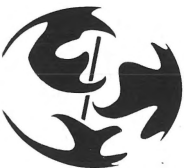


VARISCAN STRUCTURES IN SOUTHWEST WALES¹

P. L. HANCOCK², W. M. DUNNE² & M. E. TRINGHAM³



ABSTRACT

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Palaeozoic rocks in the Variscan domain of SW Dyfed, Wales, were deformed under anchimeta-morphic conditions during the late Carboniferous. Within the Pembrokeshire Coalfield a 1 km wide zone of conjugate folds and thrusts, external to the northern limit of slaty cleavage, is used to define the Variscan orogenic front. South of the front there is a progressive increase in the average amplitude of macrofolds across three further structural zones. Folding about a WNW axial trend was single phase except within a few narrow belts of refolded folds. Wrench and normal faults which developed during and after folding resulted in the axial elongation and clockwise rotation of the region.

Structures in the paratectonic Caledonides controlled the locations of four WSW trending Disturbance Belts of Variscan age to the north of the front. In the Druidston Haven Horst, the westernmost of these Disturbances, Caledonian folds and cleavage were refolded approximately coaxially during the Variscan.

The Variscan fold belt is cut by several, laterally impersistent, major strike faults which can not be regarded as separating allochthonous blocks. Although displacements were dominantly reverse or normal the evolution of the faults during folding probably involved some scissor motion. On the Johnston Thrust northward overthrusting was followed by dextral strikeslip.

INTRODUCTION

To the north of the Variscides, Precambrian and Early Palaeozoic rocks are deformed by south or south-east facing folds in the paratectonic Caledonides (Fig. 1). Weakly to strongly deformed Precambrian to Westphalian rocks are involved in the Variscan domain to the south of the Caledonides. The boundary between the two domains is a major angular unconformity. Because the segment of the fold belt which underlies SW Dyfed (formerly Pembrokeshire) is excellently exposed on three sides its structure is known in detail, and hence it provides the most suitable area within South Wales to illustrate the tectonics of the outer margin of the Variscan orogen. Early comprehensive accounts of the general geology of SW Dyfed are those of STRAHAN ET AL. (1914), CANTRILL ET AL. (1916) and DIXON (1921). Modern accounts giving stratigraphic details are those of HARRIS ET AL. (1975) for the Precambrian, ZIEGLER ET AL. (1969) and

WALMSLEY & BASSETT (1976) for the Silurian, ALLEN & WILLIAMS (1978) and FRIEND & WILLIAMS (1978) for the Old Red Sandstone, SULLIVAN (1965, 1966) for the Lower Carboniferous, and JONES (1974) and JENKINS (1962) for the Upper Carboniferous. Many of the thickness and facies contrasts, together with syntectonic sedimentary deformation structures at many levels, probably reflect early movements on proto-Variscan faults. The tectonic structures which form the subject of this account, were first reviewed in detail by HANCOCK (1973); here emphasis is given to findings which have emerged since 1973.

STRUCTURAL ZONATION

Variscan SW Dyfed is divided into two principal structural zones and four subsidiary zones (Fig. 2). Zone I is characterized by evenly distributed folds and strike faults dominantly of WNW trend, and is divided into subsidiary zones on the basis of: fold dimensions, facing directions and subordinate trends; relative cleavage development; and the geometry of the fault pattern. Significant deformation within Zone II is restricted to four WSW trending Disturbance Belts.

¹This contribution contains two enclosures.

²Department of Geology, University of Bristol, Queen's Building, University Walk, BRISTOL BS8 1TR, England.

³Esso Exploration and Production U.K., Bewater House, ESHER, Surrey KT10 9SJ, England.

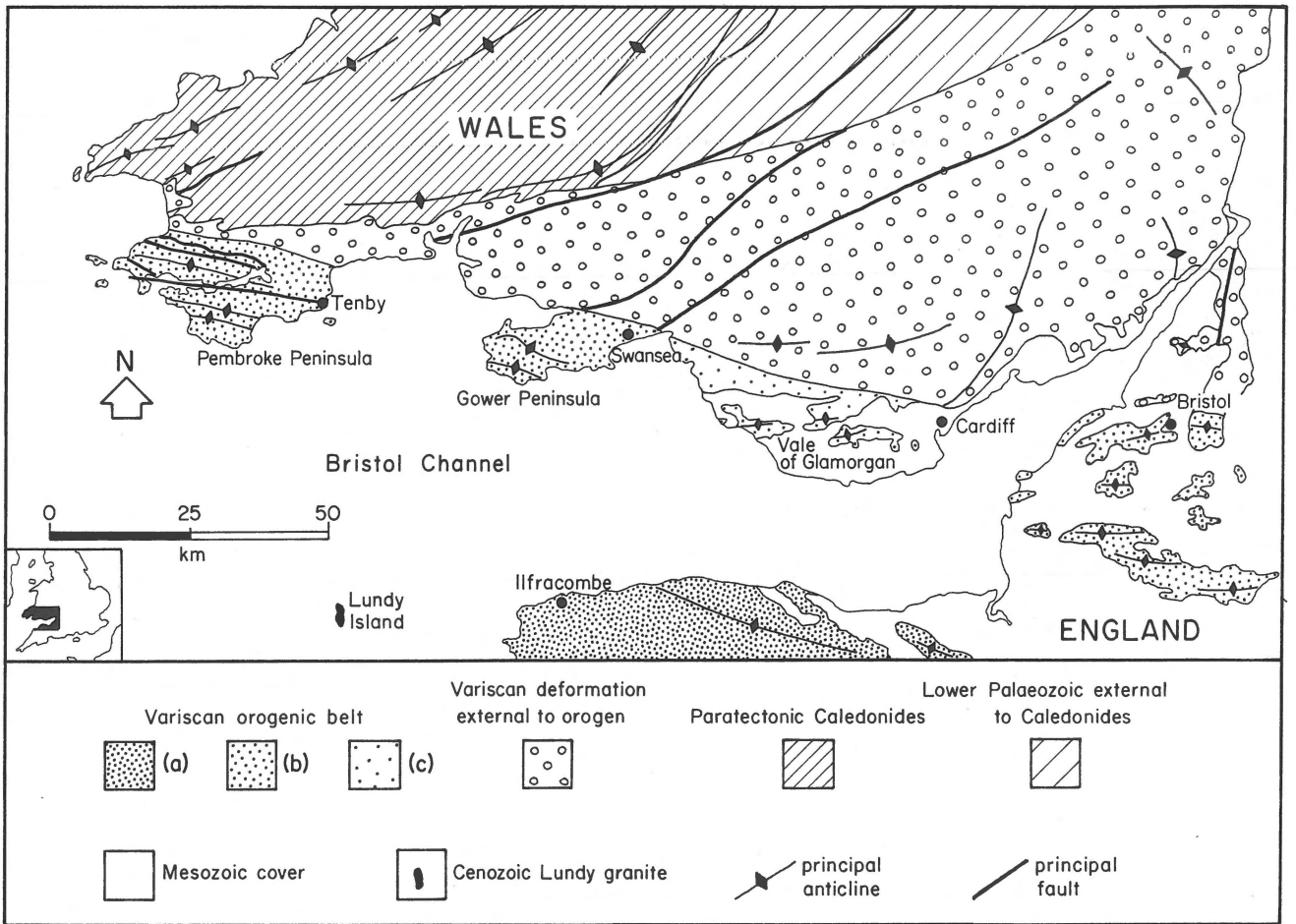


Fig. 1
Tectonic provinces in South Wales and adjacent areas of England. Within the Variscan orogenic belt Palaeozoic rocks which are strongly deformed are shown by dense stipple (a), those which are moderately to strongly deformed are depicted by intermediate density stipple (b), and those which are weakly to moderately deformed are faintly stippled (c). Modified after Dunning (1966).

Zone Ia

The zone is dominated by large-amplitude macrofolds relatively uncomplicated by parasitic mesofolds (defined here as folds of axial plane separation of less than 150 m). Axial traces principally trend WNW but there are some E-W folds (Encl. I). Hinge lines and π axes are generally subparallel and commonly plunge up to 20° east, but there are a few important west-plunging folds and some periclinal folds (Encl. I). Axial planes are upright ($80\text{--}90^\circ$) or steeply inclined ($60\text{--}80^\circ$) and in the east they are arranged in a convergent downwards fan relative to the centre line of the principal anticlinorium. In the west the facing direction is dominantly to the south (Encl. II). Some anticlines are tighter than neighbouring synclines.

Many mudstones are cut by a penetrative cleavage (S_1) arranged in convergent fans about axial planes and yielding an S_0/S_1 lineation parallel to π axes. Although cleavage is imperfectly developed in the east there are good slates in the west where strain indicators such as reduction spots, pedoge-

nic concretions and trace fossils are more flattened. S_1 spaced pressure-solution cleavage surfaces approximately normal to layering cut sandstones and limestones in the west of the zone, but are feebly developed in the east.

Although ANDERSON (1951) made SW Dyfed a classic example of the association of folds, thrusts and wrench faults, enclosure I shows that reverse strike faults are relatively uncommon in Zone Ia and that they display only minor displacements. In the east of the zone the sense of thrusting is outward and in accord with fold facing directions. The steeply inclined Ritec Fault (Encl. I and II) is commonly regarded as reverse, and according to SANZEN-BAKER (1972) it separates allochthonous blocks. Near Tenby the fault downthrows about 500 m to the north but where its outcrop enters Milford Haven the downthrow north has increased to 1000 m. The precise location of the fault trace beneath the waters of Milford Haven is unknown, but assuming it passes to the south of the Lower Old Red Sandstone rocks exposed on Stack Rock the downthrow to the north may be significantly less than 500 m (Encl. II). Where the presumed trace of the

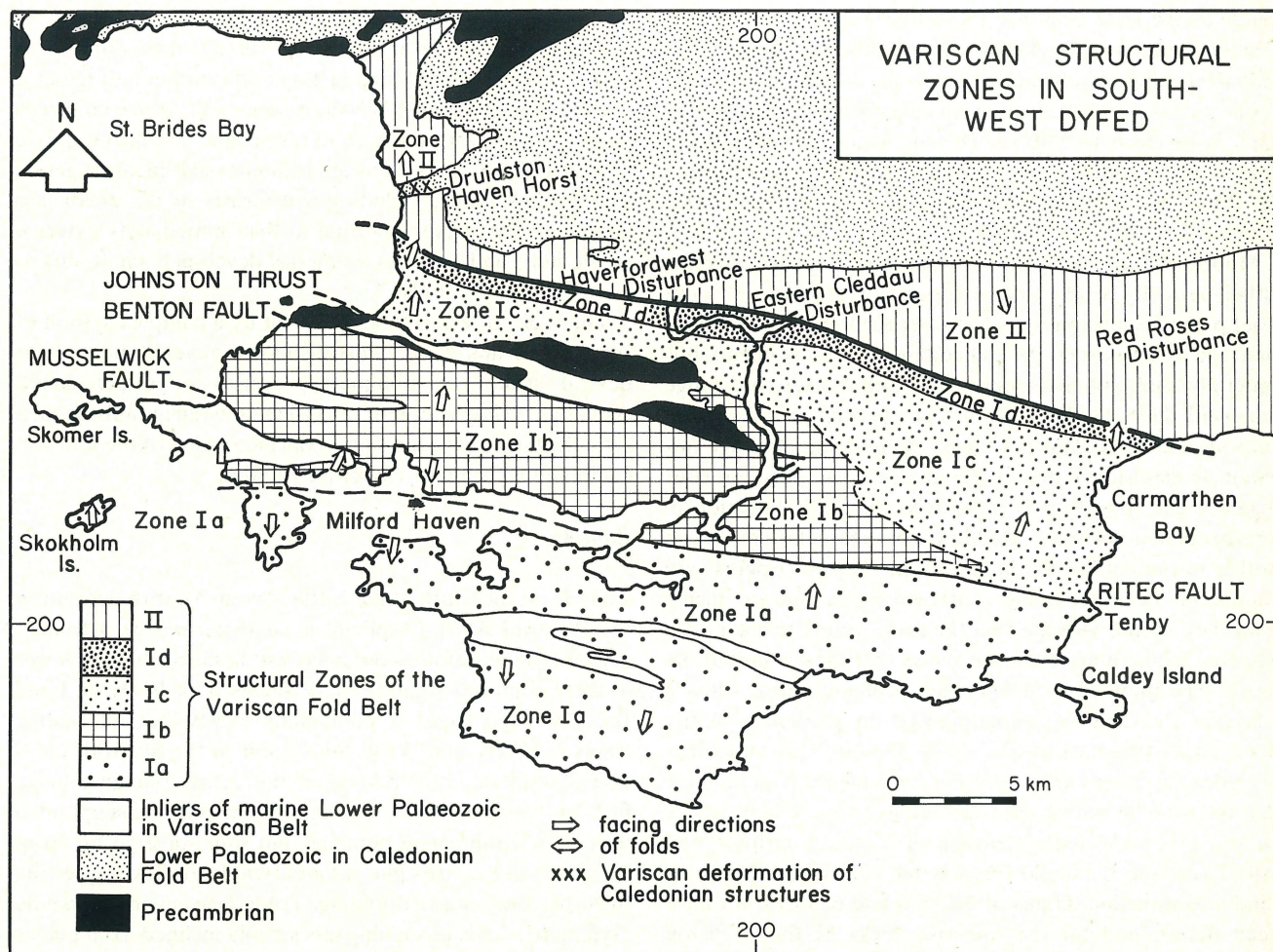


Fig. 2
Map of structural zones in Variscan SW Dyfed.

fault passes between the Dale and Marloes Peninsulas the downthrow is to the south and is less than 100 m (DUNNE, 1980). Thus it is possible to interpret the Ritec Fault as a major south-dipping, high-angle reverse fault on which translation to the north was at a maximum in the Pembroke Dock area but declined to the east and west, so that in the extreme west the rocks of the hanging-wall were lagging behind those of the footwall.

Some folds and minor thrusts are displaced by conjugate wrench faults symmetrically arranged about fold axial traces. Because the aggregate displacement on the NNW trending dextral faults exceeds that on the NE trending sinistral faults the development of the system between Pembroke Dock and Tenby involved about 5° of clockwise rotation in addition to about 10% of axial elongation. Small, adjacent, conjugate wrench faults are orientated so that the acute bisector between them is normal to the axial plane of the host fold and the obtuse bisector is parallel to its π axis. Most wrench faults are younger than the folds which they displace but some developed during the closing stages of folding. The presence

of a wrench-fault system symmetrically orientated about folds is a distinctive feature of Zone Ia. Conjugate normal faults striking at right angles to axial traces occur only in the extreme west of the zone.

The unconformity separating the marine Silurian from the Old Red Sandstone involves little angular discordance (ALLEN & WILLIAMS, 1978), and identical suites of mesostructures are present in the two groups of rocks. The underlying Llanvirnian shales are deformed by numerous small folds which may be accommodation structures in the core of the principal anticlinorium.

Zone Ib

Attitudes and styles of structures are more variable than in Zone Ia and macrofolds of smaller amplitude are complicated by abundant mesofolds (Encl. II). North of the Musselwick Fault the principal folds are the six anticlines belonging to the Winsle-Carew system (DUNNE, 1980). They plunge 30-70° ESE except in the extreme west where the plunge is

gentle to the west. South of the Musselwick Fault the moderately SE plunging Marloes-Lindsway anticline, the northern limb of which is largely faulted out, is the dominant structure. Axial planes are generally steep and face north except in local belts close to Milford Haven. Small macrofolds and congruent asymmetric mesofolds are abundant except within the Marloes-Lindsway anticline and part of the Winsle anticline.

Mudstones are cut by an S_1 penetrative cleavage which is either perfectly axial plane or forms convergent fans about axial planes. Sandstones are cut by spaced pressure-solution cleavage surfaces at 60-90° to bedding. The S_0/S_1 lineation is generally subparallel to hinge lines and π axes, but hinge lines and the S_0/S_1 lineation are not coaxial in a few folds (DUNNE, 1980). At Marloes Sands the bedding-cleavage lineation in sandstones bisects the obtuse angle between conjugate shear zones but is oblique to the S_0/S_1 lineation in interbedded mudstones. Bedding/cleavage relationships in profile in part of the Skomer Volcanic Group (Encl. I) are anomalous because, being contained in an upward facing fold, they should indicate that the rocks young to the north, whereas sedimentary evidence shows that they young to the south. The anomalous relationship probably arose when a Variscan cleavage was superimposed on previously gently tilted rocks (GRAHAM ET AL., 1977). Despite this and other evidence for minor intra-Silurian movements it is unlikely that the zone lay within the Caledonian orogenic belt (ALLEN ET AL., 1976). A single cleavage of Variscan attitude and aspect cuts the Llandeilo Flags in the core of the Marloes-Lindsway anticline. Dates of 650-570 and 625-613 Ma have been determined for the intrusive rocks of the Johnston complex (PATCHETT & JOCELYN, 1979) and the Benton Volcanic Group (HARRIS ET AL., 1975) respectively. These Cadomian rocks crop out only within the Benton-Johnston fault block.

The Musselwick Fault dips steeply south, and in the west achieves a substantial downthrow to the north as a consequence of components of reverse and sinistral slip. Remapping of the Sandy Haven region by DUNNE (1980) shows that the Musselwick Fault does not enter Milford Haven as proposed by SANZEN-BAKER (1972). The Benton Fault is also inclined to the south and on St. Brides Bay separates Precambrian rocks in the footwall from the Milford Haven Group in the hanging wall (Encl. II). About 20 km to the east, the Benton Fault separates the Milford Haven Group from the Cosheston Group. At both localities the displacement is normal and the downthrow to the south is in excess of 1000 m. Most earlier accounts of the fault described it as reverse. Stratigraphic contrasts across the Benton Fault suggest that throughout much of the Palaeozoic it controlled sedimentation. To satisfy the demands of her model of allochthonous blocks SANZEN-BAKER (1972) projects the Benton Fault as a Variscan structure through the Coalfield. However, in the well-exposed Carmarthen Bay section the Late Carboniferous rocks are not cut by a major strike fault

on-line with the Benton Fault (TRINGHAM, 1979).

A distinctive style of fault zone, restricted to Zone Ib, is well displayed in the Longoar Bay deformation belt (Encl. I and II). The 50 m wide WNW trending belt, which coincides approximately with the core of a syncline, comprises a zone in which: the S_1 slaty cleavage is intense and inclined gently south; small faults, including overthrusts to the north, are abundant; the strike is normal to that immediately external to the belt; and local refolding has developed small, downward facing kink folds.

The rocks of Zone Ib are also cut by a complex system of small strike and cross faults displaying reverse, normal, or dextral strike- or oblique-slip senses of displacement. Although a simple system of conjugate wrench faults is missing, the faults achieved some axial elongation of the fold belt combined with minor clockwise rotation.

Zone Ic

Zone Ic, in the south of the Little Haven-Amroth division of the Pembrokeshire Coalfield, is characterised by abundant asymmetric mesofolds contained within macrofolds of lower average amplitude than those of Zones Ia or Ib (Encl. I and II). The axial trend is dominantly WNW but alternating trains of WNW and WSW folds occur in the St. Brides section (TRINGHAM, 1979). Most of the gently plunging hinge lines of the impermanent, non-cylindrical folds are subparallel to π axes within small domains, but some diverge by up to 20°, and some π axes plot on great-circle girdles, suggesting that there was local refolding. Folds face north, markedly asymmetric folds possessing less steeply inclined axial planes than nearly symmetric folds. Chevron folds deform sequences comprising thin alternating layers of sandstone and mudstone but folds of parallel style are characteristic of massive sandstones. Channel sandstones or synsedimentary folds are deformed by tectonic folds of complex geometry (TRINGHAM, 1979).

A regional S_1 axial-plane slaty cleavage cuts Namurian mudstones near Tenby, but elsewhere a penetrative cleavage is restricted to mudstones in fold cores, and it dies out south of the northern margin of the zone. Sandstones and freshwater limestones are cut by a spaced pressure-solution cleavage nearly normal to beds and giving an S_0/S_1 lineation parallel to π axes but oblique to some hinge lines.

Strike faults include low-angle overthrusts with a sense of transport to the north, high-angle reverse faults, and moderate- to high-angle normal faults. Because some thrust surfaces are curved it is likely that thrusting and folding were partly contemporaneous. The high-angle normal faults are younger than the folds.

The southern boundary of the zone in the west is the Johnston Thrust, a 100 m wide fault zone inclined gently south, along which translation of the Precambrian Johnston complex over the Late Carboniferous rocks probably exceeded 3 km (Encl. II). Immediately east of the Cleddau the

effects of the Johnston Thrust zone are dispersed throughout subordinate faults (Encl. I) while in the Carmarthen Bay section there is little evidence to support the idea that a thrust achieving a substantial displacement intersects the coast (TRINGHAM, 1979). Such an eastward extension of the Johnston Thrust zone is demanded by SANZEN-BAKER's (1972) model of allochthonous blocks.

In the St.Brides section the Johnston Thrust zone comprises three fault-bounded units which TRINGHAM (1979) proposed evolved in the following sequence:

- D₁ regional development of E-W trending, north facing folds and S₁ cleavage in the northern unit in continuity with the remainder of the Coalfield;
- D₂ local folding about NW-SE axes in the central unit;
- D₃ development of an S₂ cleavage in the southern unit and juxtaposition of the central and southern units;
- D₄ folding about SSW plunging axes in the southern unit during dextral displacements on the Johnston zone, folds in the central unit are refolded and thrusts and cleavage in the southern unit are deformed.

Cross faults, including conjugate normal faults and dextral strike-slip or oblique-slip faults partition the folds and strike faults of the zone. In the south they strike NNW at right angles to most axial traces but towards the north the strike swings to become NE-SW (Encl. I). The bulk strain achieved by the development of the cross fault system involved components of axial elongation and clockwise rotation.

Zone Id

The approximately 1 km wide zone is exposed entirely within the central part of the Little Haven-Amroth Coalfield (Fig. 2). It is characterized by WNW trending conjugate folds accompanied by thrusts which show displacements in accord with the sense of facing of the fold which they cut (Encl. II). In the Carmarthen Bay section the zone is represented by a single conjugate macrofold but in the St.Brides section there are several smaller conjugate macrofolds (TRINGHAM, 1979). Although a penetrative cleavage in mudstones is absent, an S₁ spaced cleavage in sandstones persists throughout the zone. Conjugate high-angle normal cross faults striking NE-SW cut the folds.

Zone II

Throughout much of the zone rocks dip uniformly south except in four WSW Disturbance Belts which are more widely separated in the east than the west (Fig. 2). The Red Roses Disturbance comprises a south facing, WSW plunging macrofold couplet and associated strike faults. Mudstones in the Old Red Sandstone within the Disturbance are cut by a feeble S₁ cleavage dipping steeply south. The Eastern Cledau and Haverfordwest Disturbances are principally fault zones, but also contain folds superimposed coaxially but not coincidentally on Caledonian orogenic structures.

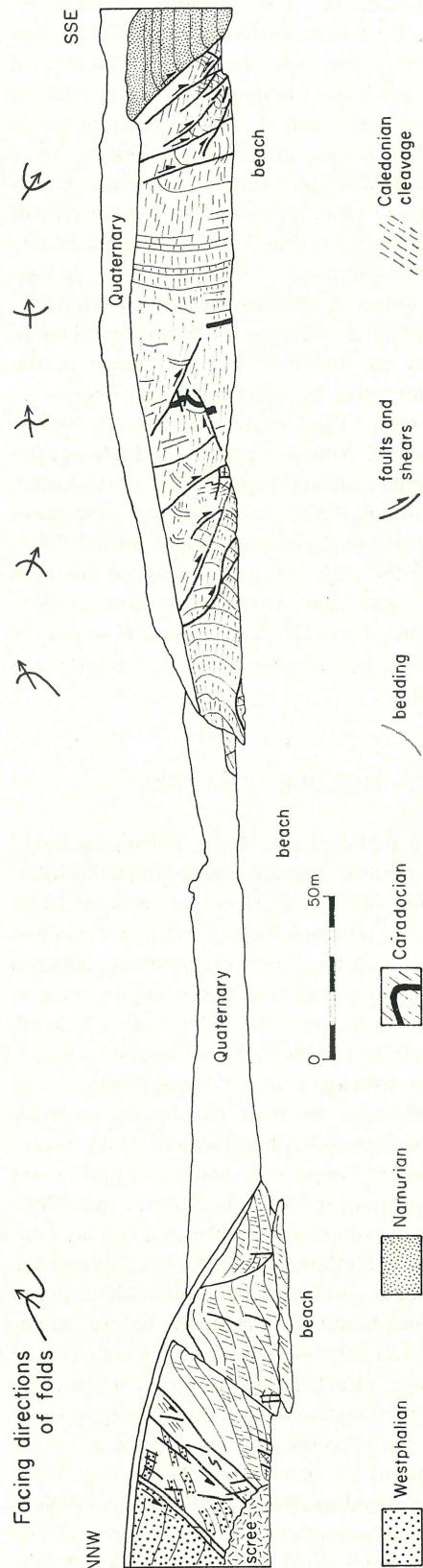


Fig. 3 Structural profile through the Druidston Haven Horst to show the influence of Variscan deformation on Caledonian structures.

As a consequence of being well-exposed in a 400 m section, the Caradocian rocks in the Druidston Haven Horst, bounded by normal faults in the westernmost Disturbance, allow the influence of Variscan deformation on Caledonian orogenic structures to be assessed. The principal Caledonian structure is the core of a WSW trending south facing anticline cut by an axial-plane slaty cleavage. The northern limb was only weakly deformed during the Variscan, but the steep southern limb was refolded approximately coaxially, resulting in the development of four narrow belts of either recumbent or downward facing folds (Fig. 3). The Caledonian slaty cleavage was deformed into open antiforms and synforms and the whole assemblage cut by normal faults downthrowing south. Quartz/carbonate dip veins in the northern limb of the Caledonian fold are undeformed while those in the southern limb are deformed by millimetric-scale folds.

About 300 m north of the Druidston Haven Horst, the Westphalian rocks of the Nolton-Newgale Coalfield are deformed by an anticlinal-synclinal pair of open, north-facing, west-plunging macrofolds. An S_1 spaced cleavage in sandstones persists to the north of these folds. Minor normal faults striking NE-SW cut the rocks of the zone whose northern boundary is the Newgale Fault with a downthrow south in excess of 1200 m (Encl. I and II). As enclosure II shows the Nolton-Newgale Coalfield forms a graben where it intersects the St. Brides Bay coast.

AGE OF THE DEFORMATION

Relationships between the marine Early Palaeozoic rocks and the Old Red Sandstone indicate that south of the Johnston Thrust the region did not experience late Silurian Caledonian orogenic folding although it was unstable for much of the early Palaeozoic, and there is a major break between Ordovician and Silurian sequences. The southern limit of Caledonian orogenic structures is probably buried beneath the Little Haven-Amroth Coalfield. The youngest rocks deformed by Variscan structures are of Westphalian D age (JENKINS, 1962), and hence the main movements probably occurred in late Westphalian-Stephanian times. With the exception of the Johnston Thrust zone and some fault zones immediately to the north of it, folds and cleavage developed during a single phase accompanied by thrusting and lag faulting. Wrench and cross faulting probably started during the closing stages of folding and continued after folding. DIXON (1921) believed wrench faulting was complete before the development of gash-breccia masses which he presumed to be of Permo-Triassic age, (Encl. I) and HANCOCK, (1964) demonstrated that the joint system in the Late Palaeozoic rocks was formed before the breccias. However, THOMAS, (1971) has argued that some of the breccias are Tertiary, and it is noteworthy that an isolated small basin of Palaeogene-?Neogene clays and gravels occurs close to the outcrop of the dextral Flimston Bay Fault (Encl. I), a structure which may

connect southwards with the Sticklepath-Lustleigh-Lundy Fault, known to have been active during the Cenozoic.

DISCUSSION

Interactions between Caledonian and Variscan structures

It is clear from the stratigraphic evidence that during the late Palaeozoic deposition was strongly influenced by active structures, probably long-established basement fractures. Although Caledonian orogenic structures were sufficiently well-defined beneath Zone II for them to determine the locations of the Variscan Disturbance Belts, their absence, or greater depth of burial, beneath Zone I allowed an 'original' Variscan direction to develop. Nevertheless older basement fractures were reactivated, displacements on them not necessarily being the same as in the early Palaeozoic. The increasingly thin-skinned style of tectonics towards the north may be a consequence of the Early Palaeozoic basement in the north being both more rigid and shallower than in the south. According to BROOKS ET AL. (in press) the Precambrian basement is deeper than 3 km, its outcrops in the Benton-Johnston fault block belonging to a local thrust slice which is separated from a buried basement high about 2 km to the south.

Structures in the Druidston Haven Horst indicate that the principal result of Variscan deformation on Caledonian orogenic structures was approximately coaxial refolding, a conclusion conflicting with the view that Variscan events in SW Wales resulted in a swing in the strike of the Caledonian fold belt (Fig. 3).

Continuity and characteristics of major strike faults

SANZEN-BAKER'S (1972) model of allochthonous blocks each separated by about 5 km and juxtaposed during the Variscan, demands that the Ritec, Benton and Johnston Faults extend the entire length of the fold belt in SW Dyfed. Further, OWEN'S (1974) correlation of the Johnston Thrust with the Carreg Cennan Disturbance north of the Main South Wales Coalfield also implies that the Johnston Thrust cuts the Coalfield. Although the Ritec Fault may extend the entire length of the segment, the Benton and Johnston faults do not extend eastwards as major faults cutting the rocks of the Coalfield (TRINGHAM, 1979).

Displacements on the Johnston Thrust involved early overthrusting to the north and later dextral shear (TRINGHAM, 1979). During the Variscan movements the Benton Fault achieved a normal downthrow to the south; it may be a lag fault associated with the Johnston Thrust. The Variscan evolution of the Musselwick Fault involved oblique reverse motion, the component of strike-slip being sinistral. The Ritec Fault is a high-angle reverse fault along most of its length; the small normal displacement in the extreme west perhaps

being a consequence of a lag effect close to one end of the fault.

Definition of a Variscan orogenic front

Innumerable small-scale maps show the Variscan front passing through SW Dyfed although lines to the south have been proposed. MATTHEWS (1974), DUNNING (1977) and NAYLOR & SEVASTOPULO (1978) who review arguments about the location of the front in the British Isles conclude that it is defined in different ways in different areas, and that some lines correspond to facies boundaries. The relative merits of several possible tectonic lines in SW Dyfed are discussed by HANCOCK ET AL. (in press) who conclude that the 1 km wide belt of conjugate folds and thrusts forming Zone Id, and external to the indefinite northern limit of slaty cleavage, provides a sufficiently distinctive and laterally continuous frontal belt (Fig. 2). By defining the front as a narrow zone they recognised that it is unlikely to be as sharp as a stratigraphic contact, and that the selection of a major strike fault is unrealistic unless it is laterally continuous. Although Zone Id constitutes an easily recognizable frontal zone it is not suggested that Variscan movements were not substantial to the north, but rather that their character became weaker and increasingly influenced by basement structures.

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