and constrains the rugged basalt upper interface although does not reproduce the low velocity zone placed between the basalt and the basement because of the difficulty of constrain the base of the basalt layer. Some Metropolis simulations were used to assess the reliability of tomographic inversions depending on several factors: accuracy in identifying phases, uncertainty in picking, frequency of signal, thickness of basalt layer, etc. The results show that the most probable model for the sub-basalt layer features high dispersion in velocity and thickness. In order to overcome this problem, we supposed that two wells were drilled through the basalt, constraining in this way, the thickness and velocity of the basalt layer as well as the velocity at the top of sub-basalt sediments. Considering this additional information, phases from the basement can be inverted to better reproduce the original synthetic model. A detailed velocity model was obtained from wide-angle reflection data. Using this velocity model a pre-stack depth migration was performed, obtaining results that are consistent with the normal incidence stacked image. The base of the basalt layer can be inferred where this layer is thick enough but, as shown in the synthetic simulations, where the basalt thins, all information about the bottom interface of the basalt is lost.

The Metropolis Algorithm

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The Baysian based Metropolis algorithm is a special type of Markov Chain Monte Carlo search that uses a constrained random walk that to explore the local environment around a given model. Hence, by testing a large number of possible models it is possible to map the uncertainty in the data into uncertainty in the model. The basis of the method is:

1) apply a random perturbation to the current model to give a candidate model
2) evaluate the likelihood of the candidate model
3) apply acceptance criteria:
    1. if the candidate model is more likely then accept it as the current model;
    2. if the candidate model is less likely then accept as the current model subject to a prior probability distribution;
    3. if the candidate model is rejected then return to existing current model and try again;
4) repeat until a sufficient number of models are accepted and compute posterior distribution.

A typical inversion algorithm searches for an optimum model in the shortest number of iterations, though this quickly identifies a solution it does not provide a robust measure of the uncertainty. In many situations, such as tomographic inversion of data that may contain low-velocity layers, prejudice is needed in the inversion process to constrain parts of the model that are in the null space of the data. The Metropolis algorithm is an ideal complement to the inversion process as by its nature it will highlight the parts of the model that are poorly constrained, also it can give confidence in phase identification and pick uncertainty. However, the simple chi-squared misfit parameter is not sufficient on its own as this misfit value can only be calculated for data points fitted by the model (hit rate). Hence, it is possible to have a chi-squared of one or less but only fit a proportion of the picks. To compensate for this problem we have devised a modified misfit function that is formed from both chi-squared and the hit rate parameters. The relative weighting of these two parameters is critical to the success of the Metropolis code so as one does not dominate the other.

Examples of the results from the Metropolis algorithm are shown for long-offset seismic data that include both reflected and refracted phases and a low-velocity layer beneath a high velocity basalt. There is a clear link between reducing the pick uncertainty on the observed data by increasing frequency content and improved confidence in the model. But reducing the pick uncertainty below the realistic limit imposed by the data in the expectation that it will improve the model does the reverse, and makes the most probable model less like the true starting model. This is because in complex models a waveform on the data may be an interference between more than one phase so over optimistic pick uncertainties precludes the correct model from the likely solutions to the tomographic inversion where these data have been associated with a single phase.

Our conclusion is that all tomographic inversions need to be rigorously tested by a Metropolis like algorithm so the true uncertainty can be appreciated.

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