

The NE Atlantic region: a reappraisal of crustal structure, tectonostratigraphy and magmatic evolution – an introduction to the NAG-TEC project

GWENN PÉRON-PINVIDIC^{1*}, JOHN R. HOPPER², MARTYN STOKER³,
CARMEN GAINA⁴, THOMAS FUNCK², UNI E. ÁRTING⁵ &
JOHANNES CORNELIS DOORNENBAL⁶

¹*Geological Survey of Norway, Leiv Eirikssons vei 39, 7040 Trondheim, Norway*

²*Geological Survey of Denmark and Greenland, Øster Voldgade 10,
1350 Copenhagen K, Denmark*

³*British Geological Survey, The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP, UK*

⁴*Centre for Earth Evolution and Dynamics, University of Oslo, PO Box 1028,
Blindern, 0315 Oslo, Norway*

⁵*Jarðfeingi (Faroese Geological Survey) Brekkutún 1, PO Box 3059,
FO-110 Tórshavn, Faroe Islands*

⁶*TNO – Geological Survey of The Netherlands, Princetonlaan 6,
3584 CB Utrecht, The Netherlands*

*Correspondence: gwenn@ngu.no



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The NE Atlantic region and its continental margins (Fig. 1) hold unique information for understanding many aspects of Earth science, from global geodynamics to palaeoceanography and global environmental change. It also holds some of the world's most important hydrocarbon reserves from the North Sea, along the Atlantic margins of Ireland, Britain and Norway, and into the Arctic in the Barents Sea. Historically, studies in the NE Atlantic were important for establishing many of the key ideas during the early part of the plate tectonic revolution. Linear magnetic anomalies along the Reykjanes Ridge were identified as early as in the 1960s (Heirtzler *et al.* 1966) and provided strong evidence for the seafloor spreading hypothesis (Dietz 1961), which by then had been established as a new and holistic theory (Ewing & Heezen 1956). At the same time, Iceland was already recognized as an intriguing anomalous entity (Böðvarsson & Walker 1964) and contributed to knowledge about how Earth's magnetic field reversed its polarity through time. The fact that rifting occurs in close association with old sutures and orogenic belts led Wilson to propose that the Atlantic Ocean closed

and opened again, establishing the concept of the 'Wilson tectonic cycle' (Wilson 1966; Dewey 1969). The North Atlantic continental margins have long been considered as archetypal, and divergent margins world-wide are commonly described as 'Atlantic-type passive margins'. However, it is now accepted that these so-called 'passive' margins remain dynamic long after break-up, including post-rift vertical movements of up to kilometre scale. The type examples for such epeirogenic movements being, once again, the North Atlantic margins (Praeg *et al.* 2005).

Today, the NE Atlantic region remains at the centre of ongoing fundamental controversies regarding the scales of mantle convection, the origin and extent of mantle plumes and their roles in plate tectonics, and the process of plate break-up (e.g. White & McKenzie 1989; Foulger & Anderson 2005; Lundin & Doré 2005). Regardless of diverging views on how various processes operate to shape the region, understanding the geological and tectonic history of the NE Atlantic has had and will continue to have major implications for understanding global geodynamics.

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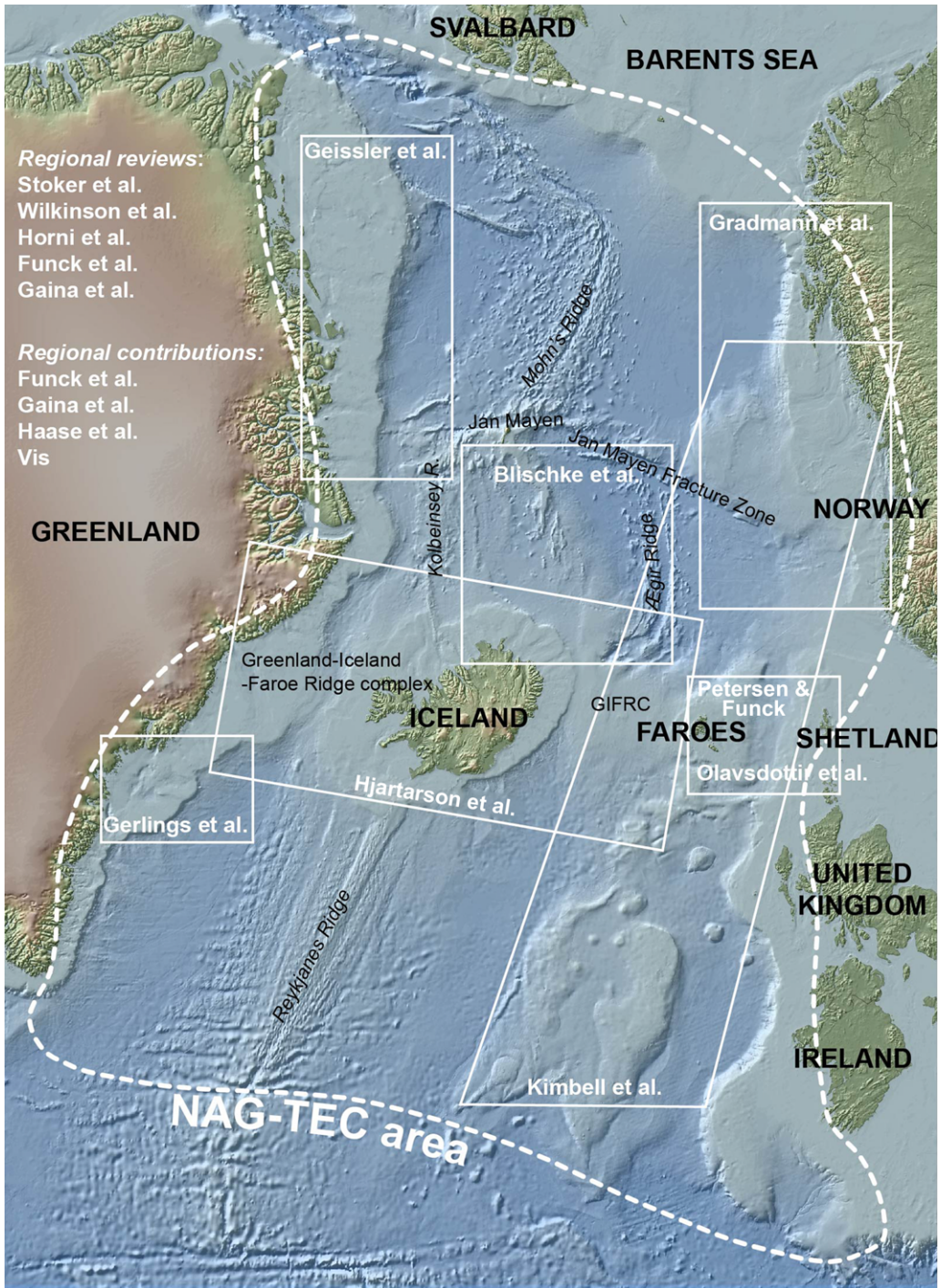


Fig. 1. Bathymetric map of the NE Atlantic. The top left-hand column lists the contributions of this Special Publication that deal with regional studies. The white squares on the map locate the local studies.

The NAG initiative and NAG-TEC project background

The Northeast Atlantic Geoscience (NAG) group comprises ten geological surveys from northern Europe under a cooperative framework that was initiated in September 2008. These include the BGR (Germany), BGS (Britain), GEUS (Denmark and Greenland), GSI (Ireland), GSNI (Northern Ireland), ÍSOR (Iceland), Jarðfeingi (the Faroe Islands), NGU (Norway), SGU (Sweden) and TNO (The Netherlands). The primary aim is the sharing of scientific knowledge and resources on major scientific and societal issues that are of common interest to all of the surveys.

Among the projects that have since initiated, an effort to understand the tectonic development of the NE Atlantic region resulted in the formation of the NAG-TEC Group, consisting of the BGS, GEUS, GSI, GSNI, ÍSOR, Jarðfeingi, NGU and TNO. In the spring of 2009, representatives of the surveys met to discuss the initiative with a particular emphasis on continental margin evolution and understanding deep-water basins. A series of further workshops and meetings were held during 2009 and 2010, accompanied by close discussions with, and recommendations by, representatives of the oil and gas industry, as well as ongoing dialogue with the survey directors. From all of these discussions, it quickly became apparent that in order to define fundamental questions that would motivate future projects, it was necessary to compile a comprehensive database of geoscientific information encompassing the entire region. The ultimate goal of the NAG-TEC project was to create a unified compilation of key geological and geophysical data relevant to the understanding of the tectonic, stratigraphic and magmatic development of the region, with a particular focus on the margins and sedimentary basins. This would provide comprehensive constraints to facilitate detailed conjugate margin comparisons and regional correlations, notably to de-risk scientific and industry exploration in poorly known areas.

After intense marketing with oil companies in the spring of 2011, the NAG-TEC project was officially launched during a workshop in Copenhagen on 1 June 2011. The project was led by the GEUS, partnered by the BGS, GSI, GSNI, ÍSOR, Jarðfeingi, NGU and TNO. The BGR secured funds to help sponsor the project, which, together with nine oil companies who signed up early, allowed the project to start. By the end of project, an additional five companies had joined the group, providing approximately half the funds needed to complete the Atlas. Another four companies purchased the database and Atlas after completion, showing the ongoing value of comprehensive regional studies such as this. Partners and collaborators from universities, other

research institutes and government agencies (see the Acknowledgements) helped at various stages during the course of the project to ensure the completeness and quality of the compilation protocols and products.

The tectonostratigraphic Atlas and ArcGIS database

The original focus of the project was to collect and assess as much geophysical and geological information as possible, compiling all published and publicly available information and datasets. In addition, a substantial amount of unpublished data owned by the geological surveys or other contributors were added to the database. This process created an overview of the state of knowledge of the entire region by listing the available data, revealing where major data gaps still exist. The final ArcGIS database provides a foundation from which ongoing research and exploration into the frontier regions of the Atlantic and into the Arctic can build.

The process of data gathering underlined the virtual non-existence of systematic compilations of tectonostratigraphic information over the entire NE Atlantic region, and that differences between local nomenclatures hampered regional correlations. These correlations were central to one of the main goals of the project, which was to provide an understanding of a full-rift system and conjugate margin evolution. The project provides quantitative constraints on key basin parameters, such as crustal thickness, burial and exhumation history, an understanding of key unconformities and their interpretation, information regarding the interaction between volcanic events and sediments, and the importance of the pre-existing structure. The key outcomes from the NAG-TEC project are the provision of a better understanding of potential links between surface processes and deeper crustal and mantle processes, constraints on continent–ocean transition zones, deep-water basin evolution, a unified stratigraphic and structural framework, and regional correlations and comparisons.

The compilation of the *NAG-TEC Tectonostratigraphic Atlas* (Hopper *et al.* 2014) and the GIS model behind it was completed on 1 June 2014. The Atlas, GIS database, and the accompanying geophysical datasets and database of references are today in wide use amongst the surveys, as well as the company sponsors. The Atlas offers thorough descriptions of the various datasets, related compilations, uncertainties and modelling results, and includes chapters dealing with the major geophysical and geological disciplines such as stratigraphy, structural elements, bathymetry, gravity, magnetic, seismic, heat flow and tomography. It also presents

chapters and sub-chapters documenting the regional plate kinematics, the identification and characterization of basement types, regional structural elements maps, Devonian–Cenozoic stratigraphic distribution maps, stratigraphic correlation charts of the post-Caledonian succession, and, finally, regional volcanism, including geochronology, geochemistry and volcanic facies characterization. Following a 2 year confidentiality period, the Atlas was made publically available in June 2016 and can be purchased via the NAG-TEC website (<https://www.nag-tec.org>). The underlying GIS project will be released in June 2019, and is in active use by the surveys and companies for defining future work and exploration.

This Special Publication: towards an understanding of the NE Atlantic region

As noted above, the main goal of the NAG-TEC Atlas and GIS database project was to focus on the empirical data; however, one final objective of the project was also to publish aspects of the scientific questions, which is a crucial remit of all of the geological surveys. Following the release of the Atlas in 2016, this Geological Society of London Special Publication offers the first published scientific communications based on the NAG-TEC project or using results from the NAG-TEC compilation. The contributions presented in this Special Publication span a wide range of geoscience methods and disciplines, which offer scientific analyses, descriptions, modelling and interpretations that we consider as marking today's status of knowledge at a regional scale. As can be appreciated, the NAG-TEC project (Atlas and GIS database) involved much more compilation and research than is evident from the papers presented here. In addition to summarizing the main contributions of the volume, a short overview of additional important results is presented at the end. For further information, the reader is referred to the NAG-TEC Atlas (Hopper *et al.* 2014).

The 17 papers presented in this volume encompass a broad range of issues related to crustal structure, tectonostratigraphy and magmatic evolution of the NE Atlantic region. The mix of papers falls into two main categories: (1) regional reviews and contributions; and (2) more process-orientated and/or area-specific papers. The categorization and geographical spread of the papers is shown in Figure 1.

Stratigraphy

A major overview of the Late Palaeozoic–Mesozoic stratigraphy of the NE Atlantic region is presented by **Stoker *et al.* (2016)**, who describe the distribution, structural setting, stratigraphy, depositional

environment and correlation of these rocks across the conjugate margins and along the axis of the proto-NE Atlantic rift system. The establishment of a regional stratigraphic framework, based on a strong observational record, has provided important new constraints on the timing and nature of sedimentary basin development in the NE Atlantic by challenging the 'classic' view of palinspastic reconstruction in the central part of the proto-NE Atlantic rift system, with implications for the break-up of the Pangaeon supercontinent. In particular, there is currently a lack of evidence for a substantive and continuous rift system along the proto-NE Atlantic until the Late Cretaceous.

Geochronology and volcanism

Four papers detail various aspects of the regional volcanic history.

Wilkinson *et al.* (2016) present a thorough geochronological review of all available published ages related to magmatic activity in the NE Atlantic. They undertook an evaluation of the quality of each published age, and produced a filtered dataset and optimized age model for the North Atlantic Igneous Province (NAIP). In particular, $^{40}\text{Ar}/^{39}\text{Ar}$ and K–Ar age data have been recalculated to a common reference system to allow across province comparisons, and all data have been recalibrated to the Geological Time Scale 2012 (Gradstein *et al.* 2012).

A compilation of the NAIP volcanic activity is described by **á Horni *et al.* (2017)**, who undertook a regional summary of the volcanostratigraphy based on an established methodology of seismic facies analysis of the volcanic units (e.g. Symonds *et al.* 1998; Planke *et al.* 2000). This formed the basis for reassessing the eruption volumes and production rates of the province, along with an investigation of the variation of the spatial patterns of volcanism along the margins. The Greenland–Iceland–Faroe Ridge complex (GIFRC) was not included in the volcanostratigraphy but, instead, forms a separate contribution by **Hjartarson *et al.* (2017)**, who reveal several new potential abandoned rift centres, mapped as syncline and anticline structures. These formed by extensional processes through rifting and rift jumps, causing crustal variations through time, apparently more common within the ridge complex than in the adjacent oceanic floor. Rift-jump events and crustal volume variations across the GIFRC can be linked to mid-oceanic ridge opening processes since 55 Ma, which challenges the long-held view that it formed as a hotspot track (Bjarnason 2008).

Geissler *et al.* (2016) describe the NE Greenland margin, where the break-up-related volcanic complexes are comparable with the better-known Mid-Norwegian–SW Barents Sea conjugate. Seismic facies types match between the conjugate pair and

show strong lateral variations. By focusing on the spatial and temporal evolution of the magmatic activity at late-rift and early oceanic drift stages, they are able to confirm that the initial oceanic rifting occurred subaerially in the area immediately north of the Jan Mayen Fracture Zone until about 49 Ma, when the spreading axis submerged below the sea level and normal oceanic crust was accreted.

Crustal structure

The crustal structure of the overall NE Atlantic has been one of the main targets of the NAG-TEC project and, together with the stratigraphic compilation, one of the major topics requested by our industry sponsors.

Seismic refraction profiles represent a unique dataset to constrain the depth to the basement. Unfortunately, the coverage is very inhomogeneous, with relatively good coverage along the NW European margins, but only a few profiles along the East Greenland margins and in the central parts of the ocean. **Funck *et al.* (2016a)** undertook a review and compilation of all existing refraction profiles in the NE Atlantic. The resulting seismic refraction database, combined with results from receiver functions and gravity information, was then used to compile various maps, such as the top-basement and Moho depths (**Funck *et al.* 2016b**), from which a crustal thickness map was derived, providing a consistent comparison of conjugate and along-strike variations in structure.

The paper by **Haase *et al.* (2016)** describes a 3D regional crustal model for the NE Atlantic, based on the integration of seismic constraints and gravity data. For the NAG-TEC Atlas, the 'DTU10' gravity dataset provided by Andersen (2010) had a homogeneous coverage and sufficient good resolution for the purpose of the project. Haase & Ebbing (2014) used it as their main input to compute Bouguer, free air, isostatic and tilt derivative versions of the grid to the Atlas and GIS database. Based on this first-order compilation, and on additional information from the seismic refraction compilation (see Funck *et al.* 2014), the model presented by Haase *et al.* (2016) offers a 3D perspective of the basement and Moho geometries in the NE Atlantic that permits an improved resolution of some areas, such as basins along the NE Greenland margin, as well as the GIFRC. The maps generated are particularly useful in areas with poor seismic data coverage, in particular where the Moho and basement maps obtained from the seismic refraction database are very coarse and lack detailed structure (Funck *et al.* 2016a).

Focused studies

The following six papers present in more detail specific regions within the NE Atlantic or discuss topics

related to the evolution of the oceanic basins and their continental margins.

The controversial distribution and causes for Cenozoic compressional structures along the NW European margin is discussed in **Kimbell *et al.* (2016)**. They compare the locations of the post-break-up anticlines with the crustal thickness maps derived from the NAG-TEC database. A correlation between the compressional structures and the distribution of high-velocity lower crust and/or partially serpentinized upper mantle is noted, and they suggest that the lithospheric weakening resulting from crustal hyperextension and partial serpentinization of the upper mantle, commonly viewed as a probable factor in the location of the compressional deformation, cannot account for all the post-break-up reactivation mapped in the region. Based on first-order rheological considerations, these authors suggest that an alternative weakening mechanism could include ductile lower crust and lithospheric decoupling.

On a similar theme, **Gradmann *et al.* (2017)** use simple isostatic calculations to compare to various geophysical datasets in order to identify areas of inconsistencies. Along the Mid-Norwegian margin, they use the density model built for the Haase *et al.* (2016) gravity inversion to forward-calculate bathymetry. They propose that the misfits with the observed bathymetry point to poorly understood regions that require further investigations.

The Jan Mayen microcontinent (JMMC) is one of the most striking structural features of the NE Atlantic, although its origin, evolution and boundaries are still highly debated. **Blischke *et al.* (2016)** present a revision of the architecture and structural development of the JMMC, with a specific emphasis on its Cenozoic evolution and relationship to the rift–drift transition during the emplacement of the Kolbeinsey Ridge. The authors update the structural interpretation, including all available seismic datasets, combined with other available geophysical data, borehole records and plate tectonic reconstructions (Gaina 2014). On this basis, they are able to highlight similarities in structural trends between the microcontinent and the Jameson Land (East Greenland) and Faroe–Shetland basins, suggesting that the three areas formed an en echelon set of rift basins that developed prior to the final opening of the NE Atlantic Ocean.

The Faroe–Shetland region is of particular interest to the oil and gas industry; however, much of the Faroese continental margin remains poorly understood due to the widespread cover of volcanic rocks associated with the NAIP. In order to establish what is and what is not known, **Ólavsdóttir *et al.* (2016)** present a review of the stratigraphy and structure of the Faroese margin, with an emphasis on providing both context and constraints for

ongoing discussions of the processes and events that have helped to shape this complex tectonic region. Seismic refraction data provide some indications of the pre-volcanic geology, which probably includes Archaean rocks overlain by a Mesozoic (Cretaceous?) cover. As a complement to this paper, **Petersen & Funck (2016)** provide a review of the seismic refraction models available in the Faroe–Shetland area and how the sub-basalt rocks were constrained in the individual studies. This allows for a better assessment of the pre-volcanic geology. Despite the seismic imaging problems due to the presence of the volcanic rocks, the review concludes that the Faroe–Shetland Basin is floored by thinned continental crust, overlain by sub-basalt sedimentary rocks.

Further west, **Gerlings *et al.* (2017)** describe the Ammassalik Basin of SE Greenland. This somewhat isolated basin is inferred to be conjugate to the basins in the northern Hebrides–Rockall region, and might contain at least 4 km of sediment. Proven sediments in the basin are of Cretaceous (Albian) age, but rocks as old as Permian–Triassic (as proven in the Hebridean basins) cannot be discounted. Sampling this basin would provide important information to better constrain the Upper Palaeozoic–Mesozoic history of this enigmatic southern segment of the NE Atlantic Ocean.

The oceanic domain and regional kinematics

Two papers by **Gaina *et al.* (2016, 2017)** gather information about the oceanic sub-basins in the NE Atlantic and propose a classification of oceanic crust domains linked to regional kinematics. **Gaina *et al.* (2017)** assess the break-up and oceanic spreading history of the NE Atlantic based on detailed mapping of magnetic anomalies, fracture zones and derived isochrons. A new oceanic lithosphere age grid and associated grids of seafloor spreading rates and asymmetry in crustal accretion were used to identify possible connections between tectonic and magmatic events and the formation and distribution of seamounts and volcanic edifices in the NE Atlantic oceanic domain (**Gaina *et al.* 2016**). They conclude that seamount formation and oceanic basement morphology are intimately related to the complex interplay between variations in relative plate motion and episodic plume activity.

The oil perspective

The paper by **Vis (2017)** offers an applied aspect to this volume, by combining the information of the NAG-TEC Atlas and GIS database with clustered oil-slick data from the Global Offshore Seepage Database, with the aim of identifying active oil seepage. In order to illustrate the strength of the

NAG-TEC database to support studies in underexplored areas in the NE Atlantic region, the author focused on three regions with oil-slick observations but with no current hydrocarbon activities: the Western Barents Sea Margin, the Irish Atlantic Margin, and the East Greenland and Jan Mayen regions. The potential value of integrating such diverse datasets in a frontier exploration area is discussed.

Additional key Atlas results

The above contributions span a wide range of geoscience methods and disciplines to offer scientific analyses, descriptions, modelling and interpretations that we consider as marking today's state of knowledge of the NE Atlantic at a regional scale. It is worth mentioning that the NAG-TEC project involved more compilation and research than published in this Special Publication. Several ongoing investigations could not be completed in time to make this volume, but will hopefully be available in other journals in the near future. The reader is referred to the original NAG-TEC Atlas (**Hopper *et al.* 2014**) for additional information, and some of the key highlights are described below.

The refraction compilation (**Funck *et al.* 2014**) further enabled the construction of basement-type maps (oceanic, continental, volcanic and non-volcanic transitional) and an assessment of areas with high-velocity lower crust, exhumed mantle or serpentinized mantle. The basement-type map permitted the NAG-TEC group to also work on a revised identification of the continent–ocean boundary (COB) (**Hopper *et al.* 2014**). Published COB locations usually vary considerably as they depend in large part on the dataset used, including both processing and display parameters. The strength of the NAG-TEC approach resides in the regional uniformity of the compilation that allows consistent mapping. Based on the basement-type map of **Funck *et al.* (2014)**, **Hopper *et al.* (2014)** constructed a regionally consistent line that connected the landwards-most points of seismically defined oceanic crust, which was then compared to the potential field grids, to the structural map and to plate kinematic reconstructions. Even with this regionally consistent approach, some problem areas remain, especially in areas with sparse seismic data.

The NAG-TEC project also included the compilation of the structural elements maps available over the entire NE Atlantic. G. Kimbell led the compilation shown in the Atlas. The resulting map includes GIS elements produced by the Norwegian Petroleum Directorate (**Gabrielsen *et al.* 1990**; **Blystad *et al.* 1995**), by the Petroleum Affairs Division (**Naylor *et al.* 1999**), and elements from the

Faroe–Shetland area based on the map published by the BGS and Jarðfeingi (Ritchie *et al.* 2011), as well as elements from the north Rockall area based on the map published by the BGS (Hitchen *et al.* 2013). For East Greenland, the structural elements are derived primarily from Hamann *et al.* (2005) and Tsikalas *et al.* (2005), with revisions based on re-analysis of available seismic, gravity and magnetic data compiled for the NAG-TEC project.

The contribution by Ártíng (2014) summarizes the compilation of geochemistry information related to the regional North Atlantic Igneous Province volcanic activity; the authors compiled, quality-controlled and cross-checked mapped occurrences of volcanic activity over the NE Atlantic.

Finally, the structure of the entire mantle from the Moho to the core–mantle boundary has been investigated by Spakman (2014) using seismic tomography. He provides an overview of the three-dimensional structure and shows a comparison between seven published models from different research groups, showing a miscorrelation between the short-wavelength details (<500–1000 km). Based on this, Spakman (2014) recommends caution when interpreting tomographical models of the North Atlantic mantle structure.

Our thanks go to every colleague who participated in the NAG-TEC project. This includes the more than 80 staff of the geological surveys who directly participated in the various tasks, including data compilation, quality control, uncertainty assessment, modelling, interpretation, graphic design and construction of the GIS database. We are also grateful to all of our colleagues from collaborating universities and other research institutes, including: the Alfred Wegener Institute (Germany); the Centre for Earth Evolution and Dynamics, University of Oslo (Norway); the University of Bergen (Norway); University College Dublin (Ireland); the University of Iceland (Iceland); and Utrecht University (The Netherlands).

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Correction notice: The original version was incorrect. The list of NAG partners was missing NGU (Norway). This has now been added.

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