Seismic volcanostratigraphy of the NE Greenland continental margin

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Abstract: The Early Eocene continental break-up between the NE Greenland and the mid-Norwegian–SW Barents Sea margins was associated with voluminous magmatism and led to the emplacement of massive volcanic complexes including wedges of seawards-dipping reflections (SDR). We study the distribution of these break-up-related volcanic rocks along the NE Greenland margin by revisiting existing seismic reflection data and comparing our observations to better-studied segments of the conjugate margin. Seismic facies types match between the conjugate margins and show strong lateral variations. Seaward-dipping wedges are mapped offshore East Greenland, the conjugate to the Vøring continental margin. The geophysical signature of the SDRs becomes less visible towards the north, as it does along the conjugate Lofoten–Vesterålen margin. We suggest that the Traill Ø volcanic ridge is a result of plume–ridge interactions formed between approximately 54 and 47 Ma. North of the East Greenland Ridge, strong basement reflections conjugate to the Vestbakken Volcanic Province are interpreted as lava flows or 'spurious' SDRs. We discuss our findings in conjunction with results from seismic wide-angle experiments, gravity and magnetic data. We focus on the spatial and temporal relationships of the break-up volcanic rocks, and their structural setting in a late rift and initial oceanic drift stage.

Supplementary material: The figures show the original seismic data used as the base for the interpretations shown in this paper. The seismic profiles are marked on Figure 1 (in the paper) as numbers 1 to 10 and are available at https://doi.org/10.6084/m9.figshare.c.3593780

The onset of continental break-up in the NE Atlantic region marked a culmination of an approximately 350 myr period of predominantly extensional deformation and intermediate cooling events subsequent to the Caledonian Orogeny (Ziegler 1988; Doré *et al.* 1999; Skogseid *et al.* 2000; Tsikalas *et al.* 2008; Faleide *et al.* 2010). Through the late Palaeozoic and Mesozoic, lithospheric thinning resulted in large sedimentary sag-basins controlled by regional detachment faults. Some of the early rift events were associated with magmatism, others were not. The final continental break-up occurred in the Early Eocene (at *c.* 54 Ma – magnetic Chron C24: e.g. Ziegler 1988; Doré *et al.* 1997) and was accompanied by massive magmatism that caused the formation of the North Atlantic Igneous Province (NAIP: Saunders *et al.* 1997), which extends into the NW Atlantic west of Greenland (Baffin Bay/Davis Strait) and extensively into the NE Atlantic from the Charlie Gibbs Fracture Zone south of Greenland to the Senja Fracture Zone in the north. Igneous rocks emplaced around the time of

break-up are mainly associated with voluminous extrusive complexes, thick initial oceanic crust or transitional crust with magmatically underplated material (high-velocity lower-crustal bodies) and intrusives. According to Eldholm & Grue (1994), a volume of 1.8×10^6 km^3 of flood basalts was emplaced onshore and offshore over an area of approximately 1.3×10^6 km^2. á Horni *et al.* (In review, this volume) estimated that the total volcanic volume including deeper intrusives, is approximately 9×10^6 km^3. Some authors favour a mantle plume contribution for these large volumes (e.g., Storey *et al.* 2007).

Hinz *et al.* (1987) provided the first detailed seismic study of the East Greenland continental margin, and summarized important findings published earlier by Hinz (1981), Mutter *et al.* (1982) and Talwani *et al.* (1983). These studies reported the presence of wedge-shaped bodies bounded at the top by a prominent seismic unconformity and generally exhibiting an internal pattern of divergent reflectors with ubiquitous seawards dips (the so-called 'SDRs' – seawards-dipping reflectors). Drilling during DSDP Leg 38 (Eldholm *et al.* 1986) proved that these wedges are composed of extrusive basaltic rocks, distinctly different from that of oceanic layer 2, of much greater thickness and erupted in a subaerial to shallow-marine environment (Hinz *et al.* 1987). However, a strong scientific debate about the structural and temporal setting of emplacements has remained. One model preferred a late rift stage with dyke intrusions, implying pre-break-up emplacement (Hinz 1981); the other preferred an origin by incipient seafloor spreading, implying post-break-up emplacement (Mutter *et al.* 1982). In consequence, the crust beneath the SDRs differs in both models: modified (transitional) continental crust is assumed in the late rift-stage model, and oceanic crust produced by seafloor spreading in the assumed post-break-up model.

Hinz *et al.* (1987) found a high degree of symmetry on the conjugate East Greenland and mid-Norwegian margins. Both along-strike and across-dip variations in the structure of the wedges are comparable, as well as the relationship to magnetic lineation patterns. Since the northernmost SDRs are landwards of lineation C24 at both margins, a late rift phase might be plausible (Hinz *et al.* 1987). Further south, SDRs are imaged at lineation C23 (disturbed), which would support a true seafloor-spreading origin of the SDRs. From these early observations, Hinz *et al.* (1987) concluded that initial subaerial seafloor spreading took place partly on highly extended continental crust (as evidenced by the geochemistry of basalts drilled in ODP 642: see Viereck *et al.* 1988). Recent geochemical analysis combined with C, Pb, Sr and Nd isotope compositions of drill-core ODP 642 samples

indicate the interaction of mid-ocean ridge basalt (MORB)-type melts with continental material, partly including highly radiogenic pelagic sediments rich in organic carbon deposits (Meyer *et al.* 2009; Abdelmalak *et al.* 2016*a*).

Later, Tsikalas *et al.* (2005, 2012) and Berger & Jokat (2008) provided new seismic data and details on the internal structure of the margin and its evolution, but did not focus on the magmatic activity and its variation along the margin. Voss & Jokat (2007) and Voss *et al.* (2009) studied the deep structure of the margin and the extent and volume of the magmatic underplate by means of wide-angle seismic data, and demonstrated the impact of break-up-related magmatism on the margin structure.

Results of comprehensive geophysical and geological studies along the SE Greenland volcanic margin are summarized in Larsen & Saunders (1998) and Hopper *et al.* (2003). Massive well-developed packages of SDRs could be mapped across the shelf and far offshore (e.g. Holbrook *et al.* 2001; Hopper *et al.* 2003).

While Hinz *et al.* (1987) argued that there is a well-developed symmetry between the NE Greenland and mid-Norwegian margins to the north of the Jan Mayen Fracture Zone (JMFZ), Elliott & Parson (2008) showed clear asymmetries between the Hatton Bank and the SE Greenland rifted margins. We re-evaluate the distribution and characteristics of break-up-related volcanic rocks along the NE Greenland continental margin (Fig. 1), applying the recent concept of seismic volcanostratigraphy proposed by Elliott & Parson (2008). This will allow for a detailed characterization of the temporal and lateral variations in the SDRs along the margin to better understand the volcanic activity before, during and after break-up.

Seismic volcanostratigraphy

Based on seismic observations along the North Atlantic and Western Australian rifted margins, Planke *et al.* (2000) developed a concept of seismic volcanostratigraphy to characterize volcanic deposits along passive continental margins based on seismic facies. Six seismic facies units had originally been defined: landward flows, lava delta, inner flows, inner SDR (seaward-dipping reflector), outer high and, finally, outer SDR. These units were interpreted in terms of a five-stage tectonomagmatic margin evolution model. The widely used concept was applied to various volcanic margins and underwent further modifications (e.g. Elliott & Parson 2008; Calvès *et al.* 2011).

Elliott & Parson (2008) adapted the Planke *et al.* (2000) model to characterize the Hatton Bank rifted
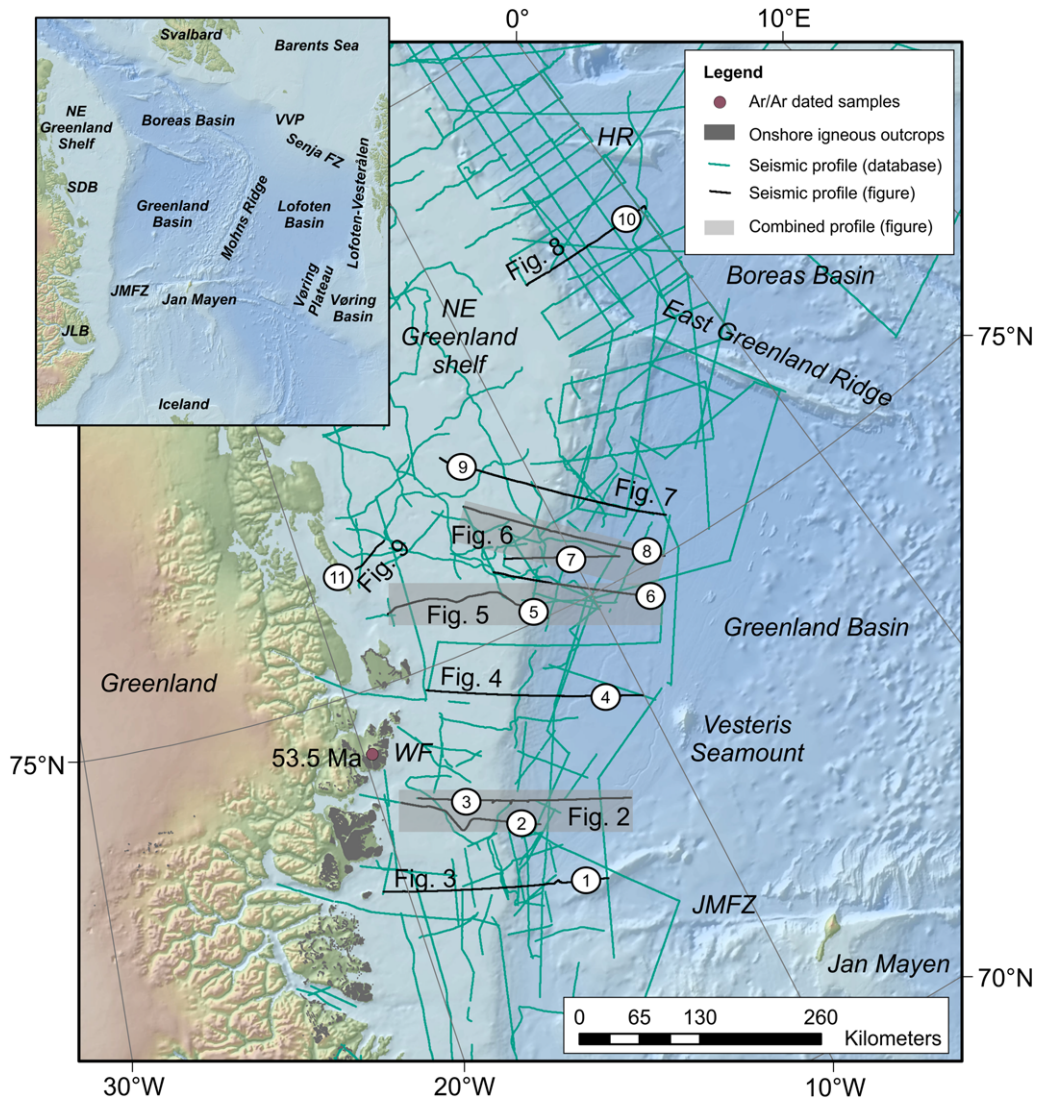
Fig. 1. Seismic reflection data (turquoise lines) along the NE Greenland continental margin used in this study. Profiles marked in black are shown in the figures. Profiles are numbered as follows: 1, AWI-20030550; 2, KAN91-05A; 3, AWI-20030560; 4, AWI-20030350; 5, KAN91-21; 6, AWI-20030370; 7, KAN95-11; 8, AWI-20030380; 9, AWI-20030390; 10, AWI-20020655; 11, KAN94-07. Dated magmatic outcrops (see Ganerød *et al.* 2014). HR: Hovgard Ridge; JLB: Jameson Land Basin; JMFZ: Jan Mayen Fracture Zone; SDB: southern Danmarkshavn Basin; VVP: Vestbakken Volcanic Province; WF: Wollaston Foreland.

margin, conjugate to the SE Greenland margin. Besides the main seismic facies units of Planke *et al.* (2000), Elliott & Parson (2008) slightly modified and added more characteristic features along volcanic rifted margins, such as rubbly basement and volcanic cones, but also included the smoothness or roughness of the nearby true oceanic basement (smooth, transitional, rough: see Funck *et al.* 2014; Gaina *et al.* 2016). The original outer SDRs

were classified as oceanic SDRs by Elliott & Parson (2008).

Data

Our re-evaluation of the NE Greenland margin is based on a combined set of existing and publically available seismic reflection data (Fig. 1). We

reviewed data previously used in separate publications by Hinz *et al.* (1987), Tsikalas *et al.* (2005) and Berger & Jokat (2008, 2009). Since the data were acquired over a period of more than 40 years using different seismic acquisition systems and processing protocols, the quality of the seismic reflection images varies greatly. However, the major seismic facies units (e.g. SDRs, outer high/volcanic mound) originally proposed by Planke *et al.* (2000) can be identified and characterized. In our description and interpretation, we follow the work of Elliott & Parson (2008), which additionally includes the concept of oceanic basement morphology.

The different seismic facies types were interpreted as shown on selected sections (Figs 2–8)

and mapped along strike; and the extent of the distinct volcanic types were interpolated in-between the sparse seismic profiles based on gravity and magnetic data (Haase & Ebbing 2014; Nasuti & Olesen 2014). In addition, we incorporated interpretations from regional wide-angle seismic profiles (Funck *et al.* 2014; Funck *et al.* 2016 and references therein) to account for magmatic additions to the base of the crust (as high-velocity lower crust and oceanic layer 3B).

Observations

In the following, we describe observations along selected seismic reflection profiles that illustrate
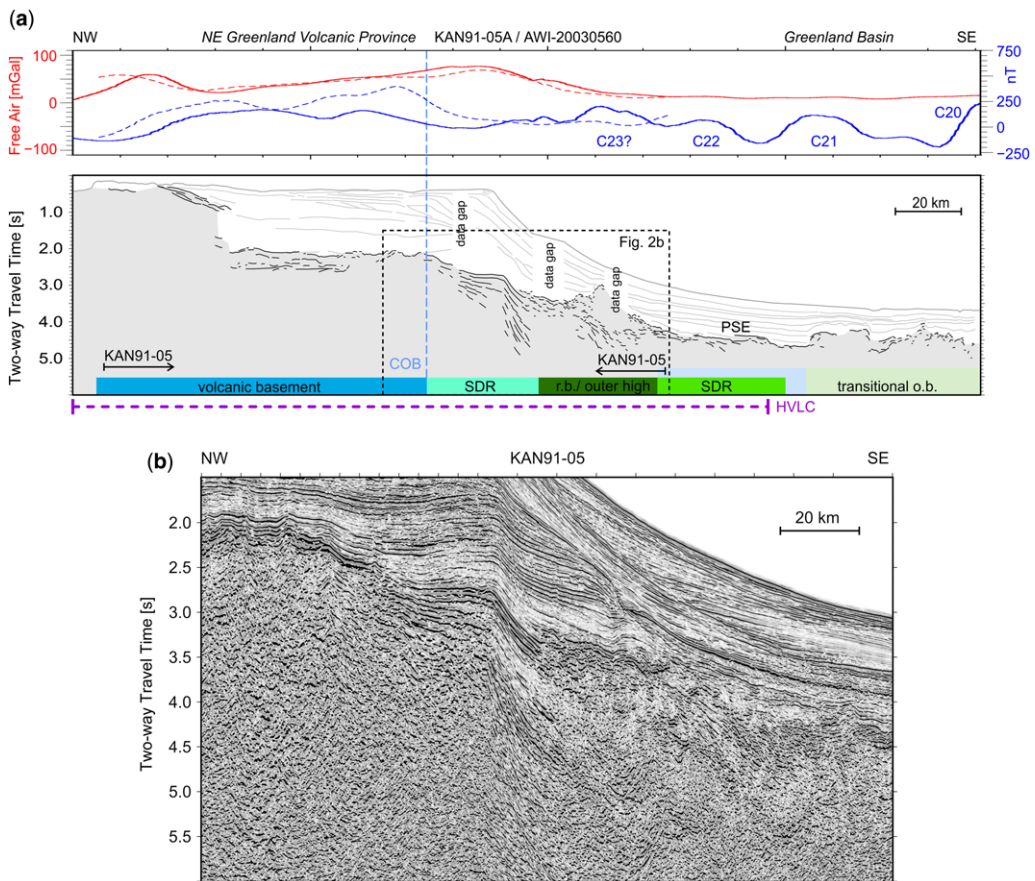
Fig. 2. (**a**) Interpretation of combined profiles KAN91-05A and AWI-20030560, illustrating the various volcanic seismic facies types. Helicopter starts and landings caused data gaps along line AWI-20030560 during the acquisition. The grey-shaded area marks the acoustic basement below the Cenozoic sedimentary cover. The continent–ocean boundary (COB) is as defined in Funck *et al.* (2014). The extent of the high-velocity lower crust (HVLC) (layer 3B in the oceanic part) as modelled by Voss & Jokat (2007) is indicated at the bottom. Gravity (Haase & Ebbing 2014) and magnetic (Nasuti & Olesen 2014) data are plotted on top. (**b**) Reflection profile KAN91-05A showing the interpreted seawards-dipping reflection (SDR) sequences in detail. o.b., oceanic basement; PSE, pseudo-escarpments; r.b., rubbly basement.
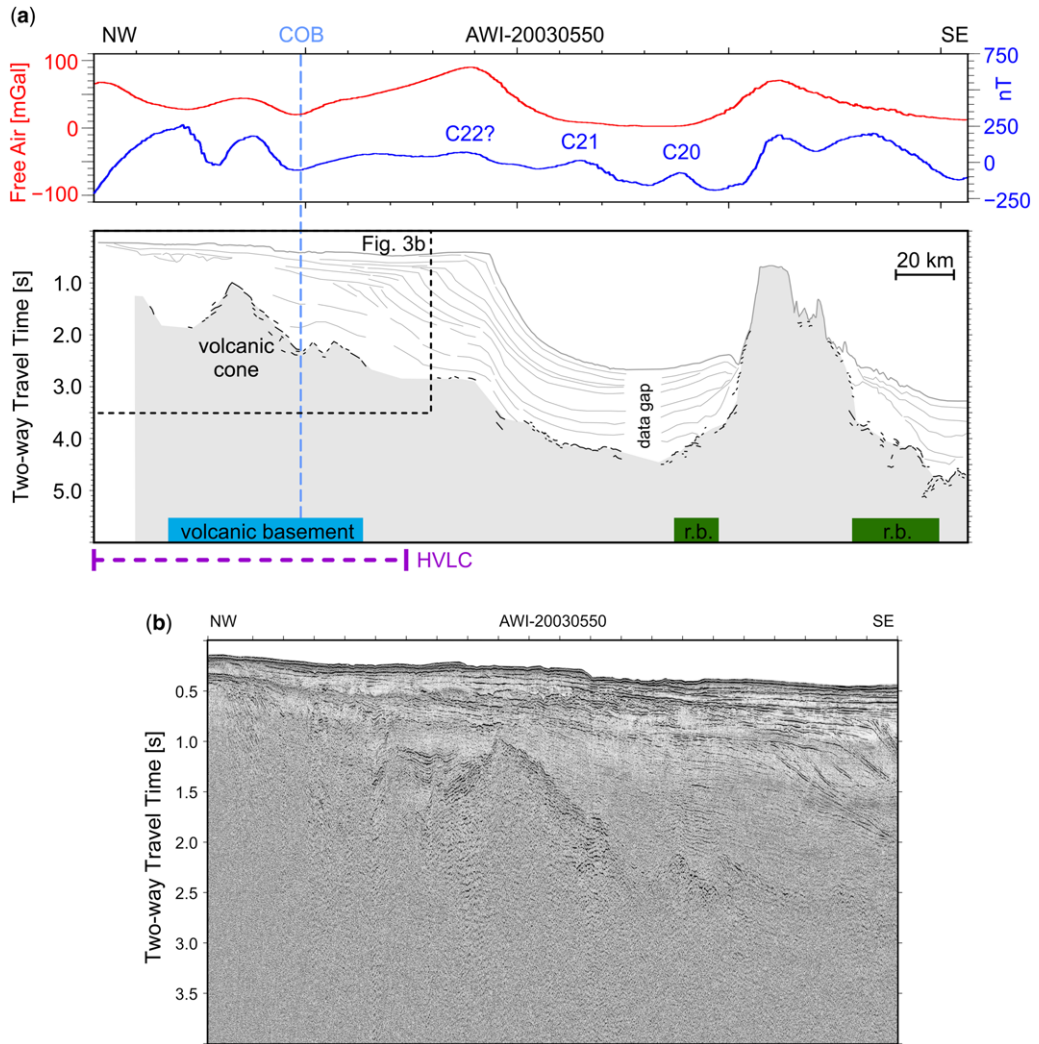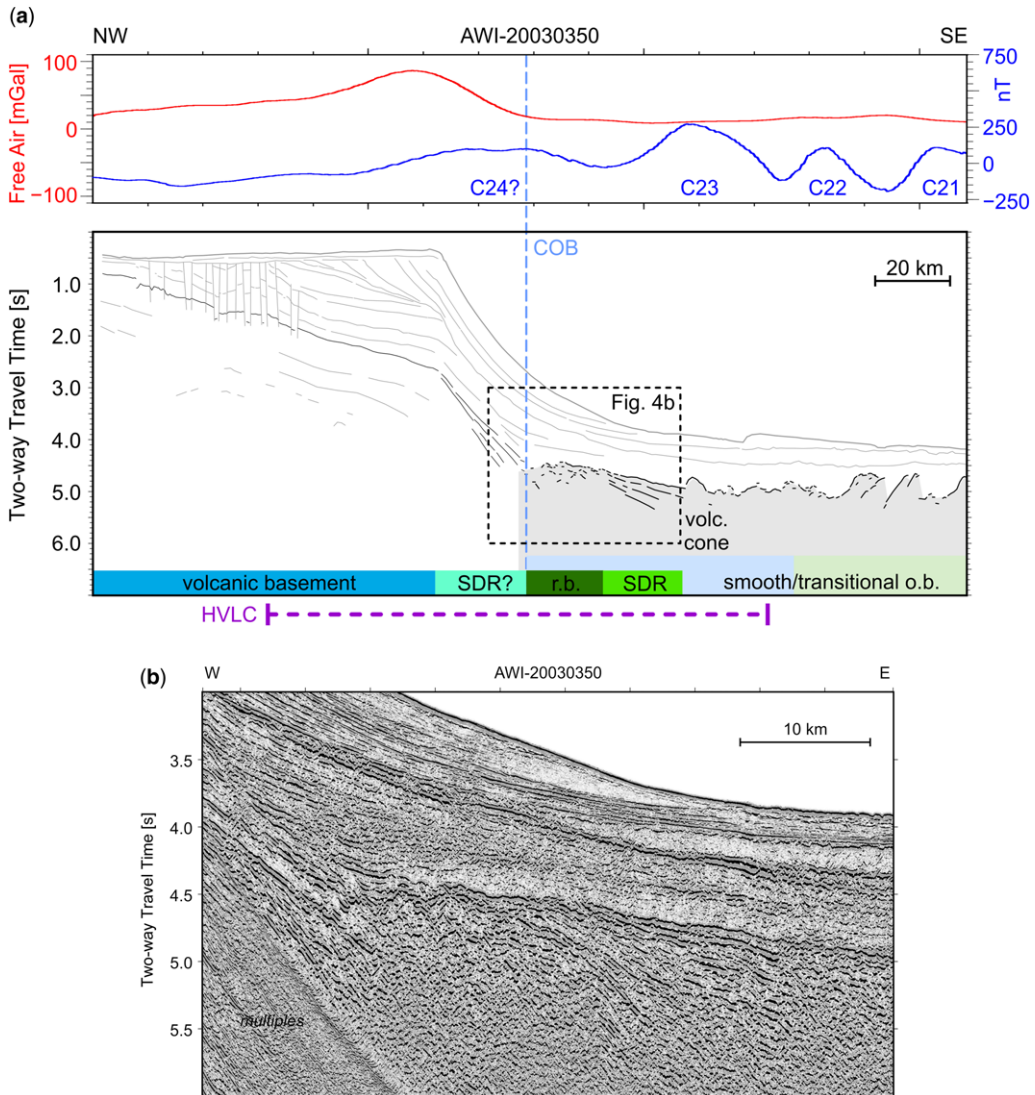
Fig. 3. (**a**) Interpretation of profile AWI-20030550 across the shelf just to the north of the JMFZ. The grey-shaded area marks the acoustic basement below the Cenozoic sedimentary cover. The continent–ocean boundary (COB) is as defined in Funck *et al.* (2014). The extent of the high-velocity lower crust (HVLC) (layer 3B in the oceanic part) as modelled by Voss & Jokat (2007) is indicated at the bottom. Gravity (Haase & Ebbing 2014) and magnetic (Nasuti & Olesen 2014) data are plotted on top. Line intervals of rubbly basement (r.b.) are marked in dark green. (**b**) Detail of profile AWI-20030550 showing the volcanic cone or ridge buried beneath the Cenozoic sediments.

the general quality of the data and the distribution of the magmatic features along the NE Greenland margin, from the JMFZ in the south to the NE Greenland sheared margin in the north.

The combined profiles KAN91-05A and AWI-20030650 image the shelf and the adjacent ocean basin at about 73.5° N (Fig. 2). This transect is the best example to illustrate the general volcano-stratigraphic model as originally proposed by Planke *et al.* (2000) for the conjugate Vøring

plateau–margin. High-amplitude continuous reflections, close to the seafloor at the western end of the transect, indicate the presence of lava flows beneath a thin sedimentary veneer that might be tied to nearby basalt outcrops along the East Greenland coast at Wollaston Foreland (age *c.* 53.5 Ma: Price *et al.* 1997) (see Fig. 1). A major scarp offsets these lava flows (volcanic basement) beneath the shelf. From the data, it is not fully understood whether this scarp represents a major fault. At the

Fig. 4. (a) Interpretation of profile AWI-20030350. The grey-shaded area marks the acoustic basement below the Cenozoic sedimentary cover. The continent–ocean boundary (COB) is as defined in Funck *et al.* (2014). The extent of the high-velocity lower crust (HVLC) (layer 3B in the oceanic part) as modelled by Voss *et al.* (2009) is indicated at the bottom. Gravity (Haase & Ebbing 2014) and magnetic (Nasuti & Olesen 2014) data are plotted on top. (b) Detail of profile AWI-20030350 showing the rubbly basement. o.b., oceanic basement; r.b., rubbly basement; SDR, seawards-dipping reflection; volc., volcanic.

position of the shelf break, the reflection pattern of the acoustic basement (a wedge of high-amplitude reflections) resembles the inner SDRs of Planke *et al.* (2000). SDRs also continue beneath the shelf slope along profile KAN91-05A (see Fig. 2b), while the flanks of an outer high (magmatic centre) are imaged on profile AWI-20030560. Beneath the shelf-rise sediments, lava flows (high-amplitude

continuous reflections) with pseudo-escarpments *sensu* Larsen (Larsen 1990) are imaged, which represent the outer SDRs of Planke *et al.* (2000) and oceanic SDRs of Elliott & Parson (2008). Further eastwards in the Greenland Basin, transitional (regarding roughness) oceanic basement is imaged. Voss & Jokat (2007) map magmatic underplating (high-velocity lower crust–oceanic layer 3B) up to
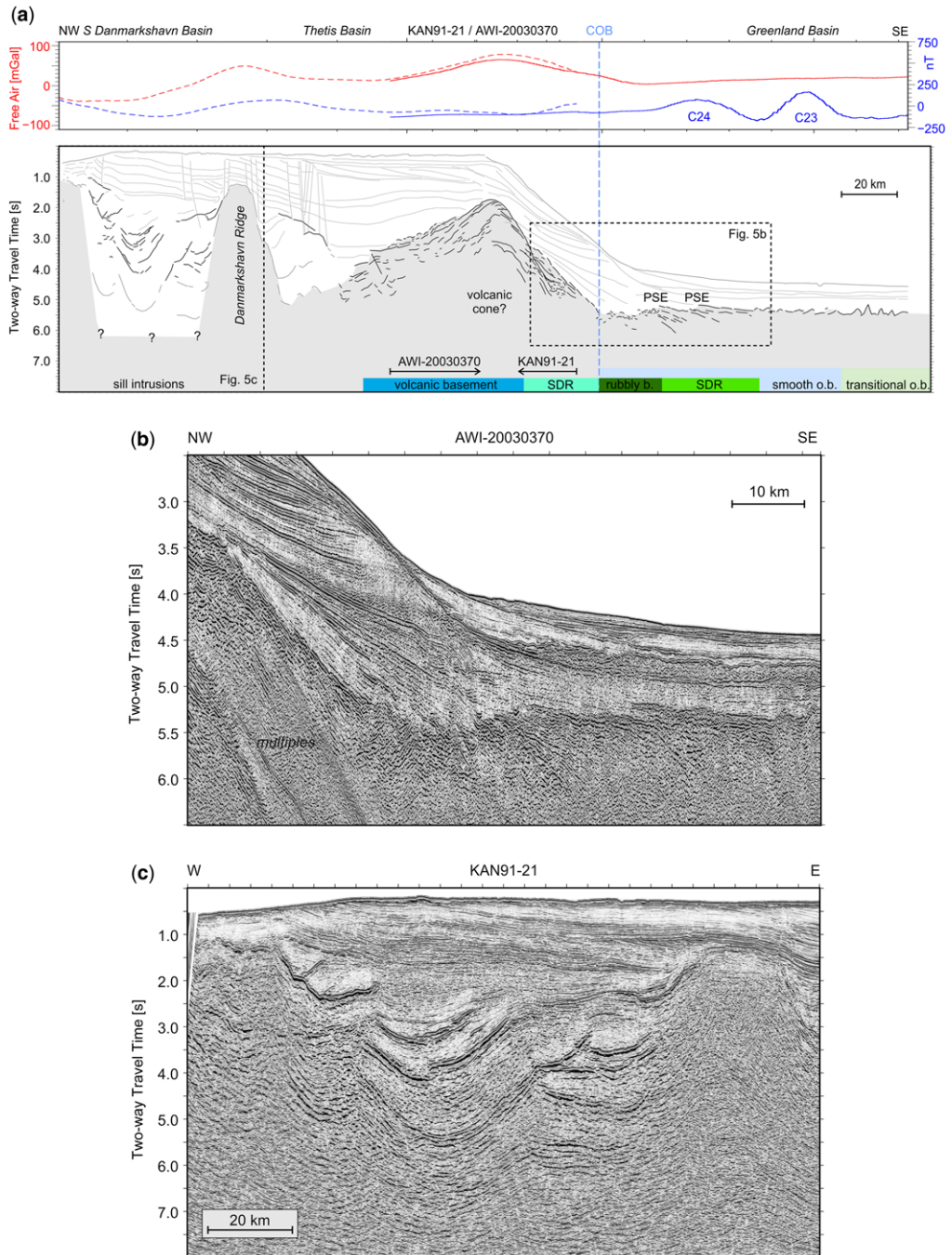
Fig. 5. (**a**) Interpretation of combined profile KAN91-21 and AWI-20030370 spanning from the East Greenland coast towards the Greenland Basin. Continent–ocean boundary (COB) is as in Funck *et al.* (2014). Gravity (Haase & Ebbing 2014) and magnetic (Nasuti & Olesen 2014) data are plotted on top. Sill complexes are imaged in the southern Danmarkshavn Basin. (**b**) Seismic section of profile AWI-20030370 illustrating the rubbly basement and the outer (oceanic) SDRs with its pseudo-escarpments. (**c**) Seismic section of profile KAN91-21 illustrating the sill complexes in the southern Danmarkshavn Basin. o.b., oceanic basement; PSE, pseudo-escarpments; rubbly b., rubbly basement; SDR, seawards-dipping reflection.
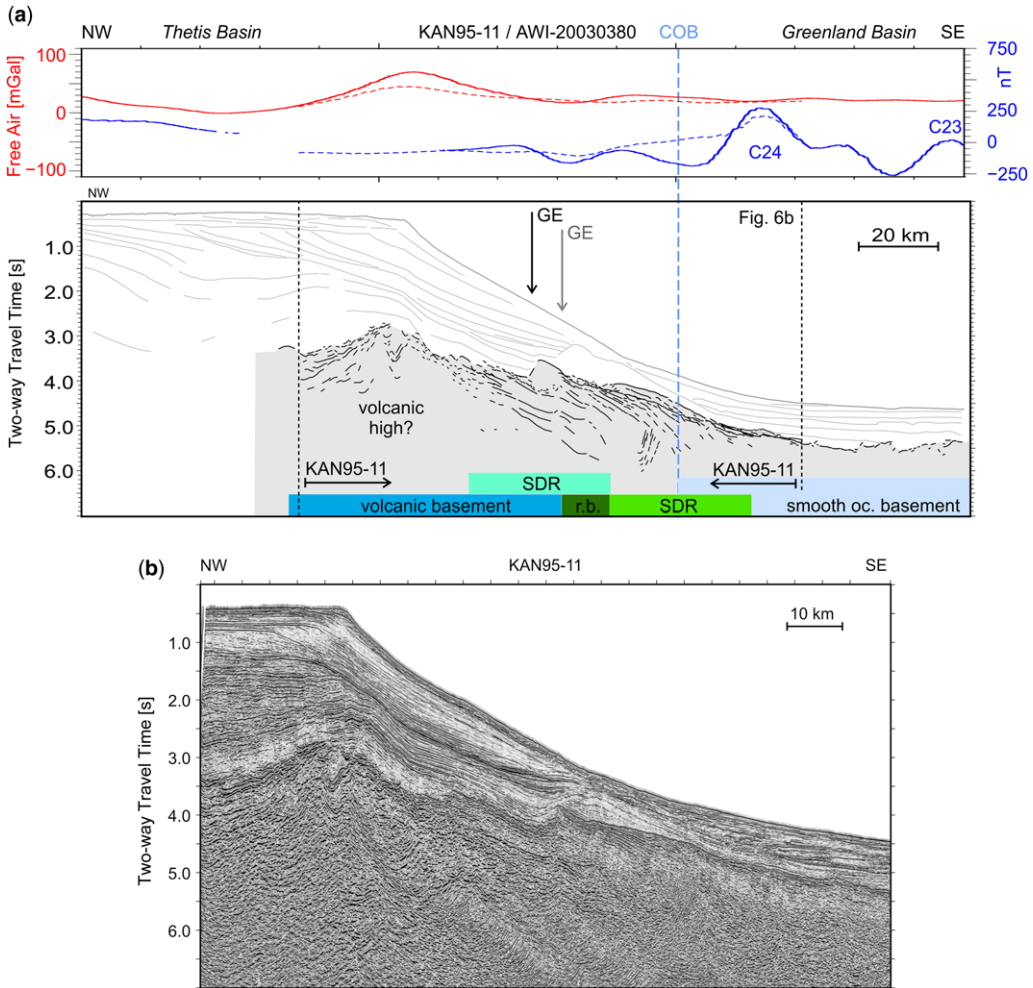
Fig. 6. (**a**) Interpretation of combined profiles KAN95-11 and AWI-20030380 imaging the magmatic complexes at the continent–ocean boundary (COB). The COB is as in Funck *et al.* (2014). Gravity (Haase & Ebbing 2014) and magnetic (Nasuti & Olesen 2014) data are plotted on top. (**b**) Data of profile KAN95-11 clearly showing the seawards-dipping reflections (SDRs) beneath the continental slope and rise. GE, Greenland Escarpment; oc., oceanic; r.b., rubbly basement.

Chron C22 and slightly eastwards within an area where SDRs and a smooth oceanic basement are mapped.

Seismic profile AWI-20030550 images the shelf at about 73° N and extends into the SW corner of the oceanic Greenland Basin just to the north of the JMFZ (Fig. 3). Owing to the thick sedimentary cover, the seismic resolution of the acoustic/basaltic basement is limited. The profile crosses the area, where the nature of the underlying crust and the position of the continent–ocean boundary (COB) is highly debated (e.g. Voss & Jokat 2007). The profile shows a mountain-like feature buried beneath the inner shelf sediments. The gravity data and, in particular, the tilt derivative (Haase & Ebbing 2014) indicate that this structure may represent a ridge. The magnetic data (Nasuti & Olesen 2014) show strong anomalies in that area. So an interpretation suggesting a volcanic cone or ridge is plausible. Close to the shelf break, there are sparse reflections on top of the acoustic basement, which could be interpreted as lava flows or the top of the SDRs. Transitional oceanic basement is mapped between the shelf and the mountain-like feature to the east in an area where Voss & Jokat (2007) did not map magmatic underplating or oceanic layer 3B. The
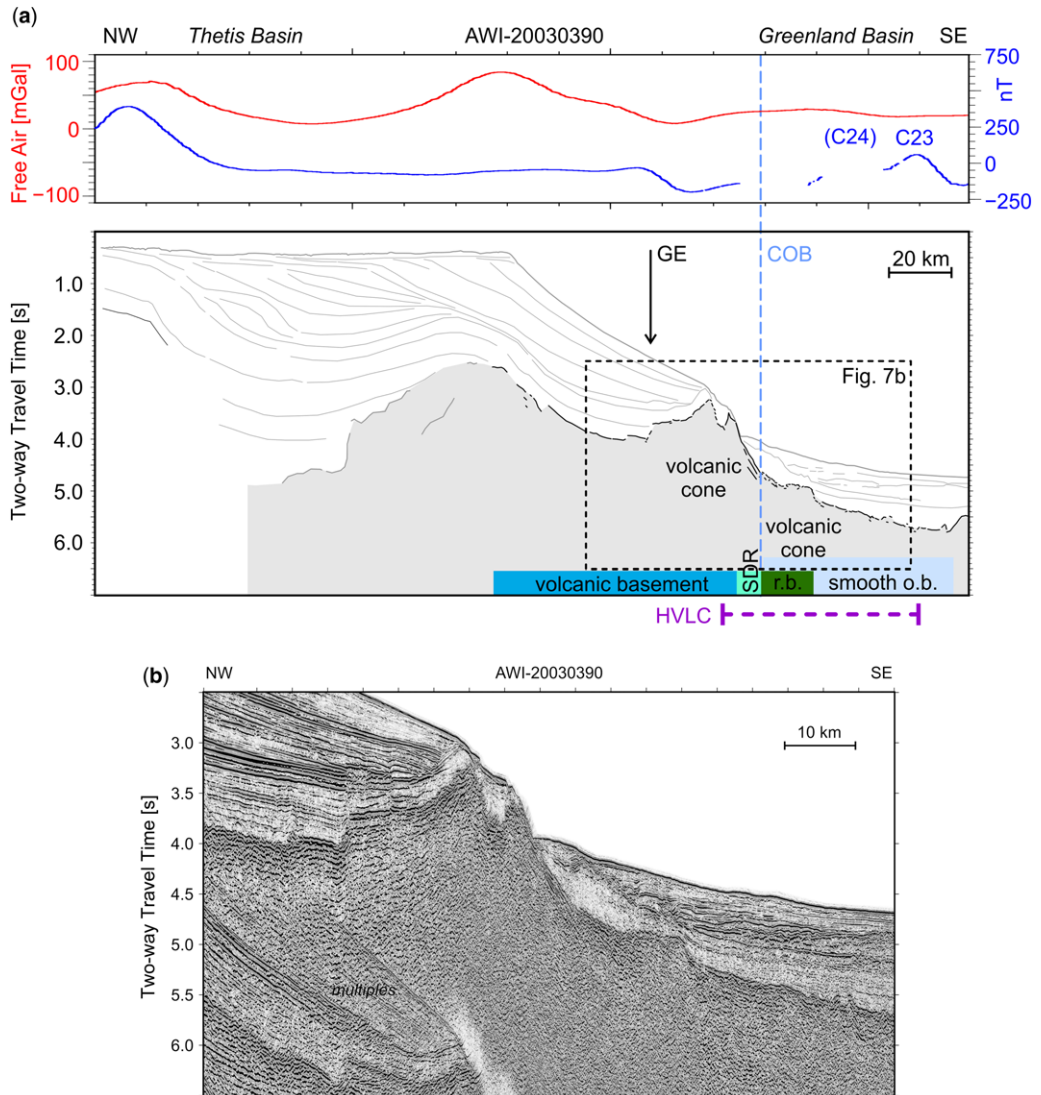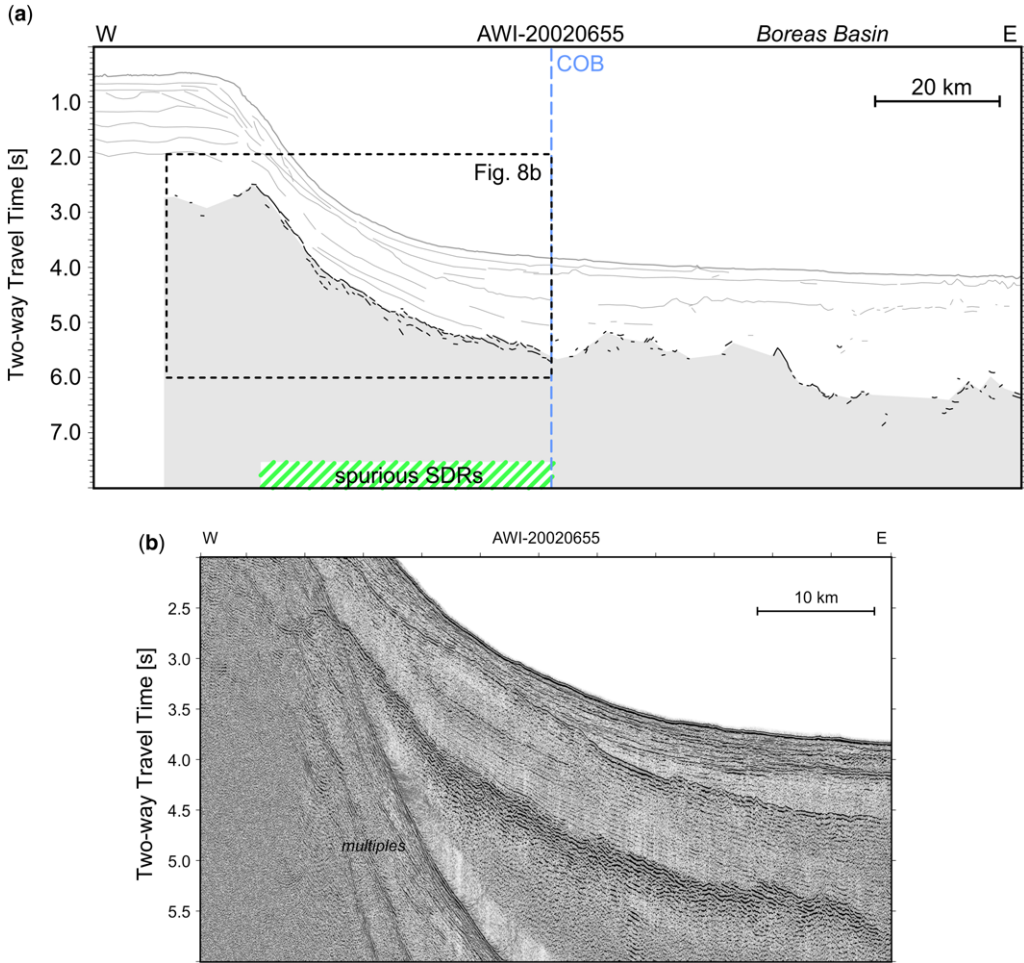
Fig. 7. (**a**) Interpretation of profile AWI-20030390. The continent–ocean boundary (COB) is as in Funck *et al.* (2014). The extent of the high-velocity lower crust (HVLC) (layer 3B in the oceanic part) as modelled by Voss *et al.* (2009) is indicated at the bottom. Gravity (Haase & Ebbing 2014) and magnetic (Nasuti & Olesen 2014) data are plotted on top. (**b**) Seismic section of profile AWI-20030390 showing details of the COB. GE, Greenland Escarpment; o.b., oceanic basement; r.b., rubbly basement; SDR, seawards-dipping reflection.

mountain-like feature imaged to the east (Fig. 3a) might be a volcano or volcanic ridge emplaced after the break-up of the Greenland Basin, and therefore is not further discussed below.

The area between 73.7 and 74.4° N is not well covered by our data (Fig. 1). However, thick sediments can be imaged along sparse lines on top of most probably basaltic flows/crust, as indicated by aeromagnetic data (Voss & Jokat 2007; Nasuti &

Olesen 2014). Line AWI-20030350 crosses the shelf at 74.5° N (Fig. 4). Here the thick sediments beneath the shelf did not allow imaging of the acoustic basement. However, strong continuous reflections indicate the presence of lava flows beneath the Cenozoic sediments. Beneath the shelf slope, seawards-dipping basement reflections are interpreted as magmatic SDRs. Further basinwards, rubbly basement (chaotic reflections: see Fig. 4b) is

Fig. 8. (**a**) Interpretation of profile AWI-20020655 at the western flank of the Boreas Basin. The continent–ocean boundary (COB) is as in Funck *et al.* (2014). (**b**) Detail showing the spurious seawards-dipping reflections (SDRs), which might actually be simple lava or hyaloclastite flows and not SDR wedges. Note that there are multiples at the western part of the profile that mask the primary reflections.

imaged at a position where the outer high is expected, following the concept of Planke *et al.* (2000). Eastwards, a small wedge of outer SDRs could be imaged, adjacent to a small cone, which we interpret as an extinct volcano. This cone could be the potential vent for lavas forming the outer SDR wedge. Transitional oceanic basement is imaged towards the centre of the basin. Along this transect, the various published COBs are in good agreement with only minor differences (see Funck *et al.* 2014). There is evidence from seismic wide-angle data (line AWI-20030300, Voss *et al.* 2009) of small-scale magmatic underplating close to the COB, and of an oceanic layer 3B beneath the mapped outer SDRs and smooth oceanic basement.

Profile AWI-20030370 images the volcanic facies of the acoustic basement around 75.5° N (Fig. 5). The profile's reflectivity pattern of the acoustic basement implies the existence of basalt flows beneath the outer shelf. However, beneath the shelf slope, no clear SDRs can be imaged and rubbly basement can be observed beneath the shelf rise, instead of the outer high of the Planke *et al.* (2000) conceptual model. Further seawards, outer SDRs with pseudo-escarpments are identified (Fig. 5b), followed by transitional oceanic crust. This transect is extended towards the East Greenland coast by profile KAN91-21 (Fig. 5), which crosses the Danmarkshavn Basin and the Danmarkshavn Ridge. Strong, upwards-concave reflections

(Fig. 5c) can be interpreted as magmatic sill intrusions, well known from the Jameson Land Basin in East Greenland (e.g. Larsen & Marcussen 1992) and the Vøring Basin (e.g. Berndt *et al.* 2000). The structural high beneath the shelf break imaged on profile KAN91-21 (Fig. 5) lies over a cone-like structure that appears to be covered by lava flows. The existing data do not make it possible to clearly differentiate whether this cone-like structure is of igneous origin or marks the outer marginal high of the Thetis Basin (see Bjerager *et al.* 2014), as postulated by Haase & Ebbing (2014) based on gravity data.

The combined section KAN95-11 and AWI-20030380 images the margin at about 75.7° N (Fig. 6). The seismic energy on line AWI-20030380 was not sufficient to clearly characterize the acoustic basement beneath the shelf. Profiles KAN95-11 and AWI-20030380 are very close to each other. Both profiles clearly image magmatic features close to the COB. The SDRs are more pronounced along profile KAN95-11 (see Fig. 6b) than along other lines in that area. We therefore suggest that the profile images a regional magmatic centre, with rubbly basement extending landwards, which is marked as 'volcanic basement' in Figure 6. This indicates that the magma might have been emplaced in a shallow-marine environment, forming hyaloclastites instead of smooth far-extending lava flows. Lava flows and a major pseudo-escarpment (the formerly called Greenland Escarpment) exist beneath the slope. Recently, this structure has been recognized as a lava delta front similar to the Vøring and Faroe–Shetland escarpments, and was named as Thetis Escarpment (see Abdelmalak *et al.* 2016*b*). Seawards of the SDRs, a smooth

oceanic basement suggests the existence of laterally extending lava flows on top of the oceanic crust. At the seawards end of the profile, the roughness of the oceanic basement becomes more transitional, indicating less magmatic activity along the palaeo-mid-ocean ridge.

Profile AWI-20030390 images the volcanic basement at about 76.0° N (Fig. 7). Similar to the previously described profile, the signal penetration does not allow clear characterization of the acoustic basement beneath the shelf. Strong basement reflections indicate the presence of lava flows beneath the slope. However, these lava flows are probably not as thick as observed further south. At the continental rise, a basement high could represent a volcanic edifice with an escarpment at its western flank, previously called the Greenland Escarpment. Seawards of this basement high, there are spatially very limited SDRs bounded by rubbly basement and smooth oceanic basement further seawards, suggesting minor magmatic activity during break-up. Voss *et al.* (2009) reported minor underplating westwards of the COB and a thin oceanic layer 3B along nearby seismic line AWI-20030200, where we map weak SDRs and smooth oceanic basement.

Profile AWI-20020655 images the margin at about 77.9° N (Fig. 8), which is located to the north of the East Greenland Ridge. The extent of the profile does not allow the basement beneath the shelf to be characterized, but strong and laterally coherent reflection at the base of sediments beneath the slope indicates the presence of lava flows on most probably transitional or highly extended continental crust. However, the geometry of the reflectors does not allow these reflections to be classified as true SDRs. Therefore we call them 'spurious'
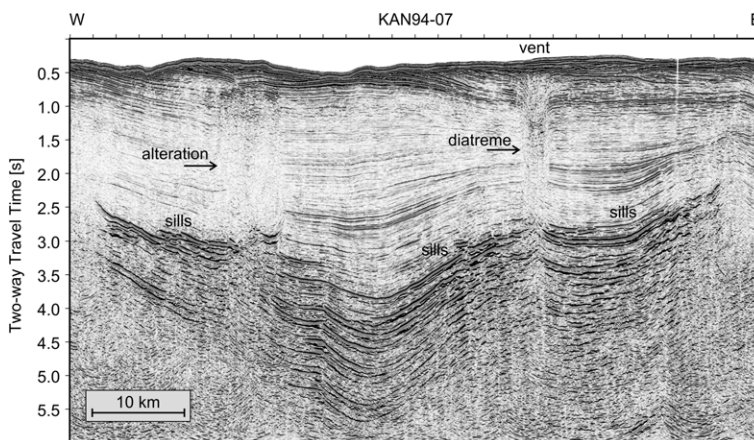
Fig. 9. Profile KAN94-07 showing sill intrusions and a volcanic–hydrothermal diatreme–vent system in the southern Danmarkshavn Basin.

SDRs. Further seawards, the data show a very rough oceanic basement, which indicates a more tectonic than magmatic imprint during the formation of the oceanic crust. This part of the continental margin is conjugate to the Vestbakken Volcanic Province on the SW Barents Sea continental margin, where Faleide *et al.* (1988, 1991) found indications of Early Eocene lava flows.

Figure 9 shows a section along the southern Danmarkshavn Basin. This part of the early rift basin is highly intruded by magmatic sills, and can be regarded as the northwards extension of the sill provinces in the Vøring and Jameson Land basins, as stated earlier. Some of the sills are connected to a palaeo-surface (most probably late Paleocene or Early Eocene in age) by diatreme-vent structures resembling hydrothermal vent complexes well known from the Vøring Basin (Planke *et al.* 2005).

Discussion

Figure 10 shows the compilation of volcanic facies along the East Greenland margin based on the seismic interpretations along all seismic lines and illustrated above for selected lines. Additional constraints for the spatial distribution of the different seismic volcanic facies units are obtained from aeromagnetic (Nasuti & Olesen 2014) (Fig. 11) and gravity data (Haase & Ebbing 2014), which are used to interpolate between the seismic profiles. Figure 12 shows plate kinematic reconstructions for the study area for time slices at 52 and 49 Ma. In Figure 12, we concentrate only on the area between the JMFZ in the south and the Greenland and Senja fracture zones in the north.

There are four major topics that will be discussed in detail: (1) the distribution of break-up volcanics along the NE Greenland margin (including the margin bordering the Boreas Basin); (2) the comparison with the conjugate mid-Norwegian margin; (3) the sill complexes and hydrothermal vents in the southern Danmarkshavn Basin; and (4) the East Greenland Shelf Magmatic Province including the Traill Ø–Vøring magmatic complex (or Traill Ø–Vøring Igneous Province – TVIP).

### Break-up volcanics along the NE Greenland continental margin

Outer SDRs are commonly assumed to be emplaced in a late rift stage (e.g. Voss & Jokat 2007) or during an early oceanic stage, when the continental margin was already subsided below the sea surface (Elliott & Parson 2008). As has already been stated by Hinz *et al.* (1987) and Voss & Jokat (2007), and confirmed by the new interpretation (Fig. 10), the age of the outer SDRs becomes younger to the south,

towards the JMFZ. Between latitudes 76° and 74.8° N, the outer SDRs are located close to the interpreted magnetic Chron C24 (*c.* 54 Ma); around latitude 73.2° N, however, they are placed close to Chron C22 (*c.* 49 Ma). Bastow & Keir (2011) proposed that SDRs could be the product of rapid stretching and associated fast decompression melting of an already partially molten mantle during the final rupture. The production of SDRs during a late rift stage or initial seafloor spreading stage is proposed by various authors who studied the western Afar Depression region (the Erta Ale and Tat'Ali ridges: e.g. Bastow & Keir 2011; Bosworth *et al.* 2012; Pagli *et al.* 2012).

In our case, most of the outer SDRs (with the exception of the northernmost SDRs) are located seawards of the COB as defined by Funck *et al.* (2014). That means that, along the NE Greenland continental margin, the outer SDRs define the landwards boundary of 'normal' oceanic crust accretion. The juvenescence of the outer SDRs to the south is also in accordance with the distribution of the rough, intermediate and smooth oceanic crust. The transition to rough morphology is close to magnetic Chron C20o (43.4 Ma: Gaina *et al.* 2002) in the south, but close to magnetic Chron C22 (49.3 Ma: Gaina *et al.* 2002) in the vicinity of the East Greenland Ridge. According to Voss *et al.* (2009), there is evidence of a magma-starved break-up and a rapidly thinning oceanic crust until Chron C21 (*c.* 47 Ma) in the northernmost part of the NE Atlantic oceanic system. The transition from smooth to transitional oceanic crust morphology is also wider to the south, indicating a continuing magma supply in the evolving southern Greenland–Lofoten Basin. But the smooth oceanic basement might be also a result of a faster spreading rate.

The lateral extent of the outer SDRs and the smooth oceanic basement correlate partially with the imaged oceanic layer 3B extent along the NE Greenland margin (see Voss & Jokat 2007; Voss *et al.* 2009) (see Figs 2, 4 & 7). Therefore, the smooth oceanic basement could generally be used to map the lateral distribution of the oceanic layer 3B away from the seismic wide-angle profiles. All the above-mentioned observations point to a high magma supply during the early drift phase. This is in accordance with the fact that the Early Eocene spreading was the fastest in the history of the Norwegian–Greenland Sea (Tsikalas *et al.* 2002; Gaina *et al.* In press, this volume).

Close to the COB, we mapped a volcanic facies that we named 'rubbly basement' and which forms a structure more similar to an 'outer low' (Fig. 5), and its location within the volcanic sequence fits the 'outer high' definition in the Planke *et al.* (2000) model. According to that model, the outer highs are emplaced in a shallow-marine environment as
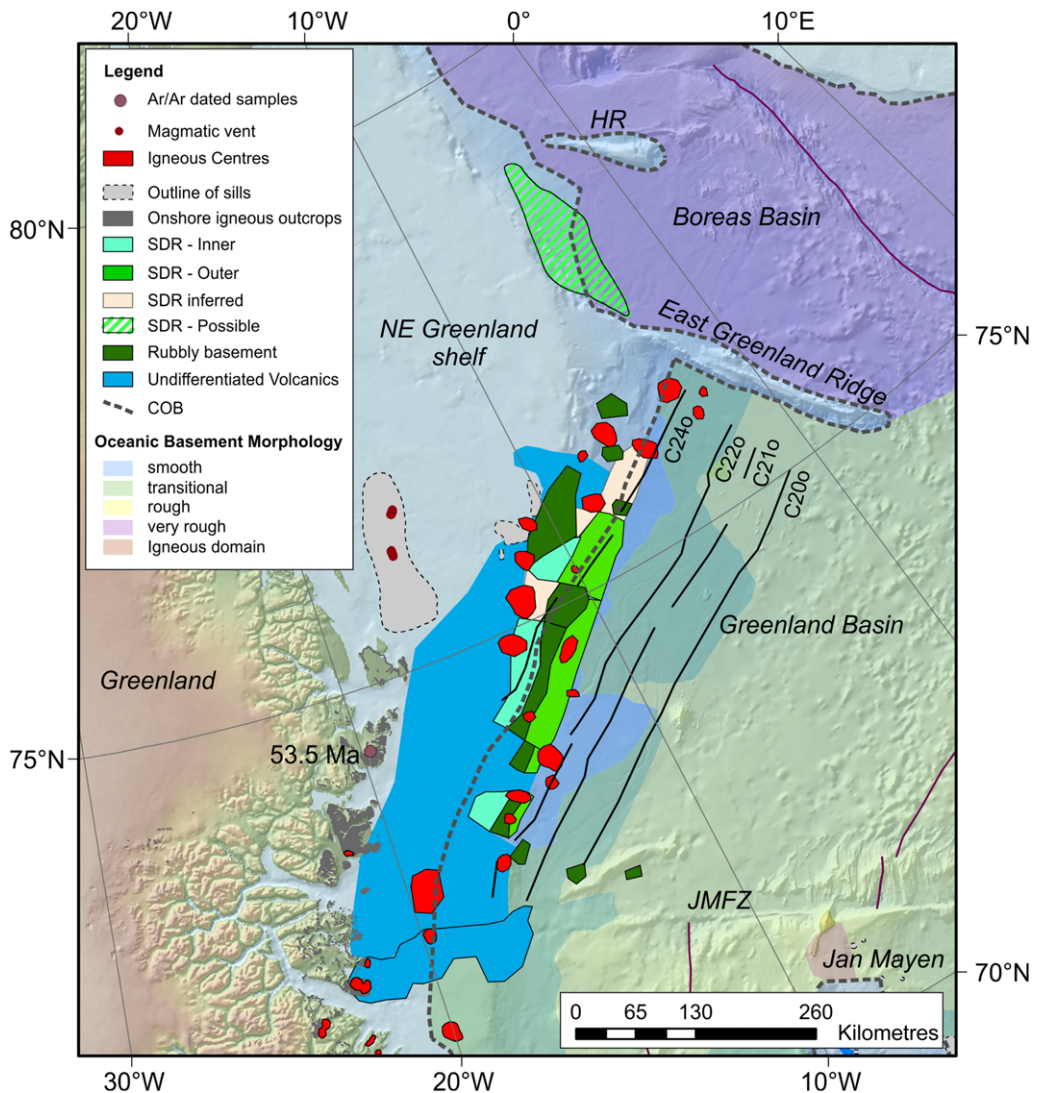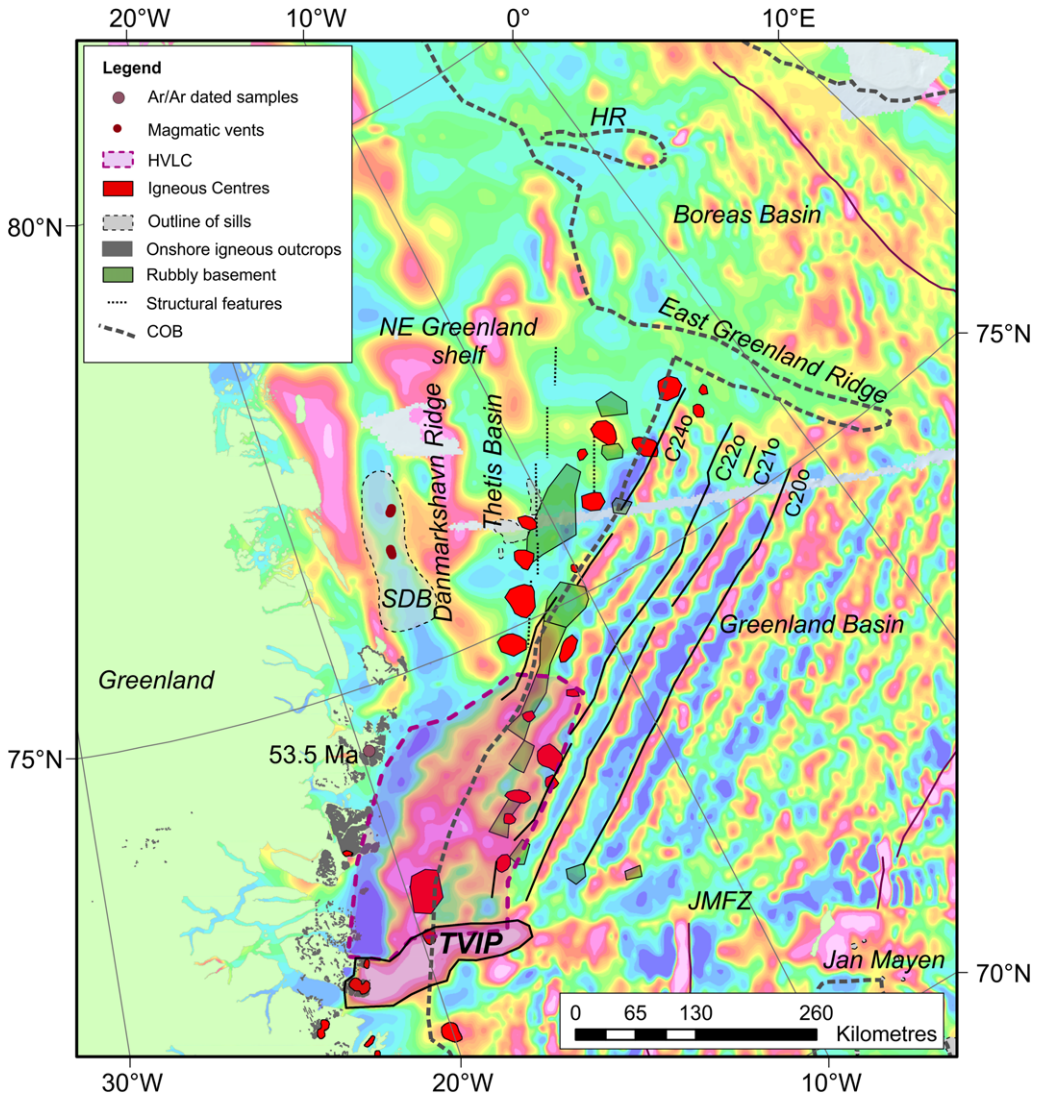
Fig. 10. Volcanic facies map of the NE Greenland margin shown together with interpreted magnetic lineations from Gaina *et al.* (2009) and dated magmatic outcrops (Ganerød *et al.* 2014). The volcanic facies for Jan Mayen is taken from á Horni *et al.* (2014). The facies 'SDR inferred' marks areas where we do not have clear seismic evidence for the existence of SDRs. The dashed grey line marks the position of the continent–ocean boundary (COB) (Funck *et al.* 2014). HR, Hovgard Ridge; JMFZ, Jan Mayen Fracture Zone; SDR, seawards-dipping reflection.

hyaloclastite ridges and represent the deepening stage of the margin. The area with the rubbly basement along the NE Greenland continental margin is about 10–30 km wide (Fig. 10), quite similar to the width of the outer highs along the Hatton Bank continental margin (7–14 km: Elliott & Parson 2008). Roberts *et al.* (1984) proved at DSDP Site 554 that the outer highs are actually composed of hyaloclastites and fractured pillow basalts. The rubbly basement is located more seawards in the southern

part of the study area, in accordance with the outer SDRs. Interpreting the rubbly basement as being related to volcanism in a shallow-marine environment, we conclude that the area close to the JMFZ was above sea level for a few millions years more than the northern part of the Greenland Basin, and that the (proto-) spreading axis deepened with time from north to south. In that sense, the outer SDRs do not mark the general onset of oceanic crustal accretion as interpreted by Voss & Jokat

Fig. 11. Magnetic map of the NE Greenland margin (Nasuti & Olesen 2014) shown together with the magnetic lineations of Gaina *et al.* (2009) and dated magmatic outcrops (Ganerød *et al.* 2014). Selected volcanic facies types (rubbly basement, igneous centres, magmatic sills and vents) are overlain. Black dashed lines indicate the trend of Thetis Basin marginal highs. The continent–ocean boundary (COB) is as in Funck *et al.* (2014). The extent of the high-velocity lower crust (HVLC) (layer 3B in the oceanic part) as modelled by Voss & Jokat (2007) and the western part of the Traill Ø–Vøring Igneous Complex are outlined. HR, Hovgard Ridge; JMFZ, Jan Mayen Fracture Zone; SDB, southern Danmarkshavn Basin; SDR, seawards-dipping reflections; TVIP, Traill Ø–Vøring Igneous Complex.

(2007) but, rather, the oceanic crustal accretion at a submerged mid-ocean ridge. Therefore, the outer SDRs and the rubbly basement alone cannot be taken as a stand-alone justification to map the COB.

The inner SDRs along the NE Greenland margin cannot be mapped with the same confidence as the outer ones. This could be due to data coverage and

quality at the often sea-ice-covered shelf. However, it could also be the case that there were no large continuous fissures producing thick and coherent magmatic wedges. Most probably, the lava flows originate from local magmatic (igneous) centres and spread radially. Possibly, the magma supply was not yet as high and laterally focused as it was
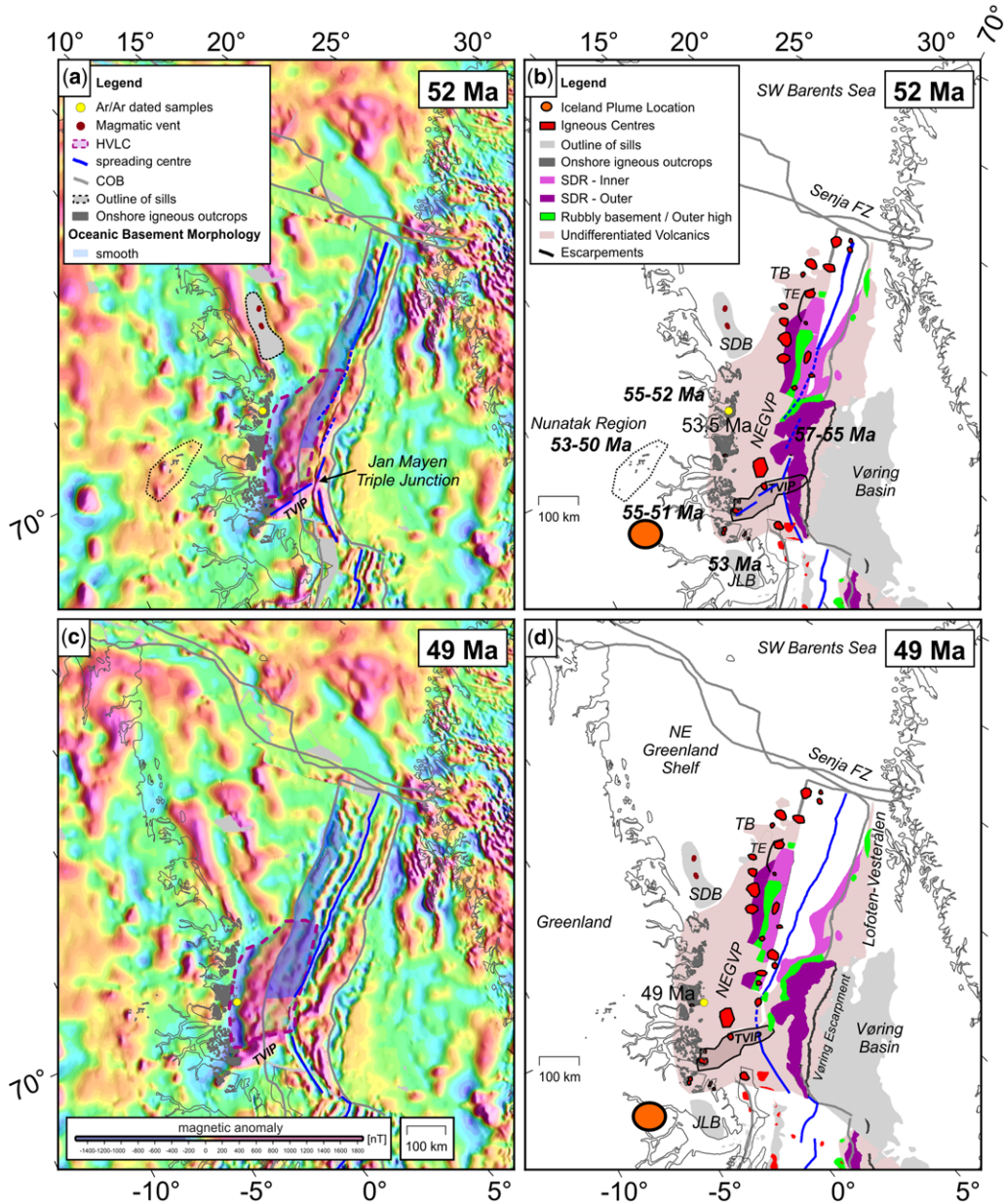
Fig. 12. Plate kinematic reconstructions for 52 and 49 Ma (in a fixed European Plate frame). For reconstruction parameters see Gaina *et al.* In press, this volume). (**a**) & (**c**) show a reconstructed magnetic anomaly grid (Gaina *et al.* In press, this volume); and (**b**) & (**d**) show interpreted volcanic facies types from this study and from Abdelmalak *et al.* (2016*b*) for the conjugate mid-Norwegian margin. Ar/Ar ages of magmatic rocks are indicated after Larsen *et al.* (2014) (in bold type) and Ganerød *et al.* (2014). The reconstructed location of the Iceland plume is based on the Doubrovine *et al.* (2012) model. COB, continent–ocean boundary; FZ, Fracture Zone; HVLC, high-velocity lower crust; JLB, Jameson Land Basin; NEGVP, NE Greenland Volcanic Province; SDB, southern Danmarkshavn Basin; SDR, seawards-dipping reflections; TB, Thetis Basin; TE, Thetis Escarpment; TVIP, Traill Ø–Vøring Igneous Complex.

the case during the emplacement of the outer SDRs along the proto mid-ocean ridge. This also concurs with the uneven distribution of landwards flows (volcanic basement). No voluminous volcanism appears to have been active along the evolving continental margin north of 75° N. This is also evident in seismic wide-angle data, showing only a thin and narrow high-velocity lower-crustal body (magmatic underplating/oceanic layer 3B) close to the line of final break-up (Voss *et al.* 2009; Funck *et al.* 2016).

Most of the mapped igneous/magmatic centres are placed in close spatial relationship to the SDRs, but do not form long continuous ridges. Based on the magnetic field and gravity data, we assume that they are more like elongated central volcanoes or rift flank volcanoes similar to those found today onshore Iceland (e.g. Sæmundsson *et al.* 1980; Harðarson *et al.* 2008; Óskarsson & Riishuus 2013), as well as in the western Afar depression and the North Ethiopian Rift (e.g. Ebinger & Casey 2001; Keir *et al.* 2013). The seismic data also show that there is no evidence of a single far-reaching continuous Greenland Escarpment. Igneous centres mapped along the Thetis Basin marginal high might not all be true magmatic centres, as stated above. Some might represent existing rift-related topography covered by lava flows during the break-up magmatic pulse. However, the positions of our volcanic highs or magmatic centres beneath the shelf are controlled by the early rift architecture rather than the line of final break-up.

The margin north of 77° N bounding the Boreas Basin shows only weak indications for break-up-related magmatism. The basement reflections landwards of the COB indicate the presence of basalt flows or, perhaps, hyaloclastites. However, there is no wedge-like structure resembling real SDRs. Instead, the spurious SDRs indicate that there is minor volcanism during the Early Eocene rifting similar to that observed in the Vestbakken Volcanic Province at the conjugate SW Barents Sea continental margin (e.g. Faleide *et al.* 2008).

Comparison with the conjugate Norwegian continental margin

The conjugate Norwegian continental margin was extensively studied, especially the segment comprising the Vøring marginal plateau and the Vøring Basin. Besides seismic investigations, this area was also the target of several scientific DSDP and ODP legs, as well as commercial drilling campaigns. Eldholm *et al.* (2002) and Tsikalas *et al.* (2002) discussed the segmentation of the margin, which is interpreted to have influenced the abundance of magmatism during break-up. This along-margin segmentation stems most probably from ancient pre-rift-inherited lithospheric structures and later

Mesozoic rift transfer or accommodation zones (Eldholm *et al.* 2002; Tsikalas *et al.* 2002).

Prominent SDR wedges could be mapped on the Vøring marginal plateau (most recent works by Abdelmalak *et al.* 2015, 2016*a*, *b*), conjugate to the East Greenland Magmatic Province *sensu* Hamann *et al.* (2005) (see Fig. 12). These SDRs originally provided the basis for the concept of seismic volcanostratigraphy as published by Planke *et al.* (2000). In addition to the primary facies types, seismic data reveal cross-cutting dyke swarms and sill intrusions beneath the SDRs, as well as lower series lava flows along the Vøring marginal plateau (Abdelmalak *et al.* 2015, 2016*a*). A model discussing the deeper structure of the volcanic margins based on a comparison between along the Norwegian margin and outcrops from the Swedish Caledonides suggests that the conjugate East Greenland Magmatic–Vøring Plateau province was a site of intensive magmatic activity shortly before, during and also after the final break-up.

Along the Lofoten–Vesterålen margin, break-up lavas cover almost the entire continental slope and terminate in the vicinity of the shelf edge against older fault scarps along the Lofoten–Vesterålen margin (Tsikalas *et al.* 2001, 2002). However, only sparse original seismic data are published for the northernmost Lofoten–Vesterålen margin, showing no or only weakly developed SDR wedges west of the COB (Tsikalas *et al.* 2002). Eldholm *et al.* (1984) interpreted smooth basement dipping reflectors at the Lofoten margin, but did not identify SDR-like structures further north at the Vesterålen margin. Generally, only a single outer (continuous) SDR wedge is mapped seawards of a basaltic flow unit (e.g. Abdelmalak *et al.* 2015, 2016*b*) (see Fig. 12). The data from the NE Greenland margin do not support a continuous magmatically active zone along this segment of the break-up line. However, there are magmatic centres with characteristics similar to the central volcanoes in the recent Iceland rift zone (Óskarsson & Riishuus 2013), where clear evidence of two SDR wedges (inner and outer SDRs) can be observed in the seismic data. As the data coverage in that part of the NE Greenland margin is rather sparse, this interpretation needs to be substantiated by further studies.

The break-up volcanic sequences in the mid-Norwegian margin include two prominent escarpments: the Vøring Escarpment on the Vøring margin; and the Faroe–Shetland Escarpment on the Møre and UK margins further south. The Vøring Escarpment consists of an approximately 350 km prominent feature along the Vøring margin with a height ranging between 200 and 1600 m (Abdelmalak *et al.* 2016*b*). It separates the Vøring Marginal High to the west from the Vøring Basin to the east. Further north, the Vøring Escarpment does not

continue into the Lofoten–Vesterålen margin. There, the escarpment seems to represent a volcanic build-up or simply a flow front. On the NE Greenland conjugate margin, a similar escarpment (Greenland or Thetis Escarpment) facing to the west is identified. The Greenland Escarpment presents a limited extent compared to the Vøring and Faroe–Shetland examples (Abdelmalak *et al.* 2016*b*). This indicates that most of the NE Greenland margin was subaerially exposed, and the lava front reached the water-filled rift basin to the north (Thetis Rift) and SE (Vøring Rift).

Seismic data along the sheared and rifted SW Barents Sea margin are sparser. No SDRs and seafloor-spreading anomalies have been identified at the marginal high in the Vestbakken Volcanic Province (see Faleide *et al.* 1991). Smooth opaque basement reflections are interpreted as lava extruded during the break-up (Faleide *et al.* 1988, 1991). Tsikalas *et al.* (2002) assumed that the complete Vestbakken Volcanic Province was captured on the Eurasian side of the rift after Chron C21n (47 Ma). Our data show comparable reflections along the sheared NE Greenland margin. Hence, we think that the rifting and later drifting were symmetrical without any early rift jump. Tsikalas *et al.* (2002) and references therein also report renewed magmatism near the Eocene–Oligocene transition and during the late Pliocene.

Sill complexes and hydrothermal vents

Sill complexes are imaged by numerous high-amplitude reflections in the southern Danmarkshavn Basin, mainly within the Cretaceous successions (Figs 5 & 9) (see Hamann *et al.* 2005). These are similar in style and position to the sills observed in the Cretaceous–Paleocene sediments of the Vøring and Jameson Land rift basins to the south (e.g. Skogseid & Eldholm 1989; Skogseid *et al.* 1992, Larsen & Marcussen 1992). Given the age of the Utgaard Upper Sill in the Vøring Basin (55.6 Ma: Svensen *et al.* 2010), the sills most probably represent a late rift phase (pre-break-up) event. Most of the magma seems to be intrusive; possibly, the buoyancy of the magma was not large enough to reach the palaeo-surface (Neumann *et al.* 2013). Only a few explosive vents could be detected in the southern Danmarkshavn Basin (Figs 9 & 10) but, perhaps, this observation is biased by the scarce seismic coverage of the area. These structures are similar to well-described and widespread vents in the Vøring Basin (e.g. Berndt *et al.* 2000; Planke *et al.* 2005).

NE Greenland Volcanic Province (NEGVP)

Hamann *et al.* (2005) defined the NE Greenland magmatic province dominated by Palaeogene

plateau basalts beneath the shelf between about 72°30′ and 75° N. Unfortunately, our seismic reflection data base covers this part of the margin only sparsely. Along most of the existing profiles, the acoustic basement is not well imaged. However, two of the seismic sections prove the existence of a volcanic basement composed of possibly landwards lava flows and volcanic ridges and mountains (Figs 2 & 3). This interpretation is supported by magnetic and gravity data (Haase & Ebbing 2014; Nasuti & Olesen 2014). Furthermore, wide-angle seismic data image an up to 15 km-thick high-velocity lower crust beneath the wide shelf, which was interpreted as Palaeogene voluminous magmatic underplating by Voss & Jokat (2007) and Voss *et al.* (2009). Figures 10 and 11 show the outline of this magmatic underplating, which has a width of 120–130 km.

The NEGVP is a key region in pre-break-up reconstructions of the NE Atlantic, but there is some disagreement over the location of the COB (e.g. Voss & Jokat 2007; Funck *et al.* 2014). Clear magnetic anomalies indicate that, at least in the northern part, there was some kind of initial seafloor spreading starting close to anomaly C24 (*c.* 54 Ma). However, in the southern part close to the JMFZ, the magmatic activity seems to have been less focused at that time. This could mean that this part was an area of long-lasting Iceland- or Afar-type rifting and initial subaerial oceanic spreading close to the Jan Mayen triple junction (Gaina *et al.* 2009) (see Fig. 12) as a result of increased magma supply and multiple rift zones. The position of the rubbly basement/outer high indicates that the volcanism was subaerial until about 49 Ma (Chron C22) in that area (Fig. 12).

A compelling feature of the NE Greenland margin is the Traill Ø–Vøring Igneous Complex (Olesen *et al.* 2007; Gernigon *et al.* 2009). It clearly stands out as a continuous magmatic feature in the magnetic data (Fig. 11). Unfortunately, it is not well covered by seismic data. Olesen *et al.* (2007) associated this igneous complex with magmatism at the time of Chron C22 (49–50 Ma) and related it to contemporaneous magmatic intrusions in East Greenland. There seems to be a link to the initial magmatic lineament proposed by Nielsen (1987) and Larsen (1988) between the Kangerlussuaq Intrusion (50 Ma, Noble *et al.* 1988) and Traill Ø. Gernigon *et al.* (2009) proposed anomalous melt production and igneous activity during the early spreading history of the Norwegian–Greenland Sea in the Early Eocene (Ypresian) by linking the TVIP to mapped magnetic anomalies. In their model, the western JMFZ represents a leaky fracture zone similar to the Azores triple junction today. Døssing & Funck (2012) suggested that the change in plate motion around C22 (as postulated by Gaina

et al. 2009) could have had an influence on the activation or deactivation of this leaky fracture zone.

However, the magnetic anomaly pattern (e.g. Gernigon *et al.* 2009) suggests that the Traill Ø–Vøring continuous magnetic anomaly may have already partly existed before Chron C21. Talwani & Eldholm (1972) had speculated that they might represent original geological structures of Palaeozoic or even Precambrian age. The basalts drilled in ODP Site 642E1 on the Vøring Plateau are dated to 54.3 Ma (Sinton *et al.* 1998). This age implies a magmatic phase close to the initial seafloor spreading (chrons C24, 53.5 or C24o; 54 Ma; according to Gaina *et al.* 2002) in the Greenland–Lofoten Basin.

According to Eldholm *et al.* (2002) and references therein, the upper series drilled in the Vøring Plateau represent transitional, mid-oceanic tholeiitic basalts and altered, interbedded, basaltic vitric tuffs emplaced at about 55 Ma. There is contemporaneous magmatic activity on the conjugate East Greenland Shelf, as indicated by a dated basalt sample in the Wollaston Foreland with an age of 53.5 Ma (Price *et al.* 1997) and recent age data from a wider area along the coast (55–51 Ma: see Fig. 12) (Larsen *et al.* 2014). At the same time or shortly after, outer SDRs were emplaced in the northern Greenland–Lofoten Basin (see above).

A comparison of the Early Cenozoic evolution of the NEGVP with recent activity in the Afar depression and the north Ethiopian rift shows a number of similarities. The late rifting and early oceanic spreading in the NE Atlantic Ocean might have taken place in an en echelon pattern and with partial overlap of two or multiple rift/spreading zones (cf. Ebinger & Casey 2001; Keir *et al.* 2013). In this case, the Traill Ø–Vøring Igneous Complex could be an abandoned magmatically active detachment (cf. Ebinger & Casey 2001). As discussed by Wolfenden *et al.* (2005), there is little evidence of final break-up along such crustal- or lithospheric-scale detachments. The location of 'magma injection zones' seems to define finally the line of break-up and seems to establish a regime similar to spreading along normal mid-ocean ridges (Wolfenden *et al.* 2005). In our case, the line of final break-up seems to be associated with the position of the early (inner) SDRs along the northern part of the rifted NE Greenland margin south of the East Greenland Ridge. Rubbly basement, outer highs and outer oceanic SDRs then indicate the submergence of the evolving magma injection zone (spreading centre) below sea level, as proposed by Planke *et al.* (2000).

Alternatively, Traill Ø volcanic ridge is the result of a plume–ridge interaction, as the postulated (pre) Iceland plume position was very close to the East Greenland margin at early seafloor spreading times (see Gaina *et al.* In press, this volume). A similar volcanic, elongated feature has been described in the Indian Ocean (the Rodriguez Ridge) and was formed over 8 myr (from *c.* 11 to 3 Ma) due to the interaction between the Central Indian Ridge and the Reunion Plume (e.g. Morgan 1978) or elsewhere in the oceanic realm (for a review, see Dyment *et al.* 2007).

Conclusions

Revisiting the seismic volcanostratigraphy along the NE Greenland continental margin, we confirm the previously reported strong variations in seismically imaged magmatic and volcanic structures. There are no clear indications for break-up-related magmatic structures in the region where the JMFZ meets the East Greenland Shelf. This could be partly caused by the masking effect of the thick sedimentary cover and partly due to the poor quality of data, but more probably it could represent the structural setting involving the pre-break-up Traill Ø–Vøring Igneous Complex. Along most sections of the margin between the JMFZ and the East Greenland Ridge, we image SDRs and related seismic facies types similar to the conjugate Vøring continental margin. The visibility of the SDR sequences on seismic data decreases towards the north, as it does along the conjugate Lofoten–Vesterålen margin and also towards the TVIP in the south. North of the East Greenland Ridge, strong basement reflections conjugated to the Vestbakken Volcanic Province are interpreted as lava flows or 'spurious' SDRs. At the northernmost sheared margin, there are no indications for the emplacement of break-up-related volcanic rocks. Sill and vent complexes in the southern Danmarkshavn Basin show spatial and temporal relationships to the counterparts in the Jameson Land and Vøring basins. As proposed earlier, the positions of the outer highs or rubbly basement are evidence of margin subsidence, but are not diagnostic for the location of the COB or onset of oceanic crustal accretion. The seawards extent of the outer (oceanic) SDRs and the smooth oceanic basement correlate partially with the extent of initially formed oceanic layer 3B along the NE Greenland margin.

Our seismic volcanostratigraphic interpretations along the rifted NE Greenland margin and the conjugate Norwegian margin, together with potential field and seismic wide-angle data, confirm that the initial oceanic rifting occurred subaerially in the area immediately north of the JMFZ until about 49 Ma, when the spreading axis submerged below the sea level and normal oceanic crust was accreted. We also postulate that the Traill Ø volcanic ridge could have been formed as a result of plume–ridge interactions in the early seafloor-spreading time period.

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