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Geophysical lineaments and deep continental structure

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Lineaments may be detected remotely by imaging electromagnetic radiation both inside and outside the visible spectrum and by examining the natural force-fields, particularly the magnetic and gravitational. Most electromagnetic imagery shows shallow structure which is readily correlated with surface geology. Gravimetry and magnetometry may show much deeper structure which is unrelated to surface structure or incompatible with its most obvious downward extrapolation. Seismology then offers scope for the high-resolution study of buried lineaments revealed in this way.

From such examinations it is clear than many lineaments do not traverse the entire vertical extent of the lithosphere. Internal horizontal detachment may cause once through-going structures to become segmented. A number of examples will be given, including local Scottish examples: the Great Glen Fault and the Cruachan Lineament.

Geological mapping and shallow-penetration remote sensing has shown that surface lineaments in both oceanic and continental crusts are commonly associated with strike-slip faulting. Because of their straightness, lengths, and associated displacement, it is usually assumed that the fractures are near-vertical and cut down through the whole of the lithosphere.

Recent deep seismic-reflection surveys have shown that the deep crust and upper mantle contain sub-horizontal surfaces, some of which may be caused by shearing across them. The lithosphere thus appears to be segmented by vertical and horizontal slip surfaces which may have either moved together or independently at different times. This allows vertical surfaces to be hidden under horizontal ones.

As an example, it is argued that the vertical Cruachan Lineament, hidden below the Dalradian nappes of the Scottish Caledonides, has controlled the displacement of the inclined Moine Thrust and that both are displaced by a shallow vertical shear (the Great Glen Fault) that, west of Scotland, fails to penetrate the base of the crust or a horizontal mantle slip surface below. An explanation is offered that requires a 50 km sinistral shift of the Great Glen Fault, a large part of which is detached from the deep crust by late movements on the Thrust.

1. LINEAMENTS ON MAPS

A lineament is formed by the intersection of two sub-planar surfaces. Exploration of the Earth's surface yields maps which show lineaments caused by the intersection of near-vertical geological boundaries with the ground. Such boundaries, which are linear over tens of kilometres, are very often fractures or shear zones. Simple brittle failure mechanisms suggest that vertical fractures are associated with horizontal slip or shearing, at least originally; they may be reactivated later with oblique slip.

Mapping of such lineaments leads to a view of old continental basement made up of blocks, bounded by steep fractures or shear zones (their ductile equivalents), which have been jostled about in varying stress fields. Sometimes the horizontal displacements across the lineaments are estimated to be very large (tens or more of kilometres) on lineaments that are hundreds of kilometres in length. Thus, for example, the Alpine Fault in New Zealand is at least 1300 km long and may have a 500 km displacement (Suggate 1963).

Geophysical lineaments are detected by remote observation. The most significant discoveries have been those of the existence of transform faults in the ocean floor, from bathymetry and the offset of magnetic lineations of ocean crust caused by sea-floor spreading (Vacquier 1965). These were two primary discoveries that led to the theory of plate tectonics. Continental structure is more complex and long linear features are less obvious. Here, remote sensing has been of great value in tracing major fault zones across areas of current mountain-building which are of difficult access, for example the Altyn Tagh Fault at the NW margin of the Tibetan Plateau (Tapponier & Molnar 1977).

Observations of such lineaments may be readily tied by surface mapping to known geology. More puzzling are remotely sensed lineaments, which cannot be so linked. Because 'photography' in and just beyond the visible spectrum only reveals shallow features, other means of remote sensing are used to seek deeper structure. Gravimetry and magnetometry have been particularly successfully applied to the detection of deep lineaments. A well-documented example is the mid-continent 'high' in N America, now known to be caused by intracontinental Keweenawan rifting with dense, magnetized volcanic rocks filling the narrow rift to cause the gravitational and magnetic anomalies (Chase & Gilmer 1973). The rift is concealed by a large thickness of intracratonic basin sediments, but has been proved by drilling. More speculative and less obvious is the offset of these anomalies and those related to the Appalachians claimed by Kinsland (1984) to indicate a NW–SE horizontal sinistral motion of 800 km in early Palaeozoic time. This was independently suggested by Carey (1976).

2. Lineaments on vertical sections

In the last ten years there has been a major effort to examine the deep structure of the lithosphere by seismic reflection profiling. These techniques are adapted from those used by oil companies to explore sedimentary basins were the targets that are imaged well are sub-horizontal boundaries. Vertical boundaries are very poorly imaged and may only be inferred to be present from zones in which sub-horizontal reflectors are absent, and then not with certainty because there are other reasons why sub-horizontal reflectors may fade laterally.

Two sorts of reflectors have been observed in the deep crust (see, for example, Brewer *et al.* 1983). The first has reflectors with dips of around 20–30°, which can often be tied to thrust zones exposed at the surface; some dipping reflectors occur in the deep crust and mantle without cutting through to the surface, but are thought to be part of a thrust set by virtue of their parallelism with known shallower thrusts. The second kind of reflector is near horizontal, and may be one of a thick packet characteristically occurring in what may be regarded as the lower crust, or as part of a thinner reflective layer in the crust, either at its base or in the mantle. These reflectors rarely rise to the surface so it is difficult to be sure of their origins: they may be produced by shearing along horizontal detachments or may represent 'original' or intrusive layering of basement rocks.

In one or two cases it is likely that such horizontal reflectors are caused by shearing because dipping reflectors associated with shearing root into them. An outstanding example is provided by COCORP data across the Southern Appalachians (Cook *et al.* 1981) where an upper crustal decollement separates an allochthonous basement cover from a buried autochthon that may include early Palaeozoic sedimentary rocks far from the exposed thrust front. An example from the mantle is provided by the WINCH data (Brewer *et al.* 1983) and is discussed below.

3. A THREE-DIMENSIONAL BLOCK STRUCTURE FOR CONTINENTAL BASEMENT

The circulation drawn from the two preceding sections is that continental basement may be dissected by near vertical shears, by sub-horizontal shears and by shears dipping at angles like those of thrusts. The tendency of an old shear zone to be reactivated depends on the applied stress field and its relative orientation, and on temperature. Kusznir & Park (1984) have shown how continental lithosphere may have a mid- or lower crustal detachment if the temperature gradient is high enough to make a quartz-dominated layer susceptible to creep. In the variety of events of crustal extension, shortening, uplift, and erosion that are common in mountain building, it is easy to envisage how changing load and temperature on a rock in mid-crust may give rise to a time sequence of movements on different surfaces. It has long been recognized that thrusting and folding, often occurring together, are diagnostic of crustal shortening and thickening; and that as a result of thickening the vertical principal stress is increased and may become more compressive than the along-strike horizontal stress. After this, the fold belt is susceptible to strike-slip faulting. This sequence is shown by strike-slip faults displacing folds and thrusts. There may be an intermediate phase when strike-slip faults terminate as thrusts and both move together. The foreland fold belt of the Variscan front in Pembrokeshire provides a fine example of this (Dixon 1921).

Thus steep shear zones, inferred from mapping of surface geology and force fields such as gravity and magnetism, may not transect the whole lithosphere. This applies particularly to old shears, which may have been sliced up in later movements along shallow-dipping shears. This suggests that the Great Glen Fault is superficial crustal structure with a limited sinistral movement in late Caledonian time, partly taken up by small late movements on the Moine Thrust. The Great Glen Fault displaces a deep crustal vertical shear zone, the Cruachan Lineament, which is itself concealed by Caledonian nappes. The Tertiary igneous centre of Mull is fixed by the intersection of the Great Glen Fault and the Cruachan Lineament. The Cruachan Lineament continues to the northwest, explaining the sigmoidal outcrop patterns of both the Moine Thrust and Outer Isles Fault.

4. SHEAR ZONES AT THE WESTERN EDGE OF THE SCOTTISH CALEDONIDES

(*a*) *The Great Glen Fault*

This is one of many NE–SW faults cutting the Scottish Caledonides (figure 1.) Some of the faults have a demonstrable sinistral strike-slip displacement of a few kilometres. There have been many estimates of displacement on the Great Glen Fault, for example: 100 km sinistral (Kennedy 1946); 2000 km sinistral (Van der Voo & Scotese 1982); 100 km dextral (Garson & Plant 1972). It is likely that small late movements allowed extension of the Moray Firth sedimentary basin (McQuillin *et al.* 1982). Here the concern is with late Caledonian movements: modest Mesozoic movement is a tolerable addition to the synthesis below.

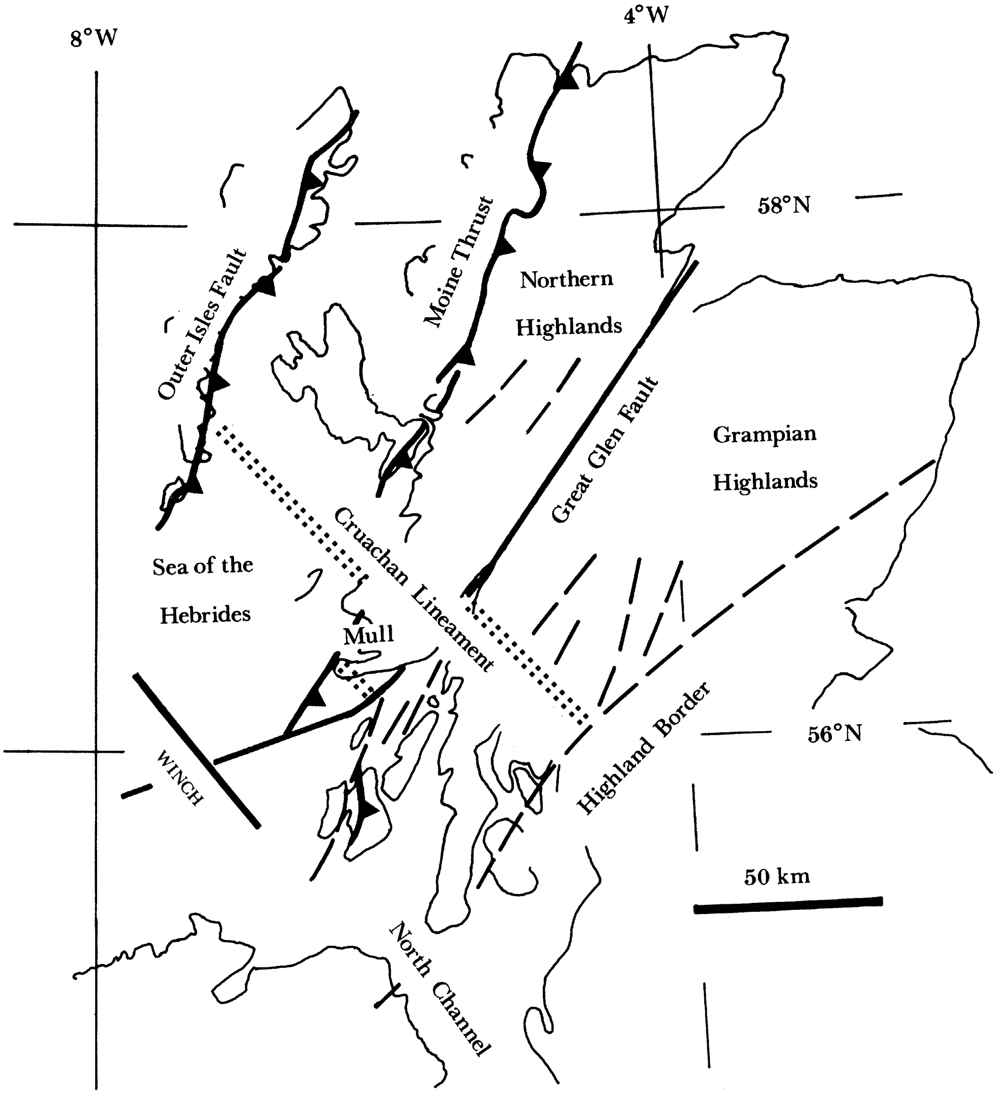

FIGURE 1. Map of northern Britain showing major shears within the Caledonides. Position of part of WINCH deep seismic reflection profile shown.

Two facts together suggest that the Caledonian displacement on the Great Glen Fault is among the estimates of smaller magnitude. First, the Fault takes a sharp 20° bend to a more ENE–WSW course south of Mull (figure 2), as indicated by correlation of the submarine trough in rockhead with the topographic shape of the Great Glen itself (Barber *et al.* 1979; Rashid 1978; Wilson 1979). Secondly, Lewisian rocks occur both to north and south of that course, overthrust by Caledonian rocks just east of Iona on the northern side and just east of Colonsay on the southern side (see, for example, Westbrook & Borradaile 1978), where the thrust is downthrown to the east by the Loch Gruinart Fault.

From submarine geophysical mapping (Wilson 1979) and consideration of the Lewisian aeromagnetic 'high' the two thrust belts are offset across the Great Glen Fault sinistrally. Supposing these to have been originally the same thrust (part of the Moine Thrust zone) and taking Westbrook and Borradaile's depth of 3 km to, and dip of 15° for, the thrust that is east

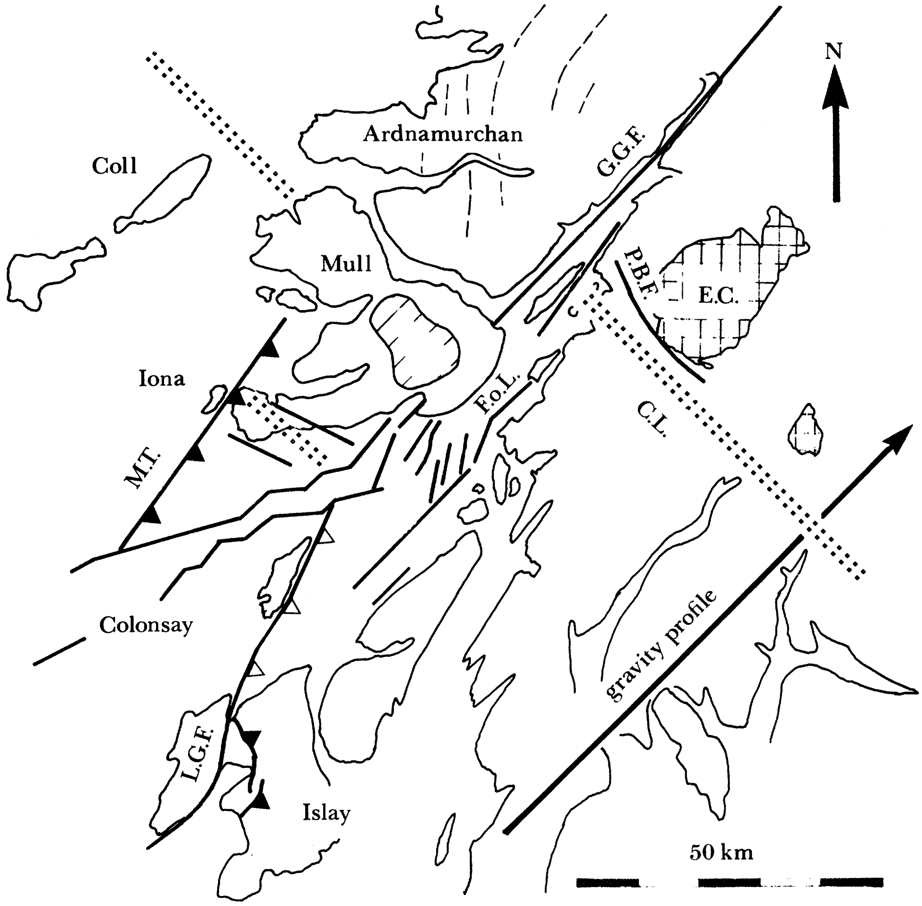

Figure 2. Detailed map of fault pattern at southwest end of the Great Glen Fault. C.L., Cruachan Lineament, indicated by double row of dots; G.G.F., Great Glen Fault, shown as solid line with many splays; M.T., Moine Thrust, shown with solid triangle on hanging-wall side, open triangle where thrust cut off against fault at depth; L.G.F., Loch Gruinart Fault; P.B.F., Pass of Brander Fault; F.o.L., Firth of Lorne; E.C., Etive Complex (including Cruachan Granite); acid plutons immediately north of Cruachan Lineament shown with cross-hatching; Mull Tertiary Igneous Centre shown by diagonal ruling. Pecked lines in Ardnamurchan indicate swing in strike of banding in Moine rocks.

of Colonsay, a strike-slip movement of about 25 km is required in the basement. (We assume the Colonsay block to be uplifted between Great Glen and Loch Gruinart Faults.)

Such limited strike-slip motion should lead to recognizable correlations across the Great Glen to the northeast. The juxtaposition of deeper (Moine) rocks and higher metamorphic grade on the north side of the Great Glen with younger, lower-grade rocks on the south suggests a vertical component of motion of the order of 4 km. Such vertical motion could be generated as a component of oblique movement, of the block north of the Great Glen, to the southwest in a direction given by the intersection of the vertical Great Glen and the dipping Moine Thrust. This would yield apparent sinistral strike-slip of about 30 km along the Great Glen and an apparent heave on the Moine Thrust of 12 km. This motion does not alter the outcrop position of the Moine Thrust relative to the Great Glen, and so the total movement is given by adding this oblique slip component to the 25 km of strike-slip displacement of the thrust belt inferred above.

Thus the Great Glen Fault appears to have formed by the northern Highlands moving southwestwards above the Moine Thrust by about 50 km, with no more than half this motion being transmitted to the foreland basement; the rest being taken up by the Moine Thrust.

Two further independent pieces of evidence support this idea. First, the single fracture zone encountered in the Great Glen itself splays repeatedly from the southern end of Loch Linnhe to the southwest. Faults propagate towards the splays if analogies with tensile fracture in glass are correct (Bahat 1980). Thus the Great Glen Fault appears to propagate to the southwest, probably from stresses being transmitted through the crust above the thrust zone. Secondly, the Great Glen Fault does not appear to cut significant deep reflectors on the WINCH profile over the basement to the WSW of Mull (figure 3). The fault here is seen as a half graben in Mesozoic sediments beneath a Tertiary cover. At depth the fault zone has both sides faulted. The fault zone certainly cannot go vertically down because it would then obscure what is seen on WINCH as a very clear mantle 'thrust' zone. This flattens at depth into a near-horizontal mantle detachment at about 40 km, which can be traced from the North Channel to the Sea of the Hebrides with no major offset across the Great Glen Fault (figure 3). So the fault has no obvious effect on the Moho, nor on topmost mantle structure, in this area. The obvious conclusion is that the fault is dying out in this direction, with displacement taken up on a variety of splays as well as upper crustal shears like the Moine Thrust.

An explanation of all these features is offered in the concluding synthesis, after consideration of another major structure offset by the fault.

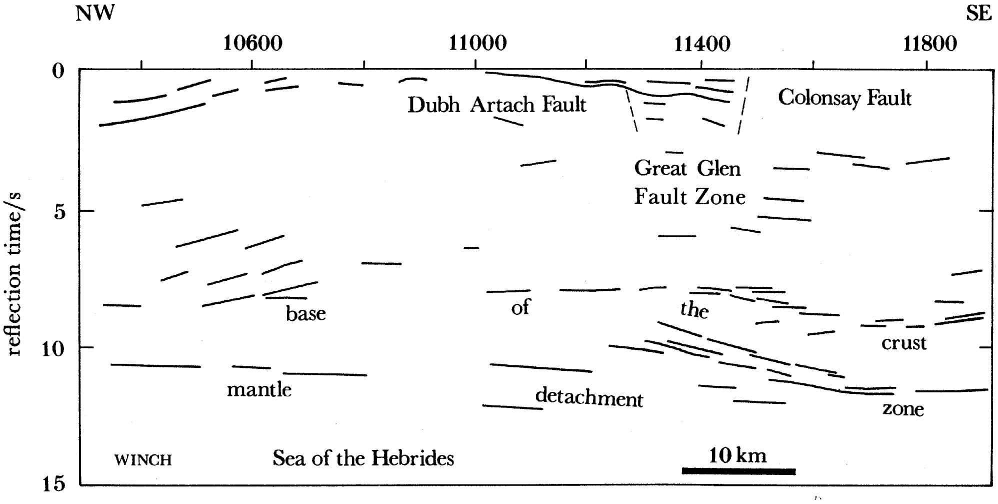

FIGURE 3. Line drawing of the most prominent reflections on part of the WINCH deep seismic reflection profile in the Sea of the Hebrides. Shot-point numbers indicated along top of drawing. Base of the crust lies at about 30 km, mantle detachment at about 40 km. Drawn from time-migration section provided by Shell Expro U.K.

(*b*) *The Cruachan Lineament*

This feature runs NW–SE across the Grampian Highlands from just south of the Etive complex (Cruachan granite) to the Highland Border at Loch Lomond. It is defined by a steep gravity gradient, up to the southwest (Hipkin & Hussain 1983; also figure 4 of this paper). Hipkin and Hussain correlated a gravity gradient with the surface outcrop of the Moine–Dalradian boundary (as defined by the B.G.S. 10 mile: 1 inch geological map). However, the

Cruachan Lineament continues its course to the southeast well beyond its part coincidence with the surface Moine–Dalradian boundary; it must be a deeper structure, controlling surface outcrops. The Lineament may be correlated with a number of geological contrasts.

(i) Moine rocks are absent from the sequence above the Moine Thrust Zone to the southwest.

(ii) There are no large Caledonian plutons in SW Scotland to the southwest of the Lineament (Hall 1985; Watson 1984). Apinite pipes occur along the Lineament (Watson 1984).

(iii) Dalradian rocks to the southwest show unusually high peak metamorphic pressures (Graham & Harte 1985).

(iv) Regional geochemical and lithogeochemical variations show similar correlations (Plant *et al.* 1984).

(v) Isotopic evidence from a small diorite SW of the Lineament indicates different crustal contamination from that of the Etive complex (Halliday, personal communication).

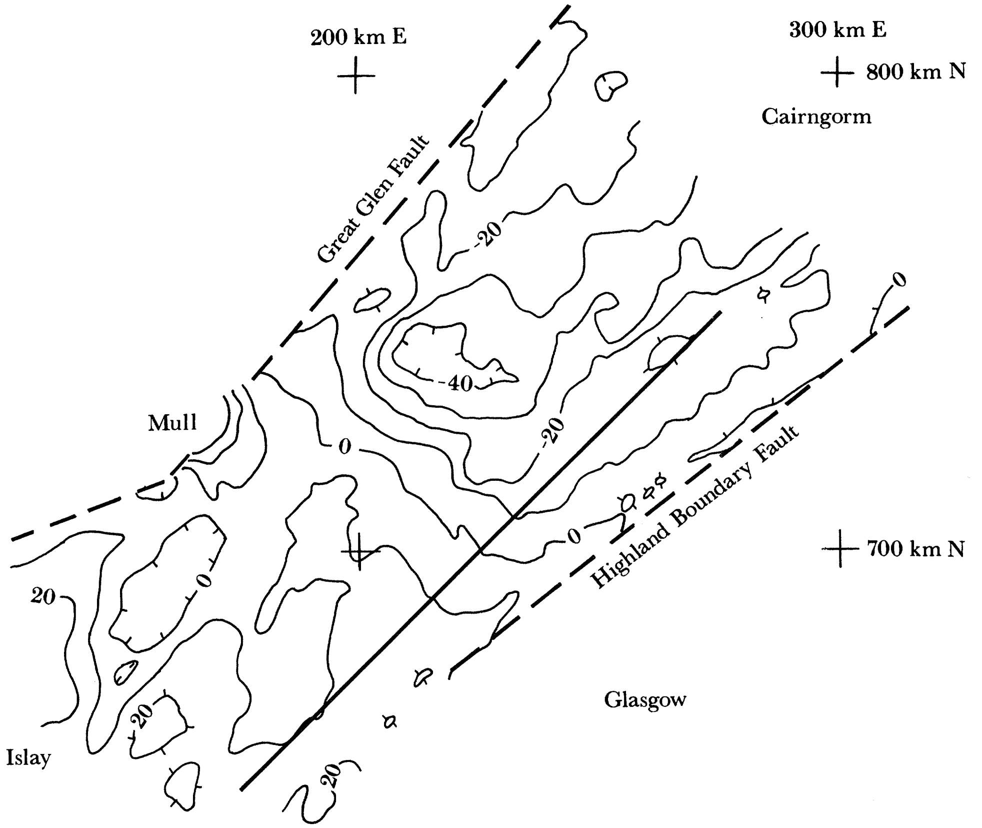

FIGURE 4. Bouguer gravity in the Grampian Highlands redrawn from Hipkin & Hussain (1983) to show the NW–SE trend of the Cruachan Lineament caused by the sharp rise in gravity to the southwest. Contour values in milligals. Full line shows position of gravity profile of figure 5. Gravity contours reproduced by kind permission of the Director, British Geological Survey.

All this evidence is of recent publication: that the Lineament remained obscure for so long is because the SE-verging Tay nappe crosses the Lineament without apparent effect. The edge of the gravity effect was noted by McLean & Qureshi (1966) in work on the regional gravity of the Midland Valley, and McLean (1978) used the Pass of Brander (Cruachan) Fault as a reactivated basement structure to define the edge if his 'Clyde Belt' of late Palaeozoic structure.

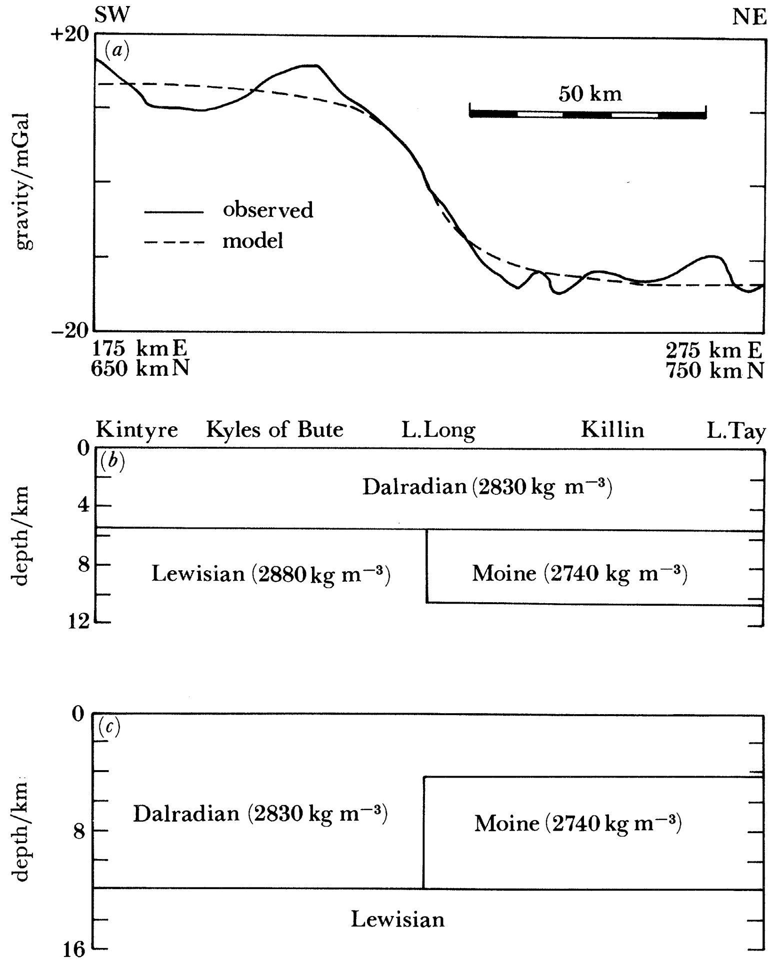

FIGURE 5. (*a*) Gravity profile across the Cruachan Lineament along the line shown in figure 4; solid line shows observed and broken lines shows model results. (*b*, *c*) Two simple two-dimensional models of subsurface structure; both give the same model gravity values. Rock densities indicated taken from Hipkin & Hussain (1983).

Very simple gravity models may be fitted to the gravity anomaly (figure 5), showing that contrasts among known rock groups with densities given by Hipkin & Hussain (1983) can provide an upper crustal source of the anomaly. These models give only approximate ideas of the structure. The profile is taken along the Tay nappe flat belt as clear as possible of known granites to the northeast of the Lineament, but this forces the profile too close to the end of the anomaly, where Highland Border effects begin to reduce the validity of two-dimensional models. Furthermore, the densities are means of ranges with quite large standard deviations (typically ± 70 kg m^{-3}) and, for the Lewisian, a geographically restricted sample; thus density contrasts are not well defined.

What the models do show is that for the likely order of density contrasts the source must be in the top half of the crust and must be fairly strongly inclined (a source of similar density contrast extending to the surface would need to have a dip of 20° or more; as the source becomes buried the dip must steepen to maintain the gradient).

Of the two models, that showing a thickened Dalradian succession may be more likely and the depth to the top Lewisian would be reasonable for the depth to the thrust zone as estimated by Hall *et al.* (1984) on WINCH and by Westbrook & Borradaile (1978) if their 'thrusts' flatten out a little below the surface structures modelled. It may be that the nearest gross model of the structure is some combination of the two, with a thrust at the top of the Lewisian stepping up across the Cruachan Lineament as a sidewall ramp.

The Cruachan Lineament appears to be one with a pre-Dalradian history which moved to preserve a large thickness of Moine sedimentary rocks of low density on its northeastern side. This may imply vertical or horizontal post-Moine movement affecting these, and older, rocks. The Lineament may extend downwards into, or through, the deep crust. If it does, it need not necessarily show evidence of this in the gravity field. This is one of the problems in tracing the Lineament across the Great Glen Fault, because the component of upthrow to the northwest across the Fault would reveal a deeper level of erosion, deep enough to remove some or most of the effect of the gravity model. In the slice overlying the Moine Thrust on the northwest side of the Great Glen Fault, a 50 km sinistral shift would take the Lineament to SW Mull. Moine exposed there could be the last vestige of a thinning towards the Lineament. It is implicit in the above discussion that the Lineament in the Grampian Highlands cuts down through into the basement below the Thrust; but it may not necessarily do so. If it does, then its trace in the sub-Moine Thrust basement north of the Great Glen Fault would be offset sinistrally about 25 km, taking it directly below the Mull Tertiary Igneous Centre. If the trend of the Lineament remains NW–SE then the basement structure would pass through northern Mull, between Ardnamurchan and Coll to the Outer Hebrides. The sigmoidal outcrop required of the Moine Thrust between Skye and Iona may be related to a sidewall ramp effect (constraining the Moine Thrust transport direction to parallelism with the Lineament). A similar sigmoidal outcrop is observed on the Outer Isles Fault, just where the Lineament is predicted to go. In all these possible positions of the Lineament to the north of the Great Glen there is no significant gravity anomaly, except that associated with dip of the Moine Thrust and its swing in strike (probably parallel but westward of the swing in regional strike in the Moines in the Ardnamurchan area shown in figure 2).

5. SYNTHESIS

The Cruachan Lineament is a pre-Dalradian basement structure that has permitted the preservation of a large thickness of Moine metasediments on its northeastern side. During the 'main' Caledonian crustal thickening episode the Moine Thrust moved the cover several tens of kilometres with roughly this trend. The Cruachan Lineament may have behaved as a steep sidewall ramp. Late in the crustal thickening process the load stress came to exceed the minimum horizontal principal compressive stress, and a régime of strike-slip faulting was initiated. Propagating towards the thrust margins of the thickened region, the tendency was to push the Northern Highlands to the southwest, sinistrally past the Grampian Highlands (figure 6). This was achieved along pre-existing weaknesses in the metamorphosed rocks: strike-parallel structures, such as slides, in the Dalradian (see, for example, Bradbury 1985).

As the marginal areas were approached, stress was partly transmitted to the basement underlying the Moine Thrust, total detachment on the Thrust being resisted by the need to climb ramps that had been sidewalls like the Cruachan Lineament, but were now footwalls. The most easily reactivated weaknesses in the basement had a more east–west trend than the propagating fault so that movement was refracted into basement shears. The problem of taking the fault movement round a 30° bend as it entered basement was resolved by massive splaying and subsidiary movement along other basement weaknesses with a more north–south trend than

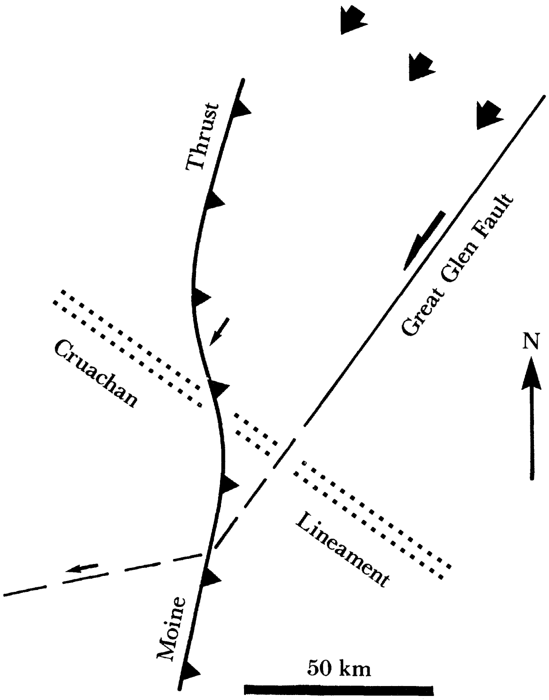

FIGURE 6. Model of development of the Great Glen Fault. Northern Highlands block, contained between the Moine Thrust and the Great Glen Fault, moves southwest with components of movement on both bounding faults. Ramping over Cruachan Lineament enhances stress transfer to basement which has different trend of easy movement. As the Great Glen Fault propagates southwestwards, strike-slip around the bend at the basement surface causes local shattering, manifest in splay faulting. About 50 km of sinistral strike-slip on the Great Glen Fault is dissipated by movement on the Moine Thrust and on splay faults: the Great Glen Fault dies out to the southwest.

the main fault, so that the refraction angle was reduced to a net 20°. The plan view of the Fault zone in the basement (figure 2) shows alternating trends of bounding shears (Wilson 1979). On the outside of the bend a series of NE–SW and N–S sinistral shears affecting the Dalradian succession (Spencer 1971) and picked out by glacial erosion in the Firth of Lorne (Hall & Rashid 1977) testify to overall extension around the outside of the bend. The resistance of the basement to NE–SW shearing may have led at an early stage in the movements to a local NW–SE tension within the suprathrust block, exploited by the intrusion of strike-parallel late Caledonian dykes.

The net movement of about 25 km within the basement was split, with splaying from the main fault zone well beyond the bend. The movement on the main fault was thus reduced to the southwest as successive splays took their share. The resultant effect was that deep crustal and upper mantle structure appears continuous across the position of the fault zone SW of Iona. Meanwhile, the Grampian Highland block itself moved obliquely above the Moine Thrust to provide a component of movement of the order of 10 km up the Thrust and 30 km of sinistral shear on the Great Glen Fault (adding to the 25 km basement component to produce a net movement of 50 km or so). The oblique slip involved uplift of the Grampian Highlands by about 4 km to place Moine rocks of relatively high grade against Dalradian rocks to the south of the Fault.

Later Mesozoic and Tertiary movements may modify the precise locations of each block, but only by amounts similar to those attributable to the uncertainties in this synthesis.

The Mull Tertiary Igneous Centre was intruded at, or alongside, the intersection of the Great Glen Fault and the Cruachan Lineament. The latter has a nebulous course to the northwest of the Great Glen but may link sigmoidal bends in the Moine Thrust and Outer Isles Fault zones.

These ideas were prompted, after ten years of detailed marine work in the Firth of Lorne, by the realization that on the WINCH data the Great Glen Fault does not go straight down into the mantle. This synthesis accounts for that fact and a variety of other peculiarities of the land and marine data. If it is correct, then we must not assume that major lineaments invariably transect the lithosphere.

Marine work around Mull was started under Adam McLean's guidance. He sought to explain the location of the Tertiary Igneous centres and first pointed out to me the significance of NW–SE structures in Palaeozoic Scotland. He glimpsed the Cruachan Lineament, but it was only to be seen properly after Roger Hipkin's excellent compilation of, and commentary on, regional gravity in northern Britain, with Dr A. Hussain.

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Shell Expro U.K. provided the migration of the WINCH line on which figure 3 is based, and also supported my work on WINCH with the BIRPS group in Cambridge.

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