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iSIMM pushes frontiers of marine seismic acquisition

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Last summer (2002) the iSIMM (integrated Seismic Imaging and Modelling of Margins) project successfully completed a seismic programme on the northwest European Atlantic margin with OBS acquisition by the NERC vessel *Discovery* and Q-Marine acquisition by WesternGeco's *Geco Topaz*. This project is pushing the frontiers of technology in seismic acquisition targeted at sub-basalt and deep crustal imaging. These data will constrain new theoretical models which address the development of rifted continental margins, including the effects of dynamic support by mantle plumes and the production and intrusion of igneous melt.

Geological targets

Break-up of the North Atlantic in the early Tertiary was accompanied by widespread magmatism caused by interaction of the Iceland mantle plume with lithospheric rifting (Barton & White 1997). Massive lava flows extended away from the rifted margin across the hydrocarbon-bearing basins on the Atlantic margin (e.g. Richardson *et al.* 1999), and sill intrusion, igneous underplating and lower-crustal intrusion were also widespread. This had the effect of producing permanent uplift in those areas.

The magmatism provides a challenge both to imaging basin structure, and to modelling the subsidence and development of the continental margins. The iSIMM programme integrates strategies for imaging and then modelling the effects of the extrusive lavas, sills and lower-crustal intrusions. Many of the imaging difficulties can be surmounted by using very long offsets (long streamers or two-ship methods) (White *et al.* 1999) with a broad-band, low-frequency source, and by using static ocean bottom seismometers (OBS).

We acquired combinations of new streamer, OBS, gravity and magnetometer data in two long transects across contrasting continental margins (Fig. 1). The first transect crosses the Faroes-Shetland Trough, the Faroes Shelf, the adjacent continental margin and oceanic crust (Fig. 2), using coincident wide-angle OBS acquisition and long-offset, multi-streamer swaths. This margin displays both extensional and strike-slip components, and is close to the presumed mantle plume cen-

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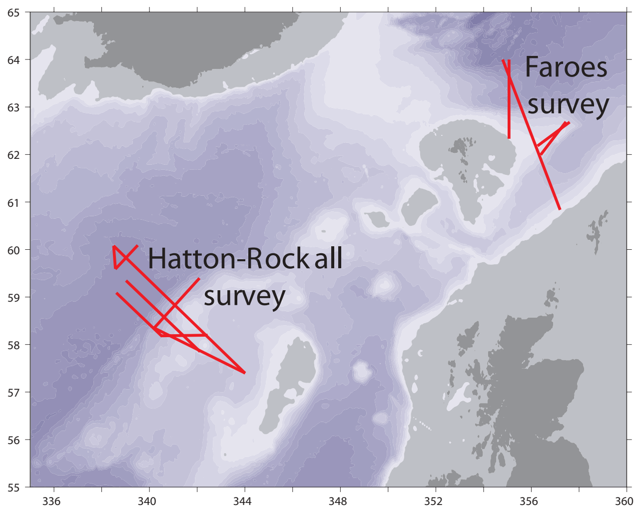

Figure 1 Location of the two surveys on contrasting North Atlantic rifted continental margins.

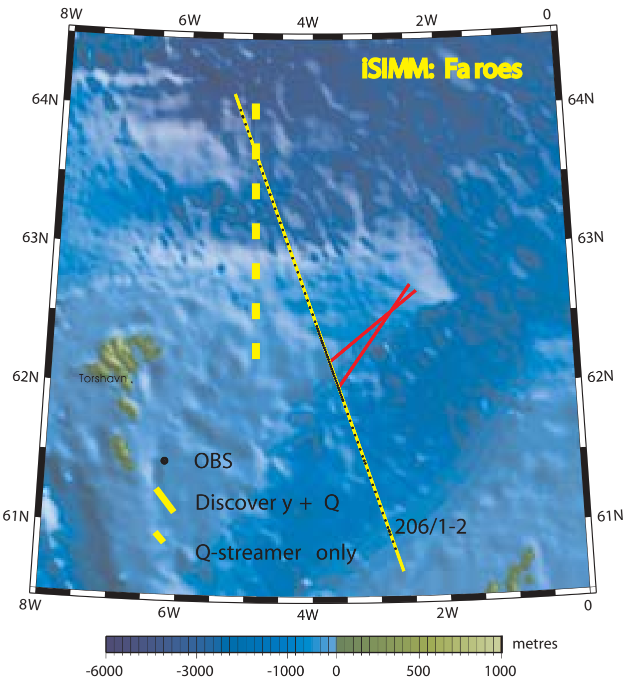

Figure 2 Location map of the profiles shot across the Faroes margin. Black dots mark 85 OBS and three vertical array positions which were overshot by *Discovery* (yellow line). The same line was acquired by WesternGeco's *Geco Topaz* shooting into a multiple Q-streamer swath. *Topaz* also acquired a second, north-south transect across the continent-ocean transition (broken yellow line), and *Discovery* also shot into the OBS along two offline tracks (red lines).

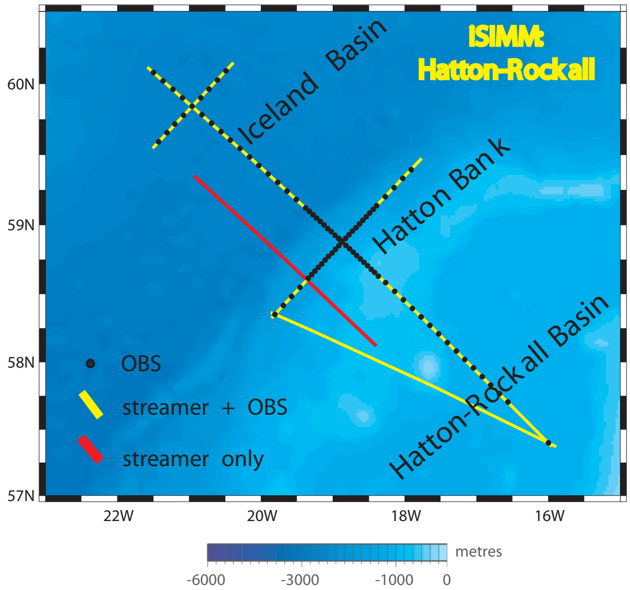

Figure 3 Location map of the Rockall-Hatton Bank acquisition. Black dots mark 89 OBS and one vertical array location overshot by *Discovery* (yellow lines), while also acquiring seismics on a 3 km streamer, together with magnetic and gravity data. Red line shows an additional 3 km streamer seismic, magnetic and gravity profile acquired across the margin after the OBS had been recovered.

tre. The second transect, acquired with simultaneous OBS and standard-offset streamer data, crosses the Hatton-Rockall Basin, Hatton Bank and well out onto the adjacent oceanic crust (Fig. 3), in an area where previous work has shown there to be considerable underplating, sills in the sediments and extensive lavas extruded close to sea level (Morgan *et al.* 1989). This margin extended in a dip direction, and is further from the mantle plume (Smallwood & White 2002).

Both surveys extended from 120 km to 160 km over the adjacent oceanic crust, in order to measure igneous crustal thickness variations following the first 15 Ma after break-up: the plume temperature was pulsing on a 3–5 Ma timescale (White 1997), and the oceanic crustal thickness provides a sensitive thermometer of the mantle temperature. Such plume temperature variations are crucial in assessing the hydrocarbon potential of the adjacent basins since they cause rapid regional uplift and subsidence, and have been postulated to control sedimentation pulses (White & Lovell 1997).

The deep-waters of rifted continental margins are the frontier exploration areas for the hydrocarbon industry, and a sound understanding of the break-up process and the nature of the continent-ocean transition is of prime importance to oil industry exploration in these regions. However, the recent discoveries of heterogeneous (depth dependent) stretching and mantle exhumation are not predicted by existing quantitative models of rifted margin formation, which are usually based on intra-continental rift models subjected to very large stretching factors. New quantitative models of rifted margin formation are being developed and tested as part of the iSIMM project. Two-phase flow models of mantle flow and melt transport, previously used successfully at ocean ridges, are being adapted to the initiation of sea-floor spreading and the formation of rifted margins. The new quantitative model of rifted margin formation will also be used to model and predict subsidence and heat flow history at rifted margins for deep water exploration.

Airgun source design

Our objective was to produce a broad-band, low-frequency source, because scattering due to stacked lava flows acts as a low-pass filter (e.g. Pujol & Smithson 1991). We achieved this partly by towing the airguns on both vessels unusually deep, at 18–20 m, so that the bubble frequencies were enhanced by the sea surface reflection. Adapting the approach of Avedik *et al*. (1996), we also designed an airgun source that aligned the first bubble pulses from a range of different sized airguns, rather than aligning the primary pressure spike in the conven-

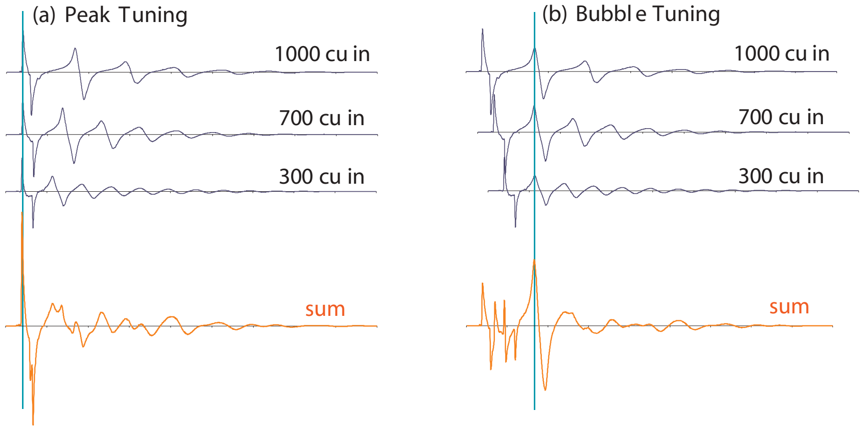

Figure 4 Illustrative diagram showing superposition of single airgun signatures towed at 20 m depth to achieve: (a) a source tuned on the peak to enhance the high frequency primary pulse, or (b) tuned on the bubble to enhance the lower frequency bubble pulse. The latter has a richer low frequency bandwidth at the cost of a complex front end. Each trace lasts 900 msec.

tional manner (Fig. 4). This produced a waveform with peak output in the range 9–11 Hz. The resultant source, though much richer than a conventional source in the 3–30 Hz band, has a complex waveform, particularly at the front end (Fig. 4). For the long-offset Q-profiles WesternGeco recorded calibrated hydrophone data near each source element for every shot, which will allow shot-by-shot designature (Ziolkowski *et al*. 1982). On the OBS profiles, we deployed vertical arrays of hydrophones in the deep water to allow us to record the actual far-field signature. In order to test this new source we shot the OBS profiles in the Faroes region twice, once with a 6300 in^3 array tuned on the first bubble pulse, and the second time using the same gun array tuned in a conventional manner on the first pressure spike.

Wide-angle (OBS) data

On both profiles we deployed 85 four-component OBS from the *Discovery*, with a 14-gun, 6300 in^3 array towed at 20 m depth. Our low-frequency sources provided strong wide-angle arrivals out to ranges beyond 120 km (Fig. 5), achieving penetration through the lava flows and the underlying crust and well into the upper mantle. This will enable us to image the underplating, and the velocity model we derive from the OBS will be used for pre-stack depth migration of the sub-basalt arrivals recorded on long-offset streamer data along the coincident profile.

Long-offset Q acquisition

The *Geco Topaz* acquired two Q swath profiles (Fig. 2), one, 375 km long overshooting the Faroes OBS profile, and the second, 180 km long providing another transect across the continent-ocean transition. The Q acquisition focused on the pre-basalt sequence, since conventional seismic satisfactorily images post-basalt sediments. For sub-basalt penetration, we used deep towed source and streamers, bubble tuning on the source and shot-by-shot signature estimation.

The FLARE profiles (Fliedner & White 2001) showed the benefit of using wide-angle PP reflections and diving waves

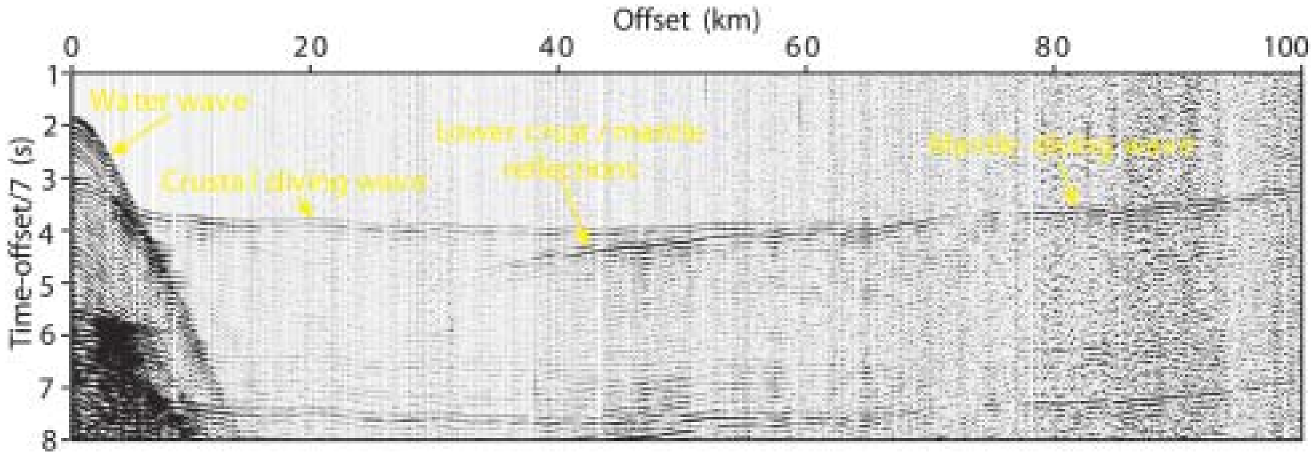

Figure 5 Sample profile acquired using low-frequency airgun source array from an OBS deployed near the Faeroes ocean-continent boundary, with main phases labelled. Data is band-pass filtered 3–18 Hz, and only every second trace is displayed after a running trace mix. Reduction velocity of 7 km/s means that arrivals with a phase velocity of 7 km/s are horizontal in this display.

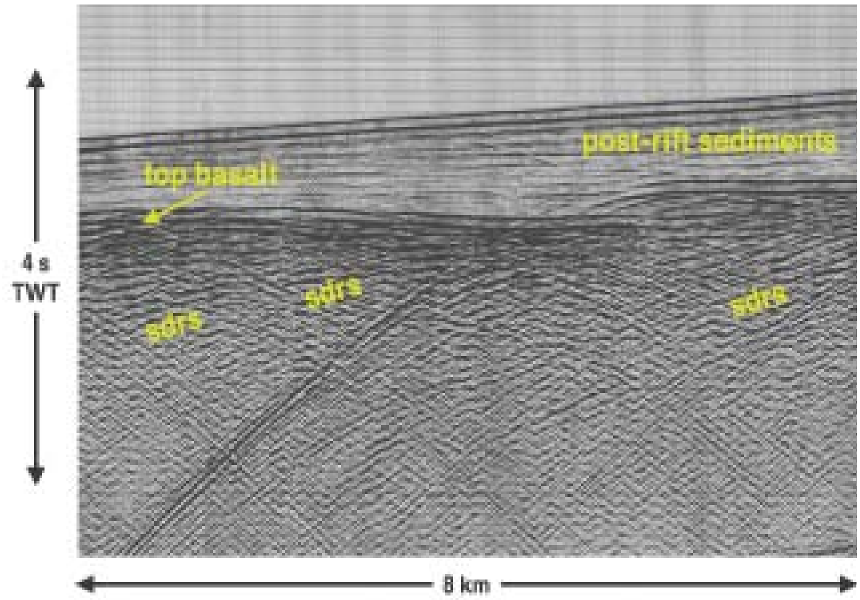

Figure 6 Sample on-board brute stack to limited offsets from one of the Q-Marine streamers north of the Faroes, showing a large fault, hummocky basalts giving many diffraction tails and seaward-dipping reflectors sequences (sdrs).

for sub-basalt event identification and velocity analysis. This requires at least 12 km offsets and a corresponding long recording time. Emsley *et al*. (1997) reported success in imaging sub-basalt structure using events believed to be double mode conversions, possibly converting to shear at the basalt top. Although not a universally applicable technique, similar events have been seen in the FLARE streamer data. Their identification on OBS records is facilitated by the OBS polarisations, so correlations between the OBS and Q data should allow greater confidence in event identification. Recording mode conversions on the Q data and tagging them from the OBS data requires long offsets, long record lengths, coincident positioning and survey-to-survey signature correlation.

Top and bottom basalt surfaces are believed to be rough, especially where the basalts have been extruded under water. Sub-aerial flows are often relatively smooth and extend over many kilometres, while sub-marine extrusion proceeds in bursts as the water quenches the basalt into pillows and hyaloclastites. The rough surfaces create side-scattering and their imaging becomes a 3D task. 3D was too costly for this experiment, but some cross-line control was obtained by recording a 2D swath. Multiple streamers with good relative positioning from streamer control and acoustic bracing will allow 2D sensor arrays to estimate directions of wavefronts moving across the streamer antenna. A sample of the onboard brute stack data is seen in Fig. 5 from north of the continental transition, showing significant structure, hummocky basalts and seaward-dipping reflectors.

Summary

The new seismic data will enable us to image both the shallow basalt flows and underlying sediments, the lower-crustal igneous intrusions and underplate, and thus to place constraints on the igneous distribution and volumes. These feed back into the subsidence modelling. Preliminary results from both seismic and subsidence analyses show that there was a rapid drop in the temperature of the mantle plume immediately following continental break-up, which impacts in a substantial manner on the subsidence history in the adjacent Faroes-Shetland, Rockall and North Sea basins.

Acknowledgements

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