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Tectonic framework of the Celtic Sea and adjacent areas with special reference to the location of the Variscan Front

PIERS R. R. GARDINER

Geological Survey of Ireland, 14, Hume St., Dublin, Eire

and

DONALD J. R. SHERIDAN

Marathon Mining Ireland Ltd., 65/68 St. Stephen's Green, Dublin, Eire

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Abstract—Structural trends in the Celtic Sea area indicate that Variscan deformation patterns were inherited from Caledonian basement structures, and that the regional fold alignment is arcuate with a regional WSW–ENE direction rather than WNW–ESE (Armorican). There is no lateral structural continuity between Southern Ireland and South Wales–Southwest England. Three major structural provinces arranged en échelon across the Variscan foldbelt are recognised: (a) Southwest England, where there was complex deformation of a major basin; (b) the South Wales–Mendips foreland area, with strong basement/cover interaction and (c) the Southern Ireland graben and flanking platform province. Late Palaeozoic depositional patterns indicate that Southern Ireland and Southwest England were separated by a WSW–ENE trending platform bounded on the north by the inherited Wexford Boundary Lineament and to the south by a previously unidentified major Palaeozoic fault zone, here termed the Bristol Channel Lineament. The South Wales–Mendips Variscan successions accumulated on this intervening Wales–Celtic Sea platform, and were partly influenced by rejuvenated Caledonian fault lines. It is suggested that the northern margin of the Rheno-Hercynian foldbelt (the Variscan Front) be taken along the Bristol Channel Lineament, which can be traced for some 400 km southwestwards towards the Goban Spur on the continental margin. This permits a rationalisation of both tectonic and major facies boundaries in locating the front. It is also suggested that the structurally localised nature of the Southern Ireland basin be recognised by designating it as the Southern Ireland Zone of the Variscan foldbelt.

The sites of Mesozoic rifting in the Celtic Sea and adjacent areas, although complex in detail, appear to have been located along the Wexford Boundary and Bristol Channel Lineaments.

INTRODUCTION

AS CONVENTIONALLY depicted (e.g. Dunning 1966, 1977, Krebs 1976, Zwart & Dornsiepen 1978, Lefort 1980) the Rheno-Hercynian sector of the Variscan fold belt in the Southern British Isles is shown transecting the earlier Caledonian structural framework, whilst subsequent Mesozoic faulting and basin development in this offshore sector is apparently along Caledonian trends (Ziegler 1978). The anomalous Caledonian–Variscan relations arising from this interpretation have led to difficulties in satisfactorily locating the northern limit of Variscan orogenic deformation (i.e. the Variscan Front, Fig. 1) westwards from mainland Europe; depending on the criteria used, different positions have been proposed with no conformity with major facies boundaries or margins of major geotectonic divisions (cf. Matthews 1974, Dunning 1977). As recognised at present (Fig. 1 inset), the trend of the front in this area diverges markedly from that of the other Variscan structural zone boundaries. Indeed, it has been suggested (Gardiner 1978) that the generally held position of the Variscan Front in Southern Ireland merely reflects pre-existing structural controls in a localised basin, and that the Rheno-Hercynian structural zone has been influenced by basement massifs and swings southwestwards through the Celtic Sea from southern Britain.

Problems therefore exist in identifying a significant structural feature which can be taken as marking the northern limit of Variscan orogenic zones (the front) and whether there is a westward continuation of the fold belt from Southern Britain, or merely a number of fault controlled ensialic sites of tectonism (Matthews *et al.* 1980). As a contribution to the resolution of these problems, the tectonic framework of the Celtic Sea and adjacent areas and its bearing on Variscan deformational and depositional patterns is examined in this paper.

DEFINITION OF THE VARISCAN FRONT IN NORTHWEST EUROPE

This structural boundary at the junction between orogenic and foreland folding is currently positioned where there is evidence of major thrusting. The difficulties of this approach have been assessed by Matthews (1974), Dunning (1977) and Hancock *et al.* (1981). They noted that in several places (e.g. SW Dyfed, Mendips, The Ruhr) there is a choice of thrust boundaries with the probability that thrusting was merely a function of locally shallowing pre-Variscan basement or the relative incompetence of strata within the foldbelt, and that the, thrusts do not necessarily mark the northern boundary of Variscan orogenic

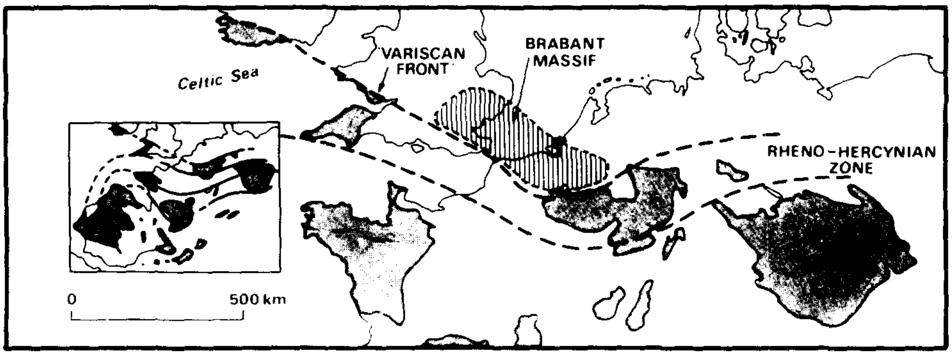

Fig. 1. Map of Northwest Europe showing the outcrops of the Variscan foldbelt to the south of the conventional position of the Variscan Front, after Dunning (1977) and Zwart & Dornsiepen (1978). Inset map shows the positions of Variscan structural zones on a pre-Permian reconstruction (after Ries 1979).

deformation. Nor is thrusting everywhere developed along the conventional line of the front, for example, in part of Southern Ireland, South Glamorgan and Wesphalia. In these areas facies boundaries or thickness variations have been utilised to determine the line. The possibility of taking the northern limit of slaty cleavage as the marker line was evaluated by Matthews (1974), and discarded because of distributional inconsistencies in Southwest Britain and Ireland. In Ireland for example, Variscan penetrative cleavage fabrics occur up to 60 km north of the conventional position of the front, and locally in Lower Carboniferous rocks north of Dublin (Max 1979). At present therefore, the customary line of the front is based on locally different criteria, leading Dunning (1977, p. 176) to conclude that "it is unprofitable... to try and define a unique Variscan Front".

It is clear that many of the difficulties exist because of basement/cover relationships, stemming from the inherent premise that the widely separated Variscan outcrops of the Rheno-Hercynian zone of northwestern Europe are lateral correlatives of the same structural unit. If however the exposed northwestern part of the Variscan foldbelt (Fig. 1) includes fault controlled localised basins influenced by pre-existing basement structures, as has been suggested for Southern Ireland (Gardiner 1978), the possibility exists that there was a continuous structural basin further south, and that its northern limit could be a realistic boundary position for the so-called Variscan Front. If so, then such a line would be genetically related to both facies boundaries and geotectonic divisions. This aspect is discussed further after the relevant evidence is presented.

MAJOR STRUCTURES IN THE CELTIC SEA AND ADJACENT AREAS

Within the last decade a considerable amount of information has been obtained concerning the post-Palaeozoic tectonic framework of the Celtic Sea/Western Approaches region. Presentation has usually been in generalised form (e.g. Ziegler 1978), but recently details of specific areas have been published (Kamerling 1979, Dingle & Scrutton 1979, Robinson *et al.* 1981). It is now known that the area has a WSW–ENE structural grain, with fault bounded Mesozoic basins separated by ridges of Palaeozoic basement with thin Mesozoic veneers (Fig. 2). Of particular interest are the structural trends shown by these basement ridges, and the nature of their boundary faults.

The Cornubian platform (Fig. 2) is bounded to the south by the South Cornish Fault Line, of which the Southern Boundary Fault further to the west-southwest may be a lateral extension (Dingle & Scrutton 1979). The trend of both faults is consistent with those of the adjacent Variscan structures onshore (Fig. 2), and it seems reasonable to presume that this reflects a WSW Variscan structural trend throughout the offshore extension of the platform, as suggested by Hill & Vine (1965) and Blundell (1975) on geophysical grounds (also see Avedik 1975, fig. 3). On this basis, the platform essentially consists of deformed Variscan strata and associated intrusives, which accords with the sparse sampling records. Cleaved Devonian (?) shales crop out in the area of the Haig Fras Granite (Smith *et al.* 1965) and south Goban Spur (Dingle & Scrutton 1979). The latter area is also intruded by presumed Variscan granites and basic igneous rocks (Pautot *et al.* 1976) and as such is regarded as an extension of the Cornubian platform (Dingle & Scrutton 1979).

Details about the northern margin of the Cornubian platform have been obtained from seismic studies (Kamerling 1979, Marathon Petroleum Ireland, Ltd., unpublished data). These show that a major fault (indicated "A" in Fig. 3) with an associated minor graben feature expressed in strata of Upper Cretaceous and younger age (see Kamerling 1979, fig. 6b, shot points 65–80), can be traced with certainty for a minimum of 40 km on a closely-spaced seismic grid. Its inferred lateral trace is suggested by more widely-spaced seismic control. To the east, although dislocated by NW–SE trending faults (Kamerling 1979), it seems likely to equate with the thrust fault (feature "B", Fig. 3) mapped by Lloyd *et al.* (1973), both faults being to the south of major synclinal areas developed in Mesozoic strata. The thrust fault of Lloyd *et al.* (1973) in turn probably relates eastwards via a dextral offset along the Cotherstone Fault Line (Brooks & Al-Saadi 1977) into the onshore inferred Cannington Thrust, (feature "C" l, Fig. 3). (Dunning 1966, Wills 1971,

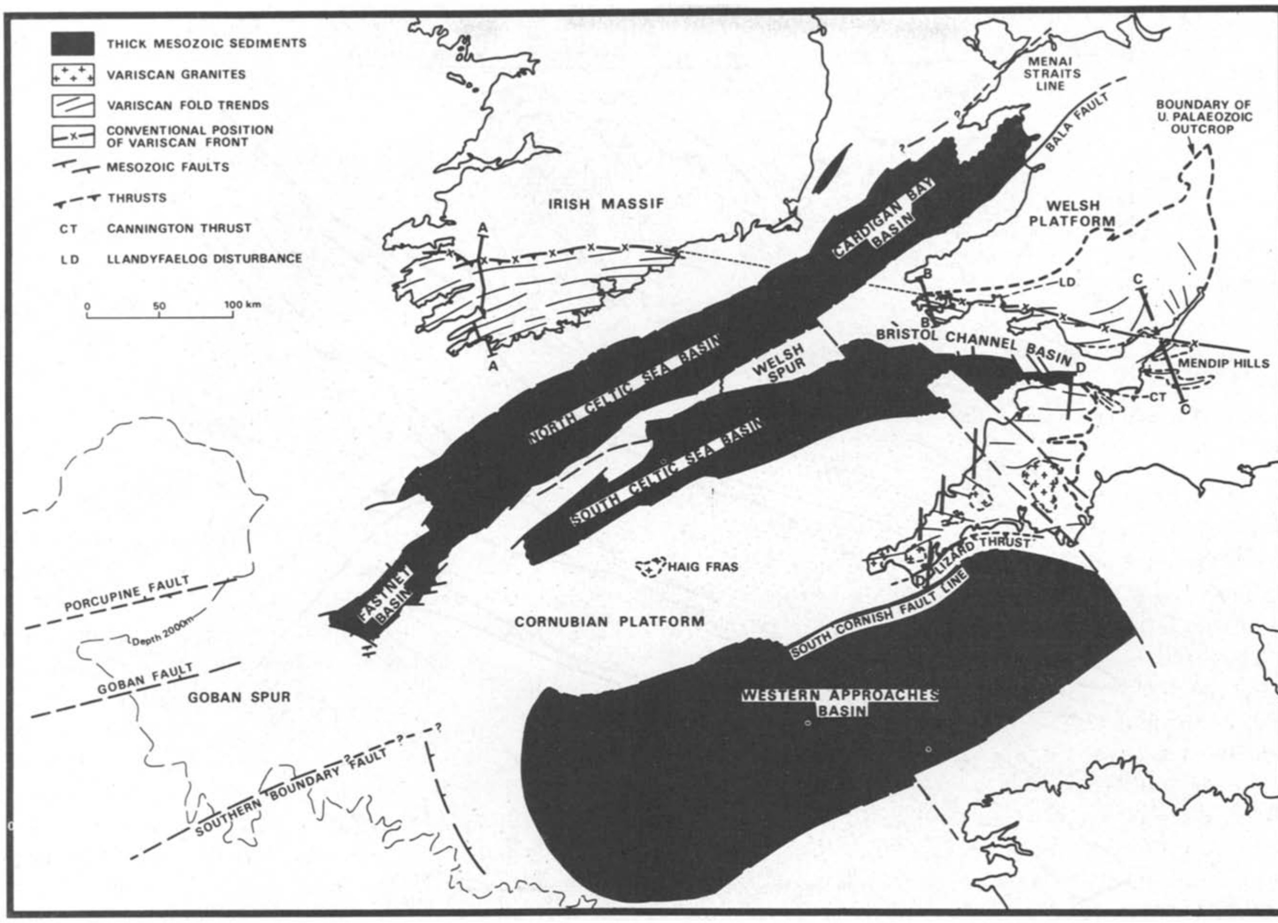

Fig. 2. Mesozoic tectonic framework of the Southwestern British Isles and adjacent continental margin. Offshore data from Pegrum & Mountenay (1978), Zeigler (1978), Dingle & Scrutton (1979), Kamerling (1979), Robinson *et al.* (1981) and Fig. 3 of this paper. Onshore structural trends from Dunning (1966) and Max (1979). Black areas show locations of thick Mesozoic sediments. A–A, B–B, C–C, D–D, are the lines of the sections shown in Fig. 4.

Brooks & Thompson 1973), though the nature of the latter under Exmoor has been disputed (Matthews 1974, 1977a, Brooks *et al.* 1977). To the west, the fault can be traced as an arc in a southwesterly direction past the Haig Fras granite, intruded in presumed Devonian slates (Smith *et al.* 1965), and hence has a lateral extent of at least 400 km (Fig. 3). It is also coincident with a zone of steep gravity gradients offshore (Davey 1971), and was considered by Kamerling (1979) to be parallel to the earlier ('Hercynian') structural grain in the Bristol Channel area, which controlled the line of the subsequent Mesozoic tensional graben development. The Goban Fault (Fig. 2) may be a westerly extension of this fault boundary (cf. Dingle & Scrutton 1979), although there is intervening structural complexity in the area of the Fastnet Basin (Robinson *et al.* 1981).

The boundaries of the Welsh platform and associated Welsh Spur reflect a WSW–ENE structural trend. The faulted northern margin appears to have been reactivated along inherited Caledonian structures because it has a marked Caledonoid trend and appears to pass eastwards (Kent 1975, Whitbread 1975) into the onshore Caledonian Bala Fault (Figs. 2 and 3). The more arcuate southern margin is essentially a mirror image of the northern side of the Cornubian Platform, suggesting that the Mesozoic rifting of the South Celtic Sea and Bristol Channel Basins was initiated along a single deep-seated lineament. The sites of Mesozoic faults in the Fastnet Basin (Fig. 2) have also been ascribed to earlier Caledonian lines of weakness, the basin being generated in a dextral shear regime (Robinson *et al.* 1981). The Welsh Platform and Welsh Spur essentially consist of Lower Palaeozoic strata, but further to the southwest no information is available concerning the thickness of the Upper Palaeozoic rocks. Pre-Mesozoic basement has been penetrated in six wells in the Irish sector (Fig. 3). A cleavage fabric was evident only in Esso/Marathon well 56/20-1, suggesting that Late Palaeozoic sediments deposited to the north of the Cornubian platform were, at least in part, shielded by basement from intense Variscan deformation.

The faulted southern margin of the 'Irish Massif' is again along a WSW–ENE Caledonoid trend, with the likelihood that the site is controlled by the location of pre-existing basement lineaments. At the eastern end, seismic records show that it passes into the Menai Strait, Line at Anglesey a suggested major Lower Palaeozoic structural discontinuity (Barber & Max 1979). This fault line can be traced southwestwards off Ireland, where both seismic (Marathon, unpublished) and gravity data (Davey 1971) show major down-faulting along the southern margin. This fault line is located along the inferred site of the Palaeozoic Wexford Boundary Lineament identified by

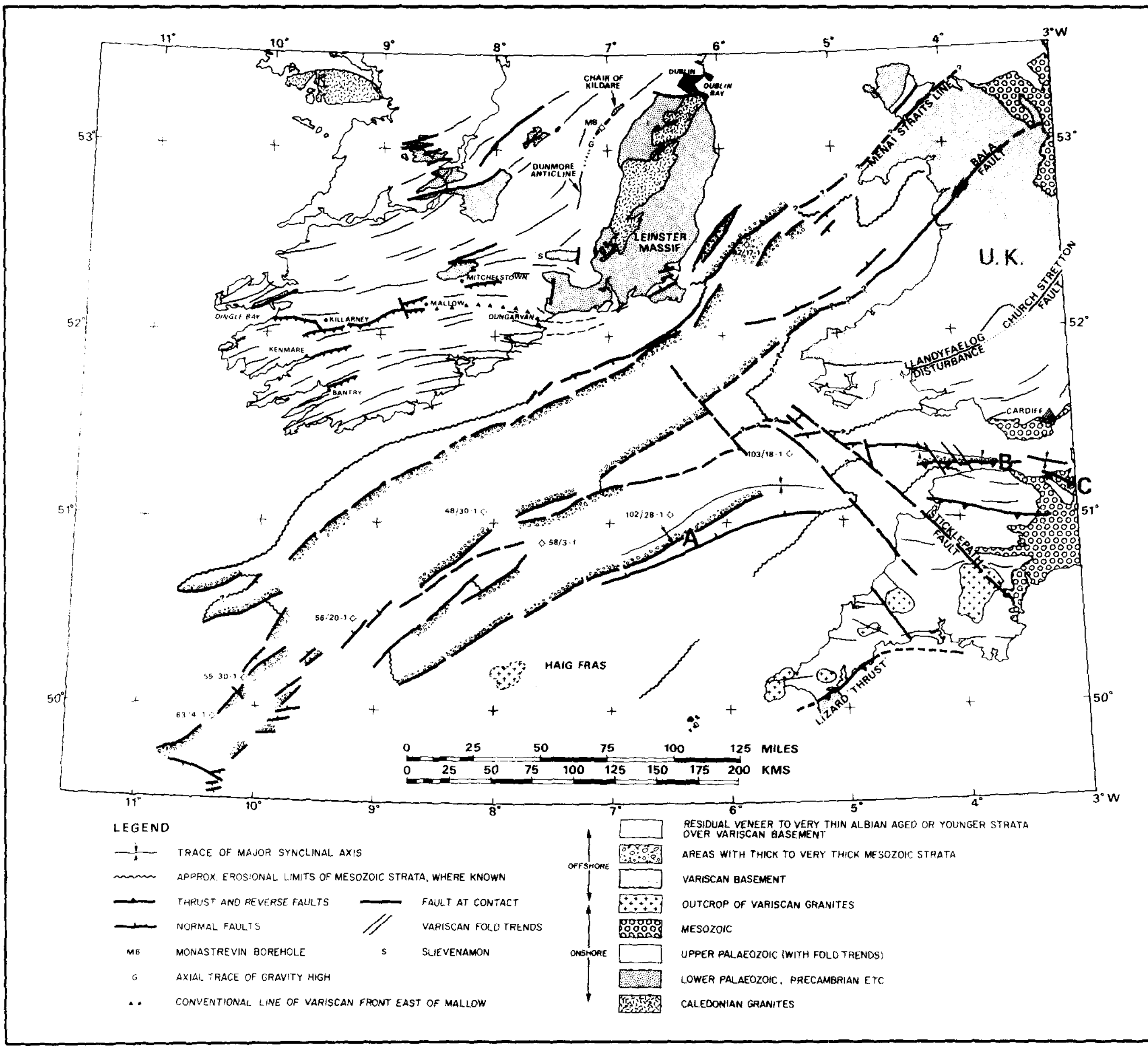

Fig. 3. Simplified tectonic framework of the northern Celtic Sea and adjacent areas. Offshore geology adapated in part from Wills (1951), Lloyd *et al.* (1973), Kamerling (1979), Robinson *et al.* (1981) and company sources. UK onshore geology after Dunning (1966). Irish onshore geology in part after Max (1979) and company sources.

MacCarthy *et al.* (1971), along which there was apparently repeated differential movement in both the Early (Gardiner 1975a) and Late Palaeozoic (MacCarthy *et al.* 1971, Gardiner & MacCarthy 1981). Devonian transcurrent movement along this Wexford Boundary Lineament—Menai Straits Line has also been suggested by Nutt & Smith (1981). It is possible that the Porcupine Fault (Dingle & Scrutton 1979) is an extension of this fault zone (Fig. 2), with the reversed throw being related to fault inversion, of which several examples exist in the Fastnet Basin (Robinson *et al.* 1981).

On a regional scale four conclusions can be drawn. First, that Mesozoic rifting in the Celtic Sea area was essentially controlled by the structural grain of the underlying basement. Second, that these structural trends were essentially WSW–ENE, although somewhat flexed (Fig. 2). Third, that there is no evidence that a WNW–ESE 'Armorican' structural trend influenced the subsequent fault tectonics; indeed, the conventional line of the Variscan Front cross-cuts the offshore structural framework with no apparent genetic relationship (Fig. 2). Either Variscan structures had no influence on the subsequent structural history, or they are parallel to 'Caledonoid' trends. Finally, that whereas the Cornubian platform is essentially Variscan basement, the Welsh Platform and its offshore extension is a Caledonian massif.

ONSHORE VARISCAN OROGENIC STRUCTURES

These are seen in three areas; Southwest England, South Wales, and Southern Ireland (Figs. 2 and 3).

Southwest England

This is a region of complex tectonics, with thrusting, nappe structures, and polyphase deformation, in which a number of structural zones have been identified (Sanderson & Dearman 1973). These zones were generated at differing structural levels, and the variation in deformation style may be related to either deep fractures rooted in basement within the infra-structure of the fold pile (Matthews 1977a) or rotation during increasing shear strain with depth (Sanderson 1979). A N–S eclectic section (Fig. 4d) shows that the gross structure of the Carboniferous strata is that of a crudely symmetrical fanned synclinorium with folds facing towards the flanking margins, with the implication of there having been compression between two basement massifs (cf. Freshney & Taylor 1980). The fold trends are locally variable but are regionally consistent with the adjacent boundaries of the Cornubian Platform. The strike variations can plausibly be assigned either to fold generation at different structural levels or to basement control (Matthews 1977a), or to late-stage flexing by the intrusion of the Cornish batholiths (cf. Waters 1970).

South Wales–Mendips

In contrast to Southwest England, the Variscan folds are relatively simple upright structures (Figs. 4b & c), with marked strike variation and thrusts locally developed. In the Bristol area the N-trending orientation of the fold axial traces is attributed to basement control by Dunning (1966, 1977), but they swing into parallelism with the E–W trend of the northern margin of the Bristol Channel Basin (Kamerling 1979) as the latter is approached. The WNW–ESE trends in south Pembrokeshire (now SW Dyfed) (Hancock 1973) are apparently anomalous, since they diverge markedly from structural trend of the faulted margins of the Welsh Platform. Apart from this area the line of the front as taken by Dunning (1966) transects the fold trends, being arbitrarily located on the basis that it "separates Variscan folding of Armorican trend from Germanotype Variscan folding whose northward converging trends are determined by basement structures." (Dunning 1977, p. 174). Clearly this specific position bears little relation to surface Variscan structures (Fig. 3), and other local positions in the Mendip Hills or the Bristol Somerset Coalfield have been sugges-

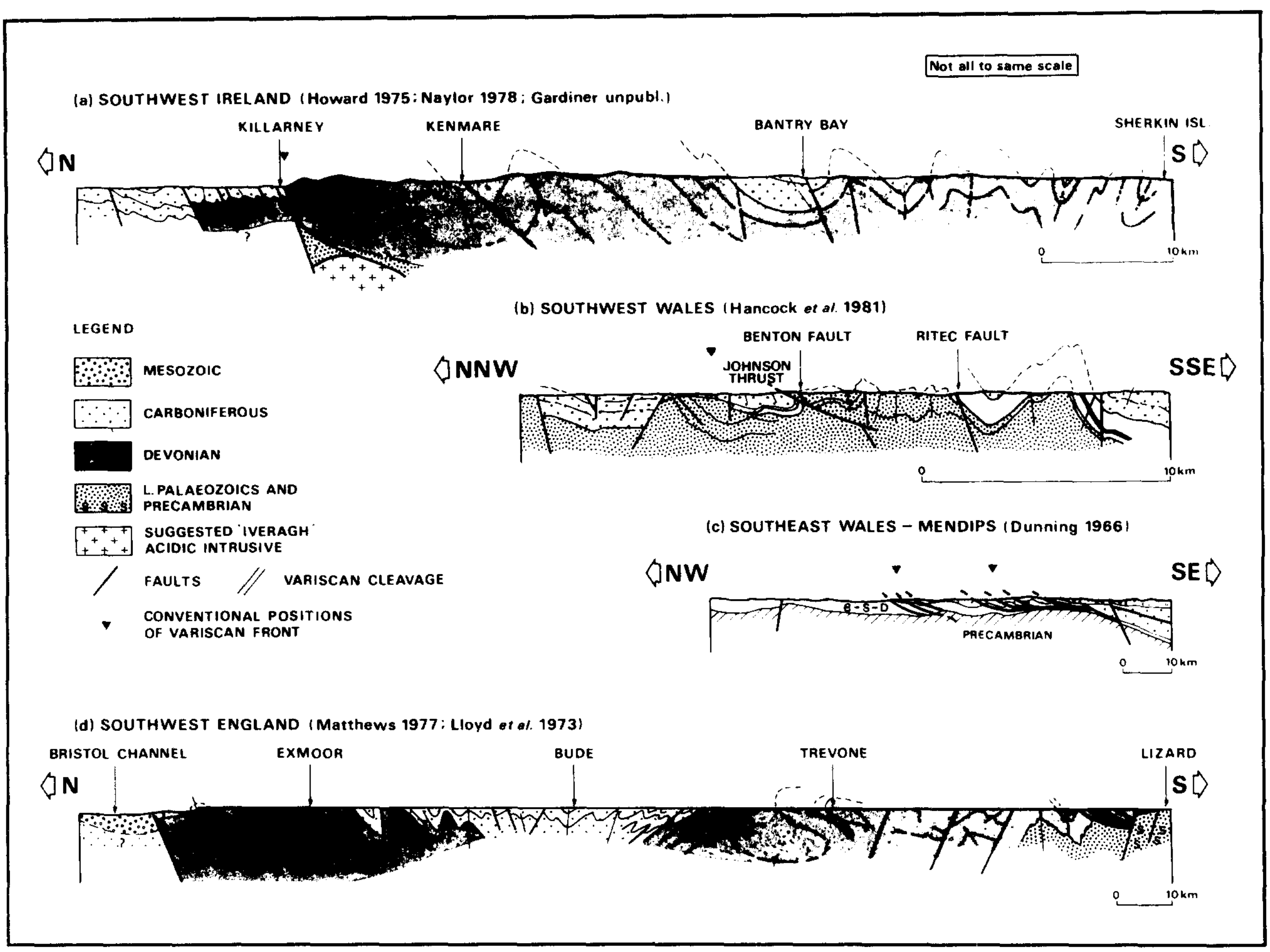

Fig. 4. Synoptic structural profiles through the northern Variscan foldbelt. For locations of sections see Fig. 2.

ted (e.g. Dunning 1977).

The Variscan folds of Pembrokshire trend parallel to the major Ritec Fault and Johnson Thrust, which separate different structural zones (Hancock 1973). The Benton Fault, and perhaps the Ritec Fault, were active in latest Silurian times (Allen & Williams 1978), and the structural pattern is a reflection of basement controls, especially within and along the northern margin of the Little Haven–Amroth Coalfield (Hancock 1973, Hancock *et al.* 1981). Further evidence of shallow basement is seen in the area of the Llandyfaelog disturbance some 50 km to the east (Fig. 3) where Old Red Sandstone strata show Variscan structures controlled by Caledonian basement trends, with post-Carboniferous faulting along the fundamental Caledonian fracture zone of the Llandyfaelog disturbance–Church Stretton Fault line (Cope 1979). This apparently anomalous area of south Pembrokeshire is, in a regional context, therefore interpreted as merely a feature of local basement/cover relationships that are characteristic of the South Wales–Mendips area. Significantly however, some of the folds in the southern part of South Pembrokshire (south of Milford Haven) face to the south (Hancock *et al.* 1981), suggesting the possibility of compression against uplifted basement in the Bristol Channel.

Southern Ireland

Two structural zones in this area were identified by Gill (1962), namely a zone of 'cleavage folding' separated from more open fold structures to the north by what is conventionally taken as the Variscan Front. This boundary is marked by north-directed thrust faults between Mallow (Gill 1962) and the Killarney–Dingle Bay area in the west (Walsh 1968), but between Mallow and Dungarvan (Fig. 3) is drawn along the fold trends, although the sharp northern boundary to the tight fold styles in this latter sector suggest the likelihood of thrusts at depth. The 'cleavage folding' zone is characterised by tight major folds with steeply-dipping axial planes that show a regional fanning and gross synclinorial structure in the west (Fig. 4a). A penetrative cleavage is typically developed in incompetent strata, polyphase fold deformation is locally present (Wingfield 1968, Gardiner, unpublished), and major reverse faults occur at Bantry and Kenmare (Figs. 3 and 4a). In contrast, the fold style of the more northerly structural zone is one of small amplitude, more open, small-scale parasitic folds, local décollement (Brennand 1965, Philcox 1964) and thrusts, features recognised by Philcox (1964) as reflecting shallow basement control. There is also a marked contrast in strike trends. The zone of 'cleavage folding' has an arcuate trend (Fig. 3) with folds tightening eastwards, while the area north of the 'front' is clearly influenced in trend by the outlines of the Caledonian massifs and the mid-Devonian Leinster granite pluton.

Recent work has indicated the presence of a number of basement elements prior to Variscan deformation. To the east is the Caledonian Leinster Massif with its thin Upper Palaeozoic cover and core of granite. The low gravity values associated with this pluton (Fig. 5) extend southwestwards, implying a concealed extension of the granite in this direction (Murphy 1960), at least as far as Slievenamon, where granite has been reported (Gill, in Capewell 1956). The gravity low centred about the Iveragh Peninsula is also thought to reflect a buried silicic intrusion (Howard 1975), indicating a shallower basement in this sector rather than thickening of the Upper Palaeozoic sequence as suggested by Naylor & Jones (1967) and Clayton *et al.* (1980). Along this northern perimeter is the South Ireland Lineament (Fig. 5), a major structural line during the Early Palaeozoic (Gardiner 1975a), which geophysically can be traced with varying degrees of confidence from Dingle Bay northeastwards along the concealed margin of the Leinster Granite to Dublin (Gardiner & MacCarthy 1981). To the north of this lineament there are Lower Palaeozoic inliers, and the Upper Devonian cover is markedly reduced in thickness compared with the sequences to the south of it and west of the Leinster Massif, with evidence of differential movement along the lineament during the Late Palaeozoic (Horne 1970, Gardiner 1975b, Gardiner & MacCarthy 1981). It is bounded immediately to the north in the Dingle Bay–Killarney area by a concealed metamorphic basement ridge (Horne 1970, 1975) and basic igneous intrusives (Howard 1975), and delimits a more positive block from the basin to the south. The arcuate shape of the southern foldbelt appears to be due to deformation of the basinal sequence against this platform and the Leinster Massif (Gill 1962, Gardiner 1978), with the Dingle Bay–Mallow Thrust belt reflecting overthrusting along the basement margin. To the northeast of Mallow, shortening of the thin cover was apparently controlled by the local basement geometry (Philcox 1964). Localised thrusts occur to the north and south of Mitchelstown (Schultz 1971, Wardlaw 1961). Subsurface thrusts have also been recognised by the Athlone Prospecting and Development Corporation near Monasterevin (MB, Fig. 3) over a deep-seated geophysical feature (Robinson 1971) which here marks the South Ireland Lineament (Gardiner & MacCarthy 1981), and it is likely that the strike of the Dunmore anticline (Fig. 3) is also basement controlled. Thus, although the 'front' demarcates differing strain regimes to the west of Mallow, it apparently splits to the east as a result of basement control, an aspect recognised by Philcox (1964). The conventional position of the front between Mallow and Dungarvan (Fig. 3) is therefore merely the southernmost line of several possible options, although a realistic regional structural boundary in view of the marked change in fold styles. The evidence thus suggests that the Variscan fold and thrust structures along the conventional 'front' are the result of local basement–cover relationships, and that they are strongly influenced by inherited Caledonoid controls.

Along the south coast, the Variscan folds trend WSW, apparently flexing around the southern end of the Leinster Massif (Fig. 3). This alignment is parallel to the Wexford Boundary Lineament, along which locally steep gravity values indicate the presence of shallow fault-bounded basement (Davey 1971, see Fig. 5). This suggests

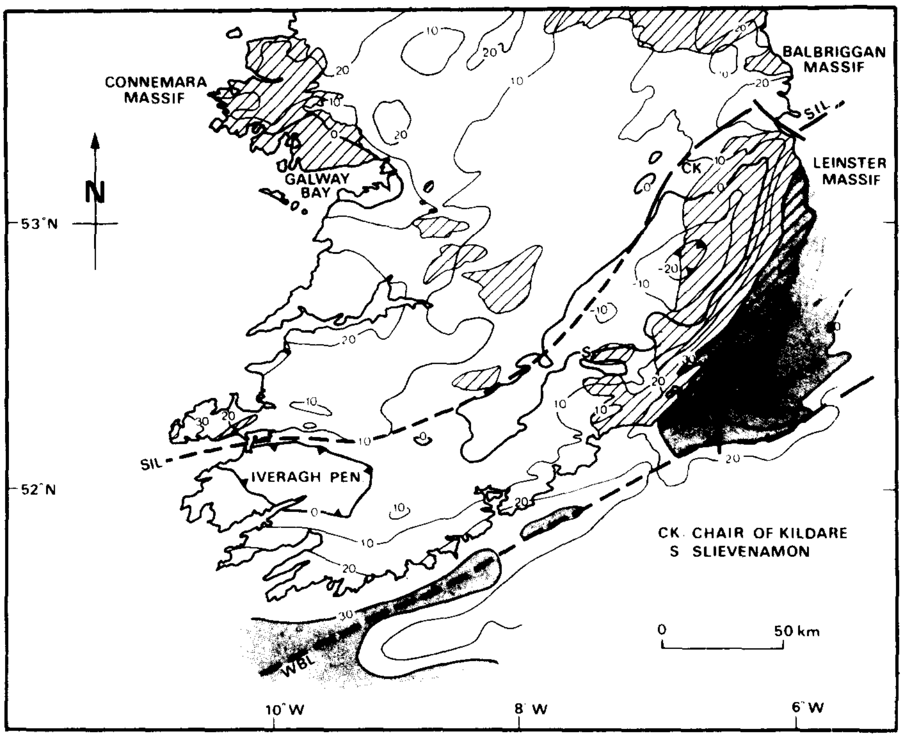

Fig. 5. Bouguer gravity anomaly map of Southern Ireland and near-shore areas (from Davey 1971, Howard 1975, Murphy 1979). Regions with gravity values higher than 30 milligals are stippled. Lined areas are Lower Palaeozoic Massifs. SIL. South Ireland Lineament, WBL. Wexford Boundary Lineament. Location of lineaments after Gardiner & MacCarthy (1981). Continuous line along the SIL marks the location of deep fractures recognised from detailed geophysical studies.

that the zone of 'cleavage folding' resulted from graben deformation between three major basement elements; the platform area bounded by the South Ireland Lineament, the Leinster Massif, and a southern block bounded by the Wexford Boundary Lineament. This concept is supported by the convergent fan of axial planes in the southwest of the fold belt (Fig. 4a), by the tightening of the major folds as they are traced eastwards, and by the parallelism of the fold axial traces to the margins of the basement blocks. There is no simple 'Armorican' trend as conventionally depicted. As originally suggested by Gardiner (1978), Variscan deformation in Southern Ireland is thought to have occurred in a localised basement controlled setting.

Regional Inter-relationships

Marked contrasts exist between the three areas. The Variscan structures of Southwest England reflect complex orogenic deformation with superposed structures and recumbent folding, while the South Wales–Mendips area is a platform area of basement/cover interaction controlled by inherited Caledonian structures. Southern Ireland also shows inherited basement control, but in a localised platform and graben setting, and the folds are relatively simple upright structures. There is no evidence for a uniform Armorican trend, and the alignment of the major fold structures is inconsistent with the conventional notion that Southern Ireland is a lateral equivalent of the South Wales–Southwest England segment. The fold trends in Southeast Ireland swing ENE (Gardiner & Horne 1981) rather than ESE towards South Wales. It seems rather that the three areas are arranged en échelon within the Variscan foldbelt, and that each represents a different structural segment in a N–S profile. In both South Wales and Southern Ireland the fold trends have a Caledonoid orientation, with local deviations giving Armoricanoid fold trends as a result of either flexing around basement blocks or inherited Caledonian controls. Any lateral structural continuity would seem to lie in a westerly or west-southwesterly direction, rather than in an ESE–WNW direction.

VARISCAN DEPOSITIONAL PATTERNS

In general terms, the standard palaeogeographical model of the region is one in which the Devonian landmass of the British Isles was flanked in southern Ireland and South Wales by a south-facing alluvial plain that drained into a marine basin (the Variscan trough or 'Hercynian ocean') sited over Southwest England and the Celtic Sea area. By the early Carboniferous a marine transgression had established shelf and deltaic environments over the earlier alluvial sites, with the later Carboniferous history in the region showing a gross regressive pattern (e.g. Wills 1951, Dineley 1975, Leeder 1976, Anderton *et al.* 1979). A comparison of the Wales–Southwest England sequence with that of the Southern Ireland–Celtic Sea area should therefore provide a further correlative test. If these two areas were laterally contiguous, as would be the case if they were located on the northern margin of the Rheno-Hercynian Zone, then they should show grossly comparable N–S facies changes in their Upper Palaeozoic successions.

Wales–Southwest England

The synoptic diagram (Fig. 6) for the region reveals the well known situation of the contrasting depositional settings of the Anglo-Welsh and Southwest England basins separated by the Bristol Channel.

Following marine regression at the end of the Silurian, early Devonian alluvial sequences were deposited in Wales as a grossly coarsening-up suite largely derived from northern uplands (Allen 1974a, b, 1979). Localised southerly derived alluvial fan deposits occur however in South Wales, for example, the Llanishen Conglomerate (Allen 1975) the Ridgeway Conglomerate Formation, (Williams 1978) and the Lindsway Bay Formation (Allen & Williams 1978), and contain clasts suggestive of a Lower Palaeozoic/Precambrian source area probably located in the Bristol Channel (Allen 1979, the Bristol Channel landmass of Anderton *et al.* 1979). During this time the alluvial Dartmouth Group (Dineley 1966) was deposited in the Padstow area (Fig. 6), with subsequent transgression leading to the establishment of a condensed marine basinal facies from the Middle Devonian onwards (House 1975). This environment shallowed eastwards, with reef limestones developed in the Chudleigh–Plymouth area. Further south in the Roseland area, flysch sequences and associated volcanics were deposited in a major basin (Sadler 1973). Renewed uplift of a Lower Palaeozoic source in the Bristol Channel area resulted in the alluvial influx of the Middle Devonian Hangman Group in North Devon (Tunbridge 1978), with the poorly-known Pickwell Down Beds indicating another northerly derived alluvial input in the Late Devonian. In contrast to this continuous depositional record, uplift and mild deformation took place in Wales during the Middle Devonian. By the Late Devonian, alluvial sites were again developed here, with local northerly directed transport directions in the Plateau Beds and Grey Grits of South Wales (Lovell 1978) again suggestive of a positive influence in the Bristol Channel area (Fig. 6).

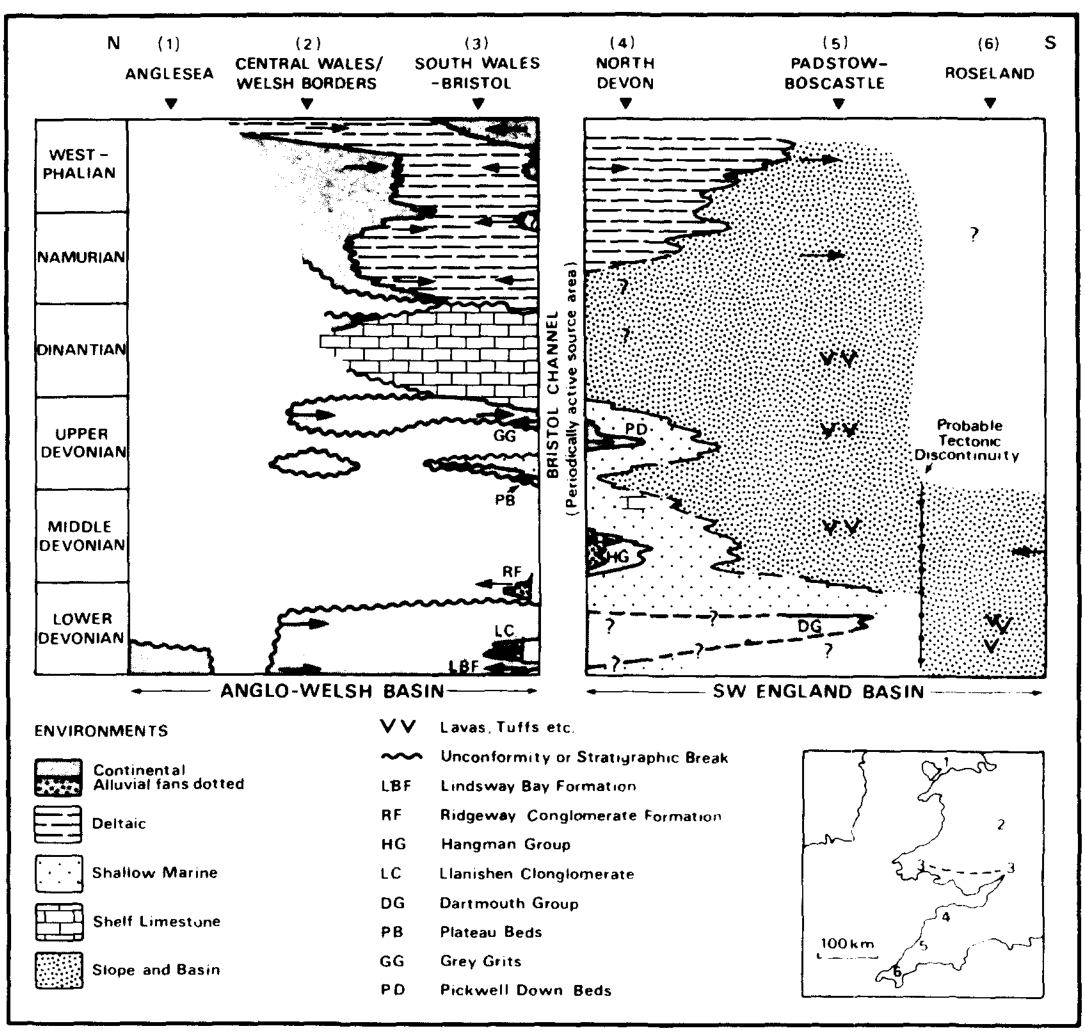

Fig. 6. Generalised environmental interpretations of the Devonian and Carboniferous successions of Wales and Southwest England. Many of the lateral correlations are uncertain. Data mainly from Burne & Moore (1971), Kelling (1974), House (1975) and Allen (1979). Other sources cited in text. Arrows indicate generalised sediment transport directions towards the north or south.

Marine transgression occurred over South Wales in latest Devonian times, with the subsequent establishment of a carbonate shelf that extended over the Bristol-Mendip area and persisted throughout the Dinantian. In contrast, progressive deepening and deposition of relatively deep-water condensed sequences continued at this time in North Devon and central Southwest England (Edmonds *et al.* 1975). Uplift in the Bristol Channel area again took place in the Namurian, and from then until the end of the Westphalian a positive welt apparently existed, separating two depositional basins (Fig. 6). In South Wales a sub-Namurian unconformity was succeeded by a fluctuating deltaic succession receiving centripetal fluvial input during this time (Kelling 1974). In central Southwest England, basinal sequences (Crackington Formation) continued to be deposited during the Namurian, with overlying Westphalian successions showing basin infilling via submarine fan complexes (Anderton *et al.* 1979). These pass laterally in North Devon into deltaic sequences (Burne & Moore 1971) which show evidence of northerly derivation and intermittent southward progradation (De Raaf *et al.* 1965). K–Ar dates further to the south indicate that northerly migrating deformation and uplift took place during the Carboniferous (Dodson & Rex 1971).

A striking feature of the Late Palaeozoic history of the region is the occurrence of repeated movement in the Bristol Channel area. Although the presence of a source area here in the Middle Devonian and Late Carboniferous has been recognised by previous workers (cf. Anderton *et al.* 1979), the marked lateral environment contrasts across this structural line indicate that it separated two entirely different depositional provinces throughout most of the Late Palaeozoic, a feature not previously recognised. To the north (Wales–Bristol–Mendips) was a complex, structurally unstable basin/platform province with an interrupted depositional record, while after the Early Devonian Southwest England was a basin and basin margin province with no obvious depositional discontinuities. The two provinces appear unrelated except at the level of the lower and upper Late Devonian transgressive pulses (Fig. 6), and for much of the Late Palaeozoic they apparently existed as separate depositional basins.

It is here suggested that differential movement along the Bristol Channel area was more profound than previously realised. Localised uplift of Lower Palaeozoic or Precambrian source rocks resulted in a detrital supply to the north in the Early Devonian (Allen 1975, Williams 1978), to the south in the Middle Devonian (Tunbridge 1976, 1978), and probably also locally in the Late Devonian, although at this stage the transgressive episodes indicate that the Bristol Channel landmass was essentially bevelled. In the Dinantian the structural boundary probably demarcated shelf from basinal sequences, while in the Late Namurian and Westphalian a rejuvenated source area in the Bristol Channel supplied sediment from older Carboniferous sequences both to the north and south (Kelling 1974). From this evidence it seems plausible to infer that a major Late Palaeozoic structural lineament existed in the Bristol Channel area, probably as a fault plexus composed of both basin and source bounding faults along which there was repeated differential movement or uplift of basement blocks.

It would seem that this Bristol Channel lineament zone marked the northern boundary of the Variscan trough of Southwest England, with sediment supplied essentially from spasmodic source areas in the Bristol Channel sector rather than from the alluvial hinterlands of Wales. If correct, this would have severely limited the amount of northerly derived clastic material available for deposition in the trough, and offers a possible explanation for the condensed 'bathyal lull' (Goldring 1962) marine sequences deposited during the Middle Devonian–Early Carboniferous in Southwest England. A further contributing factor may have been the trapping of clastic material behind active faults downthrowing to the north in the North Devon area (Matthews *et al.* 1980). On the model proposed here, it would seem that sediment derived from Welsh source areas was largely ponded against uplifted ridges in the Bristol Channel area.

Southern Ireland–Celtic Sea area

The variscan history of the onshore area reflects the presence of two major basins which experienced repeated relative and internal differential movement (Gardiner & MacCarthy 1981). These are the Dingle–Shannon and Munster Basins, separated by a now partially overthrust, intermittently positive welt along the South Ireland Lineament and flanked to the east by the Leinster Massif (Fig. 5). It was suggested by Gardiner & MacCarthy (1981) that the Munster Basin was bordered to the south by a platform area, here termed the Celtic Sea Platform (Fig. 7, inset), the boundary contact being along the structurally active Wexford Boundary Lineament. Further evidence for this is available from the scanty dated offshore data, which has been projected onto the sedimentary facies diagram in Fig. 7.

Early Devonian strata (Van der Zwan 1980) are only known in the Dingle–Shannon Basin, where the Dingle Group represents on alluvial-basin infill derived from both lateral and axial sources (Horne pers. comm., Gardiner 1975b). Following Acadian deformation this was succeeded by the localised Caherbla Group of presumed Middle Devonian age (Gardiner & MacCarthy 1981) that contains clasts derived from an upthrust metamorphic source ridge to the south (Horne 1975) sited along the South Ireland Lineament. By this time the Munster Basin was apparently established (Clayton & Graham 1975, Van Veen & Van der Zwan 1980), and its subsequent Devonian record suggests a pattern of continued subsidence, with the thickest sequences being preserved in the basin centre. In the axial region of this basin (Fig. 7) there was consistent sediment transport from the north, with alluvial fan incursions occurring after Late Devonian upland rejuvenation to the north of the South Ireland Lineament. During subsequent alluvial retreat the site of the Dingle–Shannon Basin became a stable platform area blanketed by northerly derived alluvium that spread in to the Munster Basin. The southern margin of the Munster Basin is not exposed onshore, but evidence for a southerly source area is locally shown by the Sherkin Formation (Graham & Reilly 1972), while Late Devonian lateral facies changes indicate a southerly rising depositional floor (Reilly & Graham 1976). Proximal continental sediments and tuffs of probable Frasnian age have been recorded from the Elf Well 55/30-1 on the Celtic Sea Platform (Robinson *et al.* 1981), indicating that this region was both emergent and at least a local source area in the Late Devonian. In contrast, further south in the Haig Fras area the occurrence of presumed Devonian shales (Smith *et al.* 1965) reflects the presence of a marine basin at some stage during the Devonian.

In Dinantian times shelf carbonate facies were established over the Dingle–Shannon Basin, and in view of the Late Tournaisian shelf limestones recorded from Cities-Service Well 63/4-1 (Robinson *et al.* 1981), also at least locally on the Celtic Platform. Marine shelf facies dated as Tournaisian (Higgs, pers. comm.) are also present in Esso/Marathon Well 48/30-1, indicating stable platform conditions over the Celtic Platform at this time. In contrast, the axial part of the Munster Basin underwent repeated subsidence, resulting in the deposition of an axially-located multiple deltaic prism in Latest Devonian and Early Dinantian times. This prism was bounded to the south by relatively condensed shelf or prodelta sequences (Gardiner & MacCarthy 1981). That the Celtic Sea Platform was however at least intermittently a source area is indicated by southerly derived clasts of presumed metamorphic provenance in the deltaic sequences of the Cork Harbour area at this time (MacCarthy *et al.* 1971). Further axial subsidence in the Munster Basin during the Dinantian resulted in the establishment of a deep-water basin with intermittent turbidite influxes (Naylor *et al.* 1974, Jones 1974). After Pre-Namurian basin reactivation in the Dingle–Shannon Basin (Hodson & Lewarne 1961) deep-water muddy sequences accumulated in both basins, with some evidence for a positive welt sited along the South Ireland Lineament in *Homoceras* times (Hodson 1959). Similar basinal conditions probably also existed over the Celtic Platform, because a mud-dominant marine sequence dated as E1-E2$_b$ (Higgs, pers. comm.)

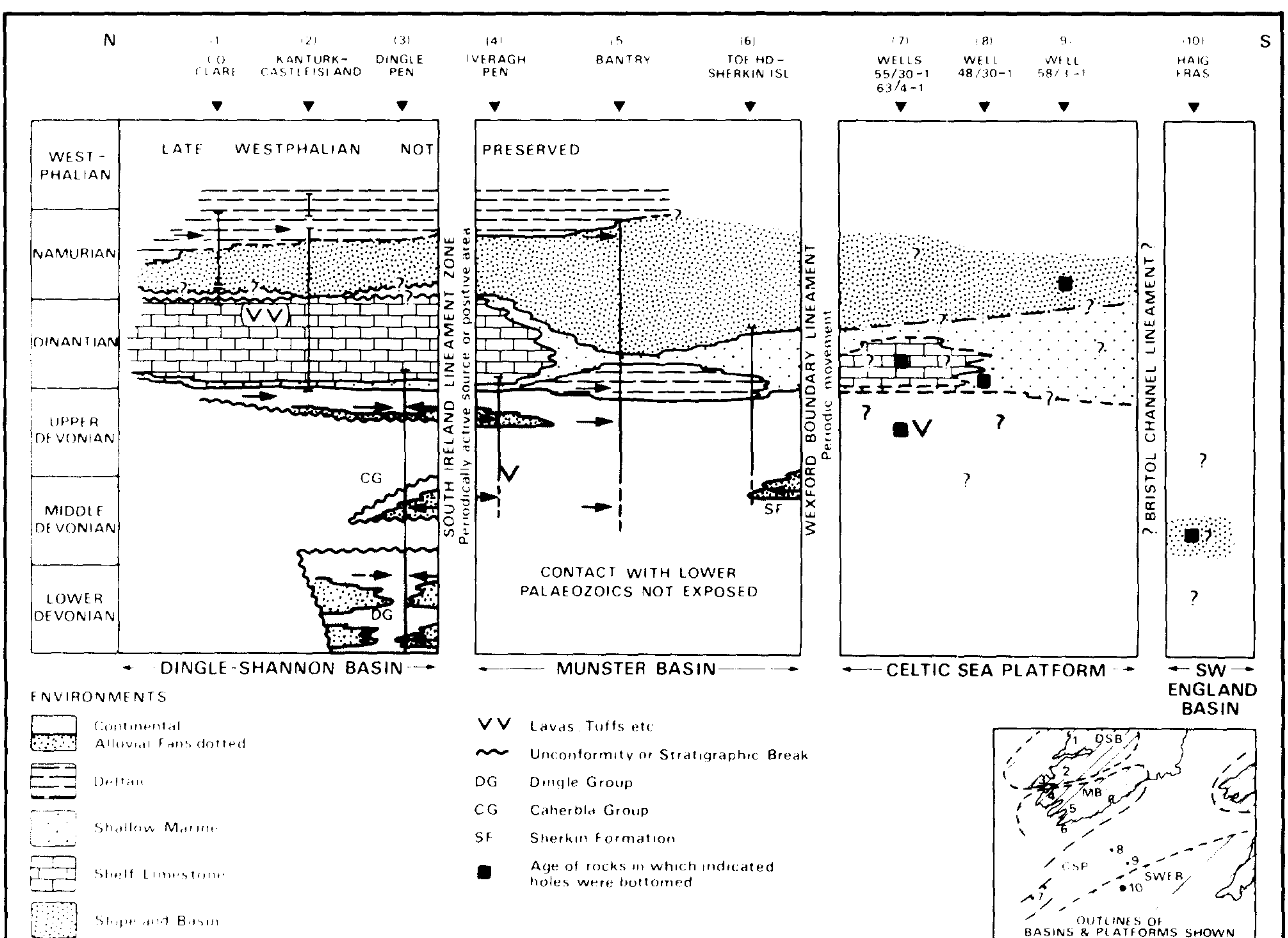

Fig. 7. Generalised environmental interpretations of the Devonian and Carboniferous successions of Southwest Ireland and the Celtic Sea area. On shore data and interpretation from Gardiner & MacCarthy (1981). Lower and Middle Devonian correlations uncertain. Vertical lines indicate chronostratigraphical limits of exposure in cited sections (lines broken where age uncertain). Data for Cities-Service Well 63/4-1 and Elf Well 55/30-1 from Robinson *et al.* (1981). The Early Dinantian age for sediments from the Esso/Marathon Well 48/30-1 and the Early Namurian age for sediments from the Marathon Well 58/3-1 are those of Higgs (pers. comm.). Arrows indicate generalised sediment transport directions towards the north or south.

was encountered in Marathon Well 58/3-1 (Fig. 7). During the Namurian southeasterly prograding sub-sea fans gradually filled the Dingle–Shannon Basin, with the subsequent establishment of deltaic conditions (Rider 1974) that persisted into the Westphalian. This clastic wedge apparently spread southwards into the Munster Basin because northerly derived Late Namurian sequences (Naylor *et al.* 1978) at Bantry (Fig. 7) have an upward-shallowing trend.

Although the offshore data are tantalisingly limited, the Munster Basin emerges as a structurally bounded localised depositional trough. There is no good evidence to support the view (Naylor & Jones 1967, Naylor *et al.* 1974, Matthews 1977a) that it passed southwards during the Devonian and Early Carboniferous into the progressively deeper-marine environments of the Variscan trough. The onshore evidence concerning the depositional history of the basin suggests that it was flanked to the south by an emergent or relatively positive stable area. This is supported by the off-shore information, which indicates that continental conditions existed in this area in the Late Devonian, and that it was at least in part a stable marine shelf in the Early Carboniferous. Only to the south of the Celtic Sea Platform is there any evidence for a marine Variscan trough in Devonian times. It would appear that the coastal margin of this trough was probably situated, until at least the late Dinantian, along the southern side of the Celtic Sea Platform, rather than off the present day south coast of Ireland.

Regional comparisons

Gross similarities in the depositional record exist between the 'foreland' successions of the Anglo-Welsh and Dingle–Shannon Basins, both also being flanked to the south by inferred lineaments that contained periodically upthrust fault blocks. No comparable pattern is evident between the Munster and Southwest England Basins. The former apparently existed as a continental graben in the Devonian and as a localised marine basin in the early Carboniferous. During this period it was bordered to the south by a stable positive area (Celtic Sea Platform). In contrast, the Southwest England Basin in post-Early Devonian times existed as a major south-facing marine basin containing both flysch and condensed sequences with some evidence of northerly migrating depocentres (Matthews 1977b), and characterised by periods of submarine volcanicity. The apparent similarities between the marginal sequences of these two basins as noted by Naylor *et al.* (1974) and others may merely reflect a similar inherited structural setting, as is also the situation with respect to the Anglo-Welsh and Dingle–Shannon Basins. These responses to tectonic stimulae may be related to the regional tensional influence of mantle processes on the pre-existing structural framework of this area of continental crust (Bott 1964, Leeder 1976), with resultant comparable syndepositional movements along different basin margins.

DISCUSSION

The structural evidence presented above indicates that on a regional scale the Variscan structures have an arcuate trend, swinging from E–W to WSW–ENE in a westerly direction as far as the continental margin. Southern Ireland is therefore not a lateral structural correlative of the South Wales–Cornwall section as envisaged by, for example, Dunning (1966, 1977) and Matthews (1974, 1977a). Instead, there appear to be three separate tectonic provinces aligned en échelon across the structural grain. The Southwest England province, with complex polyphase deformation; the South Wales–Mendips foreland province, where the laterally variable cover thickness shows basement control with upright folds and locally severe thrusting; and the Southern Ireland basin province, with major upright folds showing a convergent axial plane fan and northerly directed thrusting along the margins of bounding massifs. These contrasts are thought to be due to the role of basement massifs during the Variscan orogeny. The WNW–ESE alignment of fold trends in the northern part of South Pembrokeshire may reflect local basement controls, while the fanned fold profiles in this area, together with the opposed facing directions on either side of the Bristol Channel (Fig. 4), suggest the possibility of a basement high which influenced the deformation pattern.

The Variscan depositional record affords further confirmation of the en échelon pattern of provinces. The Munster Basin of Southern Ireland is clearly not a lateral analogue of the Southwest England Basin. The presence of presumed Devonian shales in the Haig Fras area (Smith *et al.* 1965) and Middle Devonian shales and slates on the South Goban Spur (Dingle & Scrutton 1979) suggest that laterally comparable facies to the Southwest England Basin existed to the west-southwest and were bounded by the southern flank of the Celtic Sea Platform. The occurrence of granites and basic igneous rocks in these areas is also comparable with the situation in the Southwest England Basin. The Celtic Sea Platform can therefore reasonably be considered as a westerly extension of the Wales–Mendips foreland province. In view of the syndepositional role played by the Bristol Channel Lineament, it is thought to have been a laterally extensive structural line that demarcated the southern margin of this province. This accords with the view of Dunning (1964), who suggested that the Cannington Thrust marked the northern limit of the Variscan geosyncline. Significantly, the available evidence indicates that the structural provinces recognised here match with the depositional framework.

In a Western European context the depositional affinities of the Southwest England Basin with other areas of the Rheno-Hercynian Zone (i.e. the Ardennes, Siegerland etc.) is well established (Goldring 1962, Dunning 1977, Matthews 1977b). Local differences have been ascribed to the fault controlled character of the basin in Southwest England (Matthews *et al.* 1980). In depositional terms therefore, this Variscan trough probably extended as a major geotectonic entity as far west as South

Goban Spur, even though individual depocentres may have been laterally discontinuous in space and time (cf. Anderton *et al.* 1979).

By integrating the structural and depositional evidence the following model for the Variscan foldbelt in the Celtic Sea and adjacent areas is proposed (Fig. 8). The Rheno-Hercynian Zone consists of the Southwest England Basin and its inferred lateral correlatives in the Haig Fras and South Goban Spur areas, and hence arcs in a WSW direction rather than WNW towards southern Ireland. The northern boundary of the zone, and by definition the Variscan Front, was located along the southern margin of the Bristol Channel Lineament. It is suggested that this lineament was a laterally continuous major tectonic boundary that underwent repeated reactivation. As a result, the modern expression of the front demarcates the northern margin of the Cornubian Platform as a major disjointed fault line that can be traced for some 400 km to the west of the Bristol Channel (Fig. 3). The Goban Fault, astride the continental margin, may be a rejuvenated lateral continuation. On this model the Cannington Thrust (Fig. 3) marks the easterly trace of the front, as suggested by Von Gaertner (1969) and Ramsbottom (1970). The front was flanked to the north by the pre-existing massif of the Celtic Sea–Wales Platform, which acted as a complex faulted platform/basin province during the Late Palaeozoic. It is also suggested that the localised depositional and structural nature of the Munster Basin of southern Ireland should be recognised as a separate entity of the Variscan foldbelt and termed the Southern Ireland Zone. On this basis, the Variscan Front is defined as the northern boundary of the Rheno-Hercynian Zone, but it does not mark the northern limit of orogenic deformation.

This model supplies a satisfactory rationale for the hitherto anomalous features of the Variscan foldbelt in this region. There is good agreement between major facies boundaries and major structural elements, unlike that envisaged in earlier proposals (cf. Dunning 1977). The model also reveals an accurate northern boundary to the Rheno-Hercynian Zone. This accords, on a pre-Permian reconstruction, with the sheared and structurally complex (Lefort 1979, Gaspais & Le Corre 1980) but grossly arcuate character (Fig. 9) of Variscan structural zones in Europe and the distribution of Variscan granites (Ries 1979) rather than the divergent situation conventionally depicted on maps. It also removes the problem of defining the front by the arbitrary choice of thrust faults. These may only reflect the local tectonic response to compression against shallow basement that contains complex pre-existing fractures. This study postulates that the Variscan structural framework was inherited from Caledonian precursors. These apparently also controlled the Mesozoic structural setting, because the sites of the Celtic Sea and Bristol Channel basins are compatible with an initial opening phase along the Bristol Channel and Wexford Boundary Lineaments (Fig. 3).

CONCLUSIONS

(1) Basement reactivation during the Mesozoic in the Celtic Sea area was along WSW–ENE Caledonian structural trends, with no evidence of WNW–ESE Variscan structural influence. Basin initiation may have occurred along pre-existing lineaments.

(2) Variscan fold trends are essentially controlled by the orientations of boundaries of basement massifs.

(3) There is no evidence for Variscan structural continuity between Southwest Wales and Southern Ireland.

(4) Late Palaeozoic deposition in the Southwest British Isles was influenced by earlier Caledonoid lineaments. The Celtic Sea–Wales Massif acted as a positive ridge, separating the ensialic Southern Ireland Munster Basin from the orthotectonic sequence of Southwest Britain.

(5) Variscan facies patterns and deformation trends in the Rheno-Hercynian foldbelt were primarily controlled by the southern margins of the Celtic Sea–Wales and Brabant Massifs.

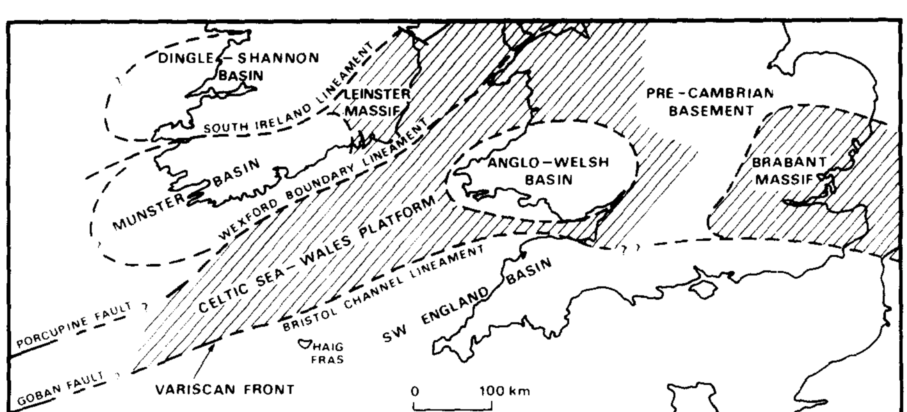

Fig. 8. Proposed Variscan geotectonic framework in the Celtic Sea and adjacent areas. Platforms and basement massifs are shaded. The outlines of basins are schematic and varied with time. Data from Dunning (1977), Gardiner & MacCarthy (1981) and this paper.

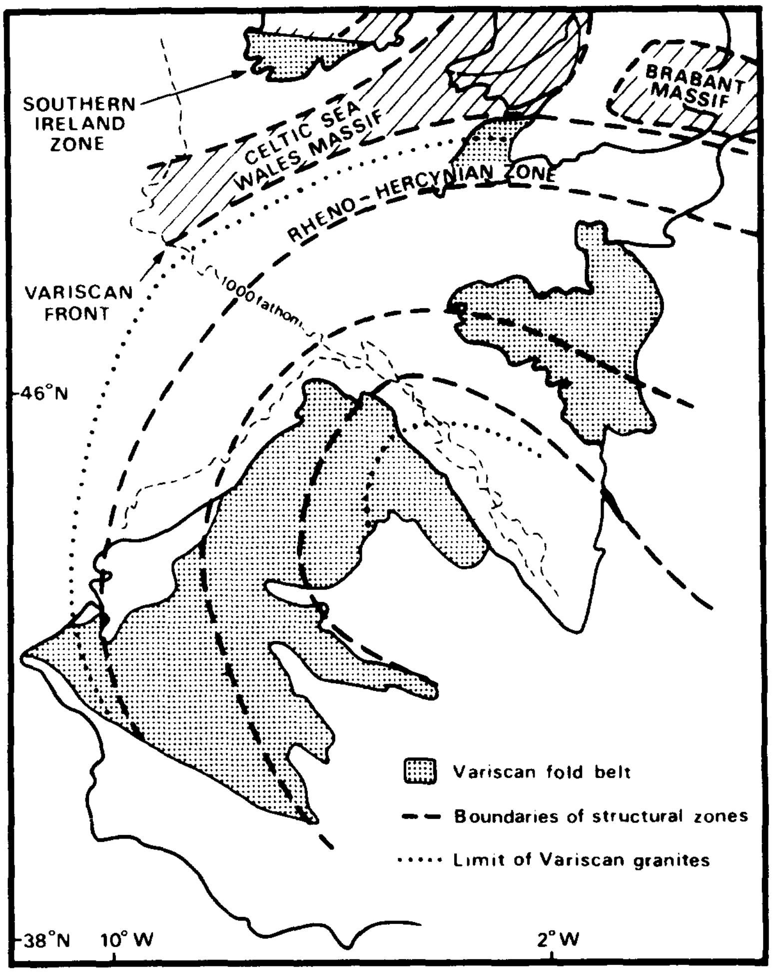

Fig. 9. Suggested location of the Rheno-Hercynian foldbelt and its relationship to other Variscan structural zones in the Celtic Sea and adjacent areas. The palaeogeographical reconstruction, the location of the Variscan structural zones in the European mainland, and the limits of Variscan granites are after Zwart & Dornsiepen (1978) and Ries (1979). Pre-Variscan basement massifs are shaded.

(6) The Variscan Front can be satisfactorily recognised if it is taken as the northern boundary of the deformed orthotectonic sequence of the Rheno-Hercynian Zone. This is marked by the arcuate Bristol Channel Lineament which flanks the Celtic Sea–Wales Massif. Variscan granites occur only to the south of this line (Ries 1979), which can be extrapolated southwestwards towards southern Spain in conformity with the other structural zones in the Variscan foldbelt.

(7) To the north of the redefined Variscan Front, Variscan deformation reflects localised basement control allied with lithological variations in a series of disconnected basins.

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