RESEARCH NOTE

On the roughness of Mesozoic oceanic crust in the western North Atlantic

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SUMMARY
Seismic reflection profiles from Mesozoic oceanic crust around the Blake Spur Fracture Zone (BSFZ) in the western North Atlantic have been widely used in constraining tectonic models of slow-spreading mid-ocean ridges. These profiles have anomalously low basement relief compared to crust formed more recently at the Mid-Atlantic Ridge at the same spreading rate. Profiles from other regions of Mesozoic oceanic crust also have greater relief. The anomalous basement relief and slightly increased crustal thickness in the BSFZ survey area may be due to the presence of a mantle thermal anomaly close to the ridge axis at the time of crustal formation. If so, the intracrustal structures observed may be representative of an atypical tectonic regime.

Key words: North Atlantic, oceanic crust, roughness.

INTRODUCTION

The contrasting morphologies of fast- and slow-spreading ridges was one of the earliest observations of seafloor structure (Menard 1960; Heezen 1960). More recently, it has been recognized that there is a gradual transition between the rift-valley structure of slow-spreading ridges and the axial high of fast-spreading ridges (Malinverno 1993; Small & Sandwell 1994). This transition may be quantified in terms of axial valley relief (Malinverno 1993; Small 1994), axial gravity anomaly (Small & Sandwell 1994) or over a longer timescale by ridge flank roughness (Malinverno 1991; Small 1994). The amplitude and sign of the axial relief and gravity anomaly appear to be controlled by the rheology of the axial lithosphere, which is a function of crustal thickness and thermal structure (Chen & Morgan 1990; Neumann & Forsyth 1993) and also, particularly at slow-spreading ridges, of the extent of serpentinization (Escartín *et al.* 1997). Anomalous axial relief occurs where there are anomalies in crustal thickness and/or mantle temperature, for example due to the presence of a mantle plume close to the ridge axis (Small & Sandwell 1994), and if these anomalies are long-lived they are reflected in the ridge flank roughness.

Close to ridge axes, where the sediment cover is thin or absent, ridge flank roughness may be quantified from bathymetric data (Malinverno 1991; Goff 1991, 1992; Small 1994). However, in older regions of the ocean basins, the relief created at the ridge axis is blanketed by sediments and can only be detected by seismic reflection profiling. This relief can only be quantified if good velocity information is available, which generally requires the use of high-quality multichannel reflection data. Although the published global coverage of such data remains too sparse for the type of statistical analysis undertaken by Malinverno (1991), Goff (1991) and Small (1994), the available data set for Mesozoic oceanic crust is now sufficiently large for meaningful comparisons to be made. For example, Ranero *et al.* (1997) suggest that the roughness of Mesozoic oceanic crust in the Canary Basin responds in a similar way to modern ridge axes to changes in spreading rate and the proximity of a mantle plume.

One of the largest multichannel seismic data sets currently available in the ocean basins is from an area of the western North Atlantic in the vicinity of the Blake Spur Fracture Zone (BSFZ, Fig. 1; White *et al.* 1990; Minshull *et al.* 1991; Morris *et al.* 1993). These data have been used as constraints on a variety of models for the tectonics of slow-spreading mid-ocean ridges (Mutter & Karson 1992; Tucholke & Lin 1994; Agar & Klitgord 1995). In this paper I compare the basement relief in this area with modern ridge flanks formed at a similar spreading rate, and show that the crust in the BSFZ area was probably formed at a ridge axis with an anomalous thermal or rheological structure.

ROUGHNESS OF MESOZOIC OCEANIC CRUST

A westward change in the character of acoustic basement from 'rough' to 'smooth' in the western North Atlantic was first
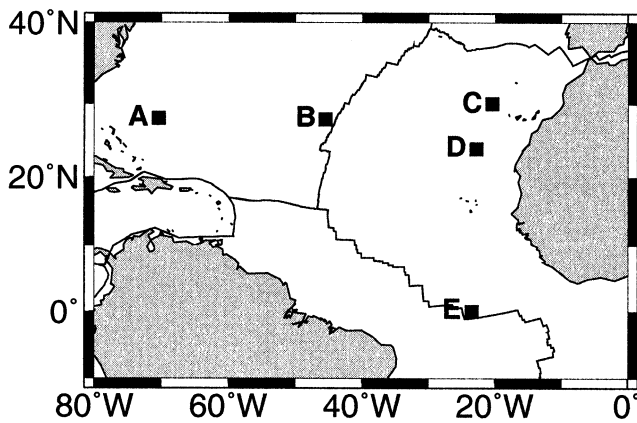
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Figure 1. Location map for all profiles used in this paper. A: Blake Spur Fracture Zone (Morris *et al.* 1993); B: west flank of the Mid-Atlantic Ridge at 28°N; C: Canaries line C (Ranero *et al.* 1997); D: OCEANS area (Henstock *et al.* 1996); E: east flank of the Mid-Atlantic Ridge at the equator.

noted by Windisch *et al.* (1965). Later work showed that their smooth acoustic basement was a Jurassic depositional surface overlying igneous oceanic basement (e.g. Klitgord & Grow 1980). However, subsequently a widespread 'rough–smooth boundary' in the igneous basement was mapped by Sundvik *et al.* (1984) and correlated with a change in spreading rate in the Mesozoic. This boundary occurs within the BSFZ survey area (Morris *et al.* 1993), and a cursory inspection of the reflection data shows that basement is indeed smoother in the western part of the survey area, with a half-spreading rate of approximately 2 cm yr^{-1}, than in the eastern part, where the half-spreading rate is close to 1 cm yr^{-1} (Figs 2 and 3). However, a comparison between these reflection profiles and bathymetric profiles from present-day spreading centres, where the presence of sediment ponds may lead to an underestimation of basement roughness, and seismic profiles from Mesozoic crust formed at the same spreading rates shows that throughout the BSFZ survey area the basement is anomalously smooth. The 'rough' basement area has a similar spreading rate to the northern Mid-Atlantic Ridge, but approximately half the relief (Fig. 3). The 'smooth' basement area also has anomalously smooth basement when compared to the equatorial Mid-Atlantic Ridge, which has a similar spreading rate (Fig. 2).

These comparisons may be quantified using the approach of Malinverno (1991), who measured roughness as the root-mean-square deviation of the top of the oceanic crust from a best-fitting straight line in a series of profiles across ridge axes. Although subsequent analyses using more sophisticated statistical approaches (Goff 1991; Small 1994) have cast doubt on Malinverno's power-law relation, the gross correlation between roughness and spreading rate is not disputed, and Malinverno's simpler approach is preferred for the limited data set studied here. Malinverno & Cowie (1993) showed that, if the main origin of oceanic crustal relief roughness is normal faulting, the roughness varies systematically with profile length, but a robust estimate can be made for profiles longer than about 100 km. Clearly the rough topography associated with fracture zones would also bias such estimates. Therefore, the following analysis is restricted to flowline profiles greater than approximately 100 km in length and away from identified fracture zones.
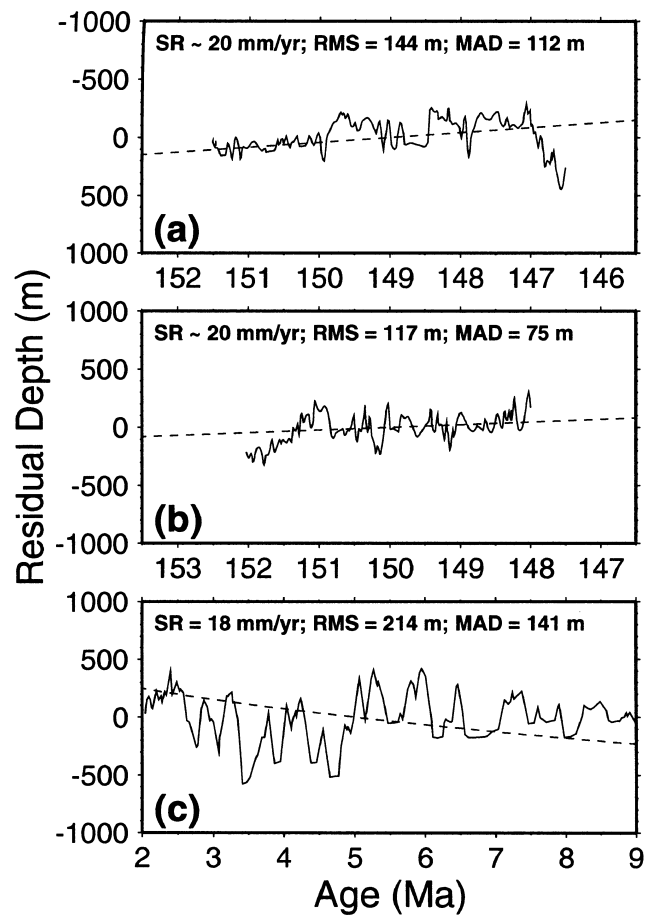
Figure 2. Solid lines show residual basement relief, after removal of a best-fitting subsidence trend, for crust formed at approximately 20 mm yr^{-1} half-spreading rate (SR). Dashed lines show the subsidence trend removed (with arbitrary reference level). All profiles are plotted with west to the left, and differences in frequency content reflect different sampling intervals. RMS is the root-mean-square roughness and MAD is the median absolute deviation of each profile (Small 1994). (a) Blake Spur line 711 before 146.5 Ma (Morris *et al.* 1993); (b) Blake Spur line 721 before 148 Ma (Morris *et al.* 1993); (c) a bathymetric profile on the east flank of the Mid-Atlantic Ridge at the equator.

These profiles and those of Malinverno (1991) may still be contaminated by the bathymetric effects of unmapped fracture zones, non-transform discontinuities and pseudo-fault traces. On young oceanic lithosphere such features may be identified using the satellite gravity data of Sandwell & Smith (1997); unfortunately on old oceanic lithosphere the reduced density contrast and increased depth of igneous basement results in weak gravity anomalies for such features that may only be detected using shipboard data, and only then if the track coverage is sufficient (e.g. Minshull *et al.* 1995). Therefore, their effects may not have been completely avoided in the profiles presented here. The isostatic response of the lithosphere to sediment loading must also be accounted for in the case of old oceanic crust. If local isostatic balance is preserved, then roughness will tend to increase with age as bathymetric deeps are loaded preferentially more than bathymetric highs. However, for the purposes of this study I prefer to assume that the lithosphere was strong enough during most of its
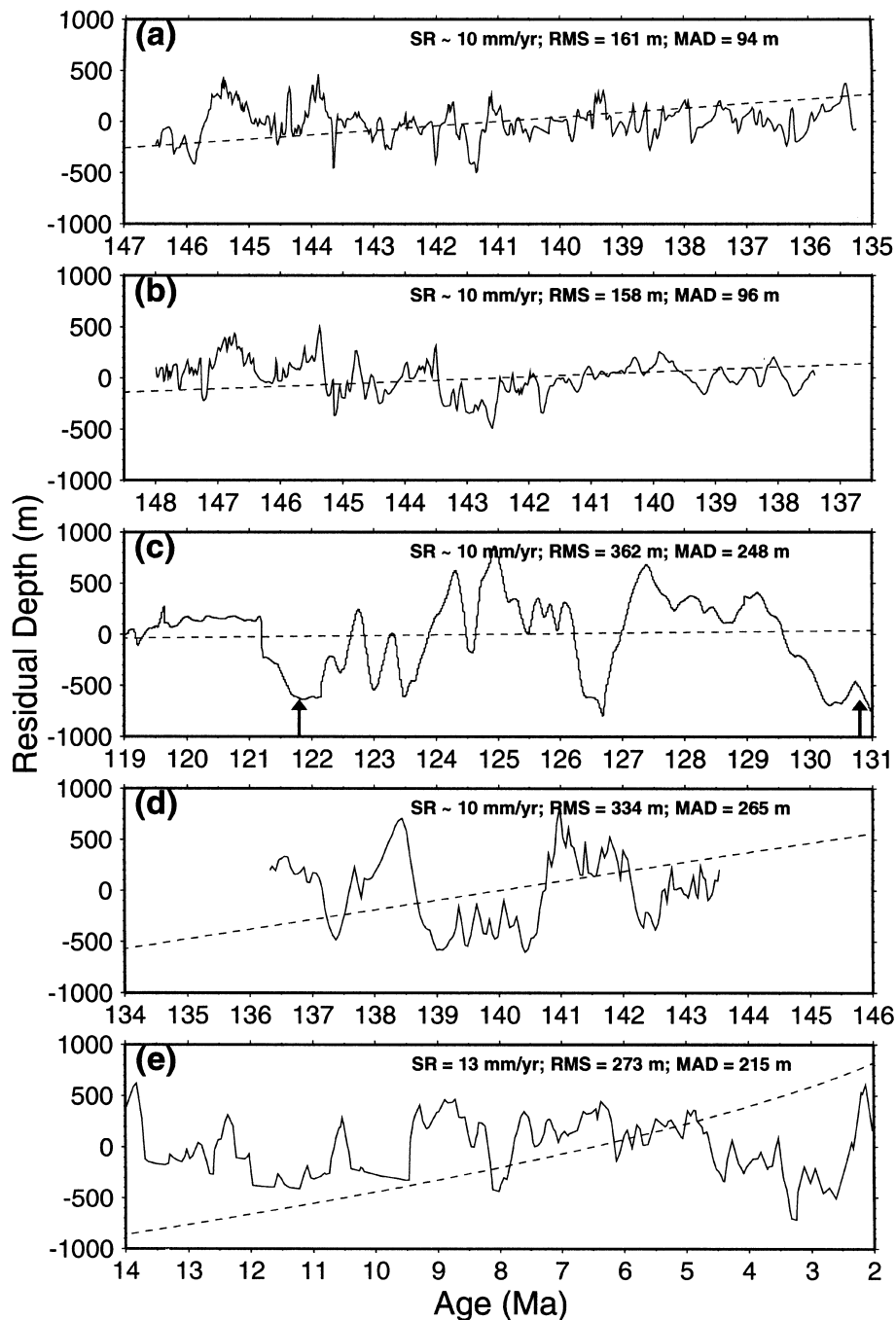
Figure 3. Solid lines show residual basement relief, after removal of a best-fitting subsidence trend, for crust formed at approximately 10 mm yr^{-1} half-spreading rate. Dashed lines show the subsidence trends removed. Annotation as for Fig. 2. (a) Blake Spur line 711, after 146.5 Ma (Morris *et al.* 1993); (b) Blake Spur lines 721 (after 148 Ma) and 714 (Morris *et al.* 1993); (c) part of Canary Basin line C (Ranero *et al.* 1997), with arrows marking approximate locations of fracture zone crossings; (d) OCEANS line 10 (Henstock *et al.* 1996); (e) a bathymetric profile on the west flank of the Mid-Atlantic Ridge near 28°N.

sedimentation history that isostatic adjustments have not occurred at wavelengths less than approximately 100 km. Such local isostatic adjustments cannot in any case explain the anomalously low roughness observed in the BSFZ area.

A selection of profiles from Mesozoic oceanic lithosphere has been compiled in Figs 2 and 3 and their corresponding roughnesses plotted in Fig. 4, with the results of Malinverno (1991) and those of Goff (1991, 1992), who used swath bathymetric data rather than long single-beam echosounder

profiles and a slightly different definition of roughness, for comparison. Spreading rates for the Mesozoic profiles are approximate only, because the precise value depends on the preferred geomagnetic timescale. For the Blake Spur area, I have used the two long flowline profiles 711 and 721 and split each at the approximate time of the spreading rate change. The location of this split is somewhat arbitrary, since the precise timing of this change and whether is was abrupt or gradual are poorly constrained. Ages throughout were
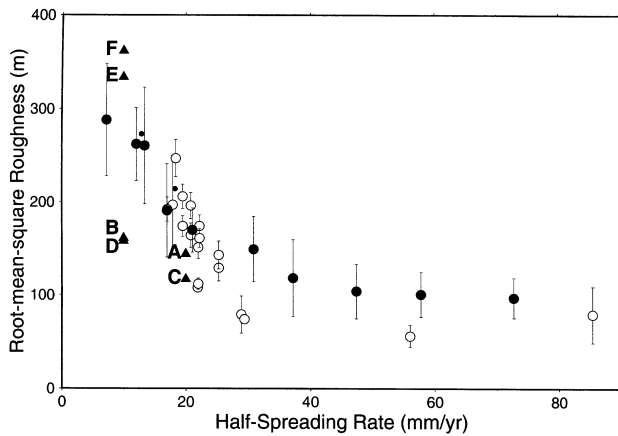
Figure 4. Ridge flank roughness versus half-spreading rate. Filled and open circles with error bars mark mean values from Malinverno (1991) and Goff (1991, 1992), respectively. Smaller circles show values derived from Figs 2(c) and 3(e). Triangles mark values from Mesozoic oceanic crust, for which spreading rates are approximate. A: Blake Spur line 711 (western part; Fig. 2a); B: Blake Spur line 711 (eastern part; Fig. 3a); C: Blake Spur line 721/714 (western part; Fig. 2b); D: Blake Spur line 721/714 (eastern part; Fig. 3b); E: OCEANS line 10 (Fig. 3d); F: part of Canary Basin line C (Fig. 3c).

calculated from the global age grid of Mueller *et al.* (1997), while spreading rates are taken from the local studies of magnetic anomalies. This grid has a fracture zone close to line 711 that is not really supported by data from the area (Morris *et al.* 1993); the profiles have been split roughly at an isochron, which corresponds to two different ages in Mueller *et al.*'s grid.

Because of the spreading-rate changes, a best-fitting subsidence trend (as a function of the square root of crustal age), rather than a straight line, has been removed from the data prior to roughness calculation. Although this trend in some cases is a poor representation of the long-wavelength bathymetric signal, in all cases the trend removal reduces the apparent roughness, and removal of a background trend is essential for the comparisons made in Fig. 4 to be meaningful. Finally, roughnesses are also estimated using the median absolute deviation (Figs 2 and 3), the statistic preferred by Small (1994) because it is more robust to outliers. The anomalous smoothness of the Blake Spur profiles is further supported by this statistic, although the rough–smooth change within these data is not so clear because this depends more on precisely where the profiles are split.

For comparison with the Blake Spur data set, I have used part of Canary Basin line C of Ranero *et al.* (1997), which is slightly oblique to a flowline, and OCEANS line 10 of Henstock *et al.* (1996), one of their longer flowline profiles. Two profiles from the present-day spreading centre have been taken from the US National Geophysical Data Centre; these profiles have roughnesses that are typical for their spreading rates (Fig. 4), so the comparisons remain valid even if these profiles do cross the off-axis expressions of unmapped ridge offsets or pseudofaults. OCEANS line 10 and the portion of Canary Basin line C used have slightly larger roughnesses than observed at spreading centres with the same spreading rate, while the basement in the BSFZ area is anomalously smooth.

DISCUSSION

There is no obvious way for roughness created at the spreading centre to be lost as the crust evolves. For example, abandoned

slow-spreading centres, which have large uncompensated relief, have been shown to maintain their relief as they age and subside (Freed *et al.* 1995). Therefore, anomalous roughness is probably due to anomalous processes when the crust was formed at the spreading centre. It is well known that regions of slow-spreading ridges affected by long-lasting mantle thermal anomalies, such as the Reykjanes Ridge, have anomalously smooth flanks (e.g. Malinverno 1991). Unfortunately, mantle plumes are not completely fixed relative to each other but drift at rates of up to approximately 30 mm yr^{-1} (Tarduno & Gee 1995), so that locations at 140–150 Ma, when the crust of the BSFZ survey area was formed, are poorly known. For example, the Cape Verde plume was in this area of the Atlantic at 140 Ma, but estimates of its location vary by more than 1000 km (Henstock *et al.* 1995).

If the BSFZ crust was influenced by a nearby mantle plume at the time of its formation, increased crustal thicknesses and large positive residual depth anomalies might be expected. No such residual depth anomaly is observed (White *et al.* 1992). However, unfortunately in both the compilation of Parsons & Sclater (1977) and the more recent analysis by Stein & Stein (1992), Mesozoic depth data are heavily influenced around 100–140 Ma by a concentration of data from the convectively supported Bermuda Rise (Detrick *et al.* 1986), and by thick sediments and uncertain ages in the Jurassic. Hence, apparent depth anomalies relative to plate models constrained by these data may not be very meaningful. Certainly, the large westward increase in basement depth seen in both profiles analysed is not predicted by any simple thermal subsidence model. Crustal thickness compilations (e.g. White *et al.* 1992) are also strongly influenced by data from the BSFZ area. However, comparison with oceanic crust elsewhere does suggest that this area has slightly thicker crust than normal, particularly in the north of the survey area. The reduced wavelength of basement relief in the Blake Spur region compared to two regions of the eastern Atlantic, noted by Dañobeitia *et al.* (1995), may also indicate a warmer crust with a thinner brittle layer during formation at the ridge axis.

The above arguments suggest that the BSFZ survey area was probably influenced by a long-lived mantle thermal anomaly at the time of its formation that thickened the crust and weakened the lithosphere. If this is the case, then models based on reflection data from this area may not be appropriate for 'normal' slow-spreading ridges, but instead may be more appropriate to sections of slow-spreading ridge axes with enhanced magmatic activity.

CONCLUSIONS

From a study of the roughness of Mesozoic oceanic basement, I conclude:

(1) the Blake Spur Fracture Zone survey area has anomalous smooth and possibly slightly thickened crust;

(2) these anomalies could be due to the influence of the Cape Verde hotspot, or to an isolated melting anomaly in the mantle when the crust was formed;

(3) tectonic models based on the BSFZ data may be more appropriate to hotspot-influenced slow-spreading ridges than to 'normal' slow-spreading ridges.

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