Challenging the Established Truths

The use of aeromagnetic data is an important tool in modern geological mapping and petroleum exploration. The advantages of recent advances in technology can be compared to the advancement from 2D to 3D seismic imaging.

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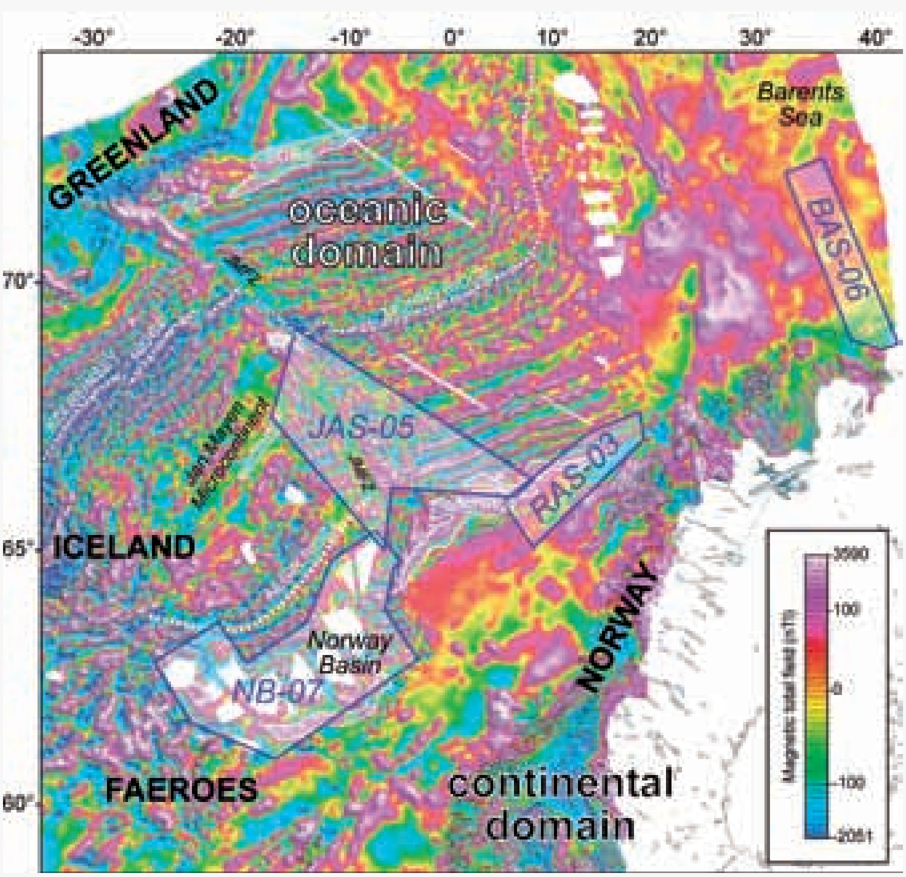
Aeromagnetic measurements were initially developed to track and detect submarines during the Second World War. However, geophysicists soon realised the scientific implication of airborne magnetic survey for earth sciences and exploration. This introduced a new era in the use of airborne magnetic surveys, and for more than 50 years aeromagnetic acquisition has been a prerequisite for geological investigations in frontier provinces.

Along with Australia, Canada, Finland, Sweden and the U.S, Norway was one of the first countries to support a vigorous government program to develop a countrywide, modern, high-resolution aeromagnetic database. This included continuous data acquisition, as well as the merging and re-processing of data from individual surveys. In this context, the Geological Survey of Norway (NGU) played, and continues to play, a crucial role in maintaining and continuously updating this national database.

With huge improvements in technology over the last decade, the Survey's most recent aeromagnetic acquisitions have proved the value of modern data. We are now able to demonstrate first order geophysical and geological features on the Norwegian Continental Shelf (NCS) and its contiguous oceanic domain.

Comparing some of the old aeromagnetic surveys with new data is like comparing 2D seismic lines from the 70´s with the most advanced 3D surveys. Much



Magnetic compilation of the Norwegian continental shelf and the contiguous oceanic domain, characterised by clear magnetic stripe that reflect times when Earth's magnetic field had alternatively normal and reversed polarity.
Two major geodynamic events influenced the geological history and configuration of the Norwegian oceanic domain. The first was the continental break-up event leading to the opening and accretion of the Norwegian Greenland Sea by the splitting apart of Greenland and Norway ~55-53 Ma ago. This event was associated with significant volcanic activity and lead to massive lava flow emplacement along the continent-ocean transition. The volcanics are locally expressed as seismic seaward dipping reflectors sequences (so-called SDRs). Soon after the break-up, sea-floor spreading occurred simultaneously along the Mohns and Aegir spreading axis accommodated by the Jan Mayen Fracture Zone (JMFZ).
The second main geodynamic event occurred in Oligocene times. During this stage, spreading activity decreased along the Norway Basin and gradually the Aegir Ridge became extinct as the spreading axis "jumped" westwards to form the Kolbeinsey Ridge, still active at present day. The opening of the Kolbeinsey Ridge resulted in separating a thin, long continental fragment away from Greenland. This long sliver constitutes the Jan Mayen Microcontinent, a missing continental piece between the outer Vøring Basin and the Faeroes Plateau. Blue frames represent the outlines of recat NGU aeromagnetic projects (RAS-03, JAS-05, BAS-06) and the new NB-07 survey.

The aeroplane recently used for aeromagnetic acquisition on the Norwegian continental shelf. The magnetometer is the instrument used to measure the intensity of the magnetic field along particular profiles.

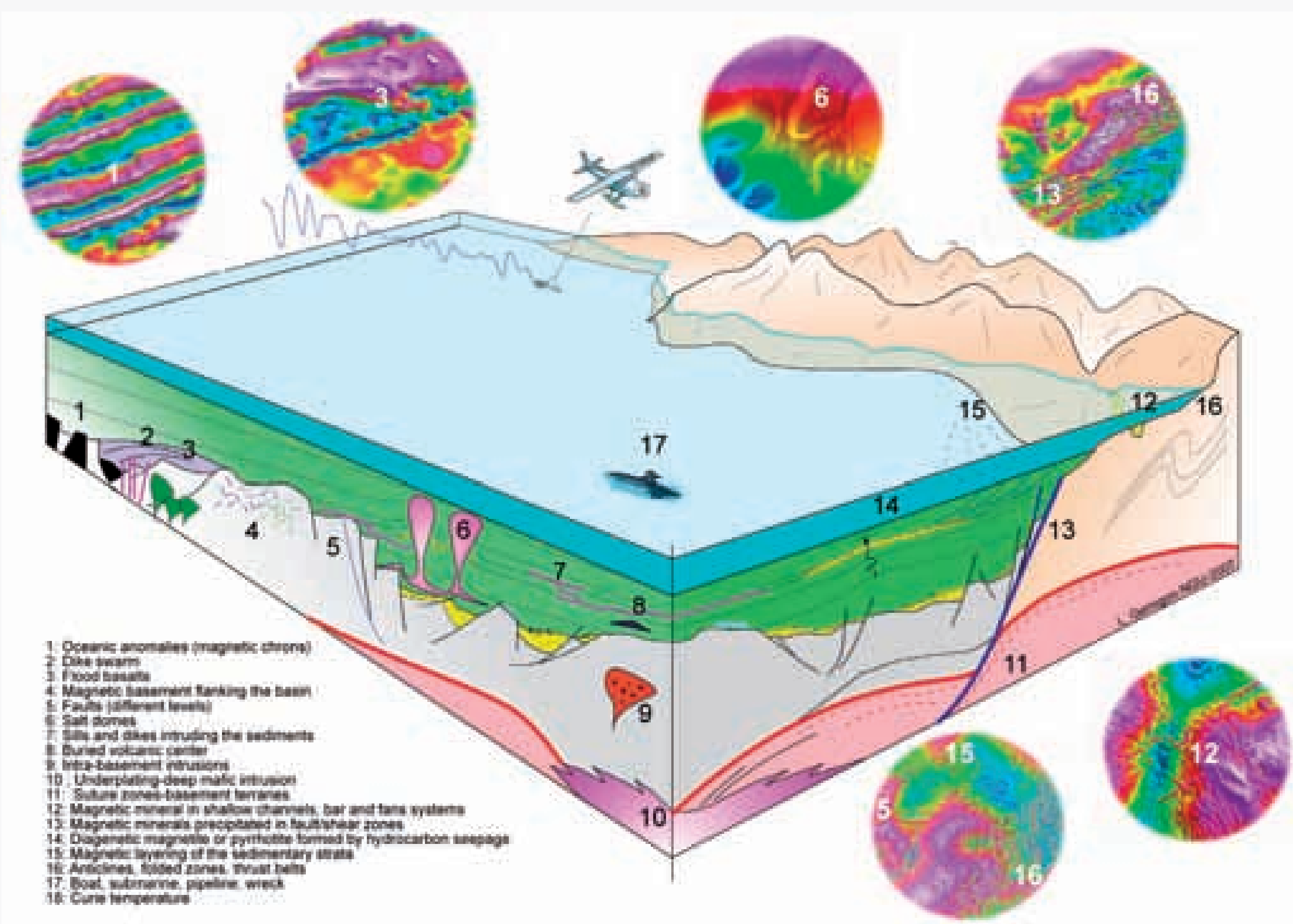
of the Norwegian Continental Shelf and contiguous oceanic domain was surveyed a number of years ago, so the surveys are not always reliable due to poor navigation or/and inadequate line spacing. In the meantime, the sensibility and sampling interval of magnetometers have increased by a factor of 10.

A need for new high-quality data has become a reality for both academia and industry. Consequently, NGU has launched a number of projects for re-mapping the Norwegian Continental Shelf and adjacent oceanic basins, using funding from the petroleum industry and the Norwegian Petroleum Directorate (NPD).

Aeromagnetic and Exploration

The delineation of gravity and magnetic anomalies are normally the first method of evaluation of a new basin or region. In frontier areas, where seismic data are sparse or non-existent, aeromagnetic acquisition remains the cheapest and easiest way to understand or refine the structural setting. Aeromagnetic data can also be useful to plan strategic new seismic acquisitions. Large aeromagnetic surveys can be undertaken efficiently and safely almost everywhere, in a short period of time and at a reasonable cost.

Also, when integrated into seismic interpretations, gravity and modern aeromagnetic information can reduce



3D cartoon and examples of the application of modern aeromagnetic surveys to basin or geodynamic studies, illustrating structures and geological units that can cause observable magnetic responses the risks of making faulty geological interpretations. Both gravity and magnetic data are physically and quantitatively independent of seismic data. A joint interpretation combining seismic, aeromagnetic and other data thus produces a synergy that helps to significantly improve and validate the geological and structural interpretation of potential prospects.

Modern aeromagnetic data is often used to confirm an interpretation. If the seismic coverage is poor, it can be combined with gravity data to verify and quantify the lateral extent of basement features, lava flows, magmatic intrusions, salt structures or sand channels observed on sparse seismic sections. High-resolution aeromagnetic surveys are also relatively inexpensive tools for the 3D mapping of faults and fracture systems spreading through hydrocarbon-bearing sedimentary levels.

With regard to the NCS, modelling of a potential field using gravity and aeromagnetic data is an efficient tool for providing particulars about sub-salt and sub-basalt features, usually poorly imaged by conventional seismic data. The most recent aeromagnetic surveys along the Nordkapp Basin (SNAS-06 and BAS-06) also revealed that salt diapirs can be clearly detected and mapped with modern aeromagnetic data.

A variety of modern methods of processing, displaying and modelling magnetic anomalies can be used in basin analysis. Several magnetic techniques support basin analysis and allow the interpreter, for example to identify and delineate deep mafic intrusions and others volcanics, or to quantify and evaluate the top of the magnetic basement and infer the location of the thickest sedimentary section. They can also detect subtle intra-sedimentary "micro-magnetic" anomalies and evaluate to some extent the temperature of the crust (Curie temperature).

The Earth's magnetic field for "dummies"

The Earth has a natural magnetic field caused by the motion of deep material within its core. This magnetic field has been known and used by navigators since the Chinese (4th century BC) and later the Vikings (8th-11th century) used "lodestones" as simple compasses to find north. Today, the magnetic anomaly map illustrates variations in the magnetic field that are mainly caused by two main sources: the induced field and the remanent field.

The induced magnetic field is the product of the intensity of the geomagnetic field and the magnetic susceptibility of the underlying rocks. When the Earth's magnetic field interacts with a magnetic mineral contained in a rock, the rock becomes magnetic. This is called induced magnetism. The same thing occurs if you place a metallic nail near a magnet, when the magnet's magnetic field will induce a magnetic field in the nail. A rock itself will be magnetic if at least one of the minerals is magnetic and the strength of the rock's magnetism is related not only to the amount of magnetic minerals they contain but also to the physical properties, such as grain size, of those minerals. Like the seismic velocity or the density, the magnetic susceptibility is a physical property of a material that reflects the material's magnetic mineral content (e.g. magnetite and pyrrhotite) and character.

The remanent magnetic field is also a property of crustal rocks, which produces a magnetic field even in the absence of an ambient field. Because of unstable viscous remanence, which over time realigns with the induced field, and the general heterogeneity of the remanent magnetization, induced magnetisation is usually prevailing.

Remanent magnetization is particularly interesting because it records the direction (normal or reverse polarity) of the geomagnetic field at the time the minerals were magnetized, for example when new oceanic material is formed during spreading. As this new material cools (from magma to rock), particles in the rock align themselves to the Earth's magnetic field. By investigating the orientation of these fixed particles in the oceanic crust, it is possible to see that the Earth's magnetic field has suddenly flipped throughout its history.

Magnetic stripes (so-called chrons), that characterise changes of the polarity of the Earth's magnetic field through time, can be identified and used to provide geological ages of the underlying oceanic basement. Using an accurate magnetic grid, each oceanic anomaly can be identified and compared to a global geomagnetic polarity time scale. Subsequently, Cenozoic ages for the oceanic basement can be used to estimate maximum ages of the overlying sedimentary sequences identified on seismic records. Consequently, the oceanic crust can now be considered as a natural "tape recording" of the Earth's spreading history.

From Basin to Geodynamic Scale

Beginning in the 1950's, geophysicists recognised linear magnetic anomalies across the ocean floor. The discovery of symmetric magnetic anomalies on both sides of mid-oceanic spreading ridges, and the subsequent development of the theory of sea floor spreading in 1962, confirmed the continental drift theory proposed by Alfred Wegner in 1915 and revolutionised our understanding of the Earth, leading to the establishment of the theory of plate tectonics in the second half of the 1960's.

A detailed account of spreading history provides crucial information about magmatic production, structures and geodynamics of the oceanic domain. A key element provided by the mapping of the oceanic systems with modern aeromagnetic data is time. The correlation between oceanic magnetic anomalies (chrons) and a proper chronostratigraphic scale allows us to accurately constrain the timing of oceanic accretion. Consequently, we can obtain good age constraints for the oceanic basement and therefore overlying sedimentary sequences. The age of the ocean floor deduced from the magnetic chrons can be used to create a series of paleotectonic and/or paleogeographic reconstructions. Placed in a time-referenced framework, deformation and movements of first order structures identified from new magnetic data-sets can be evaluated on the basis of several fundamental constraints, which provide a means of explaining the tectonic, geological and petroleum evolution of a study area.

Most importantly, the magnetic pattern can help to locate the continental-oceanic boundary and delimit the distribution of the pre-break-up sedimentary sequences. In most continental margins, like the mid-Norwegian margin, this issue allows us to define the regional and maximum ▶

extent of interesting play concepts. Advanced modelling also suggests that stress and temperature, influenced by poorly understood break-up processes and subsequent oceanic spreading, can influence the adjacent rifted margin and indirectly its petroleum system.

Remapping the Norwegian Oceanic Domain

Compared to the NCS the Norwegian oceanic domain is still poorly understood and scientific questions remain. After almost 20 years of under-exploration of the area, NGU started to re-investigate most of the oceanic domain and the continent-ocean transition in order to get an improved geophysical and geodynamic picture of the Norwegian-Greenland Sea. Both precise plate reconstruction and basin modelling require an improved dataset, and a complete and modern re-mapping of the oceanic domain is definitely a challenging task for NGU.

The work started with the RAS-03 survey along the Lofoten area and later with the JAS-05 survey acquired between the Vøring Marginal High and Jan Mayen in 2005. These surveys already support the idea that most of the fundamental structures of the Norwegian oceanic basins and adjacent margins are far from well delineated and the surveys may significantly change our long-believed convictions. After analysis of the new datasets, we came up with new challenging hypotheses for the break-up and post-break-up evolution of the mid-Norwegian margin.

Some of the first surprising results were that some long held ideas about oceanic fracture zones simply disappear with such a modern dataset. For example, the long established "Bivrost Fracture Zone", which apparently offsets magnetic chrons by 50 km, is just an artefact due to poor quality data. When you realise that this trend was used for the last 30 years to guide structural and paleogeographic models offshore mid Norway, you may easily imagine the implications of these new aeromagnetic acquisitions.

The recent NGU aeromagnetic dataset (JAS-05), acquired along the Jan Mayen Fracture Zone (JMFZ) during the autumn of 2005, also illustrates that new data significantly refines the first order geophysical and structural setting of the Norwegian offshore regions. As a result of this survey, normal and reverse magnetic chrons are now better identified and some new chrons appear in the grid. New fault segments were also identified, allowing us to re-map the entire fault system across the area.

Toward a New Geodynamic Picture

After the analysis of this new survey, NGU was able to come up with new constraints and challenging geodynamic models for the Norwegian-Greenland Sea. For example, based on the new magnetic compilation and our tectonic analysis of the JAS-05 survey, we recently proposed that a triple junction (Ridge-Ridge-Fracture Zone) was initiated soon after the break-up of the Vøring Marginal High and the Traill Ø-Vøring igneous complex . In places where a component of opening motion occurs along or close to a pre-existing oceanic transform, magmatic activity could have increased locally along such a "leaky transform" acting as a third branch. This early tectono-magmatic process ▶

Modern aeromagnetic surveying

During the last 2 or 3 decades, NGU has built up a wealth of experience in the acquisition, processing and interpretation of geophysical datasets. It continuously upgrades the regional database both onshore and offshore Norway.

Aquisition

The magnetic surveys at NGU are done from aeroplanes, with a magnetometer (so-called "the bird") towed at a sufficient distance from the plane to make the plane's magnetic effects negligible. Advances in data acquisition techniques include more sensitive magnetometers, modern Global Positioning Systems, and pre-planned drape surveys. The airborne magnetic surveys are conducted with constant flight-line orientations, usually perpendicular to the regional geological strike, and with constant line spacing. Spacing and orientation depend on the purpose of the survey, but modern standard flight line spacing for regional surveys offshore Norway varies usually from 1 to 5 km. This specification allows us to investigate both basin scale and basement features.

Processing

Modern and recent advances in processing techniques now allow us to improve the quality of data processing, and displaying procedures, such as micro-levelling and advanced gridding techniques) have significantly improved data quality and resolution, providing levels of detail that are compatible to those derived from seismic and surface geological data.

Once the aeromagnetic raw data has been collected, this data is then processed to remove the Earth's natural magnetic field (IGRF field) and any diurnal variation in the magnetic field to reveal the magnetisation due to the underlying geology (magnetic total field).

The most complex problem is probably the diurnal variation of the Earth's magnetic field influenced by solar storms, particularly active in the Arctic region (e.g. aurora borealis). It usually causes tie lines and regular survey lines to have different readings at the same geographical point. Such misfits can produce artefacts during interpolation and consequently erroneous interpretation if no suitable corrections have been applied. If the survey is close to a base station site, the lines can be partly corrected for diurnal variation. However, most of the offshore acquisition is undertaken far away from land stations and efficient statistical algorithms, and filtering is usually required to solve this issue and "level" in a proper way all the magnetic profiles. The purpose of levelling science today is to minimize the residual differences in a coherent way. Proper levelling or micro-levelling algorithms usually require close line spacing and the quality of the final result is often a function of this crucial parameter. Large line spacing does not allow proper micro-levelling and interpolation of raw data often produces erroneous or fictitious anomalies, as is still the case for some of the old surveys offshore Norway, where lines spacing may be up to 100 km.

After levelling and final gridding, a residual total magnetic field map is produced. This is a useful document for geoscientists because it reflects a physical property of the underlying rocks and highlights the structure and petrophysical properties of the ground.

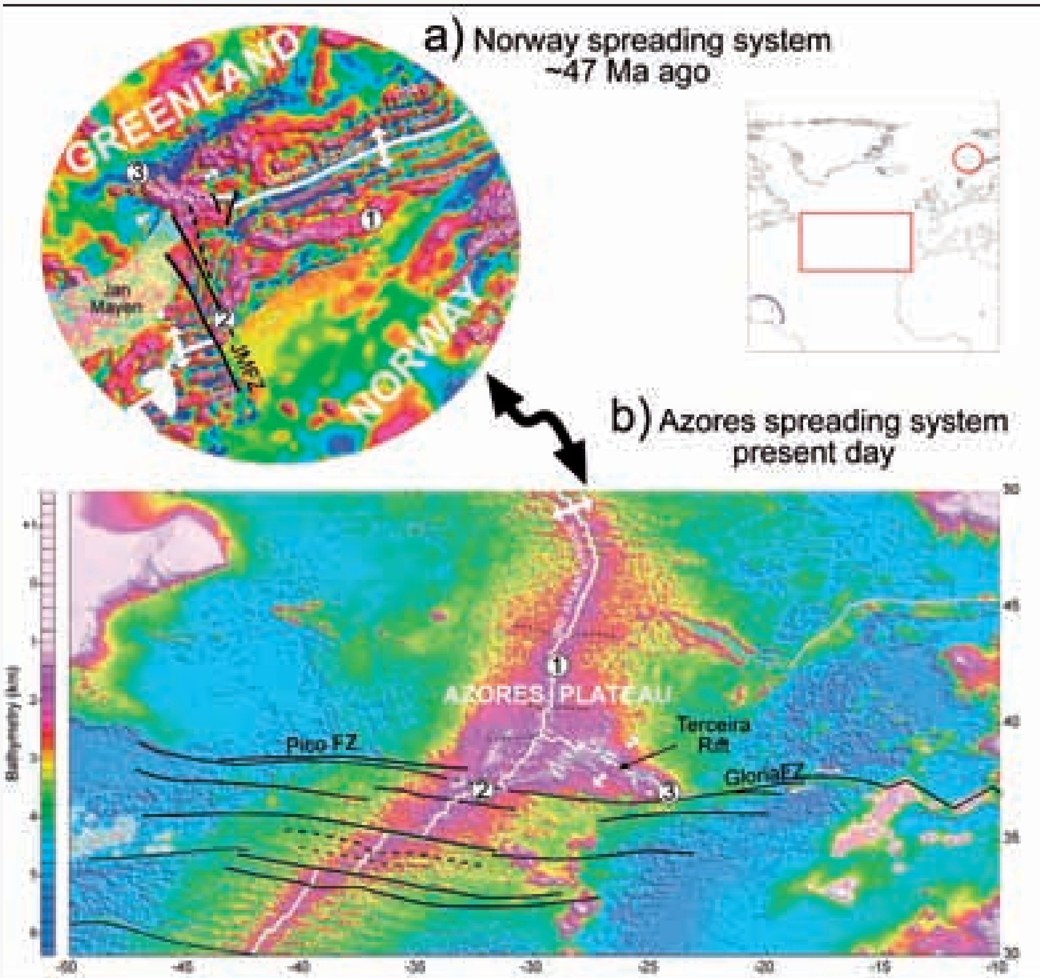


Plate reconstruction of Norway, Greenland and the Jan Mayen Microcontinent (a) soon after break-up (~47 Ma ago). The picture on top (a) illustrates a triple junction between two magnetic (magmatic) branches 1) and 2) which represent the basaltic SDRS along the Vøring Marginal High and the Traill Ø igneous complex (branch 3), now observed offshore Greenland. Such a challenging tectono-magmatic process can be compared to the active and more exotic Azores spreading system (b), In the Azores, the situation is quite similar, with the triple junction and the volcanic plateau forming along the spreading ridge and seemingly also influenced by the pre-existing oceanic fracture zones. A similar third branch (the Teiceira rift) propagates in a pull-apart setting from the spreading ridge toward the adjacent oceanic fracture zones (e.g Gloria Fracture Zone). The Azores spreading system can be used as a modern analogue to the Norwegian spreading system, initiated 55 Ma ago.

could be compared to the active and more exotic Azores system, which can be used as a modern analogue of the vintage Norwegian spreading system, initiated 55 Ma ago.

The next step of our investigation of the Norwegian oceanic domain is the ongoing survey NB-07 between the Faeroes Plateau and the outer Vøring Basin, where magnetic data remains extremely sparse and of poor quality, as suggested by the "gaps" observed in the regional compilation. We hope to get new elements to refine the tectonic setting of this oceanic basin, which is far from well understood and much neglected in the past. We expect the NB-07 survey to fill these gaps and to provide new constraints about the nature of the continent-ocean transition and the extent of sedimentary basins partly hidden by lava flows. Industry and governmental institutions have already welcomed this initiative and the NB-07 is already co-funded by ConocoPhillips, the Faroese Earth and Energy Directorate, the Norwegian Petroleum Directorate, Norske Shell, Statoil and Total Norge.

The final compilation will certainly be welcomed by most researchers and explorationists working within the fields of geodynamics and geophysics and should provide a further step in our geodynamic knowledge of the Nordic Seas.

Laurent Gernigon received a M.Sc. in Marine Geosciences and was awarded a Ph.D. at the University of Brest (France), having researched rifting and magmatism along the mid-Norwegian margin in 2002. From 1999 to 2002, he was employed as structural and regional geologist in the New Venture team with Total Exploration Norge in Stavanger. In 2002 he joined University College, Dublin and the Dublin Institute For Advanced Studies to investigate the tectonic and magmatic evolution of the Irish margins. In 2005, Dr. Gernigon moved to the Geological Survey of Norway where he works as a geoscientist with the Continental Shelf Geophysics team. His main scientific interests are the tectonic and geological evolution of the North Atlantic and Arctic regions; the interplays between extension, sedimentation and magmatism; and Earth dynamics in general.