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Letter to the Editors

Footwall uplift in the Inner Moray Firth basin, offshore Scotland

Dr. D. Barr, Mr. R. McQuillin and Dr. J. A. Donato write:

Jackson & McKenzie (1983) suggested that an isostatic model of footwall uplift could explain the presence of three-way dip closure (Fig. 1a) at the Beatrice oilfield, Inner Moray Firth. Their model requires that uplift decays in a northwesterly direction (away from the Beatrice fault) as well as to the northeast and southwest. That this is not the case can be seen from Fig. 2; northwesterly dips continue as far as the Great Glen fault and result from the oilfield's location within a major half-graben. The Inner Moray Firth as a whole is not in isostatic equilibrium: no positive gravity anomaly remains after stripping off the gravitational effects of Mezozoic sediments interpreted from seismic reflection profiles (Donato & Tully 1981, Dimitropoulos & Donato 1981, McQuillin *et al.* 1982), suggesting that the Moho lies close to its normal depth and that significant lithospheric stretching has not occurred (unlike the Outer Moray Firth/Witchground graben [Christie & Sclater 1980]). This is presumably reflected in the absence of significant Late Cretaceous to Tertiary thermal subsidence; indeed, the innermost basin experienced Tertiary uplift. It would be surprising if isostatic equilibrium had been achieved on the 10-km scale of the Beatrice structure but not on the 100-km scale of the basin as a whole.

This preservation of isostatic disequilibrium suggests that the lithosphere beneath the Inner Moray Firth is relatively rigid and capable of sustaining differential vertical stresses of the order of 10 MPa for *c.* 100 Ma. Given the absence of lithospheric thinning and perhaps of deep-rooted, steep faults which would have facilitated isostatic recovery, we prefer a basin model which invokes detachment within or at the base of the crust (cf. Wernicke 1981, Wernicke & Burchfiel 1982, Gibbs 1983). Upper crustal extension is required to accommodate the sediment volume and may be linked by a low-angle fault or shear zone to whole-lithosphere stretching elsewhere in the North Sea graben system. The post-extension history of such a satellite basin will contrast markedly with that of a basin which developed above thinned lithosphere through the mechanism outlined by McKenzie (1978). Isotherms will be depressed during extension, particularly if the lithosphere is strong enough to sustain the isostatic anomaly caused by the uncompensated basin on the time-scale of sedimentation; clearly the absence of a transient high geothermal gradient will help to preserve this strength. On a longer time scale, the buoyant effect of the low-density sediments will tend to cause post-stretching uplift within the basin, and this will be augmented by heating of the upper crust as isotherms recover and respond to the blanket of low-conductivity, highly-radioactive sediments.

Listric normal faulting above a sub-horizontal detachment provides an alternative explanation for the common occurrence of three-way dip closure in the footwalls of normal faults. Figure 1(b) is a schematic balanced cross-section (Dahlstrom 1969, Gibbs 1983) across a listric

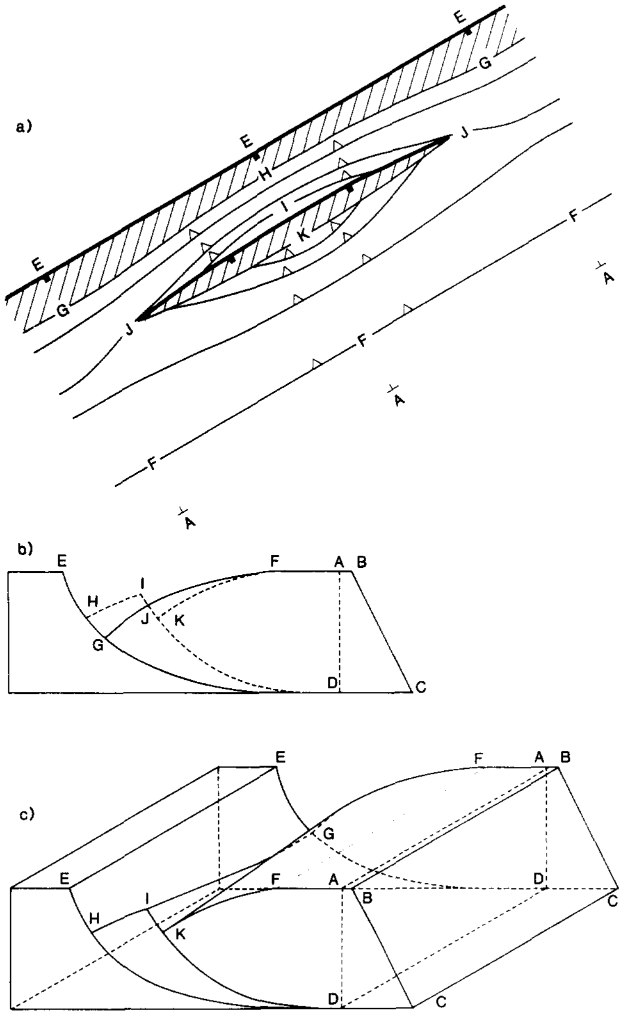

Fig. 1. (a) Schematic structure contour map of a major listric normal fault, with a synthetic normal fault representing the Beatrice structure and displaying footwall uplift and hanging-wall downwarp. (b) Balanced cross-sections through (a) (see text for explanation). (c) Dissected isometric block diagram of (a).

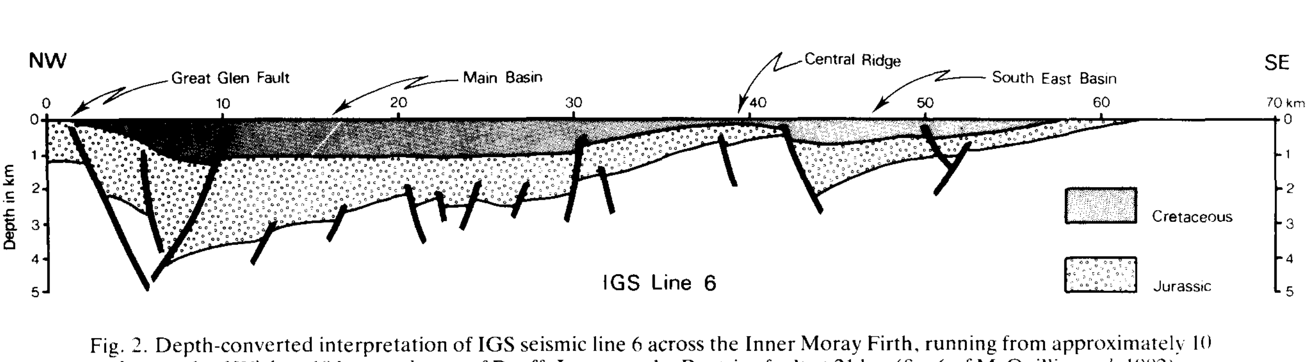

Fig. 2. Depth-converted interpretation of IGS seismic line 6 across the Inner Moray Firth, running from approximately 10 km south of Wick to 10 km northwest of Banff. It crosses the Beatrice fault at 21 km (fig. 6 of McQuillin *et al.* 1982).

normal fault, in which the areas ABCDA and EFGE are equal (to conserve cross-sectional area) and result from horizontal extension DC = EG. Bed length BG = original bed length AE and the hanging-wall block was deformed by layer-parallel simple shear. The broken lines represent a parallel cross-section in which a synthetic normal fault is present. If we assume that overall extension, DC, is consistent from one section to the other, then to balance bed length the extension associated with the synthetic fault must be compensated by a reduction in displacement at the main fault, that is, EH + IK = EG and H must be shallower than G. If the two parallel sections have a common depth to detachment, AD, then the areas EFGE and EFKIHE are equal, that is HIJGH = JFKJ. The footwall to the synthetic fault at I must be shallower than the same horizon along strike at J where the fault has died out, and so dip closure results simply from a decrease in throw at the synthetic fault. These three-dimensional relationships are represented in Fig. 1(c): the closure on the upthrown side of the synthetic fault is broadly equivalent to the Beatrice oilfield structure in the Inner Moray Firth.

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