Shallow geophysical and geological evidence for a regional-scale fault duplex in the Lower Palaeozoic of the Isle of Man

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Abstract: A distinctive set of linear anomalies is seen on potential field data crossing the Isle of Man in a northeast–southwest belt, 5–6 km wide. The lineaments occur in an imbricate pattern with three constituent trends: northeast–southwest, east–west (to east-northeast–west-southwest) and north–south. The belt can be traced into the offshore where it ties with a northwest dipping set of anomalous high-amplitude seismic reflections interpreted as fluid-filled fractures or intrusions along fractures. In the field, the lineaments coincide with northeast–southwest reverse faults, east–west dextral strike slip faults and north–south sinistral strike slip faults interpreted to have formed during northwest–southeast compression in the late Caledonian. Several of the strike-slip faults were later sites of mineralization. In addition, there is limited kinematic evidence for an earlier period of sinistral transpression on east–west ductile shear zones. A tentative model is proposed where the Manx Group is located on the eastern side of an inverted Lower Palaeozoic basin (the Manannan Basin) forming an embayment on the northwest margin of Eastern Avalonia. During closure of Iapetus, the direction of maximum principal stress (σ_1) rotated from north-northeast–south-southwest to northwest–southeast as Eastern Avalonia docked and then locked against Laurentia. The imbricate belt developed as a duplex at the eastern edge of the basin during the later stages of contraction. The implications of the model is that the stratigraphy of the Manx Group is telescoped.

Quirk & Kimbell (1997) presented work carried out in 1994 showing that a prominent set of shallow-sourced northeast–southwest to east–west linear geophysical anomalies run along the central axis of the Isle of Man, where Lower Palaeozoic rocks assigned to the Manx Group crop out. These lineaments occupy a 5 km wide belt orientated approximately northeast–southwest with a rhomboid shape, similar in some ways to the outline of the island itself. Due to the linked en echelon and lens-shaped arrangement of the lineaments it was originally termed 'imbricate zone' but is renamed the Manx Imbricate Belt in this paper. Few of the implied faults were recognized in earlier structural studies, although Blake (1905) introduced the possibility of stratigraphic repetition by thrusts in the centre of the island. It is, however, worth noting that the central part of the imbricate belt coincides with a change in fold vergence within the Manx Group interpreted by Lamplugh (1903) and Simpson (1963) to represent the trace of a major synclinorium (cf. Fitches *et al.* 1999).

Between 1995 and 1997 fieldwork was carried out on the Isle of Man in order to partially resurvey the Lower Palaeozoic Manx Group (Woodcock *et al.* 1999). By 1996 researchers in the group carrying out this work began to interpret, often independently, the presence of major northeast–southwest, east–west and north–south faults (e.g. Fig. 1). These faults are rarely observed due to poor exposure but are necessary to explain the apparent juxtaposition of different lithostratigraphic and structural domains (Fitches *et al.* 1999; Quirk & Burnett 1999). It was after recognizing the differences between these domains that the idea of

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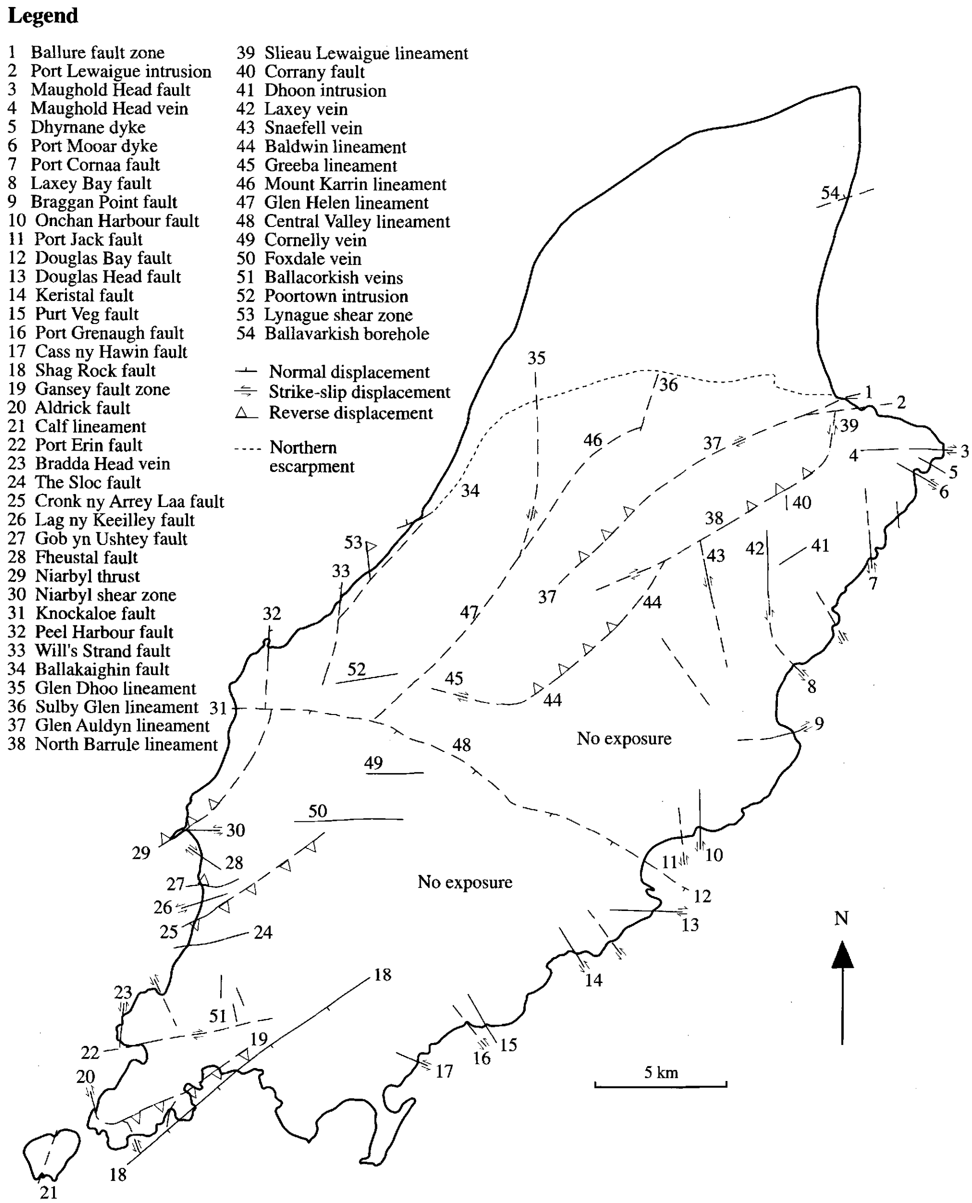


Fig. 1. Map showing observed and inferred faults affecting Palaeozoic rocks of the Isle of Man, based mostly on field work reported in Quirk & Burnett (1999).

dividing the Manx Group into a number of geological tracts was divised (Woodcock *et al.* 1999). However, it was only in 1998, when a lithofacies map had been compiled by Quirk & Burnett (1999), was it realized that there was an apparent fit between some of the important geological boundaries mapped in the field (faulted or otherwise) and the shallow geophysical lineaments originally reported by Quirk & Kimbell (1997). The objective of this paper is to compare these features in order to erect a tentative tectonic model. Detailed work on the kinematic history is required before a more rigorous structural interpretation can be developed although a start has already been made by Fitches *et al.* (1999).

Available data

The data used in this study comprise high resolution aeromagnetic images owned by World Geoscience Corporation, Bouguer gravity anomaly data owned by the British Geological Survey and Western Geophysical, marine 2D seismic data owned by JEBCO, new 1:10 000 geological field maps of the Manx Group (Quirk & Burnett 1999), published and unpublished mine data (Lamplugh 1903; Mackay & Schnellman 1963; Ford 1993; Cowin, pers. comm.), proprietary aerial photographs loaned by the Isle of Man Department of Local Government and the Environment (Kelly, pers. comm.) and sparse borehole information (Young, pers. comm.; Quirk& Kimbell 1997).

The aeromagnetic data were acquired at a height of 80 m with a 400 m traverse line spacing in a 020° direction with tie lines every 1200 m perpendicular to the traverse. The data were processed by application of standard corrections (i.e. International Geomagnetic Reference Field correction, diurnal variation removal, etc.) and by application of microlevelling and culture (human-made objects) suppression techniques proprietary to World Geoscience Corporation. The resultant total magnetic intensity anomaly data were then reduced to the magnetic pole with the aim of centring anomalies over their causative bodies. Subsequent frequency filtering operations allowed edges to be identified and mapped and semi-quantitative depth estimates of subtle magnetic anomaly variations in the subsurface geology to be made. Of particular use in this were derivative (or gradient) images and pseudodepth (or wavelength separation) slices. All aeromagnetic data were displayed using World Geoscience Corporation proprietary software making use of different colour schemes and directions of false illumination, as appropriate (e.g. Fig. 2). The onshore Bouguer gravity anomaly data were derived from 360 stations over a total area of 572 km^2 and displayed as horizontal gradient to highlight edges (e.g. Fig. 3). In addition, *c.* 200 km of migrated 2D seismic data were used to map reflective structures in the Lower Palaeozoic basement offshore to the southwest of the island.

Figure 1 is a map of observed and inferred faults and mineralized fractures based on field mapping made with reference to mine plans, unpublished aerial photographs and limited borehole data. The sense of offset shown on many of the faults was determined mostly by whether rocks on one side of the fault are thought to be older or younger than those on the other side, according to lithostratigraphic correlations presented in detail by Quirk & Burnett (1999). However, it is acknowledged that a degree of interpretation is involved in this. Whether a fault is shown as having dip-slip or strike-slip movement was based simply on its apparent dip. An arbitary value of 80° of dip was taken to discriminate between faults interpreted as normal or reverse (< 80°) and those interpreted as dextral or sinistral (> 80°). In only a few shear zones have kinematic indicators been observed (e.g. Quirk & Kimbell 1997; Fitches *et al.* 1999; Holdsworth, pers. comm.). Faults shown on Fig. 1 with no sense of movement indicated are those where correlation across the fault is equivocal. Most of the large faults are named using nomenclature from Quirk & Burnett (1999) and Woodcock *et al.* (1999), which utilize the nearest obvious place name.

Linear anomalies observed in potential field data

The magnetic response of sedimentary and metasedimentary rocks is determined mostly by the amount of iron minerals such as magnetite, ilmenite and pyrrhotite they contain. It is measured as magnetic susceptibility or how easily a rock becomes magnetized within the Earth's magnetic field. With the use of a hand-held magnetic susceptibility meter during field work, a small but significant difference has been found in the magnetic response of mudstone-rich lithofacies compared with sandstone-rich lithofacies in the Manx Group. For example, rocks containing > 90% mudstone have an average magnetic susceptibility of 0.44×10^{-3} SI (based on 73 readings, with a range of $0.2–2.1 \times 10^{-3}$ SI) whereas sandstone containing < 40% mudstone, has an average magnetic susceptibility of 0.26×10^{-3} SI (60 readings, with a range of $0.0–0.4 \times 10^{-3}$ SI). The relatively high magnetic susceptibility of mudstones in the Manx Group is probably due to the presence of significant amounts of iron, particularly ilmenite which is a common metamorphic phase in the Manx Group (Power & Barnes 1999). A difference in magnetic response in the order of a few nanoteslas is likely to occur across any steeply dipping geological boundary separating Manx Group units with contrasting amounts of mudstone. The most obvious of these types of boundaries are faults (McIntyre 1980) which are likely to appear as linear edge-type anomalies similar to those observed on aeromagnetic data from the Isle of Man (Quirk & Kimbell 1997). In addition, if the fault has been subject to fluid flow, particularly hydrothermal fluid, then it may itself produce an anomalous

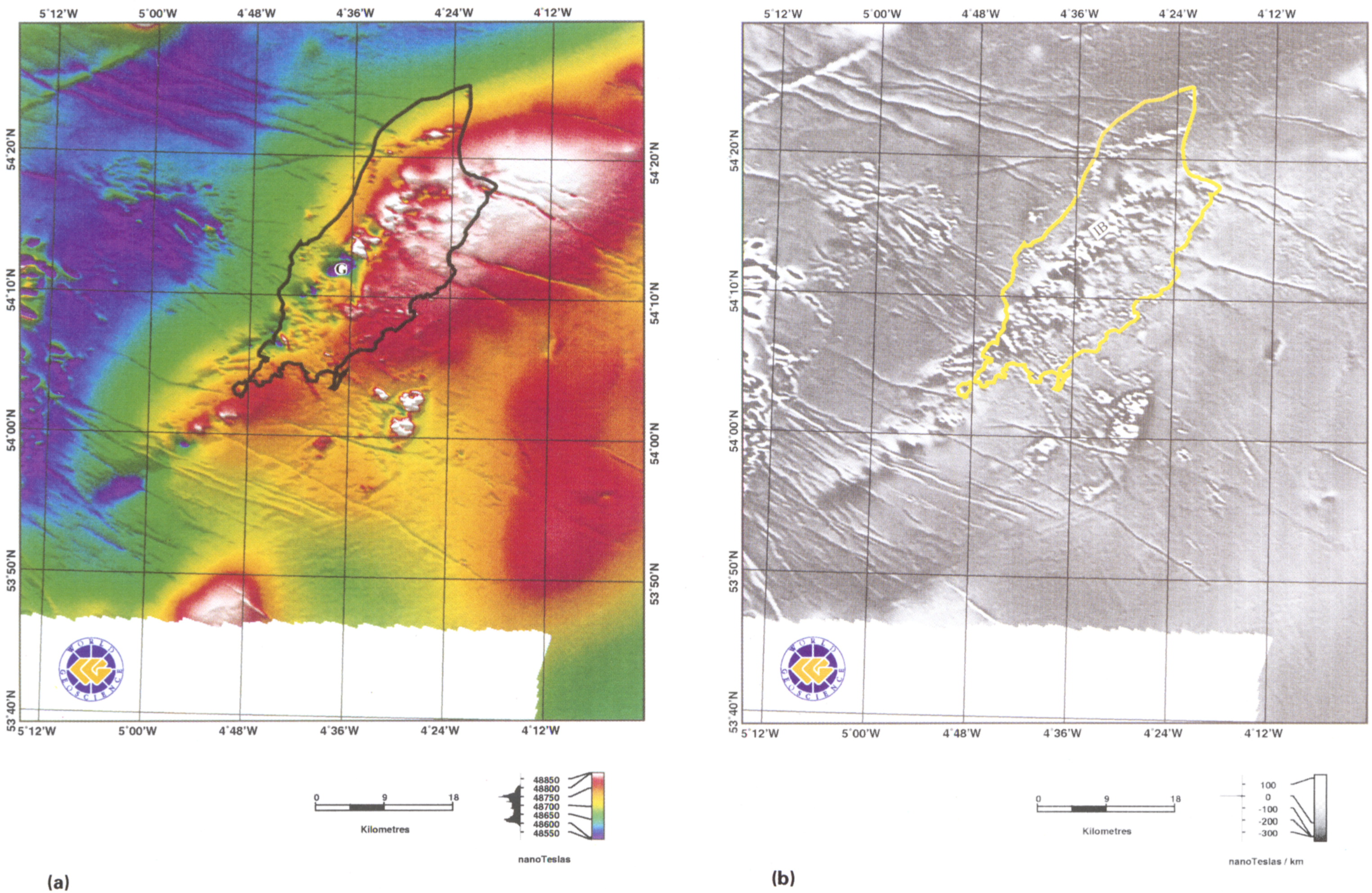


Fig. 2. (**a**) Culture-suppressed total magnetic intensity image (reduced to pole) of the Isle of Man illuminated from the north-northwest (courtesy of World Geoscience). Grid cell size, 130 m; G, Greeba Magnetic Low. (**b**) Grey scale image of first vertical derivative of total magnetic intensity image shown in (a). IB, Manx Imbricate Belt.

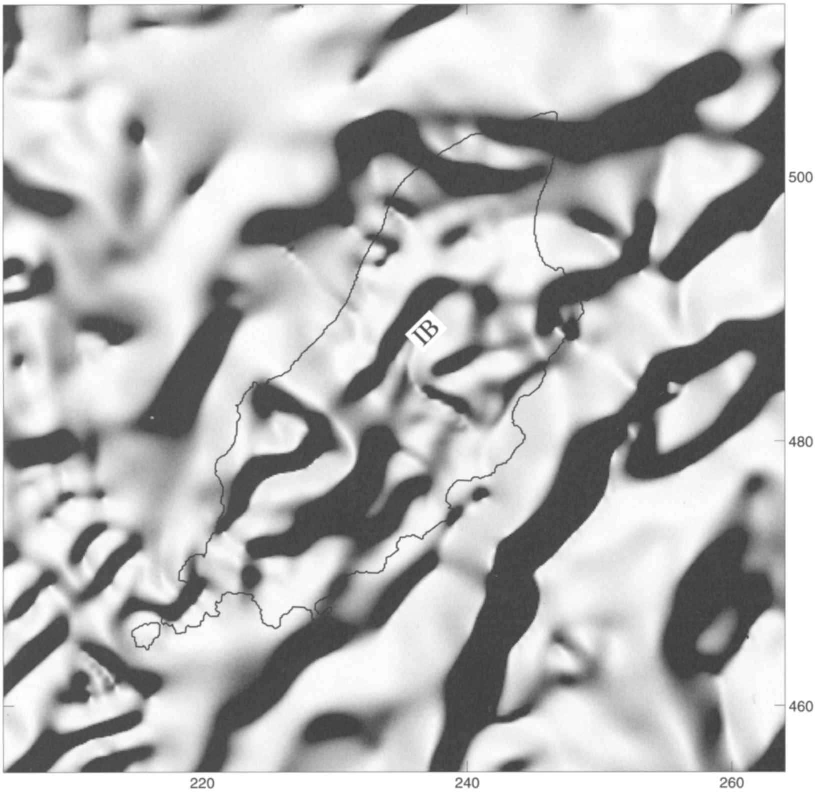


Fig. 3. Shaded relief image of the horizontal gradient of the Bouguer gravity anomaly. The original data is displayed for a larger area in Kimbell & Quirk (1999, fig. 4). Illumination is from 330°. This display highlights local features, particularly edges, but note that some apparent changes in character can relate to differences in data density and quality. IB, Manx Imbricate Belt.

response because of the effects of mineralization and wall-rock alteration (McIntyre 1980). This is likely to be the case in the Isle of Man where large east–west and north–south lead–zinc–copper–quartz veins are present (Ford 1993).

Due to the close spacing of the flight lines, horizontal resolution of the aeromagnetic data is already as high as a few hundred metres, and vertical and horizontal derivatives of the total magnetic field (e.g. Fig. 2b) help to further enhance the definition of edges. In contrast, the resolution of the Bouguer gravity data over the Isle of Man is almost an order of magnitude lower but, here again, with the careful use of derivative images (e.g. Fig. 3), it is still possible to pick out steep, near surface boundaries between rocks of contrasting density (cf. Cornwell 1972). In fact, the two potential field data sets complement each other so well that often where a lineament appears to die out on one it becomes prominent on the other (Quirk & Kimbell 1997).

The most obvious features on the aeromagnetic data are:

1. short wavelength (shallow) lineaments forming the imbricate belt that runs along the northeast–southwest axis of the island (e.g. Fig. 2b);
2. a long wavelength change from high total magnetic intensity east of the island to low total magnetic intensity west of the island at a deep boundary lying subparallel to the imbricate belt (e.g. Fig. 2a);
3. narrow, elongate anomalies trending west-northwest–east-southeast that correspond to dolerite dykes ('Tertiary-type' lineaments).

Features 2 and 3 are discussed in detail by Kimbell & Quirk (1999) and Horak *et al.* (1999), respectively, and hence this paper will concentrate on the imbricate belt and related onshore structures (1).

Manx Imbricate Belt

The short-wavelength nature of the lineaments within the imbricate belt indicates that the causes of the aeromagnetic anomalies lie probably within the upper 1 km of the crust and may therefore intersect the surface. Three trends exist: east–west (to east-northeast–west-southwest), northeast–southwest and approximately north–south (Fig. 4). In addition, west-northwest–east-southeast (to north-west–southeast) trending lineaments cross the imbricate belt (Fig. 2), corresponding to Tertiary dykes. These can lead to aliasing (false alignment) effects during interpretation because of interference with other trends. The margins of the imbricate belt are also clearly expressed on Bouguer gravity data but the internal structure is only poorly resolved (Fig. 3).

The imbricate belt consists of two segments separated by the Central Valley Lineament stretching from Peel to Douglas (Fig. 1; Quirk & Kimbell 1997). To the southwest of the Central Valley Lineament is a bow-shaped segment, 6 km wide and 20 km long. This has a straight northwest side which extends from the west coast to St Johns in the Central Valley and a curved southeast side

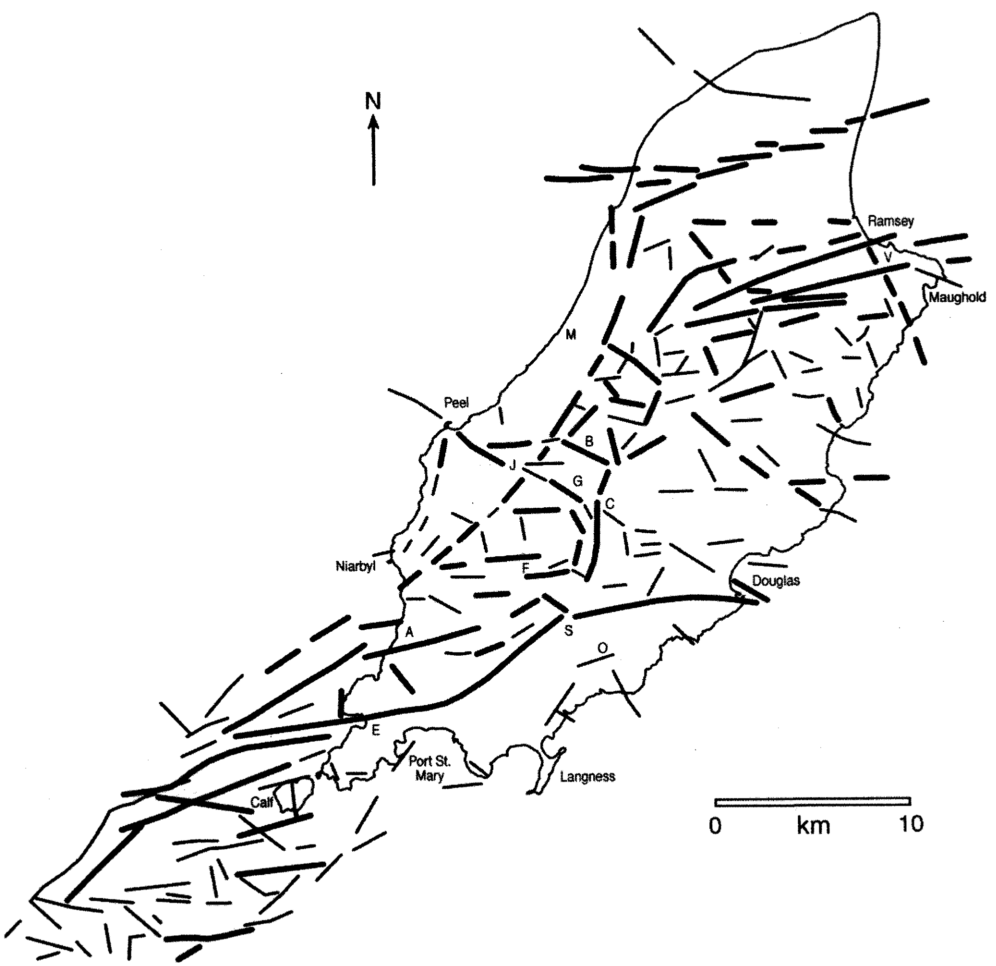


Fig. 4. Interpretation of potential field lineaments observed on Figs 2 and 3 made without reference to surface geology. Thick lines indicate the position of strong lineaments visible on high-resolution aeromagnetic data or where lineaments coincide on more than one data set; thin lines indicate the position of other lineaments visible on aeromagnetic data, Bouguer gravity anomaly derivatives and aerial photographs. Localities referred to in the text are also shown: V, Port e Vullen; M, Glen Mooar; B, Beary Mountain; J, St Johns; G, Greeba; C, Crosby; F, Foxdale Granite; A, Cronk ny Arrey Laa; S, St Marks; O, Oatlands Intrusion; E, Port Erin.

running from Port Erin to Crosby (Fig. 4). East–west lineaments within this segment have a left-stepping en echelon arrangement. A similar shaped, but less clearly defined, group of lineaments lies to the southwest of Port Erin, located mostly in the offshore but also including an area between Port St Mary and the Calf of Man. The imbricate belt is offset slightly to the left by the Central Valley Lineament (Fig. 2b). Northeast of here, the imbricate belt comprises a rhomboid-shaped segment, 5 km wide and 20 km long, defined by northeast–southwest to east–west lineaments. It seems to pinch out between Ramsey and Maughold (Fig. 4). In addition, the aeromagnetic data show a number of east–west lineaments branching off from the main imbricate belt which intersect the eastern coast of the Isle of Man.

Areas of anomalous magnetization occur within the imbricate belt, the most prominent of these

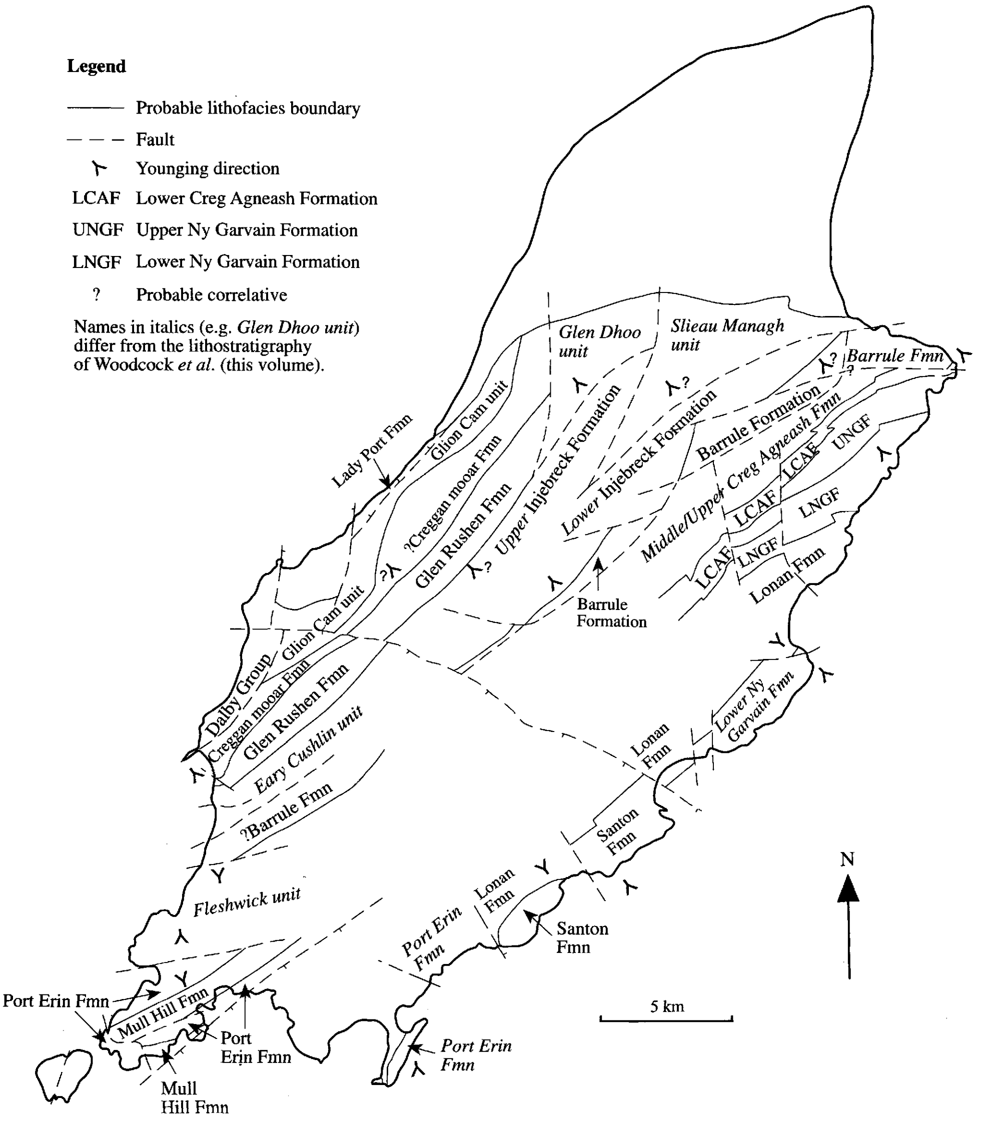


Fig. 5. Map of main lithostratigraphic units within the Lower Palaeozoic of the Isle of Man. The principal faults are also shown on Fig. 1.

being a marked low covering an area of at least 10 km^2 centred around Greeba in the Central Valley (Fig. 2a). This low is juxtaposed on its northeast side by an equally well-defined area of anomalously high magnetization around Beary Mountain (Fig. 4). A similar but smaller pair of low–high anomalies occurs close to mineral veins at Ballacorkish Vein (Fig. 1) in the south of the island lining up with a west-northwest–east-southeast Tertiary type lineament on the southeast side of the imbricate belt (Fig. 2a). Field mapping has provided no lithological explanation for these areas of anomalous magnetization but Quirk & Kimbell (1997) suggested that they may have formed during metasomatism associated with a period of hydrothermal fluid activity recorded in the Irish Sea during the early Tertiary (e.g. Green *et al.* 1997).

Coincidence of geophysical lineaments with geological boundaries

Despite the fact that the potential field lineaments shown in Fig. 4 were interpreted without reference to faults mapped in the field (Fig. 1), there is more than a passing similarity between the two maps. In fact, every strong lineament seen to intersect the coast where exposure is good seems to coincide with a faulted geological boundary and, conversely, only a few of the major faults in the Manx Group do not have a clear geophysical expression. In addition, offshore seismic data, particularly to the southwest of the island, provide clear evidence for the 3D nature of the imbricate belt (see later). The coincidence between potential field anomalies and surface geology is discussed below, separated into geographical areas for which Figs 1 and 4–6 can be used for reference.

Port Erin–Port St Mary

One of the most obvious aeromagnetic features observed on the Isle of Man is an east-northeast–west-southwest lineament intersecting the southwest coast at the north end of Port Erin (Fig. 2a). Here, a steeply north dipping fault or shear zone at [SC 193 697] is inferred from geological mapping and aerial photographs (the Port Erin Fault; Fig. 1). The fault itself cannot be observed due to a 15 m wide gap in exposure but it marks the boundary between quartzites belonging to the Port Erin Formation to the south (Fig. 5) and pebbly mudstones of the Fleshwick Unit (or Maughold Formation of Woodcock *et al.* 1999). The Fleshwick Unit has significantly lower illite crystallinity grades than the Port Erin Formation on the other side of the fault (Roberts *et al.* 1990). Depending on how the correlations are made, it accounts for between 2.5 and 5.5 km of stratigraphic offset by apparent dextral movement cutting out the Barrule Formation, at least part of the Creg Agneash Formation and possibly the Santon–Ny Garvain formations (Fig. 5; Quirk & Burnett 1999). Major folds verge towards the Port Erin fault on both sides (Fitches *et al.* 1999) and deformed pebbles within the northern wall display a gently west dipping linear fabric parallel to the inferred direction of shear on the fault.

A few kilometres east of here, between Port St Mary and Gansey, a set of southeast dipping thrusts occur in association with a major recumbent fold (the Gansey Fault Zone; Fig. 1). One of these faults extends southwest to Cregneash where it is responsible for thrust repetition of a thick quartzite interval (the Mull Hill Formation; Fig. 5). Although the continuation of this thrust into the offshore is complicated by the presence of a major north-northwest–south-southeast striking sinistral cross-fault at the coast (the Aldrick Fault; Fig. 1), it probably links up with a strong northeast–southwest trending lineament on the north side of the Calf of Man (Fig. 4).

A short north–south aeromagnetic lineament on Bradda Head, just north of the Port Erin Lineament, coincides with the Bradda Head Vein (Fig. 4). This comprises a vertical, quartz-filled and metasomatized fault which accounts for a few hundred metres of sinistral offset based on lithostratigraphic correlations presented in Quirk & Burnett (1999). A similar but north-northeast–south-southwest trending structure is observed on aerial photographs crossing the Calf of Man which is reported to be associated with quartz mineralization (Fitches, pers. comm.).

Offshore extension of the imbricate belt

The imbricate belt continues offshore to the southwest of the Isle of Man where it is crossed by several 2D seismic lines (Fig. 6a). One line in particular (Fig. 6b and c) images an unusual set of northwest dipping, high-amplitude reflections within the basement coinciding at the sea bed with the central part of the imbricate belt observed on aeromagnetic data (Fig. 2). Near the surface, the reflections occupy a zone *c.* 2.5 km wide which dip between 25 and 35°. They converge downwards and become difficult to resolve below 1.5 s two-way time travel (*c.* 4 km depth). The strength of these reflections is unusual within basement rocks, particularly in view of their relatively steep dip, and the most likely interpretation is that they image either fluid-filled fracture zones or intrusions with high acoustic impedance. Even in the case of intrusions, by analogy with the onshore, they probably occur in association with major faults or shear zones. Although not as clearly expressed on other seismic lines, the dipping reflections can be mapped for a distance of almost 25 km in a northeast–southwest (strike) direction (Fig. 6a).

The reflections on the southeast side of the dipping structure are truncated near surface by a major northeast–southwest trending normal fault which is the offshore extension of the Shag Rock Fault (Fig. 1). Onshore, this fault delimits the northwest edge of the lower Carboniferous Castletown Group cropping out between Port St Mary and Langness. Where this fault has been traced in the field using geological evidence alone (e.g. Lamplugh 1903) it shows little, if any, potential field expression. However, it coincides with the projected southeast edge of the imbricate belt linking the onshore with the offshore extension (Fig. 7) and the fault has probably exploited this zone of crustal weakening (cf. Quirk & Kimbell 1997).

A structural extension of the Isle of Man known as the Ramsey–Whitehaven Ridge occurs in the offshore, northeast of the island (Quirk & Kimbell 1997). This represents a basement block underlying a thin Carboniferous cover that is tilted by 10–15° to the northwest as a result of uplift in the footwall of the northeast–southwest Lagman Fault (Quirk *et al.* 1999). The Lagman Fault and its southern extension (the Eubonia Fault) run close and parallel to the east coast of the Isle of Man and, judging from their northeast–southwest trend, similar to the Shag Rock Fault, they may have exploited a pre-existing Caledonian structural grain (Jackson & Mullholland 1993). Both faults are normal with 1–3 km of Carboniferous and Permo-Triassic strata preserved in their southeast hanging walls. Analogous faults are not observed on the western side of the Isle of Man and therefore the Manx Group is thought to have been tilted to the northwest after the Caledonian by an amount similar to that recorded on the Ramsey–Whitehaven Ridge (10–15°).

Cronk ny Arrey Laa

A set of northeast–southwest and east–west aeromagnetic and Bouguer gravity lineaments intersect the west coast of the Isle of Man between The Sloc and Gob yn Ushtey, with the hill of Cronk ny Arrey Laa in the centre (Fig. 4). This is a steep section of coastline but, where access to the shore is possible, e.g. below Lag ny Keeilley [SC 215 745] and at Gob yn Ushtey [SC 216 756], a number of shear zones and brittle faults are exposed together with ?pre-kinematic felsitic intrusions and brecciated quartz veins (Fig. 1). At Gob yn Ushtey a 50 m wide fault zone is present, the northern wall of which trends 060°/70° NW. An 8 m wide, steeply north dipping ductile shear zone with sinistral kinematic indicators is exposed at high watermark to the northwest of Lag ny Keeilley [SC 216 747]. A short distance north of here a set of quartz veins and metasomatic tourmaline occurs in a 100 m wide fracture zone (Morris, pers. comm.) and includes a large reverse fault displaying slickensides pitching 70° SW on 045°/45° NW.

Where the coast is not accessible immediately south of Lag ny Keeilley a strong topographic feature has been used to infer the position of a major south-southeast dipping fault running from Stroin Vuigh [SC 213 742] to the north side of Cronk ny Arrey Laa, which marks the northwest boundary of the Barrule Formation (the Cronk ny Arrey Laa Fault; Fig. 1). Tentative lithostratigraphic correlations suggest that this fault accounts for almost 3.5 km of stratigraphic offset cutting out the Fleshwick Unit, the probable lateral equivalent of the lower part of the Injebreck Formation (Fig. 5; Quirk & Burnett 1999). At The Sloc, a similar change in topography and an observation by Lamplugh (1903) of quartz veining and breccia in a mine trial at The Stacks [SC 211 735] suggests that another east-northeast–west-southwest trending fault may be present at the mapped southeast boundary of the Barrule Formation (the Sloc Fault; Fig. 1).

Overall, the area between Gob yn Ushtey and The Sloc is thought to represent a zone of extensive heterogeneous deformation with both ductile and brittle movement, and evidence of intrusions and hydrothermal mineralization. It corresponds approximately with the position of Lamplugh's (1903) and Simpson's (1963) synclinorium axis to which folds verge on both sides (Fitches *et al.* 1999). It is thought likely that a similar sort of complex structure has produced the zone of dipping reflections imaged on seismic in the offshore extension of the imbricate belt (Fig. 6).

Niarbyl

Beyond the apparent northern limit of the imbricate belt at Gob yn Ushtey, an important ductile shear zone and major brittle fault is exposed at Niarbyl [SC 211 776] (Fig. 1). The fault marks the contact between the lower Ordovician Manx Group (Creggan Mooar Formation) in the footwall and the mid-Silurian Dalby Group in the hanging wall (Fig. 5), but is none the less interpreted as a thrust because of the presence of minor compressional structures (Quirk & Kimbell 1997; Morris *et al.* 1999). This faulted boundary has been mapped northwards for 7.5 km to Peel. Here it joins the Central Valley Lineament to become the Peel Harbour Fault (Fig. 1), where it also defines the western edge of the ?Devonian Peel Group.

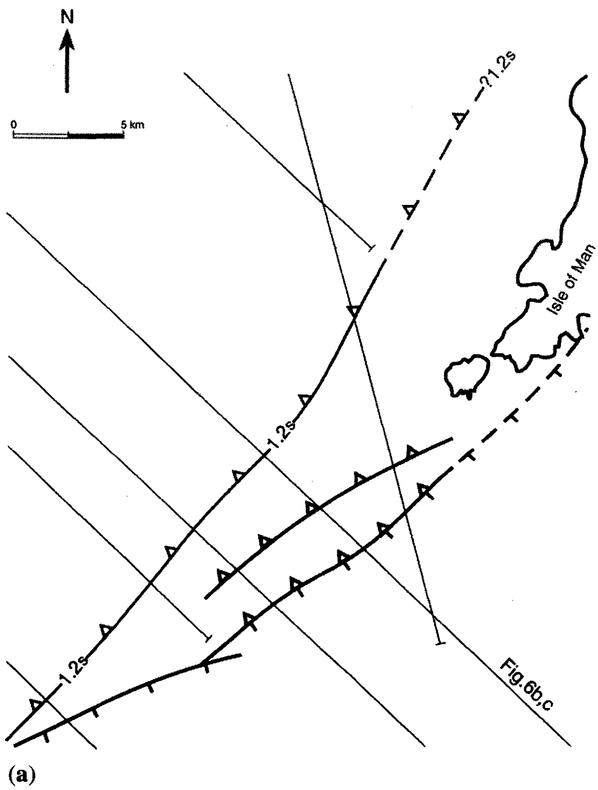


Fig. 6. (**a**) Map showing interpreted position of northwest dipping basement reflections near the sea bed (thick line ornamented with triangles) and at 1.2 s two-way time travel (equivalent to a depth of *c.* 3.5 km). Also shown are the seismic lines used (thin, straight lines) and a Carboniferous normal fault (thick line ornamented with ticks). (**b**) Northwest-southeast stacked 2D seismic line located *c.* 10 km southwest of the Isle of Man (courtesy of JEBCO). Note the prominent northwest dipping reflections within Lower Palaeozoic basement. The vertical scale is in s two-way time travel. (**c**) Geoseismic section of migrated version of the 2D seismic line shown in (b), showing prominent northwest dipping reflections within the Lower Palaeozoic basement. The vertical scale is in s two-way time travel.

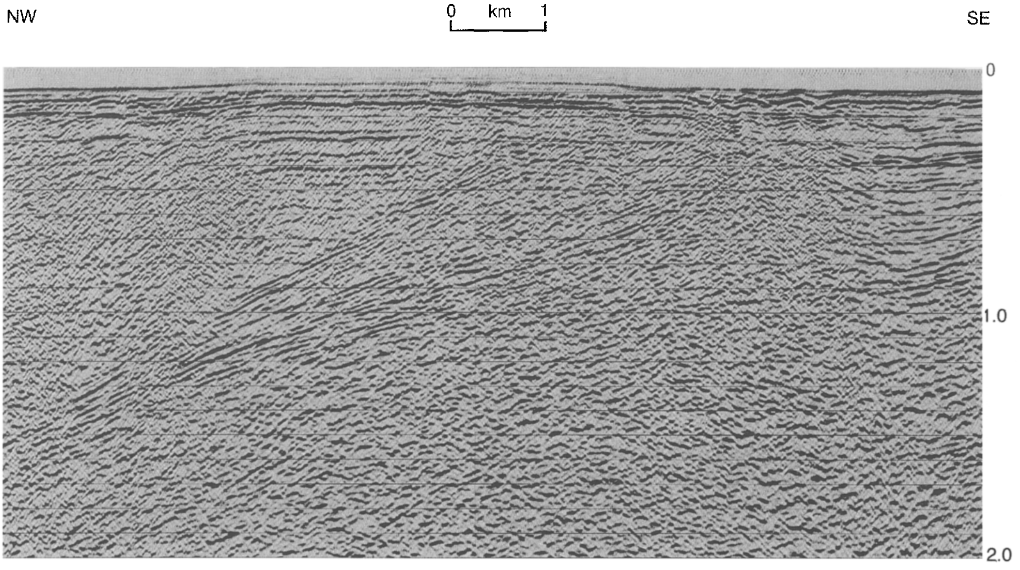
Although it is poorly expressed on aeromagnetic data, a clear edge is visible on Bouguer gravity data (Fig. 2) and Roberts *et al.* (1990) recognized the presence of anomalously low illite crystallinity values around Niarbyl probably due to strain-induced metamorphic regression. At this locality the fault trends between 070°/15° NW and 000°/60° W, and truncates the ductile shear zone occupying the footwall. The shear zone itself is several tens of metres wide and contains highly deformed sediments, disrupted felsitic intrusions and disaggregated quartz veins with a strong phyllonitic fabric orientated 105°/75° N. Kinematic indicators described by Fitches *et al.* (1999) suggest overall sinistral displacement.

Northwest coast

A ductile shear zone, smaller than the one exposed at Niarbyl, occurs on the northwest coast at Lynague [SC 281 871] (Fig. 1). In contrast to Niarbyl, the Lynague Shear Zone is orientated north-northwest–south-southeast, displaying a planar phyllonitic fabric which trends between 160°/65° NE and 125°/50° NE with a reverse (–?dextral) sense of shear based mostly on folded and boudinaged quartz veins.

Elsewhere along the coast between Will's Strand and Glen Mooar the structure of this part of the Manx Group (the Lady Port Formation; Fig. 5) is complicated by younger faults but also includes numerous northwest dipping thrusts. A north–south vertical fault forms the boundary between the Manx Group and the ?Devonian Peel Group at Will's Strand, whereas the northern limit of the Manx Group is marked by an east-northeast–west-southwest vertical fault near Glen Mooar. The Lady Port Formation is interpreted to be in faulted contact with the Glion Cam Unit a few hundred metres inland. This putative fault (the Ballakaighin Fault; Fig. 1) is thought to run parallel to the coast (Woodcock *et al.* 1999). None of the faults or shear zones in this area are clearly imaged on potential field data.

The orientation of bedding and cleavage in the Lady Port Formation is also unusual in that instead of striking northeast–southwest to east-northeast–west-southwest, as is the case for the majority of the Manx Group, north–south trends are common. Inland of Glen Mooar, around Glen Dhoo and



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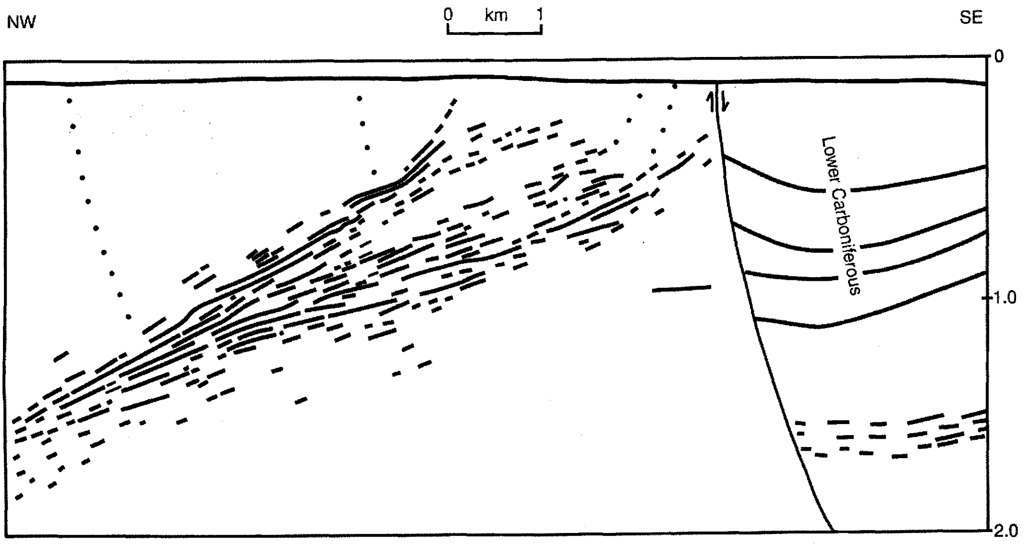

(c)

Sulby Glen, two approximately north–south trending faults are interpreted (Fig. 1) bounding the western and eastern sides of an unusual sandstone-dominated interval known as the Glen Dhoo Unit (Quirk & Burnett 1999). The mapped position of the fault bounding the western side of the Glen Dhoo Unit is supported by the presence of a mine waste heap at [SC 340 890] consisting, to a large degree, of fault breccia. It also coincides with the approximate location of a north–south trending aeromagnetic lineament (Fig. 4). The southern boundary of the Glen Dhoo Unit is probably defined by a northeast–southwest trending normal fault (the Mount Karrin lineament; Fig. 1).

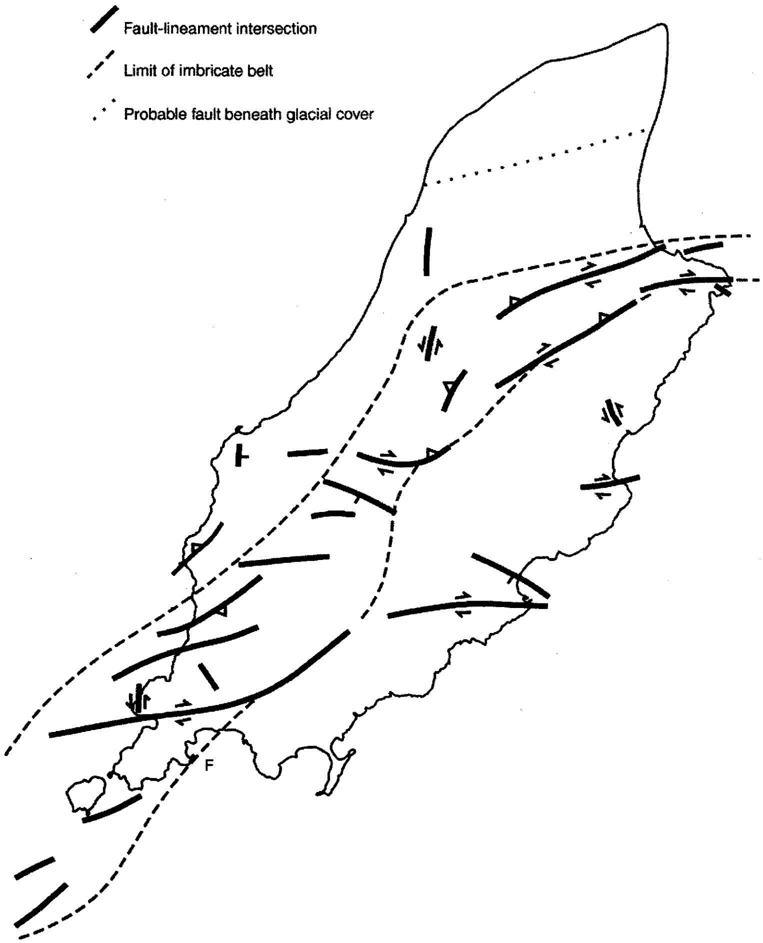

Fig. 7. Map made by integrating Figs 1 and 4 showing coincidence between faults mapped in the field and prominent potential field lineaments.

Central Valley

Aeromagnetic data show that the imbricate belt is slightly offset to the left by a west-northwest–east-southeast trending lineament running along the Central Valley between Peel and Douglas (Figs 2b and 4). On Bouguer gravity data (e.g. Fig. 3), the western half of the lineament marks the northeast edge of a gravity low, at least in part, related to the Foxdale Granite (Cornwell 1972). Field mapping and aerial photographs suggest that the Central Valley Lineament bifurcates near Peel, one strand of which coincides with an east–west fault near Knockaloe, offsetting the basal contact of the Dalby Group (Figs 1 and 5; Morris *et al.* 1999). Geophysical data described by Quirk *et al.* (1999) and Quirk & Burnett (1999) show that the lineament extends into the offshore as a set of normal faults in younger strata defining, for example, the northeast margin of the Permo-Triassic Peel Basin. Although onshore it has a marked topographic expression in that the Central Valley cuts straight through the uplands at < 50 m above sea level, it is nowhere exposed. However, field mapping of lithofacies around Douglas suggests that it corresponds to a linear feature on the shore at [SC 386 762], described as a 'pre-glacial valley' by Lamplugh (1903) but here interpreted as a fault throwing down to the southwest with the Lonan Formation on the northeast side juxtaposed against the younger Santon Formation on the southwest side (Fig. 5). The left lateral apparent sense offset of the imbricate belt is consistent with this sense of throw provided that the imbricate belt dips to the northwest as observed on seismic data (Fig. 6) and in the field at Gob yn Ushtey and near Ramsey (see below). Quirk & Kimbell (1997) suggested that the Central Valley Lineament was active during extension in the early Permian and early Tertiary but may represent an older pre-Caledonian trend.

A northern strand of the Central Valley Lineament is seen on aeromagnetic data to extend from Peel to the northeast edge of the Greeba Magnetic Low (Figs 2a and 4) where it coincides with an east–west fault (the Greeba Lineament; Fig. 1), inferred from field mapping to have cut out part of the Injebreck Formation (Fig. 5; Quirk & Burnett 1999). The lineament passes close to the Poortown mafic intrusion at the limit of the magnetic low where geophysical and borehole data show that this igneous body is broken up by east–west shear zones (Piper *et al.* 1999; Power and Crowley 1999). The Greeba Lineament is linked further east to another (probably faulted) boundary forming the southeast edge of the Barrule Formation which it appears to partly cut out (Baldwin Lineament, Fig. 5).

Maughold

The imbricate belt is seen to feather out at the northern end of Maughold (Fig. 4), directly east of the escarpment marking the northern limit of the Manx Group (Fig. 1). The aeromagnetic lineaments in the Maughold area have a dominant east-northeast–west-southwest trend, although there is interference between these and a strong west-northwest–east-southeast Tertiary-type anomaly (Fig. 4).

At Maughold Head [SC 497 915] a minimum of 250 m dextral offset is evident across a vertical or steeply north dipping east–west fault which juxtaposes younger muddy facies to the north against quartzites to the south (Fig. 1). Lithostratigraphic correlations suggest that there may be as much as 2 km dextral offset across the fault cutting out almost all of the Creg Agneash Formation (Quirk & Burnett 1999) (Fig. 5). It lines up with a major east–west vein which was mined underground near Maughold Head for copper (Cowin pers. comm.). Further to the west, the structure may join an east-northeast–west-southwest fault which is interpreted to form the southeast boundary of the Barrule Formation (the North Barrule Lineament; Figs 1 and 5). Just south of Maughold Head, at [SC 498 917], the faulted base of the Creg Agneash Formation is exposed. The contact consists of a tilted ramp-flat structure trending between 100°/70° N and 090°/20° N, which appears to be linked to the Maughold Head Fault. It has accommodated at least 50 m of shortening during the development of chevron folds in the hanging wall (Creg Agneash Formation) whereas the underlying Ny Garvain Formation is undeformed. It probably represents a minor accommodation structure developed in association with movement on the Maughold Head fault.

Between Port e Vullen and Ramsey numerous east–west and northeast–southwest shear zones, faults and brecciated quartz veins are exposed which coincide with a set of similarly orientated lineaments visible on aeromagnetic and Bouguer gravity data (Figs 1–4). The shear zones are mostly steeply north dipping associated with several pre-kinematic felsitic intrusions (Quirk & Burnett 1999) whereas the brittle faults tend to dip to the northwest and are associated with quartz veins. In addition, there are several north–south trending faults and quartz veins, one of which accounts for *c.* 50 m of sinistral offset in Port Lewaigue [SC 469 930], others having been mined for lead and copper (Lamplugh 1903; Ford 1993).

Between Maughold Head and Port Cornaa a number of northwest–southeast Tertiary dykes and north–south faults are exposed (Fig. 1). The Tertiary dykes and associated haematite mineralization are described by Quirk & Kimbell (1997) and the north–south faults by Woodcock & Barnes (1999). Corresponding northwest–southeast trending linear anomalies are clearly visible on the aeromagnetic data but north–south features are more subtle (Figs 2 and 4).

Northern inland area

Quirk & Burnett (1999) have used field evidence to suggest that a number of northeast–southwest to east-northeast–west-southwest trending thrusts and dextral strike-slip faults are present in the northern uplands of the Isle of Man (e.g. the Glen Auldyn Lineament, the North Barrule Lineament and the Baldwin Lineament; Fig. 1). These faults are responsible for cutting out parts of the Barrule and Injebreck Formations (Fig. 5). Aeromagnetic data (Fig. 2) and, to a lesser extent, Bouguer gravity data (Fig. 3) show anomalies supporting the existence of these lineaments (Fig. 4). Physical evidence for the existence of the Glen Auldyn Lineament occurs at its western end where a set of faults and shear zones were encountered in boreholes drilled in the vicinity of [SC 372 891] for the Tholt y Will reservoir (Young pers. comm.). Significantly higher illite crystallinity grades occur on the northwest side of the lineament (Roberts *et al.* 1990), supporting the interpretation that it represents a northwest dipping reverse fault (Fig. 1). Quirk & Burnett (1999) note that an unusual thickness of pebbly mudstone (> 500 m) occurs north of the Glen Auldyn Lineament, perhaps indicating that it, or a related structure, was active during sedimentation. The east-northeast–west-southwest trending Causey Pike Thrust in the Lake District is thought to have a similar origin (Webb & Cooper 1988; Hughes *et al.* 1993). The North Barrule Lineament is probably also a thrust; it coincides with the position of a trial mine adit at [SC 387 872], suggesting that it is partly mineralized. By extrapolation from offshore seismic data, Quirk & Kimbell (1997) also suggest that the steep escarpment forming the northern edge of the uplands (Fig. 1) is defined by a set of east–west faults. A corresponding lineament is clearly imaged on Bouguer gravity data and lines up with a vertical fault at Glen Mooar marking the northern limit of the Manx Group (Figs 1, 3 and 4).

In other areas inland where there is little evidence of missing stratigraphy, there is none the less some coincidence between the mapped bases and tops of thick mud-rich intervals (the Barrule and Glen Rushen Formations; Fig. 5) and the position of apparent linear aeromagnetic anomalies (Figs 2 and 4). Whether these anomalies are due only to the high magnetic susceptibility of these sediments relative to more sandstone-rich intervals (see above) or whether they show that faults have tended to concentrate at these boundaries cannot be proven because of limited exposure.

Clay Head

An east–west aeromagnetic lineament extends from near Greeba in the Central Valley to Braggan Point on Clay Head on the eastern coast of the Isle of Man (Fig. 4). Independently, field mapping has identified a 5 m wide, steeply south-southeast dipping shear zone at [SC 442 808], in the position of the lineament, which truncates the axis of the Douglas Syncline (the Braggan Point Fault; Fig. 1). It consists of foliated and disaggregated sediments and quartz mineralization, although closer examination for kinematic indicators has so far proved impossible as the shear zone occupies a precipitous gully. However, from lithostratigraphic correlations, it is calculated that *c.* 1 km of Ny Garvain Formation [equating with the Santon Formation of Woodcock *et al.* (1999)] has been cut out by apparent dextral offset (Fig. 5). Adjacent to the fault, where it is accessible, the beds in the southeast wall are overturned whereas a gentle antiform is present to the northwest. The antiform is bounded some 400 m away on its western side by a brittle thrust trending 055°/60° SE which, on the basis of drag folds in both walls, is interpreted to have dextral–reverse offset. A 2 m wide felsitic dyke with a strong foliation lies within a few metres of the fault.

Marine Drive

An east–west aeromagnetic lineament links Douglas Head at the northern end of Marine Drive to a bend in the imbricate belt close to St Marks (Fig. 4). At the coast it coincides with a 3 m wide, subvertical brecciated fault zone near Douglas Head at [SC 387 745] (Fig. 1). Based on rather tentative lithostratigraphic correlations, the fault may account for 100–200 m of apparent dextral offset (Quirk & Burnett 1999).

The fault approximately marks the northern limit of a wacke-rich lithofacies type in the Manx Group unique to Marine Drive (Quirk & Burnett 1999). This interval is in turn bounded to the south by a northwest-southeast fault at Keristal ([SC 357 732]) which offsets the Santon Formation in a sinistral sense by *c.* 1.5 km (Fig. 5). Three interpretations are possible:

- that the change in lithofacies is coincidental;
- that the Marine Drive interval occupies a fault block that has moved west, juxtaposing it against younger strata at its southern and northern ends (Fig. 1);
- that the east–west fault is an old trend controlling sedimentation of the wacke-rich lithofacies (Quirk & Burnett 1999).

Purt Veg–Cass ny Hawin

A major geological boundary lies close to Purt Veg at [SC 324 703] where thick-bedded sandstones to the east belonging to the Santon Formation are juxtaposed against thin-bedded mudstones belonging to the Port Erin Formation across a fault trending 140°/85° NE (Fig. 5). A 2 m wide fault breccia is present here with a thin Tertiary dyke occupying the northeast wall. Depending on how lithostratigraphic correlations are made, this fault may have cut out *c.* 3 km of succession by apparent sinistral movement or 0.7 km of stratigraphy by apparent dextral movement (Quirk & Burnett 1999). By analogy with the Keristal Fault, sinistral displacement is perhaps most likely, implying that the mudstones to the west of the fault are the lateral equivalent of the Creg Agneash Formation further north (Fig. 5). Alternatively, on lithofacies grounds, the mudstones show similarities with the Lonan Formation implying a dextral sense of displacement (Quirk & Burnett 1999; Woodcock *et al.* 1999). A faint aeromagnetic lineament can be traced from Purt Veg to the bend in the imbricate belt at St Marks but a more obvious northwest-southeast Tertiary-type anomaly runs through Port Grenaugh at [SC 316 705] where another sinistral fault is inferred to exist (Fig. 1).

Further to the southwest at Cass ny Hawin ([SC 298 692]), the northern boundary fault to the

Castletown Group trends 095°/75° N with sub-horizontal slickensides interpreted to have formed in the Carboniferous during northwest-southeast extension (Quirk & Kimbell 1997). However, similar to the boundary fault at Port St Mary, little evidence for the fault is seen on potential field data.

Lineaments associated with mineral veins

A number of large east–west and north–south quartz veins have been exploited on the Isle of Man for galena, sphalerite and chalcopyrite during last century and the early part of this century (Lamplugh 1903; Mackay & Schnellman 1963;Ford 1993). These are all approximately vertical, as are similar trending faults exposed on the coast. Field evidence (Fig. 5; Quirk & Burnett 1999) and mine data (e.g. Lamplugh 1903; Mackay & Schnellman 1963; Jespersen 1970; Ford 1993) suggest that they represent brittle strike-slip faults with east–west faults displaying predominantly dextral offset and north–south faults displaying sinistral offset (Fig. 1). The east–west Foxdale Vein is the longest of the exploited mineral veins and at its eastern end it forms the northern margin of the Foxdale Granite (Fig. 4). The vein corresponds with a clear east–west lineament on aeromagnetic data on which other smaller east–west veins, such as at Cornelly lead mine and Maughold Head copper mine are also visible (Figs 1, 2 and 4). North–south lineaments associated with veins such as Laxey and Snaefell mines are less clearly expressed than their east–west counterparts, possibly due to interference with other trends; e.g. with a west-northwest–east-southeast Tertiary-type anomaly at Laxey (Fig. 4). Lithostratigraphic correlations suggest that the fractures hosting the Laxey and Snaefell Veins may have accommodated somewhere in the order of 500–1000 m of apparent sinistral displacement (Fig. 5). The southern end of the Laxey Vein appears to swing to the southeast so that it joins the Laxey Bay Fault. The presence of this fault is inferred on the basis of an apparent (left lateral) mismatch between lithofacies within the Lonan Formation north of the bay and those south of the bay (Quirk & Burnett 1999)

Major intrusions

The four main igneous bodies exposed in the Isle of Man are associated with lineaments observed on aeromagnetic and Bouguer gravity data. The Poortown mafic intrusion lies close to an east–west lineament at the northwest corner of the magnetic low near Greeba (Figs 1 and 2). The Foxdale Granite occurs at the eastern end of the Foxdale Vein in the centre of a gravity low (Cornwell 1972). The older Dhoon Granite (Fig. 1) is found at the intersection of a northeast–southwest lineament and an east–west lineament which coincide with a fault and shear zone in the field (Lamplugh 1903; Mulligan, pers. comm.). It too is associated with a gravity low. The Oatlands granite–diorite complex is marked by a minor northeast–southwest lineament seen on both aeromagnetic and Bouguer gravity data (Fig. 4). These lineaments represent proven or speculative faults which are likely to have accommodated emplacement or uplift of the igneous bodies. The ages of the intrusions are poorly constrained but the Poortown body is probably late Ordovician (Piper *et al.* 1999), the Dhoon Granite is probably early Caledonian (?late Silurian), equivalent to syn-D1 (Mulligan, pers. comm.), and the Foxdale Granite is thought to be late Caledonian (early–mid Devonian; Brown *et al.* 1968), probably syn-D2 (Simpson 1965). The Oatlands intrusion is no longer exposed and its age is unconstrained. However, it is also worth noting that large and small felsitic intrusions of probable pre-kinematic origin are found within or adjacent to many of the major shear zones and faults described above, implying that they are long-lived tectonic structures.

Tectonic interpretation

By integrating the evidence for faults and shear zones observed or inferred in the field (Fig. 1) with lineaments identified on potential field data (Fig. 4), it appears that the Manx Group is traversed by a set of major faults forming the imbricate belt first identified by Quirk & Kimbell (1997). The most common fault trend is east-northeast–west-southwest (Fig. 7). Based mostly on the shape of the lineaments observed on aeromagnetic data, Quirk & Kimbell (1997) suggested that the Manx Imbricate Belt represents a fault duplex formed by sinistral transpression during closure of the Iapetus Ocean in the Silurian. Recent field mapping generally does not support this kinematic interpretation in that: east–west to east-northeast–west-southwest faults are usually steep or vertical with evidence of apparent dextral offset; northeast–southwest faults seem to represent thrusts; and west-northwest–east-southeast faults are typically normal. Only steep or vertical north–south to north-northwest–south-southeast faults show evidence of sinistral offset (Fig. 1). The implication is that the imbricate belt is a duplex formed instead by northwest-southeast contraction (Fig. 8). However, the offset recorded on these faults may only represent that of the latest stage of movement which, in most cases where the faults are exposed, is brittle in nature and post-dates major Caledonian structures such as east-northeast–west-southwest

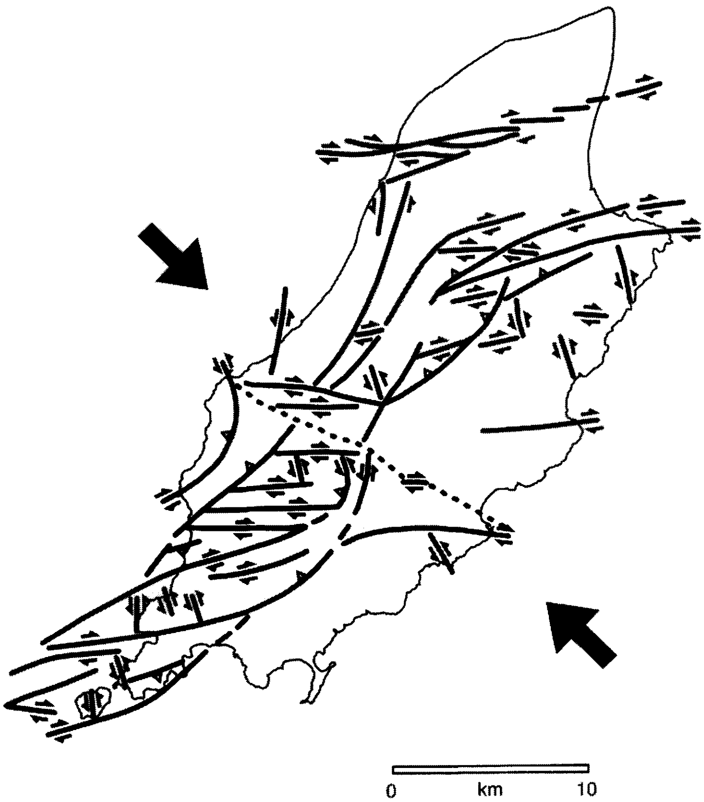

Fig. 8. Conceptual interpretation of fault lineaments active in the Isle of Man as a result of northwest-southeast compression during the late Caledonian. The imbricate belt trending northeast–southwest along the axis of the island is interpreted as a contractional duplex.

trending D1 folds and cleavage (cf. Fitches *et al.* 1999). In contrast to the faults, limited kinematic evidence on older ductile shear zones indicates that east–west lineaments, such as the Niarbyl Shear Zone, were mostly subject to sinistral movement and north-northwest–south-southeast shear zones, such as the Lynague Shear Zone to dextral movement. This suggests that there was an earlier phase of north-northeast–south-southwest directed compression, possibly associated with sinistral transpression within the imbricate belt. Although evidence for the timing of shearing relative to cleavage is not clear-cut, it is assumed here that at least some of this movement pre-dates D1 structures.

Two explanations for these observations are possible:

- that the brittle structures were formed in a tectonic event separate to that responsible for the ductile structures, e.g. in the Variscan rather than the Caledonian Orogeny;
- that the brittle structures were only the latest stage of an evolving Caledonian collisional event.

Quirk & Kimbell (1997) have already described north-northeast–south-southwest orientated Variscan reverse faults in Carboniferous strata imaged on marine seismic data close to the Central Valley Lineament. However, the offshore extension of the imbricate belt, either the Ramsey–Whitehaven Ridge to the northeast of the island or the Shag Rock fault to the southwest, seems unaffected by Variscan compression (Quirk *et al.* 1999). Therefore, the second explanation is favoured here with an early Caledonian (?late Silurian) period of ductile shearing associated with sinistral transpression and a late Caledonian or Acadian phase (?early Devonian) of reverse and dextral strike-slip faulting due to northwest–southeast compression. A possibly analogous change from sinistral transpression in the late Silurian to dextral transpression in the early Devonian is recorded

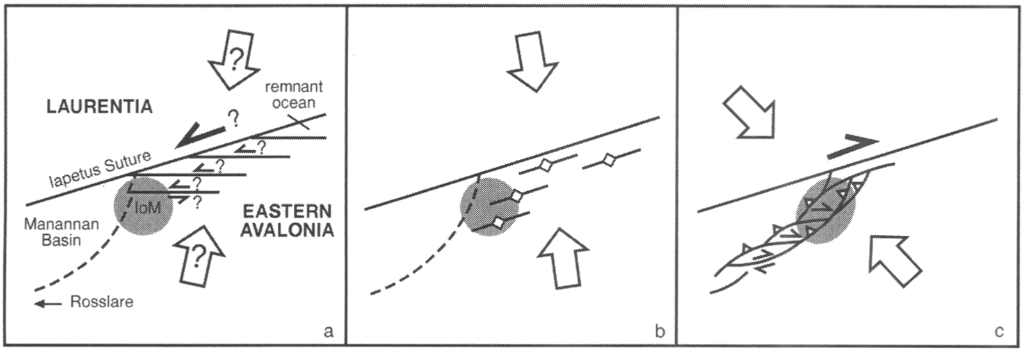

Fig. 9. Simplified model of possible plate interactions of Eastern Avalonia with Laurentia during the Lower Palaeozoic based on the orientation and kinematics of structures interpreted on the Isle of Man (stylized in grey). See text for discussion. (**a**) Possible sinistral transpression and ductile shear (convergence oblique to the Iapetus Suture); (**b**) D1 deformation (early orogenic shortening perpendicular to the Iapetus Suture); (**c**) brittle contraction (final orogenic shortening perpendicular to eastern margin of the Manannan Basin).

further west on the southeast side of the Iapetus Suture in Newfoundland (D'Lemos *et al.* 1997).

As shown in Fig. 9, the imbricate belt in the Isle of Man overlies a deep magnetic boundary, thought by Kimbell & Quirk (1999) to represent the eastern edge of a thick succession of poorly magnetic Lower Palaeozoic sediments occupying the newly named Manannan Basin. This basin is interpreted to lie south of the Iapetus Suture as an embayment on the northwest side of Eastern Avalonia and stretches between the Isle of Man and Ireland, north of Rosslare (Fig. 9a). It was probably formed by rifting during the Tremadoc. Arenig-age sediments of the Manx Group in the Isle of Man and the Ribband Group in Ireland (McConnell *et al.* 1999) represent exposed parts of the basin. The preceding discussion indicates that the northeast tip of the Manannan Basin was subject to an anticlockwise rotation of stress as Eastern Avalonia docked with Laurentia in a manner similar to regional models proposed by, for example, Soper *et al.* (1992) and Piper (1997). Initial closure of Iapetus is interpreted to have been oblique in a north-northeast direction such that some of the movement was taken up by sinistral strike-slip along east–west shear zones (Fig. 9a). As the remaining oceanic crust was eventually consumed, the two continents locked up, causing D1 folds and cleavage to develop parallel to the suture as σ_1 rotated anticlockwise (Fig. 9b). Finally, deformation was accommodated by contraction in a direction approximately perpendicular to the eastern edge of the Manannan Basin forming a thrust duplex with associated dextral strike-slip faults (Fig. 9c). The timing of D3 structures is uncertain (Fitches *et al.* 1999) but flat-lying D2 cleavage and folds may have formed as a result of thrust stacking during the late stages of movement in the duplex.

Three important implications follow on from this model. Firstly, the stratigraphy of the Manx Group is telescoped (cf. Quirk & Burnett 1999); secondly, correlations with the Ribband Group are justifiable (cf. McConnell *et al.* 1999); finally, rather than a large batholith underlying the whole of the Isle of Man, granite intrusions form discrete plutons, probably emplaced by late-stage movement on faults within the imbricate belt [cf. Cornwell (1972), Crowley & Power (1999) and Kimbell & Quirk (1999)].

Conclusions

Three Lower Palaeozoic trends identified on high-resolution aeromagnetic data and in the field they represent northeast–southwest thrusts, east–west to east-northeast–west-southwest dextral strike-slip faults and north–south sinistral strike-slip faults. These were active during northwest-southeast compression in the late Caledonian when a northwest dipping contractional duplex is thought to have formed at the eastern margin of a Lower Palaeozoic basin developed on the northwest side of Eastern Avalonia. Earlier tectonic movement in the opposite sense is recorded on ductile shear zones, associated with disruption of pre- or syn-kinematic felsic intrusions and disaggregation of quartz veins. This may reflect an episode of sinistral transpression during closure of Iapetus before the Laurentia–Eastern Avalonia plate boundary became fully locked. D1 structures, such as folds and cleavage, are thought to have formed during an intermediate stage of north-northwest–south-southeast compression. The Isle of Man was tilted to the northwest during post-Caledonian tectonic events. However, except for the west-northwest–east-southeast trending Central Valley Lineament, and similarly orientated Tertiary dykes, younger structures are rarely imaged onshore with potential field data.

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