Mesozoic and older rift basins on the SE Greenland Shelf offshore Ammassalik

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Abstract: Seismic reflection data and shallow cores from the SE Greenland margin show that rift basins formed by the mid- to Late Cretaceous in the offshore area near Ammassalik. Here termed the Ammassalik Basin, this contribution documents the area using reprocessed older shallow seismic reflection data together with a more recent, commercial deep seismic reflection profile. The data show that the basin is at least 4 km deep and may be regionally quite extensive. Interpretation of gravity anomaly data indicate that the basin potentially covers an area of nearly 100 000 km². The sediments in the basins are at least of Cretaceous age, as indicated by a sample from just below the basalt cover that was dated as Albian. Dipping sediment layers in the basins indicate that older sediments are present. Comparison of the data to the conjugate Hatton margin where older basins are exposed beneath the volcanic cover shows similar stratigraphy of similar ages. Reconstructions of the position of the basin during the Permian–Triassic and Jurassic suggest that older sedimentary strata could also be possible. In contrast to the conjugate Hatton margin, possible older strata subcrop out below the seafloor along the shallow margin, providing a future opportunity to sample some of the oldest sediments to determine the onset of rifting between SE Greenland and the Hatton margin.

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The SE Greenland margin formed in response to rifting and break-up between Greenland and Europe during the Late Cretaceous–early Eocene (e.g. Larsen & Saunders 1998) (Fig. 1). Based on single-channel seismic data collected in the 1970s, B. Larsen (1980) and H.C. Larsen (1980) hypothesized the presence of Cretaceous sedimentary strata in the offshore areas near Ammassalik. However, the presence or absence of offshore sedimentary basins remained mostly speculative because of the massive cover of volcanic material that erupted just prior to and during final break-up (see Hornı´ et al. this volume, in review, and references therein). The problems inherent with seismic imaging below basalt is that it mostly obscures possible basins below the lava flows. Nevertheless, shallow, high-resolution seismic reflection data collected in 1997 along the shelf near Ammassalik confirmed the presence of apparent sedimentary layering stratigraphically below the basaltic cover (Hopper et al. 1998). During a subsequent shallow coring campaign, sedimentary rocks of Albian age were recovered from below the basalt, demonstrating for the first time the presence of older, Mesozoic sedimentary rocks in the offshore area (Thy et al. 2007).

In this contribution, the sedimentary basin offshore SE Greenland, here termed the Ammassalik Basin, is investigated further using older seismic reflection data in conjunction with a recent commercial, deep seismic reflection profile and regional gravity anomaly data. Three key seismic lines from the 1997 survey were reprocessed to better image possible basins in the area. The 1997 lines run perpendicular to the coast and the commercial line runs along the margin, tying together the older data. The reprocessing is described briefly, along with an interpretation and assessment of the probable thickness of the basin sediments. The approximate extent and dimensions are interpreted based on gravity data, indicating a substantial basin covering approximately 100 000 km². Plate reconstructions and comparison with the conjugate
margin and regional data suggest that the Ammassalik Basin was part of a well-developed Mesozoic rift system that is also observed along the Hatton margin. Along the northern Rockall and Hebrides margins, NE of the Hatton and Rockall basins, significant basin formation and development occurred throughout the late Palaeozoic and Mesozoic (e.g. Stoker et al. 2014, 2016). Several studies have suggested that significant pre-Cretaceous extension and basin formation must have also occurred in the Hatton and Rockall basins (Cole & Peachey 1999), although this is currently unproven and controversial (Stoker et al. 2016). The possibility of older sedimentary successions within the Ammassalik Basin is therefore considered here in light of reconstructed stratigraphic distribution maps back to Permian–Triassic times.

Regional setting

Onshore geology

The onshore area along SE Greenland is dominated by the Palaeoproterozoic Nangssugtoqidian Orogen (Fig. 2) (see Kolb 2014 for a recent summary). South of Kap Gustav Holm, no rocks younger than Proterozoic are known to crop out. Large onshore basaltic dykes, which can also be interpreted on the magnetic anomaly map, are Proterozoic in age (Riisager & Rasmussen 2014). The onshore region is thus devoid of any known Palaeozoic or Mesozoic rocks, and the geological history of the region over this time interval is mostly unknown.

North of Ammassalik, the nearest known sedimentary outcrops are found on Kap Gustav Holm (Figs 1 & 2). These are described as Upper Cretaceous–Cenozoic sandstones (Wager 1934), but little subsequent work has been carried out on these outcrops. They were described by Myers et al. (1993) as a 150 m-thick sandstone unit containing marine fossils near the top, and metamorphosed by a coastal dyke swarm and a nearby gabbroic intrusion, which is Eocene in age (Lenoir et al. 2003). The succession must therefore be older than this.

Further north, Cretaceous–Paleocene sedimentary rocks of the Kangerlussuaq Basin (Fig. 2) have been well studied and are described in Larsen et al. (1999). The Kangerlussuaq Basin consists of
an approximately 1 km-thick Cretaceous–Palaeocene sedimentary succession (Larsen et al. 1999; Henriksen et al. 2009). The sediments onlap crystalline basement to the east and north: however, the base of the succession is not observed elsewhere (Larsen et al. 1999; Henriksen et al. 2009). The sedimentary rocks belong to the Kangerdlugssuaq and Blosseville groups (Soper et al. 1976; Nielsen et al. 1981). The oldest exposed deposits are Upper Aptian–Lower Albian alluvial and shallow-marine deposits. Upper Cretaceous marine mudstones interbedded with thin turbiditic sandstones overlie these successions. In the early Paleocene, submarine fan sandstones were deposited along the northern basin margin, whereas mudstone deposition continued within the basin. Fluvial sheet sandstones and conglomerates of latest Paleocene age overlie unconformably the offshore marine succession (Larsen et al. 1999, 2001, 2006). In the mid-Cretaceous, the basin underwent transgression that led to a Late Cretaceous–early Paleocene highstand, which was followed by extensive uplift and basin-wide erosion in the mid-Paleocene. Subsequently, renewed subsidence and extensive volcanism initiated immediately prior to and during break-up.

Offshore geology

The offshore area is dominated by the Palaeogene volcanic province associated with the opening of the North Atlantic (e.g. Larsen & Saunders 1998). Because of its importance for understanding volcanism associated with the development of the North Atlantic Igneous Province, most work along the margin has focused on seaward-dipping reflectors are observed. These define the main volcanic cover along the margin (see Horní et al. this volume, in review). Magnetic chron C20–C24 are marked.

Fig. 2. (a) Bathymetric map of the SE Greenland margin near Ammassalik showing the available seismic data along with ODP legs 152 and 163 drill sites 917 and 988, and ODP Leg 163X drill site SEG80B. Thin grey lines indicate older single-channel seismic data from the 1970s; black lines are multichannel seismic data from the 1980s to present. The three DLC97 seismic lines (thick black) discussed in this paper are marked on the map, as is the TGS2012 profile (dashed line). Mid-Cretaceous sediments are exposed in the Kangerlussuaq Basin north of the Ammassalik Basin (e.g. Larsen & Saunders 1998). In addition, possible Cretaceous–Palaeocene sediments are found near Kap Gustav Holm (Myers et al. 1993). The Nagssugtoqidian Orogen boundaries are marked as dark blue dashed (south) and red dashed (north) curves. (b) Map of the magnetic anomaly onshore and offshore of SE Greenland (Nasuti & Olesen 2014). The dark shaded areas offshore represent the area where seaward-dipping reflectors are observed. These define the main volcanic cover along the margin (see Horní et al. this volume, in review). Magnetic chron C20–C24 are marked.
seafloor spreading between SE Greenland and northern Europe has occurred since then (e.g. White 1997).

While the early rift branch into the Labrador Sea was largely magma-starved (Chian & Louden 1994; Chian et al. 1995), the second rift branch was accompanied by extreme volcanism with a spike in volcanic productivity at break-up time (Holbrook et al. 2001; Storey et al. 2007). This volcanic event buried the main marginal basins. Consequently, the pre-Cenozoic tectonic evolution and basin history is poorly established, especially off the SE Greenland margin. Along the conjugate margin, basin evolution is linked to better investigated areas further east, where extension and basin formation began in the Palaeozoic as the Caledonian and Variscan orogenic belts collapsed (e.g. Ziegler 1988). In the Rockall Basin, the main rifting occurred in the Early Cretaceous, but reconstructions suggest that older rifting with $\beta$ stretching factors of up to 1.6 must have occurred (Cole & Peachey 1999). In the Hatton Basin, the main rift phase is generally assumed to be mid-Cretaceous (McInroy & Hitchen 2008). Of particular importance along the Hatton margin are several basalt-free windows where older basins are observed (Fig. 3). Albian sedimentary rocks were sampled in shallow cores taken by the British Geological Survey in 1999 from these basalt-free windows (Hitchen 2004). Analogous to the Rockall Basin, older rifting is thought to be likely (Cole & Peachey 1999). Nevertheless, the pre-Cretaceous history of the outer basins along the Hatton and Rockall margins is presently unconstrained by direct sampling.

**Data and methods**

The description and dimensions of the Ammassalik Basin are based primarily on seismic reflection data supplemented with gravity anomaly data. Most seismic reflection data collected along the SE Greenland margin was in support of ODP campaigns to sample the basaltic sequences (Larsen & Saunders 1998; Holbrook et al. 2001). Thus, most profiles are located further offshore, straddling the continent–ocean transition (Fig. 2a). Less attention was paid to the areas closer to the coast and possible underlying sedimentary sequences.

In this study, data from two seismic surveys were used. In 1997, a high-resolution survey was collected by the Danish Lithosphere Centre in support of a drilling campaign that used a 5 m rock-drill system to drill multiple holes along a stratigraphic transect. Seismic profiles were acquired as close to the coast as conditions would allow in order to locate the eastward edge of the basalt sequences for sampling of the oldest flows. The data were acquired with a high-resolution seismic system consisting of...
of 4 × 40 cubic inch sleeve guns chained together in a small cluster spaced 50 cm apart. Data were recorded on a 96-channel, 594 m streamer with a 6.25 m channel interval. In 2012, a commercial seismic profile was shot by TGS using a 6 km streamer and 3350 cubic inch tuned array. Three of the profiles from the earlier survey, DLC97-07, DLC97-08 and DLC97-09, showed reflectivity suggestive of older sedimentary basins stratigraphically below the basalts (Hopper et al. 1998). The commercial seismic line tied these three profiles together and confirmed the presence of significant sedimentary sequences.

Processing of the commercial seismic line followed current industry standards, and included multiple attenuation and pre-stack time migration. The earlier data, however, had only limited processing initially since the focus of the early studies was on the basalt cover, rather than on the underlying sequences. Only brute stacks of DLC97-08 and DLC97-09 have been published previously (Hopper et al. 1998; Thy et al. 2007, respectively). Therefore, the three DLC97 profiles were reprocessed to better image the sedimentary stratigraphy.

The reprocessing flow included SEG-D to SEG-Y conversion with geometry assignment, a source-signature deconvolution where the source wavelet is derived from averaging the direct wave, normal move-out correction and stack, post-stack Kirchhoff migration, coherence enhancement (dip scan stack: ±2 ms/trace), amplitude balancing, and bandpass filtering (10–20 Hz low-pass cutoff, and either 200–250 Hz or 50–100 Hz high-pass cutoff depending on target area). Because of the short streamer, multiple attenuation was not attempted and it is generally difficult to detect any signal below the first multiple. An exception, described further in the following ‘Interpretation of seismic and gravity data’ section, is for the case of line DLC97-09, where signals from some deep reflections are strong enough to penetrate through the multiples.

Because of the limited seismic coverage, only four profiles, it is difficult to establish the dimensions of the basin. Therefore, regional gravity data was used to estimate the potential lateral extent of the basin and to help define the main structural trends. The gravity data are from Haase
located, where a Proterozoic gneiss was sampled in shallow cores (Thy et al. 2007). Albian sandstone was recovered at Site SEG80B. The samples show that the high is a Proterozoic orthog- neiss (Thy et al. 2007). Seaward of this, a 12–13 km-wide section of dipping sedimentary strata is imaged, indicating the presence of a significant sedimentary basin. The basin is interpreted to be downfaulted relative to the Proterozoic basement. At the seaward-most edge of the basin close to the uppermost part of the stratigraphic succession, an Albian sandstone was recovered at Site SEG80B (Thy et al. 2007). Stratigraphically, these are the probably the youngest of the pre-Cenozoic strata imaged along the profile. Just seaward of this site, a step in the seafloor morphology is interpreted as the overlying basalt cover. This is in accordance with samples taken at all sites seaward of SEG80B. Dating of the basalt samples show they were extruded immediately prior to and during continental break-up (61–56 Ma). Both the sediments and the basalts dip seaward, and the samples consistently become younger seaward. Further seaward, a wedge of post-basalt Cenozoic sediments has been deposited. This sedimentary wedge is clearly imaged in the seismic profile (illustrated in the interpreted seismic section: Fig. 4a), but is not the focus of this paper.

The sedimentary basin imaged between the Pre-cambrian basement and Palaeogene basalts has a thin (c. 20 ms TWT (two-way time)) cover of Quaternary sediments overlying an up to 2.2 s dipping sequence of strata. In places, the sedimentary sequences are folded (Fig. 4c) and the section is reminiscent of the sections from Hatton Bank (Fig. 3) (Hitchen 2004). The folding appears to be deformational and some faults may be reversed, although this cannot be demonstrated unambiguously. It is suggested that the folding may be related to post-extensional inversion. Nevertheless, the overall seaward dip of the sedimentary successions suggests that the oldest sedimentary rocks subcrop out to the west. The uppermost and youngest sediments are to the east, where Albian-aged deposits were recovered just below the basalt (Thy et al. 2007). Thus, despite the possibility of later inversion, an overall significant stratigraphic thickness is indicated. Based on the substantial stratigraphic thickness indicated below the Albian deposits, we infer that basin development initiated well before the mid-Cretaceous, implying a significant Early Cretaceous rift phase, comparable to that inferred on the Hatton Bank (Cole & Peachey 1999; Hitchen 2004). Given the significant stratigraphic thickness, the presence of even older Mesozoic–Palaeozoic deposits cannot be ruled out.

Strong reflections within the shallow section are likely to be sill intrusions, as would be expected given the strongly volcanic nature of final rifting and break-up. Deeper strong reflections are also observed, however. Calculations of possible multiple energy paths show that these cannot be multiples from any of the main shallow reflections and thus some must be primary reflectivity (Fig. 5). Reflections at roughly 2.3, 2.8 and 3.2 s cross-cut the third and fourth water bottom multiples (Fig. 5). Modelling possible interbed multiples shows that the 3.2 s may be an interbed multiple of the overlying 2.3 and 2.8 s reflections (see Fig. 5, lower-right corner). The 2.8 s reflection may thus represent the base of the basin. Alternatively, the 2.3 s event is the basement reflection. Nevertheless, the basin has a significant depth of 1.7–2.2 s and is bounded by steep normal faults. Assuming P-wave

Fig. 4. (a) An interpretation of seismic line DLC97-09. At the most NW part of the line ODP drill site SEG32 is located, where a Proterozoic gneiss was sampled in shallow cores (Thy et al. 2007). To the east, the seismic data clearly show a succession of dipping and folded sediments (see also Fig. 3b). The base of this basin is at approximately 2.8 s. At the SE limit, Albian sedimentary rocks were recovered at ODP drill site SEG80B (Thy et al. 2007). Immediately east of this site, the basaltic cover is observed along the rest of the line. The approximately 30 km-long most NW part of the line is covered by a wedge of Cenozoic sediments. The two boxes indicate a close-up of the seismic sections in (b) and Figure 5. (b) Close-up of the top approximately 600 ms of the sedimentary basin observed on line DLC97-09. The location of the ODP drill site SEG80B is indicated in the most SE part of this seismic image. Note the succession of dipping and folded sediments. The dip direction of the sedimentary layers shows that the subcropping sediments become older towards land (NW). Some strong reflections are probably from sill intrusions. The box indicates a close-up of the seismic section in (c). (c) A close-up of folded and dipping strata along line DLC97-09. Notice how thin (c. 20 ms) the Cenozoic cover is. The seismic image is strikingly similar to that from the conjugate Hatton Bank (Hitchen 2004).
velocities of 3–4 km s$^{-1}$, a basin of up to 4 km thick is indicated. This is consistent with regional gravity inversion, which shows that the depth to basement along the shelf here is 4–5 km deep (Haase et al. 2016).

**Profile DLC97-08**

DLC97-08 is an approximately 63 km-long line that runs across the SE Greenland Shelf south of Ammassalik and terminates seaward at the limit of the basalt cover (Fig. 6). The landward-most approximately 6.5 km of the line images the Proterozoic basement with a thin layer of Quaternary sediments on top. The next approximately 15 km of the profile shows a distinct change in seafloor morphology (Fig. 6b). The seafloor shows prominent relief, probably carved out by Neogene glacial erosion. Seismic imaging below the seafloor in the bathymetric low is characterized by chaotic reflectivity, in contrast to the more acoustically transparent continental basement further landward. The section with chaotic reflectivity may indicate a softer substrate than the Proterozoic basement, and thus the reflectivity could indicate the presence of sediments or meta-sediments (see also the following discussion of profile DLC97-07).

Seaward of the segment with chaotic sub-seafloor reflections, a sedimentary basin is clearly imaged and can be traced for another 35 km along the profile (Fig. 6c). The basin is interpreted to be downfaulted relative to the Proterozoic basement. Extensional faults offset and deform the strata, compartmentalizing the basin with a main and deepest section situated in the middle of the profile (Figs 6c & 7a) and second thinner section located at the seaward end of the basin. Smaller, minor pockets of older sediments separated by fault blocks appear throughout the profile (Fig. 7b).

In the main part of the basin (Figs 6c & 7a), a thin layer of horizontally deposited sediment is interpreted as Quaternary cover. It is up to 80 ms thick, although some of this may be ringing of the source and the cover may be even thinner. Seaward-dipping sedimentary strata are reasonably clear immediately below the cover, although the imaging quality quickly degrades with depth. Strong, low-frequency reflections are interpreted as sill intrusions that follow the basin stratigraphy (Fig. 6c) and are even more clear in the first multiple (Fig. 7a). Reflectivity appears to continue to at least the first water bottom multiple at 2.1 s, indicating that the base must lie deeper than the multiple. Although not well imaged, some faulting is also indicated that, together with the steep dip, suggests tectonic activity after deposition. The sediments seem to be more horizontal in the seaward section of the basin, although the imaging here is significantly poorer (see Figs 6a & 7b).

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**Fig. 5.** A close-up of the deeper part (1500–4000 ms) of the sedimentary basin imaged on line DLC97-09; see Figure 4a for the location. Note the strong reflection that cross-cuts the third multiple at 2000–2500 ms, as well as the strong reflections at approximately 3000 and 3300 ms. Calculations of multiple energy show that the lower strong reflection could be an interbed multiple of the two reflections above (see the line drawing in the bottom right-hand corner). This suggests that the middle of strong reflections may be the base of the basin and that the basin is >2.5 s deep.
Fig. 6. (a) An interpretation of the seismic line DLC97-08. The boxes indicate close-ups of the seismic sections in (b) and (c), and in Figure 7. The legend is shown in Figure 4a. (b) Close-up of the landward-most flank of the sedimentary basin. Note the change from a smooth and flat seafloor to a seafloor with high relief from NW to SE. Below the smooth seafloor there is very little reflectivity, except for some low-frequency noise approximately 100 ms below the seafloor. The most NW part of the line is interpreted as Precambrian basement with a thin Cenozoic cover. In contrast, chaotic reflectivity is observed beneath the seafloor with high relief, suggesting a change in the underlying geology (see the discussion in the text). (c) Close-up of the top approximately 600 ms of the sedimentary basin observed in the centre of line DLC97-08. Like profile DLC97-09 described earlier, the seismic data show a succession of dipping strata with volcanic sill intrusions and a thin cover (up to c. 80 ms) of Quaternary sediments. The dipping strata are presumed to be Cretaceous and possible older sedimentary rocks. Rotated fault blocks are observed throughout the basin, which on this line is approximately 30 km wide. It is not possible to determine the basement depth along this line since it is concealed beneath the strong water bottom multiple. The most SE part of the line may just intersect the basalt cover, as indicated in Figure 2a. However, it is not possible to determine this from the DLC97 data.
The last 6.5 km and seaward-most part of the line images a series of normal faulted blocks with a thin cover of Quaternary sediments.

Profile DLC97-07

DLC97-07 is approximately 50 km long and runs parallel to DLC97-08 to the south. The 18 km landward-most part of the line displays a relatively smooth, low-relief seafloor morphology similar to the landward-most part of line DLC97-08 (Fig. 8). Hence, this part is also interpreted as Proterozoic basement. The seaward-most part of the line shows a seafloor morphology with low relief and evidence of shallow seaward-dipping reflectors interpreted as basalt flows, thus marking the feather edge of the break-up volcanism. In-between the basalt flows and the interpreted Proterozoic basement is a section with high seafloor relief with chaotic reflectivity, very similar to that observed along DLC97-08 (see seaward part of Fig. 6b). Small pockets of Quaternary sediments are deposited in the deepest part of this bathymetric depression. The regions of high relief are probably the result of erosion by continental glaciations. The stronger, more resistant areas were less affected by erosion and show more subdued relief, whereas areas with less resistant bedrock eroded more easily, resulting in the distinct seafloor morphology.

Sedimentary and metasedimentary rocks are likely to be more prone to erosion than basement, and we suggest that these bathymetric troughs are part of the Ammassalik Basin. Clear sedimentary stratigraphy like that imaged on profiles DLC97-08 and DLC97-09, however, are not apparent on this profile.

TGS seismic line

A commercial seismic line from 2012 ties the previous three profiles together (Fig. 9). Precise location information is confidential, so tie points along the southern part of the profile are not shown and the horizontal scale is unspecified for the northern portion where it crosses the SEG80B shallow core location. The profile covers two main basinal depressions. The northernmost one crossing the shallow core site is bounded on both sides by apparent basement. Although Proterozoic basement can be difficult to distinguish from a Palaeogene basaltic cover, the basaltic cover often shows a step-like morphology and is characterized by intra-basaltic reflectivity from the stacked lava flows. In contrast, the Precambrian basement appears acoustically transparent. Thus, the area to the north of the northernmost basin is interpreted to include a basaltic cover and the basin may continue to the north beneath it. The Proterozoic crystalline basement
separates the northern basin from the main basin further south, however.

The main part of the basin is very well imaged (Fig. 9). At least 2 s (3–4 km, assuming typical P-wave velocities) of sedimentary layering can be interpreted, showing that the sediment thickness here is consistent with that interpreted along DLC97-09. As noted earlier, this is also consistent with a depth to basement of 4–5 km from the regional gravity inversion (Haase et al. 2016).

The basins appear to be deformed and a number of intra-basinal extensional structures, graben and half-graben, are interpreted within the southern sub-basin. The Ammassalik Basin is therefore

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**Fig. 8.** (a) An interpretation of the seismic line DLC97-07. The box indicates a close-up of the seismic data in (b). The most NW part of the line is interpreted to be Precambrian basement with a thin cover of Cenozoic sediments. The most SE part of the line has a more step-like seafloor morphology, possibly indicating a basaltic cover. The legend is shown in Figure 4a. (b) Close-up of the central part of line DLC97-07 that crosses a significant bathymetric depression characterized by a high seafloor relief. The seismic image shows the same kind of high-relief seafloor and chaotic reflectivity as DLC97-08 (blue-shaded area: Fig. 5b). This area is tentatively interpreted to be underlain by a sedimentary basin.

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**Fig. 9.** (a) An interpretation of a commercial seismic line acquired by TGS in 2012. The line runs parallel to the coast and crosses the three DLC97 seismic lines. The seismic line confirms the existence of a large sedimentary basin south of Ammassalik, possibly more than 100 km long and approximately 2 s deep. A succession of dipping and folded sediments is observed, similar to those of the DLC97 lines. Steep faults and graben-like structures are also imaged. The older sediments are intruded by sills and covered by a thin layer of Quaternary sediments. The line crosses a large basement block that separates the larger basin south of Ammassalik from the smaller basin to the north along DLC97-09.
interpreted to have formed in response to rifting. Subsequent deformation has affected the basin and led to its present outline. Folding of the strata also resembles that imaged on DLC97-09 and is similar to the inversion of Cretaceous basins observed on the Hatton Bank (Fig. 3) (Hitchen 2004). Compressional inversion may thus have affected the Ammassalik Basin, although direct evidence of compression in the form of unambiguously imaged compressional faults remains to be documented. Part of the deformation is also interpreted to relate to magmatic intrusion of the basin. Furthermore, fairly steep faults have been interpreted that may be related to a component of strike-slip deformation.

**Gravity anomalies**

Gravity data were used to estimate the potential size and structural trends of the basin. Details regarding the regional gravity anomalies are given in Haase *et al.* (2016). Figure 10a shows the tilt derivative of the isostatic anomaly. The tilt derivative enhances edges of features that generate anomalies (Miller & Singh 1994). Here, the analysis is restricted to the shelf, where the anomalies reflect the shallow structures. Anomalies to the east are associated with the continent–ocean transition, and shelf-slope edge anomalies are avoided as they are less straightforward to interpret. On land, the anomalies are likely to reflect the topography beneath the ice sheet rather than the crustal structure.

Where the seismic line DLC97-08 and the TGS seismic line intersect regions of positive tilt, Proterozoic basement sub-crops at the seabed and regions of positive tilt are interpreted to represent basement highs along the shelf. This is particularly clear on DLC97-08 and suggests that a pronounced basement ridge bounds the main part of the Ammassalik

![Fig. 10. (a) Map of the tilt-derivative of the isostatic gravity anomaly onshore and offshore of SE Greenland. The tilt is positive over interpreted basement highs, and negative over interpreted sedimentary basins. (b) Possible extent of the Ammassalik Basin based on available seismic, bathymetric, gravimetric and magnetic data, together with the pre-break-up reconstructed position of the Hatton margin basalt-free windows containing Cretaceous sediments. The main section of the Ammassalik Basin runs from Ammassalik southward towards ODP drill site 917. This main part of the basin varies from a few kilometres to approximately 30 km wide, up to 4 km deep and potentially more than 200 km long. Landward of the main part of the basin there is a basement high. Adjacent to the basement high and along the coast there may be another sedimentary basin intruded by dykes. North of Ammassalik, line DLC97-09 crosses a smaller basin without a basalt cover. The gravity data suggest a potential sedimentary basin along the coast landward of drill site 988 and north of line DLC97-09. The position of the Hatton Bank basins suggests that the Ammassalik was part of a continuous rift system in the Early Cretaceous. The total area covered by the basin areas interpreted on the SE Greenland margin is approximately 100 000 km².](image-url)
The region of negative tilt that the TGS seismic line follows is interpreted to represent the main part of the basin. To the east, where there is no seismic coverage, a region of negative tilt is separated from the main basin by a linear region of positive tilt. This is interpreted as a basement high separating the main basin from an additional sub-basin to the east, as shown in Figure 10b. Thus, it is suggested that the basin continues beneath the basalt cover here.

The two westernmost areas of negative tilt separated by the basement high merge to the south and a low anomaly continues towards ODP Site 917, where sedimentary and meta-sedimentary rocks just below Paleocene basalt were recovered (Vallier et al. 1998). Interpretation of both the seismic and gravity data becomes complicated in this region. The possible southern continuation of the basins along the margin is uncertain, but seems unlikely. Reconstructing the positions of the Hatton Bank basins shown in Figure 3 to their position along Greenland at 80 Ma shows that they are along-strike and just to the south of the southern limit of the Ammassalik Basin, as interpreted here (Fig. 10b). The reconstructed positions are based on the poles of rotation of Gaina (2014).

Discussion

The seismic reflection data presented here show unambiguous sedimentary basins offshore SE Greenland. The main part of the basin appears to be just to the south of Ammassalik, and is documented by lines TGS2012-10, DLC97-07 and DLC97-08. A smaller basin is also clearly imaged just to the east of Ammassalik along the DLC97-09 profile, as well as in the TGS data. Although apparently smaller, the latter basin is significant because it was sampled by a shallow coring campaign, providing key evidence for Albian sandstones below the Paleocene basalts (Thy et al. 2007). The significant stratigraphic thickness indicated along the seismic profiles and the observed structural pattern suggest that major Cretaceous rifting affected the region. While the sparse seismic coverage makes establishing dimensions of the basin and interpreting the orientations of key structures and basin confining faults difficult, the interpretation shown Figure 10 indicates a sizable basin of approximately 100 000 km². In addition, while Cretaceous sediments are proven by core samples, the existence of pre-Cretaceous strata should also be considered. Possible ages for the basin are discussed based on plate reconstructions back to Permian–Triassic times.

Figure 10b shows reconstructed Campanian (80 Ma) positions of the basalt-free windows where Cretaceous sediments sub-crop out along the Hatton margin. These align well with the Ammassalik Basin trend outlined here. The southward continuation of the Ammassalik Basin is therefore suggested to be located on the Hatton margin. This implies a major transform boundary just south of the ODP legs 152 and 163 drilling transect. The position is approximately conjugate to the Anton Dohrn Lineament (Fig. 1), which is a prominent but complex region where transfer offset between the northern and southern Rockall basins occurs (Kimbell et al. 2005). It coincides with offsets in the continent–ocean boundary and is interpreted by Kimbell et al. (2005) to be a precursor of the oceanic transform faults that formed during early seafloor spreading (Featherstone et al. 1977; Smallwood & White 2002). Kimbell et al. (2005) showed that the main offset must predate seafloor spreading. If the interpretation here of the Ammassalik Basin and its southern continuation onto the Hatton margin is correct, then the main offset is likely to have occurred in the Late Cretaceous (Campanian–Maastrichtian) and after the deposition of most of the Cretaceous fill, which must be older than the Albian strata immediately below the basalts.

A central unresolved issue for understanding the regional Mesozoic development is at what point a through-going rift system developed between SE Greenland and NW Britain and Ireland (see Stoker et al. 2016 for a full summary). While eventual break-up in the Paleocene shows that by Late Cretaceous time this must have occurred, the older history remains enigmatic. Historically, most reconstructions show that this may already have occurred by the Jurassic (see Stoker et al. 2016 and references therein), which has obvious implications for understanding the development of regional petroleum systems.

Cole & Peachey (1999) proposed that pre-Cretaceous rifting and stretching are required in both the Rockall and Hatton basins to eliminate overlap between a small Rockall plate and the main European Plate. They estimated a pre-Cretaceous β stretching factor of 1.6, which would probably have resulted in a substantial and deep basin in these outer-margin areas.

Figure 11 shows reconstructed sediment distribution maps compiled during the NAG-TEC project (Stoker et al. 2014). It should be noted that, in these reconstructions, rigid plates are assumed and so margin deformation is not accounted for, and will lead to some distortion in the present-day size of basins v. their pre-stretched lateral extents (Gaina 2014). The Cretaceous fits at 100 and 80 Ma show...
Fig. 11. Plate reconstructions of stratigraphic distribution maps from SE Greenland and the European conjugate margins from the Permian–Triassic (250 Ma: red/purple), Jurassic (160 Ma: blue) and Cretaceous (100 and 80 Ma: green). The Ammassalik Basin is outlined in orange.
that the Ammassalik Basin overlaps well with areas inferred to contain Cretaceous basins along the conjugate margins. The Jurassic (160 Ma) and Permian–Triassic (250 Ma) fits are similarly intriguing, although the uncertainties of these fits are large (see Gaina 2014), and the ridge plate assumptions remain problematic. In particular, since the Cretaceous extension has not been accounted for, the position of the Ammassalik Basin could be further SE towards Ireland and Britain.

On the conjugate British and Irish flank of the North Atlantic, proven Jurassic sequences occur along the inner margins and in the Rockall Basin, but only limited Jurassic sedimentary sequences have been found on the Faroe–Shetland platform, and there is little information on the region between Rockall Basin and Faroe–Shetland region. Thus, it remains equivocal to what extent a significant Jurassic system had developed through the region as opposed to more isolated and disconnected basins (Stoker et al. 2016). As shown in the reconstruction, a possible Jurassic rift system would be likely to include parts of the SE Greenland margin, near to where the data presented here show the presence of a significant basin. Considering the Permian–Triassic reconstructions at approximately 250 Ma, the region of the Ammassalik Basin overlaps with areas of inferred Permian–Triassic basins along the NW British margin and the Faroe–Shetland platform. Here it suggested that some of the thick sedimentary accumulations in the Ammassalik Basin imaged in this study could be early Mesozoic and possibly even Palaeozoic in age, although this can ultimately only be proven by sampling the sequences.

Conclusions

The Ammassalik Basin offshore SE Greenland has been investigated using a combination of reprocessed shallow seismic reflection profiles, a recent commercial deep seismic reflection profile and gravity data. The results show the present-day vertical thickness of the basin is at least 2 s, or 4 km. This is consistent with gravity inversion results showing a depth to basement of 4–5 km along the shelf off Ammassalik (Haase et al. 2016). In several areas, steeply dipping strata are imaged over several kilometres of profile, indicating that the stratigraphic thickness of the basin fill could also be significant. Apparent folding and possible fault reversal indicate that later inversion and compression also affected the basin. Owing to the sparse seismic data, however, inversion cannot be demonstrated unambiguously.

The main basin fill is interpreted to be a result of rifting and extension between SE Greenland and the Hatton margin prior to eventual break-up and seafloor spreading, which initiated in the latest Palaeocene—earliest Eocene. Samples recovered from the stratigraphic top of the succession along one profile are Albian in age (Thy et al. 2007), indicating significant Early Cretaceous rifting and basin formation. Reconstructions to the conjugate margin show that the main part of the Ammassalik Basin is along-strike from areas of the Hatton margin where mid-Cretaceous sediments were recovered. This suggests that a well-developed regional rift basin system existed between SE Greenland and the Hatton/Rockall regions by this time. The boundary between the Ammassalik Basin and the basins along the Hatton margin coincides with the Anton Dohrn Lineament. It is suggested that strike-slip and transform motion developed in the Late Cretaceous, with the northern part of the basin system left on the Greenland side and the southern part of the system left on Hatton side after final break-up.

The older history of the basin is unconstrained by the available data. Reconstructions going back to the Jurassic and Permian–Triassic, however, show intriguing possibilities that a through-going rift system separating SE Greenland from the Hatton Margin could be older than Cretaceous. A sampling campaign targeting the oldest sediments where the data here show that they onlap Precambrian basement would provide important information regarding the complete history of rifting of the North Atlantic between SE Greenland and Europe.

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