Offshore geology

Interpretation of the offshore geology around Greenland is based mainly on seismic surveys, supplemented by aeromagnetic and gravimetric data and, in the case of southern West Greenland, by data from five exploration wells drilled in 1976–77. Offshore South-East Greenland six holes have recently been drilled (three are shown on the map) in connection with the Ocean Drilling Project (ODP; H.C. Larsen *et al.* 1996). The coverage of geophysical data in different areas is, however, uneven, and is dependent on ice conditions. Off southern West Greenland, where there are only scattered icebergs and no pack ice in the late summer and early autumn, more than 37 000 km of seismic data were acquired by industry in the 1970s and a further *c.* 23 000 km of non-exclusive data have been acquired in this area since 1990 (Christiansen *et al.* 1996). On the other hand, the often ice-infested areas off East, North-East and North-West Greenland are only covered by reconnaissance surveys, principally as a result of the KANUMAS and North Atlantic D (NAD) surveys. The KANUMAS project was a marine seismic reconnaissance project financed by six major oil companies, with the Greenland-Danish national oil company Nunaoil A/S as operator (Larsen & Pulvertaft 1990; Pulvertaft 1997). In the 1990s KANUMAS surveys acquired *c.* 7000 km of seismic data off North-East and central East Greenland, and *c.* 4000 km of data off North-West Greenland. The North Atlantic D project was a combined aeromagnetic and seismic survey of the East Greenland shelf carried out by GGU in 1979–83. During this project *c.* 8000 km of seismic data were acquired off central East and South-East Greenland (Thorning *et al.* 1982; Larsen 1985). In Nares Stræde (Nares Strait) and off North Greenland, where no seismic data exist, interpretation of the geology is based on aeromagnetic and sparse gravity data alone. Aeromagnetic and shipborne magnetic data constitute the main source of information in oceanic areas.

The map is designed to show two general aspects of offshore geology: (1) the extent of continental crust [a], oceanic crust [c–g] and of the intervening, poorly understood, transition zone [b], and (2) the distribution of sedimentary basins and major faults. Where extensive volcanic units are known to occur in areas underlain by continental crust, their distribution is also shown.

The general distribution of offshore and onshore sedimentary basins is shown on Fig. 54.

The continental margin off East and North Greenland

In general terms, the continental margin off East Greenland between latitudes 60° and 76°N can be described as a volcanic rifted margin (Larsen 1990; Larsen *et al.* 1994a). The position of the continent–ocean transition was drawn on the basis of aeromagnetic data supplemented by characteristic features in the NAD reflection seismic data. The absolute seawards (eastern) limit of continental crust cannot overlap areas where linear magnetic anomalies characteristic of oceanic crust can be identified. Along the entire volcanic rifted margin seaward-dipping reflectors can be seen in the seismic data. These arise from subaerial lava flows or groups of flows which were erupted in the early stages of sea-floor spreading prior to differential subsidence below sea-level. In connection with the seaward-dipping reflectors buried volcanic escarpments may occur. These are landward-facing escarpments formed at the landward end of the dipping reflectors, where lava flows interdigitate with sediments (Fig. 46; Larsen & Jakobsdóttir 1988; Larsen 1990).

The zone off East Greenland shown on the map as underlain by transitional crust [b] was drawn in a rather arbitrary manner, at least with regards to its width. This zone is thought to consist of continental crust with increasing numbers of dykes and other intrusions as oceanic crust is approached. Much of the onshore coastal area around and south of Kangerlussuaq (68°N) is very intensely intruded by Early Tertiary coast-parallel

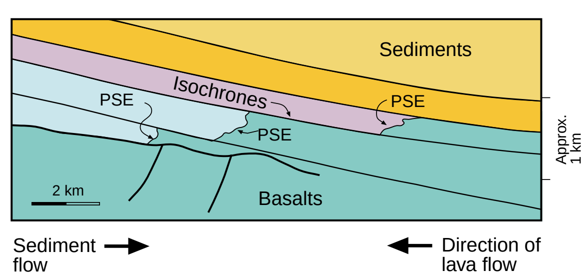

Fig. 46. Cross-section based on seismic section, illustrating the formation of so-called pseudo-escarpments (**PSE**) at the landward end of dipping basalts. **Sediments**: pale blue to light brown layers; **basalts**: dark green. Landward direction to the left. Slightly modified from Larsen (1990).

dyke swarms (Nielsen 1978; not shown on the map). Aeromagnetic data indicate that these dyke swarms continue south-westwards under the shelf as far south as 63°N (Larsen 1978). Such intense dyking suggests the proximity of the continent–ocean boundary, i.e. the outer edge of the transition zone.

Since the map went to press, intensive research has been carried out off southern East Greenland along Leg 152 of the Ocean Drilling Program Transect (ODP sites 914–919, *c.* 63°N) (Larsen & Saunders 1998; Larsen *et al.* 1998). Results of this research indicate that the continent–ocean boundary, defined here as the point at which thinned, intensely dyked continental crust finally gives way to a sheeted dyke complex, is situated about 12 km landwards of the shelf break (Larsen & Saunders 1998, fig. 12). The shelf break here is the edge of a thick prograding wedge of glaciomarine sediments. The inner boundary of the continent–ocean transition zone, defined as the point at which faulting and thinning of continental crust begins, lies 25–40 km landwards of the continent–ocean boundary (Larsen & Saunders 1998, fig. 12; Larsen *et al.* 1998, fig. 7). Thus the continent–ocean transition zone may be a little wider than shown on the map, and the continent–ocean boundary probably lies about 25 km north-west (landwards) of the position shown on the map.

At about latitude 68°N the eastern margin of continental Greenland trends obliquely across the linear

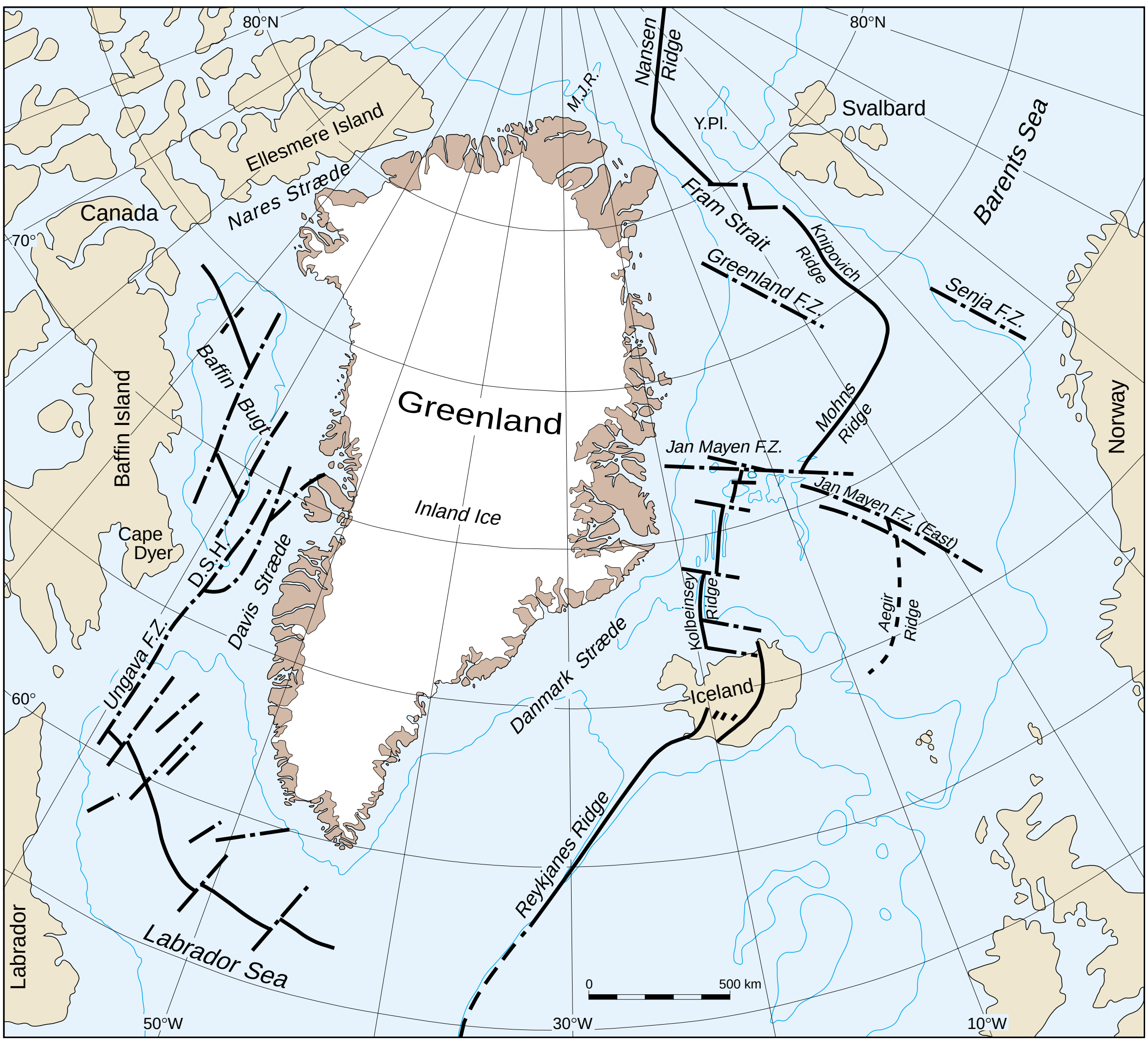

Fig. 47. Map of offshore regions around Greenland showing distribution of fracture zones (**F.Z.**) and ocean floor ridges. **M.J.R.**: Morris Jesup Ridge; **Y.Pl.**: Yermak Plateau; **D.S.H.**: Davis Strait High. The bathymetric contour shown is at 500 m.

magnetic anomalies in the oceanic crust. This is not regarded as the expression of a transform fault, but rather as an oblique ocean–continent transition along a former propagating spreading ridge. The presumed continental crust north of this zone may be intensely intruded by dyke swarms, but it is not thought to have reached the stage of being true oceanic crust. The propagating spreading ridge did not break through to the Jan Mayen Fracture Zone (*c.* 72°N) until close to anomaly 6 time (*c.* 22 Ma). A similar situation, but in much less accentuated form, is seen north of the Jan Mayen Fracture Zone where it seems that the spreading ridge propagated towards the south-west (Fig. 47).

The north-east margin of continental Greenland, north of 78°N, has a very different character. It is shown as a former intracontinental transform plate boundary. According to current interpretations of the history of the opening of the Greenland – Norwegian Sea and Arctic Ocean (e.g. Vogt & Tucholke 1989; Eldholm *et al.* 1990; Kristoffersen 1990) a substantial dextral lateral displacement of Svalbard relative to North-East Greenland took place in the time interval corresponding to magnetochrons 24R–13 (earliest Eocene – earliest Oligocene), prior to the opening of the Fram Strait between Greenland and Svalbard. In the early Oligocene a spreading ridge, the Knipovich Ridge, linking the Mohns Ridge and the Nansen Ridge, developed along the site of the earlier transform fracture, and since this time the flanking continental margins have developed as passive margins separated by an obliquely spreading ocean.

What little is known about the continental margin and ocean–continent transition off North Greenland has been summarised by Dawes (1990). One particular outstanding problem here is the nature of the crust underlying the Morris Jesup Ridge and its conjugate feature, the NE-trending part of the Yermak Plateau, north of Svalbard (Fig. 47). The most favoured interpretation is that these are volcanic plateaus overlying oceanic crust (Kristoffersen 1990, and personal communication 1993), although Dawes (1990) argues that the Morris Jesup Ridge has a complex structure and that it may contain appreciable continental remnants below a thick cover of volcanic rocks.

The continental margin off West Greenland

The continental margin off southern West Greenland also presents problems of interpretation, although more reflection seismic data are available from this area.

Distinct linear magnetic anomalies can be seen in the Labrador Sea off South-West Greenland (Srivastava 1978). The earliest magnetic anomalies trend NNW–SSE, while the younger anomalies (24 and younger) trend NW–SE, parallel to an extinct spreading axis roughly midway between Canada and Greenland.

The oldest unambiguous magnetic anomaly in the Labrador Sea is anomaly 27. The crust landward of this is shown as transitional crust on the map, but the nature of this crust is in fact not known. Srivastava (1978) and Roest & Srivastava (1989) indicated that linear magnetic anomalies could be identified much closer to the continental shelf than anomaly 27, suggesting 31 or 33 as the number of the oldest anomaly. However, modelling of the magnetic data acquired by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) during seismic transects across the Labrador Sea has shown that the data fit a model assuming oceanic crust with alternating strips of normally and reversed magnetised crust landwards as far as anomaly 26R or 27R (Chalmers 1991; Chalmers & Laursen 1995). Landwards of this a model assuming thinned continental crust intruded by reversed magnetised igneous material provides the best fit with the observed data. South of 62°N it appears that a serpentinised peridotite subcrops sediments in the outer part of the transitional zone and that the remnants of continental crust are very thin (Chian & Louden 1994; Chalmers 1997). Be this as it may, the transition zone between typical oceanic and normal continental crust is certainly much wider off southern West Greenland than it is thought to be anywhere off East and South-East Greenland. The seawards limit of normal continental crust off southern West Greenland lies well to the south-west of the continental slope, at water depths of more than 1500 m. This interpretation of the distribution of crustal types is supported by the structural pattern seen in the seismic lines. Both the normal continental crust and the zone of transitional crust show large tilted fault blocks overlain by syn- and post-rift sediments. The oldest sediments are most likely of Early Cretaceous age (see later).

The crust under Davis Stræde (Davis Strait) is estimated to be 22 km thick (Keen & Barrett 1972), which is intermediate between the thickness of normal oceanic and continental crust. There is a basement high below the strait (the Davis Strait High, Fig. 47), where the sedimentary cover is thin and locally even absent. Tertiary volcanic rocks have been penetrated by drilling on the Canadian side of the high (Srivastava 1983), and it has been suggested that the high is a volcanic plateau formed by hotspot volcanic activity, for which there is also evidence in the form of thick picritic lavas of Paleocene age in the Disko – Nuussuaq – Svartenhuk Halvø area in central West Greenland and at Cape Dyer (Fig. 47) on the south-east side of Baffin Island in Canada (Clarke & Upton 1971; Clarke & Pedersen 1976). However, on the Greenland side of the strait, sediments interpreted as of Late Cretaceous age have been traced on seismic lines westwards from the Ikermiut-1 exploration well (66°56′N) onto the eastern flank of the high (Chalmers *et al.* 1995), in which case the high is formed of pre-Late Cretaceous rocks. The crust under Davis Stræde is therefore interpreted by the Survey as being formed of thinned continental crust, in accordance with the interpretation of the distribution of crustal types farther south.

The nature of the crust underlying Baffin Bugt is not obvious. There are no distinct sea-floor spreading magnetic anomalies in this region, so interpretation of crustal types must be based on other geophysical criteria.

In the central, deep part of Baffin Bugt refraction seismic experiments have shown that the crust is very thin, the M (moho) discontinuity lying only 11 km below sea-level. The cover of sediments exceeds 4 km in all but the southernmost part of the bay. Seismic velocities in the crust below these sediments are in the range 5.7–7.0 km/sec (Srivastava *et al.* 1981; Balkwill *et al.* 1990), in agreement with those known from oceanic layers 2 and 3. Gravity and magnetic evidence is also consistent with the interpretation of the central part of Baffin Bugt as being underlain by oceanic crust (see Balkwill *et al.* 1990 for a review and further references), and this interpretation is adopted on the map. Recently, however, geophysical evidence has been presented which indicates that in north-western Baffin Bugt continental crust is replaced oceanwards by a layer of serpentinised mantle, which would account for the lack of linear magnetic anomalies (Reid & Jackson 1997). The absence of linear sea-floor spreading magnetic anomalies could also be attributed to very oblique spreading (see Roots & Srivastava 1984) and to the dampening effect of the thick sedimentary cover.

In the absence of sea-floor spreading magnetic anomalies, the landward limit of proven oceanic crust cannot be placed with any degree of confidence, and existing geophysical data are not sufficient to allow any interpretation of the position, width and nature of the continent–ocean transitional zone. The area underlain by continental crust has been delineated on the evidence of crustal thickness and structural style (large extensional faults and rotated fault blocks), the latter being known from a recent reconnaissance seismic survey conducted in the area by Nunaoil A/S as part of the KANUMAS project (Whittaker *et al.* 1997).

The nature of the geological structure underlying Nares Stræde (Nares Strait), the linear seaway separating Greenland from Ellesmere Island (Fig. 47), has for some time been a controversial subject (Dawes & Kerr 1982). Geophysicists have argued that the strait is the site of a major transform fault with a left-lateral displacement of more than 100 km that accommodated the opening of the Labrador Sea and Baffin Bugt during the Early Tertiary, and also of movement normal to the strait (e.g. Srivastava 1985). On the other hand geologists familiar with the surrounding onshore geology find that the maximum net lateral displacement of sedimentary facies belts and Ellesmerian structural features across the strait is of the order of 25 km (e.g. Okulitch *et al.* 1990).

Recent work in Baffin Bugt has diminished the likelihood that Nares Stræde is the site of a major transform fault, because the direction of transform fracture zones and hence spreading movement in this area is almost north–south, or at an angle of about 40° to Nares Stræde (see Fig. 47; Wheeler *et al.* 1996; Whittaker *et al.* 1997). It appears that Baffin Bugt spreading has been accommodated to a substantial degree by a series of rifts in the Canadian Arctic Islands together with compression in the Eurekan orogen.

Offshore sedimentary basins

Reflection seismic surveys have shown that large sedimentary basins occur offshore East Greenland between latitudes 67°–72°N and 75°–77°N, and offshore West Greenland between 63°–68°N and 73°–77°N. In the intervening areas off both East and West Greenland there are extensive Lower Tertiary basalts below which there are expected to be thick sedimentary successions, but these cannot be resolved in the seismic data.

North-East Greenland shelf (72°–80°N)

The existence of thick sedimentary successions on the North-East Greenland shelf was first suggested on the basis of interpretation of aeromagnetic data (Thorning *et al.* 1982; Larsen 1984). Judging from the known geology of the Barents Sea, the Norwegian shelf and onshore North-East Greenland, the age of these sediments is likely to be Devonian to Recent, with unconformities in the middle Permian and in the Cretaceous. From the gravity data, combined with the structural style seen in

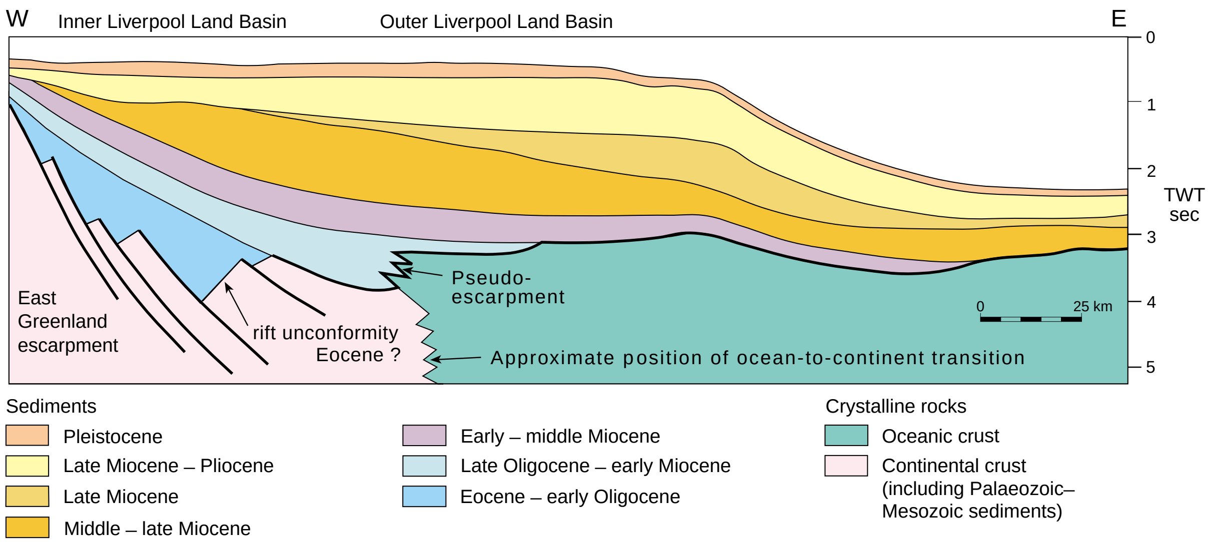

Fig. 48. E–W cross-section across the transition from continental crust to oceanic crust and the overlying Liverpool Land Basin at *c.* 71°N, East Greenland. Vertical exaggeration × 3.8. From Larsen (1990, plate 6, profile E).

some of the seismic lines acquired as part of the KANUMAS project, the presence of a widespread salt formation has been interpreted on this shelf. By analogy with the known geology of the Barents Sea area, it is presumed that this salt is of Late Carboniferous – Early Permian age.

On the shelf between latitudes 72°15′ and 75°30′N extensive volcanic rocks of presumed Early Tertiary age have been interpreted from the aeromagnetic and seismic data (Larsen 1990). In the near-shore area these are exposed at the seabed; eastwards they become increasingly deeply buried under younger sediments. It is considered almost certain that the pre-Tertiary sediments interpreted to the north and south of this area continue beneath the volcanic rocks.

Strong magnetic anomalies suggest the presence of igneous intrusions in the sedimentary and volcanic rocks at around 72°N.

Liverpool Land Basin, central East Greenland (70°–72°N)

A very thick succession of sediments can be recognised in the seismic data offshore Liverpool Land. The sediments are particularly thick within the part of the area underlain by continental crust, where the base of the sediments cannot be identified on the existing data. The upper part of the sedimentary succession is a virtually complete Tertiary succession up to 6 km thick; this formed a large prograding wedge that spread out across both continental and oceanic crust from the mouth of present-day Scoresby Sund. In the part of the area underlain by continental crust the Tertiary succession lies with angular unconformity on block-faulted and tilted sediments of pre-Tertiary (Late Palaeozoic – Mesozoic) age (Fig. 48), while where the Tertiary sediments have prograded into the area underlain by oceanic crust, the subsurface consists of subaerial lavas seen as seaward-dipping reflectors in the seismic data (Larsen & Jakobsdóttir 1988; Larsen 1990).

Blosseville Kyst Basin, East Greenland (67°–70°N)

More than 4 km of post-middle Eocene sediments occupy an elongate, coast-parallel sedimentary basin off the Blosseville Kyst. The sediments lie entirely on a subsurface of Lower Tertiary basalts. In the area underlain by continental crust there are almost certainly Mesozoic and Paleocene sediments beneath the basalts, as there are onshore and farther to the south (Ocean Drilling Program well 917A; Larsen *et al.* 1994a). However, it is not possible to interpret the geology underlying the basalts on the basis of existing seismic data.

Locally, as for example off Kap Dalton (69°25′N), there are pronounced positive features in the subsurface to the sediments; these are believed to be buried volcanic edifices.

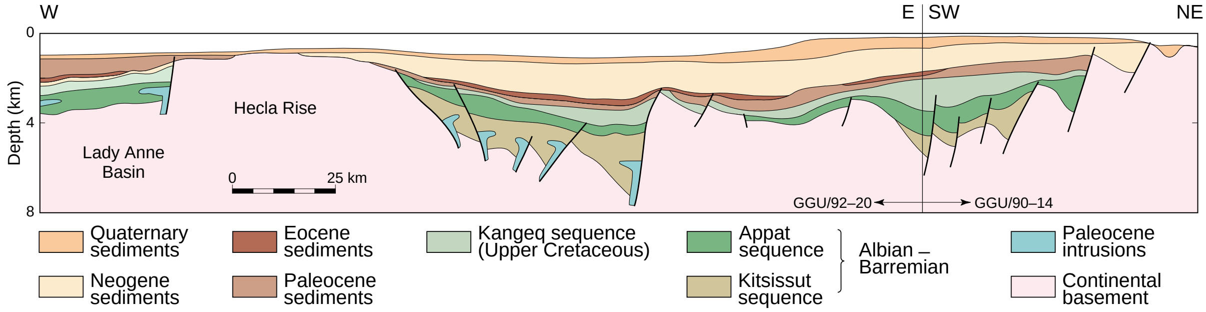

Fig. 49. Cross-section of offshore southern West Greenland at *c.* 64°30′N, west of Nuuk/Godthåb, based on interpreted and depth-converted seismic data. Vertical exaggeration × 5. From Chalmers *et al.* (1995).

Southern West Greenland (60°–68°N)

The earliest sediments offshore southern West Greenland are pre- and syn-rift sequences up to 3 km or more in thickness, the Kitsissut and Appat sequences (Fig. 49); by analogy with the better known Labrador Shelf, these are believed to be Early Cretaceous (Barremian–Albian) in age (Chalmers *et al.* 1993). These successions are overlain by a widespread Upper Cretaceous mudstone sequence, the Kangeq sequence, the upper part of which was penetrated in the Ikermiut-1 well (*c.* 67°N) . A major hiatus spanning the interval Campanian – early Paleocene (Nøhr-Hansen 1998) probably reflects the same episode(s) of faulting, uplift and erosion as are recorded in the succession in the Nuussuaq Basin. Following these disturbances fan sands intercalated with mudstones were deposited.

Deposition of mudstones continued into the early Eocene, but from the middle Eocene sedimentation was dominated by coarser clastic sediments deposited in simple prograding sequences. There are hiatuses within the Eocene in all of the West Greenland wells (Nøhr-Hansen 1998). During the Eocene, compressional structures developed in the area west of the Kangâmiut-1 (66°09′N) and Ikermiut-1 wells as a consequence of transpression along the transform system linking the sea-floor spreading axis in the Labrador Sea with that in Baffin Bugt, west of the map boundary (Chalmers *et al.* 1993).

Central West Greenland (68°–73°N)

The Lower Tertiary basalts exposed onshore in the Disko – Nuussuaq – Svartenhuk Halvø area continue offshore where they have been mapped from seismic and magnetic data over the entire area between latitudes 68° and 73°N. In the eastern part of this area the basalts are exposed at the seabed and have been sampled by dredging, but to the west they become increasingly buried under a cover of Eocene and younger sediments. While the upper surface of the basalts can be mapped easily from the seismic data, the base of the basalts

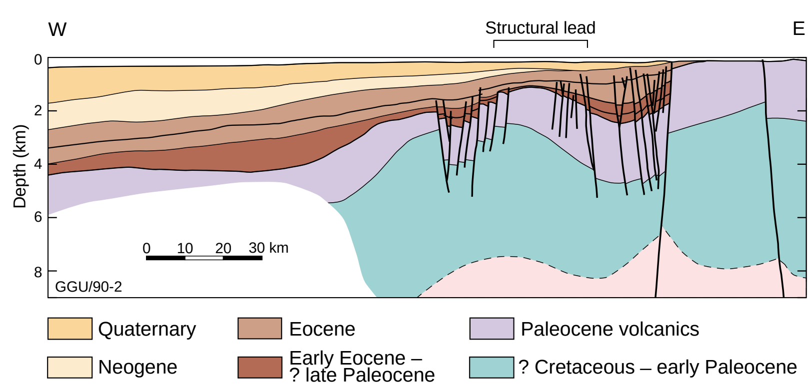

Fig. 50. Cross-section of offshore central West Greenland at *c.* 69°30′N, west of Disko. Drawn from depth-converted seismic data. Vertical exaggeration × 7. From Whittaker (1996).

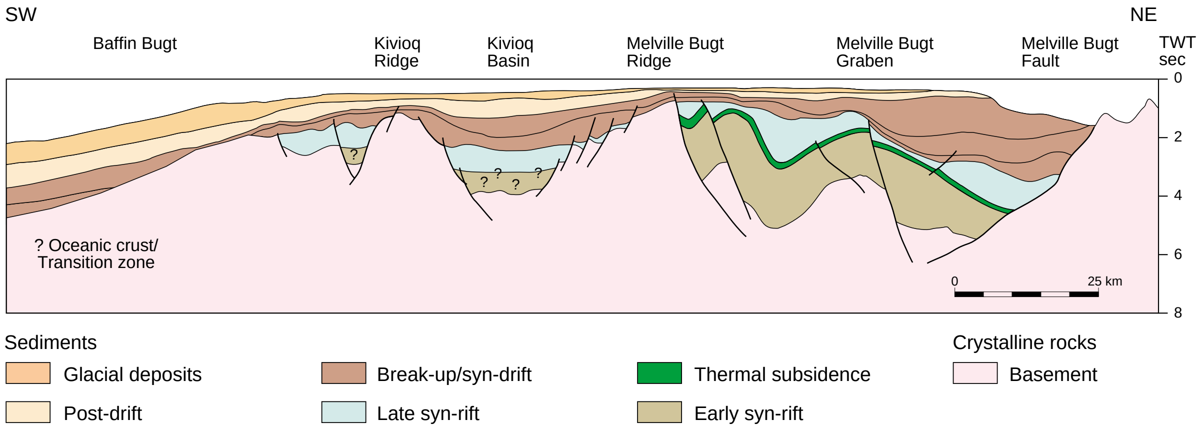

Fig. 51. Representative cross-section compiled from seismic reflection data from offshore North-West Greenland at *c.* 75°N, south-west of Melville Bugt / Qimusseriarsuaq. Vertical exaggeration × 2.5. From Whittaker *et al.* (1997).

usually cannot be interpreted and there are seldom distinct reflections from the underlying formations. Locally, however, as for example at *c.* 69°30′N, the basalts are thinner, and reflections from underlying sediments can be seen. In this area the basalts are only about 1300 m thick, and the thickness of underlying sediments may be as much as 5 km (Fig. 50; Whittaker 1996).

North-West Greenland (73°–77°N)

North of 73°N the new seismic data acquired as part of the KANUMAS project have confirmed the existence of a very deep graben or half-graben in the west and south-west part of Melville Bugt (Fig. 51; Whittaker *et al.* 1997). This had earlier been outlined from aeromagnetic and gravity data acquired in the late 1960s and early 1970s. The new data have also revealed several other graben and half-graben structures extending to the northern limit of the survey at 76°30′N. In the Melville Bugt graben the thickness of sediments exceeds 13 km. By analogy with the onshore geology of West Greenland and north-east Canada, the main phase of rifting is thought to have taken place in the Cretaceous, prior to sea-floor spreading in Baffin Bugt. Later, parts of the area were subjected to marked inversion.

Mineral deposits

Mining activities have been carried out in Greenland since the middle of the 19th century, with the cryolite mine at Ivittuut as the only long-term mine; it was in operation for a period of 130 years. The cryolite deposit was associated with a granite intrusion in the late Proterozoic Gardar Province of South Greenland (p. 26; Fig. 52, locality 5), and represents an example of a very rare type of mineralisation; there are only very few equivalent deposits in the world (Pauly & Bailey 1999). Other mining activities in Greenland have exploited more common types of mineralisation. The two most important were both lead-zinc deposits – one at Mestersvig in East Greenland was associated with quartz veins of probably Tertiary age, and the other at Maarmorilik in central West Greenland was a stratabound mineralisation in the Proterozoic Mârmorilik Formation (p. 20).

Mining activities have so far been very limited in view of the expected potential of such a large country. However, systematic exploration did not commence until the late 1950s and 1960s when new legislation governing the mineral sector was introduced to encourage the mining industry to undertake exploration. This