Geological Society, London, Special Publications

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Geological Society, London, Special Publications 1997, v.124; p135-159.
doi: 10.1144/GSL.SP.1997.124.01.09

Notes

Structural evolution of the Isle of Man and central part of the Irish Sea

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Abstract: Gravity, aeromagnetic, seismic, borehole and outcrop data from the Isle of Man area have been used to study the structural framework and tectonic evolution of the central part of the Irish Sea since the Ordovician. The area has been affected by two major compressional events (Caledonian and Variscan), three rifting events (early Carboniferous, early Permian and ?late Jurassic) and a period of thermal uplift (early Tertiary). A large part of the Isle of Man consists of early Ordovician turbidites ('basement') interpreted to have been deposited in a back arc or fore arc basin that was inverted during the Caledonian orogeny. Major NE–SW and subsidiary NW–SE strike-slip faults were initiated at this time, some of which were later reactivated to form important basin controlling faults in the Irish Sea. Post-Caledonian basin subsidence was initiated in the early Carboniferous with a period of NW–SE directed extension followed by thermal sag which ceased at the end of the Carboniferous as a result of Variscan compression. E–W extension in the early Permian led to the development of new extensional faults which have influenced the thickness of the Collyhurst Sandstone in the offshore. Post-rift thermal sag continued throughout the late Permian and the Triassic. A late Jurassic period of extension has been proposed in order to explain post-Triassic offset across major normal faults east of the Isle of Man although direct evidence of syn-rift or post-rift strata has been removed by erosion during uplift in the early Tertiary. This uplift was due to thermal doming of the crust, an event which was associated with the intrusion of a large number of dolerite dykes. The structural evolution of the Isle of Man has also been influenced by a major NW–SE trending basement fracture known as the 'Central Valley Lineament' which extends into the offshore to the SE and NW of the island. The lineament appears to be important in defining areas of different hydrocarbon prospectivity in the Irish Sea.

The Isle of Man occupies a central position in the Irish Sea. It is bounded to the east by the Eubonia and Lagman basins, to the west by the Peel Basin and by the Solway Basin at the NE end of the island (Fig. 1). The island has a population of approximately 70 000 and covers an area of 572 km^2. The Isle of Man is a self-governing dependency of the British Crown and is not part of the UK nor the European Union. The Manx Government extended its Territorial Sea from 3 to 12 miles in September 1992 by purchasing it from the UK Government for £800 000. A first hydrocarbon licensing round was announced on 6 December 1994 and closed on 28 March 1995. To date 11 blocks and part blocks covering the entire NE sector of Manx Territorial Sea have been licensed, including several blocks awarded in two out-of-round awards announced on 12 February 1996. The area is important for fishing and recreation and contains diverse marine life including several species of sea mammals, basking sharks and shellfish. Consequently certain environmental restrictions will apply to seismic and drilling activities.

Very little geological work has been published about the Isle of Man. To date, the best source of information is a field guide by Ford (1993). This guide serves as a useful summary of the previous (limited) observations and ideas on the geology exposed onshore. However, the current paper represents the first published attempt to describe the structural evolution of the Isle of Man and aims to provide some new ideas on the hydrocarbon prospectivity in the central part of the Irish Sea.

The paper is based on a study between longitudes 3°50′W and 5°20′W and latitudes 53°52′N and 54°32′N where one of the authors (Kimbell) generated and manipulated Bouguer gravity anomaly images and the other author (Quirk) interpreted these data in conjunction with 2D seismic, high resolution aeromagnetic data, onshore and offshore well information and field observations (Table 1). The Bouguer gravity data are shown in Figs 2a and b and a summary of the integrated interpretation is presented in the form of a structural lineaments map in Fig. 3 and a tectono-stratigraphic column in Fig. 4. The main part of the text and Fig. 6 aim to

From Meadows, N. S., Trueblood, S. P., Hardman, M. & Cowan, G. (eds), 1997, *Petroleum Geology of the Irish Sea and Adjacent Areas,* Geological Society Special Publication No. 124, pp. 135–159.

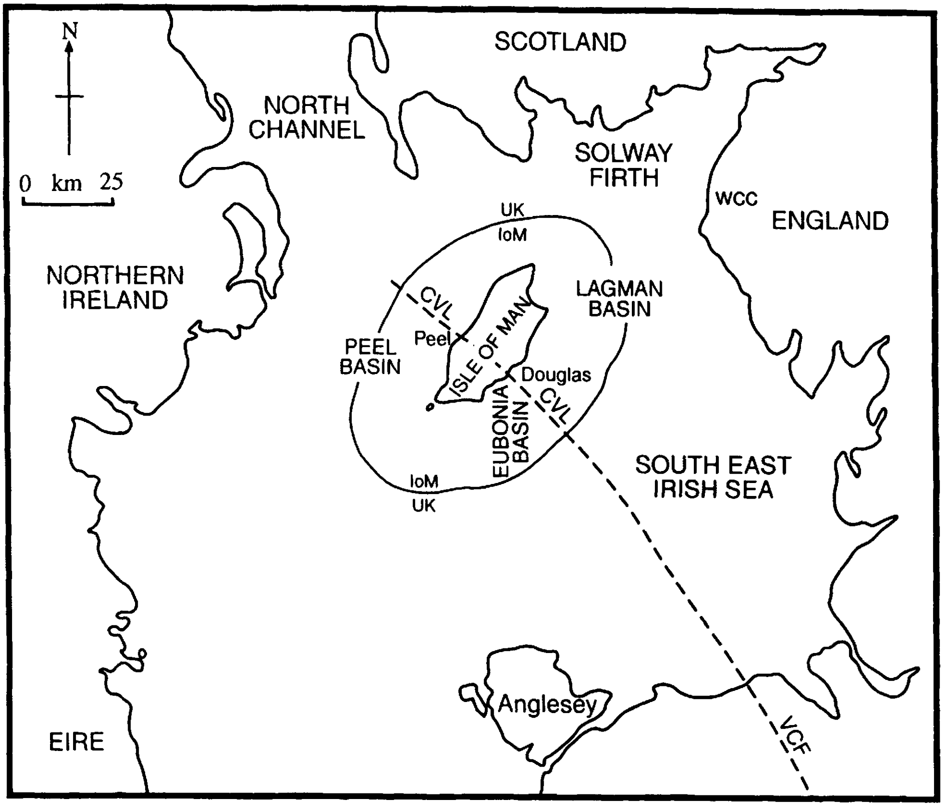


Fig. 1. Location map of the central part of the Irish Sea showing the boundary between Isle of Man and UK territorial sea (CVL = Central Valley Lineament; VCF = Vale of Clywd Fault; WCC = West Cumbrian Coalfield).

Table 1. *Main data used in study*

Data type	Details
Bouguer gravity anomaly and derivatives	Onshore data – 360 stations; offshore data – typical line spacing 3–6 km (data owned by Western Geophysical & BGS)
High resolution aeromagnetics and derivatives	400 m traverse spacing; 125 m image pixel size (data owned by World Geoscience)
2D migrated seismic lines	300 km of data mostly along SE coast of Isle of Man (data owned by Western Geophysical) + 200 km of oil company proprietary data + various regional lines
Onshore borehole cores	103 m of core from three wells in north of Isle of Man (Ballavarkish, Shellag Point & Cranstal) drilled by Riofinex in 1985–1987 (now stored by Manx National Heritage)
Released offshore well formation	Composite logs, TWT information and palynological data from wells 112/25-1 and 112/30-1
Field observations	15 weeks fieldwork over 5 years undertaken by one author (Quirk)

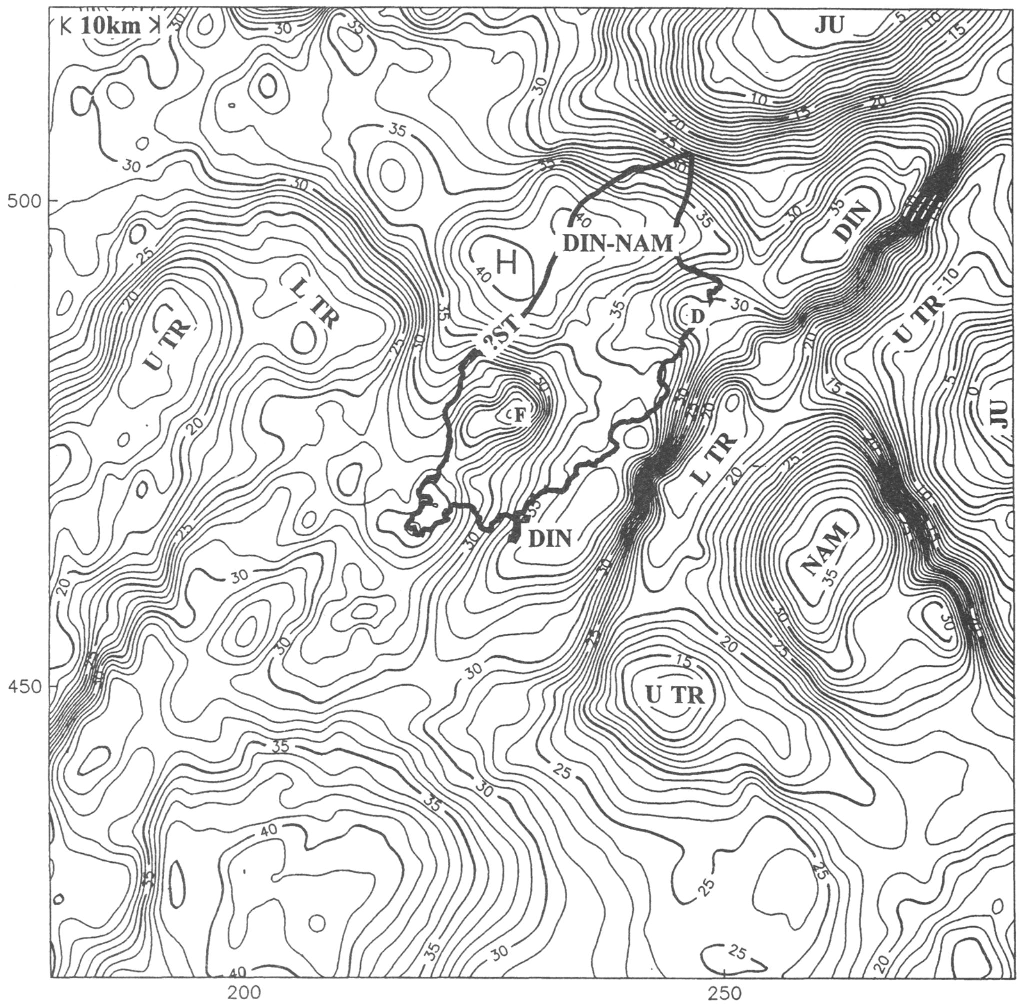


Fig. 2. (**a**) Bouguer gravity anomaly map of the Isle of Man and central part of the Irish Sea, courtesy of BGS and Western Geophysical; contour interval = 1 Mg (1 milligal); Bouguer reduction density = 2.20 Mg m^{-3} (offshore), 2.70 Mg m^{-3} (onshore). Note the correlation between gravity anomaly values and the exposed solid geology where DIN = Dinantian, NAM = Namurian, L TR = Lower Triassic, U TR = Upper Triassic and JU = Lower Jurassic, ? ST = Upper Carboniferous or Devonian. F = Foxdale Granite; D = Dhoon Granite; H = gravity high north of Peel.

show when the main lineaments were active since the early Palaeozoic and are based mostly on seismic and field evidence.

Lower Palaeozoic (Caledonian) basement

Eighty per cent of the exposed rock on the Isle of Man consists of low grade Lower Palaeozoic turbidites, related meta-sediments and early intermediate intrusions known collectively as the Manx Group. The sediments are commonly bioturbated, indicating that oxic conditions prevailed during deposition. Based on a limited collection of acritarchs and graptolites, these rocks are dated as early Ordovician (Downie & Ford 1966; Molyneux 1979; Rushton 1993) and the acritarchs are Avalonian in affinity (Molyneux 1979). Recent fieldwork on the Manx Group by Quirk & Ford (1994) and a reappraisal of the acritarch data (Molyneux 1979; Cooper *et al.* 1995) have shown that many of the structural and stratigraphic interpretations of the early Palaeozoic of the Isle of Man made by Lamplugh (1903), Gillott (1956) and Simpson (1963, 1968) are difficult to justify.

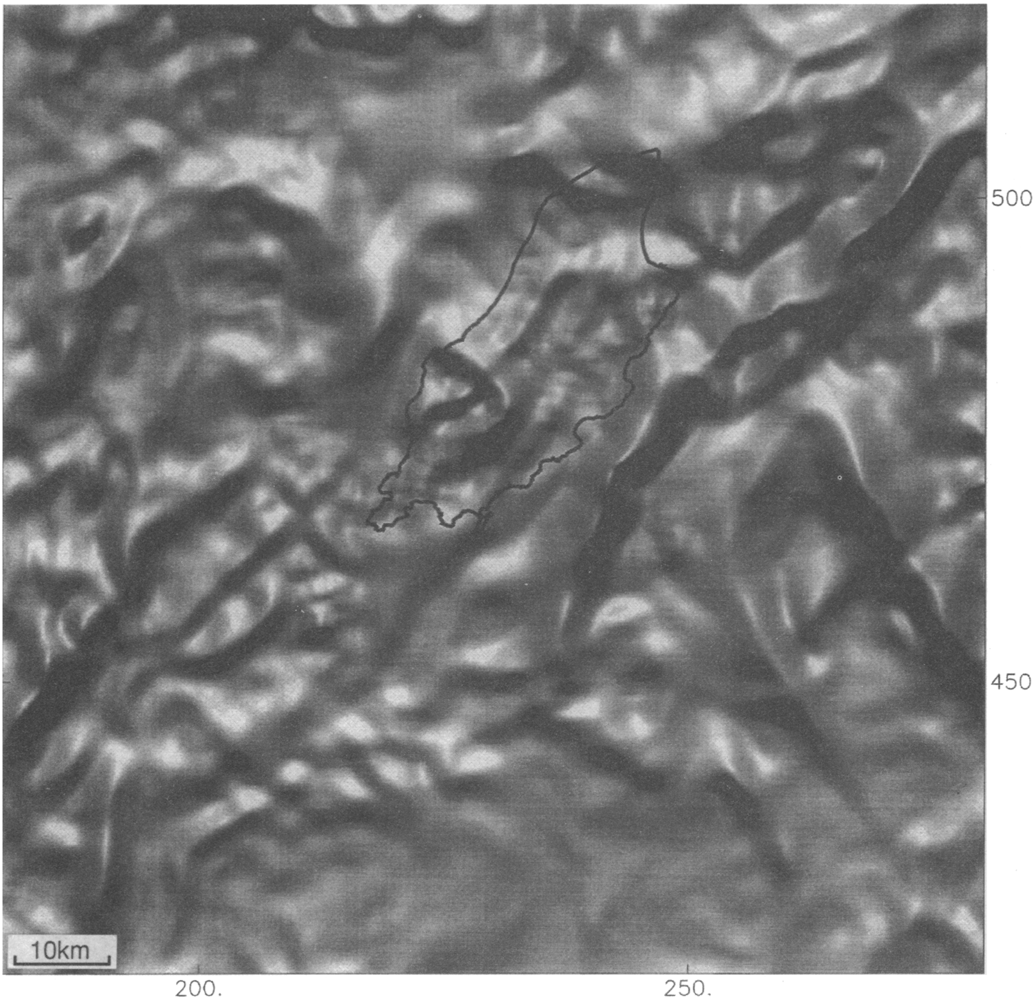


Fig. 2. (b) Scalar horizontal gradient of Bouguer gravity anomaly displayed as pseudo-relief illuminated from the north.

However, Simpson's (1963) observation still holds true that a remarkable thickness of Manx Group sediment (?5000 m) was deposited over a relatively short period of time (?10 Ma) based on minimum estimates by Molyneux (1979).

The NW coast of the Isle of Man lies within a few kilometres of the SE edge of the Caledonian Iapetus suture (McKerrow & Soper 1989; Todd *et al.* 1991; Quirk & Ford 1994) which fully closed in the late Silurian (Soper *et al.* 1992a). Caledonian compressional structures in the form of cleavage, folds and thrust faults are orientated ENE–WSW on the Isle of Man. NW–SE and NE–SW oriented vertical shear zones are also exposed on the NW coast and are attributed to Caledonian strike slip. In addition, syn-tectonic quartz veining is common and syn- and post-tectonic granitic bodies are present.

Back arc basin

Current Caledonian plate reconstructions would place the Isle of Man at the NW edge of Eastern Avalonia, the most northerly of the landmasses on the southern side of Iapetus (e.g. Soper & Woodcock 1990; Todd *et al.* 1991; Soper *et al.* 1992*b*). The SE coast of the Isle of Man consists

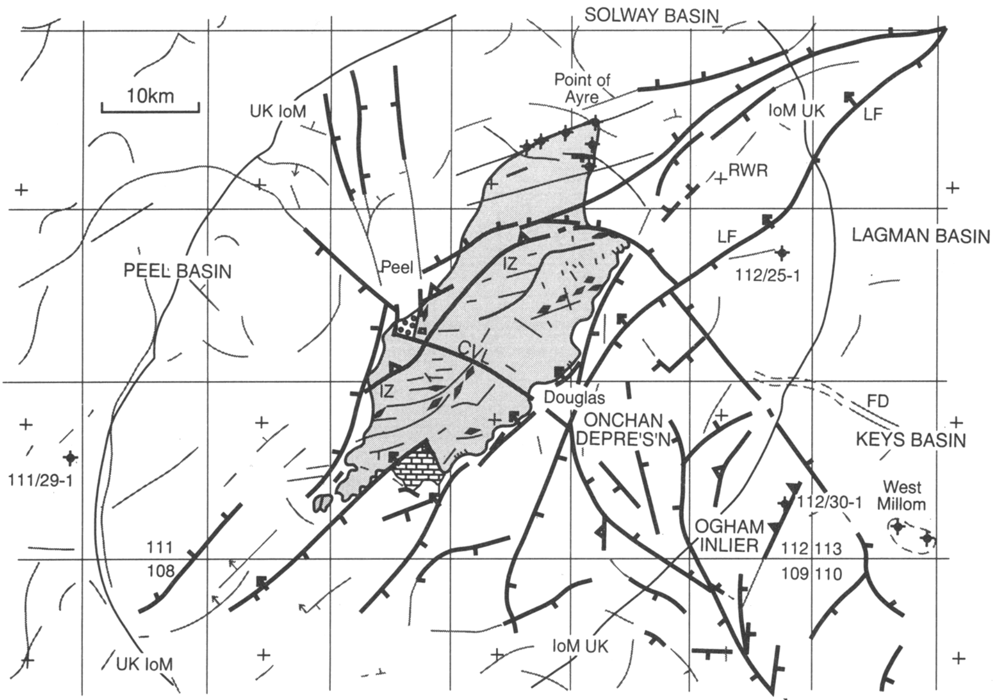


Fig. 3. Interpreted structural lineaments in the Isle of Man and central part of the Irish Sea (brick ornament = outcrop of Castletown Group; dotted ornament = outcrop of Peel Group; CVL = Central Valley Lineament; RWR = Ramsey–Whitehaven Ridge; IZ = imbricate zone; FD = Fleetwood Dyke; LF = Lagman Fault; thick black lines = major faults & fractures; single grey lines = inferred faults; ticks on faults = normal down-throw direction; triangles on faults = reverse up-throw direction; arrows on faults = steeply dipping strata on up-thrown side; double grey lines = dolerite dykes; grey pod shapes on the Isle of Man = felsite dykes & granite intrusions); the positions of seismic lines shown in Figs 10 & 19 are also indicated as double black lines.

mostly of sand-rich meta-sediments including pure quartzites with NW-directed palaeocurrents which support these plate reconstructions. The centre of the island is dominated by fine grained meta-sediments which are interpreted as deep water, distal deposits. However, along the NW coast of the Isle of Man, medium to coarse grained greywackes are common which contain rare flute casts indicating SE-directed palaeoflow from an unknown land source to the NW (Quirk & Ford 1994). Mud-supported breccias with diverse sedimentary clasts occur, particularly to the NE of Peel (Fig. 3), which are interpreted to have been deposited as fault-induced debris flows from areas of shallower water. Juvenile fragments of intermediate-mafic rocks are found as lithic clasts within the greywackes and conglomerates along the NW coast and rare tuffaceous horizons are also present. Intermediate sills and dykes are widespread throughout the Isle of Man and many of these appear to have been intruded into soft sediment.

It therefore appears that, rather than representing a passive margin on the NW side of Eastern Avalonia, the SE and NW coasts of the Isle of Man represent two sides of a tectonically active basin of early Ordovician age. The source of sediment from the NW is thought to be either an island arc or an accretionary prism implying that the Manx Group was deposited within a back arc or fore arc basin. The basin was inverted during Caledonian orogenesis at the end of the Silurian but has continued to uplift and subside several times since then. It is therefore worth bearing in mind that, by virtue of the widespread occurrence of coarse-grained meta-sediments, quartz veins and granitic rocks within the Manx Group, these rocks represent a potential source of sand for younger intervals.

Sinistral transpression

High resolution aeromagnetic data over the Isle of Man reveals a left-stepping *en echelon* structure or

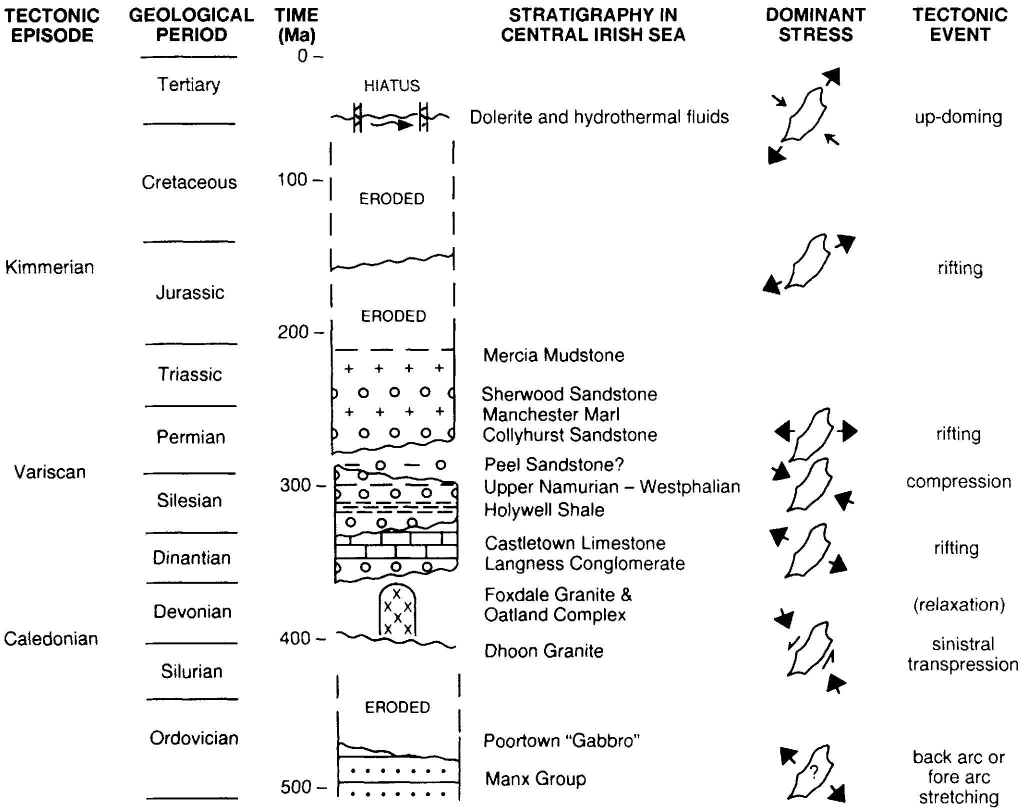


Fig. 4. Summary stratigraphy of the central part of the Irish Sea in relation to main tectonic events.

imbricate zone about 5 km wide and running for at least 40 km along the length of the island (Fig. 5). Total field magnetic anomalies have a pronounced negative component indicating the presence of strong reversed magnetization in the Manx Group within this zone. The margins of the imbricate zone are orientated NE–SW and the imbricate pattern itself is produced by ENE–WSW to E–W trending lineaments, 1–5 km long, which are spaced at intervals of approximately 2 km (Fig. 3). The structure is also visible on a horizontal gradient display of the Bouguer gravity anomaly (Fig. 2b) but is less clearly delineated than on the higher resolution aeromagnetic data (Fig. 5).

At the northern end of the imbricate zone, a prominent escarpment marks the boundary between uplands to the south, comprising Manx Group metasediments, and lowlands to the north, consisting of recent glacial sediments which are underlain progressively away from the escarpment by Carboniferous, Permian and Triassic strata. On the NW coast, an extension of this escarpment crops out as an obvious fault affecting both Manx Group strata and overlying Pleistocene sediments. There are even recent reports of minor earthquakes close to the escarpment at Ramsey (Fig. 6a). It is therefore thought to mark the position of a major fault which crosses the southern end of the Ramsey–Whitehaven Ridge (Fig. 3).

Outcrop is fairly limited within the imbricate zone except in the SW where it intersects the western coast of the Isle of Man between Port Erin and Niarbyl (Fig. 6b). Even here access is difficult because of the presence of precipitous cliffs except close to the NW margin of the imbricate zone south of Niarbyl. Here a set of north-dipping, NE–SW to E–W shear zones and faults are exposed which coincide with the orientation of the main lineaments on the aeromagnetic data (Figs 3, 5, & 7). Faults orientated E–W to ENE–WSW consist mostly of shallow- to moderately dipping thrusts whereas faults trending closer to NE–SW are generally steeper and kinematic indicators suggest that they have moved in a sinistral-reverse sense of oblique slip. These field observations coupled with the left-stepping nature of the imbrication (Fig. 3)

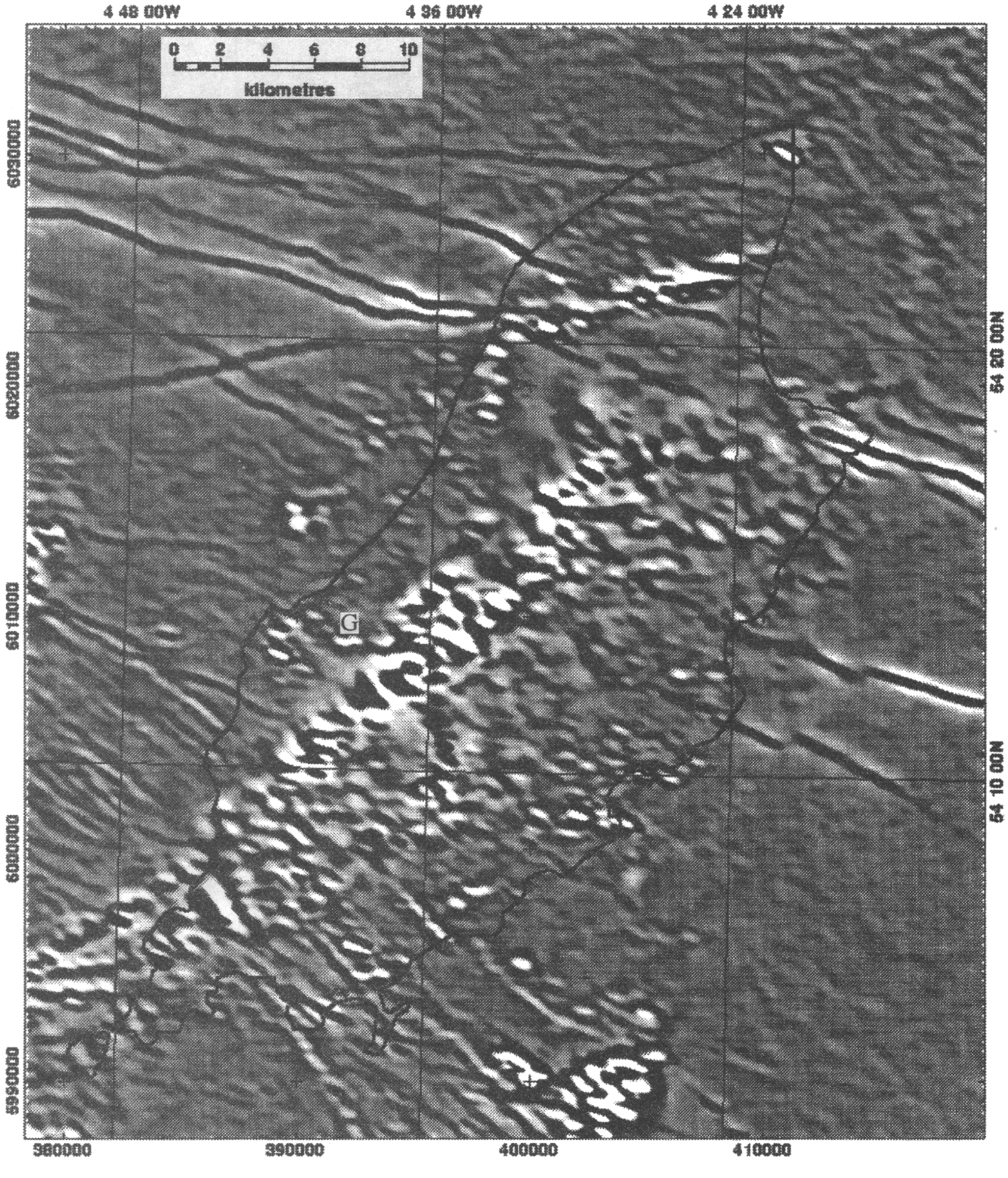


Fig. 5. Grey scale image of first vertical derivative of reduced-to-pole magnetic field from high resolution aeromagnetic survey, courtesy of World Geoscience. The data have been filtered to accentuate short wavelength anomalies from near-surface sources (black = low; white = high). The most obvious features are NW–SE trending lineaments which correspond with Tertiary dolerite dykes but note also the NE–SW oriented imbricate structure running through the centre of the Isle of Man. G = Poortown Gabbro.

suggests that the zone represents a fault duplex formed by sinistral transpression (Fig. 6b). The widespread occurrence of ENE–WSW trending Caledonian compressional structures on the Isle of Man indicates that the duplex developed during final NNW–SSE directed closure of Iapetus. Evidence for sinistral transpression on late Caledonian structures in other areas along the NW margin of Eastern Avalonia (e.g. Soper *et al.* 1992*a*) supports this view.

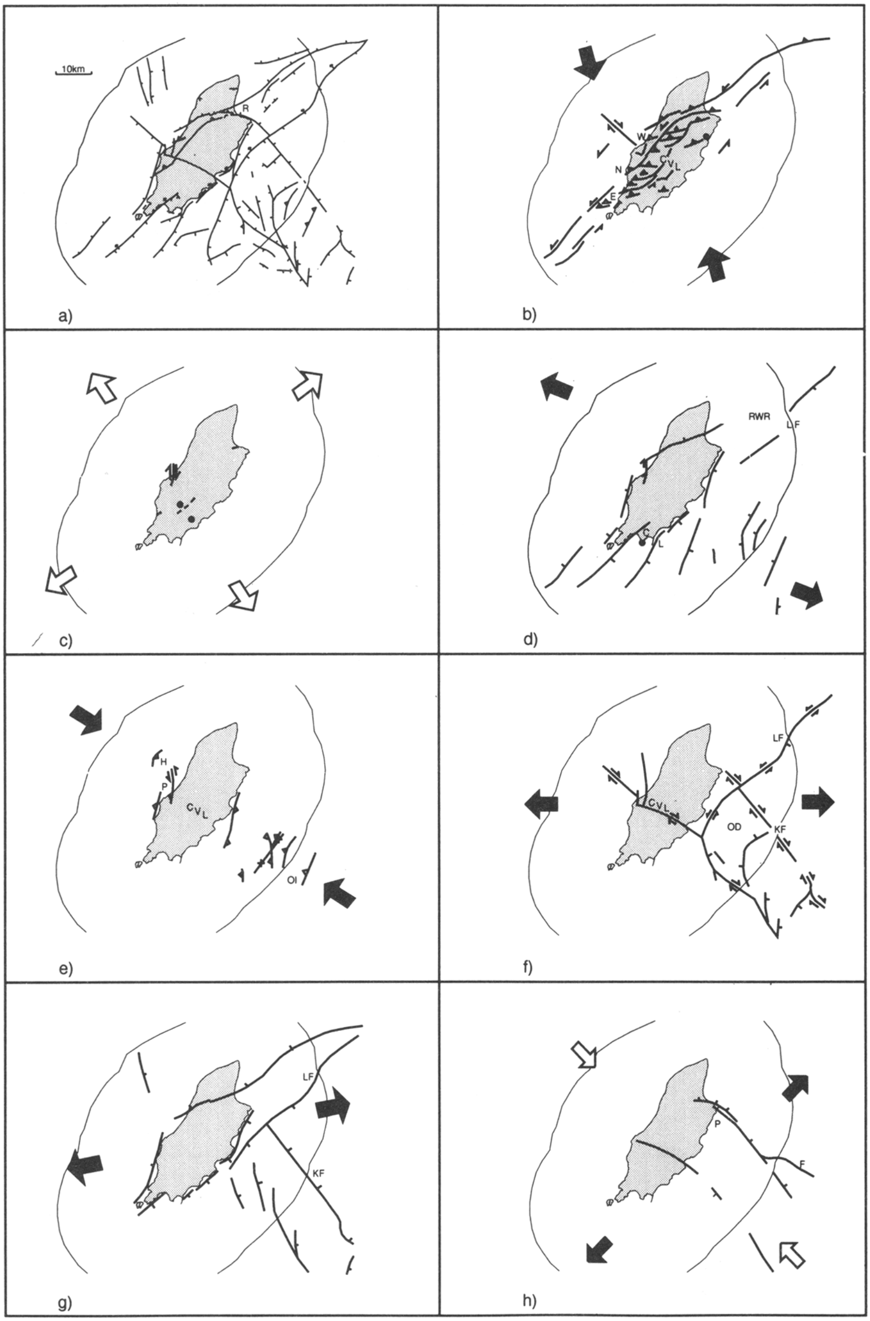


Fig. 6. Interpreted structural history of the central part of the Irish Sea: (**a**) present day fault pattern (R = Ramsey); (**b**) late Silurian (Caledonian) tectonic activity (N = Niarbyl, E = Port Erin, W = Will's Strand, CVL = Central Valley Lineament); (**c**) Devonian tectonic activity (solid circles and dotted lines = granitic & felsitic intrusions); (**d**) Dinantian–earliest Namurian tectonic activity (C = Castletown, L = Langness, solid circle = volcanic pile, RWR = Ramsey–Whitehaven Ridge, LF = Lagman Fault); (**e**) end Carboniferous (Variscan) tectonic activity (P = Peel, OI = Ogham Inlier, H = Bouguer gravity high, CVL = Central Valley Lineament); (**f**) early Permian tectonic activity (OD = Onchan Depression, LF = Lagman Fault, KF = Keys Fault, CVL = Central Valley Lineament); (**g**) late Jurassic (Kimmerian) tectonic activity (LF = Lagman Fault, KF = Keys Fault); and (**h**) early Tertiary tectonic activity but excluding most of the Tertiary dolerite dykes visible in Fig. 5 (P = Port Mooar, F = Fleetwood Dyke).

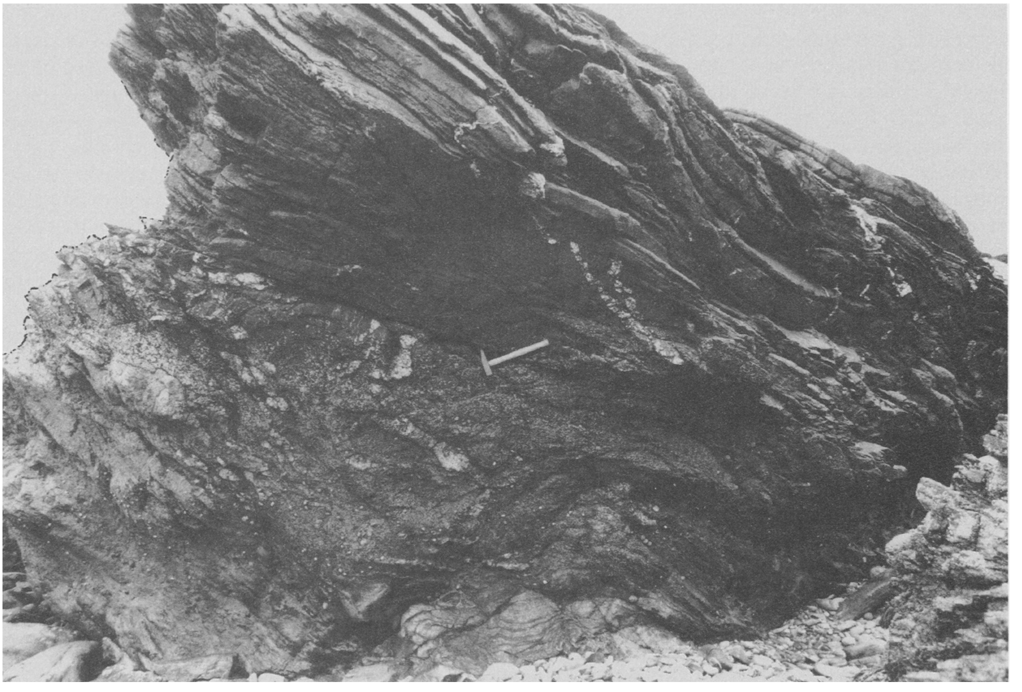


Fig. 7. Part of a major fault exposed at Niarbyl (see Fig. 6b). Note NNW-dipping thrust plane adjacent to hammer which separates deformed mudstones in the footwall from fairly undeformed greywackes in the hanging wall.

It is interesting to speculate why the imbricate zone is associated with anomalous reversed remanent magnetization. Pre-deformation intermediate dykes are orientated mostly ENE–WSW, sub-parallel to the imbricate zone. However, these are fairly evenly distributed throughout the Manx Group, are rarely vertical and are generally less than 1 m thick. They are therefore unlikely to be observed on aeromagnetic data. A highly sheared mafic rock (the 'Poortown Gabbro') is quarried 5 km east of Peel and a similar body is exposed on the coast nearby at Will's Strand (Fig. 6b). These can be resolved as weak aeromagnetic features but are located outside the imbricate zone (Fig. 5). Many granitic bodies and felsite dykes occur within and on the SE side of the imbricate zone (Fig. 3) but most of these post-date shearing and they are unlikely to have an anomalous magnetic response. In contrast, most of the early Tertiary dolerite dykes which run through this part of the Irish Sea show a marked reversed magnetic response similar to the anomalies present within the imbricate zone. However, these trend NW–SE, perpendicular to the imbricate zone, and do not appear to be concentrated within it. Instead one possible explanation for the anomalous magnetism can be found at the NE end of the imbricate zone on the Isle of Man where a significant amount of iron mineralisation is present, some of which has been mined in the past. The iron mostly occurs as haematite and siderite although pyrrhotite has also been reported (Lamplugh 1903) and magnetite may develop at depth. These minerals occupy fissure veins and zones of metasomatic replacement. A 5 m wide zone of mineralization is exposed at Port Mooar (Fig. 6h) in the NE wall of a major Tertiary dyke which can be traced to the Fleetwood Dyke in the offshore (Fig. 3). This consists of metasomatic haematite and siderite, and dolomite in fractures between brecciated material. Furthermore, where rocks are exposed elsewhere along the imbricate zone, they consist predominantly of pelites with pyrite porphyroblasts, siderite concretions and related metalliferous minerals. It is therefore possible that the reversed magnetic anomalies present within the imbricate zone are due to high metal concentrations within the Manx Group, some of which may have been redistributed by hydrothermal fluids associated with dyke intrusion in the early Tertiary.

Central Valley Lineament

The imbricate zone is transected and offset slightly by a NW–SE trending lineament (Fig. 5) which coincides with the position of the Central Valley at surface on the Isle of Man. This valley is an important geomorphological feature; it separates the northern uplands from the southern uplands and links the two main bays on the NW and SE coasts (Peel and Douglas, respectively) (Fig. 3). Hence, the lineament is called the 'Central Valley Lineament' in this paper. The lineament is clearly imaged by Bouguer gravity data, where it can be traced for some distance offshore both to the NW and SE of the island (Fig. 2a), and, on seismic data, a linked set of NE- and SW-dipping faults which offset Carboniferous and Permo-Triassic strata occur along the trend (Fig. 3). It crosses the East Irish Sea and apparently links up with the Vale of Clwyd Fault in North Wales (Fig. 1). To date, no hydrocarbon discoveries have been made on the SW side of the Central Valley Lineament, suggesting that it has had a fundamental influence on basin prospectivity.

Although the Manx Group is not exposed anywhere along the Central Valley Lineament, some smaller NW–SE Caledonian shear zones are exposed at other places along the coast. Also, a marked change in the lithofacies of the Manx Group occurs to the north and south of Peel, approximately where the Central Valley Lineament is projected to lie, suggesting that it may have influenced sedimentation during the early Ordovician on the NW side of the Isle of Man. However, at least some of this change is probably due to post-Caledonian sinistral offset and so any early Palaeozoic movement on the Central Valley Lineament remains speculative.

Later reactivation

Offshore, in Upper Palaeozoic and Mesozoic rocks of the central part of the Irish Sea, large NE–SW and NW–SE faults are fairly common (Fig. 3). These are thought to represent Caledonian shear zones similar to those described on the Isle of Man which have been reactivated during later basin evolution. In contrast, an ENE–WSW to E–W trend, which represents the general strike of Caledonian thrusts on the Isle of Man, is comparatively rare in the offshore. This may reflect the fact that the thrusts are shorter and less steeply dipping than the Caledonian strike-slip faults (Fig. 6b) and were consequently more difficult to reactivate.

Post-inversion relaxation

Caledonian compression ceased in the early Devonian (Soper *et al.* 1987) at approximately the time when a suite of granitic and dioritic rocks were intruded on the Isle of Man (Lamplugh 1903; Brown *et al.* 1968; Cornwell 1972) mostly to the south of the Central Valley Lineament (Fig. 6c). These rocks are uncleaved and show evidence of extension during the later stages of intrusion as, for example, in NW–SE orientated pegmatite veins and NE–SW orientated granitic dykes. It appears, therefore, that post-orogenic relaxation was associated with some crustal melting and possible upper mantle fractionation during a period when maximum principal stress was vertical and minimum principal stress was orientated either NE–SW or NW–SE (Figs 4 & 6c).

A package of continental red beds known as the Peel Group crops out on the northern side of Peel (Ford 1993). On the basis of their similarity with Old Red Sandstone facies these rocks have until recently been assigned a Devonian age (Allen & Crowley 1983; Crowley 1985). However, mostly on structural considerations, the present authors believe that there is a possibility that the Peel Group is latest Carboniferous in age and is hence discussed later.

Dinantian–early Namurian rifting

Lower Carboniferous onshore

The earliest firmly dated post-Caledonian sediments on the Isle of Man are a succession of Lower Carboniferous (Dinantian) limestones and associated rocks that crop out in the south of the Island around Castletown (Fig. 6d). These range in age from Arundian to Brigantian and are known as the Castletown Group (Dickson *et al.* 1987). The succession is more than 350 m thick and consists predominantly of interbedded pale-coloured and dark-coloured limestones with minor dolomites and shales. These occur within an outlier approximately 5 km wide that is fault-bounded to the NW and is dip controlled to the SE where the oldest rocks are exposed. Evidence is seen in the strata for syn-depositional tectonism (e.g. Quirk *et al.* 1990) and the entire outlier is interpreted as representing an exhumed half graben that was first active during the early Carboniferous (Figs 6d & 8).

The base of the Castletown Group is marked by a conglomerate of Tournaisian age at Langness (Dickson *et al.* 1987, Fig. 6d). Langness is an elongate, NE–SW trending peninsula which is joined to the mainland by a narrow natural causeway. The SE side of the peninsula consists entirely of rocks belonging to the Manx Group which the conglomerate directly overlies on the NW side (Fig. 8). A major SE-dipping normal fault is inferred to exist to the SE immediately offshore (Fig. 3).

The conglomerate at Langness is sedimentologically immature and contains angular clasts of locally derived Manx Group metasediments. Within the section, which is approximately 25 m

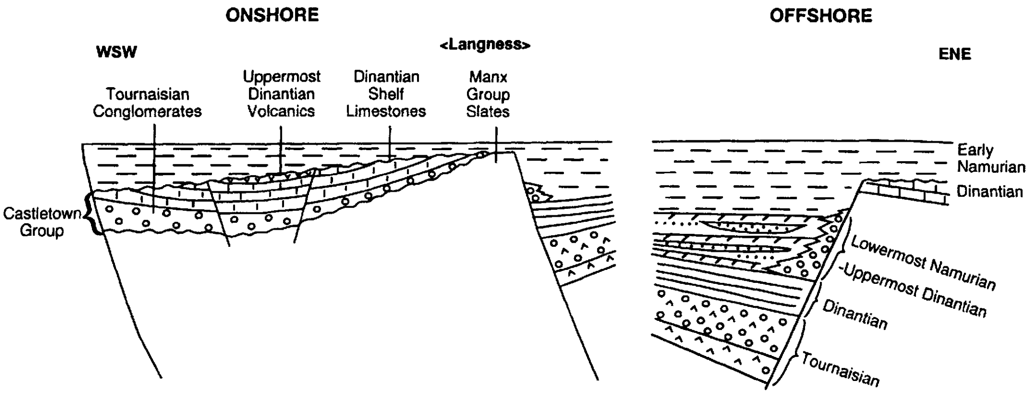


Fig. 8. Schematic geological cross-section through Lower Carboniferous strata onshore and offshore Isle of Man.

thick, syn-depositional thickening can be seen to occur on the down-thrown side of various minor faults. The faults trend N–S, E–W and NE–SW and are thought to have developed due to the effects of gravity in the up-thrown foot-wall of the major fault. On the down-thrown side of this and other major NE–SW faults a thicker, hanging-wall sequence is likely to occur (Fig. 8).

At the very base of the conglomerate, a thin stratiform veinlet consisting of chalcopyrite, quartz, calcite and minor galena is developed in the most easterly part of the outcrop on Langness. Larger, vertical veins with a similar mineralogy occur in the underlying Manx Group and it is possible therefore that they have an early Carboniferous or younger age.

Most of the younger strata within the Castletown Group consist of rather monotonous alternations between pale coloured calcilutites-bioclastic calcarenites and dark coloured calcilutites-mudstones. Small algal bioherms are developed in places. Many of the mudstones are organic rich and terrestrial plant remains, brackish water bivalves and marine goniatites are preserved at certain levels. In some of the dark limestones all porosity is filled with bitumen and in places veins of calcite within the pale limestones contain hard droplets of bitumen.

The youngest part of the Castletown Group consists of a pile of late Brigantian basaltic volcanic rocks, the base of which is erosive and below which the underlying limestone is baked. These rocks are difficult to resolve on aeromagnetic data, suggesting that the pile is not particularly thick. They consist mostly of thick sheets of volcanic breccia with obvious flow textures. A large proportion of the breccia clasts consist of limestone and occasional limestones are interbedded with the breccia. In addition, pillow lavas, slump structures and volcanic sand are present in the lower part of the volcanic pile indicating that at least some of it was deposited sub-aqueously. At the SE end of the outcrop, the volcanic pile is faulted against Asbian limestones where various volcanic vents and fissures are exposed. Faults, fissures and dykes within the volcanic rocks form a concentric pattern, sub-parallel with the margins of the volcanic pile, suggesting that it represents part of a collapsed caldera.

The Castletown Group is interpreted as having been deposited during a period of rifting associated with NW–SE extension (Fig. 6d). Coarse-grained bioclastic limestones and dolomitized limestones of Dinantian age have been encountered in boreholes below the glacial cover in the north of the Island (Fig. 9) indicating that subsidence also occurred to the north of the Ramsey–Whitehaven Ridge during the early Carboniferous (Fig. 6d).

Lower Carboniferous–basal Namurian offshore

By correlation with Well 112/25-1 (Fig. 11), the top of the Dinantian on seismic data consists of a high amplitude increase in acoustic impedance expressed either as a single reflection or the uppermost of a set of high amplitude reflections (e.g. Fig. 10). A significant part of the seismic data that was interpreted in detail during the study was from the Ogham Inlier and an adjacent offshore area east of Douglas named the 'Onchan Depression' (Fig. 3). Within this region, a package of discontinuous reflections is seen overlying the top of the Dinantian which varies in thickness from below seismic resolution up to 350 m in thickness, using an estimated seismic interval velocity of 4000 m s^{-1}. This package clearly onlaps the top of

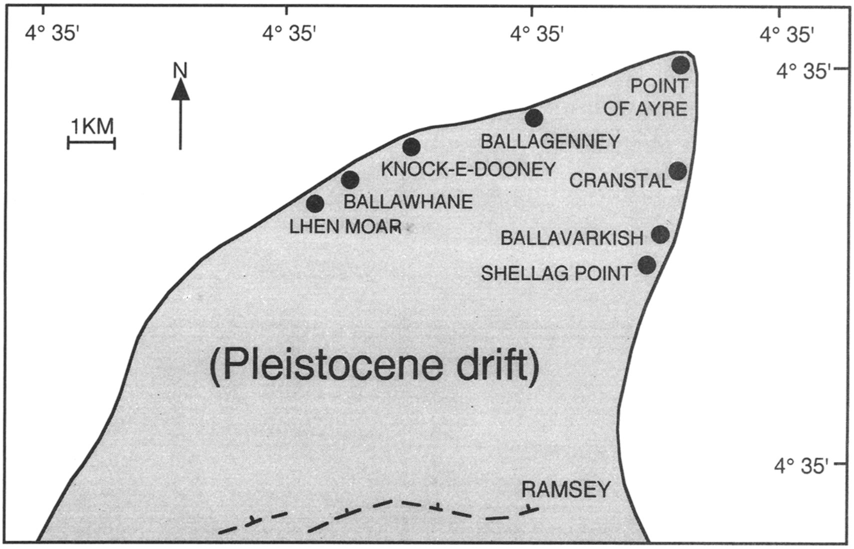


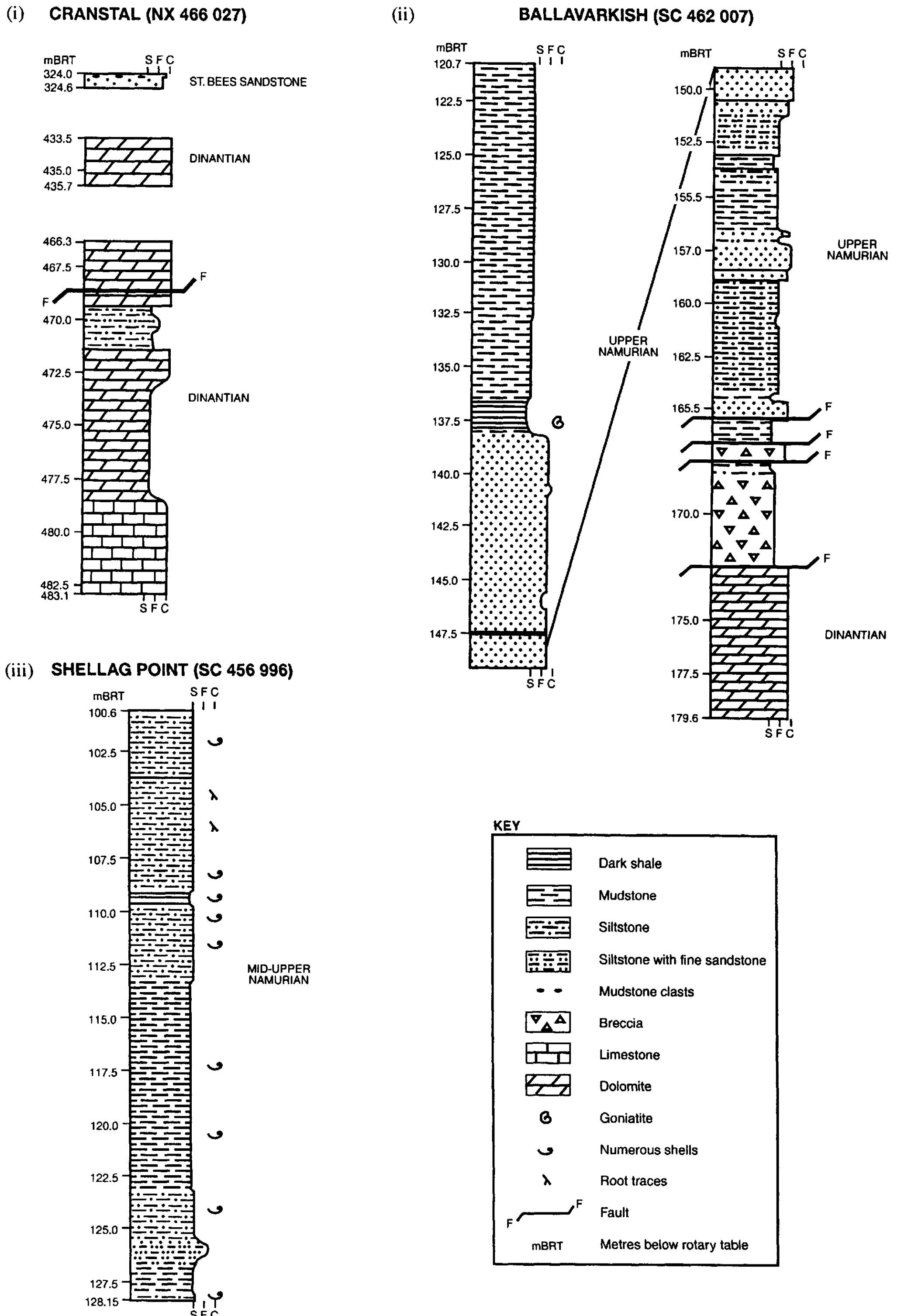
Fig. 9. (**a**) Location of shallow boreholes in the north of the Isle of Man shown in (b) and Fig. 18. (**b**) Sedimentary logs (made by N. S. Jones and D. G. Quirk) of cores stored at the Manx Museum from: (i) Cranstal borehole; (ii) Ballavarkish borehole; (iii) Shellag Point borehole.

the Dinantian (Fig. 10) and is thickest in the hanging wall of NE–SW to N–S trending normal faults. It correlates with a thin sequence or an unconformity in the footwall. The package is absent in Well 112/25-1 due to erosion and lies below TD in Well 112/30-1 but these wells help constrain its age as earliest (basal) Namurian. The reflection configurations suggest that it represents a late syn-rift sequence which corresponds approximately with the volcanic rocks exposed onshore in the Isle of Man (Fig. 8).

In some places where the basal Namurian is thick on the hanging wall side of syn-depositional normal faults it is anomalously reflective. By analogy with work by Bott & Johnson (1967), Leeder (1987), Leeder & Strudwick (1987) and Collier (1991), it is suggested that this fault-controlled seismic facies may correspond with 'Yoredale'-type sediments (Fig. 12) which comprise cyclothems of shallow water limestones, pro-delta mudstones, fluvio-deltaic sandstones and delta top coals of Dinantian–earliest Namurian age. A possible source for fluvio-deltaic sand in the late Dinantian has been identified in Anglesey where fluvial channel sandstones cut through Brigantian shelf limestones (see Walkden & Davies 1983). Palaeocurrents are to the north and NE in Anglesey; i.e. towards the central part of the Irish Sea. A second more obvious potential source of sand is the Isle of Man itself. It is difficult to know whether the Manx Group was exposed at this time. However, the general NE–SW trend of the present day coastline, parallel to Lower Carboniferous faults (Fig. 6d), and the presence of Manx Group clasts within the basal conglomerate at Langness suggests that the Isle of Man may have been up-faulted during the Dinantian. Seismic data indicates that to the NE of the Isle of Man, the Ramsey–Whitehaven Ridge also formed an active fault block during the early Carboniferous bounded by the Lagman Fault to the SE (Fig. 6d). It is overlain by a thin Dinantian succession displaying a divergent stratal geometry similar to that interpreted for the Castletown Group onshore (Fig. 8).

Away from the immediate hanging wall of the Lagman Fault (Fig. 3), Well 112/25-1 encountered Upper Dinantian limestones with occasional thin sandstones and mudstones becoming common towards the top of the interval (Fig. 11). These may represent the distal correlatives of 'Yoredale' cyclothems that consequently should become more sand-rich towards the Lagman Fault.

The possible existence of sand-prone 'Yoredale' cyclothems in the immediate hanging wall of early Carboniferous normal faults represents a potential new hydrocarbon play in the central part of the Irish Sea. Fluvio-deltaic sandstones and fractured limestones may form reservoirs sourced from interbedded mudstones and coals and sealed by the mudstones or overlying Holywell Shale (see below). End Carboniferous inversion structures around the Ogham Inlier form particularly attractive targets (e.g. Fig. 12). Oil shows were encountered in Well 112/30-1 within Upper Carboniferous sandstones (Fig. 13), in an off-structural


(i) CRANSTAL (NX 466 027)
mBRT
S F C
324.0
324.6
ST. BEES SANDSTONE
433.5
435.0
435.7
DINANTIAN
466.3
467.5
F
F
470.0
472.5
DINANTIAN
475.0
477.5
480.0
482.5
483.1
S F C
(ii) BALLAVARKISH (SC 462 007)
mBRT
S F C
120.7
122.5
125.0
127.5
130.0
132.5
135.0
137.5
140.0
142.5
145.0
147.5
S F C
UPPER NAMURIAN
mBRT
S F C
150.0
152.5
155.5
157.0
160.0
162.5
165.5
170.0
175.0
177.5
179.6
S F C
F
F
F
F
UPPER NAMURIAN
DINANTIAN
(iii) SHELLAG POINT (SC 456 996)
mBRT
S F C
100.6
102.5
105.0
107.5
110.0
112.5
115.0
117.5
120.0
122.5
125.0
127.5
128.15
S F C
MID-UPPER NAMURIAN
KEY
Dark shale
Mudstone
Siltstone
Siltstone with fine sandstone
Mudstone clasts
Breccia
Limestone
Dolomite
Goniatite
Numerous shells
Root traces
F
F
Fault
mBRT
Metres below rotary table

(b)

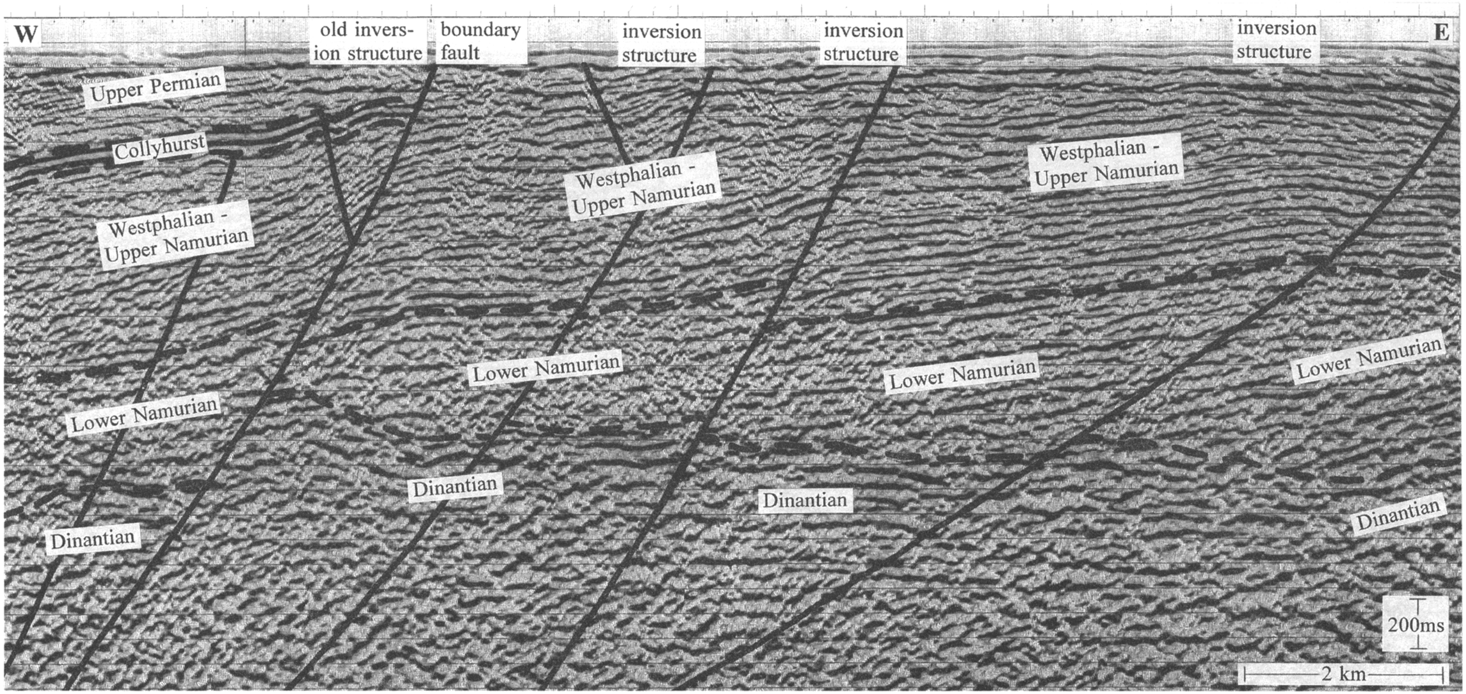


Fig. 10. Migrated 2D seismic line, courtesy of Western Geophysical, across the boundary fault separating the Onchan Depression (W) from the Ogham Inlier (E) in order to show the major faults affecting Carboniferous and Permian strata. Note normal and reverse fault movement at different levels. The Lower Namurian consists mostly of the Holywell Shale; the Collyhurst Sandstone is abbreviated here to Collyhurst.

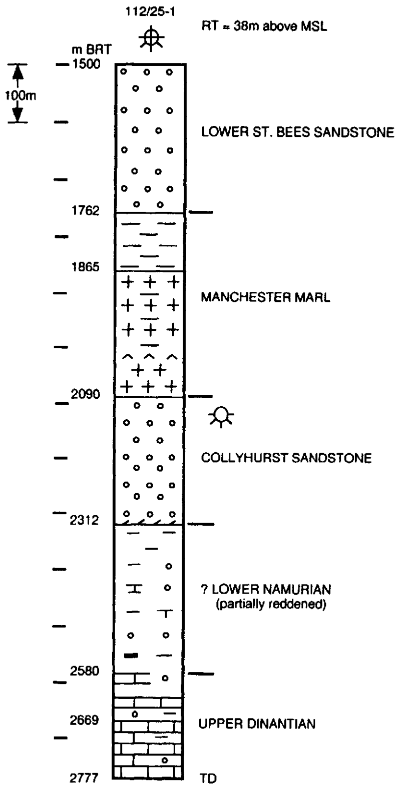


Fig. 11. Simplified stratigraphic log of the lower part of Well 112/25-1.

position, suggesting that hydrocarbon charge has occurred in the area.

Silesian sag

The basal Namurian interval is overlain by the Lower Namurian Holywell Shale, the upper part of which was encountered in Well 112/30-1 (Fig. 13). It has a characteristic appearance on seismic sections comprising discontinuous reflections that become more coherent towards the top where subtle clinoforms are sometimes visible. The Holywell Shale is a thick, organic rich mudstone which is the main hydrocarbon source rock in the SE Irish Sea area (e.g. Armstrong *et al.* this volume). The lower part was deposited during transgression associated with the onset of rapid thermal subsidence after rifting ceased. The end of transgression is marked by a maximum flooding surface interpreted as Chokierian (H1) in age based on data in Ramsbottom *et al.* (1978). This maximum flooding surface is developed as an organic-rich shale which has high natural gamma radiation and is oil-prone. The middle and upper parts of the Holywell Shale contain increasing amounts of land-derived material and are gas-prone (Armstrong *et al.* this volume), thought to reflect the onset of deltaic progradation. Around the Ogham Inlier and Onchan Depression, where it has been mapped using seismic (e.g. Fig. 14), the Holywell Shale varies in total thickness from approximately 200 to 1000 m based on an interval velocity of 4000 m s^{-1}

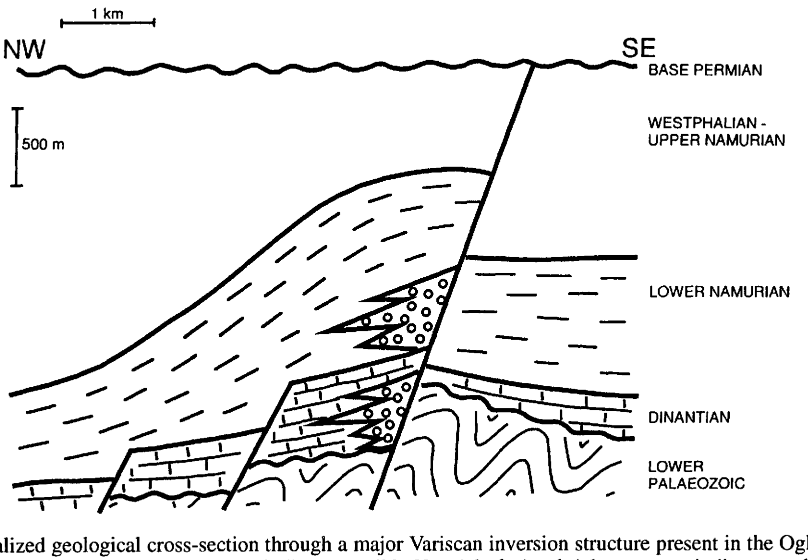


Fig. 12. Idealized geological cross-section through a major Variscan inversion structure present in the Ogham Inlier based on confidential seismic data. Circles indicate possible Yoredale facies, brick ornament indicates carbonates and dashes indicate mudstone.

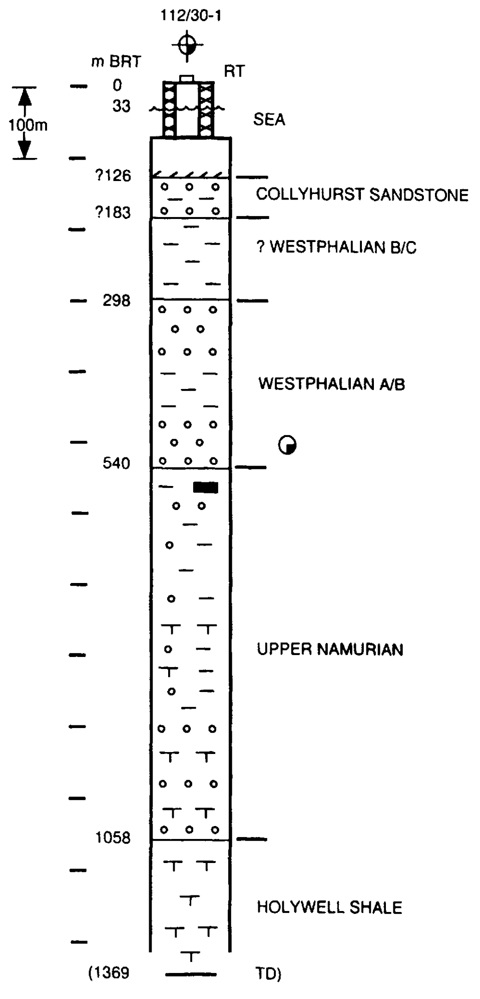


Fig. 13. Simplified stratigraphic log of upper and middle part of Well 112/30-1.

derived from well data. Reflection characteristics indicate that this variation is mostly due to the infilling of earlier rift-related topography (see Fig. 10).

On the Isle of Man, Silesian rocks have only been encountered in boreholes below the glacial cover in the north of the Island (Fig. 9). The oldest of these are Kinderscoutian in age and are mud-dominated (Fig. 9b(iii)). These mudstones contain both plant and shelly material and are thought to represent the uppermost part of the Holywell Shale. TOCs of more than 4% have been measured by one author (Quirk) with vitrinite reflectance values in the order of 0.6%.

Above the Holywell Shale and below the base Permian unconformity, most of the Silesian (Upper Namurian–Westphalian strata) has a tramline-like appearance on seismic sections; i.e. local thickness variations are not observed (e.g. Fig. 10). This indicates that by the late Namurian the area was unaffected by normal faults and was subsiding passively due to the effects of thermal subsidence. Close to the top of the Upper Namurian, apparent truncation of underlying reflections is sometimes observed. A subtle unconformity at approximately the same level has also been observed in the Southern North Sea (Quirk 1993) and onshore UK (J. F. Aitken pers. comm. 1995).

Well 112/30-1 encountered an overall regressive sequence from the Upper Namurian to the Lower Westphalian (Fig. 13). The sediments in the upper part of this interval are fairly typical of the Westphalian in that they consist of lacustrine-deltaic facies and include coarse-grained fluvial sandstones and occasional thin coals. In total, 350 m of Westphalian strata were penetrated in Well 112/30-1 below the base Permian unconformity. In the West Cumbrian Coalfield (Fig. 1), a thickness of approximately 500 m of Westphalian A to Westphalian C/D is present. A 30 m thick, coarse-grained fluvial sandstone known as the Whitehaven Sandstone occurs near the top of the preserved section (Jones 1992) and this or equivalent sand bodies may have reservoir potential in the Irish Sea as they do in the Southern North Sea (e.g. Quirk 1993) and onshore UK (e.g. Rothwell & Quinn 1987; Fraser & Gawthorpe 1990; Storey & Nash 1993).

Seismic data across the Onchan Depression indicate that, below the base Permian unconformity, more than 1000 m of Westphalian section is present above the interval penetrated in Well 112/30-1 (Fig. 15), based on an interval velocity of 4000 m s^{-1} derived from well data. By analogy with the Southern North Sea, this section is thought to be Westphalian C–early Stephanian in age (see Quirk 1993). The area where these young Silesian rocks are present is confined to a pre-Permian syncline, the axis of which trends NE–SW (Fig. 15).

End Carboniferous (Variscan) compression

Where Silesian rocks occur in the offshore, they are gently folded below the base Permian unconformity (e.g. Fig. 15). NE–SW to N–S trending reverse faults are also present which seem to represent reactivated Dinantian normal faults (e.g. Figs 10 & 12). These compressional structures are interpreted as having formed during WNW–ESE-directed Variscan (end Carboniferous) shortening (Fig. 6e). The Ogham Inlier is a Carboniferous inversion

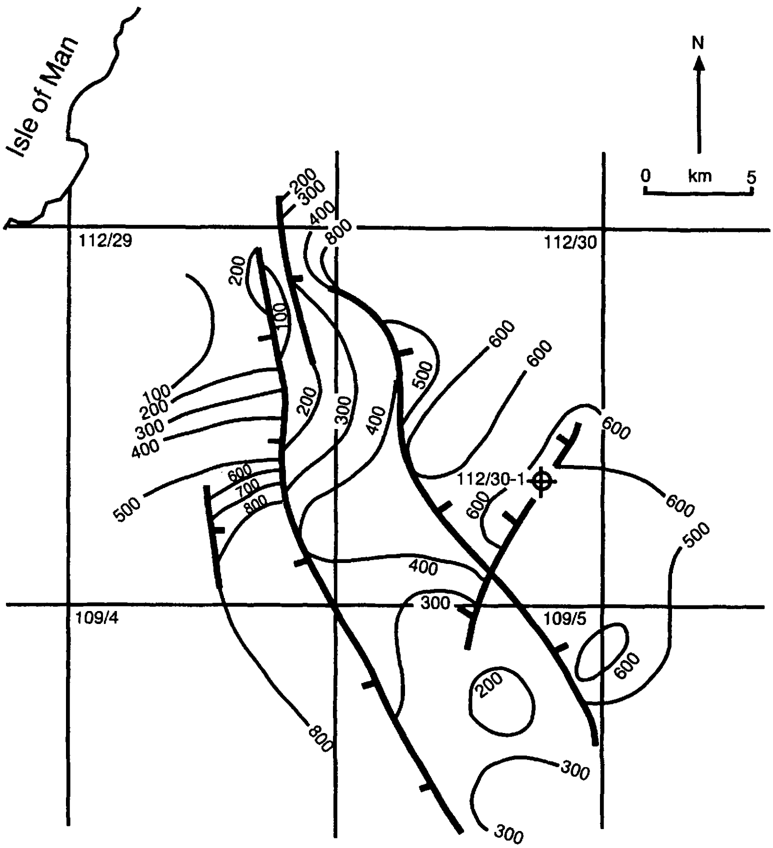


Fig. 14. Isotime thickness map of the Lower Namurian (top Dinantian–top Holywell Shale) around the Onchan Depression and Ogham Inlier. Isochore contour values are in milliseconds two way time.

structure which was initiated at this time (e.g. Fig. 12), as is the pre-Permian syncline mentioned above.

Ogham Inlier

The Ogham Inlier is clearly imaged as a relative Bouguer gravity anomaly high (Fig. 2a). The highest part of the inversion structure occurs to the SW of Well 112/30-1 (Fig. 15) where most Westphalian strata were removed by erosion at the end of the Carboniferous. It is possible that some of the eroded material may have been redeposited as molasse within the adjacent pre-Permian syncline (Fig. 15). To support this idea, a comparison is made here with the Peel Group on the opposite side of the Isle of Man.

Peel Group

The Peel Group on the NW side of the Isle of Man occurs in a similar structural position relative to the Central Valley Lineament as the pre-Permian syncline in the Onchan Depression on the SE side (Figs 3 & 6e). About 1000 m of continental strata ('red beds') are exposed (Ford 1993) along the coast NE of Peel (Fig. 3) including fluvial sandstones, interfluvial mudstones and calcretes. Most of the sandstones contain a large proportion of lithic fragments. However, in the lower part of the section, medium grained sandstones with some reservoir potential are present. These consist of well rounded quartz grains with calcite cement.

The Peel Group is juxtaposed at the northeastern end of the outcrop against Manx Group metasediments by a boundary fault that is oriented N–S and inclined steeply to the west. The overall structure of the Peel Group is that of a northwards plunging, eastwards verging monocline in that close to the boundary fault the beds dip gently to the north and further away from the fault they dip steeply to the NW. The monocline probably developed as an inversion structure as a result of reverse movement along the boundary fault.

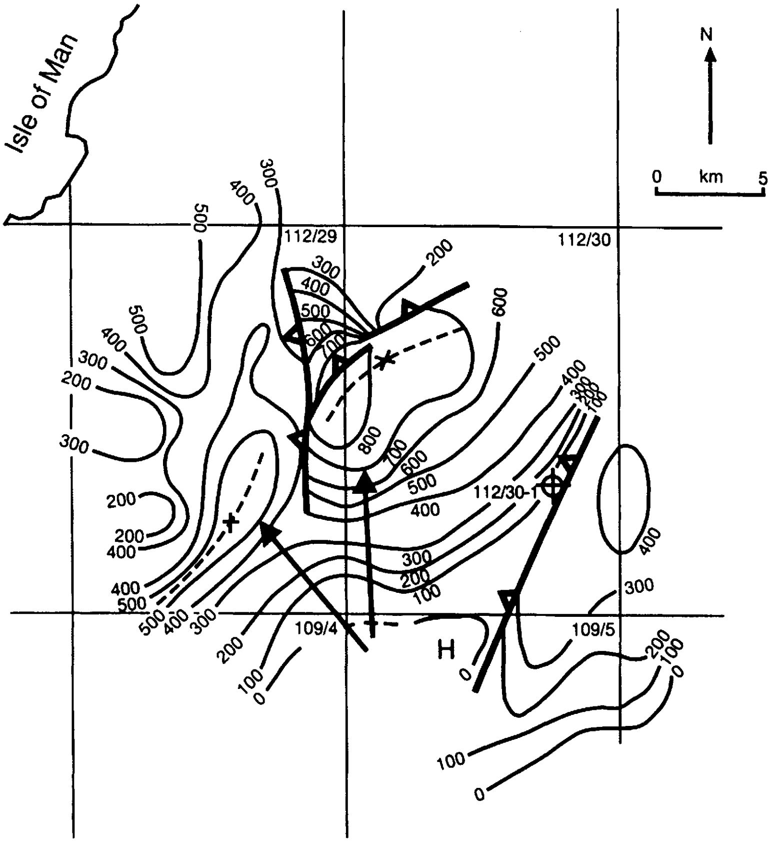


Fig. 15. Isotime thickness map of the Westphalian C/D to early Stephanian (top Westphalian B–base Permian) around the Onchan Depression and Ogham Inlier. Isochore contour values are in milliseconds two way time. Dotted line with cross indicates axis of pre-Permian syncline; large arrows indicate possible transport direction of molasse-type sediment from the highest part of the Variscan inversion structure in the Ogham Inlier (H).

Similar structures are observed on seismic sections within Upper Carboniferous strata at the margins of the pre-Permian syncline in the Onchan Depression (Figs 10 & 12), where they are assigned a Variscan age (see above).

The Peel Group is completely devoid of palynomorphs although some calcified root structures and one large sandstone burrow have been identified. These sediments have been interpreted by Allen & Crowley (1983) to be early Devonian in age but, unlike the basal conglomerate within the Castletown Group, they contain no clasts of Manx Group material. It is instead tentatively suggested, by analogy with the offshore, that the Peel Group is late Carboniferous in age and therefore equivalent to red beds of Westphalian C/D to early Stephanian age onshore UK (e.g. Besly 1988).

A set of asymmetric folds, extensional faults, glide planes and slump structures occur within the Peel Group at the northern end of the outcrop (e.g. Ford 1972). Most of these indicate movement to the SE and are thought to have developed as a result of gravitational processes. The type of deformation displayed within these sediments (e.g. Fig. 16) suggests that tilting occurred due to tectonism during or soon after sedimentation. One possibility is that the boundary fault was active during deposition. However, adjacent to the boundary fault, the Peel Group is brecciated and, judging from the angular nature of the clasts, fault movement appears, at least in part, to post-date lithification of the sediment. Furthermore, no thickening of the strata is observed towards the fault and the grain size of the sediments seems to be unrelated to the fault. There is therefore no evidence for syn-depositional movement on the boundary fault nor for the existence of a growth fault further to the SE. Instead, a Bouguer gravity

Fig. 16. SE-directed slump-like fold in the Peel Group near Will's Strand. Note hammer for scale.

anomaly high has been identified to the NW of Peel which is similar to the gravity signature of the Variscan inversion structure forming the Ogham Inlier (Figs 2a & 6e). It is suggested, therefore, that the gravity-related structures observed in the Peel Group developed due to syn-depositional over-thrusting in the area to the NW (Fig. 6e) and the sediments themselves represent molasse-type deposits. The boundary fault was probably formed during the later stages of compression, associated with folding and over-steepening of the molasse deposits. This model does not exclude the possibility that the sediments are Devonian in age and were affected by both late Acadian and Variscan compressional events.

Early Permian rifting

In the offshore many normal faults can be seen on seismic reflection data that post-date the Westphalian but pre-date the base Permian unconformity (e.g. Fig. 10). Where these normal faults have been mapped around the Ogham Inlier and Onchan Depression, they fall into two main sets orientated NE–SW and WNW–ESE to NNW–SSE (Fig. 6f). These faults offset earlier Variscan compressional structures and seem to record a phase of rifting and associated strike-slip during the early Permian. The direction of extension during rifting is estimated as E–W (Fig. 6f) which, on a more regional scale, corresponds with the orientation of a chain of N–S trending half graben basins of Permo-Triassic age which extend to the NW and SE of the Isle of Man (see McClean 1978; Jackson & Mulholland 1993). In the vicinity of the Isle of Man, the Central Valley Lineament, the Lagman Fault and the Keys Fault seem to have been active at this time (Fig. 6f). Early Permian rifting is also recorded in the Southern North Sea as the Saalian event where the overall direction of extension was N–S (Quirk 1993; Quirk & Aitken 1997)

Bouguer gravity anomaly lows around the Isle of Man highlight where thick, low density Permo-Triassic strata are present (Fig. 2a). The lower part of the Permo-Triassic section is represented by a red continental sandstone known as the Collyhurst Sandstone (Jackson & Mulholland 1993) which is assigned an early Permian age. Approximately 220 m of Collyhurst Sandstone was encountered in Well 112/25-1 (Fig. 11) on the down-thrown side of the Lagman Fault (Fig. 6f). In contrast, in Well 112/30-1 (Fig. 13) and shallow boreholes onshore Isle of Man (Fig. 18), the Collyhurst Sandstone is

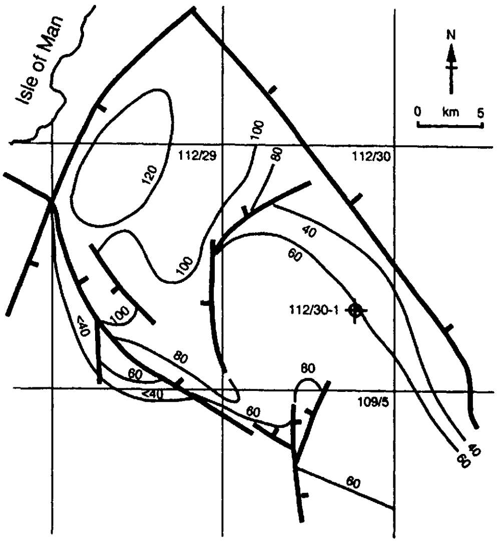


Fig. 17. Map showing normal faults active during the early Permian around the Onchan Depression and Ogham Inlier with isotime thickness of the Collyhurst Sandstone superimposed (isochore contour values in milliseconds two way time).

either thin or absent. On seismic sections the Collyhurst Sandstone can be seen as a strong positive reflection (decrease in acoustic impedance) at the top and as a discordancy between underlying (Carboniferous) reflections and overlying (Permian) reflections at its base (Fig. 10). The Collyhurst Sandstone is thickest on the hanging wall side of early Permian normal faults (Fig. 17) where it can reach thicknesses of up to 300 m based on an interval velocity of 4500 m s^{-1} derived from well data. However, reflections within the Collyhurst Sandstone appear to be fairly parallel and the variations in thickness that are observed are due to onlap rather than divergence of strata; i.e. no evidence of syn-depositional growth faulting is recorded. The Collyhurst Sandstone is therefore interpreted as having infilled remanent graben and half graben after rifting ceased. Similar to the Southern North Sea (see Quirk & Aitken 1997), early Permian syn-rift sediments have not been identified on seismic sections, suggesting that the overall effects of thermal uplift during rifting were greater than those of tectonic subsidence caused by extension. However, early Permian volcanic rocks have been discovered in the Irish Sea in Well 110/2-10 (Hardman 1992).

Well 112/25-1 encountered gas bearing Collyhurst Sandstone which failed to produce on test due to very low permeabilities. However, elsewhere around the Isle of Man, particularly in areas close to normal faults active during the early Permian (Fig. 6f), coarser grained, reservoir-prone fluvial and/or aeolian sandstones may have accumulated. Sand may have been derived from the Isle of Man or further to the NW or SE along the Central Valley Lineament (Fig. 1).

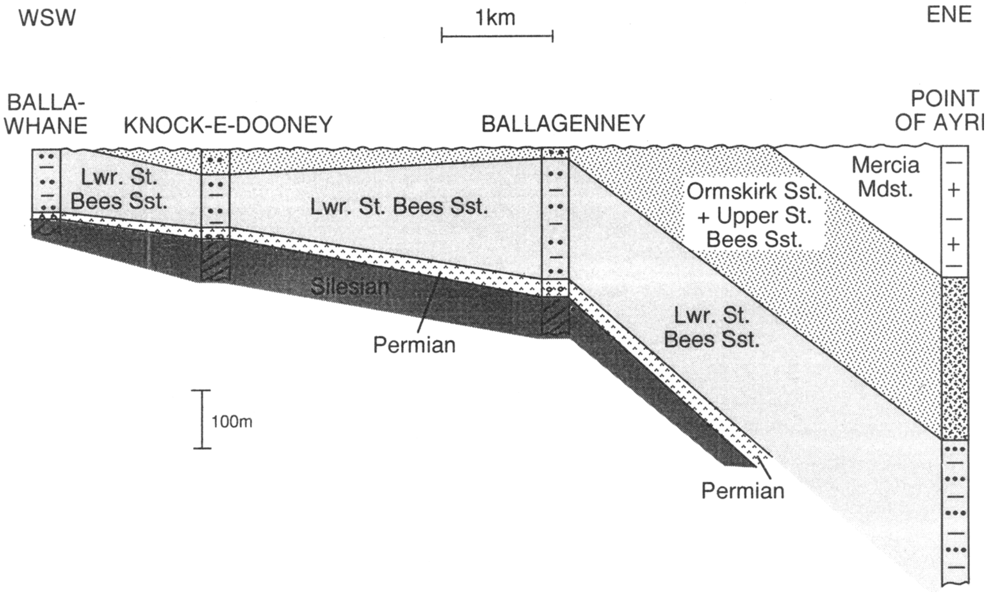


Fig. 18. Well correlation of boreholes drilled at the northernmost edge of the Isle of Man (after Gregory 1920).

Late Permian–early Jurassic sag

After deposition of the Collyhurst Sandstone, thermal sag continued on through the late Permian, the Triassic and early Jurassic when the Manchester Marl, Sherwood Sandstone, Mercia Mudstone and Lias groups were deposited (Fig. 4). Upper Permian–Lower Jurassic strata, which represent the youngest preserved solid succession in the central part of the Irish Sea, have a general layer cake expression on seismic data, apart from the presence of some halokinetic structures (e.g. Fig. 19). Hence, the Bouguer gravity anomaly contours in the central part of the Irish Sea give a general indication of the solid geology that crops out at the sea bed (Fig. 2a). No obvious divergence of reflections nor any fault-related lapping geometries are observed, although Permo-Triassic sequences are often thicker in the hanging wall of some of the major faults than those preserved in the foot wall. These thickness variations are thought to reflect isostatic readjustment on faults formed during the early Permian rather than representing evidence for renewed rifting in the Triassic.

Permo-Triassic sediments are present where the Solway Basin extends onshore beneath glacial sediments at the northern end of the Isle of Man (Fig. 18). Highly porous Ormskirk Sandstone was encountered in the northernmost borehole at the Point of Ayre (Gregory 1920).

?Late Jurassic–Cretaceous rift-sag

More than 1000 m of post-Triassic offset is recorded on some of the large NW–SE, N–S and NE–SW faults in the central part of the Irish Sea such as the Keys Fault (e.g. Fig. 19). It is tentatively suggested that these faults were active during the late Jurassic and represent a phase of Kimmerian rifting similar to that recorded over large parts of NW Europe (e.g. Ziegler 1990). The direction of extension during rifting is estimated as approximately ENE–WSW (Fig. 6g) based on the amount of post-Triassic throw present on the main faults. Approximately the same direction of extension is recorded in the North Sea at this time (Bartholomew *et al.* 1993).

A thickness of at least 500 m of sediment is estimated to have been deposited in the area during the Cretaceous as a result of renewed thermal sag following the end of Kimmerian rifting (cf. Cope, this volume and Warrington, this volume). Subsidence was terminated during the early Tertiary when the basin began to invert (Green *et al.* this volume). The Permo-Triassic rocks now exposed at the sea bed (e.g. Fig. 2a) are thought, therefore, to represent exhumed Kimmerian structures, including a major pop-up horst which underpins the present day Isle of Man (Fig. 6g).

Early Tertiary event

It is now generally accepted that the Irish Sea experienced a large amount of uplift (1.5–2.0 km) during the early Tertiary, beginning about 60 Ma ago (e.g. Holliday 1993; Green *et al.* this volume). The uplift was associated with intrusion of NW–SE orientated dolerite dykes as well as a postulated phase of hydrothermal fluid flow (Green *et al.* this volume). Hydrothermal fluids may have affected reservoir quality and are likely to have influenced source rock maturity as well as caused the removal of salt by dissolution.

Aeromagnetic data (Fig. 5) reveal a large number of linear reversed polarity anomalies crossing the Irish Sea which are due to Tertiary dolerite dykes. Several tens of such dykes have been identified on the Isle of Man. The largest of these, the Fleetwood Dyke, comes onshore on the Isle of Man at Port Mooar (Fig. 6h). The dyke here is approximately 12 m wide and trends 125°/90°. The Manx Group forms the country rock and on the NE side of the dyke this has been metasomatically replaced by haematite and quartz. It is difficult to prove whether this metasomatism occurred before, during or after intrusion but it is possible that it records early Tertiary hydrothermal fluid flow related to the formation of the dyke.

A few small NE–SW trending reverse faults are seen to cross-cut some of the Tertiary dykes exposed on the Isle of Man, for example, in an area north of Port Mooar (Fig. 6h). Evidence of small amounts of compression during the Tertiary is also recorded on some of the major NE–SW to N–S oriented faults on the eastern side of the Irish Sea (e.g. Chadwick *et al.* 1993; Haig *et al.* this volume).

Therefore, during the early Tertiary, the Irish Sea was affected by uplift, igneous and hydrothermal activity, NE–SW extension and a limited amount of NW–SE compression. These are probably related to one major tectonic event resulting from upwelling of the asthenosphere at the end of the Cretaceous which caused crustal doming, high heat flow, tectonic stretching and gravitational collapse (Figs 4 & 6h). Strangely, the area has not been affected by thermal subsidence since doming ceased in the late Tertiary suggesting that the crust was underplated by mantle-derived igneous material.

During the late Cretaceous and Tertiary, many other parts of NW Europe were affected by uplift and igneous activity (see Ziegler 1990). The early Tertiary event recorded in the Irish Sea probably only forms part of a wholesale reorganization of

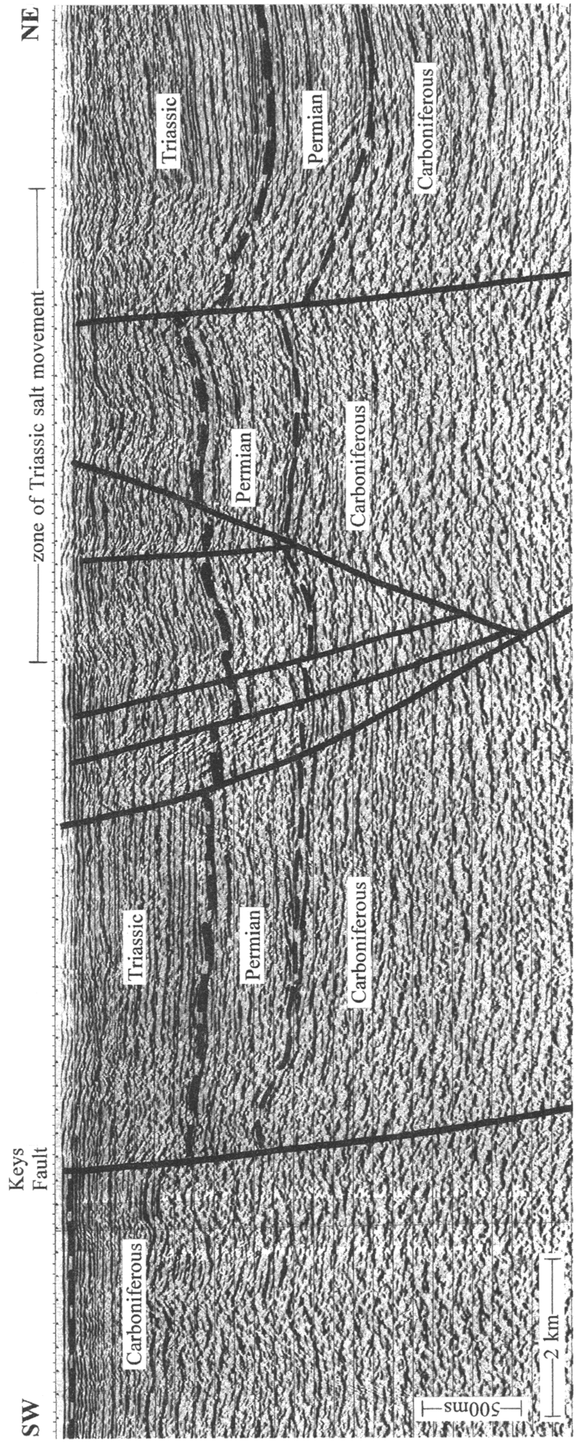


Fig. 19. Migrated 2D seismic line, courtesy of Western Geophysical, across the Keys Fault which separates the Ogham Inlier (SW) from the Keys Basin (NE). Note the layer cake appearance of Triassic strata and evidence of halokinesis.

mantle circulation patterns associated with the formation of the North Atlantic.

Conclusions

The central part of the Irish Sea reveals a structural history similar to other areas in NW Europe, namely (i) Caledonian orogenesis during the late Silurian; (ii) rifting in the early Carboniferous; (iii) thermal sag during the late Carboniferous; (iv) Variscan inversion at the end of the Carboniferous; (v) rifting during the early Permian; (vi) thermal sag from the late Permian to the early Jurassic; (vii) rifting during the late Jurassic; (viii) thermal sag during the Cretaceous; and (ix) doming in the early Tertiary. In an overall sense, each successive tectonic event has seen an apparent anticlockwise rotation in the direction of minimum principal stress such that from the early Carboniferous to the early Tertiary, the direction of extension has changed in intermittent steps from NW–SE to NE–SW. A newly identified basement structure known as the Central Valley Lineament has been active during many of the tectonic episodes and is thought to influence the hydrocarbon prospectivity over a large part of the Irish Sea. Close to the Central Valley Lineament round the Ogham Inlier and Onchan Depression it is proposed that potential hydrocarbon targets may exist at Lower Permian and Carboniferous levels.

The authors wish to thank World Geoscience, Western Geophysical, Manx National Heritage and an anonymous oil company who provided data or allowed access to material for this study. Help and advice was gratefully received from Richard Morgan, Michael Keaveny, Martin Millwood Hargrave, Paul Green, Simon Deadman, Janice Weston, Neil Jones, Ian Longley, Richard Collier, Stewart Molyneux, Trevor Ford, David Kelly, Jeanette Williams, Andrew Johnson, Wendy Horn, Roger Sims, Fred Radcliffe and Greig Cowan. Most of the diagrams were expertly drafted by Lisa Hill. Fieldwork by DGQ was partly funded by Oxford Brookes University. This paper is published with the permission of the Director, British Geological Survey (NERC).

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