Seismic investigation of the East Greenland volcanic rifted margin

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The SIGMA project (**S**eismic **I**nvestigation of the **G**reenland **MA**rgin) was designed to make accurate measurements of crustal thickness, velocity structure and seismic reflectivity along the hotspot-influenced volcanic rifted margin (VRM) off South-East Greenland (Fig. 1). SIGMA is a joint project between researchers at Woods Hole Oceanographic Institution (Woods Hole, Mass., USA) and the Danish Lithosphere Centre (DLC), and data was acquired on a cruise with R/V *Maurice Ewing* in August–October 1996.

VRMs are characterised by a prism of igneous rocks that occupies the continent–ocean transition zone in an 80 to 150 km wide belt, several times thicker than normal oceanic crust, and which extends in some regions for more than 1500 km along strike. This thick igneous crust has two characteristics on seismic data: a seaward-dipping reflector sequence (SDRS) interpreted as subaerially erupted basalt flows and intercalated volcanoclastics, and a high-velocity lower crust with P-wave velocities (7.2–7.6 km/s) suggestive of mafic to ultramafic intrusive rocks (Hinz, 1981; Mutter *et al.*, 1982, 1984, 1988; Larsen & Jakobsdóttir, 1988; White & McKenzie, 1989; Holbrook & Kelemen, 1993).

Several models for the thermal and mechanical processes involved in the formation of VRMs have been proposed, including: decompression melting during passive upwelling near a mantle plume (White & McKenzie, 1989); actively upwelling plume heads impinging on the base of the lithosphere (Richards *et al.*, 1989; Duncan & Richards, 1991; Griffiths & Campbell, 1991); enhanced upper mantle convection driven by steep, cold lithospheric edges adjacent to the rift (Mutter *et al.*, 1988) and hot upper mantle due to non-plume 'hot cells' or insulation by supercontinents (Gurnis, 1988).

SIGMA consists of four transects systematically sampling the structure of the South-East Greenland margin and the continent–ocean transition at increasing distance from the Iceland hotspot track, in order to investigate the South-East Greenland VRM with respect to the following questions:

1) What is the structure of the transition from continental to thick igneous crust, and thence to normal oceanic crust? Is the transition abrupt or gradual? To what extent does faulting play a role? Does the abruptness of the continent–ocean boundary change with distance from the Iceland plume?
2) What was the total volume of magmatism during continental breakup on the South-East Greenland margin and its conjugates, and how does it vary in space and time? How does this magmatism relate to distance from the Iceland plume and to its temporal magmatic budget? What is the proportion of plutonic to volcanic rocks, and how does this vary with distance from the hotspot track and with total crustal thickness?
3) Does high velocity lower crust exist beneath the margin, and if so, is there any evidence that its composition, thickness, and distribution change along strike? How might such changes relate to variations in melting conditions (temperature and degree of melting) with distance from the plume?
4) Is the structure of the South-East Greenland margin symmetrical with its conjugate margins on the Hatton–Rockall Bank and Iceland–Faeroes Ridge? What combinations of pure shear and simple shear processes might explain the conjugate structures?

Background

SIGMA is a wide-angle and multichannel seismic project. Existing seismic data (Larsen & Jakobsdóttir, 1988; Larsen, 1990; Larsen *et al.*, 1995, in press) had outlined the existence and location of the SDRS, but lacked good wide-angle data and the combination with crustal reflection data. The recognition of presumed under-

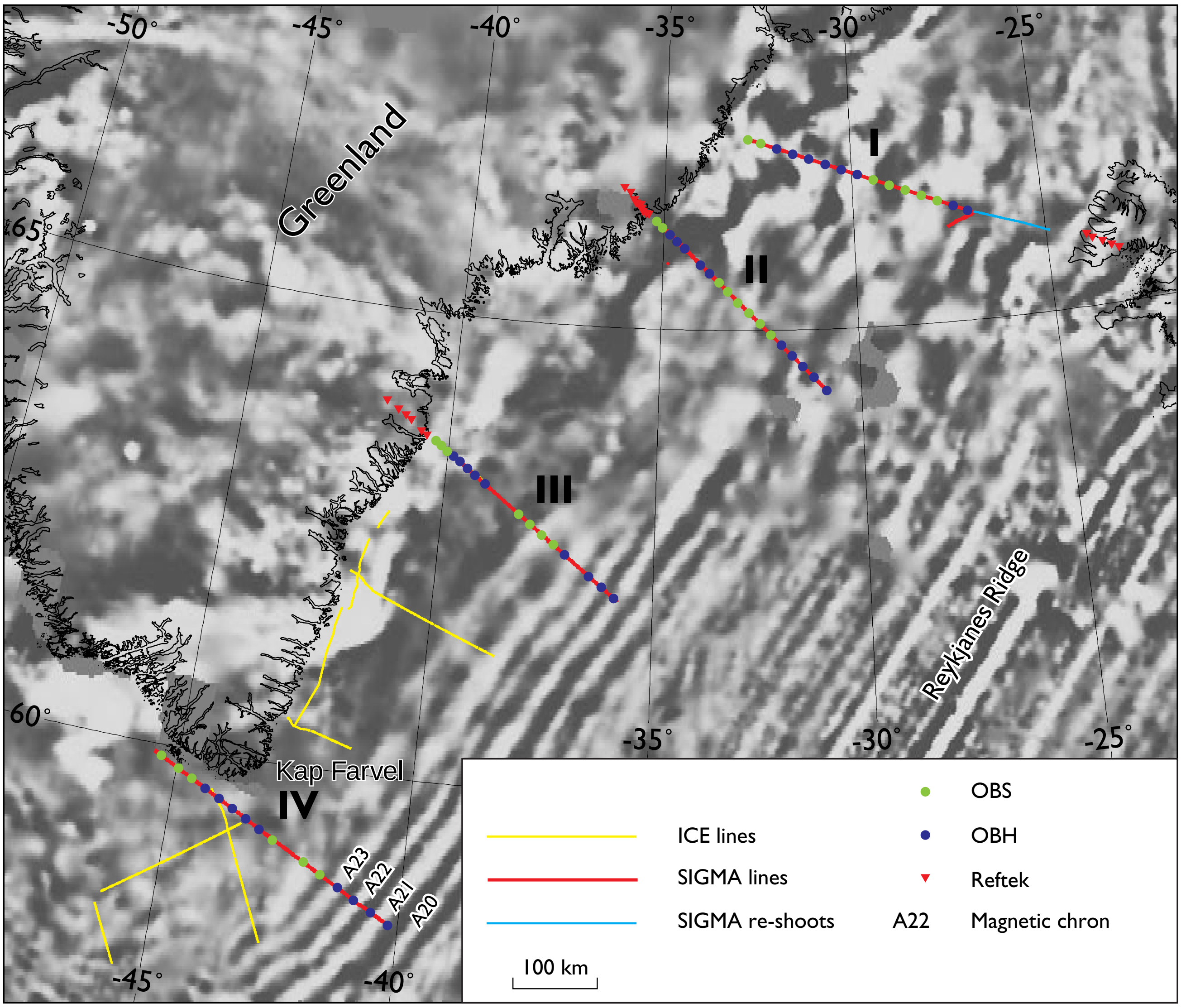

Fig. 1. The SIGMA project study area offshore South-East Greenland. SIGMA transects are shown as red lines, re-shoots without the streamer as a thin blue line, Ocean Bottom Seismometers (OBS) as green dots, Ocean Bottom Hydophones (OBH) as blue dots, Reftek land instruments as red triangles. Crustal reflection lines from DLC' ICE survey in 1994 are shown as thin yellow lines. The background is magnetic total field anomaly (Verhoef *et al.*, 1996). Chron numbers are A20–A23 indicated.

plated material at the base of the crust very close to the south-east coast of Greenland (Dahl-Jensen *et al.*, in press) made it important that the SIGMA transects were continued onshore to ensure a firm base in continental crust undisturbed by the rifting process.

Data acquisition and preliminary data processing

Data acquisition took place from R/V *Maurice Ewing* on cruise EW-9607 from August 25 – October 7 1996. A detailed account of the acquisition is given in the cruise report (Holbrook & Dahl-Jensen, 1996). The data were collected along four transects (Fig. 1) with a total of 33 000 shots from the R/V *Maurice Ewing* airgun array of 20 airguns (volume of 139 litres, 8460 in^3), and recorded on the 4 km streamer, and up to 19 ocean bottom instruments (eight Ocean Bottom Seismometers (OBS) and eleven Ocean Bottom Hydrophones (OBH).

Transect I

Transect I was placed along the basement ridge forming the Greenland–Iceland Ridge, presumed to be the track of the hotspot now under Iceland. The transect

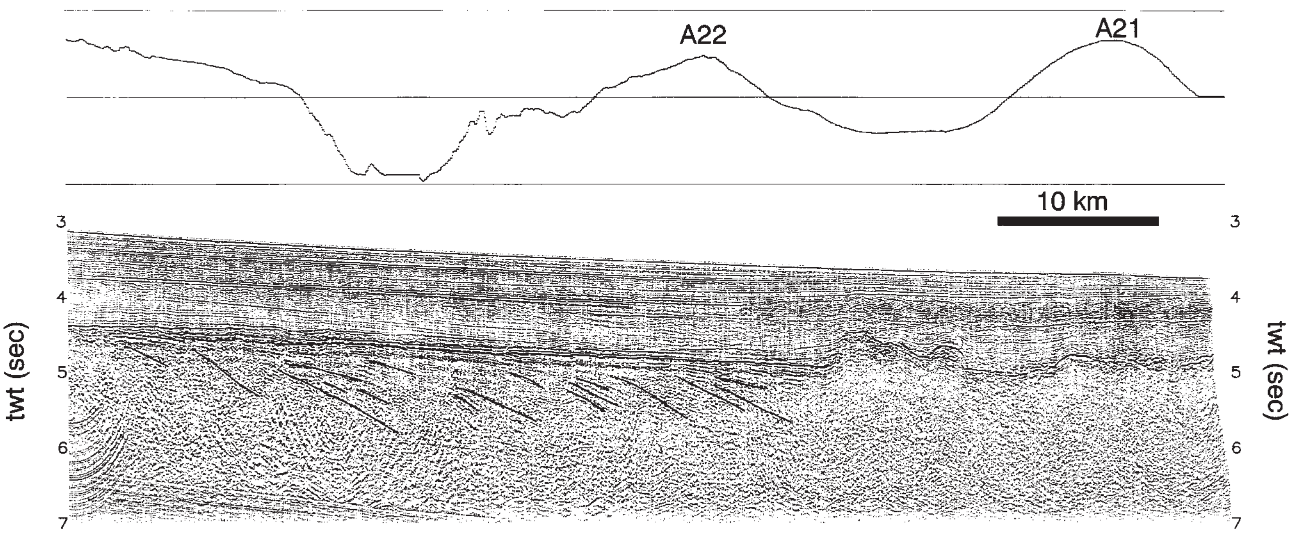

Fig. 2. Data example from Transect III. The new outer SDRS is indicated by thin black lines, and can be seen out as far as the basement ridge; the latter is situated about 5 sec. two way travel time between magnetic anomalies A21 and A22.

was recorded on 15 OBS/H, five Reftek seismometers on Iceland (in co-operation with R. S. White, Cambridge Univ., UK) and the R/V *Maurice Ewing* streamer. The OBS site closest to the Greenland coast had to be abandoned due to ice when attempting to deploy, and the next site was moved further offshore. However, the ice subsequently cleared and it was ultimately possible to shoot and acquire reflection data along the entire planned transect. Due to time constraints, the transect was not continued all the way to Iceland, but the remaining eastern part of the transect was shot without recording on the streamer on the two easternmost ocean bottom instruments and the five land stations.

Transect II

Transect II coincides with the Ocean Drilling Program (ODP) 66° transect, where some drilling took place on ODP Leg 163 (Duncan *et al.*, 1997). Many acquisition problems were experienced with the multichannel acquisition system, resulting (after several re-shoots) in an adequate but uneven coverage. Data were recorded on 19 OBS/H and 10 land seismometers. Due to programming problems with the 20 land seismometers deployed, none recorded the primary shooting of the transect, and the 10 seawards instruments recorded a re-shoot with a shot interval of 70 sec. as compared to 20 sec. on the reflection shoot. This re-shoot was done both to ensure data on the land stations and to acquire a second set of data from the OBS/H, where previous shot-noise obscured the signal, particularly in deep water. In addition to the airgun shot line, a total of 32 explosions were detonated along the landward extension of the marine line. These were recorded on the OBS/H, and for two shots also on the land instruments.

Transect III

Transect III coincided with the ODP 63° transect, for which a large body of data exists (see for example Larsen *et al.*, 1994a, b, in press). Data were recorded on 18 OBS/H, the 4 km streamer and on six land instruments. This transect was also shot twice: first with a 20 sec. shot interval for reflection and wide-angle seismic, and secondly with a 50 sec. shot interval to eliminate some of the previous shot noise on the OBS/H and for the land instruments, which due to weather problems could not be deployed in time for the first shoot.

Transect IV

Transect IV was placed south of Kap Farvel in order to cross the continent–ocean transition at sea. This is the most distal transect from the presumed hotspot track. Sixteen OBS/H were deployed and recorded in addition to the streamer. Problems were experienced with streamer balance on this transect, due to strong currents and variations in sea temperature when crossing the shelf break. An attempt to re-shoot this part of the transect did not improve the acquisition. The transect was extended approximately 60 km eastwards to follow up on results from Transect III.

Preliminary processing

The multichannel seismic data were processed to a brute stack onboard during the cruise. For all transects, geometry was assigned, taking the variable shot distance into account; velocities, inside and top mutes were picked at varying intervals, filter and deconvolution parameters chosen, and the data stacked and displayed. All data from the ocean bottom instruments were processed to offset sorted record sections, ready for interpretation. A preliminary model for Transect I was interpreted onboard.

Preliminary results

Seawards SDRS and basement high

The brute stack from Transect III in particular shows the presence of SDRS as far out as Chron 22r (49–48 Ma) (Fig. 2). This is nearly 5 Ma later than previously thought (Larsen & Jakobsdóttir, 1988; Larsen, 1990). Transects II and IV also show signs of shallow or subaerial magmatic activity up to the same time. On Transect III, the outer SDRS ends with a basement high, and further seawards the basement is reminiscent of normal oceanic top of basement (Fig. 2). A basement ridge is observed between Chron 21n and 22n on three transects (II, III and IV), and we tentatively suggest that this might be the same structure. If this is correct, the feature is over 800 km long.

Crustal thickness

During the cruise a preliminary velocity model of Transect I was interpreted from wide-angle data. The crust is 30–35 km thick along the entire transect with velocities indicating a mafic composition. This thick crust does not seem to extend south of the Greenland–Iceland ridge at early seafloor spreading times; a preliminary model of the eastern end of Transect II, only 250 km south of Transect I, shows a nearly normal crustal thickness (8.5 km) and velocity structure (layer 3 of 6.9 km/s).

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