Crustal magnetic structure of the Irish Sea region: evidence for a major basement boundary beneath the Isle of Man

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Abstract: Imaging and modelling of regional aeromagnetic data indicate a significant change in crustal magnetization across a boundary which extends northeast–southwest across the Irish Sea. A concealed magnetic basement is interpreted to underlie the area to the southeast of the boundary at mid-crustal levels, whereas relatively non-magnetic rocks lie at these levels to the northwest. The boundary does not coincide with the Iapetus Suture as defined by seismic evidence in the Irish Sea and palaeontological evidence on the east coast of Ireland. Instead, it appears to extend towards the northern margin of the Precambrian rocks of southeast Ireland. Its orientation swings sharply in the vicinity of the Isle of Man from north-northeast–south-southwest in the south to east-northeast–west-southwest in the northeast. There is an apparent correlation between the magnetic basement structure and an overlying, shallow, anomalous zone along the axis of the island which is revealed by gravity and high-resolution aeromagnetic data. Modelling indicates that shallow and deep structures may be related if both are assumed to dip to the northwest, a dip direction supported by seismic reflection data acquired immediately to the south of the island. The preferred interpretation is that the mid-crustal magnetic block is of Precambrian age and represents the northern part of an Avalonian basement which was assembled in late Precambrian–early Cambrian times. The geometry of the boundary beneath the Isle of Man may have been inherited from the pre-existing Avalonian basement architecture. Planes of weakness could have been reactivated as major, early Palaeozoic extensional structures and subsequently been active under a compressional regime during the closure of the Iapetus Ocean and the Acadian Orogeny.

The Irish Sea region spans terranes derived from the northern (Laurentian) and southern (Avalonian) sides of the ancient Iapetus Ocean. The boundary between them – the Iapetus Suture – has been interpreted from a combination of seismic reflection and faunal evidence to be a north dipping structure which projects to the surface of the Caledonian basement immediately to the north of the Isle of Man (Soper *et al.* 1992; England & Soper 1997). Long-wavelength magnetic field variations have been interpreted in terms of mid-crustal magnetization variations in the vicinity of the suture (Kimbell & Stone 1995; Morris & Max 1995). The aim of this paper is to extend the analysis of the regional magnetic anomaly pattern to the south of the suture and relate this to a model for the concealed structure beneath the critical Caledonian basement outcrop on the Isle of Man. In Fig. 1, a position is shown for the Iapetus Suture that is offset 20–30 km to the north of its inferred trace at the top of the Caledonian basement (Soper *et al.* 1992; British Geological Survey 1996); this provides an indication of its approximate location at the depths at which the principal magnetic anomalies are generated.

The regional magnetic anomaly pattern

Aeromagnetic data from a broad region centred on the Irish Sea are displayed in Fig. 2: Fig. 2a shows reduced-to-pole anomalies, upward continued by 2 km to emphasize longer wavelength effects; Fig. 2b shows the horizontal gradient of pseudogravity (Baranov 1957), a transform which associates maxima with the edges of deep-seated magnetic bodies. Images of the horizontal gradient of pseudogravity have proved valuable in the identification of major boundaries from regional aeromagnetic data (e.g. Cordell & Grauch 1985; Kimbell & Stone 1995).

Magnetic anomalies to the north of the inferred Iapetus Suture

The Galloway magnetic anomaly (G in Fig. 2a; Powell 1970) has been interpreted by Kimbell &

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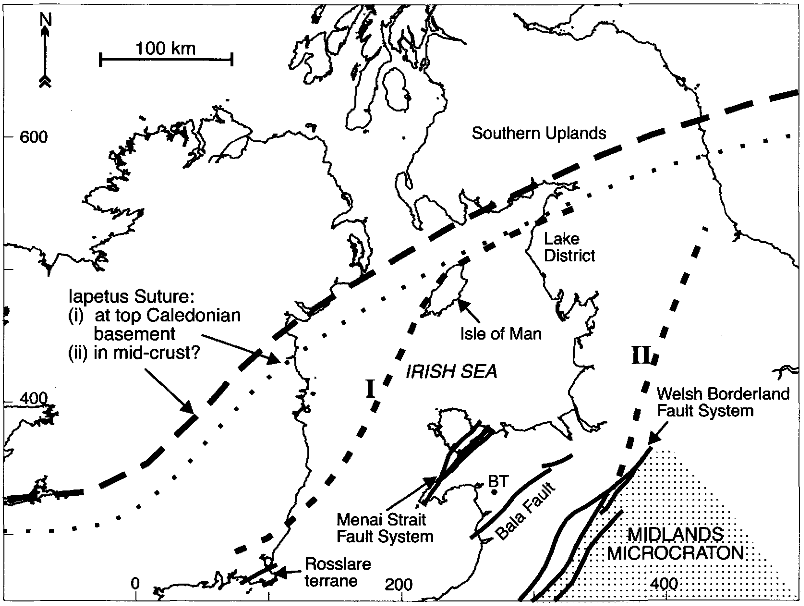

Fig. 1. Map of the region around the Irish Sea showing the approximate location of the north dipping Iapetus Suture at the top of the Caledonian basement [after Soper *et al.* (1992) and British Geological Survey (1996)] and in the mid-crust. Short dashes indicate locations of north-northeast trending magnetic lineaments (I and II). Location of Midlands Microcraton after Pharaoh *et al.* (1987); Welsh fault systems after Woodcock & Gibbons (1988). BT, Bryn-teg Borehole.

Stone (1995) as the effect of a block of magnetic mid-crustal rocks lying in the hanging wall of the Iapetus Suture; they suggest that the source is associated with Precambrian crystalline basement and/or subduction-related magmatic rocks of Ordovician age. The magnetic body may represent a distinct microterrane which originally rifted from the Avalonian continent during its northwards drift and accreted against the Laurentian margin prior to Wenlock time (Kimbell and Stone 1995; Stone *et al.* 1997). An Avalonian origin could explain the similarities in isotopic composition between granitoids subsequently intruded through this crust and those of the Lake District (Thirlwall *et al.* 1989). The position of the Virginia and Nenagh magnetic anomalies invites comparison with the Galloway feature, and the interpretation of these features by Morris & Max (1995) involves a similar juxtaposition of magnetic crustal blocks to the north of the Iapetus Suture and a non-magnetic zone to the south.

Magnetic anomalies to the south of the inferred Iapetus Suture

A conspicuous magnetic low lies immediately to the south of the Iapetus Suture in southern Ireland and extends across the Irish Sea to the Solway Firth. To the southeast of this feature are a series of prominent magnetic anomalies with a variety of trends. Magnetic anomalies immediately to the south and east of the Isle of Man (IoM in Fig. 2a) have been interpreted as evidence of a concealed magnetic basement underlying this area which could be a Precambrian crystalline basement, Ordovician magnetic intrusive and/or sedimentary rocks, or a combination of these (Lee 1989; Kimbell & Stone 1995).

A distinct magnetic anomaly can be traced between southeast Ireland and northwest Wales (RNW in Fig. 2a). In the west, the anomaly extends onshore in the vicinity of the Rosslare Terrane (Fig. 1), a metamorphic complex that may have originated in Palaeoproterozoic times, although the earliest reliable dates relate to a *c.* 620 Ma retrogressive event (Max *et al.* 1990; Winchester *et al.* 1990; Murphy *et al.* 1991; Gibbons *et al.* 1994). The magnetic anomaly appears to extend to the north of the Ballycogly Mylonite Zone, which forms the northern margin of the Rosslare Terrane, over the adjacent ?Precambrian–Cambrian metasedimentary rocks of the Cullenstown Formation. Max *et al.* (1983) identified a magnetic lineament (the Wexford Boundary Linear) corresponding to

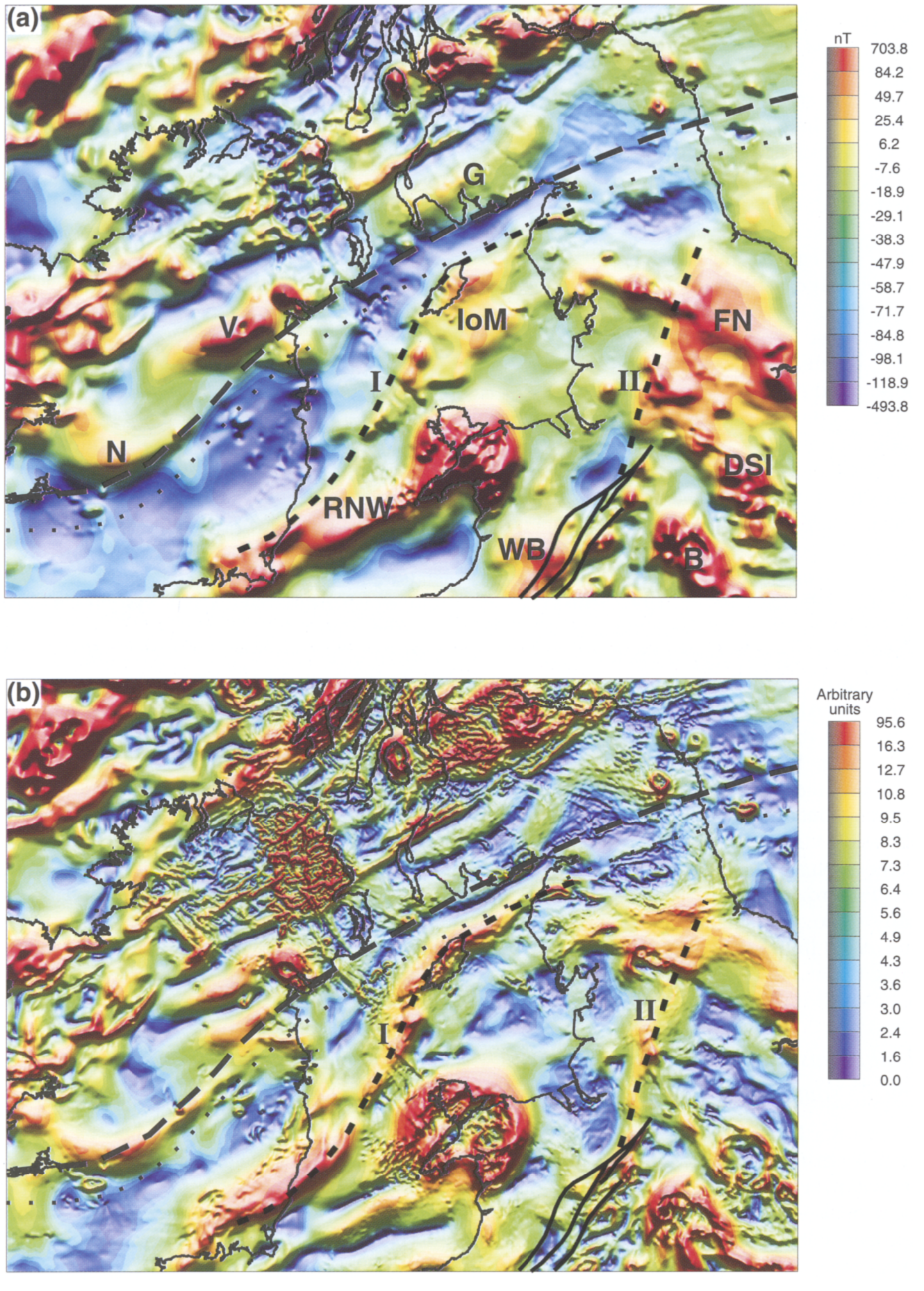

Fig. 2. Aeromagnetic images derived from the gridded data set of British Geological Survey (1998). Colour shaded-relief displays employing equal colour area and illumination from the north. Long dashes and dotted lines indicate the approximate position of the Iapetus Suture (cf. Fig. 1); short dashes indicate north-northeast trending magnetic lineaments (I and II). (**a**) Reduced-to-pole aeromagnetic field, upward-continued by 2 km. Labelled magnetic anomalies: B, Birmingham; DSI, Derby–St. Ives; FN, Furness–Norfolk; G, Galloway; IoM, Isle of Man; N, Nenagh; RNW, Rosslare–North Wales; V, Virginia; WB, Welsh Basin. (**b**) Horizontal gradient of pseudogravity.

the northern edge of the anomaly and suggested that it marks the northern limit of rocks deformed during the Cadomian Orogeny. Where the anomalous zone extends into North Wales, short-wavelength magnetic disturbances can be correlated with pyrrhotite/magnetite-bearing Lower Palaeozoic sedimentary and volcanic rocks (Allen *et al.* 1979; Evans & Greenwood 1988), but an additional, deeper source is required to explain the observed broad, high amplitude anomaly (Allen *et al.* 1979; Howells & Smith 1997). This source underlies volcanic rocks of probable Neoproterozoic age intersected in the Bryn-teg Borehole (Fig. 1; Allen & Jackson 1978), and is therefore most probably Precambrian in age, although a later (Ordovician?) intrusive origin cannot be ruled out.

Several conspicuous, northwest trending magnetic anomaly belts occur in central and northern England. The anomalies extending southeastwards from the Birmingham area (B in Fig. 2a) have been interpreted as the magnetic signature of the magmatic core of a late Precambrian (Charnian) volcanic arc embedded within the Midlands Microcraton (Pharaoh *et al.* 1991; Busby *et al.* 1993). The Derby–St Ives magnetic anomaly (DSI in Fig. 2a) has been ascribed to a belt of Ordovician magnetic intrusive rocks such as the Mountsorrel Granodiorite (Allsop 1987). Pharaoh *et al.* (1993, 1995) suggest that this, and the Furness–Norfolk feature (FN in Fig. 2a) relate to Ordovician (*c.* 450 Ma) arc magmatism associated with southwestward subduction of the Tornquist Sea beneath the Midlands Microcraton. Other explanations for the Furness–Norfolk magnetic anomaly include: shallow Proterozoic magnetic rocks (Wills 1978) and early Ordovician magnetic sedimentary rocks (as intersected in the Beckermonds Scar Borehole; Wilson & Cornwell 1982).

North-northeast trending regional magnetic lineaments south of the Iapetus Suture

Two north-northeast trending lines have been identified from the magnetic anomaly pattern and are shown in Figs 1 and 2. Line I marks the boundary between relatively magnetic crust in the southeastern part of the Irish Sea and the less magnetic zone to the northwest. This feature is particularly well imaged using the horizontal gradient of pseudogravity (Fig. 2b). It extends in a north-northeast direction between southeast Ireland and the Isle of Man, where it swings sharply to an east-northeast trend, parallel to the inferred Iapetus Suture.

Line II (Figs 1 and 2) lies on the projection of the Welsh Borderland Fault System (Woodcock & Gibbons 1988) and marks the western edge of a zone of higher anomaly values upon which the (shallower) Derby–St Ives and Furness–Norfolk features are superimposed. The latter cross-cuts this line, extending northwestward to the southern Lake District. A small dextral offset in the Furness–Norfolk axis and a change in the apparent depth to its source (deeper to the east) occurs in the vicinity of its intersection with Line II, but correlates more closely with Carboniferous displacements along the east-northeast trending North Craven Fault (between the Askrigg Block and Harrogate Basin; Kirby *et al.* 1999) than with the deeper feature. Where it is exposed, the Welsh Borderland Fault System is characterized by local magnetic anomalies associated with shallow, Precambrian magnetic rocks in structurally controlled basement highs; the Birmingham anomaly lies to the east of this fault system but further to the south the clearest evidence for deeper seated magnetic basement lies on its western side beneath the Welsh Basin (WB in Fig. 2a). Woodcock & Gibbons (1988) present evidence that admits, but does not demonstrate, major Ashgill or earlier transcurrent movements on the Welsh Borderland Fault System (in particular, on the Pontesford and Tywi Lineaments). The pattern of magnetic anomalies associated with this fault system and its northward projection are more easily explained if early tectonic movements (pre-dating the source of the Furness–Norfolk magnetic anomaly) are invoked.

3D modelling of magnetic basement

A model has been derived which can account, in a quantitative fashion, for the broad features of the magnetic anomaly pattern in the region around the Isle of Man. The modelling process involves a number of major simplifying assumptions and these must be borne in mind when assessing the significance of the results.

Modelling procedure and assumptions

Magnetic modelling is non-unique, as it is possible to generate the same anomaly field by a variety of model geometries and magnetic property distributions. A model derived by an inversion of the observed anomalies is therefore dependent on the modelling assumptions, which inevitably represent a substantial simplification when compared with the likely complexity of the structures involved. In the example illustrated here it was assumed that the long-wavelength component of the observed magnetic field was generated by variations in the depth to the top of a 'magnetic basement' with uniform magnetization. On the basis of the arguments presented by Kimbell & Stone (1995), it has been assumed that the magnetization is in the direction of the Earth's present magnetic field and the base of the layer giving rise to the magnetic anomalies lies at a depth of 20 km. The longer wavelength component of the magnetic field was separated from anomalies due to shallow sources by applying wavelength filtering as part of the model optimization process; the model illustrated employed a low-pass filter with a ramp between 27 and 56 km. A magnetization of 1.5 A m^{-1} was assumed; this value is clearly not well constrained, but it becomes difficult to model all the long-wavelength magnetic field variations observed across the region if the level is significantly lower than this, and much higher average magnetizations would be difficult to justify in terms of the likely source rocks.

The model was generated using the *Bmod* program (Z. K. Dabek, British Geological Survey), which employs wavenumber domain algorithms based on those of Parker (1972) and Parker & Huestis (1974). In order to minimize edge effects, the modelled area (460 × 380 km) was significantly larger than that shown. The inputs were regular grids with a 2 km node spacing representing the observed total magnetic field, topography and the observation surface (305 m above topography in the onshore area and a similar height above sea level in the offshore area). A generalized starting model was created by suitable shifting and scaling of a smoothed version of the pseudogravity field; the geometry of the upper surface of the magnetic layer was then optimized by an iterative process. An initial assumption was made that the average observed field over the full model area was zero; this involved applying a shift of +30 nT to the observed total field values.

Some of the shortcomings of this approach are:

- long-wavelength magnetic anomalies may be generated by lateral variations in crustal magnetization rather than topography on a uniformly magnetized basement;
- the optimization process generates a simple envelope for the magnetic source. The methods used could not, for example, generate a model incorporating dipping slabs with contrasting magnetic properties (cf. Kimbell & Stone 1995);
- separation of the observed field into 'shallow' and 'deep' components is far from straightforward. Even if there are such separate groups of sources, there is likely to be spectral overlap between the anomalies they generate, such that a 'deep' anomaly may be distorted by removal of its shorter wavelength components or superimposition of the longer wavelength components of shallow sources. The filter applied represents a compromise and, in places, suppresses features which may be part of the 'magnetic basement' (e.g. the northern extension of the Furness–Norfolk anomaly and some of the Irish Sea features). Attempts to extend the model to incorporate shallow sources proved unsuccessful because the optimization became unstable.

In view of these limitations, the derived model does not necessarily represent a 'real' surface but is rather a way of assessing the scale of the magnetization contrasts required to explain the regional long-wavelength magnetic anomaly pattern. It provides a valuable aid in identifying the location of major crustal boundaries (large offsets in a magnetic interface and/or lateral changes in magnetization).

Features of the 3D model

The model is displayed in Fig. 3a, while Fig. 3b and c show the observed and computed fields, respectively; both fields have been upward-continued by 2 km to allow easier comparison of long-wavelength features.

The model indicates changes in crustal magnetization across the region equivalent to the assumed basement magnetization extending over a vertical interval of *c.* 15 km (approximately half the crustal thickness). Given that this magnetization (equivalent to an induced magnetic susceptibility of 0.038 SI units) would be considered high even for a local, near-surface source, the inferred geometries imply substantial changes in the nature of the crust.

One of the most striking features of the model is the major reduction in crustal magnetization required to explain the low magnetic field values to the north and west of the Isle of Man. Although significant post-Lower Palaeozoic subsidence has occurred within the Solway and Peel Basins, which lie along the axis of this magnetic low, Kimbell & Stone (1995) argue that it is primarily due to pre-existing magnetization structures rather than post-collisional subsidence. Evidence to support this assertion is provided by the apparent continuity of the magnetic low beyond the limits of these basins; it crosses the southern part of Ireland (Fig. 2a) and perhaps is related to a similar magnetic feature which characterizes the Gander Terrane in Newfoundland (Jacobi & Kristoffersen 1981).

A substantial change in crustal magnetization is required to explain the broad magnetic gradient zone which crosses the west side of the Isle of Man and forms part of Line I identified from regional magnetic images (Figs 1 and 2; same label used in Fig. 3a). The 3D model confirms the change in the orientation of this magnetic boundary from north-northeast–south-southwest to the south of the island to east-northeast–west-southwest to the northeast.

By contrast, the model shows that long-wavelength magnetic field variations observed for some distance to the east-southeast of the island can be explained by relatively modest variations in the magnetic basement. However, a significant change in the depth and/or magnetization of the magnetic basement is required to explain the change in magnetic field level across Line II (Figs 1, 2 and 3a).

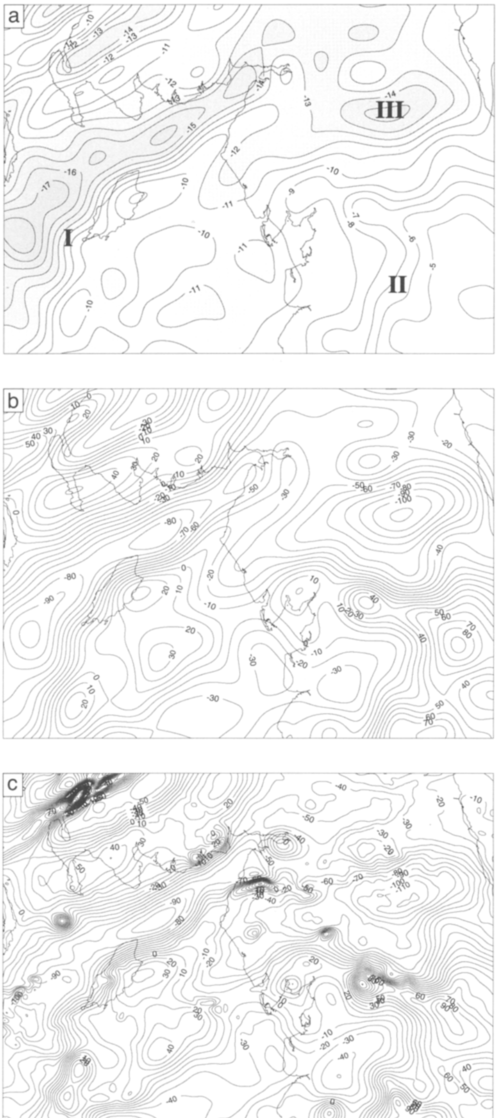

Fig. 3. Results of 3D magnetic basement modelling. (**a**) Apparent depth to magnetic basement (in km below sea level). Basement magnetization is 1.5 A m^{-1} and depth-to-base is 20 km. I–III are features discussed in the text (I and II correspond to lines with the same labels in Figs 1 and 2). (**b**) Total magnetic field (nT) computed using the model shown in (a). (**c**) Observed total magnetic field (nT) shifted by +30 nT.

A further significant perturbation in the magnetic basement in northeast England (feature III in Fig. 3a) correlates spatially with the concealed Weardale Granite (Bott 1967). This may be because of the magnetization contrast between the deep-seated granite and surrounding basement (Bott & Masson Smith 1957), although detailed magnetic modelling suggests that the magnetization contrast may extend to greater depths than those required by gravity modelling of the granite. This feature lies on an axis extending southwestwards across the Lake District (where a granite batholith also exists) and into the offshore area, where it projects towards the relative low between the two magnetic highs south-southeast of the Isle of Man (where a major granite batholith is unlikely). It is possible that, in addition to the local influence of the granites, regional east-northeast trending structures may influence the geometry of the magnetic basement in this area. Structures with this trend were active during the closure of the Iapetus Ocean and subsequent Acadian deformation (cf. Kneller & Bell 1993; Kneller *et al.* 1993; England & Soper 1997), although an earlier (Avalonian) influence is possible.

The 3D model does not allow detailed resolution of the magnetic basement structures. Its approximate nature is illustrated by the 20–30 nT difference between the maximum anomaly amplitude in the upward-continued observed and calculated fields in the vicinity of the Isle of Man (Fig. 3). In order to study the magnetic boundary further, the following sections briefly assess complementary geophysical and geological evidence from the island and present more detailed, local modelling.

Other geophysical and geological evidence

Figure 4 is a Bouguer gravity anomaly map of the Isle of Man and environs based on land stations by Cornwell (1972) and offshore data acquired by the British Geological Survey and Western Geophysical. The offshore area is dominated by the effects of variations in the thickness of the relatively low density cover sequence; major Bouguer anomaly lows are associated with the Peel Basin to the west of the island, the Solway Basin to the north and the Onchan Depression to the east (Quirk & Kimbell 1997). Onshore, Bouguer gravity anomaly lows in the vicinity of the granite exposures at Foxdale and Dhoon have been interpreted by Cornwell (1972) as the expression of voluminous granite bodies underlying these relatively restricted outcrops. In the zone between

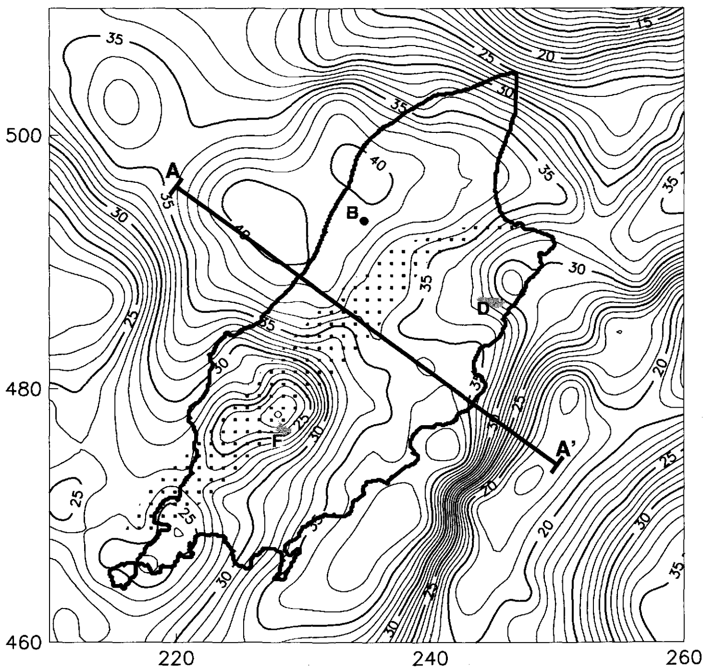

Fig. 4. Bouguer gravity anomaly map of the Isle of Man and surrounding waters. Based on surveys by Cornwell (1972), British Geological Survey and Western Geophysical. Contour interval, 1 mGal (10^{-5} m s^{-2}); reduction densities, 2.70 (onshore) and 2.20 Mg m^{-3} (offshore). Coarse stipple indicates the area of magnetic disturbance revealed by high-resolution airborne survey (Quirk & Kimbell 1997; Quirk *et al.* 1999). AA′, Location of model profile; B; Ballaugh. Granite outcrops (grey): F, Foxdale; D, Dhoon.

the two granite-related features, Bouguer anomaly values increase from east to west across the central part of the island, and in particular across a local gravity gradient zone that extends north-northeastward from the Foxdale anomaly to the vicinity of Ballaugh, then swings to an east-northeast trend (Fig. 4). Cornwell (1972) concluded that this gradient zone was unlikely to be due to concealed granite and preferred an explanation involving either a lateral density contrast within the Lower Palaeozoic rocks or the presence of denser, shallow basement underlying the exposed Lower Palaeozoic rocks to the northwest.

A high-resolution aeromagnetic survey has revealed a zone of magnetic disturbance extending in a northeast–southwest direction along the Isle of Man (Quirk & Kimbell 1997; Quirk *et al.* 1999; approximate extent indicated by stippled zone in Fig. 4). A detailed discussion of this zone is beyond the scope of this paper, but it is noted that the short wavelength of the magnetic disturbances indicates that they are due to near-surface magnetization contrasts and are thus not directly related to the underlying deep magnetic basement. Although the anomalies may relate to the original magnetization of the Lower Palaeozoic rocks, an alternative possibility is that secondary magnetic minerals have been concentrated as a result of later processes, perhaps associated with the higher metamorphism along this axis (Simpson 1964; Power & Barnes 1999). A candidate magnetic mineral is ilmenite, which developed in this zone during D_2 deformation (Power & Barnes 1999). Figure 4 illustrates that there is an approximate correspondence between the zone of magnetic disturbance and the gravity gradient zone, with the former lying immediately to the east of the latter. The magnetic data thus provide an indication of the continuity of the feature into the area where the gravity signature is masked by the anomaly due to the Foxdale Granite.

The gravity and detailed aeromagnetic data therefore indicate an anomalous, near-surface zone crossing the Isle of Man which parallels the underlying magnetic basement boundary and exhibits a similar change in trend across the island. Quirk *et al.* (1999) suggest that individual magnetic lineaments within this zone correlate with major geological boundaries, mostly faults, which separate areas of contrasting lithologies within the

Manx Group. For example, a 20 km segment of the southeast margin of the anomalous zone coincides with the faulted contact between the sand-prone Creg Agneash Formation (typical of the eastern side of the island) and the mudstone-dominated Barrule Formation, which is confined to the central axis of the island (Quirk *et al.* 1999). The centre and northwest edge of the anomalous zone coincides with a set of mostly northwest dipping reverse faults, ductile shear zones and intrusions. The current interpretation is that the anomalous zone represents a fault duplex formed during northwest–southeast compression in late Caledonian times (Fitches *et al.* 1999; Quirk *et al.* 1999).

The British Institutions Seismic Reflection Profiling Syndicate (BIRPS) WINCH-2 profile detected a north dipping reflectivity boundary to the northwest of the Isle of Man which has been interpreted as the seismic signature of the Iapetus Suture (Brewer *et al.* 1983; Hall *et al.* 1984; Soper *et al.* 1992). This feature has been correlated with the northern edge of the non-magnetic zone beneath the Solway Basin by Kimbell & Stone (1995) and does not appear to coincide with the major magnetic boundary beneath the Isle of Man, which forms the southern margin of the non-magnetic zone. The only candidate on WINCH-2 for this boundary is a set of north dipping reflections which occur towards its southern end (shot points 17 400 to 17 600) at relatively shallow crustal levels [1–3 s two-way travel time (TWTT)] within the inferred Caledonian basement (e.g. Hall *et al.* 1984, fig. 7). Recent seismic surveys by JEBCO Seismic Ltd have provided clear evidence of a northwest dipping reflective zone at relatively shallow depth [< 1.5 s TWTT (*c.* 4 km)] within the basement to the southeast of the island (Quirk *et al.* 1999, figs 3 and 5). Quirk *et al.* (1999) correlate this zone with the northeast trending belt of shallow magnetic anomalies discussed above. At deeper levels (> 5 s TWTT) two southward dipping reflector packages have been identified to the south of the island by England & Soper (1997), who infer that these are part of a conjugate set of structures developed during Acadian compression.

A possible correlation between deep and shallow structures

Given the similarities in location and trend between the deep magnetic basement boundary and shallower gravity and magnetic features, a close association is possible. This could arise, for example, because units at different crustal levels have been offset by the same, deep-seated structure, or because reactivation of an early, deep structure has influenced the subsequent evolution of the overlying rocks. The possibility of a relationship between the various anomalous bodies has been explored using 2D modelling methods along profile AA′ (Fig. 5; location shown in Fig. 4).

The gravity modelling assumes a highly simplified density structure, but none the less provides some corroboration for the conclusion of Cornwell (1972) that it is not necessary for there to be a substantial connection between the Foxdale and Dhoon Plutons in order to explain the observed gravity variations across the central part of the

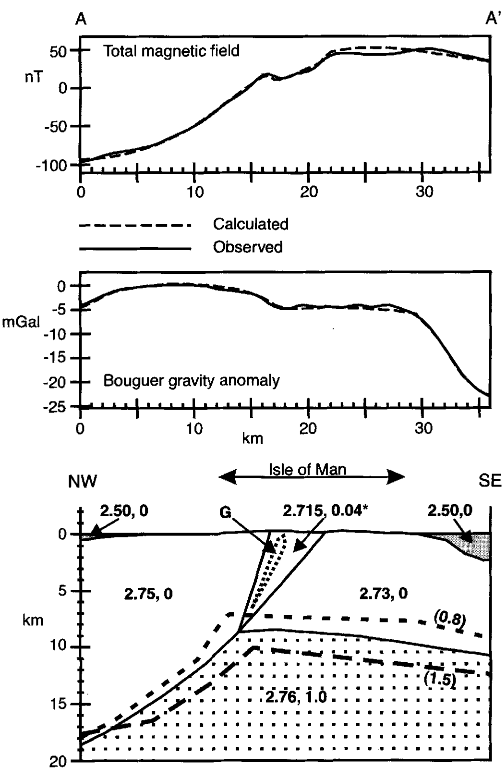

Fig. 5. 2D magnetic and gravity model for profile AA′. Stippled unit, ?Avalonian magnetic basement; no ornament, Lower Palaeozoic sequence; shaded, post Lower Palaeozoic cover. Numbers indicate density (Mg m^{-3}) and magnetization (A m^{-1}). Deep unit is magnetized in the direction of the Earth's present field while shallow unit (*) is magnetized in the opposite direction. Dashed lines show the modelled geometry of the deep magnetic source if the alternative magnetizations shown in parentheses are adopted. Dotted line shows the geometry of a granite body (G; density, 2.62 Mg m^{-3}) which could be accommodated in the model if a density of 2.73 Mg m^{-3} is assumed for the unit containing it. Assumed background fields: magnetic, –30 nT; gravity, +40 mGal.

island. These variations can be replicated by assuming relatively modest density contrasts between different Lower Palaeozoic units. However, the presence of granitic rocks cannot be ruled out altogether as the gravity effect of the central, low density zone in the current model could, for example, be generated by a concealed, sheet or lens of granite with a width of *c.* 0.5 km and a similar northwestward dip (indicated by the dotted line in Fig. 4).

A local depression in the magnetic field has been replicated by assuming a zone with weak reversed magnetization along the axis of the island. The observed magnetic profile is based on the regional data rather than the results of the high-resolution aeromagnetic survey, which indicate that the response will vary markedly depending on where the profile is drawn (Quirk *et al.* 1999). None the less, the model provides a schematic view of the spatial relationship between the zone of anomalous magnetization and the source of the local gravity gradient. More detailed investigations are required to determine whether there really is a direct correlation between anomalous magnetization and relatively low density in this zone.

The long-wavelength magnetic gradient across the island has been modelled as the effect of the northwestward truncation of a mid-crustal magnetic slab. The model includes mid-crustal magnetization variations well beyond the ends of the profile shown, because distant structures have a significant influence on such long-wavelength effects. To illustrate the range of solutions possible, derived geometries assuming three different basement magnetizations are shown. The results indicate that it is feasible to propose a link between the structures responsible for shallow geophysical anomalies across the island and the underlying northwest edge of a major magnetic basement block, providing the structures dip towards the northwest. Such a dip direction is compatible with the geometry of shallow basement reflections in the offshore area (Quirk *et al.* 1999, fig. 6). These reflections, however, have only been observed at shallower depth than the inferred truncation of the magnetic basement, which appears to coincide with a relatively 'blank' zone in deep seismic profiles (cf. England & Soper 1997, fig. 5).

Discussion

The magnetic anomaly pattern across the Irish Sea and central and southern Ireland (Fig. 2a) comprises a northeast trending magnetic low, flanked to north and south by highs characteristic of major magnetic units at mid-crustal depths. The non-magnetic zone narrows in a northeastward direction and cannot be traced along this strike beyond the UK mainland. Kimbell & Stone (1995) correlated northward dipping reflections, previously identified as the seismic expression of the Iapetus Suture, with the boundary between a northern magnetic unit and a non-magnetic zone that they inferred to be a deep wedge of partially subducted sedimentary strata. This is broadly compatible with the interpretation by Morris & Max (1995) of analogous features in Ireland. The focus of the present investigation is the southern margin of the zone of low magnetization which lies beneath the Isle of Man.

Hypotheses for the nature of the magnetic basement underlying the region to the southeast of the Isle of Man are based on an assessment of the regional anomaly pattern extending from southeast Ireland across north and central England. From this, the most likely sources of the observed long-wavelength magnetic anomalies are either parts of a Precambrian (Avalonian) basement or igneous rocks associated with Ordovician arc magmatism. Our preferred interpretation is that the magnetic basement in the vicinity of the island is principally Precambrian in age. This is because the inferred margin of the magnetic basement extends in a south-southeast direction towards the probable edge of the Precambrian basement in southeast Ireland, rather than towards any of the known Lower Palaeozoic volcanic outcrops on the east coast of Ireland. A likely contributor to the higher magnetization is the presence of magnetic Neoproterozoic igneous rocks characteristic of Avalonian basement. The magnetic signature of these rocks has been observed in the Avalon zone of Newfoundland and traced into adjacent offshore areas (Haworth & Lefort 1979). It is possible that older Precambrian magnetic units contribute to the observed anomalies, although direct evidence for such rocks within the area of interest is limited to the Rosslare Terrane, where they have not been reliably dated. Busby *et al.* (1993) suggest the possibility of ancient (pre–late Proterozoic) magnetic basement to the south of the present study area beneath the London Platform.

The above interpretation, which places Avalonian basement on either side of the Menai Strait Fault System (Fig. 1), appears difficult to reconcile with the identification of this fault system as a terrane boundary (Gibbons 1987). However, our interpretation is compatible with the model of Horák *et al.* (1996) in which the Precambrian units juxtaposed by these faults come from the same Avalonian arc system, which was dismembered by transcurrent faulting in late Precambrian–early Cambrian times (Dallmeyer & Gibbons 1987) after the Precambrian magmatism.

Therefore, it is proposed that the Isle of Man overlies the northern edge of the Precambrian

(Avalonian) magnetic, crystalline basement. The non-magnetic unit to the north and west of this boundary is inferred to be a thick succession of predominantly sedimentary Lower Palaeozoic rocks, derived from the northern margin of the Avalonian continent and stacked and thickened during the final closure of the Iapetus Ocean. The basement boundary beneath the island may have been a major extensional structure in early Palaeozoic times, perhaps associated with the rifting of Avalonian fragments such as those postulated by Kimbell & Stone (1995). The north-northeast trending segment of this boundary marks the inferred faulted margin of the Manannan Basin of Quirk & Burnett (1999) and Quirk *et al.* (1999). Rifting may have occurred along planes of weakness within the pre-existing basement and the influence of such structures could provide an explanation for the sharp change in strike observed in the vicinity of the island. Pre-existing basement structures are likely to have formed during the late Precambrian–early Cambrian assembly of Avalonia. The north-northeast–south-southwest orientation of the segment of the basement margin lying between the Isle of Man and southeast Ireland (Line I in Figs 1–3) parallels that of the Welsh Borderland Fault System (Line II), which could have been initiated at a similar time (Kokelaar 1988; Woodcock & Gibbons 1988).

The crustal boundary formed by the edge of the Avalonian basement is likely to have influenced the subsequent geological evolution of the region. In particular, it could have played an important role during compressional episodes relating to the closure of the Iapetus Ocean and subsequent Acadian deformation. The ongoing research on the Isle of Man will provide key evidence to test whether that influence can be recognized; e.g. could changes in deformation style between the east and west side of the island be related to the nature of the underlying basement? It appears likely from the form and location of the Foxdale and Dhoon Granites that the basement structure has exercised control over their emplacement, together with the processes that led to the observed zones of anomalous metamorphism and near-surface magnetization along the axis of the island.

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