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The Hercynian geology of Lydford Gorge, north-west Dartmoor, and its regional significance

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The rocks of. Lydford Gorge are divided into three informal tectonostratigraphic units: (1) The Whitelady Unit; mixed clastic-carbonate shelf sediments of Famennian Platyclymenia Stufe age, (2) the Liddaton Unit; black and dark grey pelagic shales with thin siliceous lenses and sandstones of Famennian Wocklumeria Stufe age, and (3) the Lydford Unit; a complex association of largely pelagic sediments of Upper Devonian or Lower Carboniferous age with sandstones, cherts and volcaniclastic horizons. These units are separated by thrusts. The boundary between the Whitelady and Liddaton units is a major tectonic discontinuity, the Whitelady Thrust, which is characterized by a 30m-wide zone of mylonitic fault rocks. Detailed analyses of the structure and metamorphic history shows a complex tectonometamorphic evolution involving three major deformations. The earliest and highest metamorphic grades are preserved in the cores of calc-silicate and metabasite lenses which reached medium grade conditions. Subsequent prolonged burial, but at successively decreasing depths, induced retrograde metamorphism eventually to very low grades recorded by clay mineralogical indicators.

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Introduction

Gorges and steep sided valleys cut by the River Lyd and its tributaries in the Lydford area, north west of Dartmoor, afford some 10km of continuous river and crag exposure in a region otherwise poorly exposed. For this reason Lydford Gorge has always been a key section not only in the elucidation of the local and regional geology but also in the synthesis of large-scale structure. To date, the structure of the area has been interpreted (Dearman and Butcher 1959; Hobson and Sanderson 1975; Sanderson 1979) in terms of a "Meldon" regime (Dearman 1959; Edmonds and others 1968) dominated by open, upright major folds overturned to the south, with thrusting towards the south along their inverted limbs. These studies proceeded by examination of small-scale structures but little attention was paid to the establishment of an adequate stratigraphy; this has led to misinterpretation of the structure.

Preliminary conclusions as to the nature and significance of the large-scale structure are given here with comments on the metamorphic history of the area. The presence of a thick sequence of mylonitic fault rocks along the Whitelady Thrust and an early medium grade metamorphic event significantly alter previous concepts of the style of the Hercynian orogeny in central southwest England.

Stratigraphy and small scale structure

This work forms part of the revision of the Institute of Geological Sciences 1:50.000 Sheets 337 (Tavistock) and 338 (Dartmoor Forest) by a team at the Geology Department of the University of Exeter, sponsored by I.G.S. Formal naming of stratigraphical units must await completion of the project, hence an informal stratigraphy is given.

A geological map of Lydford Gorge and the area immediately to the south is shown in Fig. 1. The Blackdown unit shown on this map is not exposed within the gorge itself and hence is not described in detail here.

Whitelady unit

Named after the Whitelady Waterfall (SX 50108345) at the lower end of the National Trust section of the gorge, this is the lowest tectonic and lithological unit observed and probably represents the deepest tectonic level for the whole project area. The total thickness is of the order of 50m although true thicknesses cannot be estimated due to complex folding. Although no useful fossils have been found during this study, House (1959) described *Imitoceras* cf. *sulcatum* and *Platyclymenia* sp., from the Manor Hotel Beds of Dearman and Butcher (1959). The locality (SX 50208324) lies within the outcrop of the Whitelady unit and fixes its age about the Platyclymenia Stufe.

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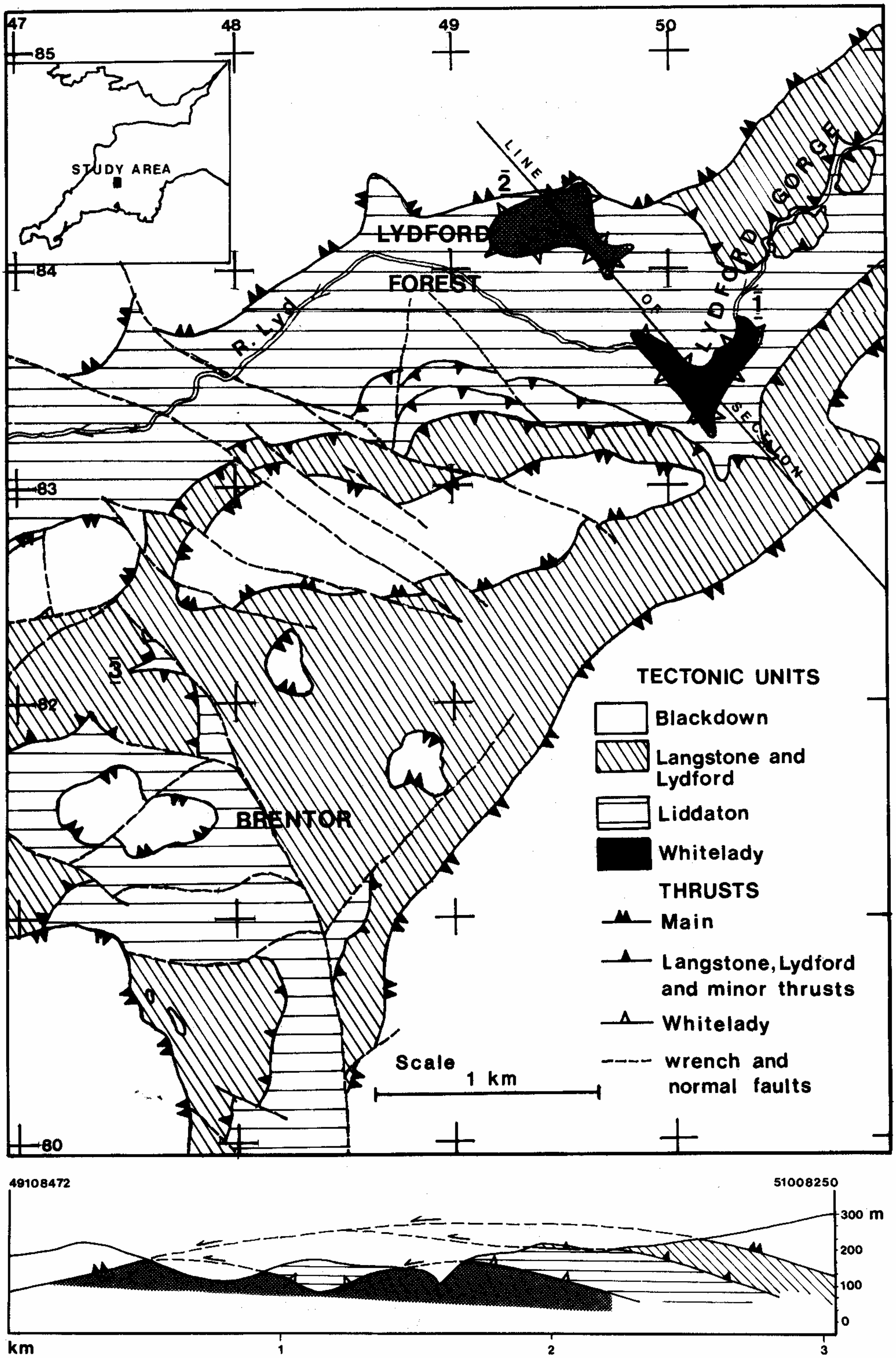

Figure 1. Geological map and section of Lydford Gorge and the surrounding area, north-west Dartmoor

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Lithologically the unit is varied and contains a diverse range of rock types. Metapelites, usually greenish-grey in colour, dominate, however, semi-pelites, psammites and thin fine grained cherty or relatively coarse grained calc-silicate lenses are common. Notwithstanding the metamorphic grade of the unit, in which coarse-grained granoblastic fabrics dominate the psammites and calc-silicate lenses, a few of the former limestones include traces of crinoid ossicles, brachiopods and some remarkably well preserved ostracods which hold promise of identification. The overall character of the calcareous lithologies suggests a shell coquina accumulated under high energy conditions. This aspect, along with the general character of the unit has led to the interpretation of this unit as a highly deformed and metamorphosed mixed carbonate-clastic shelf sequence.

Small-scale structures show that the tectonic style of the Whitelady unit is dominated by large amplitude (10m) open to tight recumbent folds (F2) whose axial surfaces are generally orientated 10 to 30° to the NW or NNW. The main penetrative S-fabric (D2) is thought to be axial planar to these folds. The occurrence of rotated porphyroblasts in metapelites containing an earlier S-fabric development and the presence of isoclinally folded quartz veins pre-dating the main folding indicates that the main S 1 cleavage has a polyphase origin. Parallelism has led to the earlier D1 deformation being generally obscured. An intensely developed non-penetrative fabric consisting of both fracture and crenulation cleavages orientated sub-vertically and trending roughly ENE-WSW, represents D3. Gentle open and upright folds and rare kink bands also relate to this deformation.

Liddaton unit

The boundary of the Whitelady and Liddaton units is marked by the Whitelady Thrust with which some 30m of mylonitic fault rocks are associated and these are described separately. The upper boundary between the fault rocks and the Liddaton unit appears to be gradational, an impression that is confirmed by X-ray diffraction studies which show a progressive change in mineralogy moving upwards away from the thrust zone.

The Liddaton unit consists of at least 100m of black to dark grey smooth phyllitic pelites and semi-pelites with occasional nodular, impure limestone developments, and horizons crowded with siliceous nodules about 2-5cm in diameter. More rarely, well-bedded laminated and massive psammites occur. The pelites and semi-pelites are commonly finely graded, indicating a distal turbiditic origin, and the overall characteristics of the unit are indicative of a pelagic sedimentary environment.

Ostracods of the *hemisphaerica - dichotoma* Zone have been recovered from a number of localities and *Parawocklumeria* sp. from Coryhill (SX 46178350). These indicate an Upper Famennian age well up into the Wocklumeria Stufe.

The deformation history of the Liddaton unit is rather simpler than that of the Whitelady unit. The main cleavage, S1, is seen at some localities to be axial planar to large amplitude (10m) open to tight folds in bedding with an orientation similar to the F2 folds in the Whitelady unit. S1 varies from a non-penetrative crenulation cleavage formed by deformation of a primary layer silicate fabric developed parallel to bedding in the psammitic and semi-pelitic components, to a penetrative slaty cleavage confined to pelitic layers. Discrete zones of intense slaty cleavage development are interpreted as ductile shear zones formed contemporaneously with SI and Fl. Later deformation (D2)is represented by more brittle strains including complex zones of imbricate thrusting within the unit and by open, upright, angular folds and kink bands whose axial surfaces trend N-S.

Lydford unit

The boundary between the Liddaton and Lydford units is everywhere thrusted but not always simply developed. The progressive migration of thrusts across earlier thrusted contacts has led to a complex intercalation of thrust slices from both units. In contrast to the Whitelady Thrust, which is a ductile structure, these thrusts are dominated by brittle features and commonly have pockets of coherent and incoherent random fabric fault rocks developed along their surfaces. The Langstone and Lydford units are shown together on Fig. 1. Lithologically the two are similar and they have identical tectonic roles. However, the Langstone unit is Lower Carboniferous whilst the Lydford unit is tentatively dated as equivalent to Wocklumeria Stufe. Only the Lydford unit is exposed in the gorge area, hence the Langstone unit is not discussed further here.

The Lydford unit consists of dark grey to dull brownish-grey slightly to very silty and sandy, micaceous pelites with numerous thin lenses and nodules of massive greywackes, graded turbiditic sandstones, impure limestones, cherts and volcaniclastics. Very few of these lenses and nodules, however, are primary. Bedding is highly transposed so that much of the unit consists of lenses of the more competent lithologies sheared out in an incompetent pelitic matrix. The unit is some 75m thick in the gorge area and is thought to represent a pelagic slump and proximal turbidite sequence in which soft sediment deformation structures have been subsequently tectonised.

The deformational style of the unit indicates that the earliest folds are syn-depositional. The SI tectonic cleavage associated with these folds is essentially non-penetrative and developed strongly only in the hinges of the folds which are sub-isoclinal to isoclinal. An S-fabric parallel to bedding which pre-dates S 1 is observed in the more semi-pelitic components and is thought to be primary sedimentary lamination modified by burial metamorphism after the main fold development, but prior to the tectonic S - fabric. On a large scale the

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Table 1. Correlation of deformation events.

Lydford unit	-	D1	(?)
Liddaton unit	-	D1	D2
Whitelady unit	D1	D2	D3

orientation of F1 is chaotic. On a local scale, within small sub-units which could represent individual slumps, orientation tends to be more consistent. Subsequent tightening of these F1 folds by loading caused development of the S1 cleavage and modification of the fold form. A correlation of deformation events for all three tectonic units is shown in Table 1.

Fault rocks associated with the Whitelady Thrust

Throughout this paper the lithological classification of fault rocks and general terminology employed is that of Sibson (1977), largely modified from Higgins (1971).

All the fault rocks from the Whitelady Thrust zone are coherent and foliated with the exception of a pseudotachylite-like lithology developed in the basal mylonites above the lower bounding surface to the thrust zone. These mylonites constitute 0.5 to 1.5m of plagioclase-chlorite-actinolite mylonites and ultra-mylonites. In thin section plagioclase and chlorite porphyroclasts are seen in an extremely fine-grained chlorite-actinolite-plagioclase matrix which shows well developed fluxion structures. Intrafolial folds and rotated porphyroclasts are commonly developed and demonstrate that transport directions were towards the north. Large areas of the mylonitic fabric show syn- and post-deformational recrystallisation (Bell and Etheridge 1971), giving blastomylonitic textures. The mineralogy and preliminary geochemical investigations indicate derivation from metabasites. A complex metamorphic history is observed, including some time spent across the hornblende-in isograd (Winkler 1979), indicating medium grade conditions. Overall, low grade assemblages dominate and these conditions appear to have been maintained over two main deformations. The highest metamorphic grades are confined to a narrow zone focussed around the basal mylonites. From textural evidence it seems that the Whitelady unit has been contact metamorphosed for a distance of about 10m below the mylonites early in its metamorphic history which implies that the thrust zone was the source of the heating. Shear heating, frictional heating or the intrusion of a basic igneous intrusion into the thrust zone during deformation are possible interpretations of the elevated temperatures along the thrust. Explanation of this problem must await the completion of further petrographic work and the assessment of theoretical considerations.

Above the basal mylonites is a 1.5m-thick zone of blastomylonitic plagioclase-chlorite-epidote-actinolite lenses in a matrix of muscovite-chlorite-quartz phyllonites. This zone is truncated upwards by a second major tectonic discontinuity which appears to post-date the deformation which formed the mylonites. Overlying this late thrust is a 30m-thick zone of muscovite-chlorite-quartz phyllonites with rare mylonitic lenses. Phyllonites are ultramylonites formed by intense ductile deformation of sheet silicate-rich lithologies by intracrystalline plastic deformation processes; accordingly the further reduction in grain size from the single figure micron range makes the study of these rocks difficult.

After the development of the foliated fault rocks a tensional phase of deformation occurred in which quartz-plagioclase-actinolite veins and joints were formed. These cut across all the mylonitic fabrics but are themselves truncated by an elaborate network of chlorite veins. It is possible that these veins represent frictional fusion of the mylonites and that although no glass phase has been identified, on the basis of their intrusive nature, an affinity with pseudotachylites (Philpotts 1964; Sibson 1977) is envisaged. Spectacular symplectic and quench textures are displayed where these originally mobile veins have reacted thermochemically and mechanically with the earlier mylonite fabrics. The implication of these textures is that two separate phases of thrusting have occurred. The first phase occurred below the quasi-plastic (QP)/elasto-frictional (EF) transition (Sibson 1977) in a ductile regime the second above this transition in a brittle regime. The late brittle thrust above the mylonites is thought to post-date both of these events.

Metamorphic history

The metamorphic history of the succession is divided into three phases, M1 to 3, approximately contemporaneous with the three deformations, D1 to 3 respectively. M1 is only observed in the Whitelady unit and correlates with the earliest phase of thrusting represented by the mylonites in the Whitelady Thrust zone. The assemblage quartz-calcite-tremolite-chlorite occurs in calc-silicate lenses up to 10 metres below the thrust and the presence of the paragenesis quartz-calcite-tremolite in the cores of these lenses indicates medium grade conditions early in the metamorphic history. The stability field of this paragenesis is highly dependent on fluid phase composition, in particular the mole fraction of CO_2 present. According to Winkler (1979), at a fluid pressure, Pf of 5kb, a value far in excess of a reasonable estimate for this situation, this paragenesis indicates a wide range of temperatures, 500-610°C, corresponding to a CO_2 mole fraction of approximately 0.1 to 0.9. At a Pf of 1kb in an earlier edition of his book Winkler (1976, 4th edition) indicated a temperature range of 480-540°12, or 510 ± 30°C, for the same range of CO_2 mole fractions. The latter is thought to be most reasonable in the situation under discussion here. The presence of an Mg-rich chlorite such

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as clinochlore or penninite to such high temperatures is possible but only in the absence of quartz and indeed no chlorite is seen in contact with quartz in the core of the lens. It seems reasonable from the present evidence to suggest that in a narrow zone below the Whitelady Thrust temperature conditions of the order of 545 ± 65°C, but probably nearer to 510°C, were attained early in the metamorphic history. The presence of hornblende in the basal mylonites confirms these parameters. The textures associated with these metamorphic grades are characteristic of contact metamorphism. The confinement of these textures to a narrow zone below the thrust implies that the thrust zone was the source of heating at least for some of its movement history.

Metapelites in the Whitelady and Liddaton units are dominated by mineral assemblages typical of incipient low grade metamorphism (lowest greenschist facies) and indeed the regional metamorphism (M2) over a large area of the surrounding country is characterized by similar grades. The assemblage quartz-mica-chlorite-actinolite-epidote-albite-calcite-dolomite is typical although in tectonic units higher than the level under discussion here assemblages including allevardite and corrensite (Velde 1977) indicate very low grades (200-300°C).

All three units are characterized by illite crystallinity (Kubler 1968) values typical of incipient low grade temperatures. A sequence of samples taken in a traverse across the Whitelady Thrust in Lydford Gorge gave a mean value of .0.23°2θ (CuKα radiation, -2 µm fraction) for 26 samples with a standard deviation of 0.03. However, the thermal profile represented by the illite crystallinity is remarkably uniform and is unaffected by the variation in metamorphic grade recorded by mineral assemblages and parageneses in the vicinity of the thrust zone. The implication is that the illite crystallinity records a late, post-thrusting, retrograde thermal imprint. The absence of any inverted thermal gradient above the Whitelady Thrust and the overall indications of a declining thermal regime in the thrust zone with time would seem to suggest prolonged burial beneath the overthrust sheet with a slow rate of uplift of removal of overburden (Oxburgh and Turcotte 1974).

Regional implications

Previous authors (Reid and others 1912; Dearman and Butcher 1959; Selwood 1971) have realised that the Lydford area is stratigraphically and structurally complex. However, some studies based on small scale structures (Sanderson 1979) and on a simplistic view of the stratigraphy (Hobson and Sanderson 1975) have led to a misinterpretation of the large scale structure.

Of fundamental importance to the present structural interpretation is the recognition that the River Lyd Slate-with-lenticles (Dearman and Butcher 1959) can be divided and mapped as three separate and distinct units. Previously the River Lyd Slate-with-lenticles was interpreted as forming the core of the Lydford anticline (Hobson and Sanderson 1975), a "Meldon" type upright fold overturned to the south. Clearly it is not possible to accommodate such a structure in the present synthesis. In addition, small-scale structures such as rotated porphyroclasts in the Whitelady Thrust mylonites indicate that the overthrust units moved from south to north, opposite to the north to south direction required by Sanderson's (1979) model for the evolution of the Variscan fold belt.

Relationships between the Liddaton and Lydford units are unclear at present, primarily due to the complexity of thrusting with which they are associated. Because the Whitelady Thrust is a single, albeit polyphase, structure, the relationship between the Whitelady and Liddaton unit is less complex. The ages of these two units (Platyclymenia and Wocklumeria Stufe, respectively) indicate a significant but not large stratigraphical gap between the two and the mylonitic style of the Whitelady Thrust demonstrates that the discontinuity is important tectonically, although it is possible that displacement along it was not large (< 10km). The Whitelady unit is the only shelf sequence identified on Sheet 337 and its position at the base of the tectonic stratigraphy identifies the unit as a suitable candidate for autochthonous or parautochthonous material over which the pelagic successions seen on the rest of Sheet 337 (Stewart 1981a, 1981b; Turner 1981; Whiteley 1981) have been thrusted.

Although many authors have described complex polyphase deformation histories from metasediments in south-west England there have been few attempts to elucidate the metamorphic history which by implication must also be complex. It now seems likely (Brazier and others 1979) that porphyroblastic biotite, feldspar and chloritoid in the Tintagel area, formerly attributed by Freshney and others (1972) to contact metamorphism, relating to the Bodmin granite, represents a second regional metamorphic event. A preliminary study of illite crystallinities by Brazier and others (1979) indicated very low and low grade regional metamorphism along the coast from near Padstow to Bude. However, these authors attributed illite crystallinity as representing temperature conditions during the main cleavage development and not changing subsequently. This interpretation is not necessarily valid. Brazier and others (1979) related illite crystallinity to a change in chemical composition of the mica. However, Dunoyer de Segonzac and Hickel (1972) have shown that illite crystallinity can vary independently of mica composition. There exists the possibility then that illite crystallinities may be used elsewhere to investigate a late regional imprint at present only recognised in the vicinity of the Whitelady Thrust. Whatever the significance of illite crystallinity, it is clear that in the Lydford area there is a complex metamorphic history spanning three deformations and represented by a wide range of metamorphic grades. This author believes that further detailed study of metamorphism in this and other areas is vital for the elucidation of the tectonic evolution of the Hercynian orogeny in SW England. Without the constraints that the metamorphic history would provide, an inaccurate concept of the tectonic history is easily formed.

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