Caledonian Structures in Britain

South of the Midland Valley

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Chapter 4

Wales

INTRODUCTION – A STRUCTURAL PERSPECTIVE
W. R. Fitches

Most of Wales is underlain by a thick pile of sedimentary rocks, ranging in age from Cambrian to Devonian, together with volcanic and intrusive rocks which are exposed mainly in the north and south of the country. These rocks collectively constitute the fill of the Welsh Lower Palaeozoic Basin, a major region of prolonged subsidence which developed as a marginal basin on the southern continental flank of the Late Precambrian–Early Palaeozoic Iapetus Ocean. It was deformed and weakly metamorphosed, mainly in Early Devonian times, during the Caledonian Orogeny in response to plate collision processes.

The edges of the basin, at least, are floored by a Precambrian–earliest Cambrian basement, which is exposed in Anglesey, the northernmost Welsh mainland, the Welsh Borders, and in South Wales. Devonian, Carboniferous, and younger strata hide the eastern part of the basin, although the transition with the Midland Platform of England is exposed within the Welsh Border Fault System and the classic Shropshire sections. In South Wales, basin and platform sequences are largely buried by Devonian and Carboniferous rocks and, with them, are caught up in the northern part of the Late Carboniferous Variscan orogenic belt.

The Welsh Lower Palaeozoic Basin is one of the world's classic geological regions in the sense that many of the basic principles of geology were first formulated there in the last century and early part of this century. The earliest work in Wales, concerned with structural geology, is discussed and referenced by Bassett (1969) in his comprehensive essay on Early Palaeozoic major structures and requires no further comment here. The observations and interpretations made by O. T. Jones, R. M. Shackleton and others earlier this century, however, remain pertinent to modern research as the following pages reveal. Since Bassett's review, research into the tectonic evolution of the Welsh Basin has undergone a renaissance, particularly in the last decade, as new ideas about sedimentary basin dynamics and deformation have been applied.

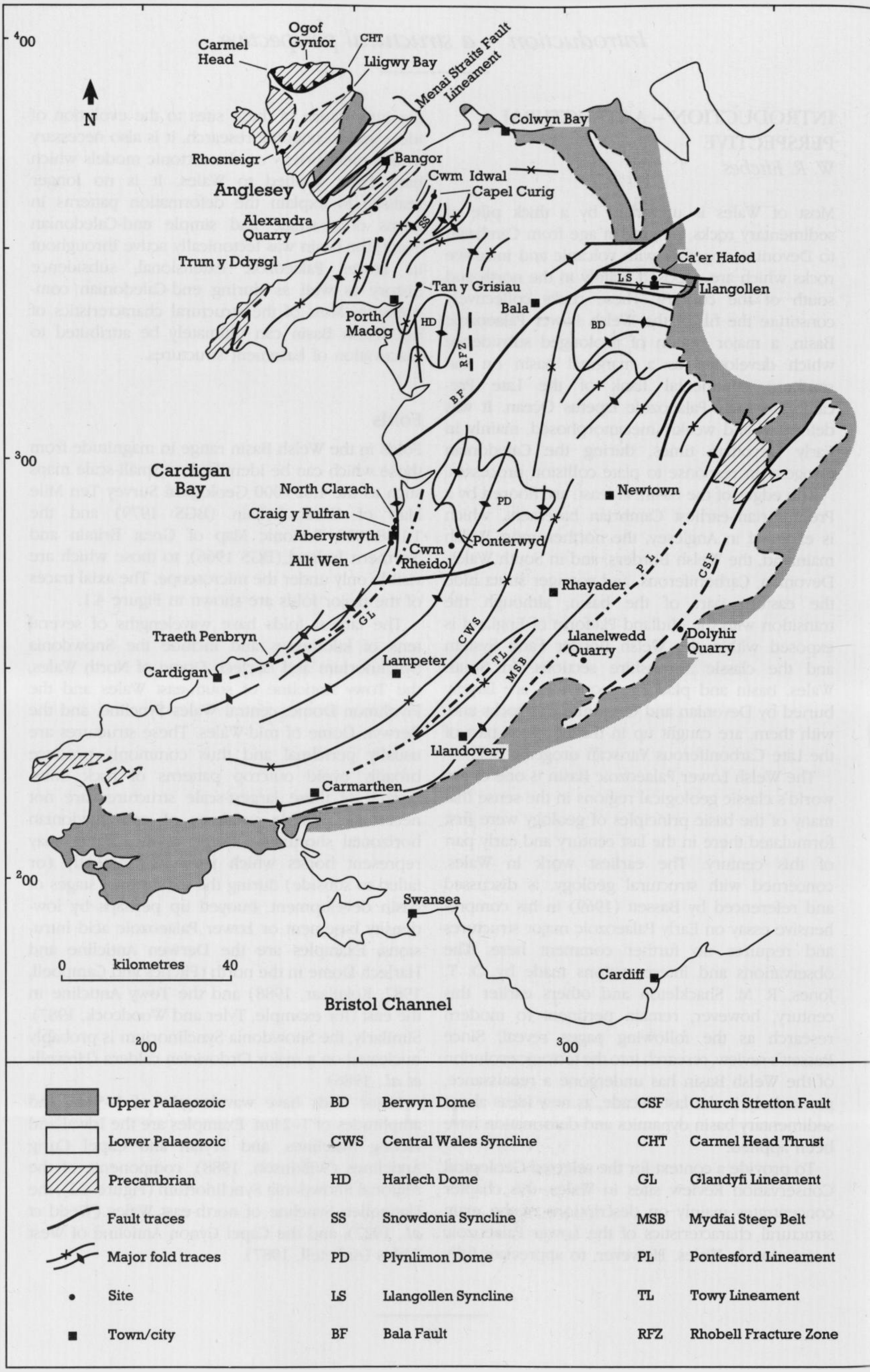
To provide a context for the selected Geological Conservation Review sites in Wales, this chapter concentrates mainly on descriptions of the main structural characteristics of the Lower Palaeozoic succession in Wales. However, to appreciate fully the importance of these sites to the evolution of ideas and to ongoing research, it is also necessary to comment briefly on the tectonic models which have been applied to Wales. It is no longer realistic to explain the deformation patterns in terms of a single and simple end-Caledonian event; the basin was tectonically active throughout its Lower Palaeozoic extensional, subsidence history as well as during end-Caledonian compression. Most of the structural characteristics of the Welsh Basin can ultimately be attributed to reactivation of basement structures.

Folds

Folds in the Welsh Basin range in magnitude from those which can be identified on small-scale maps such as the 1:625 000 Geological Survey Ten Mile Map of Great Britain (BGS 1979) and the 1:1 584 000 Tectonic Map of Great Britain and Northern Ireland (BGS 1966), to those which are visible only under the microscope. The axial traces of the major folds are shown in Figure 4.1.

The largest folds have wavelengths of several tens of kilometres and include the Snowdonia Synclinorium and Harlech Dome of North Wales, the Towy Anticline of south-east Wales and the Plynlimon Dome, central Wales Syncline, and the Berwyn Dome of mid-Wales. These structures are usually periclinal and thus commonly produce broadly ovoid outcrop patterns of rock units. Several of these largest-scale structures are not necessarily simple products of end-Caledonian horizontal shortening. Some of the domes may represent horsts which rose intermittently (or failed to subside) during the extensional stages of basin development, buoyed up perhaps by low-density basement or Lower Palaeozoic acid intrusions. Examples are the Derwen Anticline and Harlech Dome in the north (Fitches and Campbell, 1987; Kokelaar, 1988) and the Towy Anticline in the east (for example, Tyler and Woodcock, 1987). Similarly, the Snowdonia Synclinorium is probably nucleated on a major Ordovician caldera (Howells *et al.*, 1986).

Major folds have wavelengths of 1–5 km and amplitudes of 1–2 km. Examples are the Idwal and Hebog Synclines, and Tryfan and Capel Curig Anticlines (Wilkinson, 1988), components of the regional Snowdonia Synclinorium (Figure 4.2), the Llangollen Syncline of north-east Wales (Wedd *et al.*, 1927), and the Capel Cynon Anticline of West Wales (Anketell, 1987).



400
Carmel Head
Ogof Gynfor
CHT
Lligwy Bay
Menai Straits Fault Lineament
N
Colwyn Bay
Rhosneigr
Bangor
Anglesey
Cwm Idwal
Capel Curig
Alexandra Quarry
SS
Trum y Dydysgl
Ca'er Hafod
LS
Llangollen
Tan y Grisiau
Bala
Porth Madog
HD
BD
RFZ
BF
300
Cardigan Bay
North Clarach
Newtown
PD
Craig y Fulfran
Aberystwyth
Ponterwyd
Cwm Rheidol
Allt Wen
PL
CSF
Rhayader
GL
CWS
Traeth Penbryn
Llanelwedd Quarry
Dolyhir Quarry
Cardigan
Lampeter
TL
MSB
Llandovery
Carmarthen
200
Swansea
0 kilometres 40
Cardiff
Bristol Channel
200
300
Upper Palaeozoic
Lower Palaeozoic
Precambrian
Fault traces
Major fold traces
Site
Town/city
BD Berwyn Dome
CWS Central Wales Syncline
HD Harlech Dome
SS Snowdonia Syncline
PD Plynlimon Dome
LS Llangollen Syncline
BF Bala Fault
CSF Church Stretton Fault
CHT Carmel Head Thrust
GL Glandyfi Lineament
MSB Mydfai Steep Belt
PL Pontesford Lineament
TL Towy Lineament
RFZ Rhobell Fracture Zone

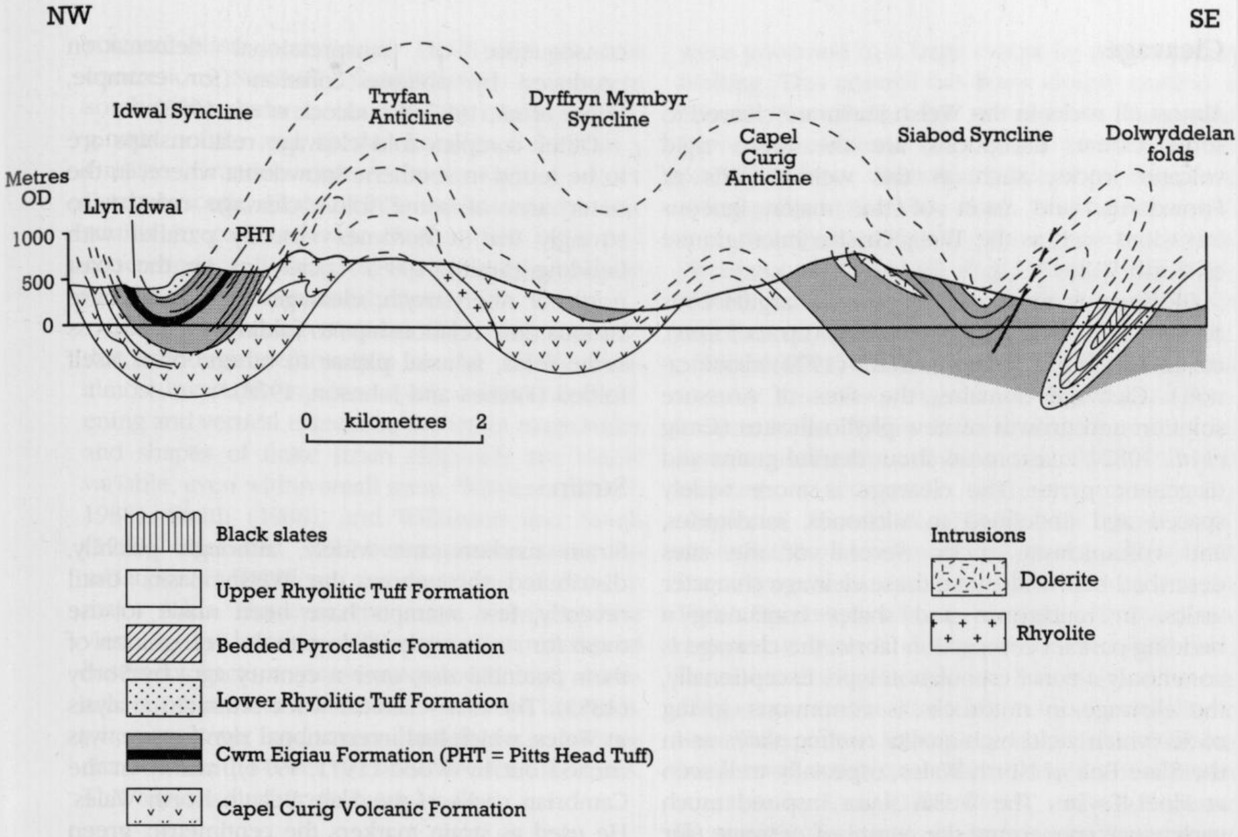


Figure 4.2 Section through the major folds of Snowdonia (after Wilkinson, 1988).

The Idwal Syncline is one of Britain's best-known structures and typifies these major folds. It is an open, almost symmetrical fold with upright NE–SW axial plane and gentle north-east plunge in Cwm Idwal. As with other major folds, however, it is non-cylindrical, non-plane, and its geometry changes markedly along its axial trace; to the north-east of the A5, in the slopes of the Carneddau, it becomes almost isoclinal and plunges steeply to the south-west. Less typically, the major folds are asymmetrical (and then usually close to tight) with one limb steep to overturned. Trum y Ddysgl is situated on the north-west overturned limb of the Idwal–Snowdon Syncline. The Hebog Syncline, the southern continuation of the same structure, also takes this form locally, where its axial plane shallows to about 60°NW from its usually vertical attitude, but the Dolwyddelan Syncline is reclined to strongly inclined along its entire length. Some major folds have an *en échelon* geometry, for example the Cwm Pennant Anticline described by Roberts (1979), Wilkinson and Smith (1988), and Smith (1988).

Figure 4.1 Map showing the traces of the principal folds and faults of Caledonian age in Wales. The localities described in the text are also shown.

Smaller-scale folds, with wavelengths between 200 and 1500 m, are locally visible in hillsides and coastal cliffs, as on the coastline south of Aberystwyth (Price, 1962). Most are revealed only by detailed mapping, as in west Wales by Craig (1985, 1987) and Anketell (1987). Outcrop-scale folds, with amplitudes between a few centimetres and 10 m, are common in some areas (for example, Aberystwyth and its hinterland) but rare in others (much of Snowdonia, for instance). Because they mimic the morphology and orientation of the major folds, these small structures provide a ready source of information about fold geometries. Such folds are illustrated in Silurian rocks at Cwm Rheidol and in the Ordovician of Anglesey, for instance at Rhosneigr.

Cleavage

Almost all rocks in the Welsh Basin are cleaved to some extent. Exceptions are the more rigid volcanic rocks, such as the welded tuffs of Snowdonia, and most of the major igneous intrusions such as the Tan y Grisiau microgranite of North Wales.

Cleavage is most clearly seen in argillaceous rocks, where it is usually a spaced (up to 5 mm), disjunctive fabric (using Powell's (1979) classification). Cleavage domains, the sites of pressure solution and growth of new phyllosilicates (Craig *et al.*, 1982), anastomose about detrital grains and diagenetic pyrite. The cleavage is more widely spaced and ill-defined in siltstones, sandstones, and volcaniclastic rocks. Several of the sites described below illustrate these cleavage character-istics. In mudstones and shales containing a bedding-parallel compaction fabric, the cleavage is commonly a zonal crenulation type. Exceptionally, the cleavage in mudrocks is continuous, giving rocks which yield high-quality roofing slates as in the Slate Belt of North Wales, especially well seen at Moel Tryfan. The Welsh slates inspired much early work concerning the nature of cleavage (for example, Sharp, 1849; Sorby, 1853), and more recently on cleavage-forming mechanisms (see Wood and Oertel, 1980; Whalley, 1973; Knipe and White, 1977; White and Knipe, 1978).

The margins of minor intrusions, notably those of dolerite dykes in Snowdonia, are commonly cleaved, the fabric being defined by aligned deformed vesicles and new metamorphic minerals such as actinolite and chlorite. Some of the plutonic bodies, including the Mynydd Mawr Granite in North Wales, also have cleaved margins.

On small-scale maps, such as Figure 4.1, the trace of cleavage usually appears to be parallel to fold axial traces. This congruence is because cleavage is approximately axial-planar to, or has a fanning relationship with, most folds. However, recent studies have revealed many examples of cleavage transecting folds. Craig (1987) showed that in parts of West Wales the cleavage is anticlockwise with respect to small folds, axial planar to larger folds, and clockwise to major folds. Cave and Hains (1986) reported numerous examples of clockwise transection from the Aberystwyth area and, in earlier unpublished work, were the first to record this phenomenon in Wales. The transection of folds by cleavage is widely recognized in the Caledonides of South Britain, where it has been interpreted as the consequence of transpressional deformation produced by oblique collision (for example, Soper *et al.*, 1987; Woodcock *et al.*, 1988).

Other complex fold–cleavage relationships are to be found in southern Snowdonia where, in the outer arcs of some folds, cleavage refracts so strongly that it becomes virtually parallel with bedding (Smith, 1988). Locally, as on the coast north of Aberystwyth, cleavage appears to have various time relationships to folding: it cuts across some folds, is axial planar to others, or is itself folded (Fitches and Johnson, 1978).

Strain

Strain markers are widely, although patchily, distributed throughout the Welsh Basin. Until recently, few attempts have been made to use them for strain analysis, despite the recognition of their potential use, over a century ago, by Sorby (1853). The now classical work on strain analysis in Wales, which had international significance, was carried out by Wood (1971, 1974), mainly in the Cambrian rocks of the Slate Belt in North Wales. He used as strain markers the centimetric, green reduction spots found widely in the grey and purple slates of that region. These spots, of diagenetic origin, were originally nearly spherical, but have been deformed into triaxial ellipsoids which have short axes normal to cleavage and long axes down the dip of that fabric. Wood calculated that up to 67% horizontal shortening and up to 157% vertical extension took place during cleavage development in the Slate Belt.

Siddans (1971) used accretionary lapilli to measure strains around the Capel Curig (or Mymbyr) periclinal anticline. Roberts and Siddans (1971) studied the shapes of various volcanic fragments in the Llwyd Mawr ignimbrite of Snowdonia, attempting to separate the volcanic compaction and tectonic strains. The strain data, obtained from some 50 sites by various workers throughout North Wales, were used by Coward and Siddans (1979) to calculate that the part of Anglesey between the Carmel Head Thrust and the Menai Straits has been shortened by 12 km during the end-Caledonian deformation, while the section from the Menai Straits to the Welsh Borders has been shortened by 43 km.

More recently, Wilkinson (1987, 1988) has made a major strain study of central Snowdonia, obtaining data from 250 sites by using a variety of strain markers, mainly in Caradoc volcaniclastic units:

volcanic clasts, accretionary lapilli and siliceous concretions. Similarly, Smith (1988), working in southern Snowdonia, has used as markers ferruginous ooliths and, in the aureole of the Tan y Grisiau Granite, contact metamorphic spots. Further south, Craig (1985) measured the low strains in parts of west Wales from deformed concretions, following on studies made by Lisle (1977) on the Aberystwyth Grits.

The more recent strain studies have revealed that, although deformation in the Welsh Basin almost invariably involves nearly horizontal shortening and vertical extension, the strain magnitudes and shapes of finite strain ellipsoids are highly variable, even within small areas. Wilkinson (1987, 1988), Smith (1988), and Wilkinson and Smith (1988) attributed this heterogeneity partly to variations in lithology and positions of sites in major folds. However, the main cause, in their view, is the location with respect to reactivated basement fracture zones; anomalously high strains are found in cover rocks above basement fractures, whereas lower and more homogeneous strains characterize the cover to blocks between fractures. This topic is further discussed below.

Faults

As information has accrued on sedimentation and volcanism in the Welsh Basin, it has become increasingly apparent that the basin was intermittently tectonically active throughout its extensional history; subsidence and sediment accumulation were accomplished to a large extent by faulting. According to some authors, notably Wilkinson and Smith (1988), these basin faults were nucleated on reactivated basement faults. Many faults were repeatedly active, particularly those comprising the Menai Straits (Gibbons, 1983) and Welsh Borders (Woodcock, 1984a, 1984b) lineaments. Most of these early faults have a Caledonoid (NE–SW) or nearly N–S strike (Fitches and Campbell, 1987).

Fault-control on sedimentary facies and thicknesses in the Lower Palaeozoic succession is now widely documented, for example: in the Ordovician of Anglesey (Bates, 1974); along the Bala Fault lineament (Fitches and Campbell, 1987) and in the Llandovery area (Woodcock, 1987a). Most of the syndepositional faulting is consistent with an extensional or transtensional regime. Similarly, the accumulation of volcaniclastic deposits and the location of intrusions (notably plugs and dykes) were governed to a large extent by contemporary faulting. This control has been closely studied in central Snowdonia by the British Geological Survey's Snowdonia Unit, which has demarcated the Ordovician Snowdon caldera fractures and apical graben (Reedman *et al.*, 1985), for example, and identified a failed rift system from dyke distributions (Campbell *et al.*, 1988), while Orton (1988) has analysed the interaction between sedimentation and faulting in central Snowdonia.

Woodcock (1984b, 1988; see Llanelwedd and Dolyhir Quarries) has shown that several lineaments in the Welsh Borders comprise complex systems of dip-slip and strike-slip faults, with folds in places, which can be interpreted as strike-slip 'duplexes'. Woodcock (1984b) and Lynas (1988) described the Clun Forest Disturbance, a NNE–SSW linear zone of anastomosing faults and folds in the Welsh Borders, as a flower structure. This structure comprises upward divergent reverse faults in a linear zone of uplift, and was caused by strike-slip displacement. The Glandyfi vergence divide in west Wales (Cave, 1984; Cave and Hains, 1986) has been interpreted as another example of a flower structure by Craig (1985, 1987), who takes this to be an end-Caledonian structure probably nucleated on a long-lived basement fracture.

Thrust faults occur on a small scale in various parts of the basin (Price, 1958, 1962). The only large-scale example, however, is the Carmel Head Thrust on Anglesey, which carries rocks of the Mona Complex over Ordovician strata (Greenly, 1919; Bates and Davies 1981). The Tremadoc 'Thrust Zone', identified by Fearnsides (1910) and Fearnsides and Davies (1944) on the basis of repetition of strata and various small-scale structures, is reinterpreted by Smith (1987, 1988) as a Caradoc olistostrome which probably slid northwards off the Harlech Dome. In mid-Wales, Jones and Pugh (1915) identified the NNE-striking, west-dipping Brwyno–Gelli Goch and Cascade–Forge Thrusts; the throw on these structures is not known (Cave and Hains, 1986).

Much of Central Wales is cut by ENE faults which displace folds and other faults, including the mid-Wales thrusts, and hence are late structures. Those mapped by Cave and Hains (1986) have dominantly dip-slip displacement. Faults with this trend are mineralized in places (Phillips, 1972; Raybould, 1976) and are perhaps manifestations of early Variscan, rather than end-Caledonian deformation (Fitches, 1987). The Bala Fault, one of the major faults of the Welsh Basin (Figure 4.1), is considered by Fitches and Campbell (1987) to have moved by strike-slip displacement also mainly during Variscan events, although parts of that structure were active as dip-slip faults during the early Palaeozoic.

Bedding planes in many parts of the Welsh Basin have been used as detachment surfaces, which are usually marked by striated thin veins of quartz, carbonate, and other minerals. Particularly outstanding examples, which first attracted the attention of researchers (for example, Nettle, 1964 and Nicholson, 1966, 1978), are found near Llangollen (Ca'er-hafod). Others, with genetically associated vein breccias, bedding-normal veins and folds, are seen at various places along the west Wales coast (Fitches *et al.*, 1986). Nicholson (1966) showed that the Llangollen veins preceded end-Caledonian deformation, although Davies and Cave (1976) ascribed those in west Wales to pre-lithification gravity sliding which accompanied fold and cleavage development. More recently, Craig (1985) and Fitches *et al.* (1986) interpreted the association of veining, bedding-plane detachment, small-scale thrust and normal faulting as the product of post-lithification hydraulic jacking followed by gravity sliding before the end-Caledonian deformation. These intriguing structures remain of topical research interest – see Traeth Penbryn and Allt Wen.

Deformation sequence

Most parts of the Welsh Basin are characterized by a single set of folds on upright, mainly NE–SW axial planes which are accompanied by cleavage. These structures are commonly described as the 'regional' or 'main' structures. They are usually attributed to end-Caledonian or Late Silurian–Early Devonian deformation (Dewey, 1969), although the current trend is to use the North American term 'Acadian' (for instance, Soper *et al.*, 1987). Woodcock (1987a) supported Jones' (1955) view that the main cleavage-forming event, in south-east Wales at least, continued into, or was confined within, late early Devonian to mid-Devonian times. Ongoing isotopic work in central and North Wales, by J. Evans (BGS), M. Dodson and P. Bishop (Leeds University), is likely to shed light on the timing of deformation in those parts of the basin, and on whether or not the 'main' structures are contemporaneous across the basin. Particularly relevant in providing time constraints on the deformation is the Lligwy Bay section on Anglesey (Greenly, 1919; Bates and Davies, 1981) where presumed Devonian red-beds are folded, cleaved and thrust: usually, elsewhere in Britain south of the Southern Uplands Fault Devonian rocks were only strongly deformed by Variscan events.

It has become clear that deformation of the basin cannot be regarded simply as a single, climactic event; several regions were tectonically active at various times during basin evolution, and even the main, end-Caledonian deformation was polyphase.

Along the N–S Rhobell Fracture Zone on the eastern flank of the Harlech Dome, Kokelaar (1977, 1979) demonstrated an early Tremadoc set of folds with steep N–S axial planes, which preceded eruption of the Rhobell Fawr Volcanic Group and, similarly oriented, end-Tremadoc folds which deform those volcanics. An end-Tremadoc regional deformation event has been recognized over much of north-west Wales on the evidence that the basal Arenig deposits are usually unconformable on older rocks (Shackleton, 1953, 1954; George, 1961; Roberts, 1979; Allen and Jackson, 1985a, 1985b). The magnitude of the sub-Arenig unconformity increases, irregularly, to the north and west of the Harlech Dome until some 5000 m of mainly Cambrian strata are cut out on Llŷn. Roberts (1979) suggested that this tectonic event involved block uplift on major faults. It is not yet clear whether this end-Tremadoc event caused widespread folding and cleavage or produced these compressional structures only along fault zones.

Allen and Jackson (1985a, 1985b) tentatively attributed localized NW-trending folds in the Harlech Dome to a late Ordovician–Silurian deformation, but structures of this age within the basin are not widespread. There is evidence, however, (Woodcock, 1984b) for strike-slip faulting along the south-east margin of the basin, of probable Ashgill age. Lynas (1970a) considered evidence for a mid-Caradoc event producing a flat-lying cleavage around the northern and eastern flanks of the Harlech Dome, perhaps in response to incipient uplift of the dome associated with volcanism. Coward and Siddans (1979) attributed this fabric to deformation in the Tremadoc Thrust zone. However, this 'early' cleavage is now interpreted as the regional, end-Caledonian cleavage, which has an unusually shallow dip because host rocks were ramped southward over the Tan y Grisiau Granite and Harlech Dome during the regional deformation (Bromley, 1971; Campbell *et al.*, 1985; Smith, 1987, 1988). The lineation on the low-angle cleavage, which earlier workers had ascribed to intersection with the upright, regional cleavage, is usually a grain shape fabric in the cleavage, generally the effect of elongate grains in the cleavage, probably caused by strong down-dip extension.

Several sets of end-Caledonian structures have been identified in various parts of Wales. Roberts (1967, 1979) recorded three deformations in North Wales. According to him, the main fold architecture, represented by the mainly NE–SW upright cleavage and folds such as the Idwal Syncline, developed first, during a D_1 event. Rare, recumbent folds with axial-planar crenulation cleavage were then imposed (D_2), and followed in turn by upright NW–SE to N–S folds and crenulation cleavage (D_3). Helm *et al.* (1963) considered that the D_3 deformation was responsible for the major arcuation of the main structures through North Wales. However, Roberts (1979) assigned the late structures to localized deformation (along zones above basement fractures according to Wilkinson, 1988); Coward and Siddans (1979) argued against this refolding model on the grounds of fold geometry.

Polyphase deformation structures are also known in mid-Wales. Fitches (1972) described, from the Aberystwyth area, a sequence of structures, closely similar to that described by Roberts (1969) in North Wales. Other examples from northern Mid-Wales were described by Martin *et al.* (1981). Tremlett (1982) and Craig (1985) suggested that the D_2 and D_3 structures probably denote localized movement near faults, rather than regionally correlatable events. Their view is supported by the close spatial association of kinks and crenulations of the regional cleavage with the Tal y Llŷn section of the Bala Fault system (Bracegirdle, 1974; Fitches and Campbell, 1987). On these grounds, the structures deforming the regional cleavage in Mid-Wales, and perhaps also Snowdonia, are Variscan rather than Caledonian – see above. In summary, the main D_1 deformation occurred in the late Silurian to early Devonian but not necessarily as a single climactic event. Earlier movements, often related to faulting and volcanic activity, caused local folding and tilting, but there is no evidence of earlier cleavage. Similarly, deformation later than D_1 is of local development and it may often be attributed to fault movement which may be Variscan.

Tectonic models

It has been shown that the main end-Caledonian folds throughout the Welsh Basin, are typically upright and non-cylindrical structures, irrespective of scale; and the main cleavage usually has an axial planar, fanning or transecting relationship with the folds. Despite this uniformity of morphology, however, the orientations of these structures are highly variable (Figure 4.1). Particularly conspicuous in North Wales is the arcuation of axial planes and cleavage from N–S in the Harlech Dome and southern Snowdonia, through NE–SW (Caledonoid) in central Snowdonia, to E–W in north-east Wales. A similar, but smaller scale, arcuation occurs about the north-western flank of the Berwyn Dome, where the NNE–SSW Central Wales Syncline turns abruptly into the E–W Llangollen Syncline. In much of central and west Wales the structures strike approximately NNE–SSW, but in the southern part of the basin they arc to ENE–WSW and then E–W. The cause of these arcuations has been extensively debated in the past and, in conjunction with the more recently recognized allied enigma of transecting cleavages, is again a topical research subject. An interrelated problem is whether or not deformation is 'thin-skinned', whether the structures flatten downward to merge with one or more detachment zones deep in the cover, or upper part of the basement, or is 'thick-skinned', that is the cover structures link with, and are partly controlled by, those deep in the basement.

Jones (1912) was the first to address the problem of arcuation in the southern part of the basin, concluding that it is a primary Caledonian feature and not a product of deflection of Caledonoid structures by a younger event. Anketell (1987) supported this view and contradicted Pringle and George's (1948) explanation which postulated subsequent warping. Shackleton (1954), concerned with northern Wales, considered that cover structures were strongly guided by fracture systems in the basement. He pointed out that on Anglesey, for example, at Ogof Gynfor, there is no detachment along the exposed cover–basement boundary and that there are small-scale examples of faults in the basement passing up into faults and folds in the cover (earlier recorded by Greenly, 1919). These and other observations led him to suggest that the structural arcuations in the cover in northern Wales are responses to moulding of structures against and above the sides and corners of basement fault-blocks.

By contrast, Helm *et al.* (1963) explained the

North Wales arcuation in terms of regional refolding of Caledonoid structures about later NW–SE axial planes. Their interpretation was countered by Coward and Siddans (1979) on the grounds that there are no structures in the region which are consistent with the inner-arc compression and outer-arc extension required by the refolding model.

Coward and Siddans (1979) went on to erect a 'thin-skinned' interpretation of northern Wales, based largely on their strain study, deducing that the cover and upper part of the basement lie on a deep detachment. They explained the structural arcuation as the result of compression of Snowdonia against a rigid block situated beneath the Berwyn Dome. Campbell *et al.* (1985) modified this indenter model, considering that the rigid block comprised the Caradoc Tan y Grisiau granite and basement rocks beneath the northern flank of the Harlech Dome.

In a radical departure from previous interpretations of deformation in Wales, Woodcock (1984a, 1984b) introduced the concept of strike-slip and transpressional tectonics to explain the end-Caledonian, and perhaps earlier, tectonic events in the south-eastern part of the basin. These views, together with an assessment of possible Variscan and younger reactivation of Caledonian structures, are developed in Woodcock (1987b, 1988) and Woodcock *et al.* (1988).

The various interpretations reviewed above have recently been elaborated upon and revised by Smith (1988), Wilkinson (1988) and Wilkinson and Smith (1988), as a result of their comprehensive strain studies in Snowdonia, and by Kokelaar (1988) from an analysis of igneous activity in northern Wales.

Based on Gibbons' (1987) conclusion that the Precambrian rocks of Anglesey and Llŷn represent an amalgamation of terranes, accreted in latest Precambrian to earliest Cambrian times by docking along NE–SW strike-slip zones, it is considered that much of northern Wales is underlain by a similarly heterogeneous basement dissected by steep NE–SW, and probably N–S, shear zones. These shear zones were reactivated, largely as brittle structures, during early Palaeozoic extension and transtension of the basin, and separated fault blocks which could move vertically and laterally independently of one another. In this way, the basement structures strongly governed Cambrian and Ordovician sedimentation patterns and igneous activity. Intermittent differential block movements during basin subsidence, some causing inversion, may have been responsible for local folding, warping, and tilting, during end-Tremadoc times for example. Subsequently, as a result of the end-Caledonian closure of the Iapetus Ocean (Soper and Hutton, 1984; Soper *et al.*, 1987) the blocks were jostled due to approximately NW–SE compression, again reactivating older faults. Block margin faults which were aligned normal to compression allowed dip-slip displacement, and induced Caledonoid folds and cleavage at and above their tips. On the other hand, faults aligned at an angle with respect to regional compression were reactivated as strike-slip faults, generating transpressive structures in the cover; *en échelon* folds, transecting cleavage and complex patterns of minor faults (Woodcock *et al.*, 1988). This model has therefore combined, modified, and developed the basement control model of Shackleton (1954) and the trans-pressional models of the Welsh end-Caledonian deformation.

ALEXANDRA QUARRY (SH 518561)

R. Scott

Highlights

Alexandra Quarry provides outstanding exposures illustrating Caledonian crustal deformation in the Welsh Cambrian Slate Belt. The Slate Belt of Wales is renowned internationally for its elliptical strain markers, the so-called reduction spots. Small strain markers such as the reduction spots were used in classic early studies of strain measurement. These features can be used to interpret the structure of the Slate Belt, which suffered the highest intensity of Caledonian deformation in North Wales.

Introduction

The overall structure exposed in the quarry is a NE–SW-trending, tight, upright anticline containing the Purple Slate Group in its core, flanked by Dorothea Grit and the overlying Striped Blue Slate Group. This broad structure is complicated by attenuation of the fold limbs and the presence of strike faults.

The geology of the Slate Belt has been investigated from an early stage in the study of Welsh geology because of the wealth of interesting structures exposed in the slate quarries. Sorby (1853, 1856, 1908) interpreted the green spots which characterize some of the slates, as the products of reduction in the sedimentary environment. He used them to estimate shortening perpendicular to cleavage of 75%, combined with 10% volume reduction: this was the first quantitative estimate of strain undertaken. The detailed account of the regional geology is that of Morris and Fearnsides (1926). More recent accounts of regional geology and theoretical structural studies are those of Wood (1969, 1971, 1974), Cattermole and Jones (1970), Tullis and Wood (1975), Wood *et al.* (1976), Roberts (1979), and Wood and Oertel (1980). The Slate Belt has featured prominently in the regional interpretations of Shackleton (1953), Dewey (1969), and Coward and Siddans (1979).

Alexandra Quarry, south-east of Moel Tryfan, was described in detail by Morris and Fearnsides (1926) and lies within the area depicted on the geological map of Cattermole and Jones (1970). The quarry provided a sample locality in the study of Wood and Oertel (1980) in their measurement of strain in the Welsh Slate Belt; and it also appears as a locality in the field guides of Roberts (1979) and Howells *et al.* (1981).

Description

Alexandra Quarry (see Figure 4.3A and B) has been excavated on a variety of levels, the lowest of which are now flooded. Exposure is excellent, although not always accessible. The structure is described at a number of sites within the quarry which are well illustrated by line drawings in Roberts (1979).

Towards the centre of the quarry (around SH 51815613), a large screen of rock separates the north-east end from the lower levels to the south-west (Locality A, Figure 4.3A). When viewed from a position on the lowest part of the track, the south-west face of this rock screen provides a cross-section of the structure perpendicular to the strike. An anticlinal hinge in the Purple Slate is flanked by NW-dipping Dorothea Grit forming the north-west wall of the quarry, and by SE-dipping, tectonically thinned, Dorothea Grit on the south-east side, with Striped Blue Slate above. A prominent greywacke bed showing boudinage occurs on the south-east limb. The screen also contains a vertical dolerite dyke. Like other presumed Ordovician dykes in the Slate Belt it is boudinaged and shows cleavage in its margins.

Although the overall structure displayed in the quarry is anticlinal, strike faults complicate the picture and, unfortunately, the presence of a large

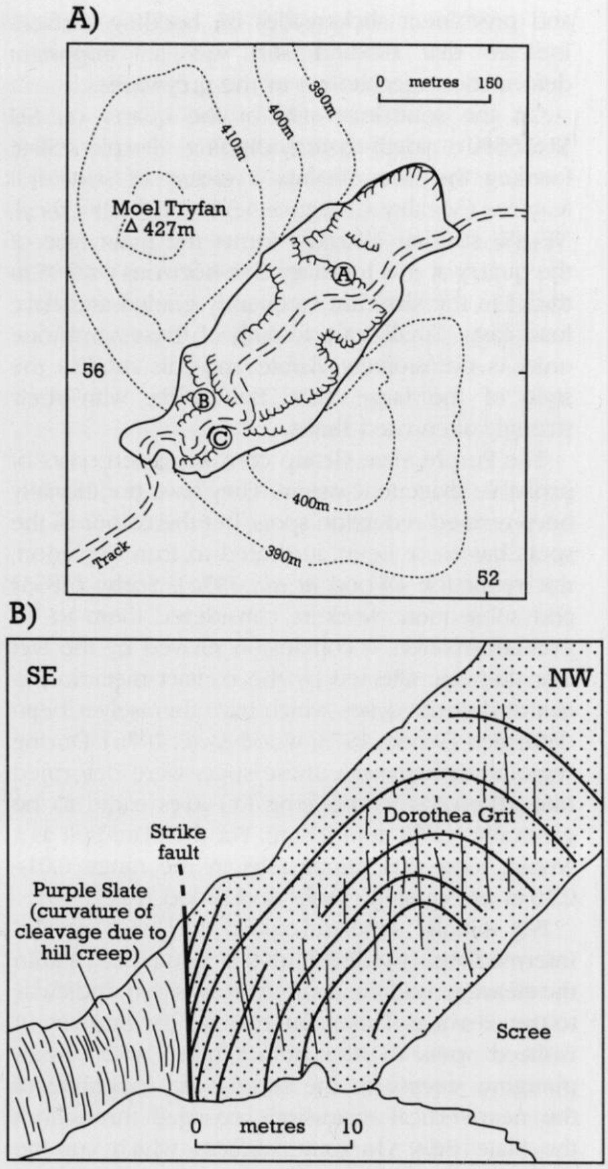


Figure 4.3 Alexandra Quarry. (A) Site map, showing Localities A–C described in the text. (B) Sketch illustrating anticline in Dorothea Grit with a faulted south-east limb. See text for explanation. Locality B of Figure 4.3A.

flooded pit immediately in front of the screen means that several of the interesting structures cannot be directly examined. This can be achieved at the south-west end of the quarry.

On the north-west side of the quarry (at SH 51615599) an anticline can be observed in the Dorothea Grit with the south-east limb faulted out against NW-dipping Purple Slate (Locality B, Figure 4.3A and B). Greywacke beds show quartz-filled tension cracks indicating extension in the outer arc during folding. A few *en échelon* quartz veins and prominent slickensides on bedding surfaces indicate that flexural slip was an important deformation mechanism in the greywackes.

On the south-east side of the quarry (at SH 51655590) south-easterly-dipping Purple Slate forming the face displays a variety of structural features (Locality C, Figure 4.3A). The subvertical, NE–SW striking cleavage forms the main face of the quarry at this location. Grit horizons (<0.05 m thick) in the slate are frequently graded and have load casts. Small-scale folding of these sandstone units is occasionally visible and this mimics the style of the large Slate Belt folds, with their strongly attenuated limbs.

The Purple Slate Group contains green spots of probable diagenetic origin. They have traditionally been termed reduction spots, but the colour of the spots has since been attributed to iron depletion, not reduction (Wood *et al.*, 1976). Sorby (1853) and subsequent workers considered them to be pre-deformation; a conclusion proved by the fact that they are affected by the contact metamorphism of dolerite dykes which have themselves been deformed (Wood, 1973; Wood *et al.*, 1976). During regional deformation, these spots were deformed into ellipsoids whose long (x) axes came to be generally <0.03 m in length. For the Slate Belt as a whole, long axis dimensions in the range 0.01–0.10 m are quoted (Tullis and Wood, 1975).

For initially spherical spots, the long (x) and intermediate (y) direction are contained within the cleavage, and the short axis (z) is perpendicular to the cleavage. This is the case for the majority of isolated spots in Alexandra Quarry, with x-axes plunging steeply to the south-west; indicative of the near-vertical extension recorded throughout the Slate Belt. On joint surfaces which cut the cleavage, the strong flattening of the spots in the plane of cleavage can be observed. Wood and Oertel (1980) recorded ordinary strains (E) (based on 67 measurements) from this quarry, of (1.00):(0.38):(−0.63); that is, the original radii of the sphere have doubled in x, increased by 38% in y and shortened perpendicular to the cleavage by 63%. The x and y dimensions of spots lie oblique to cleavage in cases where the initial shape was irregular. Examples of irregular, and occasional bedding-parallel iron depletion zones can also be observed at this locality.

Interpretation

Alexandra Quarry has been chosen to represent the principal structural features of the Cambrian Slate Belt which suffered the highest intensity of deformation in North Wales. This deformation produced a structural style in sharp contrast to the style exhibited by the volcanics of Snowdonia. Cattermole and Jones (1970) noted the sub-cylindrical nature of large folds in the Slate Belt which differs from the periclinal folds observed in Snowdonia.

Morris and Fearnsides (1926) outlined the main features of the Slate Belt. The NE–SW-oriented belt is separated by boundary faults from the Pre-cambrian and basal Cambrian volcanics to the north-west and the Ordovician slates to the south-east. Internally, the Slate Belt contains numerous fold hinges (dominantly anticlinal) whose attenuated limbs are frequently replaced by strike faults. These essential features are well displayed in Alexandra Quarry. Morris and Fearnsides (1926) described in detail the compressive features of the belt, in which category they placed the folds, cleavage, and two types of strike fault. Their type 1 'slide' type of strike fault is in essence an extreme continuation of the process of flexural slip, whereas the second type is later and post-dates, to some extent, the folding and imposition of cleavage. They estimated horizontal shortening in the belt as >40%, on the basis of evidence provided by a folded bed. They did not, however, recognize the significance of reduction spots, but did indicate that the principal movement of material during deformation was vertically upwards (based on the predominance of anticlinal hinges). Wood (1971, 1974) made a detailed analysis of strain in the Slate Belt; he estimated the tectonic thickness of the succession in the Arfon Anticline to be about double (Wood *in* Rast, 1969).

Cattermole and Jones (1970), although generally following the interpretation of Morris and Fearnsides (1926), described the structural history of the Slate Belt in terms of the deformation phases identified by Roberts (1967). In this scheme, F_1 is the main deformation phase with fold interlimb angles of 65–80° and different fold profiles dependent on lithology. The strike faults were interpreted as high-angle reverse faults.

Morris and Fearnsides (1926) interpreted the development of the Slate Belt using a model involving its compression between the rigid crystalline rocks of Anglesey and the low-lying volcanics of Snowdonia. They suggested that as Snowdonia was progressively driven to the north-west toward Anglesey during the late Silurian, folding, sliding, and cleavage formation were induced in the belt.

Roberts (1979) concluded that the similar folds of the Slate Belt were 'flattened buckle folds which are essentially the result of initial pure shear upon which later simple shearing has occurred'. The interpretation of the deformation was compatible with early suggestions that 'severe flattening was coupled with an essentially upward distention of the sedimentary pile'. The structure of the Slate Belt emphasizes the inhomogeneous nature of deformation in North Wales for which large-scale strain variation, structural position, and lithological control are all likely determining factors.

The present state of research at the site does not allow much advance on the nature of the main deformation other than to confirm the observations of Morris and Fearnsides (1926) and Cattermole and Jones (1970) that the cleavage-parallel movements have been important in the modification of the fold belt. More needs to be known about the relative age and displacement sense of these movements. However, there is no evidence to suggest (cf. Roberts, 1979) that simple shear modification rather than homogeneous flattening of the initial buckle folds has been responsible for the 'similar' folding. The upright cleavage in the context of the other Snowdonia and Anglesey sites, and of other regional research on cleavage in North Wales (Coward and Siddans, 1979; Wilkinson, 1988), does not support the concept of Morris and Fearnsides (1926) that Snowdonia was driven towards Anglesey.

Studies along the length of the Slate Belt have shown the inhomogeneous nature of deformation with tectonic thickening ranging from 50–180%. Maximum extension is coincident with plunge culminations of major folds (and vice versa) (Wood, 1974). Where spots are absent, fabric anisotropy has been used to estimate strain, based on calibration with localities where spots are present (Tullis and Wood, 1972, 1975). The strong agreement between strain, fabric anisotropy and magnetic susceptibility anisotropy has established that slaty cleavage can be accounted for purely by physical rotation (Tullis and Wood, 1972, 1975; Oertel and Wood, 1974; Wood *et al.*, 1976).

Alexandra Quarry is important as the best and most accessible locality for examining the structural features of the Welsh Slate Belt. The quarry faces provide excellent exposures of characteristic tight anticlinal folds whose limbs are replaced by strike faults. Small-scale strain markers and minor structures enable the intensity and mechanisms of deformation to be established.

The quality of strain data has allowed a detailed understanding of deformation in the Slate Belt: not only of interest in regional terms, but also from a theoretical viewpoint. These perfect triaxial ellipsoids have provided a means to quantitatively evaluate strain during the generation of slaty cleavage since the classic work of Sorby in the nineteenth century, and will remain a data source of international importance. This work has fuelled an international debate (Tullis and Wood, 1972, 1975; Oertel and Wood, 1974; Wood *et al.*, 1976) on the origin of cleavage, of considerable significance in studies of orogenic processes world-wide. The site illustrates high strain-levels typical of the Slate Belt, which suffered the highest Caledonian strains in North Wales. This is an important factor in ongoing studies of the significance of regional strain variations in the Caledonian Orogenic Belt.

Conclusions

The Slate Belt of North Wales is famous for its deformed rocks of Cambrian age. These have been compressed and folded and now take the form of cleaved slates. The area is well known for the studies which have been carried out on these rocks in relation to the extreme compression suffered by Britain during the Caledonian mountain-building phase, around 400 million years ago. Originally-spherical green spots in the muds (so-called reduction spots) are now perfect ellipsoids and have been used in classic studies to quantify the deformation. It has been shown that the sedimentary sequence has been laterally shortened by up to 63% in a north-west to south-east direction, and elongated to become up to double their original thickness. The perfect cleavage planes that characterize these roofing slates are perpendicular to the shortening and are parallel to the upward elongation. This is a classic locality for the study of folds, cleavage and strain related to the Caledonian Orogeny in Wales.

TRUM Y DDYSGL (SH 544518)

R. Scott

Highlights

Trum y Ddysgl provides a superb section illustrating a rare example of overturning of strata on the north-west limb of the Snowdon Syncline. This indicates a high intensity of deformation, and it contrasts markedly with the more open structures and lower strain seen in central Snowdonia to the north-east, along the strike of the fold structures. The site also provides important exposures of a thrust plane, a very rare feature in the Caledonian Orogenic Belt of North Wales.

Introduction

The Trum y Ddysgl site lies on the north-west limb of the Idwal–Snowdon Syncline (Figures 4.1 and 4.4) and provides a contrast in structural style to the Alexandra Quarry, Cwm Idwal and Capel Curig sites. Bedding–cleavage relationships and sedimentary structures in the steeply dipping Cambrian Ffestiniog Beds indicate that the rocks at the base of the cliffs are slightly overturned. The structure is clearly demonstrated (Figure 4.4) by three prominent quartzite horizons. The Cambrian rocks are thrust south-eastwards over Ordovician slate.

Other than the original survey (Ramsay, 1866, 1881), the only detailed description of the site appears in the account of Shackleton (1959, Figure 4.4), who presented a line-drawing illustrating the main structural features. He also presented a measured section through the Ffestiniog Beds. The site lies in an area between Snowdon (Williams, 1927) and the Slate Belt (Morris and Fearnsides, 1926) with their contrasting structural styles. It has been described in the field guide of Roberts (1979).

Description

The site consists of an almost 1 km-long cliff section (Craig Trum y Ddysgl) to the north-east of the summit of Trum y Ddysgl. The overall structure of the locality is best observed from a viewpoint to the north-east on the opposite side of the glacial cirque of which Craig Trum y Ddysgl forms the south-west wall. The site is described by means of a traverse from the north-west to the south-east (Figure 4.4).

The north-west end of the cliffs are formed from the Cambrian Ffestiniog Beds. These are dominated by grey slate with minor, thin (<0.01 m) silt layers defining the bedding. The orientation of bedding is variable, lying close to the core of the Cym-y-Ffynnon Pericline, and tight mesofolds can be seen in places (for example, at 54305208) to which the

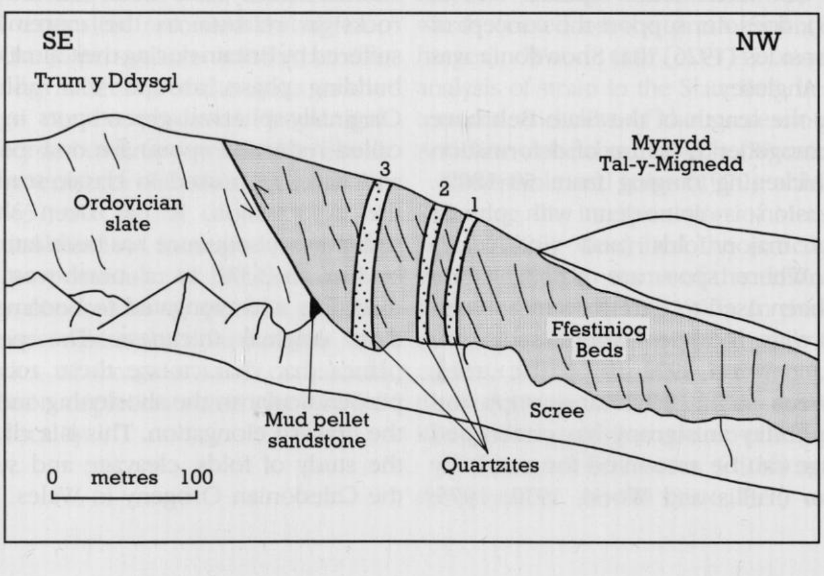


Figure 4.4 View of Trum y Ddysgl looking south-west. Redrawn from Roberts (1979), after Shackleton (1959).

consistently steep NW-dipping cleavage is axial planar. At this locality, cleavage is refracted through more prominent silt layers around the fold hinge and, on the limbs, 0.02 m-thick sand ribs show incipient boudinage. Elsewhere, the tightness of major folds is implied by the small angle between cleavage and bedding.

Traversing along the crags towards the south-east, silt and sand beds become more common until a prominent quartzite bed is reached. This bed (quartzite 1 on Figure 4.4) is the stratigraphically lowest of three prominent quartzite beds up to 20 m thick separated by equivalent thicknesses of shale with thin sandstone beds (Figure 4.4). At the top of the crags, the quartzites dip steeply to the south-east, but at the base they dip steeply to the north-west. Sedimentary structures (cross-lamination and graded bedding) in the shale–silt sequence to the south-east of the quartzite, indicate that the sequence youngs in that direction. The NW-dipping beds at the base of the crags are therefore slightly overturned; here cleavage has the same dip direction but at a lower angle.

Within the thick (sometimes conglomeratic) quartzites, numerous quartz-filled tension gashes can be observed. Some short veins are arranged *en échelon*, while others are more continuous but irregular in orientation; cross-cutting relationships are common. Between the second and third quartzite, 0.5 m-thick sandstone beds in the shale show incipient boudinage, displacement, and quartz veining. In common with the *en échelon* veining in the main quartzite beds, the sense of displacement of the minor boudinaged sandstone beds indicates that the dominant movement of higher levels is toward the south-east.

Further to the south-east along the crags, the Ffestiniog beds are thrust over dark Ordovician slates. The NW-dipping thrust plane 'climbs' the crag in a small gully. The Ordovician slates in the footwall form a monotonous sequence with steeply NW-dipping cleavage, but little indication of bedding. However, at the base of the shale sequence, just below the thrust plane, a small exposed thickness (~2 m) of mud-pellet sandstone, of possible Arenig age (Roberts, 1979), can be seen dipping to the north-west, again indicating overturning below the thrust.

Interpretation

Whereas the north-east end of the Snowdon Syncline is characterized by open folds of larger wavelength, in the south-west, wavelength becomes less and folds tighten. With this in mind, the site at Trum y Ddysgl has been chosen as a contrast to the structural style displayed in the Cwm Idwal and Capel Curig sites.

In terms of the maximal (major) structures defined by Roberts (1979), the site lies toward the northern termination of the periclinal Cwm Pennant Anticline. Tight folding associated with the Cwm Pennant Lineament is considered to have resulted from relatively intense regional deformation associated with the renewal of movement along the line of a synsedimentary fault (Smith, 1988). North of the Cwm Pennant Anticline, the Arfon Anticline becomes the maximal structure adjacent to the Snowdon Syncline. A sharp contrast exists between the strong deformation exhibited by the Slate Belt rocks (for instance, at Alexandra Quarry) on the limb of the Arfon Anticline and the less-deformed volcanic succession of central Snowdonia.

Thrusting is known from only a few rare examples in North Wales; Smith (1987, 1988) has shown that structures interpreted as thrusts by Fearnsides (1910), and Fearnsides and Davies (1944) are, in fact, the product of pre-lithification processes. The variation in fold style between high interlimb angle with upright axial planes and low interlimb angle and more inclined axial planes was attributed to local variations in shear strain by Wilkinson (1987). This model has been developed by Wilkinson (1988) and Smith (1988) who attribute the lower angle of axial planes of some folds to propagation above the tip lines of thrusts which may flatten into cover detachments, the cover–basement interface, or faults within the basement. The Trum y Ddysgl site represents a very rare location where one of these thrusts extends up to exposed levels.

The site provides an excellent example of the fold style and the more intense deformation which characterize the south-west part of the Snowdon Syncline, more particularly on its north-west limb. The section displays overturning, seen in bedding–cleavage relationships and proved by sedimentary structures. Cambrian strata are thrust south-eastwards over Ordovician slates on a NW-dipping thrust plane. Kinematic indicators in quartzite beds of the hanging wall are consistent with the south-easterly overthrusting indicated by stratigraphical relationships.

The regional variations in structural style are central to ongoing reinterpretation of the Caledonian Orogenic Belt, both in North Wales and in Britain as a whole. Particular significance is now attached to the relationship between strain intensity, reflected in fold style, and basement faulting, and this site is of special importance because of the coincidence of high strain and thrust faulting at a single locality. The full significance of these features is not yet certain and this site is likely to attract considerable further study and interpretation.

Conclusions

At Trum y Ddysgl, folding and thrusting by low-angle faults, which were formed during the Caledonian mountain-building episode, affect rocks of the Cambrian and Ordovician periods. Cambrian strata are overturned and are thrust south-eastwards over the younger Ordovician rocks, although such thrusts were a rarity in the Caledonian terrane of Wales. The intense deformation seen here, contrasts with other areas of Snowdonia where the effects of the orogeny were less pronounced.

CWM IDWAL (SH 638588–649607)

W. R. Fitches

Highlights

The Idwal Syncline is the best known and most studied major Caledonian fold in Wales. Cwm Idwal is excavated along the axis of the syncline; it provides outstanding exposures of the fold in plan and profile.

Introduction

Cwm Idwal (Figure 4.5), a glacial cirque, is cut along the hinge zone of the Idwal Syncline, which is a major end-Caledonian fold. The

Figure 4.5 Cwm Idwal, Gwynedd. The right- and left-sloping slabs above the central scree form the syncline hinge of one of the major Caledonian fold structures in Snowdonia, in Ordovician sediments and volcanics. View to south-west, cliff is approximately 300 m high. (Photo: S. Campbell.)

rocks deformed by the structure are products of Ordovician (Caradoc Series) volcanism and sedimentation and belong to the upper part of the Cwm Eigiau Formation, the Lower Rhyolitic Tuff Formation, and the lower part of the Bedded Pyroclastic Formation (Figure 4.6; Howells *et al.*, 1981). The various rocks and processes which produced them are outlined in field guides to Cwm Idwal (Roberts, 1979; Howells *et al.*, 1981) and the site is encompassed by the BGS 1:25 000 Geological Special Sheet for Central Snowdonia.

Description

The Idwal Syncline is a component of the Snowdonia Synclinorium – see Roberts, 1979; Figures 4.1 and 4.2. Its profile is exposed in the back wall of the cirque, where it is seen to be an open to close structure with a NE–SW (Caledonoid) axial plane inclined very steeply to the north-west, while the hinge line is nearly horizontal. Bedding planes in the limbs dip at about 50° toward the trough of the fold. The axial trace continues to the north-east to Llyn Idwal, then turns N–S to pass through the Idwal Cottage Youth Hostel area before ascending the slopes of the Carneddau. In the Idwal Cottage area, the fold tightens and becomes more asymmetrical as the western limb steepens more than the eastern limb, and the southerly plunge becomes moderate to steep. The tightening and increase in plunge intensify toward the closure of the fold in the Carneddau, probably because there the layered rocks were compressed against the Pen-yr-Ole-Wen rhyolite plug (on the north side of Nant Francon) (Wilkinson, 1988, p. 80).

The site exhibits a variety of small-scale structures, several of which have been recently investigated by Wilkinson (1988) during his analysis of strains in Snowdonia. In particular, he used the siliceous concretions in the Pitts Head Tuff and the accretionary lapilli in the Lower Rhyolitic Tuff to measure the amounts of shortening and extension which took place during deformation of the rocks.

The site encompasses an area of several square kilometres so, for descriptive convenience, six separate localities (A–F), containing structures representative of those found in various parts of the site, are described in the following sections (Figure 4.6).

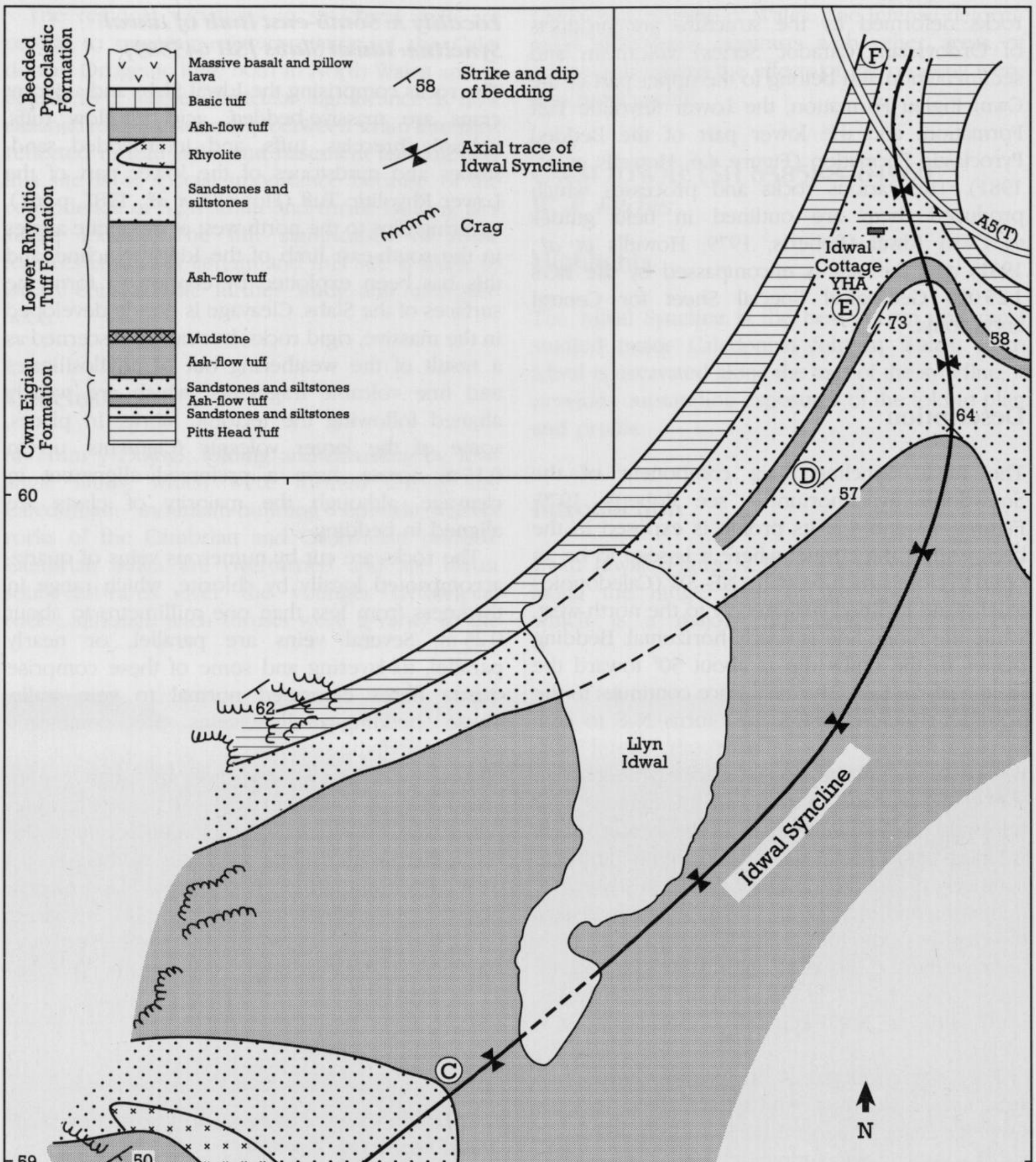
Locality A: South-east limb of Idwal Syncline: Idwal Slabs [SH 645589]

The rocks comprising the Idwal Slabs and adjacent crags are massive-bedded, acid ash-flow tuffs, volcanic breccias, tuffs, and interbedded sandstones and mudstones of the lower part of the Lower Rhyolitic Tuff (Howells *et al.*, 1981, p. 61). Layering dips to the north-west at moderate angles in the south-east limb of the Idwal Syncline, and this has been exploited by erosion to form the surfaces of the Slabs. Cleavage is poorly developed in the massive, rigid rocks, but can be discerned as a result of the weathering out of phyllosilicates and fine volcanic fragments, which are weakly aligned following the tectonic fabric. In places, some of the larger volcanic fragments, up to 0.15 m across, have a preferred alignment in cleavage, although the majority of clasts are aligned in bedding.

The rocks are cut by numerous veins of quartz, accompanied locally by chlorite, which range in thickness from less than one millimetre to about 0.25 m. Several veins are parallel, or nearly parallel, to layering and some of these comprise quartz fibres elongated normal to vein walls. These bedding-parallel veins are commonly slickensided, the striations plunging down the dip of the vein. A second type of quartz vein, accompanying the other type, or occurring independently, is horizontal or inclined gently to the south-east. Several large examples of this second type crop out high up on the Idwal Slabs. Quartz fibres in these flat-lying veins are also elongated normal to the vein walls and are parallel with the striations on the bedding-parallel veins. The flat-lying veins are seen locally to cut those of the other type. Rarely, the flat-lying veins are gently folded in the cleavage.

Locality B: Crags immediately south-west of Idwal Slabs [SH 644589]

The crags adjacent to the footpath and above the Idwal Slabs are formed of beds of upper Lower Rhyolitic Tuff Formation, comprising well-bedded sandstones, siltstones, tuffs, and tuffites (Howells *et al.*, 1981, p. 61). Here, cleavage is more strongly developed than in the Idwal Slabs, because of the better alignment of feldspars and volcanic fragments in the tectonic fabric. Large volcanic clasts and brown-weathering carbonate concretions, between 0.10 m and 1.5 m across, mostly remain aligned parallel with bedding, but some smaller


Bedded Pyroclastic Formation
Lower Rhyolitic Tuff Formation
Cwm Eigiau Formation
Massive basalt and pillow lava
Basic tuff
Ash-flow tuff
Rhyolite
Sandstones and siltstones
Ash-flow tuff
Mudstone
Ash-flow tuff
Sandstones and siltstones
Ash-flow tuff
Sandstones and siltstones
Pitts Head Tuff
58
Strike and dip of bedding
Axial trace of Idwal Syncline
Crag
F
A5(T)
Idwal Cottage YHA
E
73
58
64
D
57
62
Llyn Idwal
Idwal Syncline
C
N
50
A
B
56
Idwal Slabs
52
Twll Du
46
0
metres
300
60
59
64
65

ones have been apparently rotated towards the cleavage.

Locality C: Syncline core [SH 642591]

The well-bedded rocks at (B) dip at progressively shallower angles to the north-west into the hinge of the Idwal Syncline, forming a line of low crags which descend from locality B towards the southern end of Llyn Idwal. Clean, fresh exposures of the rocks are found in the beds of streams descending to the lake and cutting through the crags.

Cleavage is well-developed in these rocks of the fold hinge, and is formed by the strong preferred alignment of quartz grains, quartz pressure-fringes on feldspars, and phyllosilicates. The rocks also contain scattered, dark-grey accretionary lapilli, pea-sized clots of volcanic ash which were originally nearly spherical, but are now deformed into triaxial ellipsoids, flattened parallel to the cleavage and extended vertically. Volcanic clasts and carbonate concretions also commonly show strong alignment in the cleavage; contrasting with most other localities where the majority remain elongated parallel to the bedding.

Locality D: North-west limb of syncline [around SH 646601]

The Pitts Head Tuff and the sandstones, siltstones, and acid tuffs above, belonging to the Cwm Eigiau Formation, are well exposed in the north-west limb of the Idwal Syncline, in a broad strike-parallel ridge which extends from the northern end of Llyn Idwal toward the Idwal Cottage Youth Hostel. Bedding dips steeply to the south-east at angles of up to 80°, and cleavage dips at about 70°NW. Cross-bedding in the sandstones shows that the beds are the right way-up and that the structure is upward-facing.

Siliceous concretions (lithophysae) are common in the upper part of the Pitts Head Tuff. These are pea- to tennis ball-sized, white-weathering masses of silica, or very fine quartz, which were precipitated from solutions migrating through the volcanic pile soon after its accumulation. The originally nearly spherical concretions have been slightly flattened in cleavage and extended vertically during deformation.

In places along the ridge, the Pitts Head Tuff shows well-developed columnar jointing formed during cooling and contraction of the volcanic pile. The columns were originally set perpendicular to layering, but have been realigned by compression in the Idwal Syncline and now lie at angles of about 60° to layering and plunge at moderate angles to the north-west. These deformed columns afford the opportunity for the measurement of strain in the Idwal Syncline. As at the Idwal Slabs (above), this ridge contains numerous examples of quartz veins. Some are parallel with bedding, while others with a flat-lying attitude, form ladder arrays nearly parallel with bedding.

Locality E: Honestone Quarry [SH 648602]

The long, ravine-like quarry immediately above the Youth Hostel cuts along the strike of interbedded, light-coloured, fine-grained tuffs and dark mudstones of the Eigiau Formation. Bedding dips very steeply to the south-east, in the north-west limb of the Idwal Syncline, and according to cross-bedding in some tuffs, youngs to the south-east. Cleavage is nearly vertical and is unusually strong due to the high degree of phyllosilicate alignment, which is sufficiently intense to give some of the deformed mudstones a phyllitic fabric, characterized by shiny surfaces.

Locality F: A.5 road-cutting and adjacent crags [SH 649606]

A series of crags some 15 m north-east of the road exposes well-bedded volcanogenic sandstones which lie immediately above the Pitts Head Tuff. The sandstones, dipping about 70°SE, contain 0.1–0.5 m-thick layers, crowded with 10–40 mm brachiopod shells preserved in brown-weathering carbonate. These shells have been strongly deformed in the steeply dipping cleavage. On steep surfaces striking at right-angles to the cleavage, the originally gently curved shells are seen to be almost isoclinally folded.

In the cutting on the north-east side of the road, the upper parts of the Pitts Head Tuff show the very strong planar alignment of *fiammé* (pumice fragments) and other volcanic ejecta caused by compaction and welding during accumulation of the hot ash pile; this fabric is mostly parallel with

Figure 4.6 Cwm Idwal. Geological map showing the positions of Localities A–F described in the text.

bedding in the overlying sedimentary rocks. Unlike those sedimentary rocks, the welded tuffs are often uncleaved, due to their greater rigidity during deformation. However, cleavage is developed in places, usually in narrow, 0.5 m-wide zones. Locally in the tuffs, particularly rigid layers have been boudinaged, individual boudins becoming separated by 0.1–0.2 m-long quartz lenses.

In the cutting on the south-west side of the road, there are several quartz veins, mostly less than 1 m in length, which dip moderately to steeply to the south-east. These veins are arranged *en échelon* in two tension gash arrays, the larger of which is over 10 m in length. The sense of shear indicated by these arrays is top side to the south-east.

The Idwal Syncline as exposed in Cwm Idwal is a major fold with a steep NE–SW axial plane and nearly horizontal plunge. The south-east limb is represented at the Idwal Slabs (Locality A), the north-west limb at Locality D, and the core at Locality C. Toward the north-east the fold tightens, the axial plane swings to a more nearly N–S strike and the plunge becomes steep to the south, probably because the rocks were deformed against the rigid Pen-yr-Ole-Wen Rhyolite (Wilkinson, 1988). The fold is typical of those produced by the main deformation phase. It offers particularly fine, three-dimensional exposures to study the full geometry of such a major fold.

The exposures, the variety of lithologies and the presence of deformed strain markers provide an unrivalled opportunity to examine the relationships of cleavage to a main-phase fold. Cleavage is more or less axial planar to the syncline in Cwm Idwal, striking NE–SW and dipping very steeply to the north-west. Wilkinson (1988) reports that it transects the northern end of the structure in a clockwise sense in the flanks of the Carneddau, north of the site.

The character of the cleavage within the site is variable, probably because of the variations in lithology. Cleavage is commonly absent or barely discernible in the strongly welded parts of the Pitts Head Tuff (for example, Locality F). The ash-flow tuffs, breccias and coarse volcanogenic sandstones usually take a feeble cleavage; a spaced type with little grain alignment. In parts of the volcanic rocks, however, the cleavage becomes penetrative, as the volcanic clasts, quartz pressure fringes on feldspars, and new phyllosilicates take on a strong preferred alignment. The strongest cleavage within the site is found in the Honestone Quarry (for example, Locality E) where phyllosilicates in the original mudstones and fine-grained volcanic and volcaniclastic rocks are aligned sufficiently uniformly to give an almost phyllitic cleavage.

There are various strain markers within the site: originally nearly spherical accretionary lapilli (for example, Locality C) and siliceous concretions (for example, Locality D), brachiopod shells (for example, Locality F), and columnar joints which were originally elongated normal to layering in the Pitts Head Tuff (for example, Locality D). Wilkinson (1988) has used the accretionary lapilli and concretions to show that strains in Cwm Idwal are nearly plane strain: the flattening in cleavage is almost compensated for by vertical extension while there was little change in dimensions horizontally in the cleavage.

There are a number of small-scale structures exposed at the site, related to the development of the main-phase fold. These have not been studied previously but offer considerable research potential. Veins are common but appear to have attracted no comment in published literature. Of particular interest are the veins aligned parallel with bedding and those which are flat lying (for example, Localities A and D). These two types of vein are considered here to be products of flexural slip which accompanied the development of the Idwal Syncline. The bedding-parallel veins represent slip surfaces along bedding, while the others are more or less contemporaneous tension gash arrays. The slip-senses, deduced from rare *en bayonet* bedding-parallel veins, the *en échelon* arrangement of the other veins (Figure 4.7B), and the down-dip striations on bedding-parallel veins, are consistent with displacement resulting from accommodation during folding (Figure 4.7B).

Interpretation

The folding of some tension-gash veinlets (Locality A) is interpreted as the effect of flexural slip during initial buckling, as illustrated in Figure 4.7B. The observation that these veinlets are themselves folded, indicates that cleavage development outlasted parts of the flexural slip history of the fold. The boudins (Locality F) are interpreted as examples of inverse boudins (cf. Ramsay, 1983, Figure 3B); quartz veins which had been formed at the necks of early, square-ended boudins acted as more rigid layers during later, more ductile stages of extension, so that the sites of necking moved

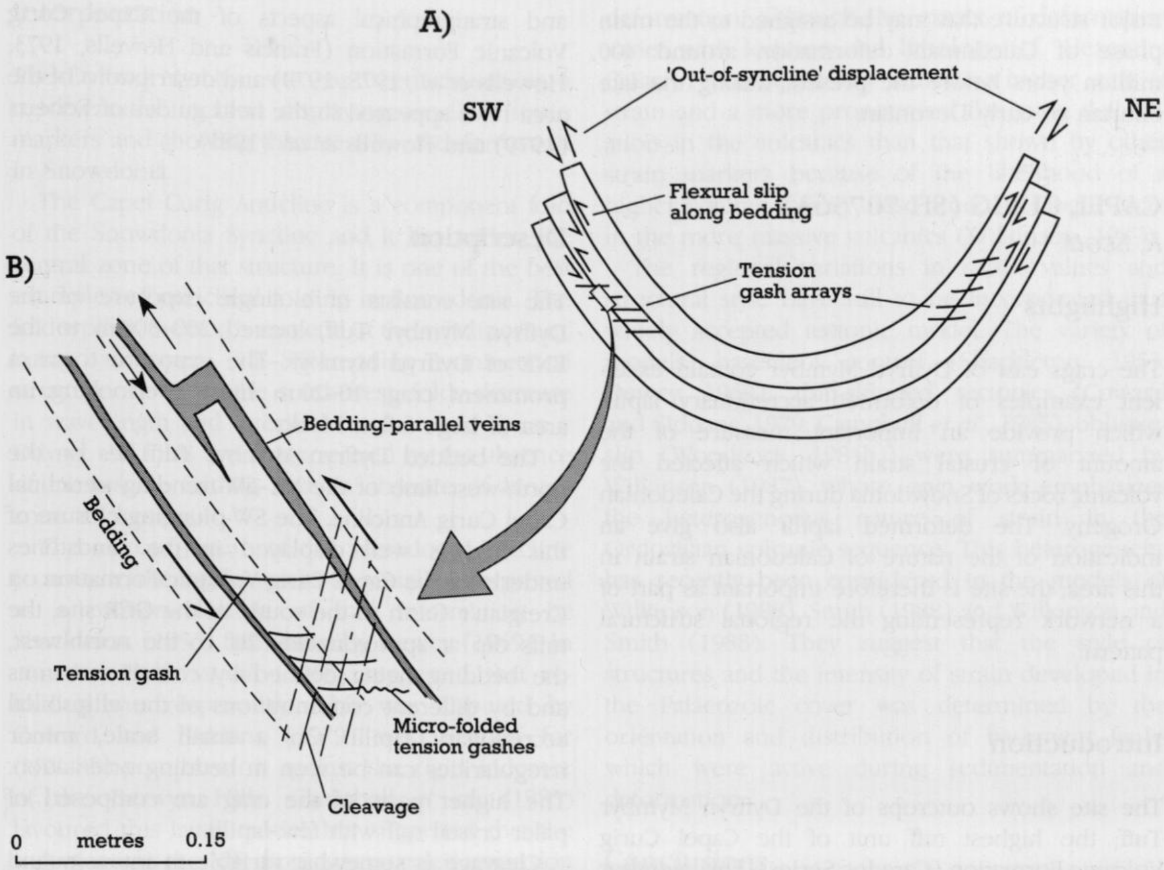


Figure 4.7 Cwm Idwal. (A) 'Out-of-syncline' flexural slip and tension gash arrays in the Idwal Syncline. (B) Combination of *en bayonet* bedding-parallel veins and tension gashes, south-east limit of Idwal Syncline (Locality A).

into the boudins which had been formed early in the progressive deformation.

The Idwal Syncline is one of the best-known Caledonian structures in Britain thanks to the superb exposures provided in the floor and walls of Cwm Idwal. The scale of the features, and the high level of exposure here, present an outstanding opportunity for detailed structural studies including three-dimensional strain variations within a major Caledonian fold, developed in the main phase during the late Silurian–early Devonian. The fold has the NE–SW trend characteristic both of Snowdonia and of the British Caledonian fold belt. The Idwal Syncline characterizes the gentler style of deformation and lower levels of strain typical of central Snowdonia, contrasting with the high strains of the Slate Belt. There is marked variation in cleavage development within the site from very weak in parts of the Pitts Head Tuff to strong and phyllitic in the mudstones of the Honestone Quarry. Other minor structures such as volcanic lapilli and deformed fossils are valuable as strain markers and have been used in recent regional studies. The locality provides the best exposed structure of its kind in central Snowdonia, with great potential for future studies.

Conclusions

The scale and three-dimensional nature of the rock exposures at Cwm Idwal provide unrivalled opportunities for detailed studies of a major fold formed during the Caledonian mountain-building period. Small-scale structures associated with the fold, including cleavage (fine, closely-spaced, parallel fractures), deformed fossils, concretions, and mineral veins are exposed at many localities, and these enable detailed studies of the nature and intensity of strain and its variation throughout the folds to be carried out. This site affords opportunities to study, in three dimensions, a major structure that may be assigned to the main phase of Caledonian deformation around 400 million years before the present during the late Silurian or early Devonian.

CAPEL CURIG (SH 707563)

R. Scott

Highlights

The crags east of Dyffryd Mymbyr contain excellent examples of deformed accretionary lapilli which provide an important measure of the amount of crustal strain which affected the volcanic rocks of Snowdonia during the Caledonian Orogeny. The deformed lapilli also give an indication of the nature of Caledonian strain in this area; the site is therefore important as part of a network representing the regional structural pattern.

Introduction

The site shows outcrops of the Dyffryn Mymbyr Tuff; the highest tuff unit of the Capel Curig Volcanic Formation (Caradoc Series). This member only occurs on the north-west limb of the periclinal Capel Curig Anticline (Howells *et al.*, 1978) and is characterized by beds rich in whole and fragmented accretionary lapilli indicative of subaerial deposition. The deformed lapilli record the state of strain in this component fold of the Snowdonia Syncline – see Figures 4.1 and 4.2. The lapilli tuff at Capel Curig has become a standard for the practical illustration of strain measurement in undergraduate teaching and in numerous textbooks (for example, Ramsay, 1967; Ramsay and Huber, 1983).

The Capel Curig district was first investigated in a systematic fashion by Jukes, Aveline, and Selwyn who undertook the primary survey, started in 1848, with maps and sections published by the Geological Survey (1851–55). The structure and stratigraphy of the district were also outlined in the North Wales memoir (Ramsay, 1866, 1881). The first detailed map and description was that of Williams (1922). In recent years, the district around Capel Curig has been incorporated in regional strain studies (Siddans, 1971; Coward and Siddans, 1979; Wilkinson, 1987, 1988). A number of studies have concentrated on volcanological and stratigraphical aspects of the Capel Curig Volcanic Formation (Francis and Howells, 1973; Howells *et al.*, 1978, 1979) and descriptions of the area have appeared in the field guides of Roberts (1979) and Howells *et al.* (1981).

Description

The site consists of a single exposure of the Dyffryn Mymbyr Tuff, located 200–300 m to the ENE of Dyffryd Mymbyr. The exposure forms a prominent crag, 10–20 m high, overlooking an area of large fallen blocks.

The bedded Dyffryn Mymbyr Tuff lies on the north-west limb of the NE–SW-trending periclinal Capel Curig Anticline. The SW-plunging closure of this fold is well displayed in the sandstones underlying the Capel Curig Volcanic Formation on Creigiau'r Garth to the south. At the GCR site, the tuffs dip at approximately 20° to the north-west, the bedding being defined by colour variations and by different concentrations of the ellipsoidal accretionary lapilli. On a small scale, minor irregularities can be seen in bedding orientation. The higher parts of the crag are composed of paler crystal tuff with few lapilli.

Cleavage is somewhat variable in intensity and irregular in orientation, refracting between lithologies. The general dip is 70° to the north-west, and the steep face of the crags runs approximately parallel to the 050°–060° strike. Large cleavage surfaces >0.15 m apart define units containing weaker cleavage surfaces which are discontinuous and occasionally anastomose around the lapilli.

The best examples of the strained accretionary lapilli can be observed at the base of the crags on either side of a small wall. Individual lapilli are near-perfect ellipsoids. They have x dimensions from 1 to 25 mm which on cleavage (xy) planes, pitch 70° from the north-east, illustrating the steep nature of extension. Some, although by no means all, of the larger crystal fragments in the surrounding tuff are also elongated parallel to the long axes of the lapilli. The y axis of the lapilli is parallel to the gently plunging axis of the south-west end of the Capel Curig Anticline. Large joint surfaces intersecting the face of the crags produce planes approximating to the (xz) axes in which flattening in the plane of cleavage can be observed. Overall, axial ratios in the lapilli ($x>y>z$) approximate to 4:3:1.

Interpretation

The Dyffryd Mymbyr site has been chosen as a representative location displaying excellent strain markers and showing the intensity of deformation in Snowdonia.

The Capel Curig Anticline is a component fold of the Snowdonia Syncline and it lies within the central zone of that structure. It is one of the best examples of periclinal folding in Snowdonia. The fold typifies the north-east end of the synclinorium, being an open, NE–SW-trending symmetrical structure. Towards the south-west, folds decrease in wavelength and interlimb angle – see Trum y Ddysgl. All folds are characterized by the absence of meso-scale folding and an absence of hinge-zone thickening.

The arcuate nature of the Snowdonia Syncline (convex to the north-west) was initially interpreted as a primary feature of the deformation by Shackleton (1953) and, later, by Dewey (1969). In contrast, Helm *et al.* (1963) suggested that refolding was responsible. This was disputed by Coward and Siddans (1979) who argued for (NW–SE) compression against the rigid indentor of the Berwyn Hills. Campbell *et al.* (1985) favoured this latter model, but suggested that the indentor was the NW-dipping concealed extension of the Tan y Grisiau microgranite. Strain has been measured in the volcanic rocks of Snowdonia (Siddans, 1971; Roberts and Siddans, 1971; Coward and Siddans, 1979; Wilkinson, 1987, 1988) using a variety of volcanogenic markers (siliceous nodules, rhyolite clasts, tuff clasts, and accretionary lapilli). The compilation of strain data by Coward and Siddans (1979) is incompatible with refolding and, therefore, disagrees with the interpretation of Helm *et al.* (1963). Wilkinson (1987) showed strain in Snowdonia to be heterogeneous, but approximating overall to plane strain with a vertical extension rarely exceeding 130% in tuffs.

The Dyffryd Mymbyr site displays excellent examples of strained accretionary lapilli. The steep, north-westerly plunge of the x axis, sub-horizontal NE–SW y axis, and shallow south-easterly plunging z axis shown by these lapilli are typical throughout Snowdonia. In common with the Lower Palaeozoic succession throughout North Wales, this indicates vertical extension in response to NW–SE compression during the main phase deformation, although the extent of deformation varies with location and lithology (cf. Alexandra Quarry). The lapilli may indicate a higher state of strain and a more pronounced flattening deformation in the volcanics than that shown by other strain markers because of the likelihood of a higher volume loss in these other lithologies than in the more massive volcanics (Wilkinson, 1987).

The regional variations in strain values and structural style have still to be incorporated in a widely accepted tectonic model. The variety of models: basement control (Shackleton, 1953; Dewey, 1969); 'thin-skinned' tectonics (Coward and Siddans, 1979; Campbell *et al.*, 1985); oblique-slip (Woodcock, 1984b)) were summarized by Wilkinson (1987), whose own work emphasizes the heterogeneous nature of strain in the Ordovician volcanic sequence. This heterogeneity has recently been considered in the models of Wilkinson (1988), Smith (1988) and Wilkinson and Smith (1988). They suggest that the style of structures and the intensity of strain developed in the Palaeozoic cover was determined by the orientation and distribution of basement faults which were active during sedimentation and deformation.

Conclusions

The tuffs at this locality contain accretionary lapilli (originally, spherical hailstone-like accumulations of volcanic ash). These now perfect ellipsoidal objects are excellent indicators with which the Caledonian strain within the Ordovician volcanic rocks of Snowdonia can be measured. Their degree of distortion makes it possible to assess the actual amount of tectonic deformation (crustal shortening) to which Snowdonia was subjected during the Caledonian mountain-building episode, around 400 million years before the present.

Strain measurement has played an important role in interpreting the structure of the Caledonian Orogenic Belt of North Wales, and there is ongoing research in this field. This site lies within the Capel Curig Anticline, probably the best example of the periclinal folds of Snowdonia, and it illustrates the open structural style of the north-eastern end of the Snowdonia Synclinorium, contrasting markedly with the site at Trum y Ddysgl where deformation was more acute.

TAN Y GRISIAU (SH 683454)

R. Scott

Highlights

This locality displays excellent examples of deformed contact-metamorphic spots in cleaved Tremadoc siltstones and pelites. The contact spots provide a means of dating the Tan y Grisiau microgranite intrusion in relation to the deformation of North Wales that was imposed during the Caledonian Orogeny. In addition, the spots and cleavage are important in the measurement and analysis of the strain imposed in southern Snowdonia during the orogeny, and this has an important bearing on the postulated 'Tremadoc Thrust Zone'.

Introduction

The site provides an example of deformed metamorphic spots in Tremadoc Series siltstones and pelites within the contact aureole of the Tan y Grisiau microgranite. The microgranite, which lies 700 m south-east of the site, has a roof area, estimated by Campbell *et al.* (1985) to measure about 10 km by 5 km, dipping beneath the site at about 20°. The aureole extends at least 1 km on this north-west side. Dark metamorphic spots are flattened in the plane of the north-dipping cleavage and are extended down dip.

Areas adjacent to the Tan y Grisiau intrusion have been the subject of numerous structural studies, of which the work of Fearnsides (1910) and Fearnsides and Davies (1944) are notable early examples. To the south-west of the microgranite lies the Tremadoc Thrust Zone, a band of crush belts and high strain which may be olistostromic. A detailed petrological study of the granite was presented by Bromley (1963) who also contributed to a series of later papers (Bromley, 1969, 1971; Lynas, 1970a, 1973; Fitch *et al.*, 1969), which were concerned with the structural relationships of the granite and its host rocks. The interpretation of the flat-lying cleavage favoured by Lynas (1970a) was combined with the thrust model of Fearnsides and Davies (1944) in the general structural interpretation of Coward and Siddans (1979).

Recent work by Campbell *et al.* (1985) has modified the general model of Coward and Siddans (1979), and has confirmed the view that low-angle cleavage around Tan y Grisiau is equivalent to the upright main cleavage elsewhere in North Wales. Smith (1987, 1988) has cast doubt on previous interpretations of low-angle discordances to the west of Tan y Grisiau. Instead, he suggests that the Tremadoc Thrust Zone (Fearnsides, 1910) may be an olistostrome.

Description

The Tan y Grisiau GCR site consists of an exposure of metasediment illustrating representative examples of the deformed contact spots. Within the exposure, Tremadoc sediments dip to the north at ~45°, with a single cleavage dipping at a slightly steeper angle in the same direction. Numerous, black contact-metamorphic spots appear throughout the sediments and different concentrations of spots help define the bedding. The spots are mainly oval in shape and generally have a maximum diameter <0.01 m, although some approach 0.02 m. Cordierite was the original mineral forming these rounded spots which now have a retrogressive mineralogy of chlorite and sericite. Occasional angular spots which are lath- or diamond-shaped may have had andalusite as a precursor.

Strain can be estimated using a combination of cleavage and joint surfaces on which various sections of the strain ellipse can be measured. The spots here are flattened in the cleavage and have *x*-axes which plunge down the cleavage surface toward the north. A grain-shape fabric in the matrix has the same orientation. Joint surfaces in a variety of orientations allow an accurate picture of the strain ellipsoid to be obtained. An average axial ratio (x:y:z:) of 1.72:1:0.67 has been calculated at the site using 30 spots (Smith, 1988).

Several thin (<0.01 m) veins cross-cut the sediments and some possess symmetrically disposed colour zoning, produced by hydrothermal alteration, which may extend up to 0.04 m into the surrounding rock. Occasionally these veins contain euhedral quartz, calcite, and minor pyrite. The veins, and the retrogressive mineralogy of the spots, are the consequence of an expulsion of volatiles from the granite during the latter stages of its crystallization.

Interpretation

Two aspects of the geology of the Tan y Grisiau area have provoked controversy in the literature:

1. the relative age of the microgranite intrusion with respect to the regional deformation of the surrounding rocks; and
2. the age of the low-angle cleavage in the aureole and elsewhere on the southern margin of Snowdonia.

Both these age relationships are crucial to the interpretation of the structural development of the area between Snowdonia and the Harlech Dome. The chosen site provides an example of the orientation relationships and strain data available for such investigations.

The accepted age of the Tan y Grisiau microgranite, with respect to deformation, has progressively changed during the course of a prolonged period of investigation. Early workers considered it to be post-tectonic (Jennings and Williams, 1891), whereas Fearnsides and Davies (1944) considered it to be post-cleavage, but to pre-date the Tremadoc Thrust (Fearnsides, 1910). Shackleton (1953) considered the intrusion to be truly synorogenic. However, more recent research has demonstrated that the intrusion pre-dated the cleavage because the contact-metamorphic spots are deformed within the plane of the main cleavage (Bromley, 1969; Coward and Siddans, 1979), an interpretation confirmed by a minimum age of 477 ± 20 Ma obtained for the granite by Fitch *et al.* (1969).

The aureole of the microgranite is characterized by a low-angle, northerly dipping cleavage which is developed only in Cambrian and Ordovician strata along the northern flank of the Harlech Dome. Lynas (1970a, 1973) interpreted this flat-lying cleavage as the product of a deformation which preceded that forming the main cleavage elsewhere. Coward and Siddans (1979) suggested that this fabric was related to the development of the Tremadoc Thrust Zone. However, the interpretation of this flat-lying cleavage as a low-angle manifestation of the steeply dipping main phase (that is, late Silurian–early Devonian) cleavage elsewhere (Bromley, 1971), has been confirmed by recent work (Campbell *et al.*, 1985; Smith, 1987, 1988).

Campbell *et al.* (1985) reassessed the model of Coward and Siddans (1979) and, while they still preferred a 'thin-skinned' interpretation of structural evolution, modified it so that the subsurface extension of the Tan y Grisiau microgranite played a dominant role in thrusting. In their model, the microgranite body acted as a rigid block over the roof of which the bulk of Snowdonia was ramped during the main Caledonian deformation. This provided an explanation for both the shallow dip of the main cleavage and the northerly dipping extension direction indicated by the contact spots and mineral grain elongation. In addition, the low angle between cleavage and bedding was thought to have facilitated dislocation along the Tremadoc Thrust Zone where shear-strain was at a maximum.

Recent work by Smith (1987, 1988) has reassessed the evidence for the existence of the Tremadoc Thrust Zone and favours a pre-deformation explanation for the features previously attributed to thrusting; features such as crushing, faulting, bed repetition, and high strain associated with the zone. A strain study, which included investigation of the deformed contact spots of the microgranite aureole, indicated relatively low strain with the exception of a narrow zone of intense prolate strains in the Rhyd area, a 7 km-long strike to the south-west. Smith (1987, 1988) considered these unusually high strains to be related to compression against the rigid subsurface extension of the microgranite, but high strains being achieved without detachment along a specific thrust plane; an assessment recently confirmed by radiometric methods.

In addition, the siltstones and shales have a 'low-angle' cleavage found extensively along the northern flank of the Harlech Dome. This cleavage and the related Tremadoc Thrust Zone have been the subject of some controversy. It is now agreed that the cleavage at the site is a variation on the main-phase regional cleavage whose low angle of dip is a local deflection related to the presence of the underlying microgranite intrusion. One interpretation (Campbell *et al.*, 1985) sees the low angle and local high strain as results of a thrust ramp which transported Snowdonia south-eastwards over the rigid block during the main deformation phase. However, Smith (1987) denies the presence of any discrete thrusting, but accepts that the angle of cleavage and its intensity has been controlled by the presence of the microgranite. Although the measurement of the deformed contact spots at this site have provided further important data for the nature of the Caledonian strain, measurements of similar spots in the contact aureole over a wider area would enable the effect of the pre-deformation intrusion to be seen in a wider context.

Conclusions

This locality shows excellent exposures of Tremadoc (early Ordovician Period) siltstones and shales which have been affected by baking by a later igneous intrusion, the Tan y Grisiau microgranite. Contact spots, a product of the baking, have developed within the altered zone (aureole) around the Tan y Grisiau microgranite intrusion. These spots may be seen to be deformed, which is evidence of tectonic deformation after the emplacement of the microgranite. The deformed spots have played an important role in resolving the debate about the age of the intrusion relative to the formation of the main Caledonian cleavage.

The microgranite was emplaced around 470 million years before the present. This is consistent with a date of around 400 million years for the main Caledonian mountain-building event, including the low-angle cleavage, which deforms the spots in the granite aureole. The unusual cleavage here has been interpreted as due to Snowdonia being pushed (thrust) southwards over the buried microgranite mass.

OGOF GYNFOR (SH 37779476–37939500)

D. E. B. Bates

Highlights

At Ogof Gynfor the Precambrian Mona Complex of Anglesey is overlain unconformably by Ordovician conglomerates and cherty shales. The dramatic folding and faulting of the two sequences is of great importance in the controversy over the stratigraphical, structural, and metamorphic relationships between the two units, which represent one type of relationship between basement and cover in the Welsh Caledonides.

Introduction

The older rocks at Ogof Gynfor (Figure 4.8) consist of siliceous Gwna Mélange of the Precambrian Mona Complex. It contains a large mass of quartzite which may form a particularly large block within the mélange. The Ordovician conglomerates, of the Torllwyn Formation of the Arenig Series, rest unconformably on this basement and are succeeded disconformably by the Caradoc Gynfor Shales. The Ordovician sequence has been strongly folded, into a series of four synclines and three anticlines, with dips up to the vertical. Both rock units have then been cut by reverse faults, giving some of the folds the geometry of hanging-wall anticlines and footwall synclines; lower-angle thrust splays are present, and finally there are steep northerly-dipping normal faults. A schistosity pervades the Mona Complex and a slaty, or spaced, cleavage the Ordovician rocks.

Matley (1899, p. 648) first described the section in detail, and used it to demonstrate the existence of a sub-Ordovician unconformity in Anglesey, and the presence of thrusting. It was also described and figured by Greenly (1919). Shackleton (1954) drew attention to the basement to cover relationships shown by the faulting, and Bates (1968) recognized the Arenig–Caradoc disconformity, and gave further description (Bates, 1972, 1974).

More recently, controversy has centred on the relationship between the Mona Complex and the Ordovician. Barber and Max (1979) have claimed that, contrary to earlier workers, both sequences were affected by a single deformation event, placing them in their Cemlyn Tectonic Unit.

Description

The sequence from Llanbadrig Point to the south side of Ogof Gynfor is formed of Gwna Mélange. At the south side of the inlet (SH 37869475) a fault with a steep northerly dip downfaults the Ordovician Torllwyn Formation to the north. It rests here unconformably on the Gwna Mélange, but the surface of the unconformity is inaccessible in the cliff. Above is a small quarry in the Arenig conglomerates, with poorly preserved brachiopods. Within the inlet are several fault-bounded masses of Gwna Mélange, Arenig Torllwyn Formation and Caradoc Gynfor Shales (Figure 4.8). On the north side of the inlet a major, vertical, WNW–ESE-striking fault separates this complex from a high ridge of Gwna Mélange and quartzite. This ridge is terminated to the north by another vertical fault, which downthrows the succession once more to bring the Ordovician conglomerates to sea-level.

The cliffs from here (SH 37829484) to the north end of the section expose the irregular unconformity between the Gwna Mélange and the overlying grits. The mélange contains a marked penetrative cleavage, which has a similar steep attitude to the spaced cleavage in the grits above.

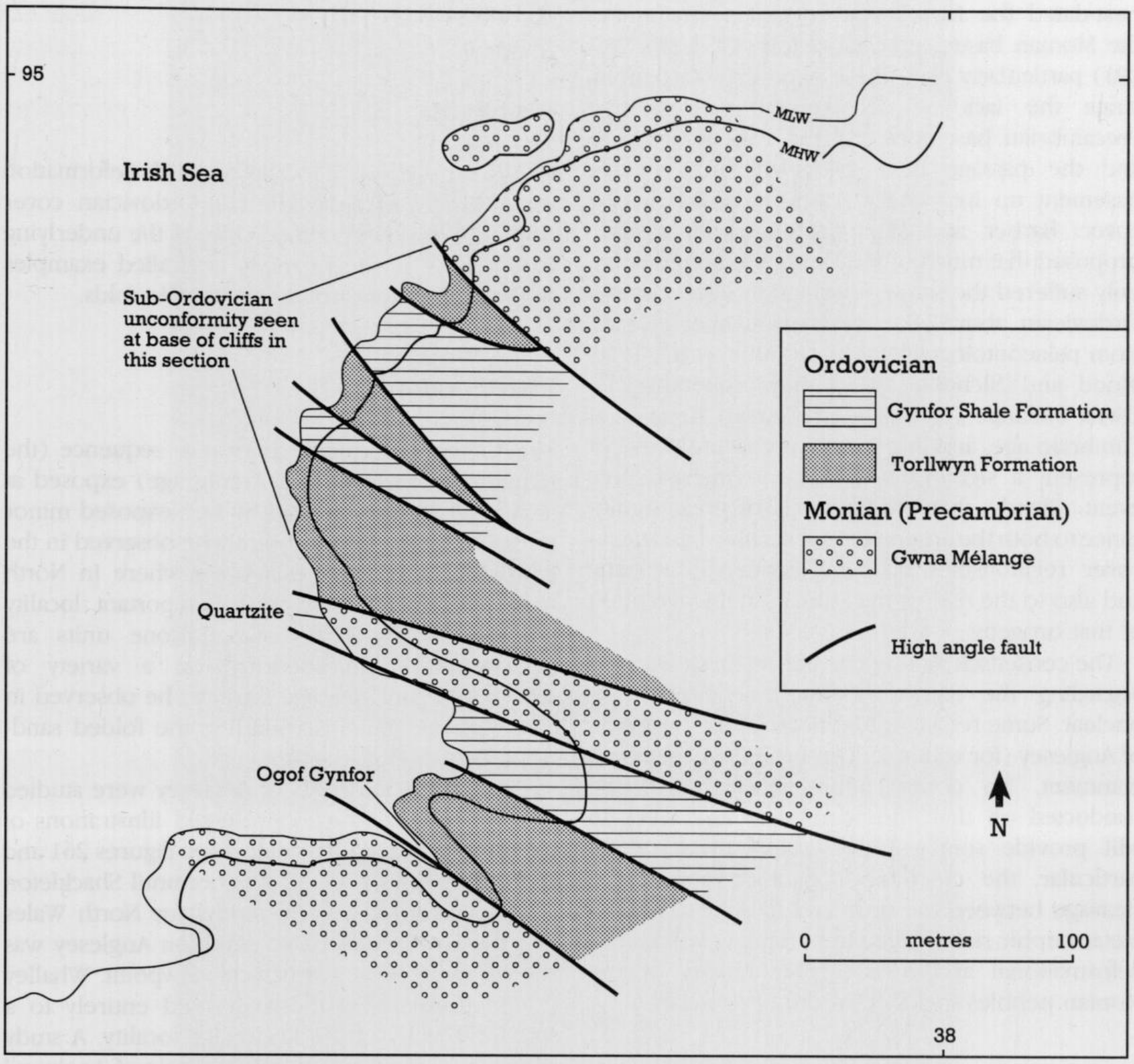


Figure 4.8 Geology of the Ogof Gynfor site.

Pebbles of Monian rocks occur in the Ordovician. The structure consists of two synclines and an intervening anticline, all faulted to some extent. The north limbs of both synclines are cut by reverse faults, which each give the appearance of footwall synclines. Thus the anticline becomes a hanging-wall anticline; the more northerly fault brings back the Gwna Mélange to the cliff top, and so no anticline is associated with it. The cleavage in the Ordovician rocks becomes more intense towards these faults. Lower-angle thrusting is also associated with the reverse fault at the northern end of the section.

Interpretation

The structural interest of this site lies in the relationships between the folding and faulting, particularly the way in which the faults are associated with folds and cleavage in the Ordovician sequence, and the way in which folds in the cover pass down into faults in the basement.

Prior to the work of Barber and Max (1979) all workers were agreed that the Gwna Mélange formed an integral part of the stratigraphical succession of the Precambrian Monian. Although Shackleton (1969) showed that the mélange was of sedimentary origin rather than tectonic, as maintained by Greenly (1919), both he and Bates (1972, 1974) agreed that the Ordovician deposition post-dated the Late Precambrian deformation of the Monian basement. Shackleton (1954, pp. 289, 291) particularly used these exposures to demonstrate the lack of décollement between the Precambrian basement and the Palaeozoic cover and the passage from clean-cut faults in the basement up into shear zones and folds in the cover. Barber and Max (1979), however, have proposed that much of the Monian of Anglesey has only suffered the same deformation history as the Ordovician above. For this reason and, in part, from palaeontological evidence (Muir *et al.*, 1979; Wood and Nicholls, 1973), they argue that the Gwna Mélange (part of their Cemlyn Unit) is of Cambrian age, and that the unconformity does not represent a significant tectonic or metamorphic event. Clearly, this hypothesis is of great significance to both the arguments concerning basement–cover relationships in the Caledonian Orogeny and also to the role of the Monian in the evolution of that orogeny.

The consensus among current research workers regarding the nature of this unconformity is unclear. Some recent publications on the evolution of Anglesey (for example, Gibbons, 1987) make no comment. No doubt, future research will be conducted on this important topic and this site will provide some of the crucial evidence. In particular, the continuity, or otherwise, of the cleavage between the units and their comparative metamorphic state will be important, as will be the deformational and metamorphic history of the Monian pebbles included in the Ordovician.

Conclusion

Ogof Gynfor provides important exposures of the unconformable contact between the Precambrian Mona Complex rocks and overlying Ordovician conglomerates and shales. Recent interpretations of the structure of Wales place great emphasis upon the significance of faults in the Precambrian basement and their influence, during the Caledonian Orogeny, on strain variation and structural style in the Lower Palaeozoic cover rocks. The structural significance of this site lies in the opportunity that it provides to examine the structural characteristics of and relationship between juxtaposed Precambrian basement and the Lower Palaeozoic, for instance, the way in which folds in the cover pass down into faults in the basement.

RHOSNEIGR (SH 317734)

R. Scott

Highlights

Rhosneigr provides a locality at which deformation on a variety of scales in the Ordovician cover sequence can be examined close to the underlying basement. The site provides unrivalled examples of strain variation around small-scale folds.

Introduction

The folded Ordovician greywacke sequence (the Nantannog Formation, of Arenig age) exposed at Rhosneigr is characterized by well-exposed minor folds. As minor folds can rarely be observed in the Lower Palaeozoic succession elsewhere in North Wales, Rhosneigr provides an important locality for their study. Folds of sandstone units are demonstrably non-cylindrical on a variety of scales. Excellent cleavage fans can be observed in the mudrock units surrounding the folded sandstone layers (Figure 4.9).

The Ordovician rocks of Anglesey were studied by Greenly (1919) who presented illustrations of the minor folds at Rhosneigr – see Figures 261 and 262 in Greenly (1919). It was not until Shackleton (1954) erected a general model for North Wales that the Lower Palaeozoic cover on Anglesey was reconsidered from a structural viewpoint. Whalley (1973) presented a thesis devoted entirely to a structural study of the Rhosneigr locality. A study of structures in the Lower Palaeozoic of Anglesey, including a description of Rhosneigr was undertaken by Bates (1974) who, like Shackleton (1954), emphasized the importance of basement control on deformation in the cover. The Rhosneigr locality was also mentioned in the paper of Barber and Max (1979).

The excellent degree of exposure at the site has allowed theoretical models of cleavage formation to be developed. In addition to the work of Whalley (1973), detailed studies include those of Knipe and White (1977) and White and Knipe (1978) which are of international significance in the study of cleavage formation. The site has also appeared in field guides (Barber *et al.*, 1981; Bates and Davies, 1981).

Description

The GCR site consists of an area of wave-cut

Figure 4.9 Rhosneigr, Anglesey. Tight minor folds in thin sandstones exemplify the intensity of the deformation in north-west Wales. The enclosing slates have been the subject of studies on the nature of slaty cleavage and strain variations around folded layers (penknife, centre, is 6 cm long). (Photo: J. Treagus.)

platform located to the west of the town. Some of the features of interest are illustrated by stereographic projection (Figure 4.10) and by line drawing (Figure 4.11).

An Ordovician greywacke sequence is deformed by upright folds on a variety of scales. Cleavage dips steeply to the north-west, as generally does bedding, but at moderate angles. The dominant sense of vergence is therefore toward the south-east. The greywacke sequence is dominated by shales, with folds delineated by discontinuous sandstone beds, generally <0.3 m thick. Knipe and White (1977) defined two types of fold based on scale:

1. macrofolds with a wavelength >10 m and
2. meso-(parasitic) folds with a mean wavelength ~0.5 m.

Two scales of non-cylindricity (fold axis curvature) can also be identified:

1. individual fold axes curve markedly within a

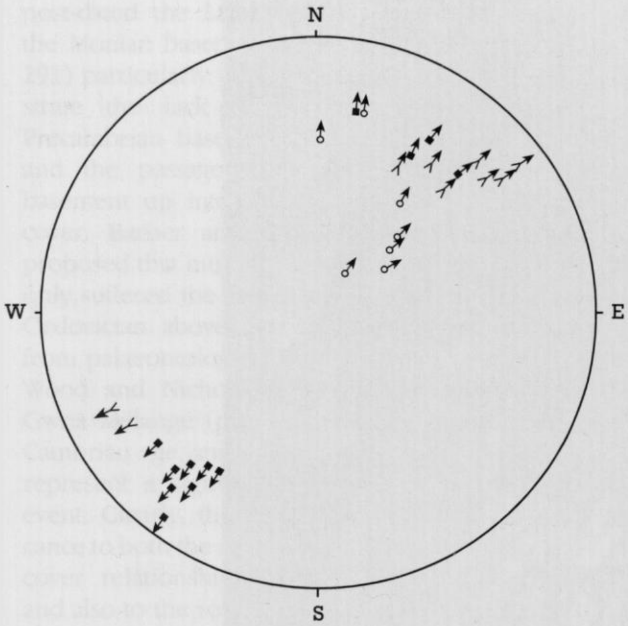


Figure 4.10 Equal-area stereographic projection of the plunge of minor fold axes at Rhosneigr. The site measurements are represented by the head of the arrow, and are divided into three subareas; circles = central, squares = NE and Vs = SW.

single exposure (for example, at SH 31637319) and

2. a general change in the plunge of folds is seen along the strike of the outcrop (Figure 4.10).

Individual mesofolds have divergent cleavage fans in the surrounding mudrocks while the cleavage refracts strongly through sandstones as convergent fans of series of spaced fractures perpendicular to bedding. Locally, cleavage in the shales is parallel to the outside arcs of the folded sandstones, defining a triangular zone of weak cleavage orientation, the finite neutral point of Ramsay and Huber (1987, p. 461). Figure 4.11 shows the pattern of cleavage displayed by the folds. A detailed account of the cleavage pattern is provided by Knipe and White (1977).

Exposed folded sandstone surfaces display fracture sets that are disposed symmetrically about fold hinges. At one location (SH 31637319), minor quartz slickensides on sandstone bedding surfaces suggest that some flexural slip was involved in fold development. Elsewhere, small quartz-filled fractures indicate extension in the outer arc of sandstone beds during folding.

Irregularly spaced rusty fractures can be observed in the mudrocks which appear to post-date the cleavage. They are generally subvertical

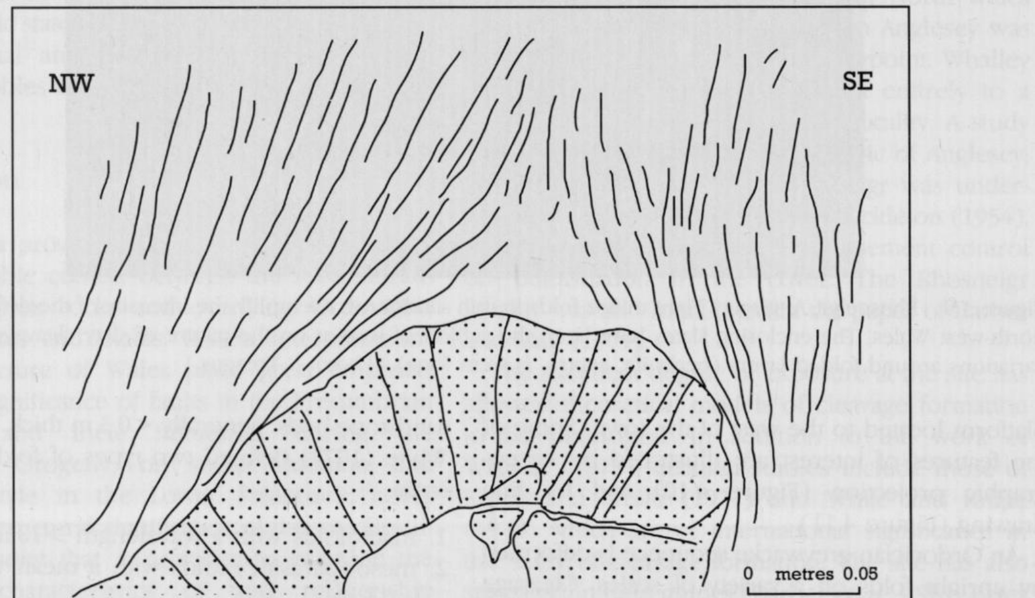


Figure 4.11 Rhosneigr. Line-drawing illustrating the strong cleavage refraction associated with the hinge of a meso-scale fold delineated by sandstone surrounded by pelite. A photograph of this fold appears in Ramsay and Huber (1983, figure 10.18).

and often strike approximately parallel to cleavage, but their orientation and spacing are very irregular. They occasionally reach widths of a centimetre and many contain a breccia of pelite fragments. At SH 31727338, folded sandstone beds are displaced along these rusty fractures, dominantly in a sinistral sense, by up to 1 m. A minor occurrence of *en échelon* quartz veining (at SH 31867350) is compatible with the sinistral displacement on the subvertical fractures. The fractures are also associated with small-scale thrusting of fold pairs (see Greenly, 1919; Figure 263).

Interpretation

The Ordovician of Anglesey lies unconformably on the Precambrian Mona Complex, many of the contacts being faulted. The majority of work on Anglesey has concentrated on the basement lithologies and their deformation. The general consensus is that this deformation was Precambrian in age (Roberts, 1979). However, as stated above, other workers have suggested that the Ordovician and Gwna Mélange were deformed together, for the first time, during the later stages of the Caledonian Orogeny (Barber and Max, 1979).

Shackleton (1953, 1954) stressed the importance of basement control on deformation of the Lower Palaeozoic cover in North Wales. He also emphasized the absence of a major décollement between cover and basement. The pattern of fold and cleavage orientations indicated to Bates (1974) that pre-existing structural trends in the Mona Complex dictated the deformation pattern in the Ordovician succession. However, the orientation of structures and degree of deformation at Rhosneigr are similar to those observed in similar lithologies on mainland North Wales where, presumably, the basement at depth had a much reduced influence on deformation in the cover.

In particular, it is interesting to note that, despite the close proximity (a few hundred metres) of the basement, the non-cylindrical nature of minor folds at Rhosneigr is compatible with the periclinal form of major folds in Snowdonia. The implication is clearly that, although the basement may have controlled the orientation of structures, the style and degree of deformation were controlled largely by processes acting within the cover. This is compatible with the 'thin-skinned' model of structural evolution (Coward and Siddans, 1979; Campbell *et al.*, 1985) and the strike-slip model of Woodcock (1984a).

Strike-slip or oblique-slip transpression during the Caledonian Orogeny may be used to explain the structures seen at Rhosneigr (see below), particularly considering its location close to faults on which major strike-slip motion has been proposed (Nutt and Smith, 1981). The rusty fractures on which sinistral displacement is apparent could with some certainty be ascribed to strike-slip movement, and a slight angle between axial traces and the strike of cleavage (Knipe and White, 1977) could be attributed to an earlier oblique-slip during the main deformation. However, considering the small-scale examples of basement faults passing up into the Ordovician cover sequence on Anglesey (see Ogof Gynfor above), perhaps the recently developed models of Smith (1988), Wilkinson (1988), and Wilkinson and Smith (1988) offer the most suitable explanation of the structure. Thus strike-slip movements on reactivated basement fractures may have provided, in a transpressional regime, the local heterogeneous strain manifested by the obliquity of cleavage to the axial planes and the late sinistral fractures.

Minor folds are rarely seen in the Lower Palaeozoic rocks of North Wales. The excellent exposure of the minor folds at Rhosneigr has made them suitable for detailed theoretical studies (Whalley, 1973; Knipe and White, 1977; White and Knipe, 1978). Knipe and White (1977) produced a detailed study of strain distribution in natural folds using a symmetrical meso-anticline from Rhosneigr, and later (White and Knipe, 1978) used slate from the site in the development of a model to explain cleavage initiation.

Conclusions

The Rhosneigr site, with its alternations of hard sandstones and soft mudstones, provides an excellent example of small-scale, non-cylindrical folding. This folding occurred during the Caledonian mountain-building phase, affecting a sequence of Ordovician sedimentary rocks. With its wealth of minor folds which are uncommon elsewhere in North Wales, the site provides an important locality at which the morphology of such folds can be compared with that of the major Caledonian folds. The outcrops here, very close to the underlying crystalline Precambrian basement, provide a location at which the influence of basement control on Caledonian deformation can be assessed, by comparison with localities on the

Welsh mainland where the cover was thicker and the structures that were developed were presumably further away from the influence of the ancient basement. Here the structures are similar to those seen further south in North Wales, and therefore are not thought to be greatly influenced by the Precambrian basement. This is an important issue in the interpretation of the Caledonian structure of Wales. The quality of these outcrops has enabled a detailed theoretical analysis to be undertaken on the basis of the relationship between cleavage and folding, and this has made a significant international contribution to studies of the origin of cleavage (Whalley, 1973; Knipe and White, 1977; White and Knipe, 1978).

CWM RHEIDOL (SN 70057955–71147920)

W. R. Fitches

Highlights

This site illustrates the morphology and style of small-scale folds which are parasitic to major folds produced during the Caledonian Orogeny; folds on this scale are uncommon in most parts of the Welsh Basin. The site also exhibits the poor cleavage characteristic of west Central Wales, and provides examples of pencil cleavage.

Introduction

The Cwm Rheidol site has been chosen to represent a profile through a series of small-scale folds, developed on the limb of a major fold, the Plynlimon Dome, in a section of Lower Silurian sedimentary rocks. The structures at this site have not been described in the literature, although they resemble those discussed by Tremlett (1982), Craig (1985), and Cave and Hains (1986) in other parts of Central Wales. The Lower Silurian rocks of this region are described by Cave and Hains (1986).

Description

The 1 km-long track section exposes a 400 m-thick succession of well-bedded sandstones, siltstones and mudstones. The succession is the 'right way up' on the evidence of the cross-lamination and ripple-marks which abound in the section. The sheet dip over the whole section is about 20° to the WNW, consistent with its position on the south-west flank of the Plynlimon Dome. The Silurian sedimentary sequence has here been shortened by 17–23%.

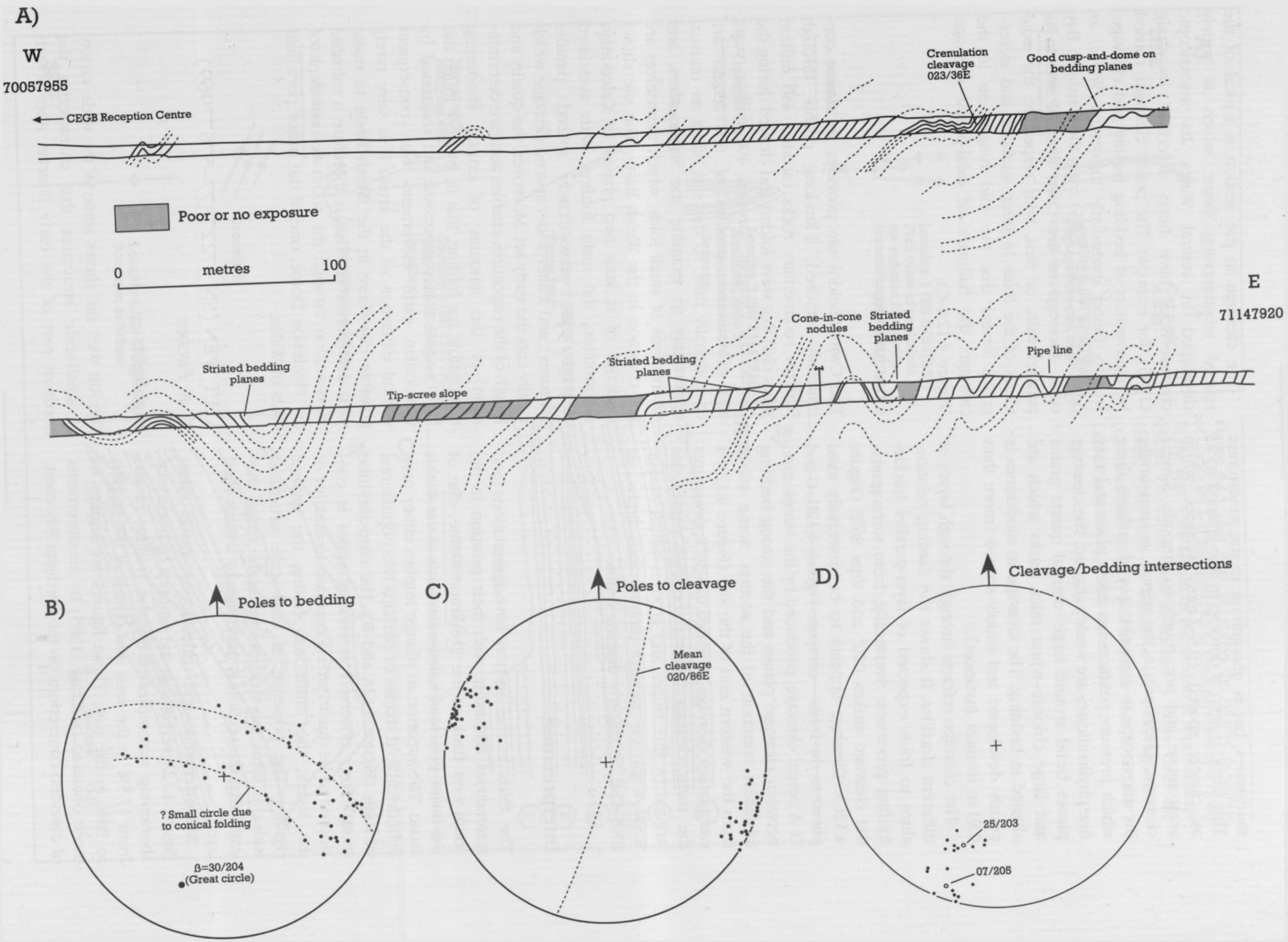
Folds occur on several scales, with wavelengths ranging from *c.* 400 m down to 0.10 m; most are in the range 1–10 m (Figure 4.12A). The folds are upward-facing, according to younging evidence, have upright NNE–SSW axial planes, plunge gently to moderately to the SSW, and are symmetrical or Z-folds in down-plunge profile. The variation in amount of plunge (horizontal to 40°SSW), obtained from stereograms of bedding (Figure 4.12B), of cleavage–bedding intersections (Figure 4.12D) and direct measurements of fold hinges, is probably due to non-cylindrical fold morphology, although there are indications of two distinct plunge populations.

The folds range from open to close, locally becoming tight with interlimb angles of less than 40°. Anticlines typically have rounded open profiles, whereas most of the synclines are close to tight with narrow hinge zones. This geometrical pattern resembles the cusp-and-lobe, or mullion structure described elsewhere by Sokoutis (1987) and Ramsay and Huber (1987, p. 397). On a smaller scale, cusp-and-lobe style structures are commonly developed in sandstone beds and are clearly seen on many bedding planes; wavelengths are usually in the 0.02–0.10 m range. These small structures, which have nucleated on sedimentary ripple structures in the sandstones in several instances, resemble the cusp-and-furrow described and illustrated by Cave and Hains (1986, Plate 17).

Most folds have Class 1B (parallel) geometry (Ramsay, 1967), but in some of the tighter anticlines and in most synclines the mudstone and siltstone layers have been slightly thickened in hinges to give a Class 1C geometry.

Cleavage is ubiquitous in the siltstones and

Figure 4.12 Cwm Rheidol. (A) Section along track showing bedding attitudes in siltstones and mudstones. Parts (B), (C) and (D) are equal-area stereographic projections of poles to bedding, poles to cleavage, and cleavage–bedding intersections respectively. (B) Dashed lines show great circle and small circle limits of the distribution and the large filled circle gives the pole to the great circle. (C) Dashed line represents mean cleavage attitude. (D) The two mean plunges of the cleavage–bedding intersections (open circles) can be seen to lie on the mean cleavage of (C) as does the pole to the bedding readings in (B).


A)
W
70057955
CEGB Reception Centre
Crenulation cleavage 023/36E
Good cusp-and-dome on bedding planes
Poor or no exposure
0
metres
100
E
71147920
Striated bedding planes
Tip-scree slope
Striated bedding planes
Cone-in-cone nodules
Striated bedding planes
Pipe line
B)
Poles to bedding
? Small circle due to conical folding
β=30/204 (Great circle)
C)
Poles to cleavage
Mean cleavage 020/86E
D)
Cleavage/bedding intersections
25/203
07/205

mudstones, but is uncommon in the sandstones. This fabric is seen at outcrop in fine-grained rocks as closely spaced (0.5–2 mm) surfaces which anastomose and are rough to smooth. Similar cleavage, elsewhere in the region, is seen under the microscope to comprise spaced surfaces along which pressure solution has taken place and very fine phyllosilicates are weakly aligned. The cleavage planes braid around large, detrital quartz grains and large chlorite–white mica stacks which are aligned in bedding. The cleavage in sandstones is poorly developed and widely spaced (more than 0.01 m in most instances).

The cleavage refracts strongly through layers of different ductility. It shows the fanning relationships to folds expected of layer-parallel buckle-folding processes. Statistically, from stereograms, the cleavage strikes 020° and dips 86°E (Figure 4.12C). Cleavage appears to be essentially axial planar to the folds – compare Figures 4.12B, C and D. A pencil cleavage, produced by the intersection between cleavage planes and the strong bedding fabric, is common in the section. Some 400 m from the western end of the site (Figure 4.12), a crenulation cleavage, oriented 023/36°E, overprints the main cleavage. Several bedding planes are striated by fine ridges and grooves which plunge WSW–WNW on westerly-dipping fold limbs, or ENE–ESE on easterly dipping limbs.

Interpretation

The folds in this section have orientations and symmetries consistent with their position in the south-west flank of the Plynlimon Dome, one of the major periclinal Caledonian folds of the Welsh Basin. The variation in plunge implies either non-cylindrical fold shapes or perhaps two populations of folds (Figure 4.12A and B). The cusp-and-lobe morphology observed at various scales is considered to be due to strong contrasts in ductility of the layers, the sandstones having the greater rigidity. The presence of large-scale structures with this form, the synclines being the cusps, may imply that the section is underlain by a thick rigid layer.

Measurements and calculations made from Figure 4.12A reveal that the amount of horizontal shortening accomplished by the folding ranges from 17.5% in the west and centre of the section to 28% in the east. These figures are similar to those obtained by Craig (1985) by measurements of distorted concretions on the Cardigan Bay coast.

The cleavage in the section is typical of the spaced anastomosing fabric which is widely developed in central Wales. Its microscopic characteristics have been described by Craig (1985), for example. The pencil cleavage, caused by intersection of bedding fissility and cleavage, is also found extensively in central Wales, as described by Craig (1985) from the Cardigan Bay coast. Cleavage in the Cwm Rheidol section is parallel with, or fans, with respect to the axial traces of the folds in steep surfaces, and stereograms reveal that the fold hinges lie in the cleavage; the hallmark of axial-planar cleavage (Figure 4.12A–C).

Conclusions

The Cwm Rheidol site provides an almost continuously exposed, 1 km-long profile through Silurian sedimentary rocks (around 440 million years old) that were folded and cleaved during the Caledonian Orogeny (around 400 million years ago). Continuous profiles of this length are exceptionally rare, so the site offers an unusual opportunity to examine the styles, sizes, and orientations of small folds, which themselves are not common in the Welsh Basin. The site shows evidence of at least two phases of Caledonian deformation, the main folding, with associated cleavage (fine, very closely spaced, parallel fractures), and a later wider-spaced cleavage which locally cuts the early set. Moreover, the quality and length of the exposures enables accurate determination of the amounts of crustal shortening responsible for folding; that is, by how much the Earth's crust was compressed and shortened by Caledonian earth movements with consequent vertical extension of the crust. It is very rarely possible elsewhere in the Welsh Basin to make such determinations. This is therefore a valuable cross-section through the south-western flank of the Plynlimon Dome, one of the major periclinal folds of Wales.

ALLT WEN (SN 57227877–57677969)

W. R. Fitches

Highlights

The Allt Wen site shows some of the wide variety of small-scale structures that characterize the northern part of the early Silurian Aberystwyth

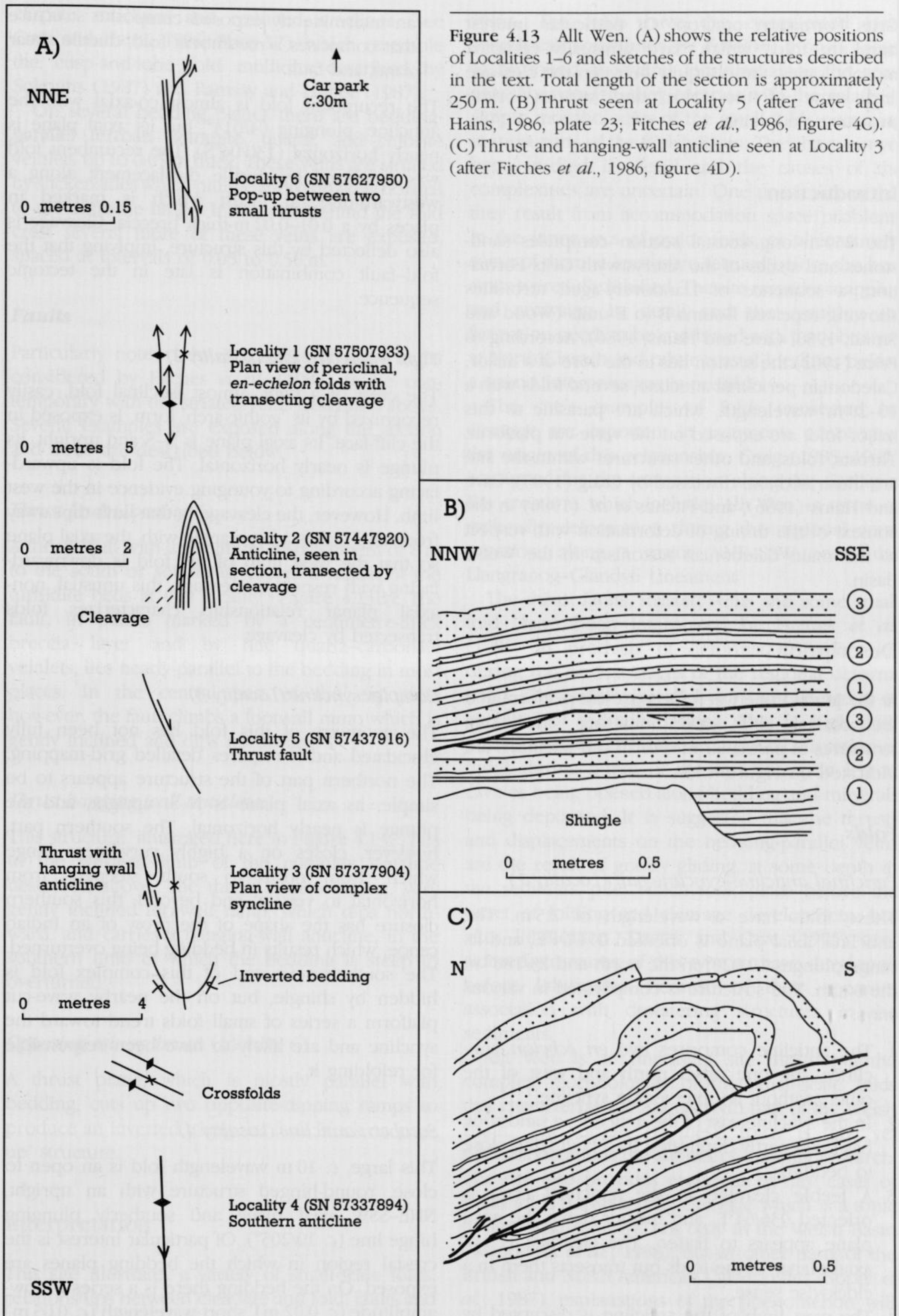


Figure 4.13 Allt Wen. (A) shows the relative positions of Localities 1–6 and sketches of the structures described in the text. Total length of the section is approximately 250 m. (B) Thrust seen at Locality 5 (after Cave and Hains, 1986, plate 23; Fitches *et al.*, 1986, figure 4C). (C) Thrust and hanging-wall anticline seen at Locality 3 (after Fitches *et al.*, 1986, figure 4D).

Grits Formation outcrop. Of particular interest here are folds which have unusually complex morphologies, the obliquity between the cleavage and some of the folds, and various brittle structures and veins.

Introduction

The 250 m-long coastal section comprises sandstones and shales of the Aberystwyth Grits Formation, a sequence of Llandovery-aged turbidites showing repeated Bouma B to E units (Wood and Smith, 1958; Cave and Hains, 1986). According to Price (1962) the section lies in the core of a major, Caledonian periclinal anticline; several folds with a 10–20 m wavelength, which are parasitic to this major fold, are exposed on the wave-cut platform. Thrusts, folds, and other structures within the site are illustrated and discussed by Craig (1985), Cave and Hains (1986), and Fitches *et al.* (1986) in the context of the timing of deformation with respect to the main Caledonian tectonism in the Welsh Basin.

Description

At the junction between the wave-cut platform and the coastal cliffs, are numerous small-scale structures of particular interest. Their positions are indicated on Figure 4.13A.

Folds

Periclinal anticline–syncline pair (Locality 1)

These folds have a wavelength of 2.5 m. The anticlinal axial plane is oriented 011/64°E, and its hinge plunges 10/020° in the north and 23/186° in the south. The structure is complicated in various ways:

1. The anticline comprises two *en échelon* anticlines, the one offset north and west of the other, without an intervening syncline;
2. In the syncline east of the anticline, a sandstone has been partly duplicated by a fault lying close to bedding;
3. A feeble cleavage in the anticlinal crest is oriented 036/64°E, and further down the axial plane appears to flatten. The cleavage is not axial planar to the folds but transects them in a clockwise sense.
4. The west limb of the anticline is disrupted by an intermittently exposed composite structure that comprises a recumbent fold, ductile shear zone, and fault.

The recumbent fold is almost co-axial with the anticline, plunging 04/014°, but its axial plane is nearly horizontal (130/04°S). The recumbent fold was produced by ductile displacement along a westward-directed thrust which is marked in places by a 0.01–0.02 m-thick breccia. Cleavage is also deflected by this structure, implying that the fold–fault combination is late in the tectonic sequence.

Tight transected fold (Locality 2)

The crest of a tight, almost isoclinal fold, easily recognized by its ‘gothic-arch’ form, is exposed in the cliff-face. Its axial plane is N–S and upright, its plunge is nearly horizontal. The fold is upward-facing according to younging evidence in the west limb. However, the cleavage in that limb dips away from, and makes a large angle with, the axial plane so that the west limb of the fold is downward-facing with respect to cleavage; this unusual, non-axial planar relationship characterizes folds transected by cleavage.

Complex syncline (Locality 3)

The geometry of this fold has not been fully elucidated and it requires detailed grid-mapping. The northern part of the structure appears to be simple; its axial plane is N–S, upright, and the plunge is nearly horizontal. The southern part, however, closes on a highly curvilinear hinge which, from north to south, steepens from horizontal to vertical and beyond; this southern closure has the shape of the prow of an Indian canoe, which results in bedding being overturned. The southernmost end of this complex fold is hidden by shingle, but on the nearby wave-cut platform a series of small folds trend toward the syncline and are likely to have been responsible for refolding it.

Southern anticline (Locality 4)

This large, *c.* 10 m wavelength fold is an open to close, round-hinged structure with an upright, NNE–SSW axial plane and southerly plunging hinge line (*c.* 10/205°). Of particular interest is the crestal region in which the bedding planes are exposed. On the bedding there is a series of low-amplitude (*c.* 0.02 m), short-wavelength (*c.* 0.05 m) cuspate anticlines and rounded synclines (see Cave and Hains, 1986, Plate 17), which resemble the cusp-and-lobe fold mullions described by Sokoutis (1987) and Ramsay and Huber (1987).

On several bedding planes there are bedding-parallel ferroan dolomite, quartz, and chlorite veinlets up to 0.05 m thick. These veins are striated by slickensides which plunge approximately normal to the anticline hinge. In the cliff behind the fold crest several more of these veins are exposed, spaced at intervals of 0.05 to 0.50 m.

Faults

Particularly noteworthy is a series of small faults considered by Fitches *et al.* (1986) to be contemporary with the striated veins described above. Several examples are exposed along the section and three are described below.

Thrust fault (*Locality 5*)

A thrust fault with a minimum displacement of 8 m to the south or south-east causes a repeat of the turbidite beds at this locality (Figure 4.13B). The fault, in places marked by a centimetre-thick breccia layer and by fine quartz–carbonate veinlets, lies nearly parallel to the bedding in most places. In the central part of the exposure, however, the fault climbs a footwall ramp which is gently inclined and dips northward.

Thrust-hanging wall anticline

This structure, illustrated here in Figure 4.13C, lies in the western limb of the complex syncline described above. The thrust climbs a long, very gently inclined footwall ramp, which dips northward, and carries a hanging-wall anticline, in the southern limb of which the bedding is steep to overturned.

Opposing minor thrusts (*Locality 6*)

A thrust plane, which is mostly parallel with bedding, cuts up two opposite-dipping ramps to produce an inverted triangular fault block or 'pop-up' structure.

Interpretation

This site illustrates a variety of small-scale folds, relationships between cleavage and fold, faults and veins. The folds have the complicated non-cylindrical, sometimes *en échelon*, morphologies to be found at several localities along the coast near Aberystwyth; they contrast with the relatively simple morphologies of the small folds occurring in most parts of the Welsh Basin. They have not yet been studied in detail and the causes of the complexities are uncertain. One possibility is that they result from accommodation space problems in the inner arcs of major folds, or alternatively, some of them at least were formed before the host strata were fully lithified. The site requires mapping and analysing in detail and the resulting information needs to be combined with that obtained at North Clarach and other coastal localities before a sound interpretation is possible.

The site's examples of folds transected by cleavage are important in arguments concerning the origin of this relationship. Craig (1985, 1987) accounted for the transection along the Cardigan Bay coastline, which includes Allt Wen, in terms of strike-slip deformation during the regional compression, along a major NNE–SSW zone, the Llangranog–Glandyfi Lineament.

The thrust faults, striated veins and some small folds have been interpreted by Fitches *et al.* (1986) as products of deformation before or during the earliest stages of the regional deformation. The bedding-parallel veins are regarded as products of hydraulic jacking. That is, high fluid pressures caused by impeded upward migration of fluids during burial of the sediment pile led to cavities being opened along bedding and minerals being deposited. It is suggested that the thrusts and displacements on the bedding-parallel veins are the result of gravity gliding, at some depth in the sediment pile, which took place before the onset of folding and cleavage development, but after lithification. Davies and Cave (1976) considered structures of this type to have developed before lithification because of their apparent association with dewatering structures in the sediments.

Allt Wen is an important site illustrating the complex morphologies of the small-scale folds that characterize the Aberystwyth part of the Welsh Basin. The origin of these folds is not yet understood and is the subject of ongoing research. The site also provides examples of rare cases of small folds transected by cleavage which is a topic under close scrutiny, not only in the Welsh Basin (Woodcock *et al.*, 1988), but in other parts of the British and North American Caledonides (Soper *et al.*, 1987); explanations of the phenomenon will lead to a clearer understanding of the plate tectonic evolution of the basin.

Several of the small-scale structures at Allt Wen have been illustrated and discussed in recent publications dealing with the timing of the structures, with respect to lithification and the regional deformation. These topics remain controversial and the site is likely to receive further attention by researchers.

Conclusions

The site at Allt Wen includes a whole suite of structures, folds, cleavage (very fine, closely spaced, parallel fractures), and faults, which affect the early Silurian-aged Aberystwyth Grits. These structures are the result of extreme compression during the Caledonian mountain-building episode, around 400 million years before the present. The complexities of the thrusts (low-angle faults), folds, and cleavage here have yet to be studied and explained fully. For instance, the cleavage slightly cuts across the planes that bisect fold limb-pairs (the axial planes). This is an uncommon relationship in fold belts but, by analogy with other Caledonian terranes in Britain, may be related to the oblique approach of the colliding continents as the Iapetus Ocean closed.

Some structures here are thought to have been generated before the main (Devonian) deformation phase of the orogeny, and to have been formed as contortions in the perhaps still wet sediment pile, or perhaps as the sediments moved downslope under the influence of gravity. Upon this folding would have been superimposed the regional tectonic pattern of folding and cleavage. This remains a site with much potential for future study.

NORTH CLARACH (SN 58508410–58578446)

W. R. Fitches

Highlights

The folds in the Llandovery Series (Lower Silurian) sedimentary rocks at the North Clarach site have unusually complicated geometrical relationships with the cleavage, which makes the site particularly important for research into the relative timing of these two types of structure. The site also provides clear, small-scale examples of cleavage transection, a phenomenon of topical research interest in the Welsh Basin. This phenomenon has implications for the understanding of the plate tectonic setting of the basin.

Introduction

This site consists of a wave-cut platform, submerged at mid- and high-tide, showing folded and cleaved turbiditic sandstones, siltstones, and mudstones of the Aberystwyth Grits Formation. These sedimentary rocks have been described by Wood and Smith (1958), and Cave and Hains (1986). The principal points of interest here are the examples of repeated (or progressive) folding and of various geometrical relationships between folding and cleavage. Cleavage transects some folds, is axial-planar to others, and locally is itself apparently folded. The platform at Clarach has been mapped at a scale of 1:50 by Mrs R. Johnson, formerly of University College of Wales, Aberystwyth. Her map is reproduced in simplified form as Figure 4.14. The structures displayed in the platform were briefly commented on by Fitches and Johnson (1978).

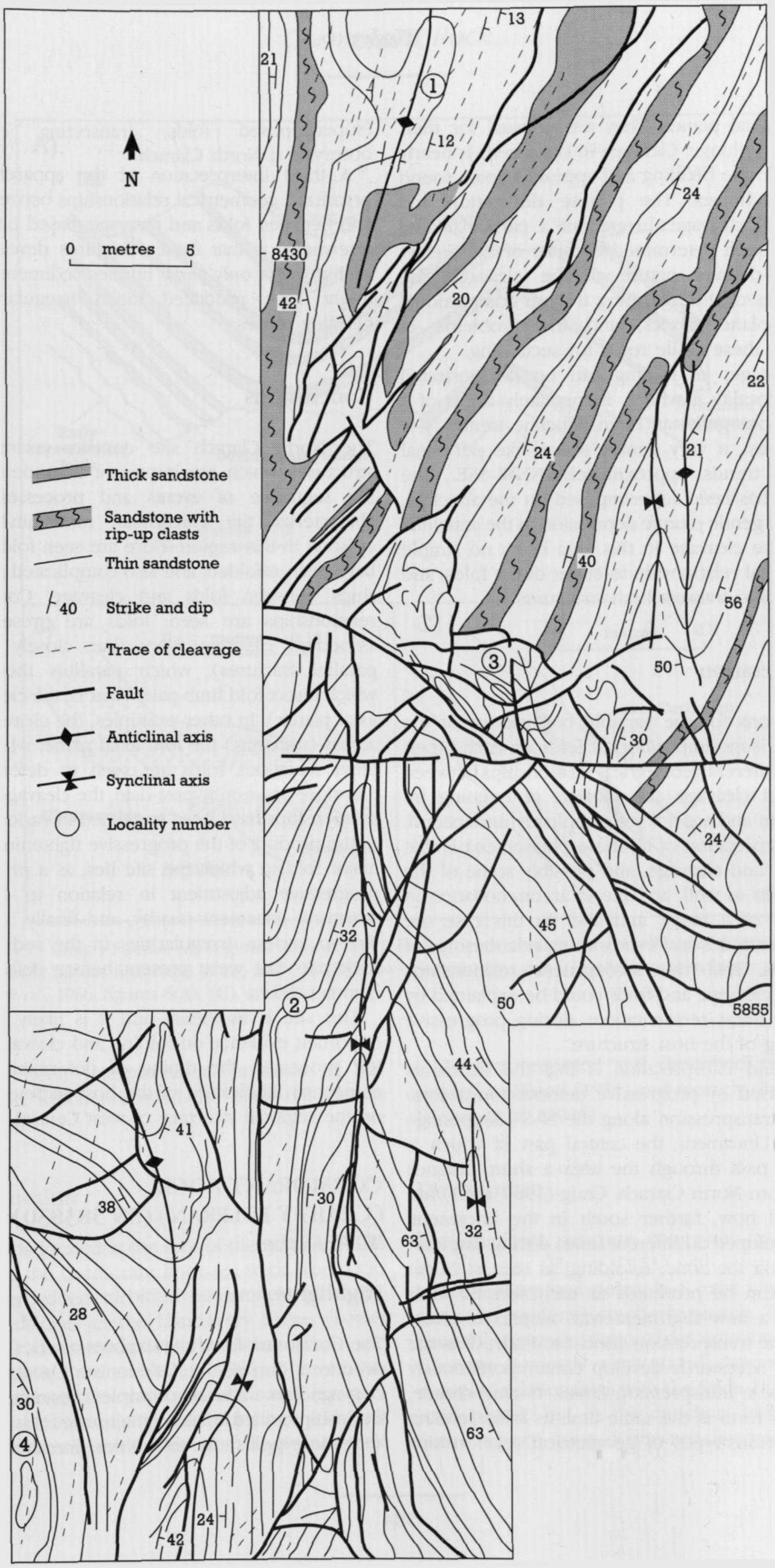
Description

A clearly recognizable example of a fold transected by cleavage is found at the northern end of the site (Locality 1, Figure 4.14). The fold is a periclinal anticline with an upright, N–S axial plane and hinge line which plunges gently north and south. Cleavage, which is well defined in the shale layers, strikes obliquely to the axial plane in a clockwise sense and dips to the WNW at a lower angle.

Several other examples of folds transected by cleavage are exposed on the platform, notably at Locality 2 where cleavage cuts both limbs of an open anticline on the western limb of a larger syncline.

Around Locality 3, where the rocks are conspicuously cut up by a complex of small faults, many of which are eroded out as gullies, several small folds appear to deform the cleavage. These folds, with metre-scale wavelengths, are close to tight structures on variable, but mostly N–S,

Figure 4.14 North Clarach. Fold–cleavage–fault relationships on wave-cut platform (modified from map produced by R. Johnson, University College of Wales, Aberystwyth, 1977). Localities 1–4 referred to in the text.



N
0 metres 5
Thick sandstone
Sandstone with rip-up clasts
Thin sandstone
40 Strike and dip
Trace of cleavage
Fault
Anticlinal axis
Synclinal axis
Locality number
8430
5855
1
2
3
4

upright axial planes. They are unusual for their very steep plunge. Cleavage in shale beds is nearly parallel to the bedding and appears to pass round the fold hinges. The precise disposition and pattern of cleavage throughout a particular fold has not been determined because of the feeble, often ill-defined nature of the cleavage, the difficulties of distinguishing it from compactional bedding-plane fabrics, and the problems of sampling these fissile rocks for sectioning.

Two stages of folding can be demonstrated around locality 4 where, immediately north of a conspicuous gully, an open anticline trends N–S. To its west, a very gentle, saucer-like periclinal syncline trends approximately NNW–SSE. The syncline has been superimposed on the anticline, causing a gentle plunge depression in the anticlinal hinge. The cleavage in this area bears no simple geometrical relationship to either of the folds, and it appears to transect both structures.

Interpretation

The reasons for the variable orientations of the folds, the superimposition of folds on each other, and the different geometrical relationships between folds and cleavage are subjects of ongoing investigation and are not yet completely understood. One interpretation of all these phenomena is that the folds and cleavage, and possibly some of the small faults as well, are due to accommodation in the core of a major anticline. In this case the variable attitudes and overprinting relationships of the folds, and the incongruent relationships between cleavage and folds could be explained by complex stress reorientations during progressive tightening of the host structure.

A second interpretation is that the structures were caused by progressive deformation accompanying transpression along the N–S Llangranog–Glandyfi Lineament, the central part of which is likely to pass through the area a short distance inland from North Clarach. Craig (1985, 1987) has described how, further south in the lineament, folds developed at different times during displacement along the zone; refolding, as seen at North Clarach, can be produced as early formed folds rotate to a new alignment with respect to stress axes in the transpression zone. Similarly, cleavage does not necessarily develop contemporaneously with folds in transpression zones. It can precede, follow, or form at the same time as folds, leading to the various types of geometrical relationships (superimposed folds, transecting cleavage) observed at North Clarach.

A third interpretation of the apparently disorganized geometrical relationships between folds and between folds and cleavage, based on studies elsewhere, is that these structures developed in unlithified or only partly lithified sediments, which might have produced initial irregularities of bedding planes.

Conclusions

The North Clarach site contains examples of structures which are important in understanding the sequence of events and processes which characterize the Caledonian mountain-building episode in this region. Here are seen folds which have been refolded, and also complicated relationships between folds and cleavage. Contrasting relationships are seen: folds are present with associated cleavage (very fine, closely spaced, parallel fractures), which parallels the planes which bisect fold limb-pairs (that is, the cleavage is axial planar). In other examples, the cleavage cuts across (transects) the fold axial plane, whereas in other situations folds are seen to deform, and therefore apparently post-date, the cleavage. These relationships have been explained in various ways: as the product of the progressive tightening of the major fold in which the site lies, as a product of progressive adjustment in relation to a major structural lineament nearby, and finally, as being due to various irregularities in the sedimentary rock pile that were present before deformation commenced.

This site is important and it is likely to yield important evidence on folding and cleavage-forming processes, the timing of deformation with respect to lithification of the host sediments, and on the regional structure of west Central Wales.

CORMORANT ROCK (CRAIG Y FULFRAN) (SN 583830)

W. R. Fitches

Highlights

The Cormorant Rock site exposes a series of folds produced during the Caledonian Orogeny. The cleavage has unusually complex geometrical relationships with the folds. Small-scale folds, termed 'tectonic ripples' in the older literature, have

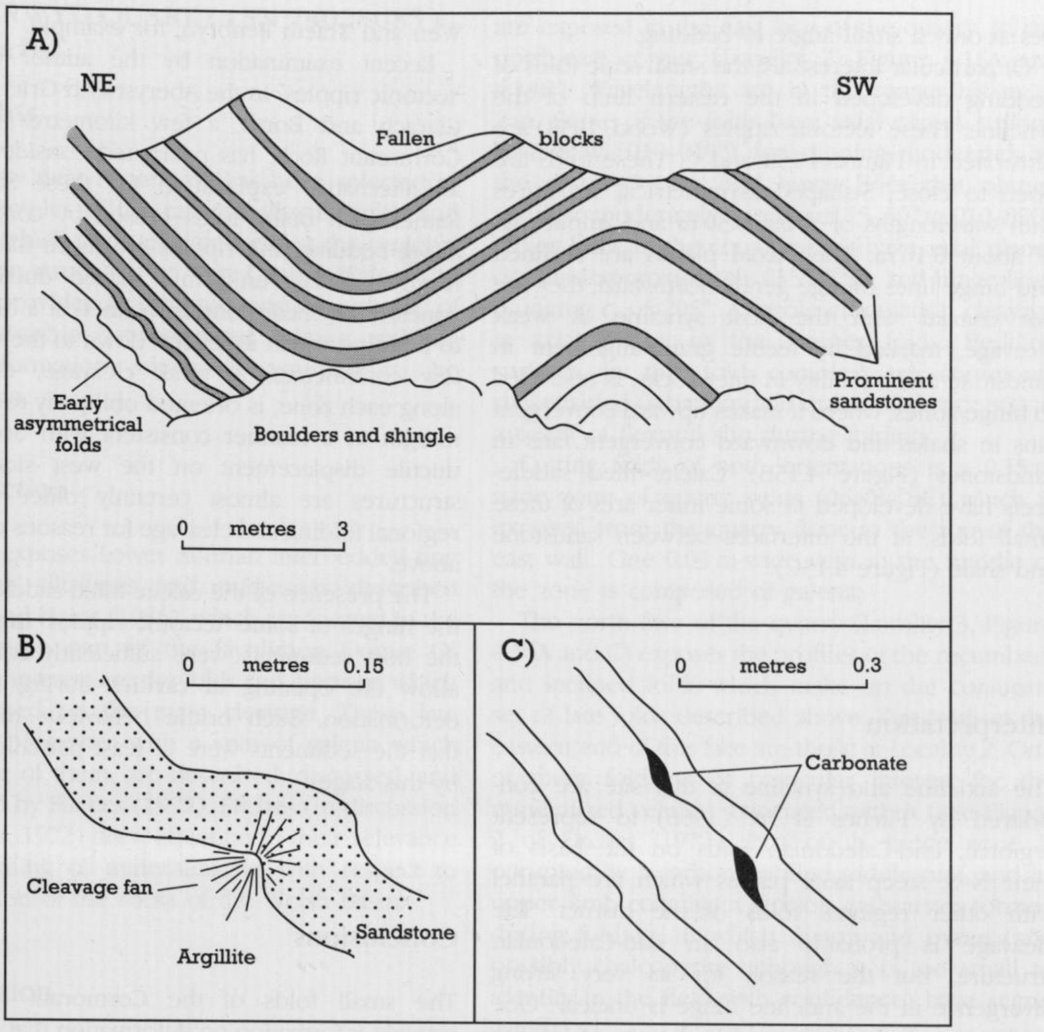


Figure 4.15 Craig y Fulfran. (A) Regional deformation folds with early asymmetrical small-scale folds on the north-eastern limb, further illustrated in (B) and (C). (B) shows cleavage fans and (C) saddle-reefs in hinge zones (after Fitches *et al.*, 1986, figures 6(A), (C), and (B)).

recently been interpreted as products of deformation which preceded the main Caledonian tectonism.

Introduction

The site is located at the foot of the main sea-cliffs opposite the Cormorant Rock sea-stack. The rocks are interbedded turbidite sandstones, siltstones, and mudstones of the Llandovery Series (Lower Silurian) Aberystwyth Grits Formation (Wood and Smith, 1958; Cave and Hains, 1986). The site has been selected for the unusually complex geometrical relationships between cleavage and folds which it shows, and for its anomalous small-scale folds, first recorded and described as 'tectonic ripples' by Wood (1958) and recently discussed by Fitches *et al.* (1986).

Description

The dominant structure comprises an anticline–syncline pair (Figure 4.15A) with a wavelength of *c.* 10 m, steep and nearly N–S axial planes, and a gentle to moderate southerly plunge. These folds probably represent regional deformation structures. Cleavage is mostly weak and ill-defined, and has complex relationships with the folds. In places it is axial planar, but in the anticlinal hinge zone it forms a very open downward-divergent fan and lies at only a small angle to bedding.

Of particular interest are the small-scale folds of bedding developed in the eastern limb of the syncline. These 'tectonic ripples' (Wood, 1958) are illustrated in Figure 4.15B and C. These folds are open to close, S-shaped asymmetrical structures with wavelengths of about 0.30 m and amplitudes of about 0.10 m. Their axial planes are reclined and hinge lines plunge gently northward; they are not coaxial with the host syncline. A weak cleavage, marked by feeble grain alignment in sandstone and a fissility in finer rocks, is restricted to hinge zones, where it makes upward convergent fans in shales and downward convergent fans in sandstones (Figure 4.15B). Calcite-filled saddle-reefs have developed in some inner arcs of these small folds, at the interfaces between sandstone and shale (Figure 4.15C).

Interpretation

The anticline and syncline at this site are considered by Fitches *et al.* (1986) to represent regional, end-Caledonian folds on the basis of their N–S, steep axial planes which are parallel with other regional folds of the district. The cleavage is probably also an end-Caledonian structure, but the reason for its very strong divergence in the anticline hinge is unclear. One explanation is that it formed in the site of intense extensional strain on the outer arc of the folds, contemporaneously with folding, as illustrated in a theoretical model by Ramsay and Huber (1987, Figure 21–26), for example, and from Snowdonia by Wilkinson (1988, Figure 4.31). Alternatively, the cleavage may locally have formed after the host layers were folded, as observed at the North Clarach site.

The 'tectonic ripples' in the limb of the syncline are not parasitic to that larger fold; they have the wrong sense of asymmetry, their axial planes and hinge lines are incongruent with respect to those of the larger fold, and the main cleavage appears to cut obliquely across them. Fitches *et al.* (1986) inferred that they preceded the development of the syncline and attributed them to gravity gliding toward the north-west which took place before, or as a precursor to, the regional deformation. On these grounds, the small folds were assigned to a family of early structures, other members of which are considered to be represented at Allt Wen and Traeth Penbryn, for example.

Recent examination by the author of other 'tectonic ripples' in the Aberystwyth Grits between Clarach and Borth, a few kilometres north of Cormorant Rock, has prompted consideration of an alternative explanation for these structures. Rather than being folds caused by compression along bedding, the ripples are more likely to be narrow, almost uniformly spaced ductile shear zones. Each shear zone is inclined at a high angle to bedding which it deflects down to the west by a few centimetres. A weak cleavage, developed along each zone, is oriented obliquely to the zone margin in a manner consistent with downwards ductile displacement on the west side. These structures are almost certainly older than the regional folding and cleavage for reasons discussed above.

The presence of the calcite-filled saddle-reefs in the hinges of some 'tectonic ripples' implies that the host sediments were sufficiently cohesive to allow the opening of cavities during the early deformation. Such brittle behaviour may imply that the sediments were at least partially lithified by this stage.

Conclusions

The small folds of the Cormorant Rock site provide information on deformation that preceded the main Caledonian folding and cleavage development in this part of the Welsh Basin. They have formed either by gravity gliding or as a result of movement on small slip surfaces (ductile shear zones). The larger-scale, but still comparatively lesser-order folding, and cleavage, here were the product of the Caledonian mountain-building phase. They are orientated in the typical N–S manner of other Caledonian structures in the region, but the cleavage is locally stongly divergent from the planes which bisect the fold limb-pairs (axial planes) of the folds. It is not clear why this is the case, but it may be due to some localized strain in the outer arcs of the folds or it may, more simply, indicate that the cleavage was formed after the folding. The site is an important one for studying the effects of the Caledonian Orogeny in this region. Because the site exemplifies relationships between folds and cleavage which are not yet fully understood, it is an important locality for current and future research.

PONTERWYD QUARRY (SN 74028085)

W. R. Fitches

Highlights

The quarry near Ponterwyd has been selected to show examples of the rare, small-scale folds and cleavage which are superimposed on the regional Caledonian structures of west Central Wales. The site also provides an example, possibly unique, of the relationship between lead veining and the later deformation which is assumed to be Caledonian.

Introduction

This site exposes Lower Silurian interbedded fine sandstones, siltstones, and mudstones, described by Cave and Hains (1986), which are located in the south-western part of the Plynlimon Dome. Of particular interest are the folds and cleavage which are imposed on the main cleavage. These late structures, together with a vein of galena which cuts some of them, are described, discussed, and illustrated by Fitches (1972). Fitches (in discussion of Phillips, 1972) drew attention to their relevance to the timing of mineralization with respect to deformation of the rocks of the Welsh Basin.

Description

Figure 4.16A, a sketch plan of the quarry, gives the location of the localities discussed below. The bedding generally strikes NNE-SSW and dips steeply westward, and is the right way-up according to the abundant cross-lamination, ripple marks and trace fossils. Cleavage strikes NNE–SSW and dips very steeply westward.

4.16A, B & C

In the west face of the quarry, immediately north of the spoil tips (Locality 1, Figure 4.16A), there are several recumbent folds of the cleavage and bedding. The axial plane of one fold is oriented 360/12°W, the hinge plunging 20/191°. The folds have open to gentle profiles, wavelengths of *c.* 0.20 m and amplitudes of *c.* 0.05 m; hinge zones are narrow and limbs are planar, giving a chevron style. A feeble crenulation cleavage is axial planar to the folds. This fabric is replaced locally by zones of very thin quartz veinlets which are also axial planar.

Several more late folds, forming a conjugate set, are exposed in the east face of the quarry, in the north-east corner (Locality 2, Figure 4.16A and 4.14B). Wavelengths are in the range 0.30 m to 2 m. Some of the folds have axial planes striking NNE–SSW (010–015°) and dipping moderately to the east (45–50°), and hinge lines that plunge gently to moderately northward 15–30° to 010–020°. Other folds in the conjugate set have axial planes oriented approximately 035/20°SE, and hinge lines plunging *c.* 05/205°. A feeble crenulation cleavage is axial planar to the steeper folds. Bedding surfaces in this fold complex are commonly slickensided (striations and quartz slickencrysts) as a result of flexural slip during folding.

Cutting folds of both orientations is a 0.15 m wide zone of quartz veins (064/84°SE) which is exposed from the quarry floor to the top of the east wall. One 0.03 m-wide vein in the middle of the zone is composed of galena.

The north face of the quarry (Locality 3, Figure 4.16A and C) exposes the profiles of the recumbent and inclined folds which make up the conjugate set of late folds described above. The folds at the eastern end of this face are those at Locality 2. One of these folds is of particular interest for the mineralized veinlets associated with it (see Figure 2 of Fitches, 1972). Part of its hinge zone is occupied by a carbonate-filled saddle-reef, and its upper limb contains a tension gash array, formed during folding, in which quartz and pyrite (and possibly chalcopyrite although it is too small to identify in the field with confidence) have segregated.

Interpretation

Folds and crenulation cleavages which are imposed on the main end-Caledonian folds and cleavage have been reported from various parts of the Welsh Basin (Roberts, 1979; Martin *et al.*, 1981; Fitches, 1972; Smith, 1988). Fitches and Roberts considered that the late (post-main deformation) folds with flat-lying axial planes, like many of those exposed in the Ponterwyd Quarry, belong to a regional set, while steep folds imposed on the recumbent ones represent a younger regional set. It was pointed out by Tremlett (1982) and Craig (1985), however, that these locally developed, late structures commonly appear to be associated with faults, and that they are therefore unlikely to be products of regional events. This fault-related explanation is supported by observations in other parts of the Welsh Basin. Near the Bala Fault, kink

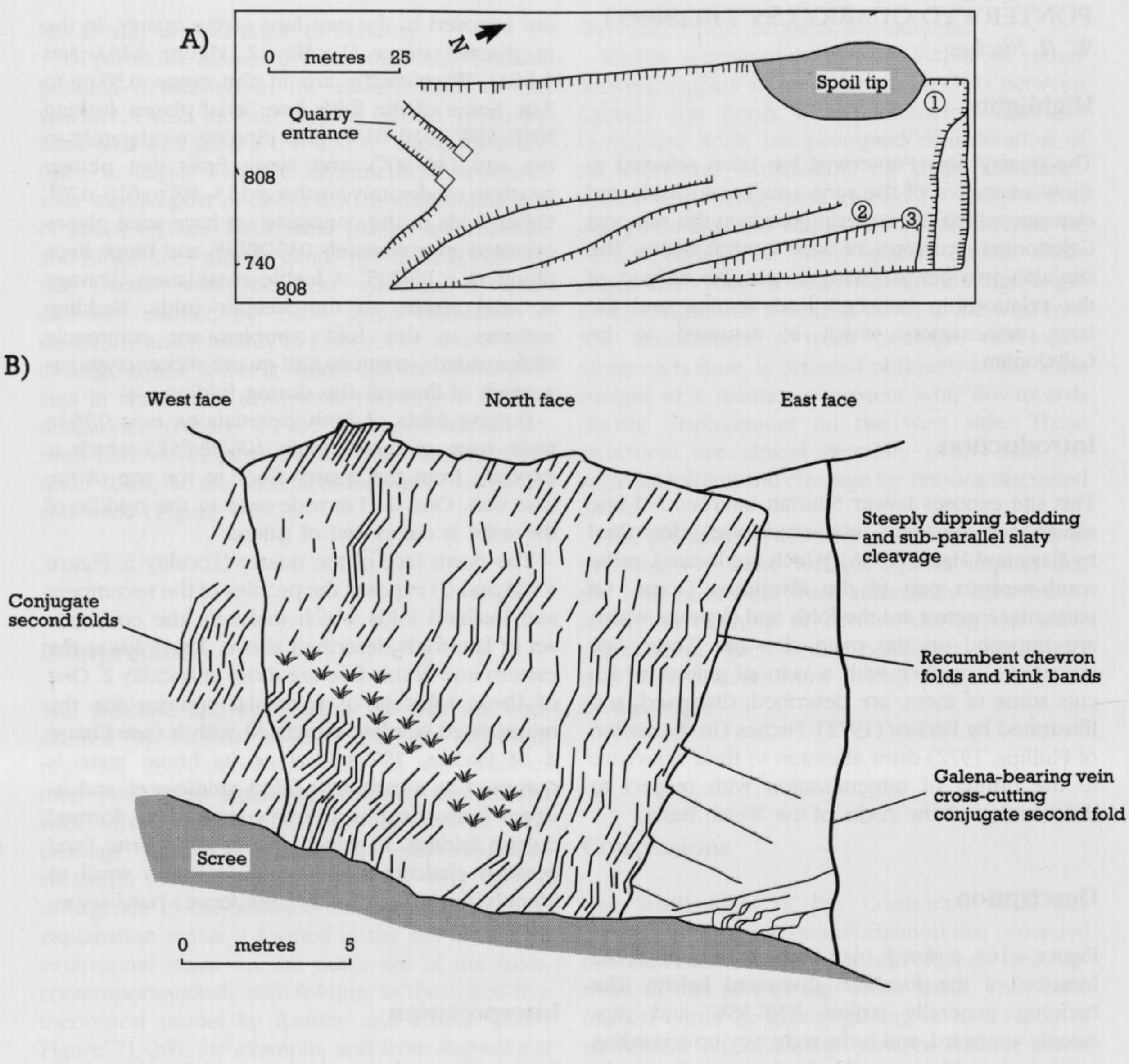


Figure 4.16 Ponterwyd Quarry. (A) Plan of quarry showing the three localities described in the text. (B) Locality 2; steeply dipping bedding and subparallel slaty cleavage deformed by recumbent second-phase chevron folds and kink bands (after Fitches, 1978, figure 1). (C) Locality 3; saddle-reefs and tension gashes (after Fitches, 1972, figure 2).

bands and crenulations, for example, imposed on the main cleavage are spatially related with the fault zone (Bracegirdle, 1974; Fitches and Campbell, 1987).

The sulphide-bearing veins in the Ponterwyd Quarry provide information on the timing of mineralization with respect to deformation in this part of the Welsh Basin. The fact that pyrite, and possibly chalcopyrite, are found in tension gashes produced during the late folding indicates local segregation of sulphides from the host rocks into low-pressure regions during deformation. The galena vein, however, cuts across, and is therefore at least slightly younger than all the late structures. This relationship of galena mineralization to the late structures shows that in this case mineralization is unlikely to be related to dewatering of the sedimentary pile during the main end-Caledonian (late Silurian–early Devonian) deformation (Fitches, in discussion of Phillips, 1972).

Conclusions

Ponterwyd Quarry contains numerous, particularly well-exposed examples of folds imposed on, and therefore younger than, the main Caledonian structures. At this site these consist of cleavage (very fine, closely spaced, parallel fractures), and steeply dipping bedding in these Silurian strata. Superimposed on these two sets of features are a variety of folds (Z-shaped and S-shaped, and sometimes chevron-shaped) and a second generation of cleavage with parallel quartz veins. The superimposed folds and the cleavage are regarded as late-Caledonian structures found uncommonly in several parts of the Welsh Basin. Mineralized veins in the quarry are associated with the second generation of structures: they provide information, possibly unique in the Welsh Basin, on the timing of relationships between the formation of lead veins and the tectonic structures.

TRAETH PENBRYN (SN 28755210–29095232)

W. R. Fitches

Highlights

The site contains the best-known examples of veins and hydraulic fracture breccias produced by brittle deformation, caused by high fluid pressures before, or during, the earliest stages of regional Caledonian tectonism.

Introduction

This site, a sea-cliff section, comprises folded and cleaved Upper Ordovician sedimentary rocks of the Tresaith Formation (Craig, 1985). These are cut by a series of veins and hydraulic fracture breccias which have been described, discussed and illustrated by Craig (1985) and Fitches *et al.* (1986). These structures are considered to belong to a family of early brittle structures, other members of which are represented at the Allt Wen, Cormorant Rock, and Llangollen sites.

Description

Craig (1985) and Fitches *et al.* (1986) have shown that the brittle structures affecting the rocks here preceded the folds and cleavage; they attributed them to dewatering processes before, or during, the onset of regional deformation.

The country rocks of the Tresaith Formation (Ashgill Series) are thinly bedded, fine sandstones, siltstones, and mudstones. The structure of the section is mostly uncomplicated bedding (065/20°SE) and cleavage (075/35°SE) maintaining nearly uniform orientations except for local interruptions by small folds, to which cleavage is axial planar.

The veins fall into two main categories:

1. hydraulic vein breccias, and
2. simple and *en échelon* veins:

1. Hydraulic vein breccias

The largest vein breccia (Fitches *et al.*, 1986, Figure 4B) is more than 10 m in length, 0.20 m in thickness, and is oriented about 030/70°SE. The vein minerals are predominantly quartz, with a little carbonate and traces of pyrite. The breccia fragments are angular pieces of local country rock, many of which are totally suspended in the vein minerals, whereas others remain partly attached to the vein walls and have been only slightly rotated and detached from the country rock. Craig (1985) and Fitches *et al.* (1986) showed that vein breccias were formed after the country rocks had undergone extensive diagenesis, but before the development of the regional cleavage.

2. Simple and en échelon *veins*

Veins composed chiefly of quartz, with minor carbonate and pyrite, are common in this section, typically about 0.05 m thick, steeply dipping and aligned mostly NNE, but varying widely in orientation. Most veins occur singly, but locally, notably near the large vein breccia, several veins are disposed *en échelon* in tension gash arrays.

Some of these veins cut the vein breccia. In places, they are deformed by small open to tight folds, with wavelengths of a few centimetres or tens of centimetres, to which the cleavage has an axial-planar or fanning relationship.

Interpretation

Microfabric evidence, obtained from breccia clasts in the vein breccias shows that the growth of phyllosilicates in the bedding compaction fabric (Craig *et al.*, 1982) preceded the formation of a pressure solution fabric, which is itself misaligned due to variable amounts of rotation of the host fragments. This evidence indicates that breccia formation followed diagenesis. That brecciation preceded the cleavage is shown in two ways. Firstly, the breccia is cut by later veins which were themselves folded and cleaved by the regional deformation. Secondly, under the microscope, an earlier grain alignment fabric in the breccia fragments is crenulated on planes which are parallel with the cleavage in the country rocks.

The simple and *en échelon* veins also preceded the development of cleavage because they are deformed by folds to which the cleavage is axial planar. Craig (1985), by measuring the lengths of veins around folds, calculated that the former have been shortened in the cleavage by about 30%.

The brecciation and deposition of the minerals hosting the fragments are attributed, by Craig (1985) and Fitches *et al.* (1986), to hydraulic fracture processes similar to those advocated by Phillips (1972) to explain the post-tectonic veins of Mid-Wales.

Craig (1985) and Fitches *et al.* (1986) considered that the vein breccias and other veins were caused by high fluid pressures which developed during burial, but after lithification, of the (Upper Ordovician) sediment pile. The vein breccias were interpreted as a manifestation of extension of the sediment sheet caused by gliding down a slope under gravity, and the *en échelon* veins were taken to represent the flank of a sheet subjected to strike-slip displacements. The various veins belong to a family of early structures, of which other members, mostly the structures of the toes and central parts of glide sheets, are represented elsewhere.

Conclusions

The Traeth Penbryn site contains various types of veins (vein breccias, simple and *en échelon* north-easterly striking veins), which have been shown to have preceded the folds and cleavage produced during the main phase of the Caledonian Orogeny. These veins are regarded as indicators of pre-tectonic or early tectonic deformation processes which are very rarely represented in Lower Palaeozoic strata. The vein breccias (veins containing angular rock fragments set in a matrix of the mineral quartz) are perhaps unique in the Welsh Basin context. They are thought to have been produced by the action of fluids under high pressure acting on fractures brought about by stretching, and perhaps sliding on a large scale, of the Ordovician sediment pile. Subsequently the whole area was affected by the Caledonian earth movements during Silurian to Devonian times; the simple veins (which are later than the vein breccias because they cut them) were cleaved and folded. The site provides the best exposures in Wales of veins and other structures which can be proved to pre-date the Caledonian mountain-building episode.

CA'ER-HAFOD QUARRY, LLANGOLLEN (SJ 215476)

R. Nicholson

Highlights

Carbonate veins here are platy and lineated. They lie along bedding and record movements, apparently tectonic, prior to the main Caledonian phase. These phenomena appear to be restricted to rocks of mid- to late-Silurian age.

Introduction

The Ca'er-hafod Quarry provides rare outcrops of a very distinctive suite of laminated carbonate veins, apparently lying along bedding, and inscribed with a very pronounced rectilinear, ridge-and-groove lineation. Both the mineral fabric of the veins and this lineation are older than the deformation episode which folded the Wenlock Series country rocks. The veins (spar beds or 'rhesog') here had their macroscopic features first described by Wedd *et al.* (1927), in the Geological Survey Memoir dealing with the Wrexham district.

Figure 4.17 Ca'er-hafod. Part of the quarry showing bedding dipping steeply south, and cleavage gently north. The outcrop of the central vein (top left to centre) shows minor folds plunging towards the observer, and ridge-and-groove lineation almost at right-angles to this. View looking east. (Photo: R. Nicholson.)

Wedd *et al.* noted the bedding-parallel nature of the veins, that they are affected by folding, the presence of a groove-like lineation on the veins, and the likelihood that there had been considerable amounts of movement along them. These authors also made clear the apparent restriction of the veins, in the Wrexham district, to the Wenlock Pen-y-glog Formation.

This slate formation, once worked on both north and south limbs of the gently easterly plunging Llangollen Syncline, has its subcrop marked by a string of disused quarries. They provide the only access to these carbonate veins, which were unknown in natural outcrops. The quarries also provide the most convenient areas in which to examine the regional cleavage; this has a moderate dip to the north, atypical of Caledonian North Wales. The Ca'er-hafod Quarry is on the north limb of the Llangollen Syncline (Figure 4.17).

The microscopic character of the veins was first described by Nettle (1964). Veins with the same mineralogy, fabric, and structure as those of the Llangollen Syncline, are found in the Middle Wenlock to Lower Ludlow rocks of areas east of Llanwrst, in northern Clwyd (Warren *et al.*, 1970). These authors, however, broadly link formation and deformation of the veins, with formation of the regional cleavage.

Description

Cleavage and bedding here have the characteristic E–W trend of this north-eastern section of the Welsh Basin. The disused quarry situated near Ca'er-hafod (Wedd *et al.*, 1927, p. 97; Nicholson, 1966, 1970, 1978) was referred to by Fitches *et al.* (1986, Figure 7D) by the name of the nearest house, Pont Glas. The 180 m-long working, opens to the east, is nowhere wider than 40 m, and is driven into the silty mudstones of the Pen-y-glog Formation. Its steep north and south walls are parallel to the strike of bedding (Figure 4.18).

Situated in the complexely folded, north limb of the Llangollen Syncline, bedding surfaces dip steeply to the south (e.g. 105/62°S). The accompanying cleavage dips moderately to the north

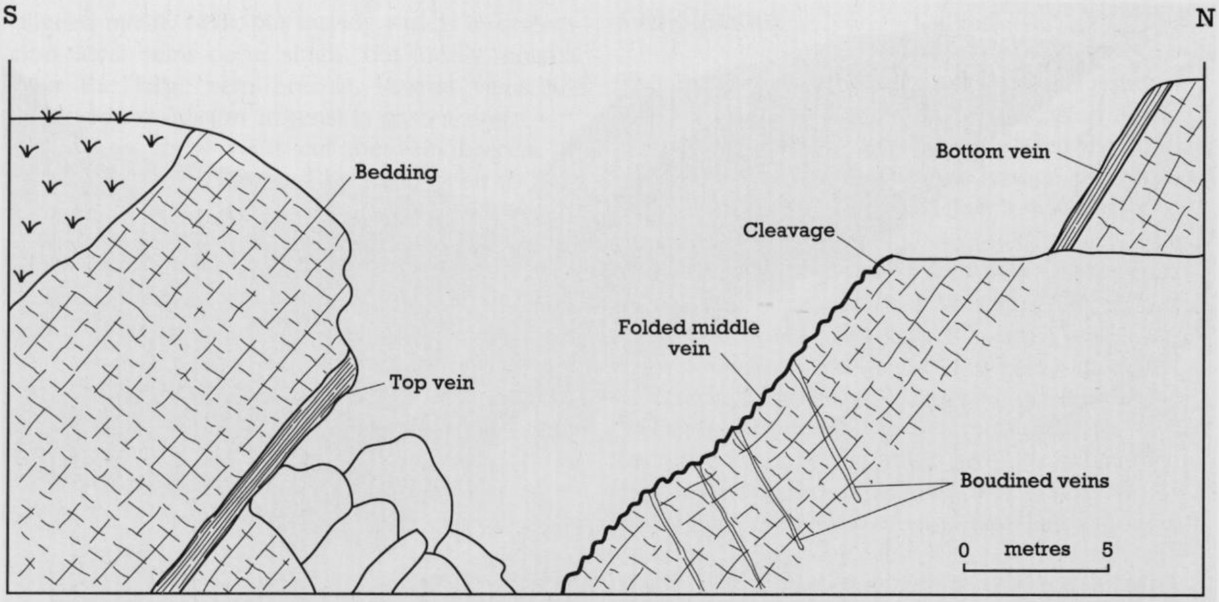


Figure 4.18 View looking west at Ca'er-hafod Quarry (Llangollen) showing steeply dipping Wenlock country rocks and spar beds (veins).

(e.g. 093/55°N), bedding and cleavage here being about perpendicular to one another, suggesting that the rocks of the quarry lie near a fold hinge. Although the Llangollen Syncline, like many of the subsidiary folds of its north limb, plunges gently to the east, the folds affecting the three veins, and the bedding–cleavage intersections in the enclosing slate, all plunge gently westwards. The moderate northerly dip of the cleavage, is typical of the syncline as a whole.

Three principal laminated veins occur in the quarry (Nicholson, 1978). All of them have a well-developed ridge-and-groove lineation on the calcite laminae of which they are made. The bottom vein, forming the north wall of the quarry, shows how this lineation may change substantially in pitch, even from the surface of one-millimetre-thick lamina to the next. The top vein, which lies at the base of the south wall of the quarry, is approximately 0.10 m thick, the thickest of the three. The central vein is the thinnest and most thoroughly laminated. As a result, it shows more regular and intensively developed folds than the other veins (Figure 4.17).

The bottom vein is partly composed of a cemented breccia. Both in this and other respects, it closely resembles that exposed in the north wall of the easternmost of the quarries of Moel y Faen (SJ 18874772; Wedd *et al.*, 1927). The other two veins of the Ca'er-hafod Quarry do not contain breccia zones.

The central vein, about 10 mm thick, is exposed for tens of metres on a mesoscopic, folded bedding surface (Figure 4.18). The published description of the modifying effects of this deformation on the primary fabric of generally vein-parallel, single-crystal plates of calcite is based on material from this central vein (Nicholson, 1978; microprobe data on calcite composition, Hamdi Lemnouar, 1988). The very numerous, small folds are periclinal in form, each having a hinge length of some 0.20 m. These hinges lie parallel to those of the larger folds. They all plunge parallel to the bedding–cleavage intersection on the folded surface and have their axial surfaces parallel to the cleavage of the slate in which they are embedded. All these field relationships confirm the interpretation based on microscopic evidence, that folding was part of the regional deformation, taking place after the veins were already fully formed.

The slates of the Ca'er-hafod Quarry also contain discordant calcite–quartz veins, apparently linked in origin with the laminated, bed-parallel veins. Instead of being folded during regional deformation, they were boudined. The early formation of these discordant fractures may be used as an indication that the cleavage here is not a structure formed during burial and related compaction and water loss (Davies and Cave, 1976). This has importance for the assessment of proposals made concerning the place of vein systems in the regional tectonics of Caledonian Wales. Fitches *et al.* (1986), for example, making passing reference to the Silurian rocks of the Wrexham district, suggest that such veins may have formed as water driven from sediments during burial was injected along chosen bedding horizons. It is supposed that such injection allows the detachment of upper levels of the sediment column, freeing them for the lateral movement that the formation of the lineation on the veins requires.

The wide, folded, bedding surface on which the central vein is exposed, also reveals the way in which a number of highly discordant veins are joined to the central vein, in a direction subparallel to the bedding–cleavage intersection. These sheets, at most 10 mm in thickness, dip more steeply to the north than cleavage, and have been extended in their plane, boudined, during the regional deformation. The evidence of extension is found in the repeated quartz-filled zones, less than a millimetre thick, that cross discordant sheets, in directions sub-perpendicular to them. The patterns of fractured calcite crystals on either side of these zones match, although they are separated by the fibrous quartz that now fills the zones (Nicholson, 1966). The formation of these extension structures, developed in planar bodies lying at low angles to cleavage when they were deformed, is consistent with the simultaneous formation of folds in the veins, lying about at right-angles to cleavage.

In all three veins, the laminae are made up of vein-parallel, single-crystal, calcite plates, which have their crystallographic c-axes at right angles to their planar surfaces. Plates very commonly have thickness to lateral extent ratios of at least 100. Their thicknesses range from 0.1 mm to over 10 mm. The amplitude of the folds later imposed on the fabric varies in direct proportion to the vein thicknesses. Deformed plates are distinguished by complex developments of *e*-lamellae (Nicholson, 1966). The calcite crystals of the discordant, boudined veins, are also plate-like in shape, although arranged in various orientations, oblique to vein walls. These plates are separated from one another by relatively coarse-grained quartz.

Nettle (1964) attributed the unusual laminated structure of the veins to the modification of earlier fabrics during regional deformation and metamorphism. This interpretation was challenged by Nicholson (1966), who emphasized the primary nature of their laminated structure, and the way that it was affected distinctively by the succeeding episode of deformation, common to veins and country rock. He later analysed the small-scale folds produced by regional deformation in the laminated veins (Nicholson, 1978), suggesting that laminae formed in repeated acts of precipitation, separated by intervals of shear. He showed that interlaminar slip in early stages of folding was accommodated through the crystal–plastic behaviour of the single-crystal, calcite plates of which laminae are made. Work hardening, however, evidently raised the resistance of the plates, so that later slip was facilitated by pressure solution instead. Both this pressure solution, and the slip accompanying it, were concentrated where the surfaces between calcite plates lay at high angles to the principal shortening strain. Consequently, the through-going stylolites that gradually evolved were sited in fold limbs, eventually extending across the vein to isolate one hinge from another.

Plates and laminae show much greater continuity in cross-sections of microfolds than in sections parallel to fold axes. This condition, appears to be primarily related not to folding, however, but to the earlier-formed lineation, which in this vein lies approximately at right-angles to fold axes. In effect, calcite plates are elongated parallel to the lineation, which is so well developed on interlaminar surfaces through these veins.

Calcite laminae are separated from one another by thin seams composed of muscovite and fine-grained quartz. The grain size of the latter may be a product of recrystallization, rather than being primary. It may be significant that this material coats the grooves and ridges cut into the calcite plates. As far as is known, however, this recrystallization may have occurred during folding, rather than at the time of formation of the lineation. Muscovite flakes, for the most part, lie parallel to the seams.

Interpretation

The interest at this site relates principally to the laminated calcite veins. The platy and lineated nature of these is itself unusual, and the veins record deformation which pre-dates the main Caledonian phase.

Both the development of the primary fabrics of the laminated veins, and the nature of the folds later developing in them, are phenomena of interest in their own right. This interest is heightened by the apparent rarity of platy, calcite fabrics like those here, even in laminated veins. Investigation of the primary character of the veins also provides an opportunity to investigate structural development at times before the regional folds and cleavage had formed. The swing of the cleavage and folds to the ESE trend at this site is of considerable regional interest.

Veins composed of primary, platy, calcite crystals, and their distinctive folds, in Britain appear to be restricted to rocks of Wenlock or Ludlow age. Nicholson (1966) has pointed out the existence of veins with platy calcite in Ribblesdale and the southern Lake District, in country rocks of similar age and sedimentary facies to those of the Llangollen Syncline. Warren *et al.* (1970) have made similar observations on the Silurian rocks of northern Clwyd. The veins of western Caledonian Wales (Fitches *et al.*, 1986), in older host rocks, although laminated and lineated like those of the Llangollen Syncline are not composed of calcite but ferroan dolomite, in which the platy morphology is unknown.

Laminated and lineated veins also apparently made up of calcite plates have been reported, however, from slates of the Appalachian fold belt of Pennsylvania (Beutner *et al.*, 1977). This occurrence resembles in several ways that of Ca'er-hafod. The country rocks, for instance, are of similar mid- to late-Silurian age. The principal veins are similarly parallel to bedding and strongly folded. At the same time, fold hinges are separated from one another by stylolites cutting across veins, as at Ca'er-hafod. There is also a set of associated, discordant and boudined calcite–quartz veins. Although vein carbonate is described as calcite, nothing is said of its morphology. But the appearance of the folded veins, in the only figure showing the folded fabric in any detail, is quite compatible with a platy form for the calcites. Two points made by Beutner *et al.* (1977) are of special interest. Firstly, it is said that the Pennsylvanian bed-parallel veins lie along faults with only small displacement; however, no evidence is given. Secondly, the Pennsylvanian laminated veins apparently occur only in the gently dipping limbs of overturned folds. This is a contrast with Ca'er-hafod, where bedding–cleavage relationships suggest that veins are exposed in the region of a fold hinge.

Accepting the evidence of the discordant veins at Ca'er-hafod, the platy shape of the calcites may be described as a habit. The plates do not seem to be bounded, that is, by the compromise surfaces developed between adjacent crystals in competitive growth (Grigor'ev, 1965; Dickson, 1983). Such a habit has been described from crystal cavities in the New Jersey zeolite region of the USA (Schaller, 1932). The habit has been described as being indicative of high-temperature growth. This is of interest as the veins of the Llangollen Syncline are accompanied by well-crystallized muscovite (see Hamdi Lemnouar, 1988 for analysis). This proposal does not fit, however, with a source of mineralizing fluids in water drawn from the sediment body itself (Fitches *et al.*, 1986), at a time before even low-temperature metamorphism had begun.

Questions are raised by the lamination of the veins, but detailed explanations have yet to appear. However, using published analyses, some proposals may be outlined. The laminated veins, for instance, may be complex examples of the crack–seal veins of Ramsay (1980); that is, veins formed by successive development of microcracks followed by successive mineral infilling. The modified version of this hypothesis proposed by Cox (1987), seems to be particularly apt, designed as it was to explain veins forming when large displacements were occurring parallel to vein margins.

The formation of the lineation offers particular difficulties. The lineation is cut deep into the surfaces of only very thin calcite plates. If the incision of the lineation were mechanical, it is difficult to understand how the mechanically anisotropic and weak calcite plates were not at the same time deformed plastically and even broken into pieces. However, there is no sign of such disruption. The process, therefore, seems more likely to have occurred through sculpting by diffusion-based processes, rather than abrasion. The lineation, in effect, may have been formed through pressure solution, the surfaces representing an unusual variety of stylolite (Ramsay and Huber, 1987, p. 655).

The site lies at the eastern end of the fold cleavage arc that characterizes the Caledonian tectonic trend in North Wales (Shackleton, 1969). As Figure 4.1 shows, the trend of folds and cleavage at this end of the arc is slightly south of east; in Snowdonia (for example, Alexandra Quarry to Capel Curig, above) it swings to the NE–SW 'Caledonoid' trend, whereas to the south (Tan y Grisiau) it becomes almost N–S and then returns through NNE–SSW (Rheidol and Ponterwyd) to NE–SW (at Traeth Penbryn). This swing has been attributed by Shackleton (1969) to moulding against basement fault blocks, by Helm *et al.* (1963) to late (post-main-phase) Caledonian deformation, and most recently by Soper *et al.* (1987) to, once again, control by the basement during the main-Caledonian (early-Devonian) phase of closure of Iapetus.

Conclusions

This site is important from two points of view. Firstly, it provides an example of the Caledonian structural trend in north-eastern Wales, where it swings to a trend slightly south of east. This trend, which contrasts with other areas in Wales, has been explained as being a result of how the Palaeozoic rocks (at this locality of Silurian age) were compressed above and against the rigid basement of older (Precambrian) rocks.

The laminated and lineated calcite veins, that are extensively developed parallel to bedding, indicate an early stage of tectonic movement in the late Silurian. Their growth requires vertical opening along bedding, but other features suggest horizontal displacements. Although the growth of these unusual platy calcite veins is not fully understood, currently they are the subject of considerable interest. It is quite clear, however, that these veins were deformed in the (post-Ludlow) main phase Caledonian deformation of the Welsh Basin, when regional folding and cleavage were developed.

LLIGWY BAY (SH 49308746–49408803)

R. Scott

Highlights

Lligwy Bay contains a rare example of (presumed) Devonian rocks deformed during the Caledonian Orogeny. As this is the only Devonian locality in North Wales, these rocks provide unique information with which to assess the duration of the orogeny in this region.

Introduction

The Devonian rocks in Lligwy Bay record polyphase deformation, involving folding, cleavage formation and thrusting. The two upper Old Red Sandstone Group formations, that is the Porth-y-mor Formation and the Traeth Lligwy Formation (Allen, 1965), lie in a broad synclinal structure. This open structure has a monoclinal fold on its northern limb; on the southern limb thrusting and tight, minor folds with axial-planar cleavage occur (Figure 4.19).

The locality was described by Greenly (1919) in his memoir of Anglesey. A sedimentological interpretation of the Old Red Sandstone by Allen (1965) included some brief comments on the structure. Bates (1974) made a reconnaissance survey of the site and confirmed the observations of Greenly (1919). A number of large-scale tectonic interpretations have used the available information on Lligwy Bay, including those of Nutt and Smith (1981) and Woodcock (1984a), and the site has also appeared in a field guide (Bates and Davies, 1981), but no detailed, modern structural interpretation has been published. No fossils have been recorded from the sequence and its Devonian assignment is based upon lithological and stratigraphical similarities with other localities in south and south-east Wales.

Description

The site consists of a varied sequence of Devonian sediments exposed in a series of low cliffs on the north side of Lligwy Bay as far north as Trwyn Porth-y-mor. The strike of bedding and cleavage is approximately E–W. The site is described from north to south and the structure is depicted on a cross-section (Figure 4.19).

On the small headland opposite Trwyn Porth-y-mor, beds dip at $<25°$ toward the south, and the dominant cleavage (S_1) dips between 50–70° to the north (Figure 4.20). In common with the site as a whole, cleavage is better developed in finer-grained siltstones and calcrete layers, where cleavage surfaces may be spaced closer than 5 mm. In sandstones, the spacing may be up to 0.20 m. In conglomerate units the cleavage is not clearly discernible. A second, localized cleavage spaced at 0.03–0.05 m offsets S_1 surfaces and dips at shallow angles to the north.

Towards the south, bedding becomes steeper, dipping to the south. It is locally overturned (around SH 49408787). Concurrent with this steepening of bedding, the principal cleavage becomes less steep, dipping at $<30°$ to the north. To the south of this location, bedding returns to a shallow southerly dip, thus defining the monoclinal structure identified by Greenly (1919), and cleavage to a more steeply north-dipping attitude.

Bedding flattens out progressively to the south of the monocline, so that beds are undulating around horizontal (at SH 49428774). A low-angle surface exposed in the wave-cut platform at this locality probably represents a small thrust. In addition, the undulating beds are affected by minor normal faults (displacements <0.5 m) which post-date the cleavage and have a variety of attitudes. Immediately to the west, (SH 49398774),

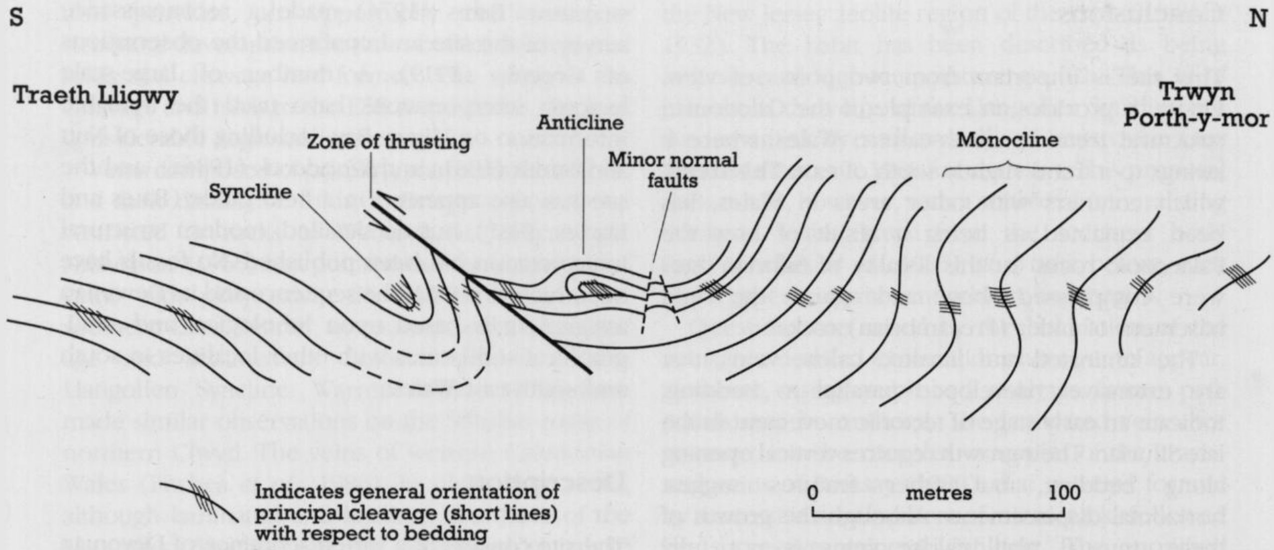


Figure 4.19 Sketch section illustrating the structure of the Devonian rocks on the north side of Lligwy Bay.

a small anticlinal hinge is exposed to which the principal cleavage is axial planar (dipping 54°N). The axis of the fold plunges gently east. This structure is the 'sharply over-driven anticline' featured in Greenly (1919; Figure 282, p. 586). The lower limb of the anticline is faulted out and, to the east, the anticline is replaced by a low-angle discordance of bedding, similar to the thrust surfaces observed close by. The fault surface has a parallel fabric which is similar in appearance, but oblique to the axial planar cleavage in the fold core; the contact between the two fabrics is not a distinct break.

From this point southwards, beds dip consistently north, first at shallow angles and then more steeply. A zone of thrusting at least 3 m wide and dipping at 40° to the north (SH 49338768) separates shallow north-dipping beds to the north from more steeply north-dipping beds to the south (Greenly, 1919; Figure 284, p. 586). In the footwall to the thrust, a tight synformal fold core can be observed (at SH 49328766). Again the principal cleavage is axial planar to the fold, dipping at ~50°N. The fold axis plunges gently east. To the south of this location, bedding dips at variable angles to the north.

Interpretation

On Anglesey, deformation of the Old Red Sandstone (which is presumed to be of late Silurian to early Devonian age) occurred before the deposition of the overlying Carboniferous Limestone succession (Allen, 1965). This, in conjunction with the site's location to the north of the Hercynian front, indicates that the deformation is not Hercynian (unless it is a freak local deformation) and therefore Caledonian, and that this phase was a post-Old Red Sandstone one. The deformed, presumed Devonian, succession at Lligwy Bay therefore provides crucial information for estimating the duration of the Caledonian Orogeny in North Wales.

A recent structural interpretation of the site is not available. However, its importance arises from the presence of deformation, rather than from its detailed interpretation. A number of important age relationships were established at Lligwy Bay by Greenly (1919), to which several additions can be made. These relationships indicate the polyphase nature of deformation. Greenly observed that cleavage was axial planar to the tight folds, but that it changed its orientation around the monocline, indicating that the monocline was a later structure. He also concluded that the thrusting post-dated the isoclinal folding because thrust surfaces are at a lower angle than, and they truncate, the cleavage. Although they may not be entirely synchronous, the spatial association between the tight folds and the thrusts does suggest that they are both a manifestation of the same deformation event. However, Greenly preferred to relate thrusting to monocline development which post-dates the

Figure 4.20 Lligwy Bay, Anglesey. Strongly developed, spaced cleavage in ?Devonian siltstones dips to the north in the hinge of a south-facing monocline. (Photo: J. Treagus.)

main cleavage (and may be related to the sporadic second cleavage). Two observations which Greenly did not make are that the principal cleavage maintains a northward dip across the broad synclinal structure and that relationships between bedding and cleavage change on the northern limb. These two observations suggest that the syncline may partly pre-date the cleavage and is therefore the first recognizable structure.

Deformation of the Old Red Sandstone at Lligwy Bay is, therefore, locally intense and polyphase, with possibly three phases of deformation and the development of thrusts. The deformation is, however, localized and, as Bates (1974) points out, is completely absent from the southern part of the inland outcrop. This variable intensity was interpreted by Bates as a reflection of basement control, deformation being most intense in the vicinity of major pre-existing faults.

The general consensus of opinion has been that the principal folds and cleavage in North Wales were produced in approximately end-Silurian times (for instance, Dewey, 1969; Coward and Siddans, 1979). A pre-Devonian age for the main deformation was based on the observation that the Devonian lies unconformably on older rocks in the Welsh Basin and elsewhere. On Anglesey, the Devonian lies unconformably on the Ordovician, the unconformity post-dating the Bodafon Thrust. This indicated to Bates (1974) that the Devonian was deposited after the main period of deformation, which was end-Silurian. However, other authors have maintained that the main deformation period extended into the early Devonian (for example, Shackleton, 1953; Jones, 1955; Woodcock, 1984a). The significance of the unconformity at the base of the Devonian is open to doubt, as it may be the result of pre-Silurian, rather than just pre-Devonian erosion (George, 1963). The evidence at Lligwy Bay is limited by the lack of a firm age for these rocks, but it supports the conclusion that the lower part of the Old Red Sandstone suffered Caledonian movements. These movements were at least as intense as those affecting the adjacent Ordovician, and they have the same sense of overturning, towards the south-east. Woodcock (1984a), after assessing the information available at Lligwy Bay, concluded that any deformation climax in late Silurian Wales probably extended at least through Pridoli time and into the early Devonian. Soper *et al.* (1987) and McKerrow (1988), assessing evidence from Wales and the Lake District, considered that the main end-Caledonian movements were probably Emsian in age, equivalent to the Acadian of the Canadian Appalachians.

Conclusions

Lligwy Bay contains sedimentary rocks, thought to have been deposited during the Devonian Period (approximately 410–360 million years before the present), which have suffered folding, thrusting (low-angle faulting) and cleavage (closely spaced, parallel fractures) all during the Caledonian mountain-building episode. The intensity of this deformation was at least as strong as that suffered by the Ordovician succession which underlies the Devonian rocks. The fact that Old Red Sandstone sedimentary rocks are deformed indicates that Caledonian deformation of some significance extended beyond the end of the Silurian and well into Devonian times.

CARMEL HEAD (SH 29079279–30709300)

D. E. B. Bates

Highlights

This is the only well-exposed and clearly identifiable, major low-angle thrust in the Welsh Caledonides. The Carmel Head Thrust, overriding an earlier steep fault and cut by later faults, can be traced eastwards for some 400 m in the cliffs and well-exposed ground to the south; it thrusts Precambrian schists southwards over Caradoc Series shales. Further east, the Ordovician Garn Breccia and overlying shales are overridden by Precambrian rocks on the Mynachdy Thrust.

Introduction

The Carmel Head region is well known for both its stratigraphical and, in particular, its structural interest. The fault relationships were first described clearly by Callaway (1884), and his conclusions were confirmed and amplified by Matley (1901) and Greenly (1919, 1920), who mapped the area on the scale of 1:2500. Greenly (1919, pp. 547–9) considered that the Precambrian Mona Complex (Monian) had been overthrust on to the Ordovician along the E–W-striking Carmel Head Thrust by about 20 km. Bates (1972, 1974) showed that the palaeogeographical arguments upon which this figure was based were incorrect. Other associated thrusts include the Mynachdy Thrust and thrusts within the Ordovician shales at this site, described by Greenly (1919), Bates (1972, 1974), Bates and Davies (1981) and Barber and Max (1979).

Description

The area shows a sequence of complexly folded and faulted units. South of Porth Ogo'r geifr there are gneisses, thought by Greenly (1919) and Barber and Max (1979) to be part of an Archaean basement, and by Shackleton (1969) to be high-grade members of the late Precambrian (Cadomian) Monian. These are faulted against cleaved Caradoc Series shales. At a small cove immediately west of Porth y Wig, the Caradoc rocks are overthrust by the Monian Amlwch Beds of the New Harbour 'Series': this is the type locality for the Carmel Head Thrust (Figure 4.21).

On Carmel Head itself, Gwna Mélange of the Mona Complex (Monian) to the east is unconformably overlain by the rather similar Ordovician Garn Formation. Towards Porth Newydd, the Garn breccias pass up gradually into graptolitic shales, with one thrust slice of Monian phyllites in the sequence. Finally, at Porth Newydd, the Church Bay Tuffs of the Monian are thrust over these shales along the Mynachdy Thrust. The Church Bay Tuffs are probably intermediate in age between the Amlwch Beds and the younger Gwna Mélange in the Monian. The principal features of the site (Figure 4.22) are described from west to east.

Porth Ogo'r-geifr

The inlet is eroded in an E–W-striking fault complex with a steep, northerly dip. On the south side (SH 29149279) sandstones and shales of the Garn Formation are exposed, faulted against the Gader Gneisses to the south. The fault is mineralized: quartz-veined gneiss and shales are exposed in a small excavation around an old shaft opening 40 m east of the head of the inlet.

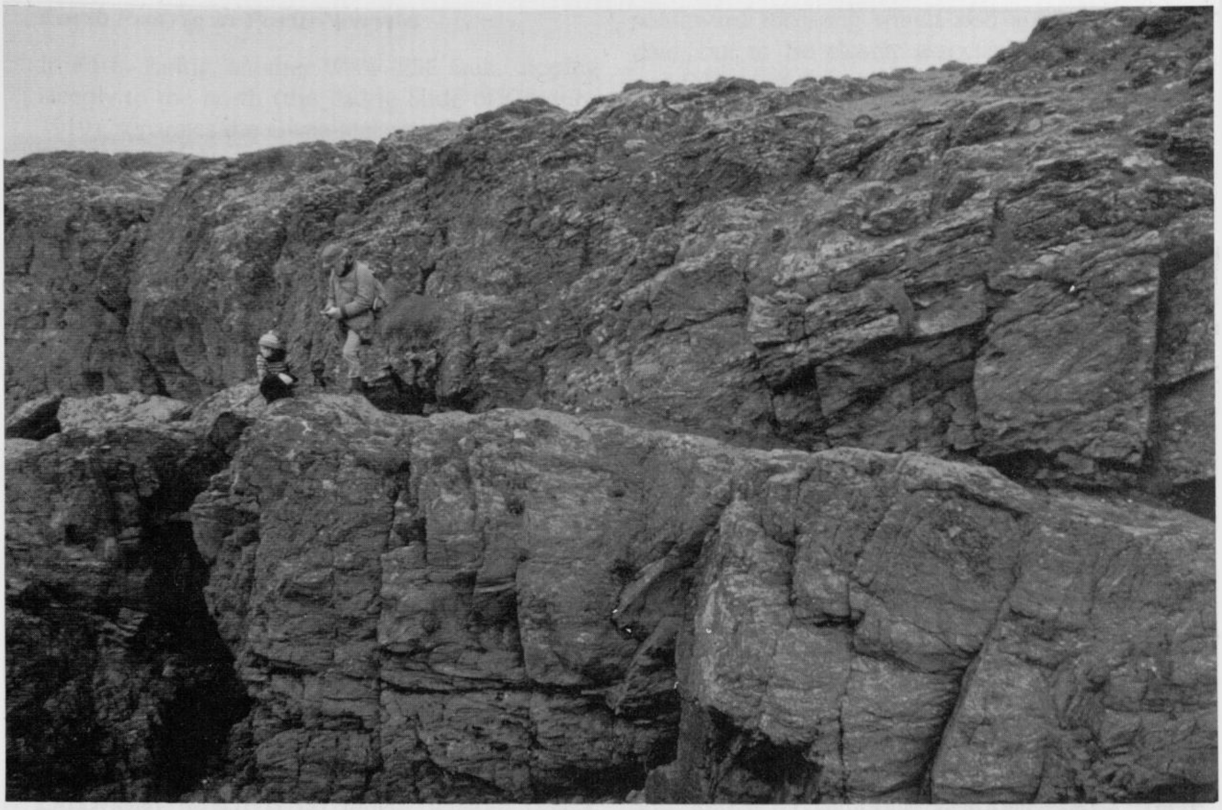


Figure 4.21 Carmel Head, Anglesey. Figure standing on the low-angle fault plane which has thrust Precambrian schists over Ordovician shales. (Photo: J. Treagus.)

Porth Ogo'r-geifr to the Thrust Inlet (SH 29579303, just west of Porth y Wig)

Well-exposed, cleaved Caradoc shales make up the cliffs, which gradually decrease in height to the north-east. A well-developed crenulation cleavage (first described by Greenly in 1919) is present, dipping at low angles to the south. This is spatially related to the thrusts, and was described by Bates (1974) as being linked to the thrust movements. It is only rarely possible to determine bedding, where lithological variations are found, for instance, in the north wall of Porth y Dyfn (SH 29399287). Here, there is a debris-flow breccia of extremely angular blocks of schist and phyllite (up to 0.60 m long) in a shale matrix. A low-angle north-dipping thrust within the shales is well exposed on the coastal rock platform (SH 29449298). There tension gashes and slickencrysts both confirm the southerly movement of the hanging wall, and the crenulation cleavage is well developed.

The Thrust Inlet

The inlet is excavated along a NNW–SSE-trending high-angle fault, which displaces the Carmel Head Thrust at the head of the inlet. The thrust itself follows the north wall, where the chloritic schists of the Precambrian Amlwch Beds overlie Ordovician shales, with the fault contact dipping gently north. The thrust cuts an earlier high-angle fault towards the low water mark. It is possible that both high-angle faults are part of the thrust sequence, although Bates (1974) interpreted the earlier one as being part of a pre-thrust phase of high-angle reverse faulting.

Porth y Wig and Carmel Head

The Amlwch Beds of the New Harbour 'Series' form the hanging wall of the thrust, and the south side of Porth y Wig, but the headland (Garn Mynachdy) of Carmel Head itself is formed of

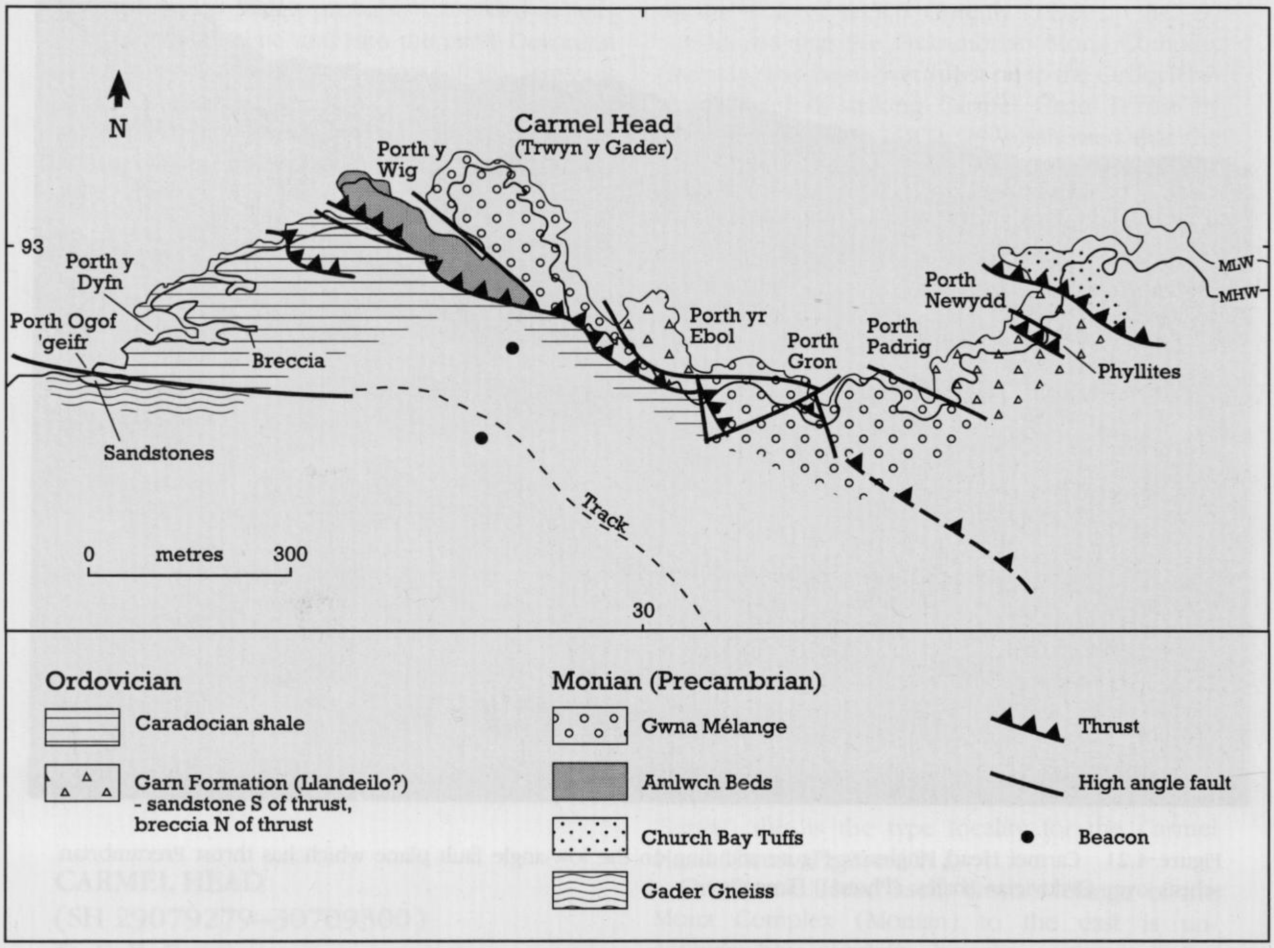


Figure 4.22 Geology of the Carmel Head site.

Gwna Mélange; its contact with the Amlwch Beds is another fault. The mélange is predominantly siliceous, but a band of carbonate mélange is also present, with clasts of dolomite and limestone up to 2–3 m long – which may represent the remains of a dismembered carbonate horizon in the parent succession.

Porth yr Ebol–Porth Gron (SH 29909288)

Three rock units are present in this section, from south to north:

1. Caradoc shales beneath the thrust.
2. Gwna Mélange on the hanging wall.
3. Llandeilo (?) Garn Formation breccias, either faulted against the Gwna Mélange, or unconformable on it.

The main thrust appears in at least five locations:

1. SH 29909288 as a small faulted exposure in the cliff.
2. SH 29969283 in a natural cave.
3. SH 30009280 and east of it along the wave-cut platform.
4. In the east wall of Porth yr Ebol.
5. On the wave-cut platform in Porth Gron.

Again the thrust is cut by ENE–WSW and N–S-trending faults. In Porth yr Ebol the Garn Formation is faulted against the Gwna Mélange, but just east of this inlet (SH 30129278), it appears to be unconformable on the mélange, although as the two formations are similar in character, the boundary is difficult to trace.

Porth Padrig to Porth Newydd

In Porth Padrig, another WNW–ESE fault, dipping steeply to the north (the Padrig Slide of Greenly, 1919), separates the Gwna Mélange from the Garn Formation to the north. The Garn Formation fines upwards (Bates, 1972) into shales with thin breccia and sandstone beds. A mass of phyllites is thrust up into the shales (SH 30649287). In Porth Newydd the Caradoc shales are complexly faulted on a small scale, and are overthrust on the Mynachdy Thrust by Church Bay Tuffs of the Monian.

Interpretation

The sequence described here is of both historical and current interest. It forms the type area or exposure of the Carmel Head Thrust, and there is here no doubt of the reality of this structure. Bates (1974), however, points out that Greenly's (1919, pp. 541-557) arguments for a 20 km southward translation on the thrust, were based on a palaeogeographical interpretation of the Ordovician, which is no longer tenable (Bates, 1972). Although Bates (1974) confirmed the N–S direction of transport from growth fibres and the orientation of the crenulation structure related to the movements, he had already observed (1972, p. 55) that the minimum movement required on the thrust is only in the order of metres.

At Carmel Head there are two low-angle faults which clearly emplace older (Monian) rocks over younger (Ordovician). There are also other parallel, low-angle faults that are probably thrusts, as well as high-angle reverse faults. Elsewhere on Anglesey the plane mapped as the equivalent of the Carmel Head Thrust is usually a high angle reverse fault. It is probable that remapping of this area, in conjunction with modern ideas on thrust geometry, may lead to revision of some of the faulting sequence, but should make the zone of even greater significance.

Models for the evolution of the structure of the Welsh Basin (for example, Shackleton, 1969; Coward and Siddans, 1979) appeal to thrusting, related to mid-crustal décollement, as a major response to the main-phase Caledonian shortening (late Silurian to early Devonian). The movements described here, although possibly closely following, certainly post-date the main-phase cleavage and folding. The Old Red Sandstone rocks at Lligwy Bay (see above) are also affected by southward thrusting which also appears to post-date, but to be closely associated with cleavage and folding of the same main phase. This thrusting on Anglesey appears to pre-date the Carboniferous succession.

Descriptions of similar thrusts elsewhere in the north Welsh Basin are rare. The most famous, the Tremadoc Thrust (Fearnsides, 1910), has been shown by Smith (1987, 1988) to be a pre-lithification structure. The thrusting at Trum y Ddysgl (see above) has the same south-easterly sense of movement but is directly related to the folding and cleavage.

Conclusions

Carmel Head provides one of the clearest, and the only convincing, examples of late thrusting in the Caledonides of Wales. Thrusts (faults lying at a low angle to the horizontal) were a major product of crustal shortening caused by compression in the Caledonian event. The amount of movement on this particular major dislocation has been the subject of dispute, but it thrusts already cleaved and folded Precambrian basement rocks south over Early Palaeozoic rocks. The thrust movements post-date the folding and cleavage which were formed by the main tectonic events of the Caledonian Orogeny, and this has significance in establishing a chronology for this period of mountain building. The clarity of the exposures hereabouts makes the region of paramount importance.

LLANELWEDD QUARRY (SO 051522)

N. H. Woodcock

Highlights

Llanelwedd Quarry provides the best-exposed section across the structures of the Pontesford Lineament, one of the major fault belts that was active between the Welsh Basin and the Midland Platform of England in Palaeozoic times.

Introduction

This working quarry exposes rocks of the Builth Igneous Complex (Llanvirn Series) of early Ordovician age, at the southern end of the Builth–Llandrindod Inlier. This inlier exposes a 'window' of Llanvirn and Llandeilo sedimentary and volcanic rocks, unconformably overlain by Upper Llandovery and Wenlock strata. Historically, most interest has focused on the volcano-sedimentary stratigraphy of the locality (Elles, 1940; Jones and Pugh, 1941, 1946, 1949; Furnes, 1978). In a structural context, this area is more important for the numerous fault zones that cut the section. These were first mapped by Jones and Pugh (1949) and interpreted as part of a strike-slip fault system by Jones (1954) and Baker (1971). The site lies in the zone of structures (Woodcock, 1984b), known as the Pontesford Lineament, which extends from the Cheshire Basin to South Wales (Figure 4.1). Although the lineament was intermittently active at least from mid-Ordovician times through to the Triassic, the principal fault displacements, both strike-slip and dip-slip, were late Ordovician to early Silurian (pre-Upper Llandovery unconformity). The best-documented displacements of up to 5 km, dextral movements, occur on faults in the Shelve Inlier, some 40 km north-east of the present site (Lynas, 1988). Woodcock (1984b) estimates that the total (dextral) movement in the zone could be in excess of 20 km. The locality has been used (Woodcock, 1987b) as an example of the structural architecture of a strike-slip fault belt.

Description

The geology of the quarry complex is summarized in Figure 4.23, based mainly on exposures in four main arcuate working faces, each 20 m high. The map shows the position of the faces in 1984, but they are being continually worked back northwards. To remove the confusing effects of the stepped topography, the map is constructed as a projection on to a hypothetical smooth surface through the top of each face.

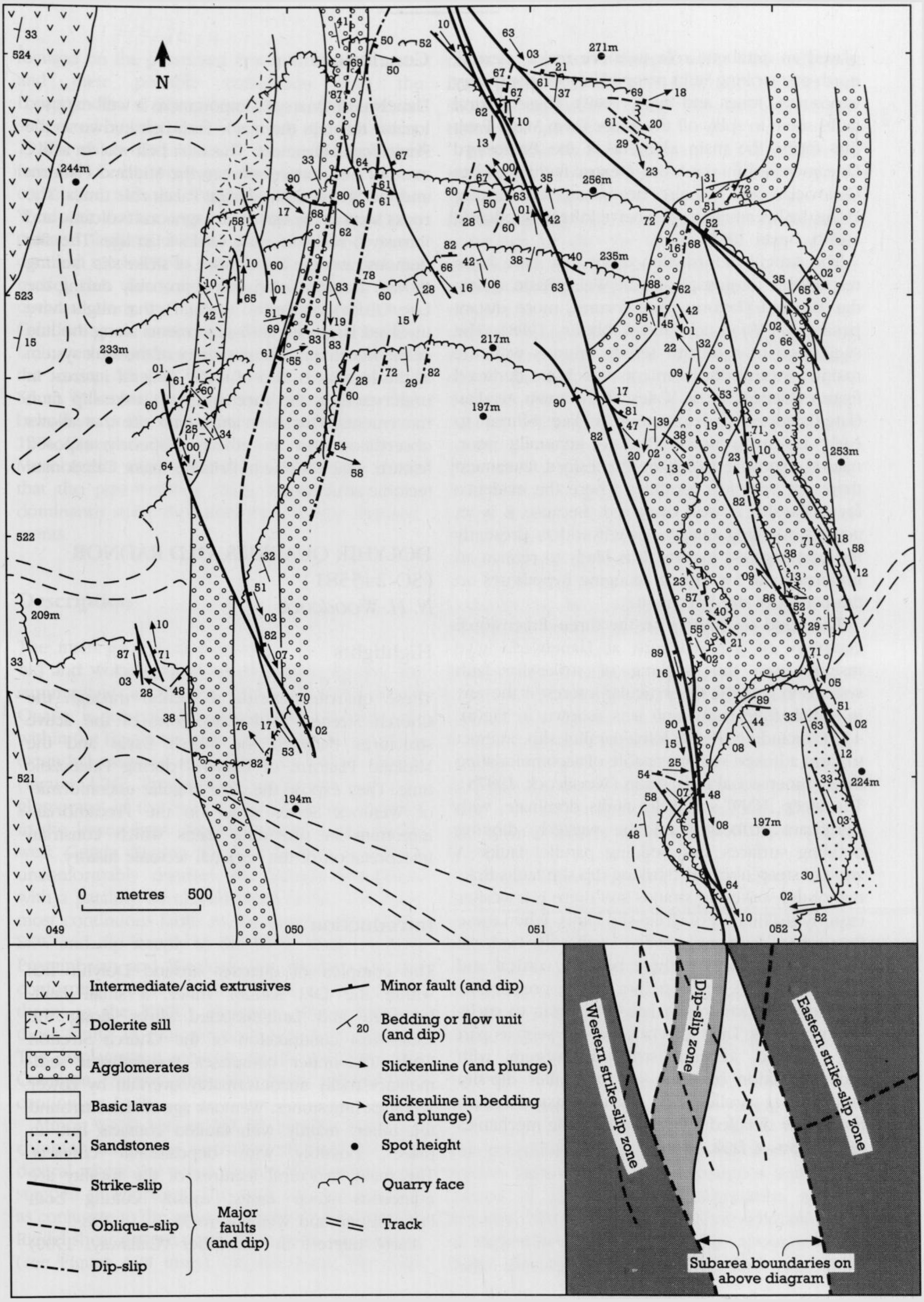
The lithological sequence is dominated by basalt lavas, mostly feldspar-phyric and highly vesicular. These contain intercalated agglomerates, a sandstone body and a dolerite sill. This structurally conformable sequence dips moderately westwards. It is cut by numerous faults, mostly striking approximately north, and dipping steeply eastwards. Three major zones of faults can be recognized, summarized as an inset on Figure 4.23. A central zone mainly comprises NNE–SSW striking dip-slip faults. This zone separates eastern and western zones containing mostly strike-slip faults with the same strike. Minor E–W-striking strike-slip faults also occur. These faults dominate the overall structure, and about 57% of them are strike-slip, 31% oblique-slip, and only 12% are dip-slip faults. Fault slip directions can be determined from cataclastic slickensides and from slickenfibres, elongate crystal growths in the fault planes. The sense of slip can rarely be determined directly from these structures. Offsets of distinctive stratigraphical units can be used to obtain dip-slip senses, but are unreliable for most strike-slip faults, because the strike directions of bedding and faults are so close. The limited data show that most of the dip-slip faults have normal rather than reverse offsets, but that sinistral and dextral offsets on strike-slip faults are equally numerous. Many of the west-dipping 'bedding' surfaces, mainly boundaries of lava-flow units, have also acted as displacement planes. They show northerly strike-slip slickenlines.

Interpretation

The faults in Llanelwedd Quarry record an important strike-slip faulting event along the Pontesford Lineament. This event cannot be dated at this locality, but mapping of the whole Builth–Llandrindod Inlier (compilation by IGS, 1977) shows that many of the faults of the strike-slip system do not cut the unconformable Upper Llandovery (Lower Silurian) and younger cover. Regional evidence suggests an Ashgill (Late Ordovician) age as most likely (Woodcock, 1984b). Llanvirn and Llandeilo rocks in the Builth Inlier are displaced by the faults and Caradoc sequences do not match across the main fault in the Pontesford area. Later reactivation of the Pontesford Lineament is suggested north-east of the Builth area by its coincidence with the fold–fault zone of the Clun Forest Disturbance, affecting rocks as late as those of the Pridoli.

Although the kinematic interpretation of the Llanelwedd faults is made uncertain by the paucity of data on slip sense, Woodcock (1984b) has proposed that the main fault sets (shown in Figure 4.23) interact to form a linked system capable of accommodating three-dimensional bulk strain. Woodcock (1987b) suggests that the NNW–SSE strike-slip faults are sinistral and that they have

Figure 4.23 Geological map of the main Llanelwedd Quarry with inset summary of main kinematic zones (after Woodcock, 1987b).


N
0 metres 500
244m
233m
209m
194m
217m
197m
271m
256m
235m
253m
224m
524
523
522
521
049
050
051
052
Intermediate/acid extrusives
Dolerite sill
Agglomerates
Basic lavas
Sandstones
Strike-slip
Oblique-slip
Dip-slip
Major faults (and dip)
Minor fault (and dip)
Bedding or flow unit (and dip)
Slickenline (and plunge)
Slickenline in bedding (and plunge)
Spot height
Quarry face
Track
Western strike-slip zone
Dip-slip zone
Eastern strike-slip zone
Subarea boundaries on above diagram

played an antithetic role to more major, dextral, north-east-striking faults mapped beyond the quarry exposures (Jones and Pugh, 1949). These dextral faults seem to splay off the major Cwm Mawr Fault that forms the main element of the Pontesford Lineament within the inlier. Dextral faulting of late Ordovician age has also been suggested further along the lineament in the Shelve Inlier (Woodcock, 1984b; Lynas, 1988).

The Ashgill deformation event may have been responsible for juxtaposing the Welsh Basin against the Midland Platform from former, more distant positions (Woodcock and Gibbons, 1988). The suggestion of a dextral sense contrasts with the mainly sinistral displacements which are deduced from evidence across Wales of the main Acadian (late-Caledonian) deformation in late Silurian to early Devonian times. Due to generally poor, natural exposure along the Pontesford Lineament there are very few localities where the evidence for strike-slip is well displayed. Because it is an actively working quarry, Llanelwedd is presently the best-exposed locality. It is likely to remain an important site for testing changing hypotheses on the nature of the lineament.

The good constraints on the three-dimensional geometry of the structure at Llanelwedd give insights into the working of strike-slip fault systems in general. Of particular interest is the way in which four main fault sets (shown in Figure 4.23), including the bedding-parallel slip, interact to form a linked system capable of accommodating three-dimensional bulk strain (Woodcock, 1987b). The steep, NNW strike-slip faults dominate, with significant strike-slip on the westerly dipping bedding surfaces and bedding parallel faults. A zone of steep northerly striking dip-slip faults links two of the strike-slip strands and there is a weaker easterly striking set of strike-slip faults. When these four sets of faults are rotated so that the regional bedding is horizontal, three become vertical and one (parallel to bedding) horizontal, presumably their original attitude in late-Ordovician to early-Silurian times. The faults can then be seen as part of a linked, dextral, strike-slip system with accommodation of strain on to smaller dip-slip and bedding parallel faults. The locality is excellent for further detailed investigation of the mechanics of this sort of fault system.

Conclusions

Llanelwedd Quarry is important as a well-exposed locality through the major fault belt known as the Pontesford Lineament. This fault belt was an active zone of dislocation between the Midland Platform and the Welsh Basin during Palaeozoic times. The rocks seen in the quarry are igneous (volcanic and intrusive) rocks of early Ordovician age. The site demonstrates the importance of strike-slip faulting during a deformation event, probably during the Late Ordovician Period (Ashgill), that might have involved large lateral displacements along the line of the lineament. The geometry of the fault system at the locality is also of some general interest in understanding the mechanics of strike-slip fault movements. This is an important site that allows observations on an otherwise poorly exposed feature, which is one of Britain's major Caledonian tectonic structures.

DOLYHIR QUARRIES, OLD RADNOR (SO 245581)

N. H. Woodcock

Highlights

These quarries provide a section through the Church Stretton Fault Zone, one of the active structures between the Welsh Basin and the Midland Platform of England during Palaeozoic time. They expose the clear angular unconformity of Wenlock Series strata on the Precambrian, important in providing dates which constrain interpretation of the regional tectonic history.

Introduction

The complex of quarries around Dolyhir lies within the Old Radnor Inlier, a small fault-bounded and fault-dissected sliver along the south-west continuation of the Church Stretton Fault. The inlier comprises Precambrian sedimentary rocks unconformably overlain by Lower Wenlock limestones. Wenlock age shales surround the inlier, mainly with faulted contacts but, in places, possibly with depositional contacts. The main structural features of the locality are numerous steep faults, mostly cutting both Precambrian and Wenlock rocks.

Early interest in the inlier (Callaway, 1900) focused on the presumed Precambrian sediments and their possible correlation with the Longmyndian of Shropshire. This correlation was supported by later work (Garwood and Goodyear, 1918) which also showed the palaeontological interest of the overlying limestones, and their correlation with the Woolhope Limestone (Lower Wenlock) further east. The recognition of important faulting within the inlier and more detailed work (Kirk, 1951, 1952) produced the model that the inlier was a basement block upthrust along the Church Stretton Fault Belt in Caledonian or later times. The inliers along this fault were important evidence for the theory that the main, NE–SW, 'Caledonoid' lineaments in South Wales and the Borderland overlie steep fault belts that cut the basement to some depth (Owen, 1974; Owen and Weaver, 1983; Woodcock, 1984a). More recent work (Woodcock, 1988) has shown that the post-Wenlock faults in the inlier have dominantly strike-slip rather than dip-slip displacements.

Description

The main geological features of the complex of old and working quarries at Dolyhir in 1985 are summarized in Figures 4.24 and 4.25. Strinds Quarry is currently being worked south-westward within the limestone only. Dolyhir Quarry is being extended eastward at all levels. In Strinds Quarry (Figure 4.24), Precambrian sandstones and conglomerates of the Strinds Formation are exposed in the lower faces, dipping steeply to the north-west. Gently dipping Wenlock Dolyhir Limestone unconformably overlies the Strinds Formation, with a patchily developed basal rudite. The three most continuous faults in the quarry strike NNE–SSW and dip steeply to the WNW. They cut both Precambrian and Wenlock and displace the unconformity surface with normal offset (downthrow to the WNW). However, slickensides on these faults all indicate strike-slip displacements. The displacement sense is mostly indeterminate. Common, minor strike-slip faults parallel the continuous faults.

Minor WNW–ESE or NW–SE striking faults are common above the unconformity, and they are dextral where the sense can be determined from stepped slickenfibres. This fault set is interpreted as conjugate to the main northerly set, forming the Riedel shear pattern common in strike-slip systems (see Figure 4.24 inset). On this basis, the main faults would have a sinistral sense. Minor dip-slip faults strike between NNE–SSW and NE–SW, and show an extensional component both above and below the unconformity.

In Dolyhir Quarry (Figure 4.25), Precambrian rocks again form the lower faces. Strinds Formation sandstones outcropping in the south-east are faulted against the finer-grained, better-bedded sediments of the Yat Wood Formation in the central and north-eastern parts. This fault zone strikes NE–SW and contains mostly south-east-dipping faults, some showing strike-slip and some dip-slip slickensides. Several subparallel faults cut the eastern part of the Yat Wood Formation, mostly showing dip-slip displacements. None of these NE–SW or E–W striking faults unambiguously cuts the Wenlock unconformity and therefore they could be pre-Wenlock, even Precambrian, in age. They all abut against, or anastomose with, a major, NNE–SSW-striking fault (SO 24425828 to 24475845) which displaces the unconformity down by about 30 m to the WNW. The central segment of this fault shows dip-slip slickensides. West of the fault, the Yat Wood Formation and Dolyhir Limestone are both cut by two subparallel major faults, one evidencing strike-slip, the other some additional dip-slip component. The unconformity surface, everywhere overlain by basal rudites, is progressively downfaulted towards the north-west part of the quarry. As in Strinds Quarry, the Dolyhir Limestone commonly shows steep NW–SE-striking strike-slip faults with dextral sense. Although the Riedel shear pattern is not so clear here it is still compatible with sinistral shear on the main northerly strike-slip faults (see Figure 4.25 inset).

Complementing the information from Strinds and Dolyhir Quarries are numerous minor exposures throughout the Old Radnor Inlier and also the extensive Gore Quarry at its north-west end. This is of less stratigraphical interest because it contains only Precambrian rocks, but it contains a suite of faults comparable with those described above (details given by Woodcock, 1988).

Interpretation

The geometrical pattern of structures in the Old Radnor Inlier is exceedingly complex and some aspects of its kinematic interpretation remain tentative. The clearest feature is the predominance of strike-slip faults over dip-slip. About 65% of faults affecting the Precambrian and over 80%

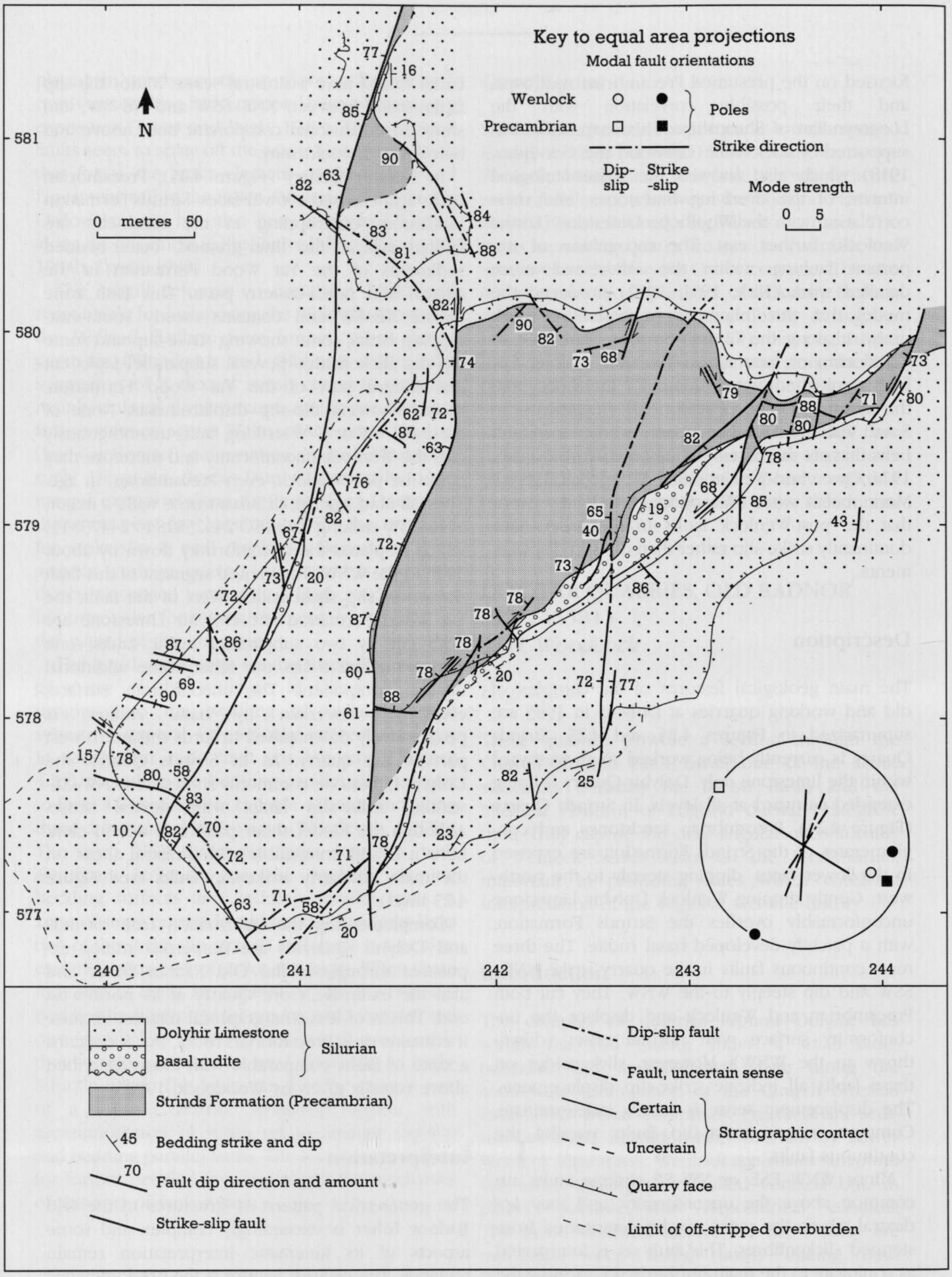


Figure 4.24 Structural map of Strinds Quarry with inset stereogram showing modal orientations of strike-slip and dip-slip faults (after Woodcock, 1988).

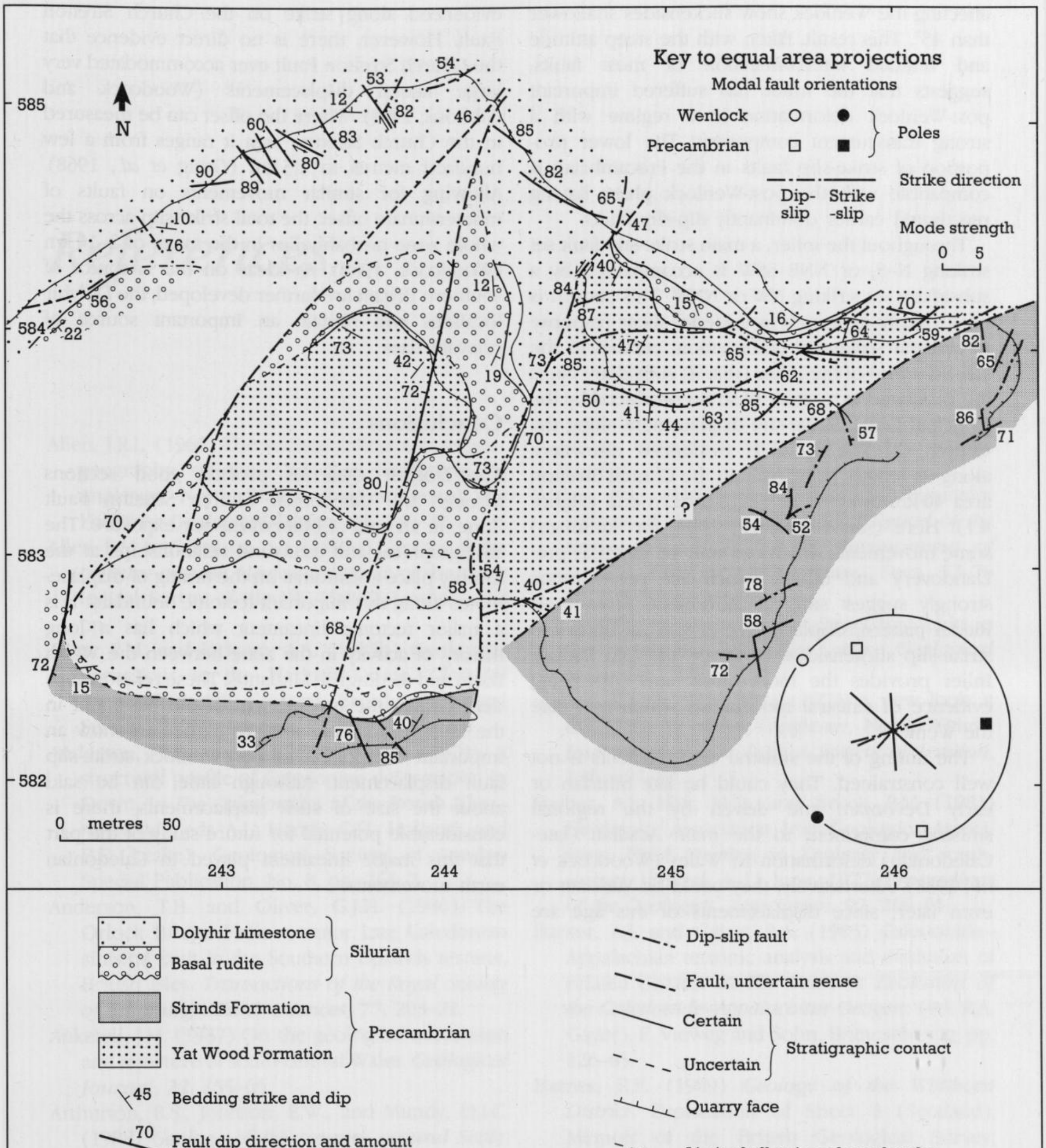


Figure 4.25 Structural map of Dolyhir Quarry with inset stereogram showing modal orientations of strike-slip and dip-slip faults (after Woodcock, 1988).

affecting the Wenlock show slickensides shallower than 45°. This result, taken with the steep attitude and braided interconnection of most faults, suggests that the inlier has suffered important post-Wenlock deformation in a regime with a strong transcurrent component. The lower proportion of strike-slip faults in the Precambrian is compatible with the post-Wenlock phase having reactivated earlier dominantly dip-slip faults.

Throughout the inlier, a main strike-slip fault set striking N–S, or NNE–SSW is accompanied by a subsidiary set striking NW or NNW. This pattern is most simply explained as a Riedel shear response to sinistral strike-slip deformation, parallel to the NE–SW trend of the inlier (that is, subsidiary faults are produced as a result of strain produced by the principal fault). Strike-slip displacement along the Church Stretton Fault is evidenced elsewhere along its length, principally in the Church Stretton area 40 km away, at its north-eastern end (Figure 4.1). Here (see Woodcock, 1988, for summary) some movements which can only be dated as pre-Llandovery and others which are post-Caradoc strongly suggest sinistral movements from their Riedel pattern, displacement of vertical beds and strike-slip slickensides. However, the Old Radnor Inlier provides the most direct and convincing evidence of sinistral movements which post-date the Wenlock.

The timing of the sinistral displacements is not well constrained. They could be late Silurian or early Devonian, and driven by the regional sinistral component to the main Acadian (late-Caledonian) deformation in Wales (Woodcock *et al.*, 1988). Alternatively, they could be Variscan or even later, since displacements of this age are evidenced along strike on the Church Stretton Fault. However, there is no direct evidence that the Church Stretton Fault ever accommodated very large lateral displacements (Woodcock and Gibbons, 1988). Where the offset can be measured in the Church Stretton area it ranges from a few hundred metres to 1.5 km (Greig *et al.*, 1968). Allowing for similar movements on faults of indeterminate offset, the total strike-slip across the whole zone probably lies in the range of 2–10 km (Woodcock, 1988). As ideas on the tectonics of southern Britain are further developed, the Dolyhir localities will remain an important source of relevant data.

Conclusions

The Dolyhir Quarries provide good sections through the Caledonian Church Stretton Fault Zone, in an area of otherwise poor exposure. The stratigraphical and structural relationships at the locality place constraints on the timing of displacements along this important tectonic boundary. It is a major tectonic lineament which has a long history of activity in the zone between the Welsh Basin and the English Midlands. These relationships demonstrate the involvement of old basement in the fault movements, and, in particular, show an important component of post-Wenlock strike-slip fault displacement. Although little can be said about the size of such displacements, there is considerable potential for future study of the part that this major lineament played in Caledonian earth movements.