Geology of the Northeast Atlantic region (Grønlandshavet and Norskehavet)

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The Northeast Atlantic region, covering the Greenland Sea (Grønlandshavet) and the Norwegian Sea (Norskehavet), can be divided into two geologically different areas, those underlain by oceanic crust and areas underlain by continental crust. The *oceanic crust* consists of Early Eocene to Holocene basalts recognised by their linear magnetic anomalies (24b and lower numbers), the oldest basalts dating back to the Early Eocene opening of the Northeast Atlantic Ocean (anomaly 24 b; 53 Ma). The oceanic crust is generally overlain by a thin layer of Cenozoic sediments. *The continental crust* consists mainly of silicic Precambrian basement, Caledonian nappes, and overlying thick successions of Phanerozoic supracrustal rocks. The boundary between oceanic and continental crust is marked on the map.

The history of the *continental margins* can be traced back in time to the Devonian collapse of the Caledonian mountain belt. This gravitationally driven extensional event was followed by a series of episodic Palaeozoic and Mesozoic rift events that culminated with continental separation in Early Eocene time. However, the North Atlantic has a much longer history, including the previous opening and closing of an older ocean named the Iapetus Ocean (the Iapetus suture is marked on the key map). The c. 300 m.y. period of episodic extension that started with the collapse of the orogen is amongst the longest known for any continental margin in the world. One typical consequence of the extension and thinning of the crust and lithosphere is that the margins subside below sea level (see section A, Mørebassenget, along the Norwegian coast). Only in areas where the margins have subsequently been uplifted are the rifted sequences exposed on the bordering mainlands (East Greenland, Svalbard, Bjørnøya and Andøya).

The *Caledonian* thrust fronts are well mapped both in Greenland and in Norway, and it is clear that the original mountain belt was split by the opening of the NE Atlantic ocean. As a result of orogenic collapse and subsequent rift events, fragmented Caledonian nappes form part of the substrate to the sedimentary deposits along the Norwegian and Greenland margins. The NE-SW-trending Caledonian structural grain, as exemplified by the Møre-Trøndelag Fault Complex, has strongly influenced the subsequent rift structures. This is an expected outcome of the so-called 'Wilson cycle' – during re-opening of previous sutures it is natural that old basement weaknesses are utilised. Because the rifting took place intermittently, and because individual rift events were separated by considerable time, the lithosphere beneath each rift was allowed to cool and to strengthen. Consequently, successive rifts tended to avoid previously rifted areas, and a pattern of shifting basins is therefore noted. The overall basinward shift in the locus of rifting is well documented in the subsurface off Mid Norway, and is also expressed in the partly exposed East Greenland margin.

On the Norwegian mainland there are few exposures of *Late Palaeozoic* and *Mesozoic* deposits. Middle Devonian redbeds deposited during the late-Scandian extensional collapse are found along the northwestern coast of South Norway (176), while Jurassic and Cretaceous strata are present on Andøya, North Norway (98, 86). On the East Greenland margin, Devonian to Tertiary deposits are more widespread and occur in basins that become sequentially younger toward the coast (171, 138, 114, 113, 99, 94, 88). The Tertiary sedimentary sequences are not seen on land on the map, but are present locally beneath the Palaeocene flood basalts (48). In the offshore area, Tertiary sediments cover most of the shelf and thick sequences have also prograded out onto the oceanic crust (sediments with yellow colours from 73 to 16), see also section A.

Just prior to continental separation, the outer portions of the margins were flooded by *subaerial Palaeocene basalts* originating from the incipient zone of break-up. The most widespread outcrops of such basalts are seen on the Blosseville Kyst in East Greenland (48), and on the Faeroe Islands (64); both areas are also marked on the key map (no. 5). Similar lava flows flooded large portions of the NE Atlantic margins. In the south, the Rockall Trough was more or less completely flooded. Farther north, the escarpments 'Færøy-Shetland-skrenten' and 'Vøringskrenten' mark the transition between subaerial and submarine lava flows, i.e. the palaeo-coastline. Similarly, lavas flooded the outer portion of the Møre and Vøring Basins off Mid Norway. Locally, hyaloclastite deltas are present landward of these lava fronts. In a releasing bend along the SW Barents Sea shear margin, Oligocene basalts form the Vestbakken Volcanic Province (39, no. 4 on the key map).

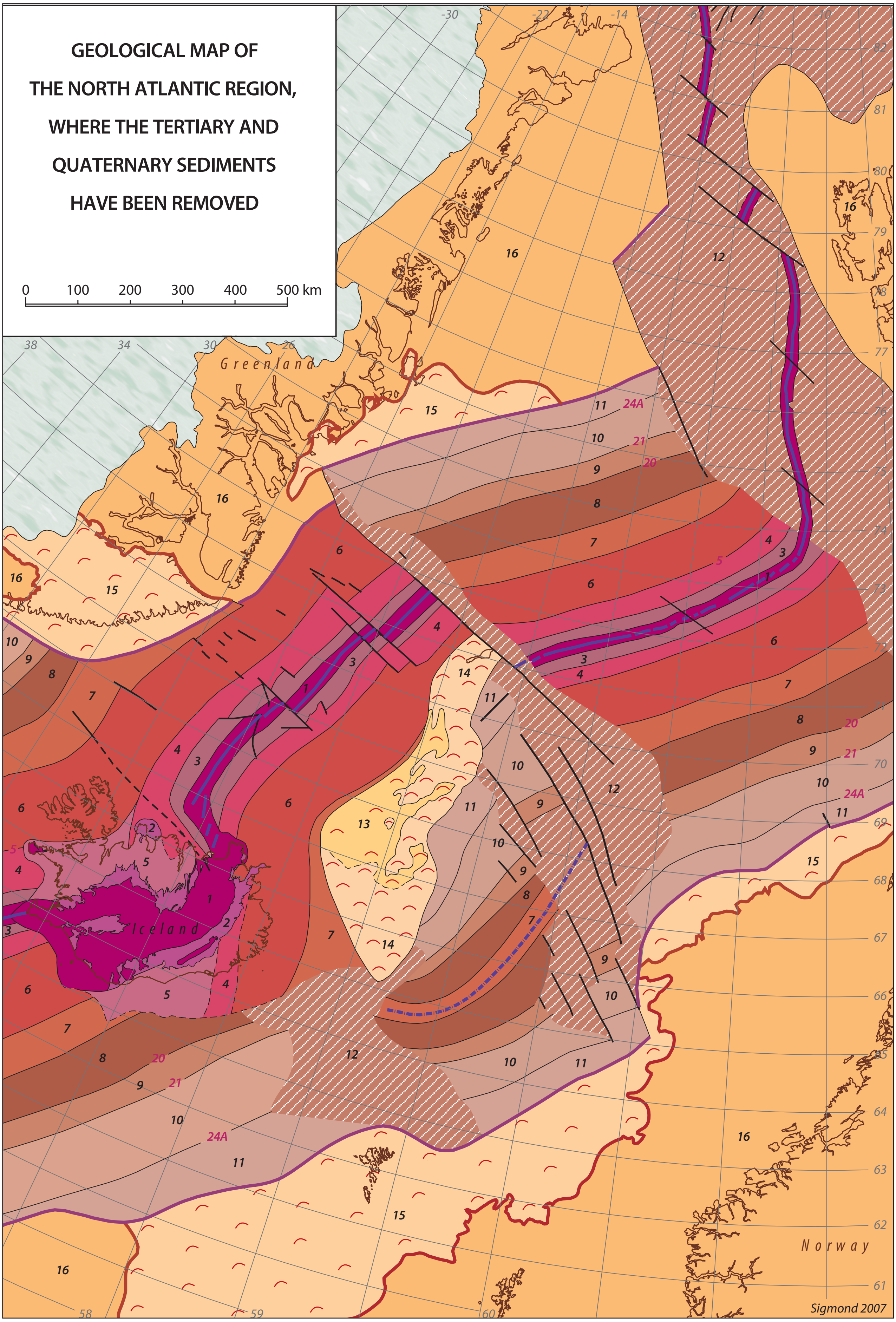
In addition, several large igneous complexes formed both onshore and offshore; some are seen in the northeastern Rockall and Hatton Troughs (74, 56), the Faeroe-Shetland Basin (59), and also in Britain (the British Volcanic Province). The subsurface of the continental margins is characterised by numerous examples and types of Palaeocene magmatic rocks, such as sills, dykes, volcanic vents and tuffs. These igneous rocks are quite voluminous and are collectively referred to as the North Atlantic Igneous Province, which is one of the world's large igneous complexes.

Prior to Late Tertiary time, the Palaeozoic and Mesozoic sequences were more widespread than they are today. However, in Neogene time the landmasses bordering the North Atlantic Ocean were uplifted and thereafter covered by ice caps inducing glacial erosion. The Mesozoic sedimentary sequences, in particular, were easily eroded because they had been deeply weathered when this region was located at subtropical latitudes (the plates of the region have since moved northwards). That the mainland areas were strongly uplifted is well illustrated by the offshore subcrop pattern. This is exceptionally well expressed along the length of the Norwegian mainland, where gradually older sedimentary sequences subcrop sequentially towards land (essentially an erosionally truncated monocline, see section C).

Despite being beneath the sea, and covered by various young sedimentary successions, the geology of the Atlantic continental margin is quite well known thanks to the intensive exploration effort for hydrocarbons since the late 1960s. A large number of commercial wells have been drilled within the rift sequences on the margins and have been supplemented by a limited number of scientific boreholes drilled mainly on the oceanic seafloor. These deep-sea drillings are marked on the map and the age and lithology of rocks in the boreholes shown to the left of the key map.

Except for the East Greenland margin, the margins are extremely well covered by seismic images, and gravity and magnetic data of the subsurface geology. Arguably, the area has the world's best sampled continental margins and the area is commonly used as an analogue for other margins. East Greenland's comparatively sparse data coverage reflects the logistical and technological challenge to marine data acquisition provided by sea ice and drifting icebergs.

The *Northeast Atlantic rift history* can be related to the break-up of the supercontinent Pangea, which started to rupture in Triassic time. Rifts formed in various places at different times as the supercontinent broke apart. Atlantic seafloor spreading was initiated in the Central Atlantic in Mid


GEOLOGICAL MAP OF
THE NORTH ATLANTIC REGION,
WHERE THE TERTIARY AND
QUATERNARY SEDIMENTS
HAVE BEEN REMOVED
0 100 200 300 400 500 km
Greenland
Iceland
Norway
Sigmond 2007

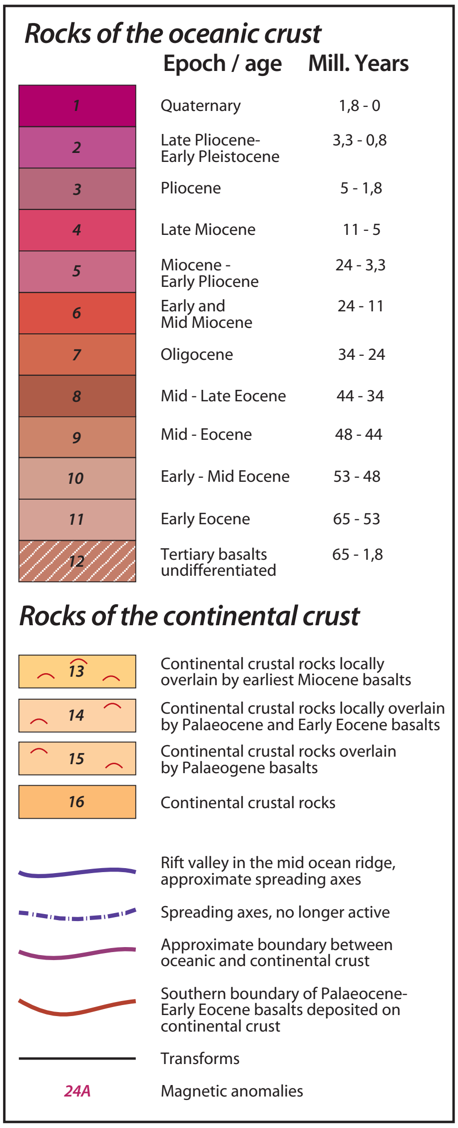


Fig. 1. The map is based on the magnetic anomalies and demonstrates both the course of spreading of the ocean floor and the discordance shown south of Iceland between the older basalts (3-8) and the younger ones (1 & 2). There is also an older discordance southeast of Iceland where rock units 4, 5 & 6 are rotated anticlockwise in relation to the normal, NE-SW-trending units 6-8.

Jurassic time, between NW Africa and eastern North America. From that region, rifting and seafloor spreading propagated northwards. The northward advancement of seafloor from the Central Atlantic first reached into the Labrador Sea and Baffin Bay on the west side of Greenland in earliest Palaeocene time (probably magnetic anomaly 29). In Early Eocene time (anomaly 24b) the opening started east of Greenland. North of Greenland, in the Arctic, seafloor spreading had also started in Early Cretaceous time. Precise links between the Cretaceous Arctic and Atlantic seafloor-spreading systems remain poorly understood. However, it appears clear that linkage was attempted. This is manifested by Early Cretaceous magmatic rocks exposed on Svalbard (102) and dykes that can be traced in magnetic datasets southeastward through the SW Barents Sea margin towards the Atlantic.

By Early Tertiary time, seafloor-spreading centres in the NE Atlantic and Arctic were linked via major shears where the plates moved past each other. The SW Barents Sea margin (from Senja to Svalbard) represents such a shear margin, and its counterpart forms the NNE Greenland margin (the Greenland fracture zone). Gradual opening of this shear margin started in earliest Oligocene time, when a major plate reorganisation event caused NW Europe (the Eurasian plate) to move obliquely away from Greenland. A major change related to this event was the abandonment of seafloor spreading in the Labrador Sea-Baffin Bay, which resulted in Greenland again becoming part of the North American plate. The difference in relative plate motions is clearly seen by comparing the trend of, e.g., the Greenland Fracture Zone with the trend of the current plate motion marked by the double arrows at the spreading ridges. Another significant consequence of the plate reorganisation was that the previous SW Barents Sea shear margin became transformed into a rifted margin. Associated with this oblique rifting, Oligocene magmatism occurred in the Vestbakken Volcanic Province (39). Approximately in earliest Miocene time (anomaly 7), seafloor spreading was established between the SW Barents Sea and NNE Greenland, forming the Arctic gateway. The precise time of opening of this gateway is a subject of ongoing research because of the major impact the cold Arctic waters have had on Atlantic oceanic circulation patterns.

A large portion of the prominent *Greenland-Faeroes Ridge* formed an important bathymetric barrier during the earlier part of the Tertiary. Opening of a gateway along this ridge east of the Faeroe Islands appears to have taken place in the Middle Miocene, when the ridge was breached. This event induced new oceanic circulation patterns in the North Atlantic, and resulted in submarine erosion by contourite currents as well as associated deposition of contourite drift sediments.

Iceland is the best known example of a surface exposure of a modern ocean ridge system, and represents a unique study area of phenomena connected to ocean spreading and active volcanism. The island is located approximately midway between the continental margins of Greenland and the Faeroes. Iceland is commonly referred to as a hotspot, but while the relationship between Iceland and the Earth's mantle remains a debated topic, it is obvious, and can be directly seen on the map, that this large island is the result of an exceptional volcanic activity. On Fig 1, with the help of the magnetic anomalies, we can easily see that the Late Miocene and younger basalts on Iceland are discordantly cutting the older basalts and the old magnetic pattern. This large volume of younger basalts also disturbs the pattern of underlying older magnetic anomalies that eventually may have existed below the younger basalts; thus, very few traces of the old magnetic anomalies are found on land on Iceland.

In Fig 1, on the map, Section A and on the key map, it can be seen that the crust of the North Atlantic is not everywhere of oceanic character. South of Jan Mayen lies a so-called *microcontinent*, a fragment of a continent surrounded by oceanic crust. Before continental separation this continental block was sandwiched between Greenland and Norway. The island of Jan Mayen is of interest as it exposes the world's northernmost active volcano, Beerenberg (2277 m a.s.l.) (Fig. 2), which experienced its last major eruption in 1970.

In Neogene time, widely spaced areas along the Atlantic margins started to rise. It is this relatively young uplift event that has generated most of the mountain topography seen in Norway today. Also Svalbard, large parts of East Greenland, and Scotland were uplifted at this time. The precise time of onset of the uplift event remains uncertain, and, if anything, its cause is even more enigmatic. However, what is clearer is that climate deterioration in the northern hemisphere in Late Pliocene time led to the build-up of major ice caps which may have nucleated on already uplifted areas. The ice caps quickly grew in thickness, resulting in major glaciers draining into the sea and eroding the mechanically weak sediments above the basement. As a result, enormous amounts of glaciomarine sediments were transported out onto the shelves. At major drainage sites, so-called trough mouth fans developed. Examples of such fans are the Storfjord and Bjørnøya fans off the SW Barents Sea margin, the North Sea fan which shed onto the Mid-Norwegian margin via the North Sea Channel, and the Scoresby Sound fan off East Greenland. These fans are so large that they are readily seen in the bathymetric contours of the map.

Fig. 2. (Left) A view of one of the lava streams and a delta of lava entering the sea on the coast of Jan Mayen. The photo was taken during one of the last major eruptions of the Beerenberg volcano on 22-23 September 1970. A few days earlier, a tongue of the Dufferin Glacier had occupied this very same lava trasé. Photo: C.A. Gløersen.

(Right) A night-time view during the same eruption, September 1970. Photo: C.A. Gløersen.

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