PROCEEDINGS

OF THE

USSHER SOCIETY

VOLUME TWO
PART FOUR

Edited by
E. B. SELWOOD

REDRUTH, DECEMBER 1971

THE USSHER SOCIETY

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CONFERENCE OF THE USSHER SOCIETY HELD AT EXETER, JANUARY, 1971

CHAIRMAN'S REPORT

By kind invitation of the Director of the Institute of Geological Sciences and the District Geologist, Mr. George Bisson, the tenth Conference of the Society was held at the District Office of the South-Western Unit of the Institute, at Hoopern House, Exeter.

This year marked a departure from the routine followed in previous years, in that no invitation address was presented. Instead, the morning sessions on January 6th and 7th were devoted to symposia on *The Structure of South-West England,* co-ordinated by Dr. W. R. Dearman, and *The re-mapping of the Teignmouth sheet* (339), co-ordinated by Dr. E. B. Selwood and Mr. G. Bisson. Field excursions on January 5th and 8th, provided an opportunity to examine the wide range of geological conditions within the area represented by Sheet 339.

The very active discussions following the presentation of both symposia indicated that members derived much benefit and satisfaction from the programme. On a personal note, I would like to thank Mr. Bisson and his staff, for the sterling efforts made to accommodate a large gathering of members ; together with the co-ordinators of the symposia, they did so much to make the meeting a success.

The 1972 Conference will be held at Torquay, when it is hoped that some new inovations will be introduced which will widen the sphere of interest of the Society. In particular, it is intended to introduce a morning session which will be devoted to Engineering Geology. An evening "teach-in" is planned to preceed this session, when invited speakers will describe some aspects of this branch of geology, particularly where relevant to the field excursion which will follow.

The committee are mindful of the very wide range of the interests of all members of the Society and hope that the broadening of the scope of the annual conference, will provide for these interests.

F. W. Sherrell, February, 1971.

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SYMPOSIUM ON THE STRUCTURE OF S.W. ENGLAND

by W. R. Dearman, E. C. Freshney, E. B. Selwood,
S. Simpson, M. Stone and R. T. Taylor

A GENERAL VIEW OF THE STRUCTURE OF CORNUBIA

by W. R. Dearman

1. Introduction

Great progress has been made during the past two decades on the detailed study of the small scale structures displayed to such advantage in the coastal exposures of Devon and Cornwall. At the same time the general stratigraphical conditions have become better known, and large areas inland have been mapped out, particularly along and to the north of the southern margin of the main Carboniferous outcrop. It was felt appropriate at such a time to attempt a synthesis of the structure, especially since the two most recent comprehensive views of the geology of S.W. England had either entirely omitted reference to the structural and tectonic evolution of the peninsula (Hosking and Shrimpton 1966), although the missing chapter has now been published (Hendriks 1971), or had dealt with only relatively minor details of the structure (Edmonds, McKeown and Williams 1969).

The broad structural pattern has been known for a long time, and one of the earliest maps (De la Beche 1839, plate 1) shows clearly the broad synclinal structure of mid-Devon and north Cornwall in which a central outcrop of carbonaceous (Carboniferous) deposits rests on a trough-like depression in the Grauwacke Group (Devonian) beneath. On successively later versions of the map (Ussher 1892, 1900, 1901 ; Edmonds *et al.* 1969) additional stratigraphic detail confirms the synclinal nature of the Carboniferous outcrop but reveals a complex interplay of Upper and and Lower Carboniferous and Upper Devonian rocks along the southern boundary which still presents problems of interpretation ; sub-division of the Devonian outcrops shows that in the southern outcrop there are two major anticlines involving the lowest Devonian rocks exposed in the peninsula, the most southerly anticline involving the problematical slates of the Mylor Series

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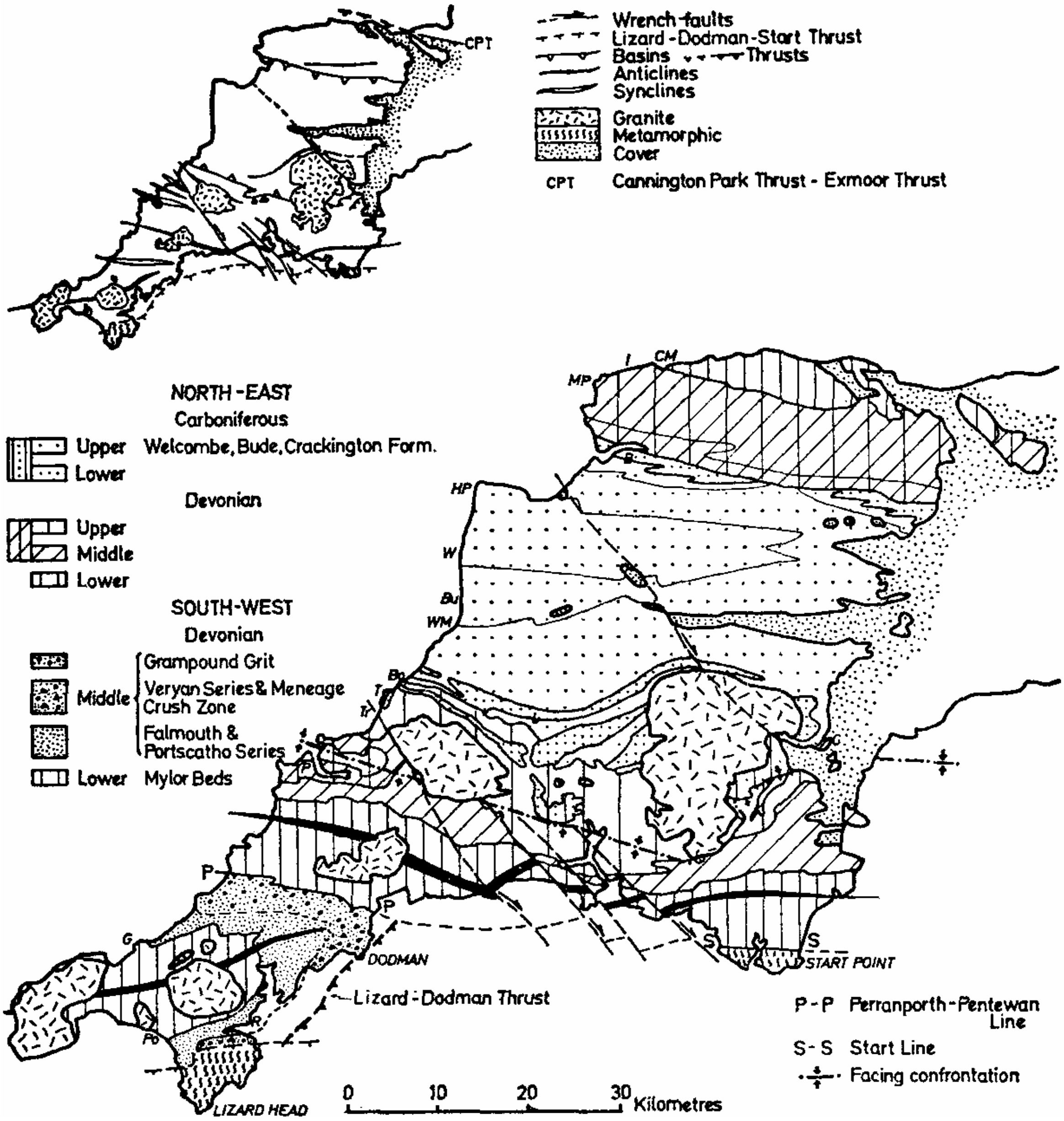

FIGURE 1 Map showing the distribution of the main lithological and stratigraphical units in Cornubia.
Inset top left : the main structural units based on 'The Tectonic Map of Great Britain'.
(B. Barnstaple; Bo. Boscastle; Bu. Bude; C. Chudleigh; CM. Combe Martin; G. Godrevy; HP. Hartland Point; I. Ilfracombe; L. Launceston; MP. Morte Point; P. Padstow; Po. Porthleven; R. Rosemullion; T. Tintagel; Tr. Tregardock; W. Welcombe; WM. Wanson Mouth).

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(Fig. 1) which on different interpretations range from Lower Devonian (Hendriks 1937, plate 22) to Upper Devonian to Lower Carboniferous (Simpson 1969: 21) in age. Relative age does not necessarily affect the structural interpretation. Structures in the Devonian rocks are limited to the south by the metamorphic rocks of the Lizard which are usually shown connected by a continuous curving ` thrust' through Dodman Point to the metamorphic rocks of the Start. The distribution of Devonian strata in north Devon is much more regular and what is generally accepted as a descending sequence of strata can be traced northwards from the Carboniferous boundary.

A general east-south-easterly trend of the main folds, possibly modified from more nearly east to west by the action of Tertiary wrench-faults (Dearman 1963), is crossed in the south in an east-north-easterly direction by the western end of the Lizard-Dodman-Start Thrust and by the line of five main granite cupolas (Fig. 1). North-north-westerly trending structures, in other words structures normal to the east-north-east trends, are also known in the Devonian slates of the southern outcrop (Wilson 1951, Dearman, Freshney and McKeown 1964, Dearman and Freshney 1966, Dearman 1969a).

It is convenient to think in terms of these two basic directions, namely an east to west direction which could be slightly south of east, and one which is east-north-east, and to consider the implications of their interaction from the tectonic point of view. The series of great anticlines and synclines in the southern outcrop of Devonian rocks deform a slaty cleavage which originally could have been predominantly horizontal - the large structures are obviously antiforms and synforms as the slaty cleavage is axial planar to folds having a wide range of interlimb angle - and so are not primary structures. Earliest folds within this zone tend to trend east-north-easterly or more exceptionally normal to this direction, and if the former is accepted as the regional trend possibly involving very much larger early recumbent folds than those seen in outcrop, then boundaries between the main stratigraphical units should and do reflect interaction between early and late major structures. Some of the evidence has already been presented (Dearman *et al.* 1969), but before reconsidering the main conclusions it may be advantageous to review briefly some aspects of recent work.

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Particularly significant advances have been the identification of two zones of intense deformation with modification of folds to the tergiversate state ; the recognition of the polyphase nature of the deformation ; the interpretation of a late phase of folding and cleavage as due to deformation induced by the rise of the granite batholith ; the determination of radiogenic ages for slates and phyllites ranging from 365 to 270 my ; the recognition of major Tertiary wrench-faulting and fold and thrust deformation associated with it.

The basic structural pattern. The regional distribution of type and attitude of minor structures has a strong symmetry element related to the main stratigraphical units. In the central areas of the Carboniferous 'synclinorium' upright open chevron folds with a poorly developed cleavage pass progressively northwards and southwards, and finally on to the Devonian outcrops, into overturned tight angular to rounded folds having a prominent axial-planar slaty cleavage. The folds face upwards and fan outwards to face north and south, and in the south become recumbent tight to isoclinal. They continue to face south as far as Padstow on the north coast, and thereafter to the Lizard boundary the recumbent first phase folds face north (Fig. 2). The possible line of this facing confrontation across Cornwall and south Devon will be discussed later.

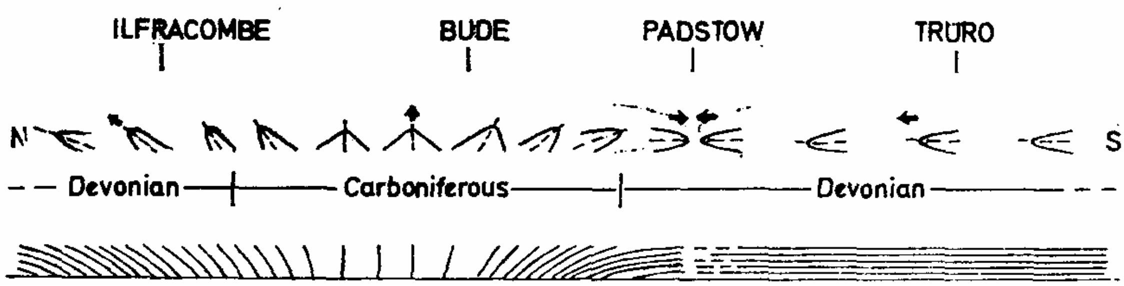

FIGURE 2. Diagrammatic cross-section across South-west England to show changes in fold style and attitude, and below, the variation in attitude of the first cleavage. Closeness of lines is intended to show relative intensity of cleavage development. Solid arrows indicate facing direction; note the facing confrontation at Padstow.

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Zones of tergiversation. There are two zones in which early recumbent folds with original axial trends slightly variable around east-north-east have been very strongly deformed normal to the slaty cleavage. As a result a strong penetrative mineral elongation has been imparted to the slates along a north-north-westerly direction, and associated folds have trends making an acute angle with this direction and also at right-angles to it (Dearman 1969). In the northern tergiversate zone, which extends on the coast from just north of Boscastle to the region of Tregardock south of Trebarwith Strand, the folds face south-south-east, west-southwest and east-north-east, and fold axial trends vary from nearly north-north-west through east-north-east and back to nearly northnorth-west. This interpretation, based on facing directions in the folds, is different from the rectangular pattern suggested earlier by Dearman and Freshney (1966). The southern zone of tergiversation north of the Lizard boundary faces north-north-west and shows a similar amount of variation in fold trend.

These two zones each occupy special positions in the tectonic pile, and appear to mark the transition between an overriding supracrustal region from a more passive recumbently folded infrastructural region beneath (Fig. 3). The penetrative lineation is a true *a*-lineation (Wilson 1951) indicating the stretching direction to which the folds are incidentally related.

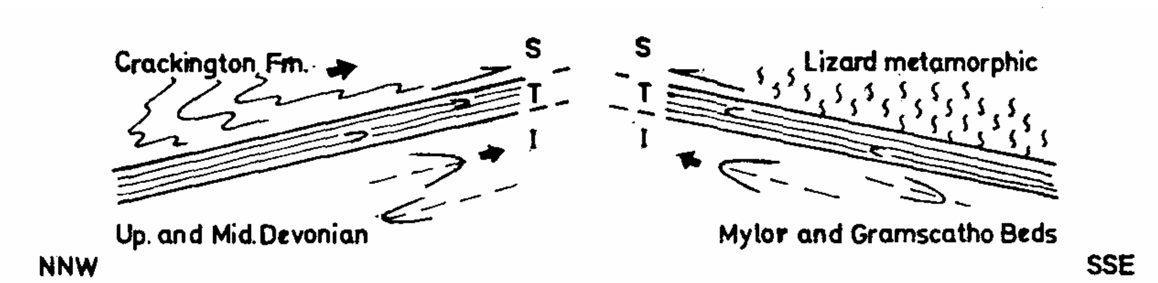

FIGURE 3. The setting of the two tergiversate zones.

Right : the southern zone, Left : the northern zone.

S, suprastructure; T, tergiversate zone; I, infrastructure.

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2. The effects of repeated deformation

In the Carboniferous outcrops and the southern region of Devonian rocks, at least two, and in particular areas three phases of folding can be demonstrated, usually with at least local development of a new cleavage. Additionally there may be open folds of slaty cleavage, often with an associated north-south strain-slip cleavage, kink bands and so on.

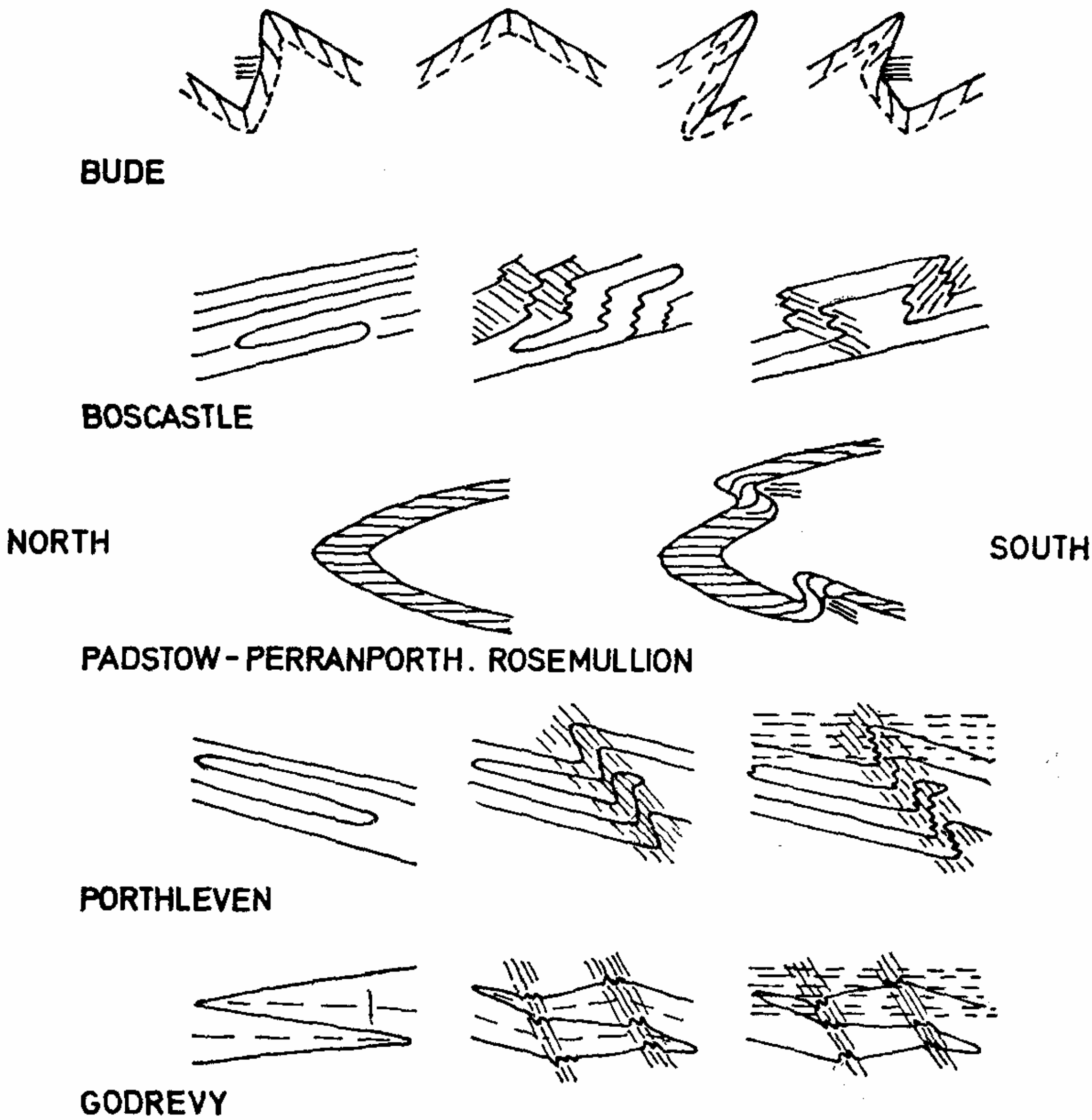

FIGURE 4. Superposed deformations. Bude, modification of upright open chevron folds by additional flexing of limbs and tightening of limb angle. Boscastle, isoclines with slaty cleavage, modified by second folds which may be conjugate. Padstow-Perranporth and Rosemullion, second phase modification of similar folds. Porthleven, three fold-phases with associated cleavages. Godrevy, three fold-phases with associated cleavages (after Smith, 1965).

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Open chevron folds in the Bude and Welcombe Formations have been flexed again to tighten fold angles at original fold hinges and to generate new folds by bending existing fold limbs (Fig. 4). The first and second generations of folds are essentially coaxial. These effects are predominantly, but not exclusively, produced by an overriding southerly drive in the central and southern parts of the synclinorium (Zwart 1964, Dearman 1967a, 1967b) ; the direction is reversed in the north. It might be thought that appeal to this mechanism as an explanation (Dearman 1969) of the great belt of recumbent folds between Wanson Mouth and Rusey High Cliff on the north Cornish coast is extending the interpretation a little too far.

South of the Rusey Fault, particularly at Boscastle and to a lesser degree at Tintagel and Trebarwith, the effects of repeated folding are magnificently displayed affecting the folds of variable trend within the tergiversate zone. The second folds (Fig. 4) trend east-north-east and there is an overwhelming preponderance of folds overturned to the north (Dearman and Freshney 1966) ; the folds appear to be generated above low angle faults and Freshney (1965) considers that they have been produced by gravity sliding induced by the rise of the subjacent batholith. The exposed granite cupolas do not appear to have affected the attitude of these second phase folds (Dearman 1968) which are also found on the coast north of the Rusey Fault towards Wanson Mouth, where the effects die out.

Between the two tergiversate zones in Cornwall first folds may be tight to isoclinal with rounded to angular shape and have been variably flattened normal to the slaty cleavage. Second folds, with crenulation cleavage, may be overturned to the north-north-west or south-south-west but usually have a constant vergence over wide tracts of country. Where they affect large first folds having a tight or more open fold angle, the effect of refolding may be to produce second (or cross-fold) systems of widely varying trends and facing directions ; this unless appreciated can lead to difficulties of interpretation (Lambert 1966).

Third phase folds of restricted geographical distribution (Turner, R. G., 1968, unpublished Ph.D. thesis, University of Newcastle upon Tyne) in steep beds overlying the batholith have associated with them a ubiquitous flat-lying crenulation cleavage

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affecting all beds as a more general response to a flattening deformation attendant upon the rise of the batholith. The flat cleavage is in places indistinguishable from slaty cleavage. The effects of this deformation (Fig. 4) have been described from exposures at Godrevy (Smith 1965) and Porthleven (Stone 1962, 1966), and Turner *(loc. cit. supra)* suggests that the flat-lying cleavage and folds in steep beds should be found everywhere in suitable lithologies within the area delimited by the 0 mgal contour on the Bouger anomaly map of S.W. England *(Bott et al.* 1958).

Repeated folding, of differing styles, developed in rocks at different tectonic levels, involving two or three major phases of mesoscopic fold development, presents difficulties of correlation. Here the dating of metamorphic events may provide the necessary clues to the equation.

The pattern of radiometric ages. Age determinations on slates and phyllites from the Variscan fold-belt of Cornubia should provide approximate minimum ages of folding and recrystallisation of the sediments. Recent work (Dodson 1962, 1963 ; Dodson and Rex 1971) shows that a fairly clear regional pattern of K-Ar ages can be superimposed on the geological map (Fig. 5). The regional pattern contains two elements ; a Caledonoid NW-SE zone in south Cornwall is truncated by a Variscan E-W zone coincident with the northern limit of the outcrop of the Gramscatho Beds and continuous into the northern boundary of the metamorphic rocks of the Start region. Age zones north of this have the same E-W trend.

Of the greatest importance is the confirmation, provided by a zone of ages of 365 to 345 m.y., that in south Cornwall the presumed Lower or Middle Devonian Mylor Beds, the Middle Devonian Gramscatho Beds and the overlying back slates and breccio-conglomerates of the Veryan Series were affected by an end-Devonian (Bretonic) metamorphic event (Hendriks 1937). The significance of the change within this sedimentary sequence upwards from predominant shale, into greywacke-shale and then greywacke-shale-chert-limestone cyclical sedimentary units culminating in shales with exotic blocks of limestone, quartzite and phyllite has been discussed by Lambert (1965) and Dearman *et al.* (1969). It is considered that a rising pre-Devonian basement, represented now by the Lizard mass and providing the exotic blocks in the Meneage Crush-Breccia and other exposures of the

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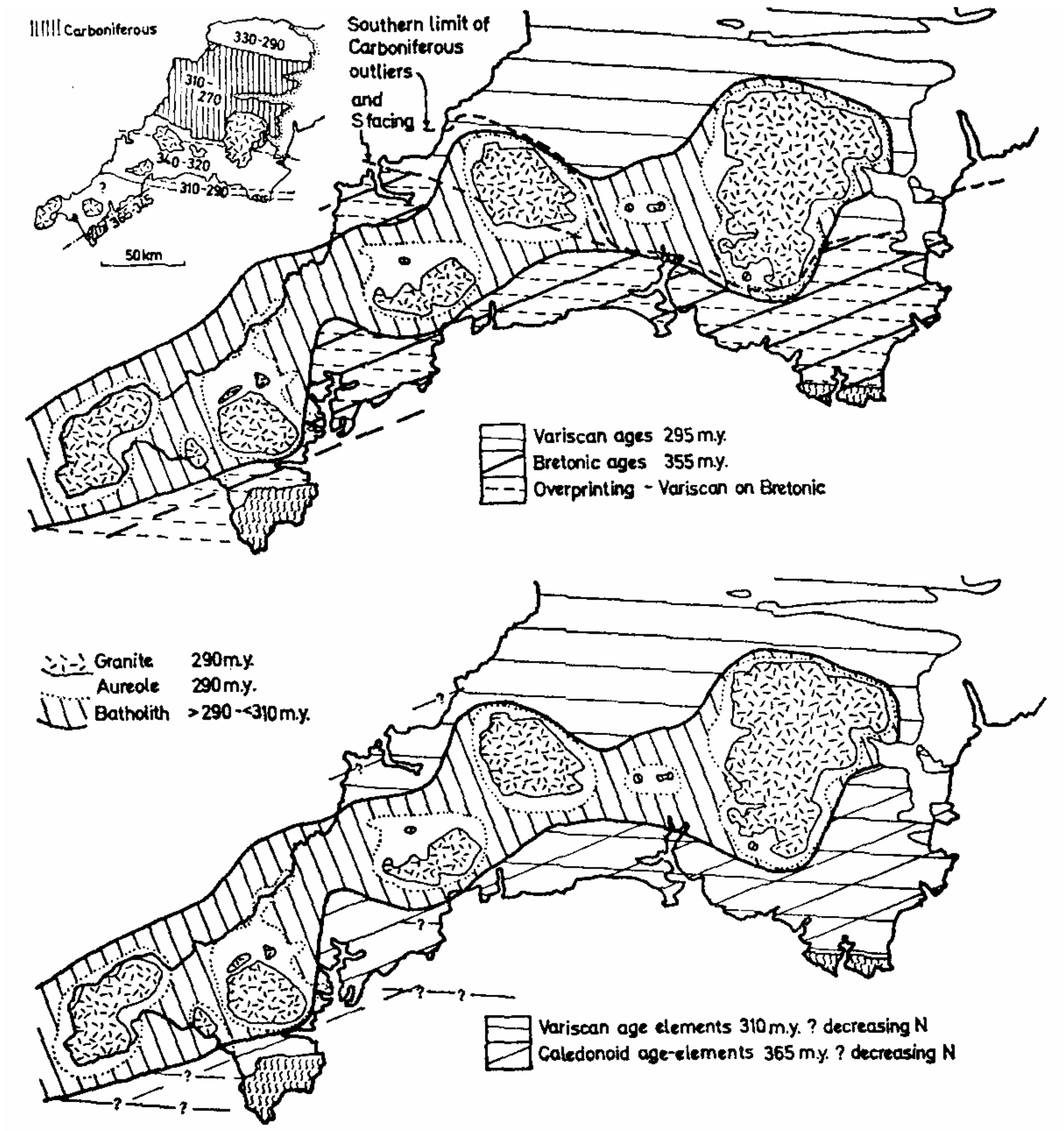

FIGURE 5. Interpretations of the pattern of radiometric ages. Bottom: Caledonoid age-elements dying out northwards, the whole superimposed by Variscan age-elements and the effect of the granite.

Top : Fixed northern limit of the Caledonoid age-elements at the position of the Padstow confrontation and its presumed extension into south Devon.

Inset top left : The age-zones of Dodson and Rex, 1971.

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Veryan Series, would provide the means of imparting a Caledonoid trend to the Gramscatho Beds. Culminating end-Devonian movements with the pre-Devonian basement being thrust over to the north-north-west as a Lizard nappe would produce and then modify the early folds in the tergiversate zone and imprint on the slates the appropriate metamorphic age.

A major problem is to decide how far to the north the effects of these early events extended ; at Tintagel there is no break in the stratigraphic sequence from Upper Devonian into Lower Carboniferous and the K-Ar age here is consistent with deformation having taken place during the main phase of the Variscan orogeny. Unfortunately, tectono-thermal and thermal events associated with the uprise of the Cornubian batholith intervene between the two areas (Fig. 5, Bottom) and it is difficult to resolve whether the southern Bretonic event had a definite northern limit, or that the metamorphic front advanced with time to the north-north-west from south Cornwall and possibly south Devon. It has been suggested (Dearman *et al.* 1969) in support of the latter that although there are no indications of crustal instability along the Start boundary to confirm continuation of the Lizard-Dodman thrust into the area, twenty miles to the north there are conglomeratic horizons in the Upper Carboniferous, containing fragments of locally derived older rocks, near Launceston (Selwood 1966) and near Chudleigh (House and Butcher 1962). A southerly source seems most likely for the pebbles in these conglomerates since as mentioned above there is no break recorded in the Carboniferous sequence to the north ; the Launceston occurrence indicates, according to Selwood (1966), “intra-Carboniferous movements involving uplift and erosion sufficient to expose Upper Devonian rocks in post-lower Namurian times”.

Other evidence may indicate lower Upper Devonian neotectonic activity to the south which could support extension of the south Cornish activity into the region of south Devon north of the Start. It has been contended that such “Tectonic activity along parallel zones, separated both spatially and temporally, supports the idea of a metamorphic front advancing from the south-south-east in south Devon and Cornwall. Tectonism associated with the Lizard-Dodman-Start zone to give an end-Devonian metamorphic event had advanced less than twenty miles north-north-west by the end of the Lower Carboniferous at the

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earliest. Subsequently the main phase of the Variscan orogeny resulted in the overprinting of the early Caledonoid structural trend and age zones by east to west structural trends and age zones of later Carboniferous age." (Dearman *et al.* 1969: 44).

The confrontation of facing directions in the Devonian rocks of Padstow, north Devon. This seems to be a reasonable explanation, supported as it is by both K-Ar ages and evidence of crustal instability, but there is an alternative explanation which is related to solution of the Padstow facing confrontation (Roberts and Sanderson 1971). Structural aspects of the Padstow area were first described by Gauss (1966, 1967) who recognized several fold events beginning with formation of similar style, recumbent tight to open folds with an axial planar slaty cleavage. There are two broad geographical areas with rather different patterns of first folds ; west and south of Polzeath near Padstow the folds face north and plunge gently WSW ; north and east of Polzeath the folds generally face south and vary greatly in trend over short distances. Recognition of later E-W trending folds of slaty cleavage and still later N.W. trending folds, both with associated strain-slip cleavages, did not help to resolve the problem posed by the facing confrontation of the first folds in two tectonic blocks containing the same stratigraphic units. "The fundamental problem of how seemingly contemporaneous regional northerly and southerly directed movements could take place during orogenesis, however, remains to be solved" (Gauss 1967: 285).

Roberts and Sanderson (1971) have re-examined the field evidence. They have recognized four phases in the regional deformation history ; the least important is the fourth phase which gives rise locally to rather open and upright folds of bedding and the earlier cleavages. The folds trend north-westerly. A third phase was found to be of restricted occurrence in purple and green Upper Devonian slates near Polzeath. The resulting folds verge towards the north-east and rotate flat-lying bedding and earlier cleavages (s_1 and s_2) into a steep position in their short limbs.

The first phase affects the area to the south of Polzeath and dies out northwards ; the second phase which affects the area to the north dies out southwards. Each phase has produced a slaty cleavage in that area unaffected by the other phase, but in a central area of overlap second structures are superimposed on first structures to produce a strain-slip cleavage (s_2) which affects an earlier slaty cleavage (s_1) (Fig. 6).

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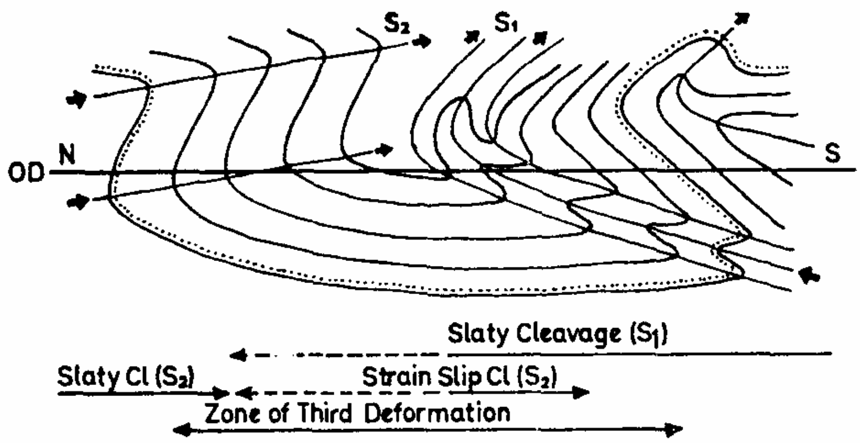

FIGURE 6. Structures at the Padstow confrontation. Solid arrows show facing direction. The dotted horizon marks the base of the Upper Devonian Purple and Green Slates. (After Roberts and Sanderson, 1971, fig. 2).

Further comments on the pattern of radiometric ages. A re-grouping (Fig. 5, top) of the K-Ar age determinations of Dodson and Rex (1971) is made to show that the central area of overlap of S_1 and S_2 is the boundary between a southern area where the age range is 320-340 m.y. and a northern area with ages from 270-310 m.y. Roberts and Sanderson (1971) interpret these ages as dating the development of s_1 as a slaty cleavage in the southern area during mid-Carboniferous times (the range is shown in Table 1), and the formation of s_2 as a slaty cleavage in the northern area at the end of Carboniferous times. The first phase structures, overriding north, are gently upward north-facing recumbent folds with slaty cleavage (Fig. 7) ; development stopped short at Polzeath and did not affect the Middle and Upper Devonian rocks to the north. The first structures to affect the rocks north of Polzeath were formed by southerly directed movements producing slightly upward south-facing recumbent folds with slaty cleavage s_2. Further north still, in the region of Tintagel, this late event saw the formation of the northern tergiversate zone beneath the southerly overriding Upper Carboniferous rocks along the margin of the present Carboniferous synclinorium.

The more southerly zone of 346-365 m.y. ages in the Roseland area of south Cornwall remains to be re-interpreted because this is a much older tectonometamorphic event (Table 1) than either of

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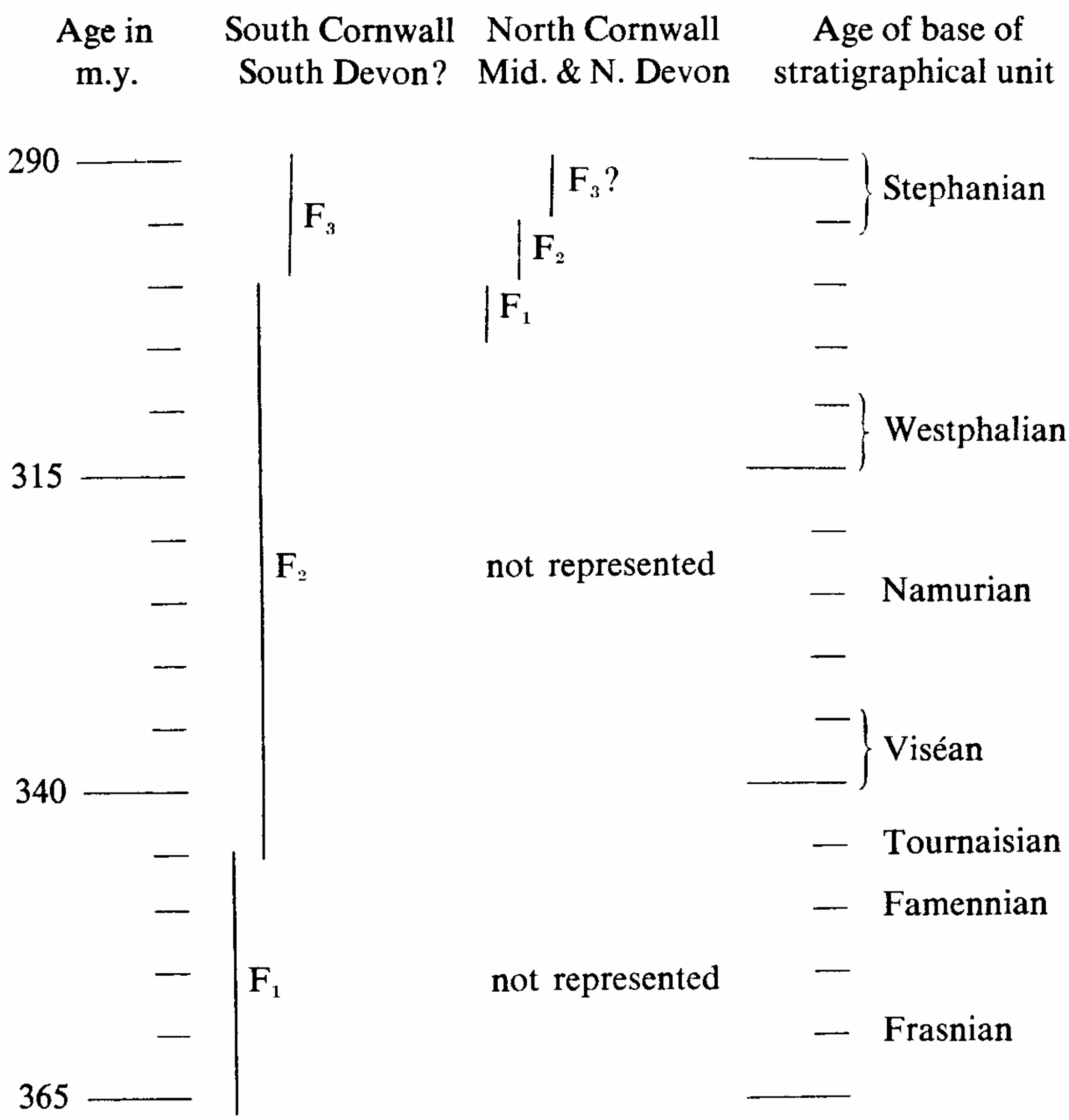
those to the north. Whether this zone decreases in age northwards towards Padstow, involving a south to north migration of deformation which may, or may not, have paused a while at Padstow remains to be demonstrated. If the 345-365 m.y. ages represent an even earlier tectonic pulse than that suggested for the Padstow region then structural evidence for superimposition of a 320-340 m.y. on to the earlier 345-365 m.y. event will have to be sought ; there is no apparent facing confrontation to help localize the area of search.

TABLE 1. The pattern of tectonic events



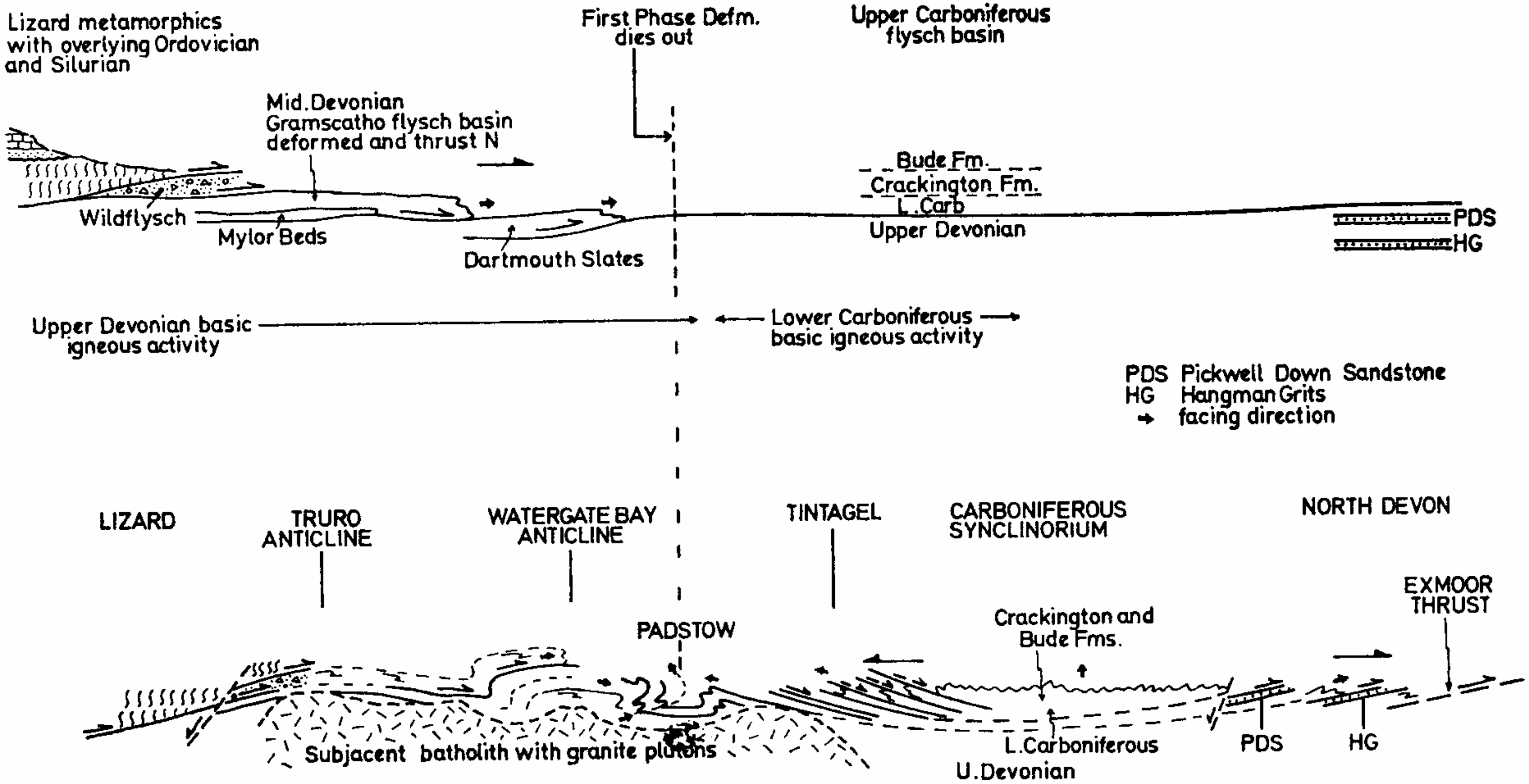


FIGURE 7. Sketch sections across S.W. England. Above: Structural pattern after the end-Devonian tectonic event in south-west Cornwall. Below : The final structural configuration after the Variscan orogeny and batholith emplacement. Broken arrows at Tintagel indicate reversal of southerly directed thrusting movements caused by the rise of the granite batholith.

It seems that the known K-Ar ages for the slates need critical appraisal in terms of possible tectonic, tectono-thermal and thermal events and their interactions, and that the subsequent cooling history of the region must be assessed. The batholith is likely to have modified or obliterated much of the evidence from possible critical areas in the slate outcrop (Fig. 5), and superimposition of tectonic phases could have caused argon loss from, for example, the critical southern region of Padstow to reduce a Bretonic age to an immediately pre-Namurian, Sudetic age. The likely paths of 'first-phase' deformations producing slaty cleavage and later fold phases are plotted with respect to time and geographical location in Table 1.

3. Significant structural lines across Cornwall and south Devon

Consideration of radiometric ages has revealed the tectonic importance of the Padstow confrontation. The probable course of this change of facing direction across the peninsula is shown on Figures 1 and 5; on Figure 1 it will be seen that the southern belt of Carboniferous outliers probably lies within the southerly facing zone, and to the east of Dartmoor the Holne Thrust separates the two zones of differing facing directions.

The implications of pulsed or phased tectonic development are that the Watergate Bay - Dartmouth and the Truro anticlines, involving Lower Devonian rocks, are major second phase flexures of slaty cleavage in the southern area produced by the Variscan deformation which deformed the rocks of the northern area for the first time. This distinguishes them from the major anticlines and synclines grouped to the north-west and west of the Bodmin Moor granite (Fig. 1 inset), such as the Davidstow anticline, which are folds produced by the emplacement of the granite.

Sanderson (1971) has shown that the structure of the northern boundary of the Gramscatho Beds at Perranporth probably involves a major slide contact with the Lower Devonian rocks to the north. Direction of movement of major northward facing recumbent folds on this slide was to the north-north-west. The junction is involved in a major second phase (southern region) monocline with a east-south-east trend. The whole of the northern boundary of the Gramscatho outcrop may be involved in this

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slide ; the outcrop of the slide gives rise to the Perranporth-Pentewan Line, and it may be that this line continues eastwards into the Start Line (Fig. 1). The structures along the Start Line is also monoclinal but it has not yet been demonstrated that the northern boundary of the Start metamorphic outcrop is a major slide.

The Lizard-Dodman Thrust has a trend appropriate to movements within the adjacent tergiversate zone and is truncated by the normal fault forming the present northern boundary of the Lizard mass.

4. Structures at the southern margin of the Carboniferous synclinorium

There are three significant areas for the study of these structures ; the coastal section from Tintagel to Rusey ; the north-west margin of Dartmoor ; and the north-eastern margin of Dartmoor. The coastal structures are reviewed in this symposium by Freshney and Taylor (1971) where late north-north-westerly directed movements down low-angle northerly dipping faults have sliced up large-scale recumbent folds in the Upper Devonian and Lower Carboniferous slates and a major overfold in the overlying beds of the Crackington Formation. This interpretation is very similar to that suggested for the north-west margin of Dartmoor (Dearman and Butcher 1959), but work on the structure of north-east Dartmoor (Waters 1970) and reinterpretation of the northwest Dartmoor structures (Selwood 1971) suggests that thrusting has been directed to the north up gently southward inclined thrust planes. This has led to recumbently folded slates being thrust over the zone of upright folds to the north. At present it is difficult to reconcile this new interpretation with the very clear exposition of the structure of this zone provided by the coastal exposures.

Bristow and Hughes (1971) have demonstrated Tertiary thrust faulting on the southern margin of the Bovey Basin on a continuation of the Holne Thrust ; the movement pattern is that adopted by Waters and Selwood for their Variscan thrust structures, and is considered to be related to Tertiary wrench-faulting along the Sticklepath Fault.

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5. The interpretative cross-sections

Two interpretative cross-sections have been drawn across the Cornubian fold belt (Fig. 7). The first section illustrates conditions at the end of the Devonian. Deformation south of the Padstow Line involves strata from Lower Devonian to Upper Devonian in age. A rising Lizard nappe involving basement metamorphics and unconformable Ordovician quartzites and Silurian limestones provided source rocks for the infilling of the Gramscatho flysch basin and the overlying Wildflysch of the Veryan Series and Meneage Crush Zone which could be Upper Devonian in age.

Major sliding led to the development of the southern tergiversate zone (Fig. 3) and brought about the present juxtaposition of the two contrasting Lower and Middle Devonian facies. The northern nappe (Fig. 7) involves the whole sequence from the Dartmouth Slates to the Upper Devonian slates of Padstow.

This early deformation provided the necessary southern source for the sediments of the Crackington Formation ; the flysch basin migrated northwards and it is unlikely that Carboniferous sedimentation took place much to the south of the Padstow Line. The Variscan tectonic episode deformed the main outcrop of Carboniferous rocks and adjacent Devonian sediments to the north and south for the first time. Outwards directed movements were associated with major thrusting in North Devon and southward thrusting in the Tintagel-Rusey zone at the southern margin of the Carboniferous synclinorium. The Tintagel thrust structures are complicated by a reversal of movement induced by rise of the subjacent batholith and the generation of second phase rucks indicating general northwards transport down gently northward inclined low-angle normal faults (Freshney 1965).

The Variscan movements produced the structures of the Padstow confrontation (Fig. 7) and the large-scale second phase folds further south.

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STRUCTURES ALONG THE SOUTHERN MARGIN OF THE CULM SYNCLINORIUM, NORTH-WEST OF DARTMOOR

by E. B. Selwood.

The structures along the southern margin of the Culm synclinorium, for long obscure, have been investigated in recent years at various points along the outcrop, by W. R. Dearman and officers of the Geological Survey. Of particular interest has been the question of the relationship existing between the essentially upright structures (lying north of an ill-defined line from Rusey on the coast to Wheal Fanny south of Bridestowe) and the flat-lying structures to the south. Dearman (1969c) has dealt with this problem with special reference to the structures on the coast and to those on the west side of Dartmoor where he believes that the recumbent folds represent “second phase modifications of minor corrugations on the main synclines”.

Rather different relationships have been established east of Dartmoor (LG.S./Exeter University contract for revision of Sheet 339), where the upright and recumbent structures are separated by an important structural break. To the south of this fault, important facies changes have been recognised within the Upper Palaeozoic and overthrusting from a southerly direction (Waters 1970) forms an important element of the structure. The contrast in facies and structural interpretations on either side of Dartmoor are anomalous and have led the author to investigate the Upper Palaeozoic rocks lying outside the granite aureole mapped by Dearman and Butcher (1959).

The area investigated lies to the east of the River Tamar and north of Tavistock and forms the north eastern part of the Tavistock and Launceston Sheet (337). Published in 1912 the map is in many ways out of date, but the basic lines are still meaningful, and this is particularly true where cherts, lavas and dolerites are delimited. Where the map is fundamentally wrong, is in the interpretation of the slaty and shaly sequences ascribed to the Culm Measures. But even here, careful reading of the Memoir (Reid *et al.* 1911) indicates that the original surveyors realised that they were presenting a grossly over-simplified interpretation of the geology and suspected the presence of Devonian strata.

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In the light of advances made in the knowledge of Upper Palaeozoic stratigraphy, it is now possible to reinterpret the stratigraphy of these slates by direct lithological comparisons supported by palaeontological data. This clearly is of considerable significance in structural interpretations.

The broad formational boundaries mapped by Dearman and Butcher (1959) within the granite aureole, can be continued westwards to a N-S normal fault, running just west of the Tamar, through Lawhitton. En route the boundary lines are shifted about 1 km dextrally by an important NW-SE wrench fault passing through Lamerton and Chillaton. The northern boundary of the River Lyd Slate with Lenticles Group maintains its straight course westward beyond the limits of the aureole and abuts against the wrench fault just south of Coryton. This contact is interpreted as a normal fault and it brings in Upper Culm slates and sandstones to the north : a continuation of the Southerly Down Sandstone Group of Dearman and Butcher. This Upper Culm would seem to be in conformable contact with the Lower Culm cherts which form a prominent ridge extending from Galford Down to Lee Down and beyond. In the low ground immediately north of the ridge a tract of Stourscombe Beds (=Slate with Lenticles) lithology stretches from Galford via Tibridge to Dippertown, and again west of the wrench fault from north of Lifton to Heale where the beds have yielded a fauna of topmost Upper Devonian age. The contact between the cherts and the Stourscombe Beds is faulted and essentially flat-lying.

North of the Devonian inliers the geology becomes complex, being considerably faulted. This appears to be part of a major fault zone which can be traced westwards (albeit displaced by wrench faults) to the Rusey Fault (see Freshney and Taylor 1971, Fig. 8). This faulting gives a situation similar to that observed east of Dartmoor.

Mapped out from the aureole, the River Lyd Slate with Lenticles Group becomes fossiliferous and continuous with the Stourscombe Beds (Upper Devonian, *Wocklumeria Stufe*) of the Launceston district. The southern boundary of this formation is effectively flat-lying, and the Lower Culm cherts which lie to the south demonstrably ride over the Devonian.

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The Culm Measures Slates mapped within these cherts occur discontinuously in the low ground between Pilistreet and North Brentor and again at Edgcumbe west of Milton Abbot ; they bear greywackes and abundant plant fragments and quite clearly belong to the Upper Culm. The identification of the *spirale* band at several points at the broadly flat-lying contact between these Upper Culm rocks and the cherts, suggests that the succession is inverted, though quite evidently there has been significant movement at the actual contact. The dolerites mapped within these slates would appear to be remnants of the former Lower Culm cover. The cherts can be traced eastwards into the granite aureole and are continuous with the Watervale Calcareous Group (Dearman and Butcher 1959).

Comparable Carboniferous successions thus seem to have slipped over Devonian strata both here and in the north. A direct correlation between the two areas is possible ; the different topographical levels of the structural break can be explained by the effects of the ENE-WSW normal fault forming the northern boundary of the River Lyd Slate with Lenticles Group.

In the northern area the stratal dips are high, but the cleavage dips gently to the south (see Coryton Slate Quarry) ; this, taking into account the succession, suggests a structural position in the nose of a major recumbent, south facing fold. The southern occurrence could thus represent the inverted limb of this fold, the normal limb of which has been replaced by a low angle fault. The general stratigraphic and structural situation suggests that this break is a lag, though thrusting, which has been established elsewhere, is possible particularly if it post-dated the development of major recumbent south facing folds - a situation described by Matthews (1966) from St. Mellion.

Further south this succession is replaced by Lower Carboniferous rocks of different facies, identified as the Tavistock Calcareous Group by Dearman and Butcher (1959). Although siliceous slates are represented, this facies lacks important cherts, but it does contain important volcanics including a prominent lava horizon. Calcareous rocks are of unusual occurrence, but the succession is strikingly similar to the Lower Carboniferous succession overlying the Tredorn Phyllites at Tintagel and

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Boscastle. It appears that this development of the Lower Carboniferous is thrust over the cherts existing to the north (Reid *et al.* 1911: 53). Such relations have been mapped out between Dunterton and Milton Abbot, and again east of the Chillaton wrench fault at Brentor where lavas belonging to this unit rest on cherts. To the west of this fault only the lavas of this unit are exposed, being themselves overthrust by Upper Culm slates and sandstones which occupy the tract mapped as Carboniferous as far south as Sydenham Damerel. To the east of the fault, this unit reappears from beneath the overthrust Upper Culm measures of Heathfield and Black Down (exposed perhaps as a result of folding associated with the development of the Petertavy dome (Reid *et al.* 1912)) to occupy an extensive area east of Lamerton and north of Tavistock.

The Devonian Slates (Whitchurch Green Slates) extending west to east from Sydenham Damerel through Tavistock to the granite do not show a conformable relationship to the rocks to the north and can be interpreted as a further thrust slice (the Culverhill and Collacombe Barton developments then representing Klippe on the Upper Culm). Regionally this latter thrust could well be a continuation of the Holne thrust known east of Dartmoor.

The distinct stratigraphical and structural units recognised within this area, thus appear to have been piled one on top of another and along thrust planes which dip southwards. This disposition of units, together with facies considerations to be developed at a later date, favour a southern source.

The faulted contact between the upright structures and flat-lying structures recorded on both sides of Dartmoor, and the likely occurrence of thrusting with a northerly sense of transport as major elements of structure, to the west of Dartmoor as well as to the east, now give structural uniformity to this belt of country. The structures described here can be identified as far west as a major NW-SE wrench fault located west of Egloskerry. Beyond this, higher structural levels seem to be represented, appearing as a result of the combined action of dextral movement along the wrench fault and important normal strike faulting.

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THE STRUCTURE OF MID DEVON AND NORTH CORNWALL

by E. C. Freshney and R. T. Taylor

1. Introduction

The broad outline of the structural basin involving the rocks of north Cornwall and Devon was mapped by De la Beche in the 1830's and modified by Ussher towards the end of the 19th century. In the early part of the 20th century Dewey noted the occurrence of thrusting around Tintagel with an apparent over-riding from north-west to south-east. At that time this did not fit combortably into the accepted structural pattern of the southwest of England. It was not until 1951 that Wilson put forward the proposition that the anomalous direction of the thrusting in the Tintagel area was due to a later deformation of the thrust planes around the nose of the Davidstow hemidome. Wilson also demonstrated by the use of minor structures that these low-angle fault planes were in fact not thrusts but showed movement down the planes from south-east to north-west near Tintagel area and from south to north in the Boscastle area. Ashwin (1957) studied the structures along the coasts of north Cornwall and Devon and produced a cross-section showing a structural thickness of several tens of thousands of feet of Carboniferous rocks involved in a broad basin form with an anticlinorial region in the middle.

Recently both Dearman (1969a) and Simpson (1970) have delineated a number of structural zones based on the style of early folding in south-west England (Fig. 8). In essence they separate a northerly region of more or less upright folding from a zone of close recumbent folds, which in turn is divided from a zone of recumbent tight to isoclinal folds in the south. The line separating the recumbent close folds of the Millook type from the recumbent isoclines is sharp and in north Cornwall it is represented by the Rusey Thrust, but there cannot really be said to be a hard and fast line between the northern upright folds and the close recumbent folds. On the coast this changeover appears to be rather abrupt, but this is due to the presence at Wanson Mouth of both major east-west strike faulting and of NW-SE trending

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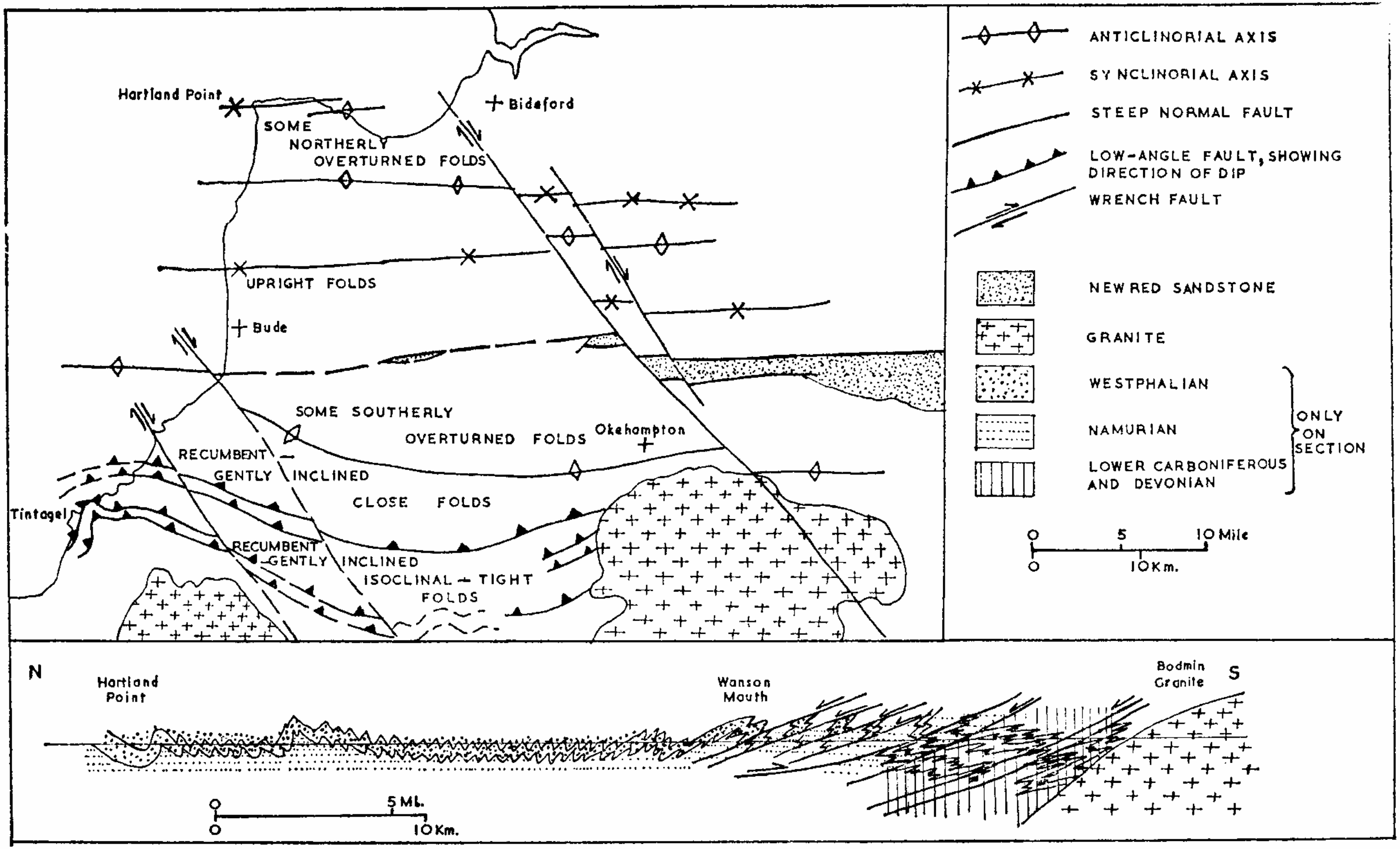

FIGURE 8. Map of Cornwall and central Devon showing the arrangement of the main structural elements. The diagrammatic section presents a situation prior to the steep normal faulting and the wrench faulting. Partly after Dearman (1969c, fig. 1) and Simpson (1970, fig. 1).

dextral wrench faults. Inland in the area to the north of Okehampton the changeover from upright to recumbent occurs in a gradual fashion, with the axial planes fanning over from a near-vertical attitute in the region around and north of Hatherleigh to comparatively gentle northerly dips around Okehampton and to recumbent south of this. The suggestion that this transition in the minor folds is due to the presence of a major overfold whose axis trends from the area of Wanson Mouth towards Okehampton (the so-called Widemouth-Okehampton line) is supported by stereographic plots of poles to bedding planes.

2. **Zone of upright folds (Figs. 8 and 9a)**

Recent work by King (1966) and current work along the coast north of Wanson Mouth towards Hartland indicate the possibility of partial facies equivalence between the Crackington, Welcombe and Bude formations and the presence of upper Namurian slates and sandstones within anticlinal regions around Hartland. Repetitions of the succession by folding suggest that the fold envelope is a gently undulating blanket the thickness of the succession represented above the *G. listeri* horizon being of the order of 2,000 to 3,000 ft (600-900 m).

Within this blanket there are a number of belts of anticlinoral and synclinorial structures made up of minor periclinal folds and it is these minor folds that are displayed so admirably in the cliff sections between Bude and Hartland. The major anticlinoria and synclinoria are responsible for the broad formational changes in the Upper Carboniferous in north Cornwall and central Devon. The most southerly synclinorium contains the southern belt of the Bude Formation which broadly speaking overlies the Welcombe and Crackington formations.

To the north of Welcombe Mouth there is a tendency for the folds to be somewhat northerly facing with northern limbs locally overturned (Ashwin 1958). This overturning mirrors to some degree the southerly overturning farther south around Bude, although upright folds are more characteristic of the succession on the east side of Bideford Bay. Many of the medium-sized structures are periclinal similar folds occurring as complementary syncline and anticline pairs which die out in each direction along their axial trend. It seems probably that the major folds may also be periclinorial in nature.

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Angular refolding of the limbs of some of the more upright folds (Fig. 9b) has been noted at several localities (Zwart 1964 ; Freshney and others 1966 ; Dearman 1967a and b, 1969c). All authors agree that these folds post-date the main deformation of the rocks but there is some disagreement as to whether they are the result of a discrete second tectonic episode as suggested by Zwart or whether they are genetically linked to the first phase of folding. The fact that these folds may face either north or south possibly indicates that they are the result of late-stage adjustment of the earlier folds under the influence of gravitational forces.

Mapping Inland by the Institute of Geological Sciences of the Okehampton, Holsworthy and Chulmleigh sheets shows that there is a broad continuity of fold structure northwards from Dartmoor towards the Bideford-Barnstaple area. Such stratigraphical and structural evidence as can be found indicates the presence of major anticlinorial and synclinorial folds similar to those occurring to the west on the coast.

FIGURE 9. Fold types in north Cornwall and central Devon.

(a) Top. Folds with a tendency to northerly over-tuning at Shipload Bay, Hartland.

Bottom. Upright accordion folds at Hartland Quay.

(b) Upright folds affected by recumbent crumples at Welcombe Mouth.

(c) Recumbent close folding at Millook.

(d) Recumbent close folding affected by F_2 ruck folds and associated crenulation cleavage north of Rusey Beach.

(e) Early (F_1) recumbent tight folds at Boscastle Harbour.

(f) Late (F_2) ruck folds with crenulation cleavage at Boscastle Harbour.

(g) Early isoclinal fold (F_1) refolded by later ruck folds (F_2) at Boscastle Harbour.

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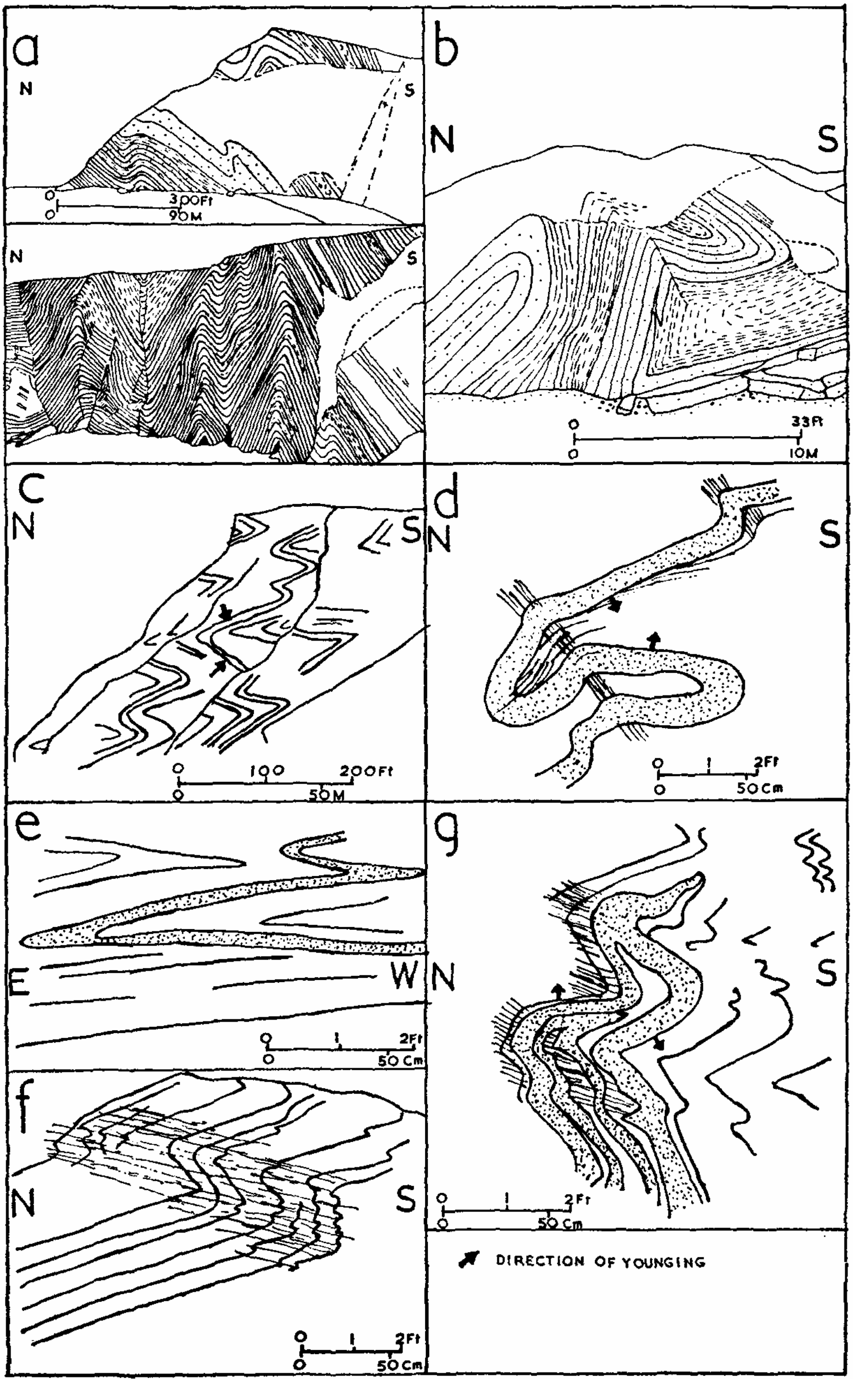

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3. Zone of close recumbent folds

The axial planes of the folds in this zone (Fig. 8) are either recumbent or gently inclined to the north and overturned northerly dipping limbs predominate (Fig. 9c and d). The folds appear to occupy the overturned portion of a major overfold caused by the overriding from the north of the upright folded blanket on to a more intensely folded infrastructure, the base of the zone being defined in the Crackington to Launceston area by a plane of decollement known on the coast as the Rusey Thrust. The great north-south extent of the outcrop of this zone on the coast between Rusey Cliff and Wanson Mouth is thought to be due to extension by normal faults dipping at low angles to the north.

4. Zone of isoclinal folds (Figs. 8, 9e, f and g)

The rocks of this zone below the Rusey Thrust are intensely deformed and show the effects of low-grade metamorphism with the development of fine chlorite, particularly in the Devonian, and fine pyrite and pyrrhotite spots which are elongated fairly constantly to the north-north-west. The earliest folding in this infrastructure is isoclinal and recumbent. Ashwin (1957, noted the presence of isoclinal folds within the black slates, siltstones and sandstones at Boscastle Harbour and he described the refolding of these isoclines by later, more angular, folds associated with low-angle faulting. The morphology of these folds and their relationship one to another has been more fully described by Dearman and Freshney (1966) in north Cornwall and by Dearman (1964, 1966) in the Launceston and Lydford areas. One of the most noticeable features is the extreme variability of direction of the isoclinal folds with an anomalous dominant trend of NNW-SSE, closely coinciding with the preferred mineral lineation already mentioned. Evidence from a deep borehole at Wilsey Down (Freshney 1969) indicates that major recumbent tight to isoclinal folds are present trending roughly E-W and apparently facing south but minor folds show the anomalous NNW-SSE trend.

The early folds are cut by a series of thrusts and other low-angle faults, some of which are similar in nature to the Rusey Thrust. The effect of these low-angle faults on the Upper Devonian and Carboniferous rocks is to produce a shuffling of the individual formations such that slices of Lower Carboniferous are

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inserted into Upper Devonian as far south as Tintagel and Tregardock. Inland the works of Dearman and Butcher in 1959 indicated the presence of low-angle faults dipping to the north, which had acted at different times as reverse faults and normal faults, and which together with earlier folding were responsible for considerable shuffling of the Upper Devonian, Lower Carboniferous and Upper Carboniferous. Associated with the low-angle faulting is a second phase of open to close folds formed in cascades and cut by crenulation cleavage. These folds show an overriding sense of movement from the south in the area to the north and east of Boscastle and from the south-east in the area between Boscastle and Tregardock. They have their strongest development in the zone of isoclinal folding but are also present near low-angle faulting within the zone of recumbent close folds to the north (Fig. 9d).

5. Structural history

It is probable that the early folding commenced in south Cornwall while Lower Carboniferous sedimentation was continuing in the north. The folds now seen as tight to isoclinal folds were originally more open and upright but as north-south compression continued and northward dipping thrusts developed against a geanticlinal rise along the present site of the Bodmin-Dartmoor granite, the upright and open folds developing in the Upper Devonian and Lower Carboniferous rocks tightened and rotated progressively to a recumbent position. It is possible that while sedimentation in the Upper Carboniferous was continuing deformation was intensified with the shearing out of the recumbent isoclinal folds and the development of an elongated mineral lineation such as the pyrite spotting occurring in the Upper Devonian and Lower Carboniferous. It is also possible that rotation of the early E-W trending minor fold axes took place during this period of intense shearing under heavy load to produce the anomalous NNW-SSE trending minor fold axes which are so common in the Boscastle, Launceston and Lydford areas. Dearman (1969b) related this and other zones of anomalous early isoclinal axial trend to zones of intense shearing movement. The latest event in the early fold development consisted of a crumpling of the Upper Carboniferous beds in the suprastructure or blanket with the development of thrust at the base of the

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suprastructure and an overturning of the upright folds adjacent to this thrust along the southern margin.

After the cessation of north-south compression the Bodmin-Dartmoor granite batholith commenced to rise. The shouldering effect of this batholith resulted in the formation of a number of low-angle faults dipping between 10 and 40° to the north with an overriding movement in that direction (Freshney 1965) and an associated second phase of folds with crenulation cleavage. Low-angle faulting can be seen to be effective as far east as Dartmoor but passing around the north side of Dartmoor towards Okehampton and Drewsteignton its effects die out due, it is thought, to the steep attitude of the northern granite junction. Many of the thrusts first produced during the earlier compressive phase of folding are thought to have been reactivated in the opposite direction as low-angle faults. One such fault, the Rusey Thrust, shows evidence of repeated movement with the refracturing of pre-existing breccias.

The next episode in the structural history of the area consists of steep normal faulting trending between E-W and ENE-WSW, most individual faults having quite small throws, perhaps in the order of 10 to 20 ft (3-6 m) although occasional larger individuals occur. Faults of this nature appear to bound the Crediton trough and it is probable that the same faults involve the New Red Sandstone outcrop near Holsworthy and reach the coast at Wanson Mouth. Cutting all earlier structures are a number of dextral NW-SE trending wrench faults. One of this group, the Sticklepath Fault has a horizontal component of movement of up to 1½ miles, although it is almost certain that this displacement is cumulative, the movement having started during the Hercynian orogeny prior to the deposition of the New Red Sandstone, continued both during and after deposition within the lower Tertiary Petrockstow Basin (Freshney 1970). There is also evidence to suggest that this fault and others of a similar trend have been active as normal faults as late as Pleistocene-Recent times.

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THE VARISCAN STRUCTURE OF NORTH DEVON

by S. Simpson

1. Introduction

Devonshire north of Dartmoor consists of two major structural units. To the north of a roughly east-west trending line running from Bampton to Bideford the outcropping rocks are of Devonian age. This is the structural unit of North Devon proper. The unit to the south is occupied by Carboniferous rocks in the main ; it too falls within the region commonly implied by the name North Devon, though in view of its very distinct character it is perhaps best separated off as Central Devon.

In a recent review of the structure of Cornubia (Simpson 1969, 1967) I have referred to these structural units as Zone I and Zone II respectively. They are the two most northerly of a series of roughly east-west trending elements of the Cornubian Variscides.

It is significant that there is a broad association between the east-west zones of the sedimentary facies of the geosyncline and those of the eventual tectonic deformation. The relationship is most evident in the general North Devon region which is miogeosynclinal in character. Webby (1966) has given a valuable account.

In a general way it may be said that Zone I is characterised by a southerly regional dip, so that the oldest strata (Lower-Middle Devonian) crop out along the Bristol Channel coast and the newest (Lower Carboniferous) along the Bampton-Bideford line. Zone II corresponds roughly with the main area of Upper Carboniferous rocks and with what has been commonly referred to as the “Culm synclinorium”.

2. **Fold Attitude**

The overall structural picture is of remarkable simplicity. Folding throughout the region trends roughly east-west. In the centre of Zone II the rather open folds have no well defined attitude ; either limb may be the steeper and, while near vertical

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limbs are not infrequent, over-turning is very rare. Along the line between Zone I and Zone II the folds are much tighter and mainly upright. Within Zone I there is a marked progressive northward overturning of the folds from south to north. With this change in the attitude of the folds which is best seen in the argillaceous units, there goes a progressive reduction in the angle of dip of the slaty cleavage which parallels the axial planes of the inclined folds. In the neighbourhood of Lynmouth the slaty cleavage dips south at about 30°. In the north of the Brendon Hills Webby (1965a) records cleavage dips of 35° south.

3. Intensity of Deformation

Accompanying the change in fold attitude is a change in the intensity of deformation. Thus in Zone II, where the fold angle of the generally chevron-type folds is seldom much less than 90°, slaty cleavage is not present, and the only cleavage is an incipient fracture cleavage in the hinges. Folds on the microscopic scale are absent and the smallest folds generally have limb lengths measured in tens of metres. The general style of Zone II folding is illustrated, for the Bude area in King (1966), and for the Westward Ho! area in De Raaf (1965). A feature first referred to by Ashwin (1957) is the brittle behaviour of beds within the fold cores which contain small faults, and buckling of the limbs in some folds. These features, which to the writer suggest very superficial structures, have resulted from the collapse of growing folds, and have been much discussed recently (Zwart, 1964 ; Dearman, 1967b). The alternative view represented by these authors' attributes the buckles to a separate deformational episode superimposing smaller flat-lying folds on the steep limbs of the original folds.

In Zone I the folds in the Pilton Beds along the boundary with Zone II are already accompanied by slaty cleavage and are present on all scales from microscopic upwards. Farther north, in the Ilfracombe Beds and the Lynton Beds, the intensity of deformation is even greater. Folds tend towards isoclinal with thickening of individual beds at the hinges in sandstones and limestones as well as in slates. The massive arenaceous formations (Baggy Beds, Pickwell Down Sandstone, Hangman Grits) generally behave as competent members and do not develop small scale folds of the

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constituent beds though strongly folded as complete formations. But a universal phenomenon is the presence of exactly north trending slickensides on bedding planes. The detailed geometry of the folds in the argillaceous Ilfracombe Beds is described in Holwill (1962). The shape of the major (macroscopic) folds in the Brendon and Quantock Hills is described by Webby (1965a, b).

The northern boundary of Zone I is almost certainly a great thrust fault which delimits a New Red Sandstone structural basin to which the Bristol Channel now roughly corresponds. The Bristol Channel could be a counterpart to the Namur Basin and the presumed thrust a counterpart of the Faille du Midi. This fault was first postulated by Bott *et al.* (1958) on geophysical evidence but there is good supporting evidence from the morphology of the North Devon coast (Simpson 1953) and the presence of a possible outcrop of the fault itself at Cannington Park.

The nature of the southern boundary of Zone II need not be discussed here except to notice that it constitutes a rough mirror image of its northern boundary. Folds tighten and overturn southwards, cleavage enters, Lower Carboniferous and Devonian strata appear.

The contrast between Zone I and Zone II is that between two tectonic *Stockwerken* (two different tectonic levels). The obvious differences are not only an effect of depth in itself, but also of the contrasted rock types - the Upper Carboniferous behaving competently when compared with the argillaceous Lower Carboniferous and highest Devonian. The Bampton-Bideford line is not a fault line but a narrow transitional zone.

4. Evolution of Structure

The regional dip of the strata towards the south throughout Zone I and into Zone II is the cause of the overall younging of the outcrops from the Bristol Channel to the latitude of Hartland. It is also the cause of the fall off in the degree of deformation (i.e. the rise through the tectonic *Stockwerke.* Clearly since the main Variscan deformation the broad North Devon region has been tilted southwards. Part, at least, of this tilt was imposed immediately after the evorogenic phase because the New Red

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Sandstone rests unconformably on the Middle Devonian near the Bristol Channel coast, and on the Upper Carboniferous near Crediton.

Totally separate evidence for the post-evorogenic tilting is the contradiction between the northerly direction of rock transport indicated by the attitude of the folds and the southerly regional dip. South dipping axial planes imply north dipping major principal compressive stresses since axial planes tend to develop at right angles to the major principal stress. Upright folds reflect a horizontal attitude for the major principal stress and a vertical attitude for the least principal stress, and this implies a horizontal crust. Inclined folds reflect this inclination of the crustal surface, and so also of the stress axes. To obtain the observed outward inclination of the folds from the centre of Zone II one requires a central elevation of the crust, flanked by depressions. Otherwise expressed, material moving under gravity will flow off a central elevation down its flanks into neighbouring troughs.

Thus as I have pointed out (Simpson 1969) the so-called "Culm synclinorium" originated on the site of a tectonic upwarp of Central Devon. From this crustal upwarp, which must also have been a region of lateral compression, rock migrated northwards as evidenced by the direction of inclination of the folds as well as the existence of the North Devon Thrust. On the south of the upwarp rock transport was southwards, the evidence being again the attitude of the folds and the presence of thrusts (Freshney 1965). It is not a synclinorium in the sense of a major down-fold constituted of congruent smaller folds. The "Synclinorium" is a structural down-warp or basin - the Central Devon Basin - which has resulted from late Variscan regional tilting and probably also of renewed Alpine tilting.

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FORM AND STRUCTURE OF THE GRANITES OF S.W. ENGLAND

by M. Stone

1. Introduction

The exposed granites are typical post-tectonic high-level plutons that cut highly folded Devonian and Carboniferous rocks. Their setting, amongst country rocks that exhibit low-grade regional metamorphism and yet have a complex deformational history is similar to that of the post-tectonic plutons of the Southern Uplands. However, the latter contain dioritic facies that are absent in the exposed plutons of S.W. England. The grade of metamorphism imposed by the granites reaches that of the hornblende-hornfels facies. There is frequent evidence for extensive external and internal metasomatism that points to the emplacement of “wet” bodies. The granites appear to be spatially closely associated with hypothermal mineralization.

2. Outcrop

The granites outcrop as six major “bosses” together with several smaller bodies. The broad outlines of the Land's End, Carnmenellis and Bodmin Moor granites are either roughly circular or have marked arcuate components. Departures from this pattern are due to incursions of the roof, as in the region north of St. Austell and in the Holne area of eastern Dartmoor. Within the individual outcrops, internal contacts between members of a complex are frequentely arcuate. In the St. Austell mass, later members are reported to be convex towards earlier ones (Exley 1959). Likewise, if Ghosh’s subdivisions in the Carnmenellis granite are accepted (Ghosh 1934), a distinct ring structure with circular or arcuate internal contacts is apparent.

Broad petrographic similarity, trend within fold belt and the continuity of hypothermal lodes and elvans between the granite outcrops (Hosking 1962) suggest that the granites are connected beneath the present surface and that they are the upward extensions of a continuous batholith. This model has been amply confirmed by geophysical work.

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3. Information derived from geophysical investigation

Bott and others (1958) have established the existence of a belt of large negative gravity anomalies, up to -50 mgal, along the granite belt, with minimum values of g that correspond with the outcropping granites. To account for the steep gradient of the isogals on the southern edge of the batholith, they erected a model for Dartmoor that has the shape of an inverted L, with the vertical limb in the south corresponding with a wide feeder channel and the horizontal limb extending northwards as a sheet c 10 km thick. This corresponds with the model visualized by Brammall (1926) on the basis of field data. The model was also used by Exley (1961) to explain the disposition of the potassic and sodic members of the granite complexes.

Later work (Bott and Scott 1966) included the construction of a computerized best fit model to a new gravity profile across Bodmin Moor. The revised model has a fairly flat roof and steep sides. The steeper gradient of the isogals in the south compared with the north is now attributed to a higher density contrast in the south compared with a lower density contrast at the northern contact. This implies an increase in the density of the granite towards the northern margin.

A recent seismic refraction investigation (Bott *et al.* 1970) gives a best estimate for the depth to the Mohorovicic discontinuity of 27 km. Seismic velocities show a continuous increase from 5.85 km sec^{-1} in the upper (batholithic) part of the crust to 6.5 km $sec.^{-1}$ at deeper crustal levels. There is no evidence for any large abrupt increase in velocity with depth down to the Mohorovicic discontinuity. The simplest interpretation is that below 10-12 km the batholith passes continuously into a residual granitic layer containing the dispersed stoped material displaced by emplacement of the batholith.

4. The Tregonning granite as a model

Poor exposure prevents the construction of accurate cross-sections of most of the granite bodies of S.W. England. However, the perfect coastal exposure between Praa Sands and the Megiliggar Rocks (Porthleven) permits the construction of an almost complete section across the Tregonning component of the Tregonning-Godolphin granite. A summary of the principal structural features observed in this section is given below.

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The main eastern contact, seen to the west of Legereath Zawn, and the eastern contact between the Tregonning granite and the main roof pendant at Rinsey are sharp and vertical. An undulating roof zone, c 10 m thick, composed of layers of non-porphyritic "lithionite" granite, leucogranite, aplite and pegmatite (Exley and Stone 1966) lies between the pelitic country rocks (Mylor Beds) and the comparatively homogeneous "lithionite" granite that constitutes the main Tregonning granite. This roof zone comes away from the granite as large sheets exposed near Tremearne (Hall 1930 ; Stone 1969), and is believed to pass into similar sheets at the western contact at Praa Sands. At this locality, the shallow dip of the contact 14° to the north-west is likely to be that of the upper surface of a flat-lying sheet that comes away from an overall steeper contact as at Tremearne.

Undulations in the roof zone appear to follow, in part, undulations in the present land surface. The magnificent exposure at Trewavas Head shows a clear banded roof overlying the main "lithionite" granite : banding lies parallel to the bedding jointing in the granite and to both the land surface and the granite/killas contact. At Rinsey, the banded roof thins out as it passes beneath the main roof pendant and a nearby smaller pendant exposed 50m to the east at low water. Thus, layering is always a clear indication of proximity to the roof.

Four sets of cleavage and associated folds have been observed within the Mylor pelites both outside and within the metamorphic aureole (Stone 1966 ; but see Dearman 1968). The principal folds and cleavage belong to the third phase of deformation. F_3 folds are small-scale recumbent folds superimposed upon the limbs of earlier steeper folds. Their axial planes are defined by a flat lying crenulation cleavage, S_3, [F_3 and S_3 correspond with F_2 and S_2 of Stone (1966). The revised nomenclature conforms to current usage (see Smith 1966)].

Neither F_3 folds nor their associated S_3 cleavage show any marked deformation as the granite contacts are approached. There may be a slight tilting of S_3 a few degrees on the western contact of the granite at Praa Sands, though minor flexures of this magnitude are common outside the aureole. Even small pendants and xenoliths at the roof near Trequean Cliff contain flat-lying folds and cleavage in the attitude they held before the emplacement of the granite.

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5. Contacts and roof in the granite bosses

Contacts between granites and country rocks are often transgressive and always sharp. There is never evidence that would suggest that granitization has played any important role in emplacement. There is frequent evidence that the present granite outcrops lie close to the original roof, so that the depth of erosion below the cover is small. The evidence is assembled below :

(a) Actual roof is exposed in the Tregonning granite, the St. Austell granite and in the small boss at Porthmeor (Land's End granite).

(b) Incursions of roof give rise to the wide aureole north of St. Austell and to the irregular shaped outcrop in the Holne area of eastern Dartmoor.

(c) Banding or layering is probably a roof phenomenon. It occurs beneath the roof of the Tregonning granite and beneath the roof at Porthmeor. It occurs in the St. Austell granite (Exley and Stone 1966) and in the Widecombe area of Dartmoor.

(d) Tin mineralization within granite plutons is confined to their upper parts, close to their roofs. It occurs at several localities within the granite outcrops of S.W. England, e.g. Vitifer area of Dartmoor, St. Just and Ding Dong areas of Land's End and the Wendron area of the Carnmenellis granite.

(e) Large rafts of basic microgranite occur at Bellever Tor and Birch Tor on Dartmoor: their size points to, though does not prove, proximity to the roof.

Away from the actual roof, contacts become steep, e.g. Porthmeor and the Tregonning granite. At the Geevor Mine (St. Just), Garnet (1963) reports that the granite contact steepens to near vertical 650 m below the surface.

Neither the Tregonning granite nor the small mass at Porthmeor are associated with deformation of the country rocks. Elsewhere, rocks of the envelopes to the granite bosses do show some disturbance in terms of tilting of folds and cleavage and apparent shouldering aside of outcrops, but the effects are not marked. Despite earlier assertions to the contrary, (Dearman and Butcher 1959), Dearman (1968b) now considers that the structures near Meldon in north Dartmoor, have not been markedly affected by the granite.

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6. Mechanism of emplacement

The Tregonning model, involving virtually no deformation of the country rocks, implies an emplacement mechanism by large scale stoping. This mechanism satisfactorily accounts for the room problem and is explained by the geophysical model considered above. The other granite bosses appear to have been emplaced in a similar manner, although there would appear to have been some forceful emplacement subsequent to emplacement by stoping. On the basis of the gravity data and the geological information, we can see the present outcrops superimposed upon a "batholithic continuum". If the outcrops were the mere undulations of the "continuum", they would be expected to be elongated in the direction of the batholith. Only Carn Brea and some of the nearby hidden ridges (Hosking 1962) have this shape. The remaining outcrops are more equidimensional or rounded in outline.

It seems likely that granite batholiths are built up by successive emplacements of magma. Most of the present outcrops are composed of two or more members. In some cases intrusive relations between granite types can be observed or inferred. Towards the end of the emplacement history of the Tregonning-Godolphin granite complex, cross-cutting leucogranites, aplites and associated pegmatites point to the development of several local generations of magma (Stone 1965, 1969). The local mobilisation and emplacement of granite within pre-existing granitic rocks can be extended to a larger scale where complexes can be built up by multiphase emplacement (see Pitcher 1970 esp. Fig. 2). Further, as the granites of S.W. England lie close to their original roofs, it would be reasonable to expect a more complex emplacement sequence beneath the present level of exposure. The petrogenetic implications of these considerations involve the successive regeneration of "granitic magma" from the granitic layer and possibly from within the batholith itself. Such a process could adequately explain the observed differentiation sequences, e.g. St. Austell sequence (Exley 1959) and the Tregonning-Godolphin granite sequence, without the necessity of invoking the magma chamber that is so necessary for much magmatic differentiation. However, most of the evidence and arguement for the petrogenetic evolution comes from mineralogical, textural and chemical data which will be considered in a future paper.

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It is concluded that the batholith of S.W. England has been built up by successive emplacements of granitic magma and that some of these intrusions have reached levels above those of the main batholith (the "continuum") to give the presently exposed granite bodies. Whilst it is likely that the latter represent the latest phases of intrusion, it is possible that there are even later granites as yet unexposed. Clearly, earlier stages of emplacement may have caused deformation or tilting of the envelope, as visualised by Freshney (1965), but those bodies reaching up to the presently exposed levels have been emplaced by passive stoping involving subsidence of material that in aggregate marks out a circular or ovoid ("ring-like") body or a composite mass of more than one such body.

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En-échelon veins in folds near Hartland, Devon (Abstract) :

by P. L. Hancock.

About 900 second order *en-échelon* and pinnate quartz veins in 40 arrays on the limbs of four contiguous chevron folds in Westphalian rocks on Blegberry Beach (SS 225260), about 2 km south of Hartland Point, display some features of general interest. Arrays and veins which are abundant in many sandstones but absent in mudstones, are orientated nearly normal to bedding planes. *En-échelon* veins are conventionally interpreted as tension-gashes initiated at 45' to an array by secondary stresses within a zone of simple shear. At Blegberry the range of angles between planar veins and the arrays which contain them is from 10° to 46°, with weak maxima at about 15° and 30°. It suggests that veins may be formed at many angles other than 45° to an array. Third order *en-échelon* and pinnate veins in arrays which are parallel and adjacent to second order veins indicate that there was a component of shear in addition to dilation on many second order veins. As viewed on upward facing bedding surfaces 27 arrays are dextral and 13 are sinistral. Dextral and sinistral arrays are parallel on some fold limbs. Sigmoidally distorted veins are not abundant at Blegberry.

Early-formed structures between Port Isaac and Tintagel, Cornwall (Abstract) : by D. M. Hobson.

F_1 folds and cleavage in Devonian and Lower Carboniferous rocks have been studied between Portquin and Tintagel. Two nearly vertical faults trending NW-SE, one passing through Port Isaac and the other through Tregardock Beach divide the area into three structural units, each characterised by a different arrangement of folds, but in which all minor F_1 folds face south.

South of the fault at Port Isaac much of the slate and volcanic succession is inverted ; minor folds are recumbent and open. Between the faults at Port Isaac and Tregardock, green slates lie on the normal limb of a major anticline. North of the fault at Tregardock, the Tintagel Volcanic Series is structurally overlain

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by a similar green slate. Minor fold profiles in both slates and volcanics indicate that the top of the Volcanic Series is inverted, and that there is a major tight recumbent anticline in the green slates above. This anticline repeats the volcanic succession on its normal limb, near Tintagel. Major thrusts recognised around Tintagel are interpreted as F_1 slides.

It is concluded that the black slates of the Trambley Cove Beds at the top of the Volcanic Series, and the black slates of the Barras Nose Beds at the base are the same formation.

Deformation analysis on the North Devon Coast (Abstract) :
by K. Jeffery.

Megascopic Hercynian structures in the Ilfracombe Group show that the tectonic symmetry axes, a, b, c, and the principal deformation axes, $X \geq Y \geq Z$ are nearly coincident. Deformation analysis of objects such as ooids, detrital grains, crinoid ossicles, worm burrows and brachiopod shells has been used to calculate the principal strains, although only ooids have been studied in detail.

Deformed objects in the rock represent the object finite deformation ellipsoid whose development has been influenced by factors such as the ductility contrast between the object and the object/matrix system, the fluctuation of the object long axis relative to the slaty cleavage plane and the object initial shape. Object principal strains and the effects of these factors have been analysed using a computer.

Such an analysis in the Ilfracombe Group has shown that the deformation is of a flattening type, producing oblate (pancake) deformed ooids. The X and Y axes are extended by similar amounts indicating almost equal extensions along directions close to tectonic a and b. The slaty cleavage is the principal XY plane formed by a pure shear deformation. Fluctuation and ductility contrasts are low. Typical axial lengths for a deformed ooid are 7.5:6.5: 1.

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SUPERPOSED FOLDING AT THE NORTHERN MARGIN OF THE GRAMSCATHO AND MYLOR BEDS, PERRANPORTH, CORNWALL

by David J. Sanderson

Abstract. The superposition of structures is described from north of Perranporth. F_1 recumbent folds associated with a slaty cleavage are refolded by F_2 folds, with northerly dipping axial planes, on both mesoscopic and megascopic scales. The fabric of the minor structures is discussed in terms of major F_2 folding and the nature of the Gramscatho boundary is briefly considered.

1. Introduction

The coastal exposures in the area of Perran Bay to the north of Perranporth represent the northernmost extent of the Gramscatho and Mylor beds on the north Cornish coast. In an attempt to investigate the nature of this important boundary the structural history of the area has been evaluated and three phases of folding recognised.

2. Description of folding

The first folds (F_1) are tight or isoclinal, originally recumbent folds with a well developed axial planar slaty cleavage (S_1). The F_1 axes plunge gently to the west (Fig. la). The F_1 folds face to the north but verge southward and are interpreted as being developed on the inverted limb of a major fold.

Superposed on the F_1 folds are numerous open to close minor F_2 folds with axes subhorizontal or gently plunging to the west-north-west (Fig. lb). The associated axial planar crenulation cleavage (S_2) is moderately inclined to the north or north-north-west at about 40°. Where the S_1 cleavage is flat lying the superposed F_2 folds verge south but where S_1 is steeply inclined the F_2 folds verge north. This arrangement of minor structures is interpreted as being the result of a major F_2 flexural fold refolding originally horizontal slaty cleavage. The effects of this refolding are shown in Figure la, where the poles to S1 lie on a great circle normal to the mean F_1 axis (β_2). The F, axes and bedding/ slaty cleavage intersections lie on a small circle about β_2. The north facing recumbent F_1 folds are refolded to become upward facing on the steep limbs of the major F_2 fold (Fig. 3).

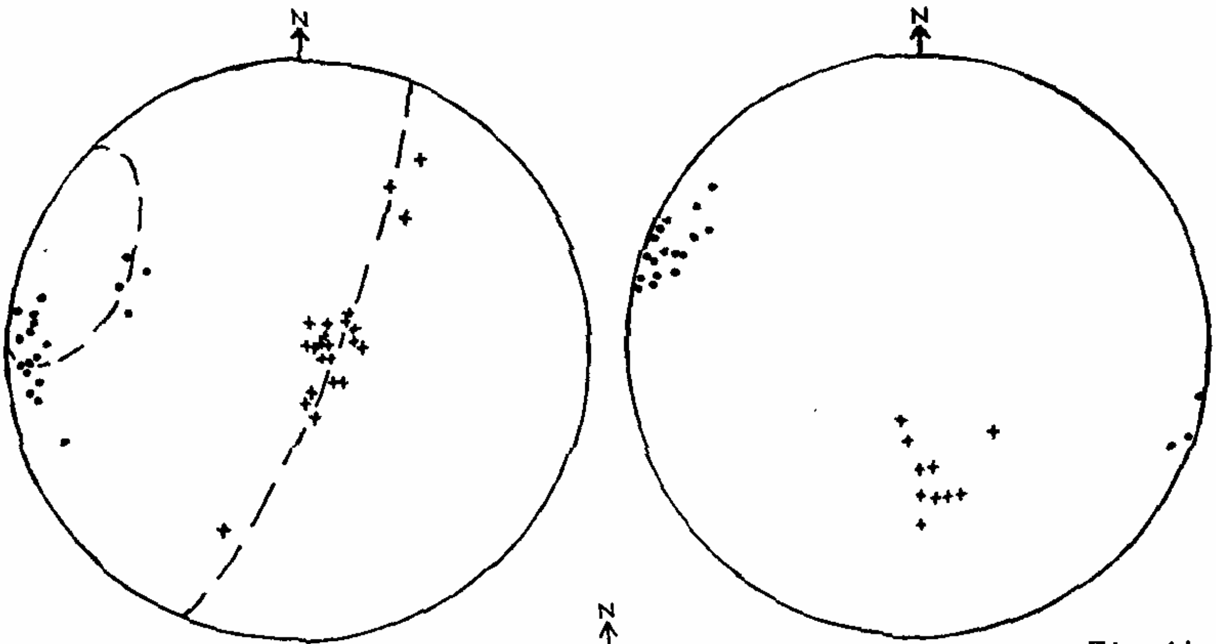

Fig. 1a

Fig. 1b

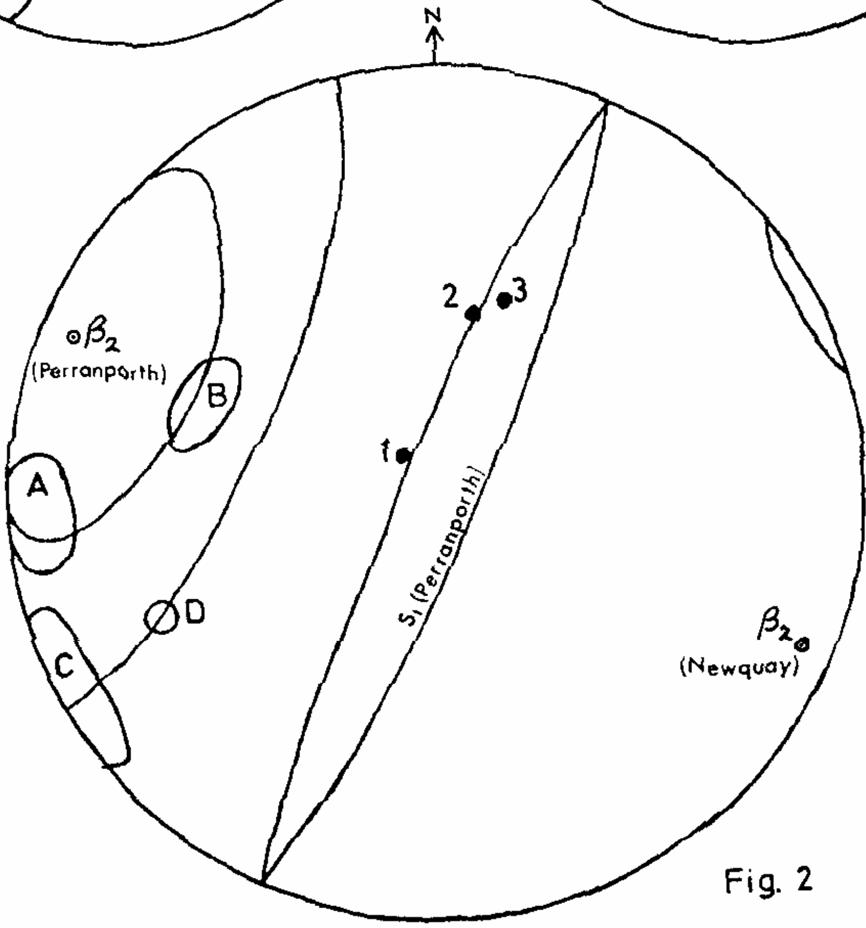

Fig. 2

FIGURE 1. Equal area plots of minor structures.
a. Poles to S_1 (+) and F_1 fold axes.
b. Poles to S_2 (+) and F_2 fold axes.

FIGURE 2. Synoptic equal area projection diagram of fabric elements at Perranporth and Newquay. For explanation see text.

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The development of minor recumbent F_3 folds and S_3 crenulation cleavage is largely confined to areas south of Perranporth and is only locally developed to the north, where quartz veins are occasionally crenulated. Oblique sections through small F_2 folds may closely resemble the S_3 crenulation.

The three phases of folding may be correlated with those described from Godrevy by Smith (1965) on the basis of the form and geometry of the F_1 and F_3 folds. The F_2 folds at Godrevy, however, have axial planes dipping steeply to the south-east and direct correlation with the F_2 folds at Perranporth is less certain. The attitude and geometry of the F_2 folds appears to be regionally variable.

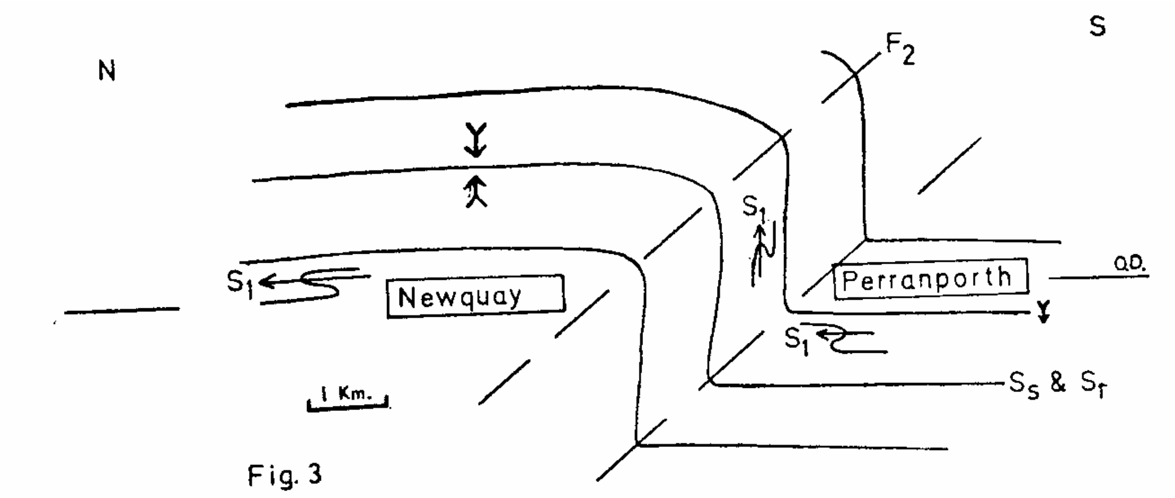

FIGURE 3. Diagrammatic structural cross-section from Newquay to Perranporth showing the arrangement of geometries of minor F_1 folds. Arrows on S_1 traces indicate facing directions and small arrows indicate younging.

3. Relationship of the Perranporth and Newquay structures

Ripley (1965) has described the structure of the area between Holywell Bay and Dinas Head, to the north of Perranporth. Throughout most of this area the slaty cleavage is flat lying, the recumbent F_1 folds having ENE-WSW trending fold axes. To the south of Newquay, however, the cleavage progressively steepens until at Holywell Bay the cleavage dips south at up to 45°, and the fold axes plunge at 30° east-south-east. These changes in attitude of planar and linear fabric elements are shown diagrammatically in Figure 2. Their relationships can be explained by flexural refolding about an axis β_2 which plunges gently to the

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east-south-east. The lineations are refolded about a small circle through CD in Figure 2 and the poles to slaty cleavage about a great circle through 1, 2 and 3. The rotation in both cases is about 35°, supporting the related geometry of these elements.

The relationships of the F_1 fabric elements in the Newquay area is thus very similar to that in the region of Perranporth, both being related to large scale F_2 folding. The near parallelism of the calculated and observed major fold axes at Newquay and Perranporth suggest the correlation of local F_2 events in these areas.

An attempt to construct a cross-section between Newquay and Perranporth can now be made in the light of F_2 folding. The large F_2 fold shown in Figure 3 has an angular synformal hinge and a more rounded antiformal hinge. This style is also seen in some of the minor folds on the flat limb of the major structure at Cotty's Point (SW757551).

Although the attitude of planar and linear fabric elements can be understood in terms of F_2 folding the implications of the vergence and facing relationships of the F_1 folds remains to be discussed. The minor F_1 folds at Perranporth face north and verge south but at Newquay they both face and verge north. The Perranporth structures are considered to be developed on the inverted limb of a major north facing recumbent fold, the right way up limb being represented by the Newquay structures (Fig. 3). It seems probable on stratigraphical and sedimentological grounds that these limbs may be brought together by an F_1 slide. The marked contrast in lithology between the Gramscatho and Mylor beds and their equivalent middle Devonian slates of north Cornwall strongly supports the tectonic nature of the boundary between these successions. Ripley (1965) describes a tightening of the fold interlimb angle of F_1 folds towards Holywell Bay which is considered to reflect an increase in deformation towards the postulated slide. Such increases in deformation are characteristic of major movement zones and slides.

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EVIDENCE BEARING ON THE STRATIGRAPHICAL SUCCESSIONS IN SOUTH CORNWALL

by E. M. L. Hendriks, M. R. House and F. H. T. Rhodes

Abstract. Lower and Middle Devonian conodonts are reported from the Nare Head, Roseland area where remnants of a succession succeeding the Came Quartzite seems recognisable : the overlying pillow lavas are not dated there, but on Mullion Island a Frasnian fauna occurs. The Gramscatho Beds have yielded a Middle Devonian conodont fauna at Pendower : Harlan Banks reports the widespread plants to be Middle Devonian. Hence assertions of the Carboniferous age for the Gramscatho are refuted. The differing Nare Head, Roseland and Gramscatho successions appear on present evidence to be in part time equivalents.

1. Introduction

Interpretation both of the structure and stratigraphy in South Cornwall is still in many respects uncertain. In such a situation palaeontological evidence is critical. This note records new fossil evidence bearing on outstanding problems, attempts some synthesis and counters some recent speculations. The finds are chiefly from both sides of Nare Head between Gerrans and Veryan Bays, Roseland, from Portloe in Veryan Bay and from Mullion Island. We are indebted to Professor W. Ziegler of Marburg for extracting and commenting on one sample collected by us. Also Miss J. Robinson and Mr. E. Druse, (as assistants to F.H.T.R.) collected further material. Professor Harlan Banks of Cornell has kindly commented on the plant material collected by the senior author many years ago.

Two distinct facies regions seem to be involved in the Roseland area and evidence is presented here to suggest they may be in part contemporaneous. Hence the palaeontological evidence from each will be discussed separately. The first facies region, which may be termed the Nare Head, Roseland succession, was used as Type section A by Hendriks (1937) before the structure was understood : essentially it comprises the sequence from the Ordovician quartzites of Carne, Roseland to the pillow lavas of Nare Head between Gerrans and Veryan Bays (Roseland) (see Holwill *et al.* 1969, p 60 for map). Remnants of the sequence are preserved elsewhere in Meneage and Gorran. The second may be

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termed the Gramscatho succession and is characterised by the rocks named the Gramscatho Beds (Hendriks 1937, 1949) and seen especially in Veryan and Gerrans Bay and south and southwest of the Helford River.

2. Nare Head Succession

Beginning with the Ordovician quartzites at Came and progressing south-eastwards to Nare Head, Roseland a sequence of progressively younger rocks seem to be recognisable which we may call the Nare Head Succession. In the summary below evidence is also included from immediately adjacent areas.

We have nothing new to add concerning the age of the Roseland-Gorran quartzites which are well established as Ordovician (Read 1906, Stubblefield 1960).

Silurian has been claimed hereabouts (for references see House and Selwood 1964: 48) and both Wenlockian and Ludlovian have been said to be recognisable. The giant pelagic crinoid *Scyphocrinites* from Catasuent Cove near Gorran (Read 1906: 21) is of particular interest in view of its widespread distribution near the Silurian/Devonian boundary (Jaeger 1968). This group is recorded as becoming extinct in the Uniformis Zone so that this record may be latest Silurian or very earliest Lower Devonian.

From the south side of Mallet's Cove (locality HR20) in Gerrans Bay the following conodonts have been identified : *Acodus* sp.,? *Hibbardella* sp., *Hindeodella* sp., *Icriodus* sp., *Neoprioniodus* sp., *Spathognathodus* cf. *transitans* Bischoff and Ziegler, *S*. sp. All representatives of the genus *Spathognathodus* which have been obtained from these samples are similar to Lower Devonian forms. **In** Germany *S. transitans* is indicative of Siegenian age. The spathognathodids from HR20 are similar, but not idential to figured specimens of *S. transitans,* therefore a Siegenian age for this sample is probable but not definite.

From Kiberick Cove (locality HR 14), in Veryan Bay, on the northeast side of the Nare Head promontory a calcareous sample from a twisted block of limestone breccia (shown as LB in Hendriks 1937, text-fig. 3) yielded *Belodus triangularis* Stauffer, *Icriodus latericrescans bilatericrescens* Ziegler,*I*. sp., *Polygnathus*

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linguiformis frankenwaldensis Bischoff and Sanneman, *S. canadensis* Walliser. *Icriodus latericrescens sensu* Ziegler 1965 is quoted by Walliser as extending from the base of the Siegenian almost to the top of the Upper Emsian, and *Polygnathus linguiformis* first appears at the base of the Lower Emsian. Hence an Emsian age is probable.

Small limestone lenticles in dark shale on the north-east side of Portloe Cove in Veryan Bay yielded *Belodus* spp., *Icriodus alternatus* Branson and Mehl, *I. nodosus* (Huddle), *I.* sp., *Lonchodina* sp., *Polygnathus linguiformis* Hinde, P. cf. *webbi* Stauffer, *P*. sp. These were taken as evidence of a Middle Devonian age.

The general regional dip in the Gerrans Bay-Nare Head region is to the south-east and pillow lavas crop out on Nare Head. We have so far obtained no determinate conodonts from limestones associated with the pillow lavas at Rosen Cliff there although Dr. S. C. Matthews has kindly searched samples for us. The Nare Head, Roseland, pillow lavas and those found southwards along the south-west strike through Meneage to Mullion Island off the west Meneage coast have previously been considered to be probably of the same age and this was supposed to be Lower Palaeozoic (Reid 1906) but late Devonian has also been suggested (Hendriks 1937). Now from dark siliceous limestones collected on the west side of Mullion Island associated with the Mullion Island pillow lavas, Professor W. Ziegler extracted and identified *Ancyrodella buckeyensis* Stauffer, a conodont characteristic of the Frasnian and commonest in the lower Frasnian. This then settles the age of the Mullion Island pillow lavas, and by analogy this age may also apply to the pillow lavas at Nare Head, Roseland twenty miles to the northeast, although clearly further confirmation is desirable.

In summary therefore, in the disturbed rocks seaward of the quartzite, between Came and Nare Head, Roseland, there is evidence to suggest that a faunal sequence is present and it includes representatives of the Ordovician, Silurian and several parts of the Devonian.

It has been suggested that the various lithologies here represented may be exotic sedimentary blocks (Lambert 1965).

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The fact that a succession above the quartzite can be recognised renders this proposal unlikely for the Nare Head, Roseland succession. Slumping and coarse clastics at Nare Head-in-Meneage, in the Manaccan conglomerate is another matter. But we cannot unequivocally state that all the records given here are from bedded units and hence a sedimentary melange interpretation cannot be ruled out.

3. The Gramscatho Succession

The crags of Ordovician quartzite in Gerrans Bay separate the Nare Head succession on the south-east from the Gramscatho Succession to the west. The landward and less altered sequence north-west of the quartzite has been described in detail (Hendriks 1937, 1949) under the name Gramscatho Beds. Conglomerates of very restricted distribution in east Meneage have yielded "*Pachypora"* and hence a mid-Devonian or later age is indicated.

Now Simpson (1969 and 1968 p: 6) has referred the Gramscatho Beds to the Carboniferous. We find no evidence to support this view. It is true that *Dadoxylon* which is the only widespread plant recorded in the Gramscatho Beds (Hendriks 1937, Lang 1929), as currently taxonomically restricted, is a Carboniferous and Permian genus, but Lang's actual comparisons were with Devonian records. Professor Harlan Banks has kindly looked into the matter of the plant determinations. Of the *Dadoxylon* figures of Lang, Professor Banks states that they show "no features not found in *Aneurophyton* from Middle Devonian". (*in litt.* 1970). His conclusion is that the flora as a whole is in no way inconsistent with a Middle Devonian age.
The only new evidence comes from limestones in the Pendower Beach Beds of the Middle Gramscatho Beds (Zone 4d of Hendriks 1937) where, in samples from three localities just east of Pendower stream the following have been determined : *Hibbardella* sp., *Hindeodella* sp., *Icriodus* sp., *Ligonodina* sp., *Neoprioniodus* sp., *Ozarkodina* sp., *Polygnathus* cf. *pennata* Hinde, *P. Webbi* Stauffer, P. cf. *webbi* Stauffer, *Spathognathodus* sp., *S.* cf. *bidentatus* Bischoff and Ziegler, *Synprioniodina* sp., *Polygnathus linguiformis* Hinde, *Belodus* sp., *Lonchodina* sp., *Prioniodina* sp. This fauna is younger than Lower Emsian because of the

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occurrence of *P. webbi* Stauffer and older than Frasnian. Hence the assignment is Middle Devonian, possibly Givetian. The type specimen of *Dadoxylon hendriksi* came from grits just west of Pendower Stream. Thus the evidence shows that the parts of the Gramscatho Beds with determinable fossils seem to be of Middle Devonian age.

Edmonds, McKeown and Williams (1969: 29) state that at Pentewan "Gramscatho Beds appear to lie with slight unconformity on the Lower Devonian Meadfoot Beds." They give no evidence for this or fossil determinations to support correlation with either division, but if this assertion proves justifiable then a lower limit is given to the Gramscatho Beds which is quite consistent with the evidence outlined above. Also the disparity between the Lower Devonian rocks of the Nare Head, Roseland succession and that farther north is emphasised.

The foregoing account gives the extent of the critical palaeontological evidence at present available bearing on the succession of the Devonian rocks in this area. Much more is needed to clarify other problems. Thus Dearman (1969: 34) gives a succession in which the Mylor Beds are placed in the Lower Devonian *below* the Gramscatho Beds, whereas Edmonds and others (1969: 26) give a succession in which the Mylor Beds are place *above* the Gramscatho Beds in the Middle Devonian. There is no palaeontological evidence given for either of these opinions, nor in either case is there a mark of doubt. Palaeontological evidence is still needed to settle this matter.

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SUCCESSIONS AT THE DEVONIAN-CARBONIFEROUS BOUNDARY BETWEEN BOSCASTLE AND DARTMOOR

by E. B. Selwood

Abstract. Successions at the Devonian-Carboniferous boundary between Boscastle and Dartmoor are described and correlated. Two principal facies are recognised, the Teign Valley Facies which occurs east of a major NW-SE wrench fault at Otterham and the Tintagel Facies represented to the west of the fault.

1. Introduction

Since the establishment of a conformable succession of strata between the Devonian and Carboniferous in the Launceston area (Selwood 1958), much progress has been made towards an understanding of rocks of similar age in adjoining areas. Although the faunal detail at Launceston is documented, an account of the lithologies is lacking ; this has led to some confusion in correlation. The aim of this paper is to present a brief survey of the lithologies, and to note equivalent formations elsewhere.

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2. **The Launceston Succession**

In the Launceston district a complex tectonic pattern makes it impossible for the succession to be observed directly. Palaeontological control at the Devonian-Carboniferous boundary is however good and a complete succession of lithologies can be pieced together, namely : -

Yeolmbridge Beds
Stourscombe Beds
Petherwin Beds.

(a) The Petherwin Beds

Recognised by Sedgwick and Murchison (1840), the fossiliferous strata at South Petherwin were described briefly by Phillips (1841) as the Petherwin Group. Later, in the Memoir covering the Tavistock and Launceston Sheet (Reid *et al.* 1911), a more detailed account of the- Petherwin Beds was given and the usage extended to cover a number of fossiliferous inliers ranging from Brentor in the south to Yeolmbridge in the north. In so doing, the range of strata was inadvertently extended to include Carboniferous rocks, and Selwood (1958) proposed that the horizon be restricted to the original usage of Phillips.

The Petherwin Beds are to be found faulted against Culm rocks 1½ miles south of Launceston, and extend westwards in a belt rarely exceeding one mile across, to Trenault. The southern limit of the formation has never been mapped but there seems to be a passage into an extensive area of virtually unfossiliferous grey-green slates.

The formation is divided into two members, but the division cannot be mapped. The upper member is extensively developed as a series of slates and thin elastic limestones yielding a shelly fauna dominated by brachiopods. The lower member is rarely exposed and is made up of cephalopod limestones, and a fine sandstone associated with silty slates. The best section, here designated the type section, is to be seen in the quarries lying west of the highway at Landlake. At present, the Gatepost Quarry (SX326821) represents the only good section in the lower member ; here 7 ft of a massive, fine-grained and calcareous sandstone is succeeded by 2½ ft of silty slates bearing many bivalves. The overlying cephalopod limestones are represented by 4½ ft of

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rottenstone and the section is completed by 3 ft. of a dark green slate belonging to the upper member. The lithology of the upper member is remarkably uniform, and is characteristically exposed at Landlake Mill (SX32858234). Some 15 ft of fresh slate can be examined ; it is calcareous, blue-black in colour and bears lenticular limestones occasionally crowded together to form bands a few feet thick. In the higher parts of the section the carbonate is leached and the slates become grey-green in colour and the limestones reduced to rottenstone. This is the characteristic occurrence of this member, for the fresh slate is never naturally exposed.

Elements of the fauna of the Petherwin Beds have been described (Selwood 1960) but the precise meaning of the fauna remains somewhat enigmatic. The interpretation of the cephalopod succession and its relation to that of the brachiopod slates is handicapped by the fact that the quarry which yielded the principal fauna is now completely obscured. Museum collections from this quarry show a considerable stratigraphic range. The presence of the trilobite genus *Asteropyge* would appear to indicate the presence of the *Manticoceras Stufe* and the ammonoid faunas range from the *Platyclymenia Stufe* through the *Clymenia Stufe,* seemingly into the *Wocklumeria Stufe.*

The fauna of the Gatepost Quarry yields *Clymenia, Kalloclymenia* and *Kosmoclymenia* from the same horizon. The association of *Kalloclymenia* and *Clymenia* noted by Schmidt (1924: 129) is unusual but has recently been reaffirmed by House (1970: 665) ; it is taken to indicate the presence of the *Wocklumeria Stufe,* for the appearance of *Kalloclymenia* marks the lower limit of the *Wocklumeria Stufe.* On this basis the faunas from the Gatepost Quarry and the obscured quarry indicate the presence of the *Wocklumeria Stufe* (most probably the *K. subarmata Zone).* However, these beds do not pass up directly into the Stourscombe Beds *(Wocklumeria sphaeroides Zone),* but into the thick succession of brachiopod slates. This fauna gives no indication of an Etroeungt age, but correlates with the Angertal Beds of the Bergischesland and the upper part of the *Clymenia Stufe. Kalloclymenia* thus appears earlier in Cornwall and so lacks the stratigraphic significance accorded to it elsewhere (conceivably the association of *Kalloclymenia* and *Clynienia* noted by

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Schmidt records the same phenomenon). The presence of *Kosmoclynienia* in the Gatepost Quarry fauna is significant ; Professor House indicates that this genus does not appear before to Vβ.

(b) The Stourscombe Beds

The name Stourscombe Beds was proposed (Selwood 1958) for a series of black or dark green slates, bearing thin siliceous seams and nodules, which succeed the Petherwin Beds. These beds crop out in the lower parts of the Kensey valley for almost two miles immediately west of Launceston ; the beds are much disturbed and seem to appear through a faulted window from beneath overthrust Carboniferous successions. A more extensive outcrop lies to the east of a north-south fault through Lawhitton (SX355823), and is continued eastwards, with tectonically defined northern and southern limits, beyond the Tamar to Dartmoor. Other small fault bounded outcrops appear in isolated localities, particularly to the north of the prominent chert ridge passing east-west through St. Stephens, Launceston.

At Stourscombe Farm (SX34458392), the type locality, where the beds are faulted into the Upper Culm, the slates are black and bear numerous minutely crystalline cherty nodules. Here a rich cephalopod-trilobite fauna is almost entirely restricted to the nodules. A few other localities, tectonically isolated from the main outcrops are also highly fossiliferous ; at Overwood (SX302872) the nodules are fewer than at Stourscombe, but the slates surrounding them are richly fossiliferous and dark olive green in colour, and at Heale (SX36138613) and Smallacombe (SX37568605) the slates are also green but the nodules appear to be absent. Elsewhere, in the extensive outcrop of the formation, fossils are rare : thin cherty seams (seldom more than 2 inches in thickness) and nodules are well distributed through the slates ; some of the seams are quartzitic due to recrystallisation but others are made up of finely divided detrital material. Occasionally the nodules are of rottenstone after limestone. The fauna which has been described from the different developments of the beds clearly indicates a topmost Famennian age *(Wocklumeria sphaeroides* Zone).

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(c) Yeolmbridge Beds

Earlier included in the Petherwin Beds, the Yeolmbridge Beds were recognised (Selwood 1958) as a series of silty slates and limestones, characteristically occurring in the large flooded quarry at Yeolmbridge (SX321875), which conformably succeed the Stourscombe Beds. These beds are extremely limited in areal extent and probably do not form a mappable unit ; the succession has been built up by an examination of a number of isolated sections.

The junction with the Stourscombe Beds can be observed at Overwood Quarry, Penfoot Quarry (SX85168324) and Stourscombe Quarry. The basal member is a dark green to black slate up to 10 ft in thickness which shows occasional bands crowded with bivalves. Silty bands become increasingly important upwards as a passage is effected into the main development of the formation, which was quarried for roofing slate. Best exposed at Yeolmbridge, this slate is calcareous and bears many fine laminae of silt and sandstone. Rarely, bands and lenses of fine sandstone up to a foot in thickness are developed ; these may show current bedding. In the higher parts of this unit the amount of silty material decreases, the slates become green in colour, and at the same time decalcified lenticles, rare in the lower parts, increase in abundance. The limestones which form the highest member of the Yeolmbridge Beds show nodular and lenticular horizons resembling the cephalopod limestones of the Devonian. Upwards the limestones become siliceous and alternate with thin greenish slates.

The limestones in the Yeolmbridge Beds have yielded a trilobite-cephalopod fauna which indicates a low Carboniferous age *(Gattendorfia Stufe).* There are also records of the Devonian trilobite *Phacops* and a clymenid from the slates at Yeolmbridge (Reid *et al.* 1911) ; it appears that the Devonian-Carboniferous boundary lies somewhere within these beds.

3. Comparisons with other areas

(a) Meldon and Lydford

Dearman (1959) established the Meldon Slate with Lenticles Group to include rocks occurring below the main Lower Carboniferous succession in the core of the Meldon anticline. The beds, which lie within the granite aureole, consist of slaty hornfels

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with bands of fine silty quartzite. No fossils are recorded but on structural considerations these rocks were placed in the Lower Carboniferous or Devonian. This lithology was later adopted as a formation by the Institute of Geological Sciences (Edmonds *et al.* 1969) and coloured on the Okehampton map (Sheet 324) to indicate the presence of rocks straddling the Devonian-Carboniferous boundary.

Later the River Lyd Slate with Lenticles Group was identified within the aureole on the west side of Dartmoor (Dearman and Butcher 1959). In this outcrop, substantial siltstones were described which had not been recognised within the formation at Meldon. No fossils were obtained, but a lithological correlation was made with the Meldon Slate with Lenticles Group, and the beds placed at the Devonian-Carboniferous boundary.

Excluding the thick siltstones, the lithology of the Slate with Lenticles groups is like that of the main outcrop of the Stourscombe Beds.

(b) Kelly-Marystow

Mapped westwards from the aureole the River Lyd Slate with Lenticles Group becomes fossiliferous and broadly continuous with the Stourscombe Beds (Upper Devonian, *Wocklumeria Stufe*) of the Launceston district. The succession in this area includes a more varied range of lithologies than would normally be included within either the Stourscombe Beds or Slate with Lenticles ; siltstones and calcareous silty slates occur at a number of widely separated localities and towards the southern limit of the outcrop a fossiliferous green slate appears. Exposures over the whole area are poor and it seems unlikely that these particular horizons will ever map out satisfactorily, but it appears that they are interbedded, or possibly infolded, with the main Stourscombe Beds lithology. The silty slate of the Manor Hotel Beds has yielded *Platyclymenia* (Dearman and Butcher 1959), but elsewhere the age of the silty lithologies has not been determined, though similar lithologies are known from the Petherwin Beds and Yeolmbridge Beds. The green slates which occur between Liddaton Green and Warracott are in places identical to those of the upper Petherwin Beds and yield a comparable brachiopod fauna ; they

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also seem to show lateral gradational relationships to the Stourscombe Beds lithology. The physical continuity of these formations, deduced but not proved at Launceston is thus confirmed. Both here and at Launceston the Petherwin Beds lithologies occur to the south of an extensive outcrop of Stourscombe Beds. This, if the formations are in part lateral equivalents, may indicate that the Stourscombe Beds thicken and perhaps range down lower stratigraphically to the north than to the south.

This succession is overridden to the south by Culm rocks but south of Lydford the River Burn has cut through the overlying cherts to expose Upper Devonian strata as far south as Brentor. Here are to be found, with other more recently discovered localities, the fossiliferous Devonian sites described by Dearman and Butcher (1959). Although horizons cannot be mapped out the rocks can be matched both lithologically and palaeontologically with the Petherwin Beds and Stourscombe Beds of the Launceston district.

The choice of a name for the lithologies described in this section, which would not appear to be divisible into mappable formations, is difficult ; the only appropriate published name is "Transition Series" (Dearman and Butcher 1959) described as a series of silty and calcareous slates lying between the Upper Devonian Slates (Whitchurch Green Slates) and the Lower Culm. The relationships existing between the Whitchurch Green Slates and the Transition Series is however not beyond doubt.

(c) Teign Valley

East of Dartmoor the same basic stratigraphic sequence exists at the Devonian-Carboniferous boundary as at Launceston, but here the rocks are folded into a series of large scale upright folds and the lithological contacts have been mapped out and proved over some miles. Chesher (1968) was able to establish a complete succession from the Upper Devonian into the Namurian and he observed resemblances between the Hyner Slates and the Stourscombe Beds and between the Trusham Slates and the Yeolmbridge Beds. Recently discovered ostracod faunas show that the Devonian-Carboniferous boundary lies just below a calcareous siltstone horizon located near the top of the Hyner Slates.

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(d) Boscastle-Otterham

On the first printing of the Boscastle Sheet (322) the Yeolmbridge Formation is show as an exclusively Carboniferous Formation (dl) in a continuous outcrop from the coast at California Quarry, Boscastle, eastwards through Otterham Station. In this section of outcrop the formation shows certain lithological differences from the Yeolmbridge Beds to the east. Overall, the slate is markedly darker, and the high silt and sand content is not developed at the California Quarry. The differences were such that it was not considered appropriate (Selwood 1961) to refer this slate to the Yeolmbridge Beds, even though it was, in part at least, of the same age as the occurrence at Yeolmbridge. Dr. Freshney has however pointed out (personal communication) that sandy horizons do come in eastwards and suggests that there is a lateral change of facies along the strike.

The lower stratigraphic relations of this formation are well displayed at California Quarry, where the black slates rest directly on a green *Spirifer* bearing slate (Tredorn Phyllites). Although for stratigraphic reasons this contact has been interpreted as an unconformity and a fault in the past, Freshney points out that it is one of the least disturbed contacts in the area and is likely to be conformable. The location of a low Carboniferous fauna in these slates suggests that the Devonian-Carboniferous boundary lies within the lowest 50 ft or so of beds or at the base of the formation.

It is now generally accepted that the Tintagel Volcanic Group (Barras Nose Beds and Trambley Cove Beds with included volcanics) overlies the Tredorn Phyllites, and it has been convincingly demonstrated (1967: *Rep. Inst. geol. Sci.,* for 1966: 88) that the group is of Lower Carboniferous age (cuII/III) and probably passes up into Namurian greywackes. The interpolation of a formation between the Barras Nose Beds and the Tredorn Phyllites by I.G.S. is entirely reasonable both lithologically and palaeontologically, but to identify this as the Yeolmbridge Formation is confusing for it appears to form part of a succession distinct from that of the Yeolmbridge Beds in its original usage.

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4. Discussion

A continuity of lithologies at the Devonian-Carboniferous boundary can be described from the Teign Valley westwards through Launceston to Otterham. However the continuous outcrop observed in the Teign Valley is not maintained west of Dartmoor, where it is unlikely that any subdivisions can be separately delimited. In general, a black slate lithology bearing siliceous and calcareous nodules and lenticles (variously known as the Hyner Shales and the Stourscombe Beds and equivalent to all or part of the Meldon Slate with Lenticles Formation and part of the River Lyd Slate with Lenticles Formation) is succeeded by micaceous slates and siltstones (variously known as the Trusham Shale and the Yeolmbridge Beds and possibly including part of the Slate with Lenticles units). The nature of the underlying strata has not been proved directly, but the evidence at Launceston suggests the rather variable lithologies of the Petherwin Beds.

East of Otterham an important NW-SE wrench fault zone has been identified by I.G.S. on the Holsworthy Sheet (323) which can be traced onto the Tavistock and Launceston Sheet (337) from Trewen towards South Hill. To the west of this fault changes occur. The Yeolmbridge Formation is seen to rest on the Tredorn Phyllites ; the prominent chert horizons which succeed the Yeolmbridge Beds and Trusham Shale to the east are replaced by the contrasting Tintagel succession ; and although the changes of facies within the Yeolmbridge Formation noted by Freshney from California Quarry to Otterham are undoubtedly there, the change across the fault zone is still significant. It would thus appear that the strata at the Devonian-Carboniferous boundary to the east and west of the fault zone were formerly more widely separated and have been brought into juxtaposition tectonically.

Wrench faulting along the fault zone has certainly played a part in bringing the contrasting facies together, but earlier thrusting may also be significant. Waters (1970) has shown that to the east of Dartmoor the Kate Brook Slate (thought to be equivalent to the Tredorn Phyllites) has been introduced from the south on a major thrust (Holne Thrust) which rides over successions including the Hyner and Trusham Shales of similar age but contrasting facies to the Kate Brook Slate. It can be argued that a comparable situation exists west of Dartmoor. Thus

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the Devonian-Carboniferous contact mapped (Sheet 337) between Tavistock and Stoke Climsland at the southerly extension of the wrench fault described above, may well represent the continuation of the Holne Thrust. Dextral movement along the fault would have the effect of carrying the Green Slates (Tredorn Phyllites, Woolgarden Phyllites), with the conformably overlying Yeolmbridge Formation and Tintagel Group, northwards on the west side of the fault to rest against rocks of lower structural levels and contrasting facies to the east.

The multiplicity of names recognised to the east of the Otterham fault is confusing ; the broad equivalence of formations is noted above, but clearly some group name is required to identify the unit. "Transition Series" (Dearman and Butcher, 1959: 56) would seem to be available but it is not entirely satisfactory, for besides the contrasting Tintagel succession, work on the revision of the Teignmouth Sheet shows that rocks of comparable age occur in further strikingly different successions. Since an element of "Transition" is likely to be common to all. it is proposed to identify this unit provisionally as the Teign Valley Facies in contrast to the Tintagel Facies west of Otterham.

ACKNOWLEDGEMENTS. I am grateful to Mr. G. Bisson who allowed me to examine manuscript maps held at I.G.S. Hoopern House, Exeter, and to the staff of the Institute, particularly Mr. E. A. Edmonds, for much helpful discussion.

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CORRELATION IN THE UPPER CARBONIFEROUS BUDE FORMATION, NORTH CORNWALL

by A. F. King

Stratigraphic and structural correlation still remains a major problem in the Upper Carboniferous of south-west England. In west Devon, between Instow and Marsland Mouth, Reading and Prentice (1965) and Moore (1968) suggested that there is a series of blocks each with its individual stratigraphical succession and separated from each other by major thrust faults. In the coastal exposures between Wanson Mouth and Boscastle, Freshney (1965) demonstrated that northerly dipping low-angle normal faults spread out the inverted south limb of an anticlinorium. At the southern margin of the Culm, Dearman (1970) summarized a possible sequence of tectonic events and showed a possible relationship between infrastructure and suprastructure.

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A study of the succession exposed between Sandy Mouth and Wanson Mouth has been completed by the author. Data were plotted in the field on aerial photographs enlarged to about 1:480 and later transferred to controlled base maps at a scale _ of 1:2500. Stratigraphical measurements were taken across the limbs of folds and plotted at 1:240 in the form of graphic logs representing sedimentary properties. Structural properties, including repetition or omission of strata by strike faults along the limbs and bed thickening along the axial surfaces were also recorded.

Six lithologic units are recognized and include (1) carbonaceous shales ; (2) variable mudstones ; (3) siltstones and thin-bedded sandstones ; (4) flaggy and average-bedded sandstones ; (5) thick-bedded and massive sandstones ; and (6) sandstones and shales with disrupted beds ('slump beds'). Their compositional, structural and organic characteristics have been summarized (King 1966) and a more detailed account will appear elsewhere. Within these units a number of facies have been recognized, many of which appear to be similar to those distinguished by De Raaf, Reading and Walker (1965) in the cyclic paralic Bideford Group in north Devon.

Correlation of 56 measured sections shows an exposed stratigraphic thickness of about 610 m. An informal working definition of the 'Bude Sandstones' (Owen in 1934) as well as nine stratigraphic units or members representing specially developed parts of this sequence is desirable. The name ` Bude Formation' is proposed to include the strata exposed between the top of the shale band with the palaeoniscid *Cornuboniscus budensis* present in nodules, termed the 'Saturday's Pit Shale', and the top of the 'slump bed', some 385 m stratigraphically below, termed the 'Church Races member'. For the purpose of nomenclatural stability, the most complete and useful reference section is between Lower Longbeak Strand (location of nodular shale : SS 19750348) and Church Races (location of slump bed : SS 19960412).

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Strat. Position	Member	Characteristics
230-240 m	Phillips's	'Slump Bed'
115-125	Saturday's Pit	Black shale with nodules containing palaeoniscids
70-105	Upton Cross	Major sandstone unit
0-20[1]	Tom's Cove	Black shale with nodules containing coelacanthid *Rhabdoderma elegans*
30-50	Earthquake	Major sandstone unit
70-90	Efford	Shale with siltstone above containing xiphosurid trails
130-150	Lynstone	'Slump Bed'
130-150 ?	Black Rock	'Slump Bed'
270-280 m	Church Races	'Slump Bed'

[1]Base of Tom's Cove taken as stratigraphic datum

FIGURE 1. Stratigraphic position and characteristics of members in Bude area.

Cycles are present in the Bude Formation but are comparatively small. The passage upwards from fine-grained sandstone to siltstones with xiphosurid trails to carbonaceous shales is thought to represent a change from fluviatile conditions with rapid deposition of fine sand, through an environment with oscillatory fluctuations in current velocity and supply, to one with slow deposition under quiet and relative deep conditions. The presence of trace fossils *Kouphichnium* and *P. ophthalmoides* are thought to correspond with changes in contemporary salinity.

Variations in the lithologic succession influenced the subsequent development of folds and faults. Plunging and alternating folds formed on very broad E-W trending anticlinoria and synclinoria with wavelengths of 2.5 km and an amplitude generally less than 0.7 km. Fracture cleavage, boudins, and minor thrust faults are associated with the generation of early folds. High-angle, E-W normal faults are responsible for crenulation cleavage, deformation of early folds and repetition of a relatively thin stratigraphic succession. NW trending dextral wrench faults of probable Tertiary age are considered to be the youngest tectonic structures in the area.

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THE UPPER CARBONIFEROUS ROCKS OF DEVON AND NORTH CORNWALL

by R. V. Burne and L. J. Moore

Abstract. Palaeontological and sedimentological evidence suggests that two distinct, but synchronous, stratigraphical successions can be identified in the Upper Carboniferous rocks of Devon and north Cornwall. One succession is developed in a basinal facies and the other can be divided into an older basinal facies sequence and a younger deltaic facies sequence. The recognition of these facts allows a simple palaeogeographical reconstruction of the Culm Syncline area to be proposed.

1. Introduction

In 1965, Reading summarised the limited palaeontological evidence for the age of the Upper Carboniferous rocks of north west Devon and concluded that a number of synchronous stratigraphical successions exist within the Culm Syncline. The purpose of the following paper is to examine Reading's conclusions and the detailed sedimentological studies completed during the last decade, in order to revise certain correlations that have been made and to demonstrate the presence of two major facies types within the Upper Carboniferous rocks.

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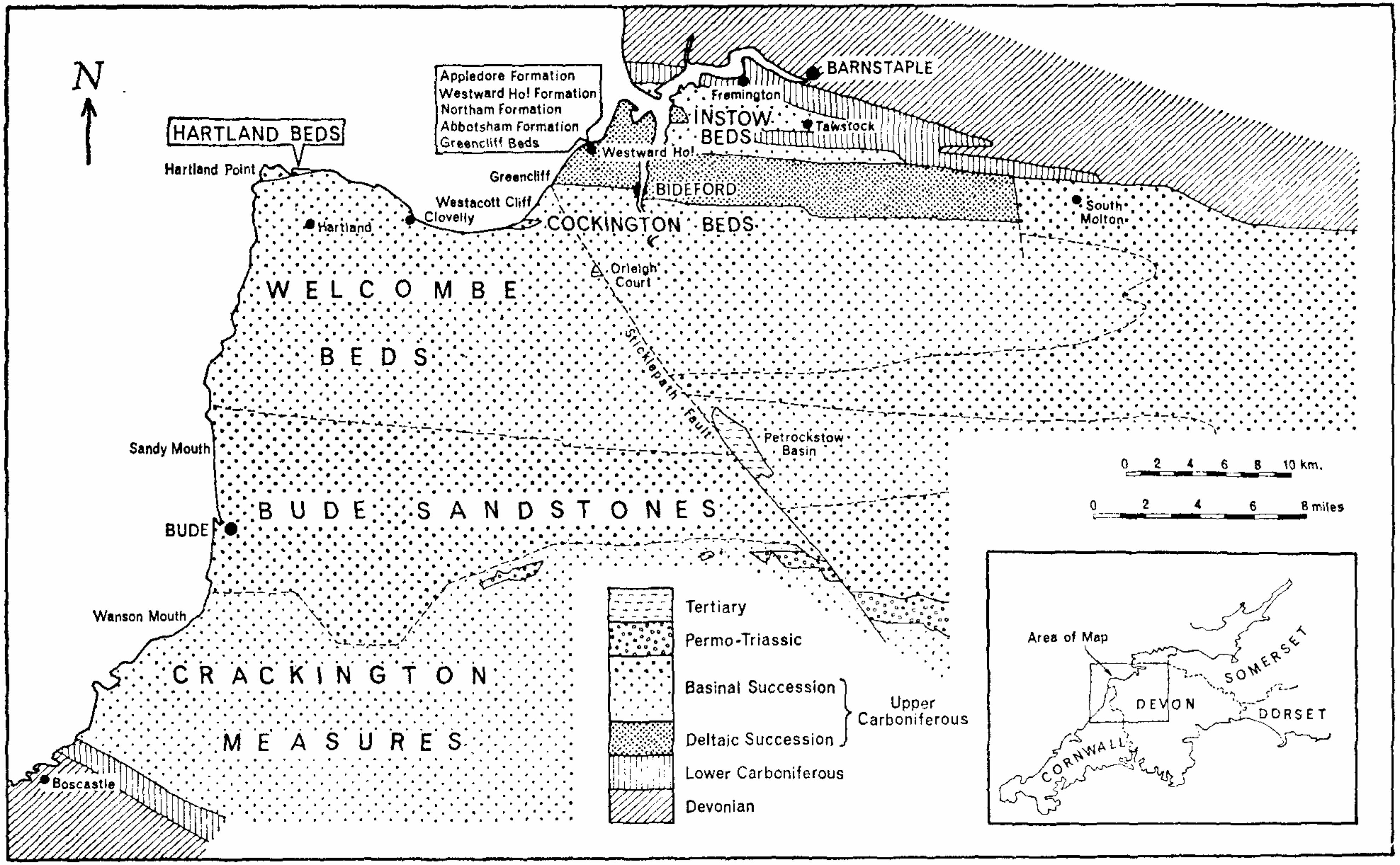

FIGURE 1. Geological Map of north Cornwall and north-west Devon.

2. **Stratigraphy and Sedimentology**

The oldest Namurian rocks outcropping on the west coast of Devon and Cornwall are found between Boscastle (SX100906, and see Figures 1 and 2) and Wanson Mouth (SX195011). These are the Crackington Measures. They contain goniatites which range in age from the Upper *Eumorphoceras* (E_2) zone to the *Reticuloceras bilingue* (R_2) sub-zone (Mackintosh 1964). To the north of Wanson Mouth, and separated from the Crackington Measures by the Wanson Mouth fault, are the Bude Sandstones. King (1966 and unpublished work) has suggested that the goniatites found at Sandy Mouth (SS201101) (Reading 1965) lie close to the top of the Bude Sandstones and not 300 m above the base of the formation as suggested by Reading. The goniatites are considered by Ramsbottom (1970) to belong to a horizon just above the *Gastrioceras listeri* marine band.

To the north of the Bude Sandstone outcrop, Moore (1968) has recognised a succession

3 Hartland Beds

2 Welcombe Beds

1 Black Mudstone Beds

The lowest horizon of the Welcombe Beds is a nodular black shale with *Gastrioceras circumnodosum,* one of the *G. listeri* marine band group of goniatites. The nodular black shale with *Gastrioceras* sp. at the base of the Black Mudstone Beds has been equated with the *G. subcrenatum* marine band (Moore 1968). Lithologically, the highest Welcombe Beds and the Hartland Beds are similar to the lowest Bude Sandstones that are exposed. One of the authors (L.J.M.) has traced the outcrop of the Welcombe Beds to the south of the Devon-Cornwall boundary. These rocks young southwards and pass under the Bude Sandstones. South of the main Bude Sandstone outcrop, the Welcombe Beds are almost completely cut out by the Wanson Mouth Fault. However, between the North and South Wanson Mouth Faults a thin series of sandstones and shales are exposed. These rocks contain G_2 age, Lower Westphalian, goniatites (King 1966) and are the basal beds of the Welcombe Beds. A stratigraphic sequence is thus established for the rocks of the west coast of Devon and Cornwall (Figure 2).

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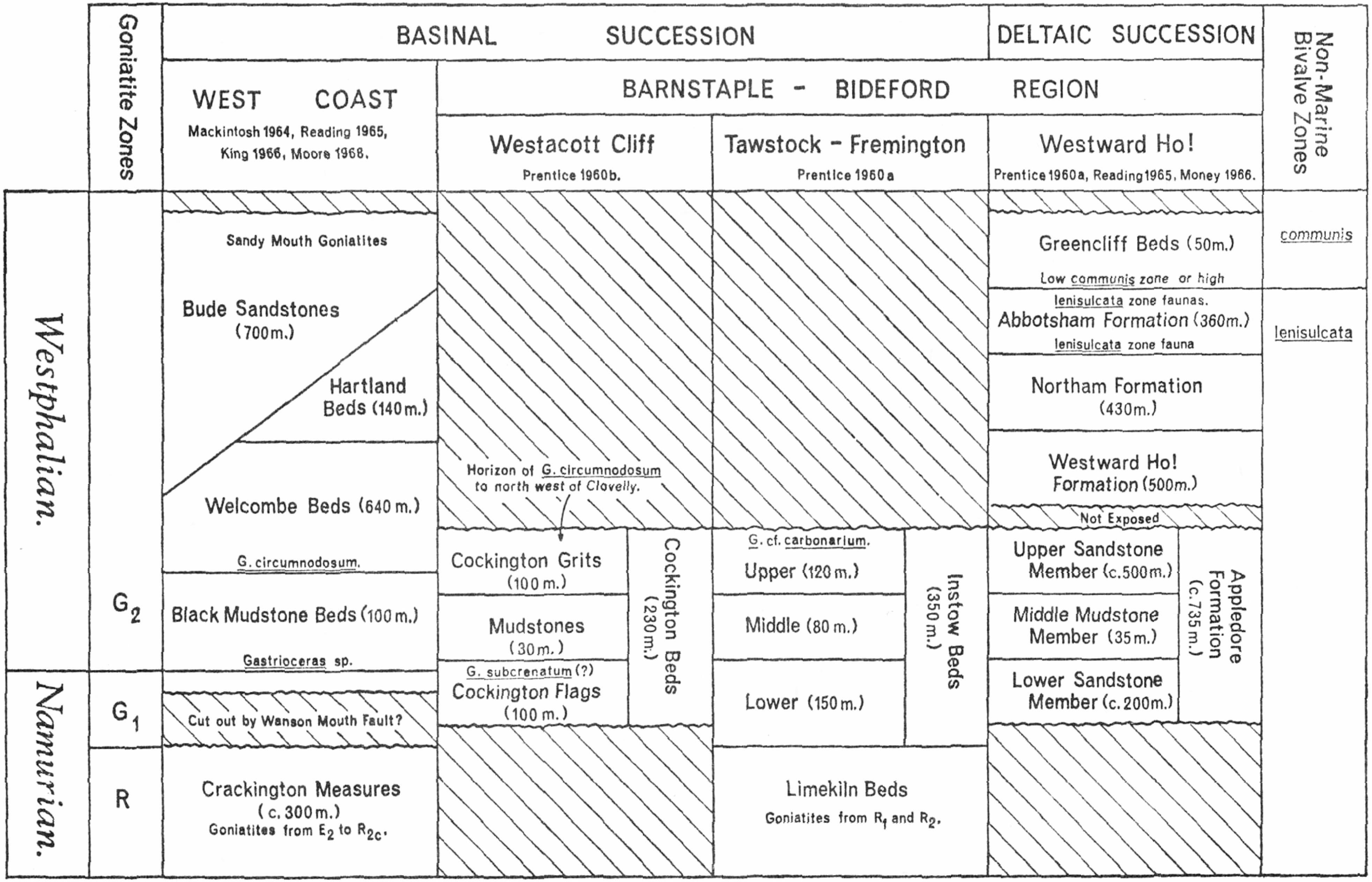

FIGURE 2. Stratigraphy of the upper Carboniferous rocks of the Culm Syncline.

Burne (1969 and 1970) has established that all the features of the Bude Sandstones are compatable with deposition by two processes, very gentle circulation of basin waters and bottom hugging currents or density underflows that may be described as turbidity currents, providing that these are defined with regard to their flow alone. The thin seams of coal that are found are allochthanous, and are integral parts of turbidites. Although small rotational slumps occur, the so called major "slump" beds described from Bude and the rest of the west coast are in fact the deposits of very high density turbidity currents and individual beds are very extensive. As these "slump" beds are generally interbedded with thick mudstones of a tranquil environment, they cannot be directly related to delta front deposits as is suggested by Edmonds *et al.* (1968). Thin and medium-bedded sandstones having sharp lower contacts with sole marks and showing graded-bedding, ripple-drift-bedding and parallel-lamination within the beds form more typical turbidites and are commonly intercalated among the mudstones.

King (1965, 1966) and Golding (1969) have described trace fossils from the Bude Sandstones. These consist of burrows, which King (1966) referred to *Planolites ophthalmoides,* and the tracks of xiphosurids. King (1965) suggested that the finding of xiphosurid tracks at a number of horizons within the Bude Sandstones indicates an environment of low salinity.

With the exception of the "slump" beds and the trace fossils, which are not known from the Crackington Measures, all the sedimentary types described by Burne from the Bude Sandstones can be found in the other rocks of the west coast. There are, however, variations in the relative importance of the various sedimentary types from formation to formation (Mackintosh 1964, Moore 1968).

Thus a mudstone and turbidite sandstone accumulating basin was established at the commencement of the Namurian and continued to exist throughout the deposition of over 2,000 m of sediment. The significant changes within the basin are an increase in sediment supply and a decrease in salinity at the end of the deposition of the Crackington Measures. These changes were followed by a change in turbidite supply direction from a westerly

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derivation for the rocks of the Crackington Measures (Mackintosh 1964) and the Welcombe Beds (Moore 1968) to a derivation from the north and east (Lovell 1965) for the Bude Sandstones.

The Welcombe Beds and the Black Mudstone Beds can be traced eastwards to the Bideford area (Moore 1968) where Prentice (1960b and see Figures 1 and 2) proposed the name Cockington Beds for the turbidite sandstones and mudstone sequence occurring in Westacott Cliff (SS398264). The finding of marine bands containing *G. subcrenatum* (Prentice 1960b) within the Cockington Flags in Westacott Cliff and *G. circuninodosum* (Moore 1968) in the Cockington Grits north west of Clovelly allow a precise correlation with the Black Mudstone Beds and the Lower Welcombe Beds to be made (Figure 2).

In the Bideford-Barnstaple area, Reading (1965) summarised the palaeontological evidence for the ages of the single succession recognised by Prentice (1960a, 1960b) and concluded that three distinct and synchronous successions exist (Also see Figure 1).

Greencliff & Westacott Cliff	Cliffs to S.W. of Westward Ho!	Fremington & Tavistock
2 Cockington Beds	3 Abbotsham Formation	1 Limkiln Beds
1 Greencliff Beds	2 Northam Formation	2 Instow Beds
	1 Westward Ho! Formation	

The juxtaposition of these successions must now be examined. The cliffs to the south west of Westward Ho ! were examined by De Raaf, Reading and Walker (1965) who concluded that the Northam and Abbotsham Formations contain nine cyclothems ; each consisting of a lower mudstone member, an intermediate member of siltstones and mudstones with occasional sandstones, and an upper sandstone member ; deposited in a complex deltaic environment. This origin was suggested by Prentice (1960b), who also concluded (1962) that the mean sediment supply direction was from the north.

The only evidence for the age of the succession is provided by non-marine bivalves which have been found at two localities in

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the Abbotsham Formation (Reading 1965). These bivalves have recently been re-examined by Calver who considers that both faunas are of Westphalian age (Figure 2) (Calver pers. comm.).

The only place where the contact between the deltaic Westward Ho! succession and the basinal, mudstone and turbidite sandstone, Westacott Cliff succession can be directly observed is Greencliff (SS405270) (Prentice 1965). The type locality of the Greencliff Beds in Greencliff has been re-examined. The Greencliff Beds-Cockington Beds junction was originally interpreted by Prentice (1960b) as a conformable stratigraphical junction from exposures in Westacott Cliff. Here Prentice interpreted a major “slump” bed as being infolded Greencliff Beds. Exposures in the Clovelly area (SS317253) show that this major "slump" bed is within the Cockington Beds and not at their base, and that its origin is the same as the so called "slump" beds of the Bude Sandstones (Burne 1970, and see above).

At the northern end of the Greencliff Beds (SS40662730), the culm horizon, which forms the topmost bed of the Abbotsham Formation (De Raaf, Reading and Walker 1965), passes upward into grey shales which have a second thin culm horizon near their base. To the south of these shales is a faulted block of coarsegrained, ripple-drift-bedded sandstone, similar in appearance to the topmost sandstone of the Abbotsham Formation. This sandstone youngs to the north. To the south of this block of sandstone is a faulted series of pale grey silty mudstones, with local, isolated, small, ripple-cross-laminated lenses of sand. Contortion of these lenses has produced a deposit which has the appearance of a slump bed. Burrows can be seen at a number of horizons. To the south of these mudstones, and separated from them by a normal fault, are strongly folded, dark shales which have a strong, near vertical cleavage. To the south of these cleaved shales is a second series of silty mudstones. All these rocks young to the north. This sequence is interpreted as a continuation of deltaic sedimentation after the deposition of the Abbotsham Formation. The finding of a high *lenisulcata* zone or low *conirnunis* zone fauna within the Greencliff Beds near Bideford (Prentice 1960b) supports this interpretation. Thus the Greencliff Beds lie stratigraphically above the Abbotsham Beds and not below the Cockington Beds (Figure 2).

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To the south of the Greencliff Beds are a series of grey shales within thin- and medium-bedded, fine grained, grey, sole-marked sandstones. These beds belong to the Cockington Beds. They are separated from the main outcrop of the Cockington Beds by a series of dextral wrench faults with a north-west south-east trend. These faults are the north-western extension of the Sticklepath Fault (Figure 1) (Dearman 1963). The shales of the Cockington Beds show no sign of having been deposited in active water and the sandstones are interpreted as having been emplaced by turbidity currents from the west (Prentice 1962) in a tranquil basin.

The junction between the Greencliff Beds and the Cockington Beds is a normal fault that can be traced as an east-west sandy hollow in the rocky foreshore. A deltaic succession succeeded by a basinal mudstone and turbidite sandstone succession to the south can be traced eastward to the Mole Valley, 3 kilometres west of South Molton (Figure 1).

The relationship between the Westward Ho ! succession and the Fremington and Tawstock succession is less easily appreciated. Money (1966) has recognised a sandstone-shale succession, the Appledore Formation, which, because of the lithological similarity of the topmost beds to the Westward Ho! Formation, possibly lies at the base of the Westward Ho! succession (Figure 2). Money was able to recognise an upper and a lower sandstone member separated by a thin central mudstone member within this Formation. Prentice (1960a) included the lower sandstone member of the Appledore Formation in the Instow Beds whose main outcrop is to the east of the river Torridge.

Prentice (1960a) records goniatites from three localities within the Instow Beds. In all cases these are identified as *Gastrioceras* cf. *carbonarium* (some of these specimens have been re-examined and are now determined as *G. circumnodosum.* J. E. Wright pers. comm.) a lower Westphalian, *G. listeri* marine band goniatite. This horizon occurs near the top of the Instow Beds.

At Fremington (SS513332) (Prentice 1960a), a mudstone and turbidite sandstone sequence is preserved in the core of a syncline of Limekiln Beds (Figure 2). The Limekiln Beds are a thin series of black shales and siltstones which contain *Reticuloceras* and are therefore of Namurian age. The overlying rocks were interpreted by Prentice as being the lowest member of the Instow Beds.

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The best exposure of the Instow Beds is found in stream sections to the south of the Lower Carboniferous rocks at Tawstock (SS555299) Here, Prentice (1960a) was able to divide the Instow Beds into two turbidite sandstone and mudstone sequence separated by a predominantly mudstone member. These three divisions were called the Lower, Middle and Upper Instow Beds by Prentice. (Figure 2). An examination of these exposures suggests that the predominantly mudstone Middle Instow Beds may be an expanded representative of the mudstone member of the Appledore Formation, the Cockington Mudstones and the Black Mudstone Beds of the west coast. If this equation is correct then the goniatite bearing nodular shale of the Instow Beds occurs at the same horizon as the nodular black shale at the base of the Welcombe Beds with its' identical fauna. The turbidites of the Instow Beds show graded-bedding, ripple-drift-bedding and sole marks and like their presumed lateral equivalents, the Black Mudstone Beds and the lowest Welcombe Beds, they are derived from the west (Prentice 1962).

The Crackington Measures, Black Mudstone Beds and lowest Welcombe Beds can therefore be shown to have a contemporaneous basin facies representative, that is older than the entire outcrop of the deltaic facies, throughout the area discussed. The deltaic facies is the lateral equivalent of the higher Welcombe Beds and the Bude Sandstones.

3. Conclusions

Although much detailed work remains to be done, it is now possible two recognise two distinct stratigraphical successions within the Upper Carboniferous rocks of the Culm Syncline. These successions are separated by a major east-west trending normal fault, with a downthrow to the north, which extends from Greencliff to the Mole Valley.

The northern, essentially deltaic, sequence commences with the deposition of the basin facies Limekiln and Instow Beds. A series of deltas then invade the basin from the north and the remainder of the succession consists of over 1,300 metres of deltaic sediments, a sequence of events originally proposed by Prentice (1960a, 1960b). The southern succession is entirely in basin facies,

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but the advance of the deltas in the north is marked by the introduction of large quantities of sand into the basin, much of this material being derived from the north.

ACKNOWLEDGEMENTS. The authors would like to thank Dr. H. G. Reading and Professor J. E. Prentice for reading and criticising an early draft of this paper.

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The Quaternary section at Porth Mear Cove (Abstract)

by B. B. Clarke.

This is one of several porths between Padstow and Newquay, where a small estuary has become partly impounded to form successively, a lake, a marsh, and then a reed covered flat, the process here repeated several times. The old lake flat is at present being cut back by the sea to expose a clear, but highly complex, section.

At the sides are two deposits of head, the lower, coarse and slaty, and the upper, finer with more clay and rough quartz lumps. The junction shows *frostkeilen* and *brodelung* structures, and a thin longitudinal crack filled with iron manganese oxide dust. In a basin excavated in the younger head are two bands of stiff grey lacustrine clay with a peat layer between. The grey clay passes upwards into a terrace gravel, and at the sides thins out into the head. There is no sharp junction between the head and the terrace gravel at the sides of the lake basin.

Both the clay and the peat provide plant and insect material. The peat has a rich flora, and both pollen and radio- carbon dating give Sub-Boreal zone VII B as the age. From it a picture of the landscape and flora of this part of Cornwall in the Bronze Age can be built up. Grasses predominated, weeds of cultivation were prolific, showing that farming communities had already arrived. There is a moderate tree flora different from the present in the abundance of *Alnus, Betula* and *Quercus,* and the scarcity of *Ulmus.* The section suggests that the tree flora and coastline have altered in the last 3,000 years.

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THE BURIED CHANNEL OF THE TEIGN ESTUARY

by E. M. Durrance

Abstract. The buried channel of the Teign drops from a level of - 10.2m at the head of the estuary to -22.9 m at Teignmouth. It is floored by Devonian slate for most of its length but New Red Sandstone breccia underlies the Teignmouth foreshore. A Late Weichselian age for the channel is suggested on the basis of correlation of levels recorded within the Exe estuary.

1. Introduction

The form of the transverse profile of the Teign east of Newton Abbot suggests the presence of a buried channel beneath the estuary. Similar buried channels have been noted from the River Dart by Codrington (1898) as extending to a depth of -33 m, and MacFarlane (1955) has found sediment thicknesses in the order of 27 m in the Erme and Taw-Torridge estuaries. Recently, Durrance (1969a) has identified two periods of channelling in the Exe estuary. The older period of channelling in the Exe has been related to the Early Weichselian sea-level low and extends to a depth of about - 52 m while the younger channels are considered to be of Late Weichselian age and are present to a depth of -30 m. Clarke (1970) working off-shore of S.E. Devon using continuous seismic reflection techniques failed, however, to record the presence of any buried channel off the Teign estuary while obtaining only very shallow levels (considerably less than -20 m) for the floor of the buried channels at the mouth of the Exe.

To resolve this problem a detailed seismic survey of the lower Teign estuary was undertaken using a twelve-geophone shallow seismic refraction unit. Wherever possible the seismic lines were situated at the level of high water of medium spring tides (Teignmouth Bar) and elsewhere at levels surveyed from this datum (2.1 m above O.D.). The position of these lines is shown in Figure 1A. To achieve continuity with the depths quoted for the buried channels of the Exe estuary (Durrance 1969a) all levels thereby obtained have been reduced to a datum presented by high water of medium spring tides at Exmouth Dock (2.4 m above Newlyn Ordnance datum).

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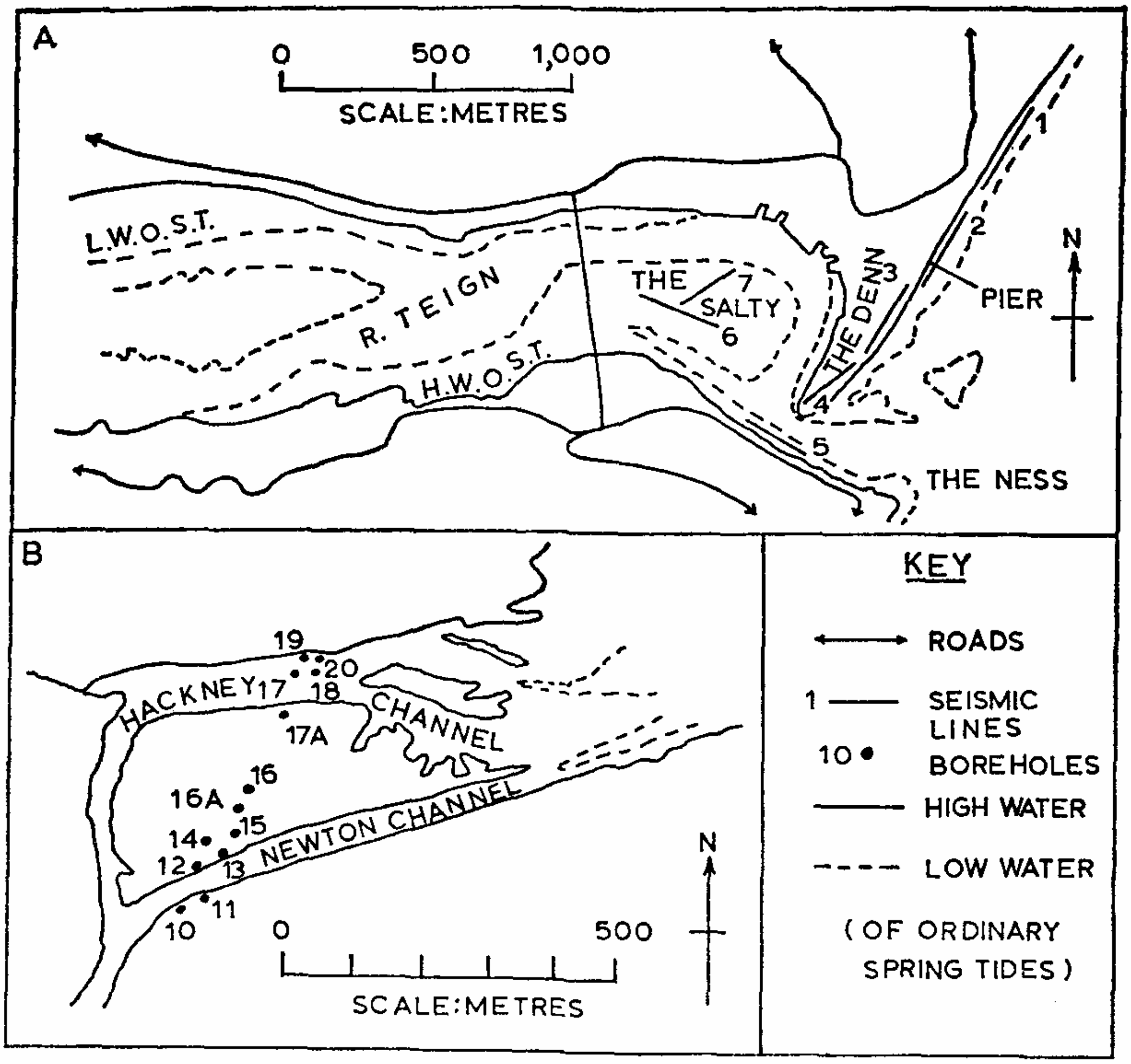

FIGURE IA. The lower Teign estuary and position of the seismic lines. B. Devon County Council borehole positions at Hackney.

2. Results from the Seismic Survey

The velocities recorded from the results of 60 successful shots have been grouped into the following classes:

Class	Velocity (ms^{-1})
A	366-396
B	1067-1433
B^1	1524-1676
D	2256-2743
E	3200-3505

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In this system the same notation for interpretation of velocity classes is used as well established from the results of the Exe seismic survey (Durrance 1969a). Class A velocities correspond to dry surface sand and occurred in the results from all seismic lines except Nos. 6 and 7. Classes B and B' correspond also to recent sediment, B to wet sand and gravel of varying degrees of sea-water saturation and B^1 to either completely saturated sands and gravels in which some compaction has taken place, or clay. Members of velocity class B were recorded from all seismic lines except Nos. 6 and 7, while those of class B^1 were found just from these two lines. Class D velocities clearly correspond to the New Red Sandstone both from its outcrop in relation to the seismic lines and the similarity of the velocities with those recorded elsewhere from the New Red Sandstone (Durrance 1969a ; Durrance and Hamblin 1969). It is interesting to note that the velocities which are assigned to both the Oddicombe and Teignmouth Breccias at Teignmouth are somewhat lower than those for the Teignmouth Breccias beneath the Cretaceous Greensand of Great Haldon and markedly lower than those for the Exe Breccias beneath Dawlish Warren. Velocities of class D were recorded from all seismic lines except Nos. 6 and 7. The interpretation of velocity class E presents a problem. The velocities of this class fall within the higher range of those determined for the New Red Sandstone breccia of the Exe estuary (Durrance 1969a), but are higher than the velocities recorded for the Teignmouth Breccias beneath Great Haldon (Durrance and Hamblin 1969). Moreover, their range is also similar to that recorded from Devonian slate (Heiland 1946). Members of this class were recorded from seismic lines 5, 6 and 7 and their interpretation is considered in more detail below. Velocities corresponding to those of classes A^1 and C found in the Exe estuary have not been recorded in any of the seismic lines arranged in the Teign estuary .

3. Boreholes

As part of the site exploration program for the proposed Newton Abbot by-pass (A380), Devon County Council, Surveyors department, have placed a series of 13 shell and auger boreholes across the head of the Teign estuary from the Hackney Channel to the Newton Channel. The position of these boreholes is shown in Figure 1B, and the results obtained summarised in Figure 2.

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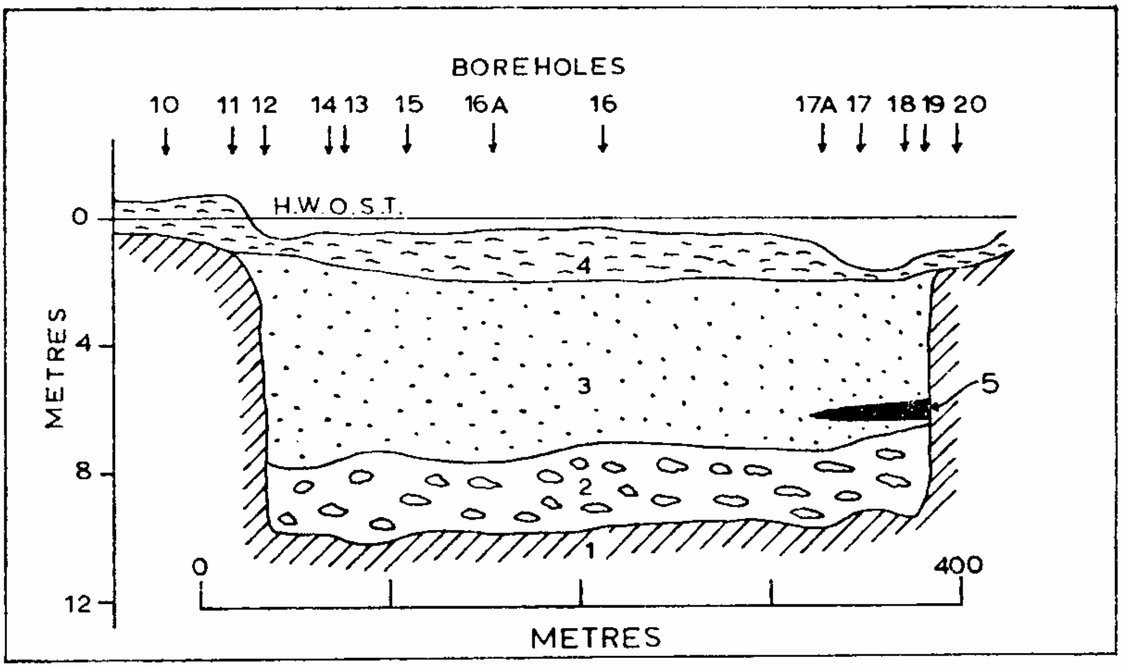

FIGURE 2. Diagrammatic section of the buried channel of the Teign at Hackney. 1. Devonian slate and dolerite, 2. Gravel, 3. Silt and fine sand, 4. Soil and modern clay, 5. Peat.

Rock-head in boreholes 10 and 11 is at -0.5 and -1.0 m respectively. Similarly, a level close to that of datum is found in boreholes 19 and 20 with rock-head at -1.6 and - 1.9 m. The remaining boreholes, however, all show rock-head levels of between -9.0 and - 10.2 m with no significant variation between them, the floor of the buried channel appearing remarkably flat. Above rock-head in these boreholes is an horizon of medium to coarse gravel which varies between 1.5 and 2.7 m in thickness and fills the buried channel to a level of about -7.4 m. Overlying this is a unit of silt and fine sand which completes the succession apart from a cover of between 0.6 and 1.3 m of modern clay. In borehole 17A, however, traces of peat are found within the silt at a depth of between - 5.4 and -6.2 m. In borehole 17 this becomes a recognisable unit slightly less than 1 m thick between the levels of -5.9 and -6.8 m. Traced toward borehole 18 the peat thins to 0.76 m at depths between - 5.9 and 6.7 m.

4. Interpretation of the Results of the Seismic Survey

As noted above, surface velocities assigned to Class B[1] were found from lines 6 and 7 which were located on the Salty. Here the lithology to which these velocities can be related is a gravel

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with a sandy matrix. The comparatively high values of class B^1 velocities indicates that some degree of compaction and consolidation has probably taken place within this material, in turn confirming the suggestion that the Salty represents a markedly stable area when compared with the sands of the Denn and Teignmouth front (Spratt 1856 ; Durrance 1969b). There is no indication that clay may form part of this unit either from its character when exposed, or from the records of the boreholes at the head of the estuary. Indeed, the correlation between lithologies showing class B^1 velocities as exposed on the Salty, and the silt, sand and gravel found in the boreholes seems quite straightforward.

The problem of the interpretation of class E velocities is, similarly, simplified by outcrop distribution, Devonian slate appearing from beneath a cover of New Red Sandstone breccia on the southern shore of the estuary upstream of the Teignmouth-Shaldon bridge. The boundary here is just above datum level and virtually horizontal, suggesting that it is at no great depth beneath the Salty-Ness beach area. The recording of class E velocities from lines 5, 6 and 7 therefore indicates the probability that velocities of this class can be assigned to Devonian slate. Evidence to corroborate this correlation is forthcoming both from the character of the refracting interface between class D and class E velocities in line 5, which indicates the presence of a sharp discontinuity, and the interpretation of velocities of about 3800 ms^{-1} by M. R. Henson (personal communication) as either Devonian or Carboniferous slate underlying the New Red Sandstone of E. Devon.

The limited extent and thickness of the peat horizon recorded by the boreholes at the head of the estuary shows that this lithology forms only a minor part of the sequence of recent sedimentation. This would indicate that the presence of extensive and thick peat horizons elsewhere in the estuary is unlikely. Interpretation of the results of the seismic survey may therefore validly assume the absence of velocity inversions within the infill of the buried channel.

The interpretation of the results from lines 1 to 5 using the correlations also established from lines 6 and 7 is given in Figure 3. Except in the case of the results from line 5 the character of the arrivals is quite straightforward. Lines 1 to 4

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show the presence of a unit of dry sand up to 3 m thick which overlies either loose sand and gravel below a variable water table (probably tide controlled), or New Red Sandstone breccia. At the northern end of the section formed by these lines the surface of the breccia is at a depth of only - 1.6 m, but towards the south it descends in three steps, first to - 10.1 m then to -14.3 m and finally to - 22.9 m. The results from line 5 indicate the presence of a layer of dry sand about 1.6 m thick overlying breccia (which crops out on the shore of the estuary at above this level just below the seismic line). Beneath the breccia is a unit possessing class E velocities, interpreted as Devonian slate. The exact depth of the slate cannot, however, be determined from the arrival times, but a minimum depth of - 12.8 m for the refracting boundary can be calculated. Lines 6 and 7 both gave the result of a unit possessing class B^1 velocities extending to a depth of -21.6 m before meeting velocities of class E which have also been assigned to Devonian slate.

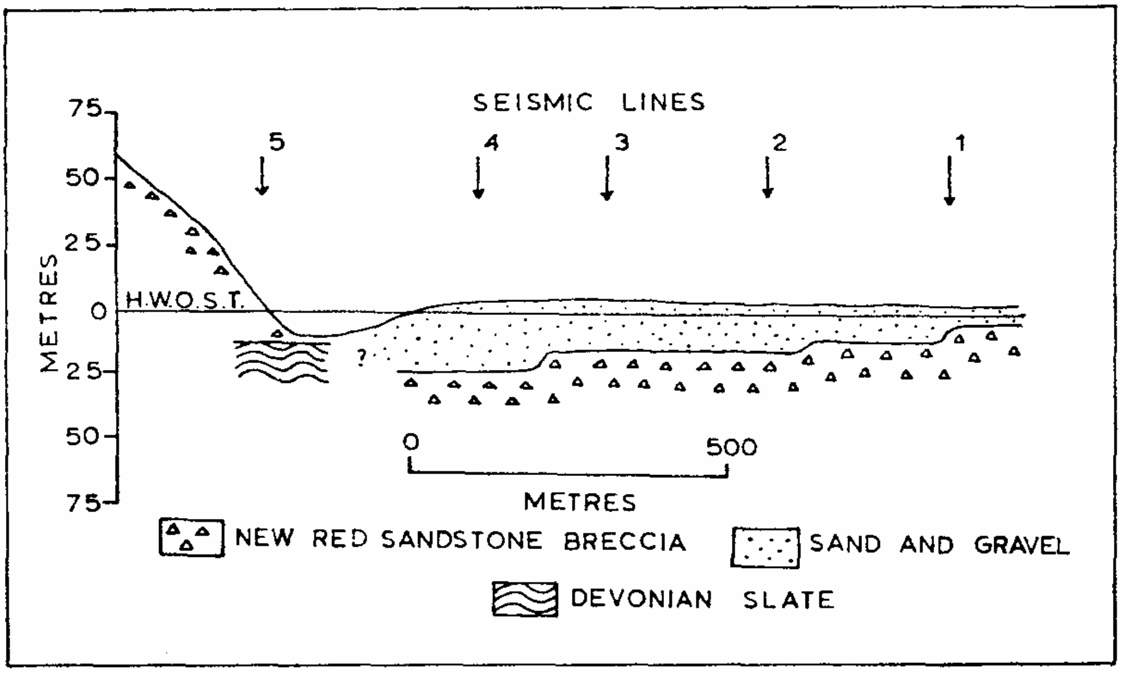

FIGURE 3. Section illustrating the relationships displayed between the New Red Sandstone breccia, Devonian slate and Recent sand and gravel beneath the Teignmouth-Ness foreshore.

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5. Conclusions

The presence of a buried channel of the Teign extending to a depth of - 22.9 m at the Denn is evident from the results of the seismic survey. Borehole records taken at the head of the estuary indicate that the floor of the channel there is at a depth of - 10.2 m. An average gradient of 12.7 m in 6 km (or 1 in 470) is therefore present. This indicates that the rise in level of the floor of the channel of 1.3 m between the Denn and the Salty in a distance of about 600 m shown by the seismic survey is of the right order. If Clarke (1970) is correct in his interpretation of depths from the seismic reflection data he employs there would then have to be a negative gradient for the buried channel over a further 4.2 km before his contour indicating a depth to rock-head of - 22.5 m and confluence with the southward trending Exe system is encountered off-shore. This is clearly unreasonable.

A comparison with the Exe estuary shows that the levels present within the buried channel of the Teign are in close agreement with those formed in the younger (Late Weichselian) channels of the Exe. Indeed, the -10.1 and -14.3 m levels in the lower Teign estuary correspond remarkably well with the - 10.4 and - 13.7 m terraces of the Exe. In addition to these known (possibly terrace) levels in the buried channel of the Teign, it is interesting to note that the floor of the channel is placed at - 10.2 m at the head of the estuary and between - 21.6 and -22.9 m at the mouth. Whether these levels can be related to the - 10.4 and - 22 m terraces found in the younger channels of the Exe must, however, remain uncertain, as by forming the floor of the channel such levels need not be widely developed.

The absence of a period of channelling in the Teign which could be correlated with the older (Early Weichselian) channels of the Exe is possibly due to the lesser influence of the Teign, compared with the Exe, in the erosional processes at work during the Late Pleistocene sea-level regressions. Such differential erosion which typically exists between major rivers and their tributaries would confine the older channels of the Teign to an area seaward of the present coastline. Evidence to support this concept comes from the younger channels, in that these systems, of equivalent age, reach a depth of - 30 m at present-day coastline in the Exe valley but only -22.9 m in the Teign. The level of the floor of

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the buried channel is therefore likely to be lower in the Exe than in the Teign for all positions near to, but not at, their confluence. That the postulated older channels of the Teign may have cut back as far as the lower reaches of the estuary to a shallow depth only to have been completely removed by erosion connected with the younger channelling is, however, possible, but no evidence remains to substantiate this.

ACKNOWLEDGEMENTS. I should like to thank Dr. R. A. Edwards, Mr. P. Blight and Mr. R. Willmington for their help in the field on various occasions, and Mr. H. Criswell, County Surveyor, Devon County Council, for permission to publish the borehole records. Thanks are also offered to the Devon River Authority, Teignmouth Harbour Commission, Teignmouth Council, the Grand Pier Teignmouth and the Devon and Cornwall Police for permission to survey areas within their control.

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PALYNOLOGY OF THE NEW RED SANDSTONE SEQUENCE OF THE SOUTH DEVON COAST

by G. Warrington

Abstract. A palynological study of the New Red Sandstone sequence of the Devon coast between Tor Bay and Seaton was commenced in connection with the re-mapping of the Teignmouth area ; 107 samples from 11 lithostratigraphical units in the sequence have been examined. Fourteen samples were productive, 8 yielding Triassic miospores and the remainder derived assemblages mainly of Upper Palaeozoic age. Two of the Triassic assemblages also contained derived Carboniferous miospores. Carnian miospore assemblages have been obtained from the middle part of the Upper (Keuper) Marls and Rhaetian miospores from the Grey Marl member at the top of the Upper Marls.

1. Previous palaeontological work

No micropalaeontological study has been previously undertaken for the whole of the New Red Sandstone of the south Devon coast and macrofossils are rare. Invertebrate burrows have been recorded by Pengelly (1863) from the Watcombe Breccia Formation ; by Laming (1966) from his Tor Bay Breccia unit, and from the Exmouth Sandstone and Mudstone and the Littleham Mudstone formations (Henson 1970). Vertebrate footprints were recorded by Clayden (1908) in the Lower Sandstones (Ussher 1876) and Shapter (1842) recorded invertebrate tracks and ". . . obscure impressions of other objects (*Posidonia*)." in the same unit; this record of "*Posidonia* " may refer to specimens of *Euestheria.*

Vertebrates are represented by fragmentary reptilian remains, referred to *Hyperodapedon* by Huxley (1869), from the base of the Otter Sandstone Formation. Walker (1969) has identified this material as *Rhynchosaurus.* Remains of an amphibian (*Labyrinthodon lavisi* Seeley 1876) were found in the topmost part of the Otter Sandstone (Johnston-Lavis 1876). Hutchinson (1879) recorded equisetalean plant remains from the basal part of the Upper Marls.

The above fossils are of little value for dating purposes. Whitaker (1869) inferred that his find of *Hyperodapedon* placed the Otter Sandstone in the Keuper. Walker's (1969) reassessment

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of this material appears to render an Anisian (lower Middle Triassic) age possible however. Romer (1947) inferred the amphibian material to be ". . . probably *Cyclotosaurus* or a similar form". The genus *Cyclotosaurus* ranges through deposits of Ladinian to Norian age.

2. The palynological study

A total of 107 samples of grey or grey-green mudstones and siltstones has been processed and examined for miospores. Many of the samples were dolomitic and, below the Upper Marls, rather sandy.

The lithostratigraphical nomenclature adopted below in the description of the samples examined is based upon the published data of Laming (1966), Henson (1970) and Woodward and Ussher (1906). The formations are discussed from the base of the sequence in Tor Bay, at the western end of the New Red Sandstone section, to the top near Seaton at the eastern end of the section. One unit mentioned, the Exe Breccia Formation, is attributable to Henson but has not yet received formal definition.

Three samples from the Livermead Beds (Laming 1966) at Corbyn's Head (SX908633), Torquay ; one from the Ness Beds (Laming 1966) at Shaldon (SX939716), Teignmouth, and four from the Exe Breccia Formation at Lympstone (SX991835), were barren.

Of 35 samples from the Exmouth Sandstone and Mudstone (Henson 1970) only two yielded miospores. One sample, from 120 m south-east of the steps at Rodney Point (SY02037957), Exmouth, yielded a number of Carboniferous miospores which are considered to have been derived from a source of upper Namurian age. Dr. B. Owens (I.G.S., Leeds) identified and commented on all the derived miospores encountered during the present study.

A sample from a slightly higher horizon in the Exmouth Sandstone and Mudstone, 91 m east of the steps at Orcombe Point, (SY02167951), yielded a well-preserved assemblage of highest Devonian and lower Carboniferous age.

Twelve samples from the Littleham Mudstone (Henson 1970) were examined. One, from Littleham Cove, (SY03928037), yielded a derived lower Carboniferous assemblage.

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Two samples from the Otter Sandstone (Henson 1970) at Ladram Bay and Sidmouth were barren.

Of the 31 samples examined from the lower part of the Upper (Keuper) Marls (Woodward and Ussher 1906), only three, from the eastern end of Higher Dunscombe Cliff (SY15808790), 42, 34 and 28 m below a 10 m-thick grey sandstone and mudstone unit which is visible high in the cliff face, were productive. The Triassic miospore assemblage obtained from the lowest of these samples included the following : *Calamospora nathorstii* (Halle) Klaus 1960, *Laevigatisporites globosus* Leschik 1955, *Punctatisporites parvigranulosus* Leschik 1955, *Retusotriletes mesozoicus* Klaus 1960, *Paraconcavisporites lunzensis* Klaus 1960, *Osmundacidites alpinus* Klaus 1960, *Cyclogranisporites oppressus* Leschik 1955, *Praecirculina granifer* (Leschik) Klaus 1960, *Corollina meyeriana* (Klaus) Venkatachala and Góczán 1964, *Duplicisporites granulatus* Leschik 1955, *D. verrucosus* Leschik 1955, *Saturnisporites granulatus* Klaus 1960, *Enzonalasporites* cf. *manifestus* Leschik 1955, *E. tenuis* Leschik 1955, *Camerosporites secatus* Leschik 1955, *Succinctisporites excentricus* Leschik 1955, *S. radiatus* Leschik 1955, *Alisporites* cf. *grauvogeli* Klaus 1960, *A. parvus* de Jersey 1962, *A. toralis* (Leschik) Clarke 1965, "*Pityosporites*" cf. *illustris* Leschik 1955, *?Sulcatisporites interpositus* Leschik 1955, *Ellipsovelatisporites plicatus* Klaus 1960, *Cuneatisporites radialis* Leschik 1955, *Klausipollenites devolvens* (Leschik) Clarke 1965, *Brachysaccus* cf. *microsaccus* (Couper) Madler 1964, *Ovalipollis breviformis* Krutzsch 1955, *O. ovalis* Krutzsch 1955, *Cycadopites accerrimus* (Leschik) Clarke 1965, *C. subgranulosus* (Couper) Clarke 1965, *Monocolpopollenites levis* Leschik 1955 and *Labiipollis granulatus* Madler 1965. Many of the species in this assemblage were described from Carnian deposits in the eastern Alps (Klaus 1960) and from the late Carnian Schilfsandstein near Basel (Leschik 1955). The presence of *Camerosporites secatus,* known only in mid- and late Carnian deposits, is of particular significance.

The second sample, from 7.7 m higher than that described above, yielded an assemblage containing some bisaccate miospores (of presumed Triassic age) but dominated by Carboniferous miospores considered by Dr. B. Owens to have been derived from two sources ; one of upper Visean-lower Namurian age and the other of upper Namurian-lower Westphalian age.

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The third sample, from 13.6 m above the first, yielded some bisaccate miospores of presumed Triassic age and a varied assemblage of Carboniferous species which could have been largely derived from lower Namurian deposits. A small number of acritarchs of Lower Palaeozoic aspect were also present, however, and suggest that some material from a Lower Palaeozoic source was also present in the sample material.

A prominent sandstone member, briefly noted by Woodward and Ussher (1906), occurs in the Upper Marls at the eastern end of Higher Dunscombe Cliff and is traceable in the cliffs further to the east. The unit is about 10 m thick and consists of whitish sandstones and grey mudstones and siltstones. Henson and the writer have obtained from this unit two varieties of ichnofossils, one of which is common in the Arden Sandstone of the Central Midlands, and large specimens of *Euestheria minuta* (von Zieten) Raymond 1946 which are comparable with those known from the Arden Sandstone in Worcestershire and Warwickshire. The petrographical, sedimentological and macropalaeontological characters of the unit observed on the Devon coast indicate that it is the same facies as the Arden Sandstone. The miospores obtained from the Devon coast unit (below) compare closely with those known from the Arden Sandstone in Worcestershire (Clarke 1965, Warrington 1970) and support the possibility that these two significant sandstone members may be time equivalents. Continuity of the facies from Worcestershire to Devon has not yet been demonstrated, though a similar member is present in the higher part of the Keuper Marl near Taunton and in the Mendip area. The sandstone member was sampled at 7 horizons 0.4 km east of Weston Mouth (SY16908800) ; 0.5 m above its base organic remains, including ?*Ovalipollis sp.* were obtained ; at 0.75m above the base further remains including ?*Ovalipollis sp.* and *Microcachryidites sp.* were obtained while 2.1 m above the base an assemblage of Carboniferous miospores derived from Namurian deposits was obtained.

At 4.8 m above the base of the sandstone member a sample yielded the following Triassic miospore species :

Calamospora nathorstii, Punctatisporites digestus Leschik 1955, *Osmundacidites alpinus, Duplicisporites granulatus, D. verrucosus,* ?*Partitisporites novimundanus* Leschik 1955, *Camerosporites*

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secatus, Enzonalasporites vigens Leschik 1955, *Patinasporites* cf. *densus* Leschik 1955, ?*Succinctisporites radiatus, Alisporites parvus, A, toralis, Klausipollenites devolvens, Ellipsovelatisporites plicatus, Labiisporites granulatus* Leschik 1955, *Sulcatisporites interpositus, Cuneatisporites radialis, Ovalipollis breviformis, O. ovalis, Brachysaccus neomundanus* (Leschik) Madler 1964, cf. *Mesostriatites hercynicus* Madler 1964, ?*Taeniaesporites kraeuseli* Leschik 1955 and *Cycadopites subgranulosus.* A possible specimen of the microplanktonic organism *Dictyotidium* was also recorded in this assemblage which bears more resemblance to those described from the late Carnian Schilfsandstein than does that from 46.8 m lower in the Upper Marls sequence at Higher Dunscombe Cliff. The age of the assemblage is regarded as late Carnian while that from the lower horizon must be slightly older but, because *Carnerosporites secatus* is present, not older than mid-Carnian.

Four samples from the red Upper Marls above the sandstone member were barren as were two from about 11.0 and 21.0 m below the Westbury Beds in alternating red and green mudstones in the higher part of the Upper Marls 1.5 km east of Seaton.

Six samples from the Grey Marls member at the top of the Upper Marls 2.4 km east of Seaton yielded two assemblages. The lower, 8.75 m below the Westbury Beds, included the following species ; *?Enzonalasporites vigens, Corollina meyeriana, Classo-pollis torosus* (Reissinger) Balme 1957, cf. *Granuloperculatipollis rudis* Venkatachala and Góczán 1964, *Ovalipollis breviforinis, Alisporites parvus* and remains of foraminifera, the latter indicating a connection with a marine environment during the deposition of the Grey Marls.

The second assemblage, from 3.5 m below the Westbury Beds, contained the following miospore species :
Calamospora ?nathorstii, Uvaesporites argenteaeformis (Bolk-hovitina) Schulz 1967, *Corollina meyeriana, Classopollis torosus, Granuloperculatipollis rudis, Ovalipollis breviformis, O. ovalis* and *Rhaetipollis germanicus* Schulz 1967.

The occurrence of *Classopollis torosus* in both the assemblages is suggestive of a Rhaetian age, the base of the range of C. *torosus* usually being considered to be at the base of the Rhaetian. This convention is followed here, the base of the Rhaetian being

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regarded as more than 8.75 m below the Westbury Beds. In the absence of data from the type Rhaetian, however, revision of this position may be necessary in the future. The presence of *Rhaetipollis germanicus* in the higher assemblage is clear evidence of a Rhaetian age (Schulz 1967).

3. **Summary of dating evidence**

The palynological evidence outlined above has proved disappointing in that only derived miospores have been recovered from the New Red Sandstone sequence below the Upper (Keuper) Marls which are proved to be of Carnian to early Rhaetian age. The reptile remains from the Otter Sandstone fortunately provide evidence for a possible Anisian age in the upper part of the palynologically barren unit below the Upper Marls. The age and relationships of the formations below the Otter Sandstone must, in the absence of indigenous miospores and other dateable fossils, remain a matter for further investigation.

4. Correlation of the south Devonshire and Midlands sequences

The available palynological evidence does not permit an unequivocal time-correlation of the whole of the south Devon coast New Red Sandstone sequence with that of the Midlands.

The Upper Marls correlate, probably almost exactly, with the Keuper Marl and the prominent sandstone member in this unit on the Devon coast is probably correlatable with the Arden Sandstone. The correlative of the Grey Marls in the Midlands sequence is unknown, miospores not yet having been found in the deposits between the Arden Sandstone and Westbury Beds in that area.

The Otter Sandstone is correlatable, on the vertebrate evidence, with the higher part of the Keuper Building Stones or basal Waterstones in the Midlands.

The position of the Budleigh Salterton Pebble Beds, though regarded as being within the Trias, is uncertain as also are the ages and correlatives of the underlying formations in the New Red Sandstone sequence of south Devon. There is no palaeontological evidence for the existence of any Permian deposits or,

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if such exist, for the definition of the Permian-Triassic boundary in south Devon. Thus, the question of the age and correlation of the formations in the lower part of the New Red Sandstone sequence of south Devon must remain a matter for further investigation.

ACKNOWLEDGEMENTS. The writer gratefully acknowledges assistance by M. R. Henson in the collection of samples and in making field observations. Dr. B. Owens kindly determined the derived miospore assemblages and reported on their probable source. A fuller account of this work is in preparation.

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MICROPALAEONTOLOGICAL EVIDENCE OF MID CENOMANIAN FLEXURING IN SOUTH WEST ENGLAND

by M. B. Hart

Abstract. As a part of a total foraminiferal study of the Albian and Cenomanian sediments of southern England the species **Orbitolina concave** (Lamark) has been studied in detail. This species has been shown to be of Lower Cenomanian age - a fact that would appear to have important implications on the understanding of Cretaceous stratigraphy in S.W. England.

1. Introduction

The Upper Greensand successions of Devon have long provided Cretaceous stratigraphers with a major problem of correlation. The Gault Clay, Upper Greensand, and Lower Chalk sequences of the south-east of England cannot at present be precisely correlated with the Foxmould, Chert Beds and limestones of the Devon coast with any certainty. The macrofaunal evidence has not been adequate until recently and even at the present time some of the conclusions from this field conflict with some of the microfaunal evidence. Until the present, the microfauna has not been studied in any detail, beyond the occasional reference to the occurrence of *Orbitolina concava* (Lamark). No attempt has been made at using this species as a stratigraphic indicator, and while one should always avoid using a single species as a guide in any work, some comments can be forwarded as to its usefulness.

2. Occurrence of O.concava

The various references to this species provide little guide as to its overall occurrence and it is only when all the relevant successions are compared that any pattern can be determined. The localities to be considered include Wilmington, Dunscombe, Wolborough, Babcombe (Devon), as well as Antrim (N. Ireland) and most important of all Ballon (Sarthe) in western France.

The Wilmington (White Hart Sandpit SY208999) sequence has long been famous for the wealth of the fauna from the grizzle in the upper part of the Cenomanian sands. The base of

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these sands, in this quarry, has not been seen until recently (1968) when a trial pit was sunk at the foot of the working face of the quarry. This exposed the basal pebble beds of the sands resting on a prominent erosion surface below which were 40 cm of glauconitic sands containing calcareous concretions. These sands rest on a complex bed of rounded sandstone cobbles that is bounded above and below by thin glauconitic marl horizons. The lower of these two marls overlies a massive bed of laminated sandstone which contains occasional cherts in the lower levels. It is this lower laminated sandstone that contains the specimens of *O.concava*.

Jukes-Browne (1900: 208) records specimens from the yellowish sands of Weston Cliff, although none have been found at this locality during the course of this present research. In the British Museum (Natural History) are specimens (B.M.(N.H.) No. P43429) from the quarry at the top of the cliff south of Dunscombe Farm, between Seaton and Sidmouth. These are recorded as occurring in the sands just below the Cenomanian Limestones, and were studied by Hofker (1963) as a part of his major work on the genus *Orbiolina* D'Orbigny 1850.

The locality at Wolborough (85506995) has recently been rediscovered by R. A. Edwards (pers. comm.) and this is perhaps the most important occurrence of this species in Devon. This small patch of greensand, 400 m south of Wolborough Church, displays shelly glauconitic sands as well as coarse grained sandy limestones. The lithology is remarkably similar to that of the type Lower Cenomanian of Ballon (Sarthe) and *O.concava* occurs in similar numbers at both localities.

In the area immediately to the north of the Bovey Basin poorly preserved specimens of *O.concava* have been recorded from Babcombe Copse (SX869766), 360 m from Babcombe Farm (SX86757699). Here they occur with other macrofossils in the chert blocks that have been assigned to the higher levels of the local succession. These blocks now lie in the overlying gravels, although rare specimens of *O.concava* have been found in the pale banded cherts that form the upper levels of the *in situ* succession.

The occurrence of *O.concava* in the Hibernian Greensands of Northern Ireland has been known for almost one hundred years. Hume (1897: 550) records this species from the lower levels of the

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Upper Glauconitic Sands of the Colin Glen section, beds that were equated by him with the *Schloenbachia varians* zone of the Lower Chalk in England. Hancock (1961) records Cenomanian brachiopods from this part of the sequence and apparently accepts a Cenomanian dating for the specimens of *O.concava* found by Hume. *Orbitolina* cf. *concava* is also recorded from the same lithological sequence in Woodburn Glen by Hancock (1961: 19). These are the only occurrences within the British Isles where there has been conclusive macrofaunal evidence of an age ; the suggested level being Lower Cenomanian. At this point, before a discussion of the stratigraphic implications, it is necessary to consider the results of recent studies of the genus *Orbitolina.*

3. Morphology of O.concava

Hofker (1963) has produced a most comprehensive study of this genus and his work is much quoted. His results however have been used with caution as many of the explanations forwarded in his account cannot be verified at the present time. This work concluded that the genus appears to be represented by one species only - *O.lenticularis* (Blumenbach). This basic unit has been separated into ‘form groups’ based on the characters of the megalospheric embryonic apparatus. The microspheric form (which is usually larger in overall dimensions) begins with a streptospiral coil whereas the megalospheric form displays an embryonic apparatus consisting of a proloculus, a deuteroconch, and a varying number of epi-embryonic chambers. This embryonic apparatus is apparently the only consistent feature on which the age of a specimen can be predicted. The details of 'Form Group IV' (Hofker 1963: 225, Fig. 20) are shown in Figure L This group is typified by the form commonly regarded as *O.concava* from the type locality of Ballon, in the Sarthe region of France. A collection of specimens from this locality are shown by Hofker (*op. cit*., Fig. 24, and pl. XVII, Figs. 15-18) and included with these is an illustration of a one of the Dunscombe specimens (pl. XVII, Fig. 14). On the basis of the author's own study and on the indications of Hofker it would seem that these specimens of *O.concava* can be used as an indication of a Lower Cenomanian age. This is in full agreement with the work of Rioult and Juignet (1965) who record *O.concava* from northern France and south-west England from sediments regarded as belonging to the *Mantelliceras mantelli* (J. Sowerby) zone of the Lower Cenomanian.

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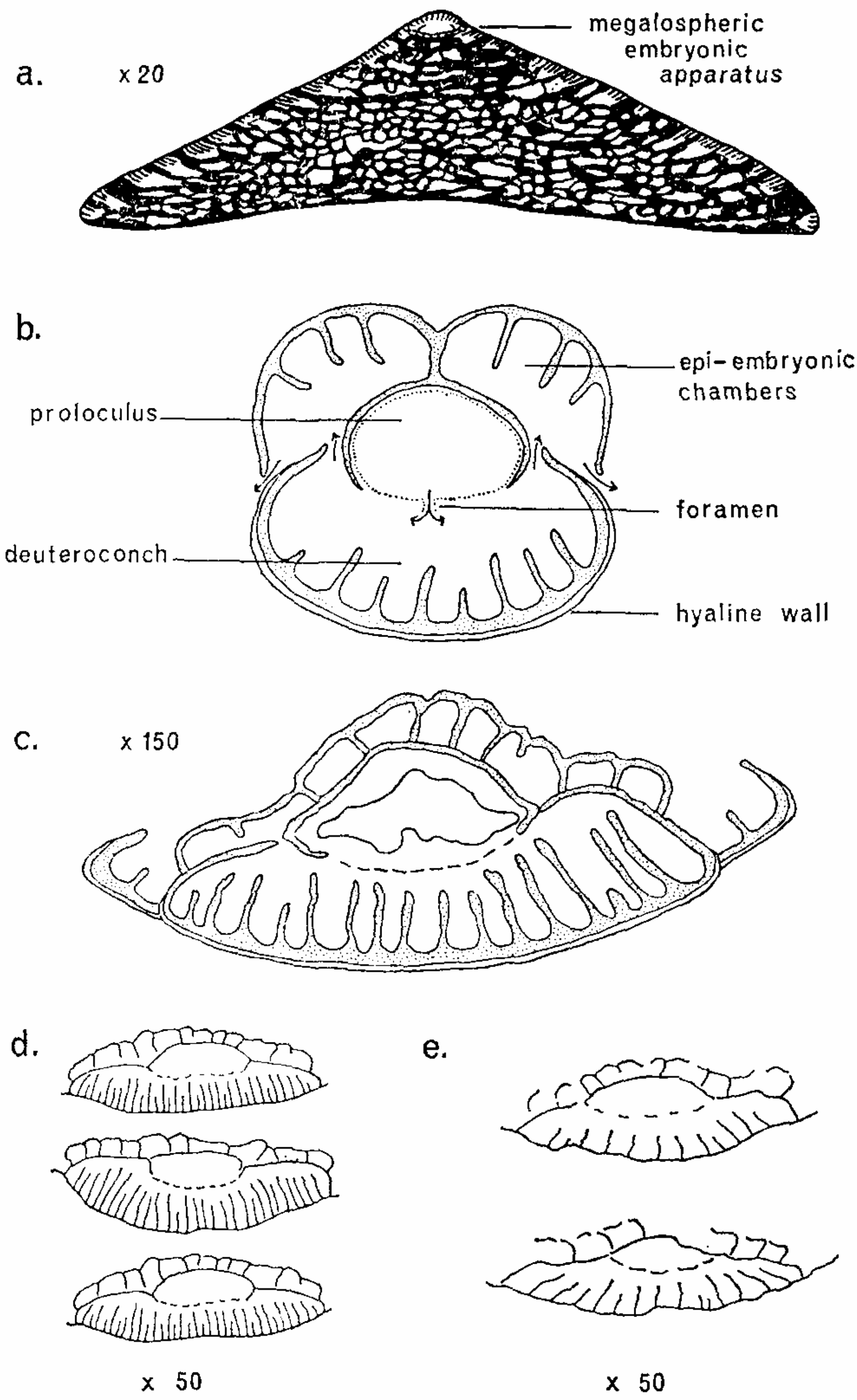

Fig. 1 Morphology of Orbitolina lenticularis.

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4. Relationship to Ammonite successions

The ammonites of the type Cenomanian of the Sarthe region have been discussed in some detail by Hancock (1959), and the following lists have been abstracted from this work. The fauna of the ‘Marries à Orbitolites de Ballon' are cited as containing *Schloenbachia subvarians* Spath, *S.* aff. *subtuberculata* (Sharpe) and *Mantelliceras hyatti* Spath, while the closely related ‘Craie glauconieuse à Pecten asper' contain a rich fauna which includes *Mariella* cf. *cenomanensis* (Schluter) and *Mantelliceras couloni* (D'Orbigny). On the basis of these faunal lists and on the work of Kennedy (1970 and 1969) it would seem that the *O.concava* fauna in France occurs at a level which includes the *saxbii* assemblage zone of Kennedy. The boundary between the *saxbii* assemblage zone and the overlying *dixonii* assemblage zone appears (on the evidence from Compton Bay, Culver Cliff and Folkstone) to correlate with the microfaunal boundary between zones 9 and 10 (see Carter and Hart in the discussion of Kennedy (1969) and Hart (1970). **In** the south-west of England non-phosphatised ammonites of this age have been found in the Eggardon Grit by Kennedy - the fauna including *Mantelliceras couloni* (D'Orbigny), *Mariella cf. cenomanensis* (Sehluter) and *Hypoturrilites gravesianus* (D'Orbigny).

FIGURE 1. Morphology of *Orbitolina lenticularis* (Blumenbach)

a. general appearance of *O.lenticularis* in axial section (x20).

b. diagrammatic representation of the megalospheric embryonic apparatus, after Hofker (1963).

c. axial section of the megalospheric embryonic apparatus of Form Group IV - typified by the species *O.concava* - after Hofker (1963) (x150).

d. axial sections of specimens of *O.concava* from the type locality of the Lower Cenomanian, Ballon, France (x50).

e. axial sections of two specimens from the Wolborough greensands (x.50).

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Kennedy (1970, fig. 19) indicates that the Eggardon Grit is only a 'local' development of the Cenomanian Upper Greensand even though it can be traced with a uniform fauna over the greater part of west Dorset and south-east Devon.

The *O.concava* faunas of Dunscombe and Wilmington (White Hart Sandpit) would appear to fall into this lithological unit and on the basis of the rest of the microfauna (as well as the ammonite evidence) it should best be regarded as being of zone 9 age. On the basis of the ammonite zonations of Hancock (1959) and Kennedy (1969) the top of microfaunal zone 10 is approximately at the level of the Lower/Middle Cenomanian boundary and all the faunal evidence would appear to agree with this correlation.

In the Haldon Hills (R. A. Edwards and R. J. O. Hamblin pers. comm.) ammonites have been found in the chert blocks that overlie the main greensand and greensand with chert successions. Some of these ammonites appear to indicate the Lower Cenomanian part of the succession and would therefore agree with the present determinations of the *Orbitolina* faunas. The dating of the Chert Beds of the Devon coast as Lower Cenomanian would appear to conflict with the published accounts of these sediments though little can be said on this subject at the present time. There are however a few other lines of evidence on this matter, although none of these can be relied upon for a direct proof of a precise dating. The microfauna of the underlying Foxmould shows an association very close to that of the Albian/Cenomanian boundary as recorded in the Isle of Wight. Recent work at Bullers Hill Quarry (SX882848) has recorded the presence of planktonic foraminiferida associated with the pale grey banded cherts seen at this locality. These forms, although belonging to a long ranging species, would appear to be forms very close to those from the Lower Cenomanian, and provide very useful secondary evidence of the age of the sands.

5. Structural implications

As indicated by Carter (p.552) and Hart (p.553) in the discussion of Kennedy (1969) there is now a foraminiferal zonation scheme for the Albian / Cenomanian / Turonian interval which has been tested over the whole of southern England. This, together

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with a correlation scheme based on the ratio between planktonic and benthonic individuals in any sample, has shown that in the mid-Cenomanian there is a sudden change in the foraminiferal population from a fauna that is largely benthonic to a one that contains a very high percentage of planktonic individuals. This palaeontologically defined non-sequence is in fact a period of folding or warping that is the main cause for the remarkable variations in thickness recorded from the Lower Chalk. Traced from Dover westwards one passes into a trough or downwarp of the micropalaeontological zones in the region of Eastbourne that can also be picked out by a sympathetic increase in the thickness of the *plenus* marls at this locality. This variation in the thickness of the *plenus* marls was plotted as an isopachyte map by Jefferies (1963) in his account of this subzone. This isopachyte map can be used to indicate the trends of these structures and in so doing one of the most striking is seen to be the Mid-Dorset Swell (Kennedy 1970, Drummond 1970), which is best seen in the area of central Dorset. At Buckland Newton, which is almost on the crest of the swell, Upper Cenomanian chalk rests directly on Upper Greensand of reported Albian age. This difference in age across the non-sequence gives some idea of the magnitude of the structure and detailed microfaunal work both in central Dorset and on the Purbeck coast demonstrates the cutting out of the Lower Cenomanian zones beneath the non-sequence.

In S.E. Devon the Cenomanian Limestones are seen to occur above this same non-sequence, indicating that this series of thin sandy limestones would be better regarded, on microfauna evidence, as being of Upper Cenomanian age. This dating is based not only on the benthonic microfauna of the zonal scheme (which might be considered suspect in such a marginal environment) but also on the occurrence of the distinctive planktonic species *Rotalipora cushmani* (Morrow) and *R.greenhornensis* (Morrow). These two species, in association with each other are recorded from the Upper Cenomanian of Belgium (Moorkens 1969), S.E. France (Porthault 1969), Texas (Pessagno 1967), California (Douglas 1969) and Colorado (Eicher 1969 ; Eicher and Worstell 1970). They also occur in such large numbers in the Cenomanian limestones and sands as to indicate that these deposits occur above the mid-Cenomanian non-sequence.

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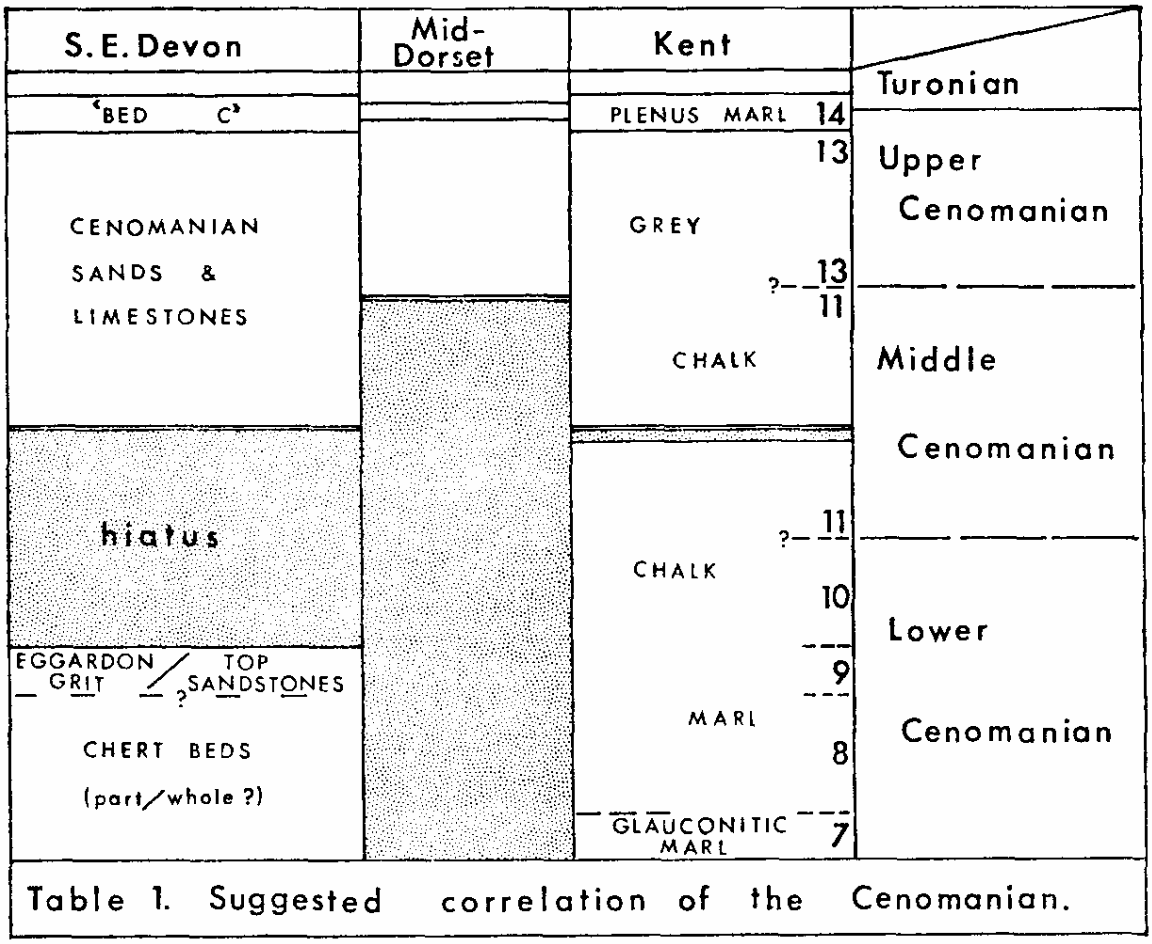

TABLE 1. Suggested correlation of the Cenomanian of southern England - with the non-sequence indicated. The small figures refer to the outline microfaunal zonation.

It is in this area of S.W. England that there are already accounts of intra-Cretaceous folding. Smith (1957, etc.) has described in detail the folds of the Upper Greensand that affect the deposition of the Cenomanian limestones. On the basis of the macrofaunal evidence at the time of this work these structures were ascribed to the Albian / Cenomanian boundary. However the evidence from the microfaunas - particularly the occurrence of Lower Cenomanian *O.concava* in the Top Sandstones below the level of folding - would place this episode of movement within the Middle Cenomanian. Table 1 attempts to show in a general way the position of the Top Sandstones in relation to the succession in the south-east of England. If the folding on the Devon coast must (on microfaunal and macrofaunal evidence) be of Middle Cenomanian age, then all the evidence leads to the

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conclusion that it equates with the mid-Cenomanian non-sequence as this is the only level at which appreciable movements have been recorded.

The other period of intra-Cretaceous folding was recorded on geophysical evidence by Durrance and Hamblin (1969) in the Haldon Hills. Although these workers had very little faunal evidence for the dating of these structures their general form was sufficient for them to suggest that they related to those recorded on the Devon coast. The dating of the *O.concava* cherts as Lower Cenomanian in no way detracts from a correlation with the folding below the Cenomanian limestones, and in many ways produces strong faunal proof that this is in fact the case.

6. Summary

The dating of the *Orbitolina concava* faunas of Devonshire as Lower Cenomanian and their subsequent equation with the ammonite faunas of the same level would seem to indicate that the intra-Cretaceous folding recorded from Devonshire is of Middle Cenomanian age ; on the basis of the microfaunas, it would seem likely that these structures correlate with the mid-Cenomanian non-sequence of the south-east of England.

ACKNOWLEDGEMENTS. The author wishes to thank D. J. Carter for his guidance and encouragement in the writing of this paper, and also the encoragement of P. Juignet of Caen who is at present working on the faunas of the type Cenomanian. The work was carried out during the tenure of a N.E.R.C. Research Studentship from 1966-69. Many workers have helped in this work both in discussion and in the collection of samples and the author wishes to acknowledge these (Mr. W. L. Diver, Dr. E. M. Durrance, Dr. R. A. Edwards, Dr. R. J. O. Hamblin, Dr. J. M. Hancock, Dr. R. P. S. Jefferies, Dr. W. J. Kennedy, Dr. H. G. Owen, Dr. E. B. Selwood, Mr. C. J. Wood.) at the present time.

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Mineralisation in the North Molten Area (Abstract) :

by Susan M. Akehurst, J. Rottenbury and R. F. Youell.

A substantial lode of barytes has been found running east-west just North of Bentwitchen. A fault has produced two parallel lodes in a manner which may also account for the layout of the copper and iron ore lodes further south.

Additional workings at Crowbarn and Stowford not recorded in the Geological Survey records have been mapped on the iron and manganese ore lodes, and a mine shaft much older than the 19th century Bampfylde copper workings excavated and correlated with the other workings.

The crystallography of the ironstones of Exmoor indicates that the assumption generally made that hematite, limonite and goethite are the normal ironstones may be only partly valid. A red ferric silicate has been confirmed in a small number of specimens.

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CASSITERITE IN THE ALLER GRAVELS NEAR NEWTON ABBOT

by R. C. Scrivener and K. E. Beer

Abstract. Grain-size and distribution analyses of cassiterite in the Aller Gravels indicate the practicality of cheap and simple beneficiation and the possible viability of tin by-production from sand and gravel operations. Similarities in lithology and heavy mineral content suggest a correlation between at least part of the Aller Gravels and the superficial deposits of the Bovey basin.

Detrital cassiterite was formerly worked on a large scale in south-west England and it seems likely that unconsolidated sediments in the Bovey basin were prospected by the tin-streamers. Apparently they were too low-grade to encourage extensive working. Recent work by Mr. J. H. W-Wilson has demonstrated the common presence of cassiterite in the superficial sands and gravels (personal communication) and a project to evaluate the economic potential of these deposits has recently begun. At the low grades so far indicated the cassiterite content could only be profitably recovered as a by-product from other commercial operations and, hence, it seemed logical to investigate also the distribution and tenor of cassiterite in any other deposit currently worked for sand and gravel. Preliminary separation showed that cassiterite was virtually absent in Greensand from Babcombe Copse (SX869766) and attention was focused upon the more promising Aller Gravels.

These beds are limited to the eastern and southern margins of the Tertiary Bovey Formation, below which they are believed to dip, forming a local basal horizon (Edwards 1970). In their northernmost outcrops the gravels are some ten metres thick, increasing southwards to attain their maximum development, about 38 m, to the east of Newton Abbot where they are worked in two pits. Bulk samples were collected from three localities: the north-west corner of Sands Copse (SX866759), a small road-side pit at the south ends of Sands Copse (SX871752), and the working face of Royal Aller Vale Quarry (SX877693). At the latter locality smaller samples were taken from differing lithologies and from some production stock-piles.

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After close screening, the sized fractions, or splits from them, were separated in bromoform and the heavy mineral crop was analysed for tin on an Ekco Mineral Analyser. Because of the special mineralogy of the "heavies" comparative standards were prepared from cassiterite and tourmaline.

Cassiterite was found to occur at all three localities in small but significant amounts. Almost all of this was present in grain sizes between 25 and 150 mesh B.S.S., with only minor amounts in finer sizes and virtually none in coarser sizes. Associated heavy minerals comprise large quantities of tourmaline, together with lesser chlorite, zircon and topaz, a little iron oxide, ilmenite, garnet, epidote and rutile. Only rarely does cassiterite occur in composite grains and usually it is free from any ferruginous patina. Most of the grains are sub-rounded, with only zircon and occasional rutile retaining original crystalline forms.

TABLE 1. Analyses of Bulk Samples

	Sands Copse (NW)	Sands Copse (S)	Royal Aller Vale
Gravel + 8 mesh	60%	76%	46%
Fines – 240 mesh	2.5%	3%	3.5%
Sand – 8 + 240 mesh	37.5%	21%	50.5%
Cassiterite in sand fraction (lb/cu.yd)	1.4	1.1	0.6
% sand of 25-150 mesh size	39%	32%	40%
Cassiterite in 25-150 sized sand (lb/cu.yd)	3.8	3.4	1.5

From the abbreviated analysis data in Table I it can be seen that selective screening at 25 and 150 mesh accomplishes a notable upgrading of cassiterite content, yielding a sized fraction readily amenable to wet gravity separation. Furthermore, the composition of the heavy mineral crops indicates that a high-grade cassiterite concentrate should be obtainable. Examination of the products from Royal Aller Quarry confirms that virtually no cassiterite is retained in the gravel fraction or lost in the discarded fine fraction ; it is confined to the sand product. This suggests, therefore, that by-production of tin could be achieved with the minimum of modification to current working methods. The washed (partially deslimed) sand fraction, which is derived from

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rotary screening at about 3/ 16 inch aperture, could be selectively size-classified to provide a 25-150 mesh feed from which cassiterite could be recovered by jigs and sand tables. Thereafter, by combination of the 25 mesh oversize, 150 mesh undersize and the jig and table rejects the currently saleable sand product could be reconstituted.

The viability of tin by-production rests largely upon total throughput, which in turn is dependent upon the bulk mineral demand and upon quarrying limitations. At current metal prices, the value of potentially recoverable tin at Royal Aller Vale Quarry amounts only to some £9,000 per 100,000 tons annual throughput and, after allowance for operational and financial overheads, such a return offers a low profitability compared with bulk mineral production. Nonetheless it is to be deprecated that an easily separable and valuable metalliferous ore should be sold, even in small quantity, as a building sand.

Examination of various lithologies from Royal Aller Vale Quarry shows the cassiterite to be preferentially contained within ill-sorted coarser bands ; better sorted sand or silt layers contain little tin and there is a similar deficiency in the coarse, highly ferruginous bands. Selective treatment of the coarser horizons is impractical, however, due to the highly lensoid nature of the sediments. The abundance of very coarse material in these horizons indicates conditions of rapid flow in which the heavy cassiterite grains were retained by the riffling effect of large pebbles, whilst very fine cassiterite continued in transport downstream. An almost complete absence of 150 mesh cassiterite in the coarse sediments is explicable, therefore, but a similar absence from better sorted finer sands and silts is enigmatic unless it is assumed that at times of more moderate stream flow the cassiteritebearing source rocks were not being actively eroded and transported. Such a conclusion would imply that the source of the cassiterite lay at considerable distance - well inside the granite rather than within the aureole rocks enclosing the northern part of the Bovey basin.

Arenaceous horizons of the Bovey Formation which have ben examined by hand-panning or laboratory separation have yielded only traces of cassiterite contained in heavy minerals crops consisting essentially of tourmaline and mica with zircon.

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These sediments, composed largely of granite-derived material, are interpreted by Edwards as outwash and flood plain deposits associated with gently graded, probably braided, streams. Under such hydraulic conditions any concentrations of cassiterite will be confined to the stream channels.

The Sands Copse gravels differ somewhat markedly from those of Royal Aller Vale Quarry. Not only do they contain appreciably more coarse detritus (Table 1) but, significantly, they lack the conspicuous lensoid stratification so typical of quarry sections in the Aller Valley. These heterogeneous gravels closely resemble, in lithology and in heavy mineral content and distribution, Neogene flood gravels seen in the " headings " of the ballclay pits with which it is suggested they should be correlated. Stratigraphical reclassification of the Sands Copse gravels does not, of course, preclude the possibility that they may be underlain by true Aller Gravels. The direct commercial effect of such reinterpretation is a more severe limitation to the depth of the Sands Copse gravels ; there is probably little reflection in terms of overall cassiterite grade.

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HEDENBERGITE AND SPHALERITE FROM THE PERRAN IRON LODE, CORNWALL

by S. Henley

1. Introduction

The Perran Iron Lode is a southerly-dipping breccia belt extending several km south-east from the northern end of Perran Bay. It varies in width from 1 m to more than 30 m and contains mainly brecciated slates, locally cemented by siderite, quartz, and sulphides ; oxidation of siderite to hematite has occurred to depths of 60 m in places.

Much information, compiled from previously published work, is given by Dines (1956), who suggests a tentative geological

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history based on this work, and lists the minerals reported from the lode. Among these minerals is hedenbergite, from Great Retallack Mine, about 3 km inland. Although its habit has been well described (Collins 1874: Reid and Scrivenor 1906) there is no description in the literature of its age and mode of occurrence. In the Geological Museum, London, there are only poor, weathered specimens, collected prior to 1906. During dump removal in 1968 and 1969, an opportunity arose to collect fresh material and a number of samples of massive black sphalerite veined by hedenbergite were obtained.

2. Mode of Occurrence

The hedenbergite is very coarse-grained, and of radiating to columnar habit, forming veins in sphalerite and slate which vary in thickness from 10 mm to more than 60 mm. Long axes of the crystals are generally perpendicular to the vein walls.

No samples have been found in which the black sphalerite is younger than hedenbergite. Sphalerite is found not only in Great Retallack Mine, but also, as brecciated fragments free from hedenbergite, and cemented by siderite, in Duchy Peru Mine to the east. Translucent red sphalerite is also to be found in the Duchy Peru Mine, associated closely with the siderite and quartz. The grain size of the massive black sphalerite is usually less than 1 mm except where recrystallisation has occurred around the hedenbergite veins, and it locally shows apparently folded streaks of pyrite and chalcopyrite. There is little or no associated quartz, or any other "spar" mineral.

3. Geological History

Evidence for age relationships in the Perran lode given by Henley (1970) conflicts with that assumed by Dines (1956), and is briefly summarised below.

In an exposure above the cliff quarry at Gravelhill Mine (at the northern end of Perran Bay), a north-north-west trending vertical vein of banded quartz cuts a wide zone of brecciated and comminuted slate, and is itself cut by a 1.5 m band of hematite and rotting siderite, with sinistral displacement of a few metres. The displacement occurred, at least in part, after

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deposition of the iron ores, as they are themselves strongly sheared. This exposure therefore established an approximate relative date of the so-called "north-south" veins, one of whose principal characteristics is the presence of banded quartz.

Thin sections of sphalerite-bearing samples from Great Retallack Mine show replacive hedenbergite in a sphalerite matrix, both veined by serpentine, and quartz and siderite post dating all three minerals. Fine-grained black sphalerite is abundant also at Duchy Peru Mine, where it is present as fragments, intermixed with slate fragments in a siderite-cemented breccia. Specimens of the siderite and quartz show complex relationships and indicate several phases of brecciation and crystallisation. Minor sulphide mineralisation involving pyrite, galena, and the translucent red sphalerite is associated with the later phases, and is probably partly contemporaneous with formation of the north-south veins, in which a similar assemblage occurs. The geological history is summarised in Table 1, in which the ideas of Dines (1956) are presented for comparison.

TABLE 1. Sequence of events in the Perran Iron Lode.

According to Dines (1956)	According to Henley (1970)
1. Formation of brecciated belt ; deposition of quartz and blende in the more open parts.	1. Initiation of faulting ; introduction of the massive black sphalerite (? as a faulted block).
	2. Metasomatism of basic rocks ; formation of hedenbergite and garnet veins. Probably a very early post-magmatic date.
2. Formation of N-S lodes and deposition of galena in these and the Perran Lode. 3. Re-opening of the Perran Lode and infilling with siderite.	3. Brecciation ; deposition of banded quartz and siderite in a number of phases separated by periods of brecciation. Formation of N-S lodes or mineralised cross-courses towards the end of this stage, followed by further brecciation and deposition of massive siderite.
4. Further brecciation and cavern formation ; filling by clay and broken sulphides and siderite.	4. Extensive replacement of siderite and sulphides by quartz (evidence not presented in this paper).
5. Oxidation in the upper parts of the lode.	5. Brecciation and cavern formation ; filling by clay, broken sulphides and siderite.
	6. Oxidation.

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4. Chemistry

New chemical analyses of hedenbergite, sphalerite, and massive white siderite are given in Table 2: in addition to this data, there are some trace element data for the siderite - 3200 ppm S, 530 ppm Zn, 355 ppm Ba, 30 ppm As, 30 ppm Sn, and 8 ppm Pb, with copper and strontium not detected by the X-ray fluorescence method used.

TABLE 2. Analyses of minerals from the Perran Iron Lode. Analyses 2 and 3 by X-ray fluorescence, analysis 1 by rapid wet methods.

	1	2		3
SiO_2	46.68		Zn	52.5
Al_2O_3	2.76	1.26	Fe	10.5
TiO_2	0.01	n.d.	S	33.5
FeO*	24.95	36.94	Cu	0.2
MgO	1.67	5.11	Mn	0.3
CaO	19.48	0.77	Pb	<0.2
Na_2O	0.26	n.d.	Cd	<0.2
K_2O	0.12	n.d.	Si	0.2
MnO	2.87	5.91		
P_2O_5	0.02	0.66		
CO_2		35.29		

* Total iron calculated as FeO.

1. Bottle-green hedenbergite from a vein in massive black sphalerite.
2. Massive white siderite fissure filling from Duchy Peru Mine.
3. Massive black sphalerite :(1) and (3) from Great Retallack Mine.

5. Discussion

The hedenbergite was probably formed by metasomatic alteration of basic igneous rocks which cut the Perran lode (Reid and Scrivenor 1906: 25), as there is very little lime in any of the other minerals in the lode - though minor amounts of ankerite are reported (Dines 1956: 443) - or in the surrounding sedimentary rocks: a median value of 0.22% CaO was calculated from 96 samples from within 5 km of the Perran Lode (Henley 1970: table 8.1).

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Garnet is also reported from the Perran Iron Lode (Collins 1874), and a specimen in the I.G.S. collections, labelled "Mount 7-346 ", comprises an aggregate of yellow dodecahedral garnets up to 5 mm in diameter, cemented by hematite. A closely similar specimen, M.R. 1891, is a garnet rock from a vein in a basic body at St. Piran's Chapel, about 1 km to the south of the lode ; intimately associated with this garnet, according to Reid and Scrivenor, are epidote and axinite, the latter suggesting a very early postmagmatic date for the alteration, by analogy with similarly metasomatised rocks around the Land's End, St. Austell, and Dartmoor granites. The apparent absence of axinite from the immediate vicinity of the Perran Lode may perhaps be attributed to progressive loss of boron from the metasomatising fluid (?vapour) as it travelled farther from the granite.

The massive black sphalerite not only pre-dates of hedenbergite, but it may also have formed before brecciation of the lode, since no specimens are known to the writer in which slate fragments are cemented by sphalerite of this type. Its mode of occurrence was described by Smyth (1887), and it is perhaps worthwhile to include his complete description.

"At the 40, 50, and 60 fathom levels, fragments of zinc blende form a valuable element in the breccia ; pieces of all sizes, from the bigness of a nut to masses of several hundredweight, and even above a ton, lie enveloped in a soft bedding ,.." ".., the blende itself is peculiar for a mineral vein : the greater part of the lumps are dark brown massive granular zince sulphide, mingled with disseminated iron pyrite, but without any of the quartz or spars or other substances that usually accompany it; and the question naturally arises, Whence did these fragments come? That question is now, up to a certain point, answered by the workings opened through the 'Swansea' whim shaft down to the stopes above the 30 fathom level. Here, resting against crystalline quartz which belongs to the north or footwall, is the blende in a solid state, more or less jointed, but for some ten feet in width, and for many fathoms in length, comparatively unbroken. Hence it is that the fragments we had met with in the deeper levels must have fallen away ".

Thus one can see that all of the sphalerite fragments now seen in the breccia were probably derived from the large body described by Smyth.

It is possible that movement on the Perran Iron Lode was initiated before intrusion of the granites, perhaps at the same time as the Lizard, Dodman, and Start boundary faults – the

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great variation in dip of the brecciated zone (Dines reports dips of from 35° to more than 65°) suggests that it may perhaps have suffered refolding - and its vertical throw appears to be quite large : a conservative estimate based on geological mapping of the area (Henley 1970) would indicate a normal displacement of 1500 m.

The weight of evidence thus suggests that the sphalerite mass was formed before large-scale movement on the Perran Iron Lode, and therefore probably before, or maybe during, emplacement of the granite batholith. The texture of the sphalerite - fine-grained, with apparently folded streaks of iron and copper sulphides - together with its lack of associated silicates, indicates some similarity with stratiform sulphide deposits, such as described by Baumann (1970). It is suggested that this sphalerite is in fact pre-granite in age, and forms part of a stratiform deposit. Its occurrence in a hydrothermally mineralised fissure would thus be fortuitous.

From the small sample of the upfaulted mass which is available for examination, it seems that exploration in depth might well prove an extensive deposit of high-grade zinc ore ; structural considerations (Henley : in preparation) suggest a steeply dipping body below the footwall of the lode.

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Geochemistry of the Permian igneous rocks of Devon (Abstract) :

by M. E. Cosgrove

Twenty-six samples, representing localities still exposed during the late 1960's, have been analysed. Eight major constituents, SiO_2, TiO_2, $A1_2O$„ Total Fe as Fe_2O„ MgO, CaO, Na_2O, K_2O were determined by X-Ray Spectrometry as were 15 trace elements Ni, Cu, Zn, Ga, As, Br, Rb, Sr, Y, Zr, Nb, Mo, Pb, Th, and U. Carbon dioxide and water were determined by conventional methods, making a total of 25 variables for the 26 samples.

After computing the analyses on a carbonate-free basis, the data was first processed by R-mode factor analysis which showed the largest contribution to the variance being mady by Ni, Rb, Y, Zr, Nb, Th, U associated with TiO_2, MgO, and K_2O ; a hybrid assemblage of acid and basic associated elements. Q-mode factor analysis, where attention is focused on the samples as opposed to the variables, was then applied to produce 2 factors which together account for 87% of the variance. A plot of factor 1 against factor 2 shows a very satisfactory classification of the rocks with olivine basalts and potash-rich minettes as "end members". Syenitic lamprophyres are separated out near the basalts, whereas the yogoitic syenites, Killerton and Hannaborough minettes form distinct intermediate groups. The leucite-bearing rocks are grouped near the Washfield and Rose Ash minettes which form the potash-rich end of the classification.

TEMPERATURE DISTRIBUTION IN THE LAND'S END GRANITE AUREOLE, CORNWALL

by P. A. Floyd

Abstract. Using (i) experimentally derived equilibria, plus a knowledge of the first appearance of an assemblage, and (ii) a simple conduction model, two geothermal gradients have been obtained for the Land's End aureole during contact metamorphism. The similarity between the two gradients obtained may be accounted for if the heat absorbed by dehydration reactions (involving pelites) has been counterbalanced by exothermic hydration reactions (involving amphibolization of basic rocks).

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1. Introduction

The object of this study is an attempt to delimit the temperature environment of the various meta-sedimentary and meta-magmatic hornfels assemblages developed in the aureole using experimentally determined P-T equilibrium data. The results will be at best only an approximation as equilibrium studies commonly represent simple systems with starting materials significantly different chemically from the bulk composition of natural rocks.

From the estimates obtained and a knowledge of where the assemblages were first developed relative to the contact. a generalised curve can be drawn to show the temperature distribution throughout the aureole progressively further and further away from the granite. This curve can then be compared with thermal models of the contact environment as suggested by Jaeger (1957, 1959).

As the aureole hornfelses are confined to the albite-epidote-hornfels facies and the hornblende-hornfels facies some indication of the temperature regime under which the assemblages developed can be obtained. However, there is considerable variation in the suggested lower and upper limits of these facies as exemplified by the work of Winkler (1967) and Turner (1968), viz :

Temperature (°C) at beginning of facies (1 kbar P_{H_2O})

Albite-epidote-hornfels	Hornblende-hornfels	Pyroxene-hornfels	References
below 400	535	645	Turner 1968: 258
about 355	410	600	Winkler 1967: 79

The major difference is in the assumed temperature range of the hornblende-hornfels facies, where a large section of Turner's hornblende-hornfels facies is in Winkler's albite-epidote-hornfels facies! A number of reversible experimental reactions that have produced typical hornblende-hornfels facies assemblages from minerals that characterize the albite-epidote-hornfels facies have now been determined for different bulk compositions and suggest the lower boundary of the former facies is in the region of 520-550° at 2 Bars P_{H_2O} (Winkler 1967: 72).

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2. **Hornfelsic assemblages**

The dominant assemblages developed in the aureole are listed in Table 1. Some of the higher-grade pelitic hornfelses are Si-poor and contain corundum and spinel. Likewise some basic and magnesian assemblages contain spinel (pleonaste) and diaspore. Small amounts of epidote-garnet ± calcite and cummingtonite-anthophyllite ± cordierite occur in the more Ca-rich and Mg-rich members of the hornblende-bearing basic hornfelses respectively. These assemblages are transitional to the calcareous and magnesian hornfelses of metasomatic origin.

TABLE 1. Dominant prograde hornfelsic assemblages developed in the Land's End aureole, Cornwall.

ALBITE-EPIDOTE-HORNFELS FACIES		HORNBLENDE-HORNFELS FACIES	
		Pelitic and semipelitic	
P1	Qu-ser-chl	P7	Qu-plag-biot-cord
P2	Qu-ser-biot	P6	Qu-biot-cord
P3	Qu-chl-and		
P4	Qu-biot		
P5	Qu-biot-and		
		Basic (± biotite)	
B1	Ilm-plag-act	B3	Ilm-plag-hbe
B2	Augite-ilm-plag-act	B4	Ilm-sph-plag-hbe
		B5	Ilm-sph-plag-diop-hbe
		Magnesian (± biotite)	
		M1	Ilm--cumm
		M2	Ilm-plag-cumm
		M3	Ilm-plag-cord-anth
		M4	Ilm-cord-anth
		Calcareous	
		C1	Sph-diop-gross

Note : Qu = quartz, ser = sericite, chl = chlorite, biot = biotite, and = andalusite, cord = cordierite, plag = plagioclase, ilm = ilmenite, act = actinolite, hbe = hornblende, sph = sphene, diop = diopside, cumm = cummingtonite, anth = anthophyllite, gross = grossularite

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3. Pressure environment

To estimate the load pressure (P_1) which existed in the aureole during contact metamorphism, it is necessary to know the thickness of the crust above the granite at the time of intrusion.

The Land's End granite cuts Lower Devonian Mylor Series sediments, while the Dartmoor granite, at the other end of the S.W. batholith intrudes rocks ranging from Upper Devonian to Namurian Culm Measures (Dearman and Butcher 1959). Unfortunately, there is no direct evidence for the possible deposition of Carboniferous sediments in the Land's End peninsula area. Wills (1952) indicates that land emerged during this period in western Cornwall to form the embryonic Armorican mountain chain, although Ramsbottom (1970), on the basic of faunal provinces, suggests that the sea covered all south-west England and northern France until the Upper Carboniferous. Devonian rocks occur in the English Channel and immediately south and west of the Land's End peninsula (Whittard 1962), although the presence of Carboniferous rocks is unproven. A combination of seismic (Hill and King 1954) and magnetic (Allan 1961) data indicate the presence of a thick (2 km) sequence of undifferentiated Palaeozoic rocks to the south of Eddystone, thrust faulted against proven Devonian that extends northwards from Eddystone to the south coast.

In general, the S.W. batholith as a whole was probably emplaced in Devonian (and older) rocks, whereas the Land's End pluton may have been covered by sediments ranging in age from the Lower Devonian to at least the upper portion of the Lower Carboniferous. Any estimate of the thickness of these rocks is complicated by pre-intrusion deformation that produced piles of recumbent folds in the Devonian strata of south-west Cornwall (Dearman 1969).

Based on a tentative estimate of a thickness of about 3-4 km. (Freshney : personal communication) and an average density of 2.8 gm/cm^3 for the regionally metamorphosed sediments, the load pressure in the aureole rocks above the granite may have been in the region of 1 kbar or less. A study of the fluid inclusions in quartz and fluorite vein materials in south-west granitic rocks also suggests a load pressure at the time of crystallization of about 1 kbar (Bradshaw and Stoyel 1968).

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A maximum lithostatic pressure can be obtained from experimentally-derived metamorphic equilibrium assemblages. Data on the aluminium silicate polymorphs (Richardson *et al.* 1969) places the triple point at 622°C and 5.5 kbars P_{H2O}. As only andalusite is observed in the aureole, pressures must have been considerably lower than 5 kbars as only a very narrow temperature range would be available for hornblende-hornfels facies andalusite-bearing rocks at this pressure. The upper limit of the hornblende-hornfels facies (Winkler 1967) cuts the minimum melting curve for the granite-water system (Luth *et al.* 1964) just below 3 kbars and as there is no evidence of country rock anatexis, pressures were probably below this value. Also, it is considered rare for low pressure contact facies developed adjacent to high-level plutons (such as the Land's End granite) to exceed 2-3 kbars (Turner 1968 fig. 36-5).

4. Temperature environment

Throughout the following discussion all temperatures quoted for experimental equilibrium reactions refer to 1 kbar, unless otherwise stated.

(a) Pelitic assemblages

Andalusite can appear in low-grade contact assemblages via the following reaction :

pyrophyllite = andalusite + quartz + H_2O (1)

A temperature of about 500°C obtained by some workers (Carr 1963 ; Althaus 1966) for this reaction is considered too high in view of the paucity of pyrophyllite in low-grade pelitic hornfelses and the common occurrence of andalusite. More recent investigations suggest an equilibrium temperature of about 410°C (Kerrick 1968). Assemblages containing chlorite, as well as andalusite-quartz (assemblage P3, table 1) are probably stable from about 410°C up to 460°C where they breakdown with the formation of cordierite (Seifert and Schreyer 1970) :

chlorite + andalusite + quartz = cordierite + H_2O (2)

The appearance of cordierite is often taken to indicate the beginning of the hornblende hornfels facies, although reaction 2 takes place about 70°C below the facies boundary. However,

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assemblages containing cordierite and little else are relatively rare and in K-bearing pelitic rocks biotite is commonly associated with cordierite. Biotite can develop early in the albite-epidote-hornfels facies, although its association with cordierite typifies the hornblende-hornfels facies. Two experimentally determined reactions have produced cordierite-biotite assemblages from low-grade musmovite-bearing pelites :

muscovite + chlorite + quartz = cordierite + phlogopite + H_2O (3)

muscovite + chlorite + quartz = cordierite + biotite + andalusite + H_2O (4)

Reaction 3 (Seifert 1970) takes place at 490°C and reaction 4 (Hirschberg and Winkler 1968) at 510°C. Differences in the temperature of the reactions and the high-temperature products developed are governed by variations in the composition of the starting materials - in particular the Mg/Fe ratio and aluminium content nature of the chlorite. Assemblages P6 and P7 (table 1) were probably stable from about 500°C to the top of the hornblende-hornfels facies where K-felspar coexists stably with cordierite. At this temperature, assemblages such as P2 (muscovite present rather than sericite) also breakdown to produce phases typical of the pyroxene-hornfels facies :

muscovite + biotite + quartz = cordierite + K-felspar + H_2O (5)

As no K-felspar has been observed in these rocks this represents the upper stability limit of the Land's End aureole pelites. Reaction 5 (Winkler 1967) takes place over a range of temperature (590-615°C) depending on the bulk Mg / Fe ratio of the rock.

On retrogression, cordierite-bearing assemblages commonly develop pinite (chlorite-sericite aggregate) that may partly pseudomorph the cordierite porphyroblasts. As only a narrow temperature range of some 20-30°C is indicated for the stable coexistence of cordierite and chlorite-sericite, Seifert and Schreyer (1970) consider that direct breakdown is unlikely and that andalusite forms as an intermediate phase before being subsequently sericitized.

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(b) Basic and magnesia assemblages

The replacement of the lower grade actinolite-albite assemblage by hornblende-andesine is considered to represent the beginning of the hornblende-hornfels facies (535°C, Winkler 1967), although on field associations with other rock assemblages, Loomis (1966) considered that actinolite-hornfelses were replaced by hornblende-hornfelses at about 450°C. Hornblende alone is stable to very high temperatures, eventually being completely replaced by two pyroxene assemblages at 755°C (Choudhuri and Winkler 1967). However, above the upper limit of the hornblende-hornfels facies at 600°C, hornblende can coexist with orthopyroxene. For assemblages B3 and B4 (Table 1) the maximum possible temperature was probably near 600°C, as orthopyroxene has not been recorded in these aureole rocks. Engel and Engel (1962) deduced the temperature of appearance of clinopyroxene in the amphibolites of the north-west Adirondack mountains as 550°C (for 3 kbars P_{H2O}). Thus, diopside-bearing assemblages, such as B5, probably developed at slightly higher temperatures than the common plagioclase-hornblende-hornfelses, although like these rocks they are stable only up to about 600°C.

Of interest is the development of the orthoamphiboles, anthophyllite and gedrite in the magnesian hornfels suite. The former is commonly found in association with cordierite and more rarely with hornblende, while the latter has been found with almandine-cordierite (Tilley 1935). Two experimental reactions are pertinent here :

chlorite + talc + tremolite + quartz =
anthophyllite + hornblende + H_2O (6)
chlorite + quartz = gedrite + cordierite + H_2O (7)

Reaction 6 (Choudhuri and Winkler 1967) and reaction 7 (Akella and Winkler 1966) occur at approximately the same temperature: 540-550°C. Cordierite and talc, produced from Al-chlorite (clinochlore) and quartz are also stable in this temperature interval (Fawcett and Yoder, 1966). The hornblende and anthophyllite assemblage is stable until 715°C (Choudhuri and Winkler 1967) when orthopyroxene is produced. Cordierite is stable over a wide temperature range and coexists with

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orthopyroxene at high temperature (Yoder 1952). Greenwood (1963) demonstrated that Mg-anthophyllite is only stable over a narrow temperature range from about 700-750°C, although it can form at lower temperatures (665°C) from talc and forsterite :

$$\text{talc} + \text{forsterite} = \text{Mg-anthophyllite} + H_2O \qquad (8)$$

The above reactions indicate that the anthophyllite-cordierite assemblage (M3 + M4, table 1) is probably developed at about 550°C and is stable up to 715°C (with hornblende) or 750°C (without hornblende).

Si-poor rocks in the magnesian suite contain spinel-diaspore-clinochlore, considered by Tilley (1935) to represent non-equilibrium assemblages. This is borne out by experimental data which indicates that spinel and diaspore can only coexist stably in a narrow temperature range of 400-430°C (Yoder 1952) or 365-405°C (Roy *et al.* 1953). These temperatures are typical of the lower portion of the albite-epidote-hornfels facies, whereas anthophyllite-cordierite assemblages typify the hornblende-hornfels facies. Clinochlore breaks down at 680°C (Fawcett and Yoder 1966) to forsterite-spinel-cordierite and places an upper limit on the clinochlore-bearing anthophyllite-cordierite assemblages. The stability range of the Si-poor magnesian hornfelses is about 550-680°C and suggests that diaspore is metastable (corundum is the stable aluminium oxide above about 375°C, Kennedy 1959) or a retrogressive phase after corundum. The first suggestion is favoured as mineralogical relationships suggest that it probably formed at the same time as the clinochlore and no corundum is evident in these rocks.

Depending on the composition, cummingtonite can develop at about 550°C (or lower with high Mg content) and can stably coexist with anthophyllite from about 525-700°C (Schurmann 1968).

The close association of cummingtonite-anthophyllite, cummingtonite-hornblende and anthophyllite-homblende assemblages in different hornfelses indicates similar temperatures of formation which is supported by the experimental data.

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(c) Calcareous assemblages

One of the problems of calc-silicate equilibria is that such assemblages are often developed from impure calcareous rocks that also contained hydrous phases, such that both CO_2 and H_2O are liberated on reaction. The total fluid pressure will be composed of variable proportions of CO_2 and H_2O, that is $P_f = P_{H2O} + P_{CO2}$. Depending on the mole fraction of CO_2 present in the fluid phase, the equilibrium temperature for some reactions is variable and generally increases as the $CO_2/CO_2 + H_2O$ ratio increases. As the early calc-silicate assemblages in the aureole were largely developed from hydrous phases, the mole fraction of CO_2 in the fluid phase (X_{CO2}) was very low, although the presence of late calcite in poorly hydrated calc-silicate assemblages indicates a notable increase. Unfortunately, the majority of calc-silicate equilibria are not strictly pertinent to the Land's End aureole calcareous rocks as they were derived from basic assemblages rather than carbonate rocks, so only limited conclusions can be drawn.

The commonest calc-silicate assemblage seen is grossularite-diopside (Cl, table 1), although Ca-plagioclase does coexist with both minerals. Depending on X_{CO2} , diopside appears between 400-550°C (Metz & Winkler 1964) via the following reaction:

tremolite + quartz + calcite = diopside + CO_2 + H_2O (9)

Temperatures are more likely to be relatively high as diopside-bearing calcareous assemblages are closely associated with diopside-bearing basic assemblages, which probably developed at about 550°C. Grossularite has been synthesized using zoisite as starting material:

zoisite + quartz = grossularite + quartz + H_2O (10)

zoisite = grossularite + anorthite + corundum (11)

Reaction 10 takes place at about 455°C (Newton 1966) and reaction 11 at 535°C (Boettcher 1970). As the parent hornfelses of the calcareous suite are generally free of quartz, coexisting grossularite-Ca-plagioclase assemblages probably developed at the higher temperature and would be stable with diopside over a range of temperature. Grossularite-anorthite are stable up to the breakdown temperature of grossularite at 850°C (Newton 1966).

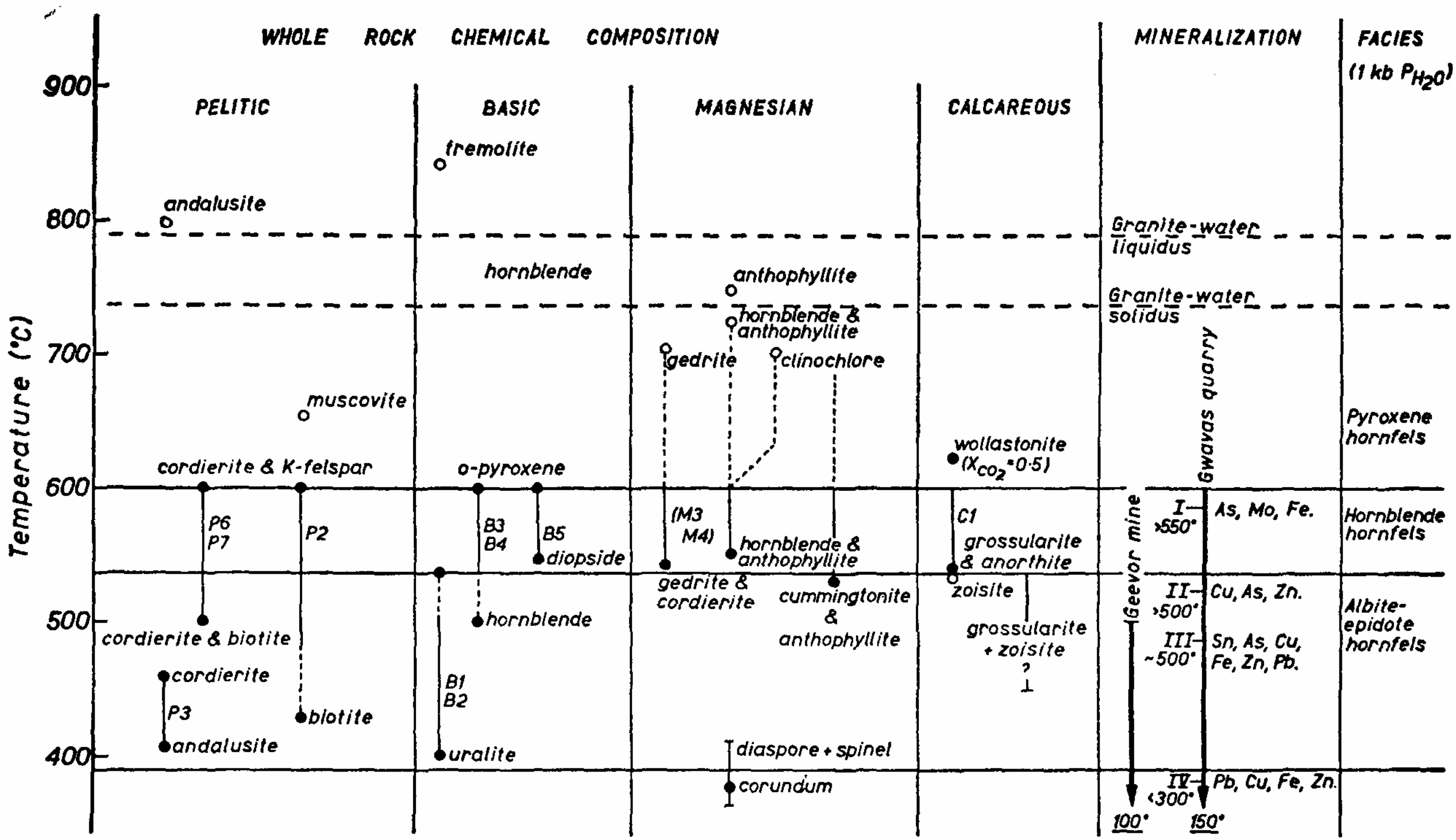

FIGURE 1. Possible stability ranges for hornfelsic assemblages of variable composition (listed in Table 1) based on experimental data at 1 kbar pressure. Temperature range for ore mineralization is shown for comparison at two localities in the Land's End aureole.

The initial appearance (dots) and subsequent disappearance (circles) of an individual mineral or mineral assemblage is also indicated.

Although wollastonite can form by the following reaction (Harker and Tuttle 1955, 1956; Greenwood 1962) :

calcite + quartz = wollastonite + CO_2 (12)

over a wide temperature range from 420°C (X_{CO2} = 0) to 670° (X_{CO2} = 1), its absence in the aureole suggests the lack of quartz in the presence of late calcite, rather than the required temperature conditions. Also any available quartz would have reacted with early grossularite to form wollastonite at about 560°C (Newton 1966) before reaction 12, viz:

grossularite + quartz = wollastonite + anorthite (13)

The apparent association of prograde zoisite with grossularite ± Ca-plagioclase is very rare in the calcareous hornfelses and must represent temperatures between 455-535°C (between reactions 10 and 11) or nearer the later temperature if grossularite is only stable in the hornblende hornfels facies and no quartz is present. On the other hand, the retrogressive replacement of grossularite by epidote and clinozoisite is relatively common and represents temperatures below 535°C. Similarly, prograde clinozoisite-zoisite-calcite assemblages (no grossularite) represent slightly lower temperatures than the dominantly grossularite-bearing assemblages. In general, the prograde epidote (s.l.) and grossularite-bearing assemblages probably developed around 525-550°C. although at higher temperatures only grossularite assemblages would be stable.

Figure 1 summaries the experimental data relevant to the formation of the aureole hornfelses. The metasomatic magnesian and calcareous suites apparently developed early in the hornblende-hornfels facies at approximately the same temperature as their parental basic hornfelses. This observation is substantiated by the close association of all these assemblages in the field. Although some of the cummingtonite and anthophyllite-bearing assemblages can be stable in the pyroxene-hornfels facies, the existence of this facies in the Land's End aureole is excluded by the non-appearance of orthopyroxene in the basic hornfelses and cordierite-K-felspar in the pelites.

The temperature range of ore mineralization for Geevor mine (Garnett 1962) and Gwavas quarry (Siddiqui 1964) is also included for comparison.

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5. Temperature distribution in the aureole

In order to estimate the geothermal gradient present in the aureole at the time of granite emplacement, two separate methods were used. It is assumed that the contact is nearly vertical and the distance from the granite at which an assemblage first appears could be measured directly off a geological map and reflects the temperature conditions operating at this distance.

(a) Method 1

From the experimental data discussed above, the approximate temperature at which any assemblage becomes stable can be gauged (see Fig. 1). From the field evidence, it is possible to find the approximate distance from the granite contact at which any assemblage first appears or is generally found. Combining both these sets of data a temperature-distance graph can be drawn which represents the temperature distribution within the aureole (Fig. 2). From the Geological Survey map (sheets 351 and 358), the maximum topographical width of the aureole is marked for Porth Kidney Sands (1.3 km wide) and the Penzance area (2.5 km wide). Although the spotted siltstones seen at Lelant Down indicate an aureole width of 1.5 km (Fig. 2), the actual aureole limit is generally unknown due to poor exposure. The presence of occasional spots in the pelitic members of the predominantly psammitic rock sequence exposed at Black Cliff to the east of the Hayle river, may, in fact, indicate the outermost limit.

(b) Method 2

In general, the temperature at any distance from the contact will depend on the size of the intrusion, crystallization temperature, latent heat of crystallization and also on the thermal conductivity, density, initial temperature and water content of the country rocks. Ideally, any model should also take account of the outward diffusion of water and endothermic dehydration reactions occurring in the metamorphosed rocks. In this particular case heat absorbed by dehydration reactions may be counterbalanced by exothermic hydration reactions during the amphibolization of the basic rocks.

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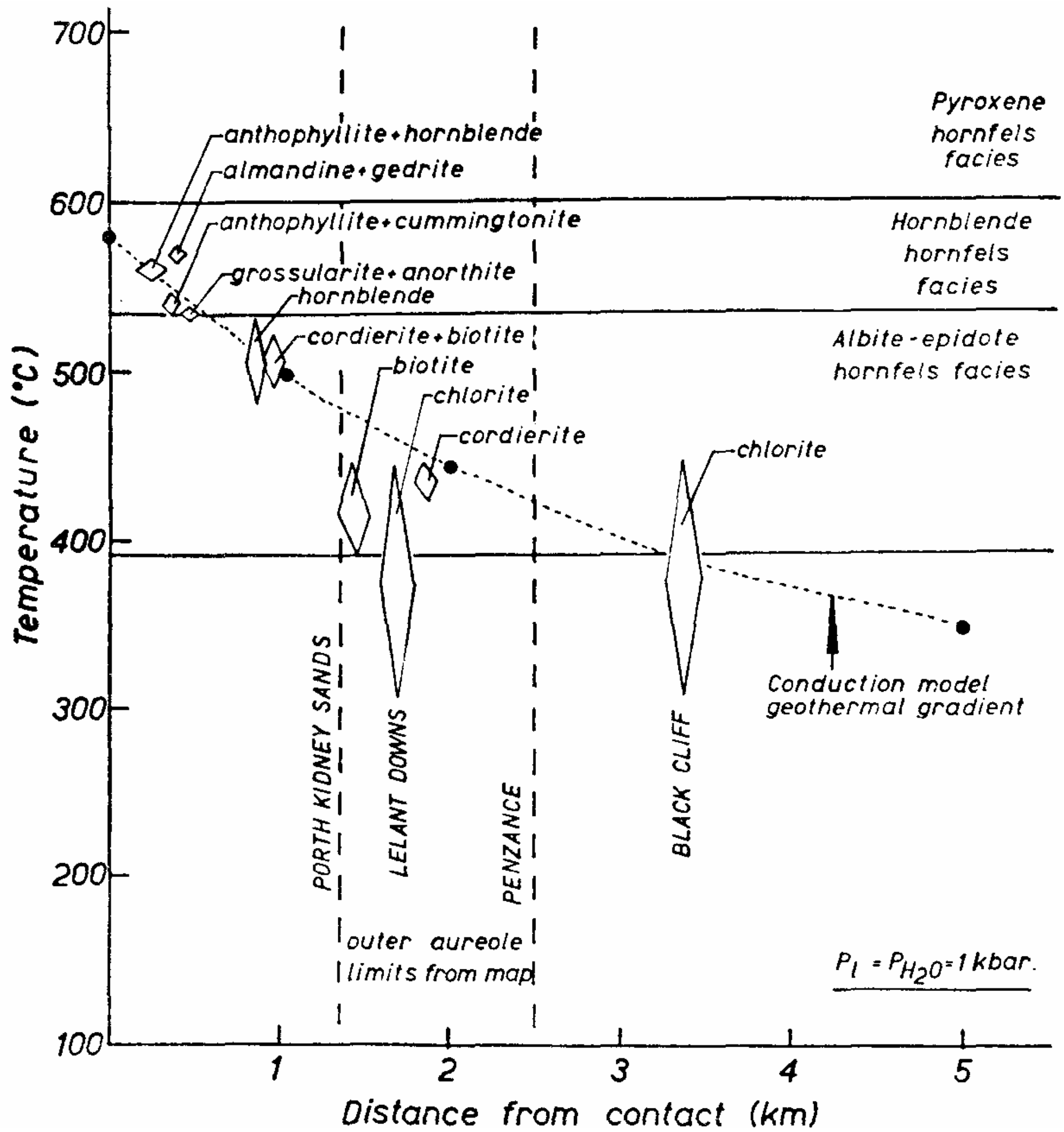

FIGURE 2. Two possible geothermal gradients in the Land's End aureole at the time of metamorphism.

Dotted line represents the temperature distribution derived from a simple conduction model. Wedges represent the initial appearance of an assemblage or mineral derived from field and experimental data. Width and height of wedges are a rough measure of the error involved.

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The approach used here is based on a simple conduction model (Jaeger 1957, 1959) for the dissipation of heat from a crystallizing magma into essentially dry country rocks. The factors used in the calculations are as follows :

1. Granite emplaced at 3-4 km. depth (equivalent to 1 kbar P_{H2O}) has a liquidus temperature of 790°C and a solidus temperature of 735°C (Luth *et al.* 1964). If the granite was entirely liquid on emplacement, the initial crystallization temperature would have been approximately 790°C.

2. Assuming the Land's End granite has a near vertical sheet-like form, its average thickness is about 10 km.

3. As some 70-80 m.y. separate the Upper Devonian regional metamorphic event in west Cornwall (Dearman 1969) and the subsequent intrusion of the Land's End granite at 273 m.y. (Miller and Mohr 1964), the lower greenschist facies assemblages developed would have probably cooled to normal crustal temperatures. At a depth of 3-5 km the temperature of the country rocks, derived from the continental geothermal gradient (Clark and Ringwood 1964), would be about 80°C.

In this simple model the temperature developed at various distances from the contact depend on the intrusion thickness and are decreasing percentages of the intrusion temperature plus the country rock temperature. The calculated temperatures (°C) are shown below and plotted on Figure 2.

Initial intrusion temperature	Country rock temperature	Temperature in aureole at:			
		contact	1 km	2 km	5 km
790	80	585	499	443	349

Surprisingly, the two curves developed are not dissimilar. The conduction model curve also indicates that the outer aureole limit (defined by the beginning of the albite-epidote hornfels facies) is about 3 km, which coincides with the maximum distance found for spotted pelites at Black Cliff, rather than at Lelant Down.

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The Hingston Down-Gunnislake Granite, Cornwall (Abstract) :

by G. R. Ward.

The Hingston Down-Gunnislake mass consists of two separate intrusions of contrasting rock type : a fine biotite granite and a coarse porphyritic tourmaline-bearing lithionite granite. Chemical analyses show that the Hingston Down granite resembles many Cornish granites in alkali content, whereas the Gunnislake granite contains a significantly higher Na_2O/K_2O ratio, is moderately enriched in lithium, and poor in iron and magnesium compared with the Hingston Down fine granite. Although shown on

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Geological Survey maps (1910) as one continuous outcrop, the two intrusions appear, in fact, to form separate outcrops, the granites of Hingston Down and Gunnislake being nowhere in contact at the present level of erosion.

The close similarity in composition between the elvan of Hingston Down Quarry and the Hingston Down granites described by Hall (1970) is supported by the present work, but analysis of the chilled margin shows a marked deficiency in sodium. An elvan dyke in Seccombe's Adit, Old Gunnislake Mine, resembles previously published elvan data in having a remarkably low sodium content and high potassium content compared with the associated granites, and may have been derived from normal granitic material by alkali ion-exchange as Stone (1968) concluded from study of the Praa Sands elvan.

The greenstones of S.W. England and their possible tectonic significance (Abstract) : by J. R. Hawkes.

There is no reason to dispute Dewey's and Flett's opinion that the greenstones of Cornubia are the products of intermittent spilitic volcanism in a region of gentle off-shore subsidence. However, their genesis in a period between the paroxsysmal stages of the Caledonian and Variscan Orogenies does present a debating point. Examined in the context of available global palaeomagnetic data and the plate theory of orogeny and ocean basin development, it seems that the basic magma probably originated from the level of the asthenosphere as a result of complex stresses produced between mid-Devonian and end-Carboniferous times by the convergence of the European and African lithospheric blocks. A further possibility is that the magma was introduced specifically into the Devonian and Carboniferous trough sediments of Cornubia through tectonic structures in the underlying lithosphere occasioned by the presence a little to the "south" of a defunct subduction zone dating from either the Cadomian or the Caledonian Orogeny. These views will be presented in greater detail elsewhere.

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