MATTERS ARISING

Geological objections to an extensional origin for the Buchan and Witchground Graben in the North Sea

CHRISTIE AND SCLATER'S refraction results[1] corroborate our inference from regional gravity[2] that the crust under the Buchan and Witchground Graben area of the North Sea is anomalously thin (see Fig. 1). However, their mechanism[3] for the development of the grabens, invoking crustal stretching by a factor of ~2 during the late Jurassic to early Cretaceous, raises serious geological problems. (1) The structure of the inner Moray Firth at lower Mesozoic levels[4] precludes both N–S extension of more than a few per cent, and significant later transcurrent movement on the Great Glen fault[5]. How can Christie and Sclater reduce their supposed N–S crustal extension of at least 60 km, along the Greenwich meridian, to zero, 200 km to the west? Our gravity modelling shows that if gross crustal extension occurred at all, it was in a NE–SW to E–W direction below the Viking and Central grabens, and not in a N–S direction across the Moray Firth. (2) The thickening of the Palaeozoic layer from near zero, at either end of their refraction profile, to about 4 km in the centre, implies up to 4 km of pre-late Permian erosion, and/or a Palaeozoic depositional basin. In contrast, their upper crustal layer seems to have an approximately constant thickness. The post-Zechstein, pre-stretching thickness of these two layers together was presumably, therefore, 5 km or less at the ends of the profile, but ~18 km in the centre. Whether or not erosion took place, it is clear that the crust was already highly anomalous by the mid-Permian so that the later, planar, 40-km deep Moho, depicted in Christie and Sclater's Fig. 4*a* as the initial (pre-stretching) crustal structure, is inconsistent with these implications from their own refraction results. (3) The major graben–boundary faults, probably active from the late Carboniferous (Stephanian) to the late Jurassic, are depicted (their Fig. 4*a*) as having had no effect on the Moho, whereas unobserved listric faults are postulated to have thinned the crust (their Fig. 4*b*) by a factor of ~2 shortly afterwards. Also not observed is the extreme rotation, of the order of 60°–80° (ref. 6), of the Jurassic and older sediments required to produce such extension—actual tilts are only a few degrees. Well developed listric faults can now be recognized elsewhere on seismic reflection sections (for example, ref. 7), but can only account for upper crustal extension of ~25%. (4) The effusion of a 3-km thick pile of mildly under-saturated alkali olivine basalts in the centre of the refraction profile[8] apparently pre-dates the initiation of the supposed stretching period by some 10 Myr, whereas rapid extension would probably result first in tholeiitic volcanism (particularly in the form of dyke swarms) before the more alkaline volcanism resulting from deeper partial melting. The only major pre-Tertiary tholeiitic dyke swarm in the region is considerably older, at ~290 Myr, preceding a major period of igneous activity in the Permian. In contrast, magmatism during the late Jurassic and early Cretaceous was trivial[8].

In view of these problems we conclude that rapid extension of the scale required never occurred. Other mechanisms such as loading of an elastic or visco-elastic lithosphere[2,9] can explain the last 120 Myr of North Sea subsidence just as readily as a thermal model, but without requiring such a catastrophic initiating mechanism.

M. J. Russell has suggested that the problem of the thin crust beneath the North Sea may be tackled by rejecting the assumption that the crust was originally of standard continental thickness and composition. The contiguity of the Scottish–Norwegian and North German–Polish Caledonides through the North Sea[10], and the implication, mainly from faunal provinciality, of three widely separated Lower Ordovician continental blocks[11], lead us to propose that the anomalous crust under the North Sea grabens may date back to the closing of a Lower Palaeozoic ocean. We therefore predict a small but significant difference in the seismic structure of the crust on either side of the grabens, as has been observed across the Iapetus suture[12] (Fig. 1). The later major tectonic and magmatic events of north-west Europe can all be ascribed, in principle, to the effects of nearby seafloor spreading in the early Permian[13], early Cretaceous[7] and the Tertiary, without resorting to an *ad hoc* stretching event.

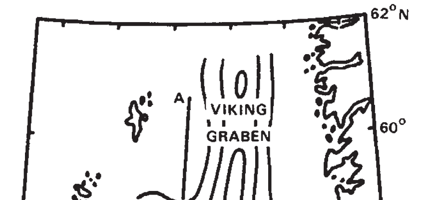

Fig. 1 Residual gravity anomaly (mGal) after removal of the effect of all Upper Palaeozoic and younger sediments (from ref. 2). AA' is refraction profile of ref. 1. Three-dimensional modelling predicts a Moho depth of 25 km below the centre of profile AA', on the lobe of overlap where the 200-km wide zone of thin crust below the Central Graben runs into the 130-km wide zone below the Viking Graben. Minimum Moho depth below the centre of each graben is 20 km, assuming a 'normal' Moho depth of 30 km and a density contrast 0.4 g cm^{-3} across the Moho.

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CHRISTIE AND SCLATER REPLY—We thank Smythe *et al.* for providing the opportunity to elaborate on the extensional model for basin formation[1]. First, it cannot be denied that extension has taken place in the North Sea, and the strong temporal correlations between North Atlantic and North Sea activity[2,3] enable us to refute the suggestion that the model is *ad hoc*.

As noted by us, evidence for the required extension must be found in the North Sea geological record for the model to be acceptable. Concerning the amount and type of extension, we would make the following points.

(1) Although the refraction line is a linear profile, this does not constrain the extension to be parallel to it or even one-dimensional and indeed the model describes areal extension[4]. Clearly, the geometry of the basin requires two-dimensional extension to have taken place in the vicinity of well 3 (ref. 4).

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