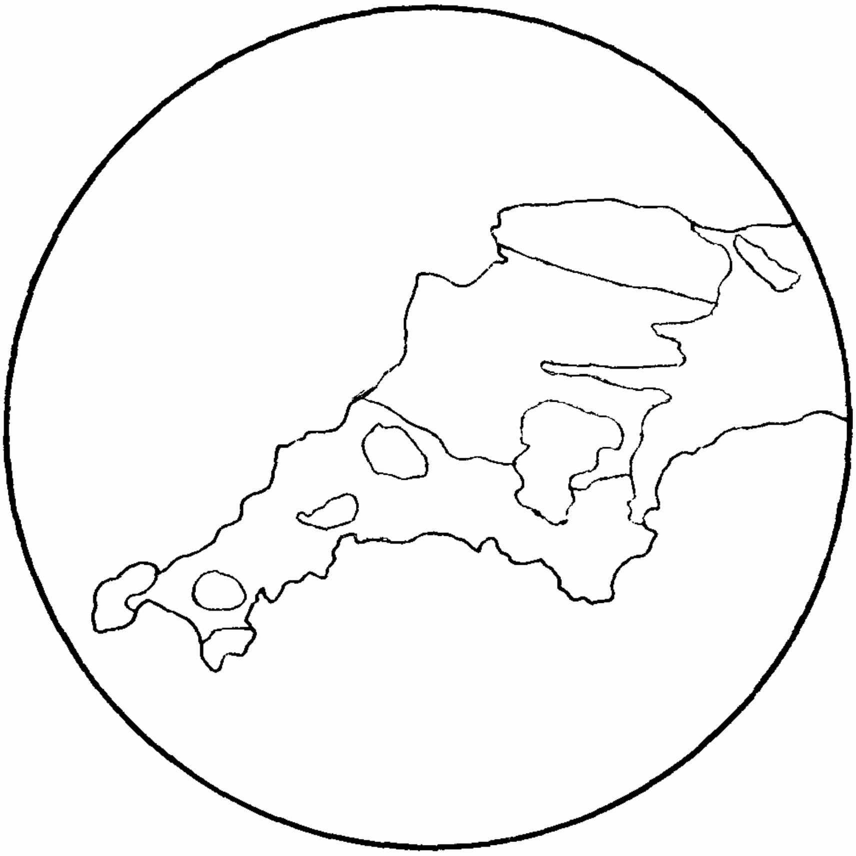
PROCEEDINGS

OF THE

USSHER SOCIETY

VOLUME FOUR

PART TWO



1978

THE USSHER SOCIETY

Membership of the Ussher Society is open to all on written application to the Secretary and payment of the annual subscription due on January 1st each year.

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USSHER SOCIETY

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Edited by
R. A. EDWARDS

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Conference of the Ussher Society held at Redruth, January 1978

Chairman's Report

Some eighty-five members and guests attended the seventeenth Conference of the Ussher Society held at Redruth on 4,5 January 1978. The accommodation in the Penventon Hotel was as spacious and commodious as at any venue of the Society. This reminded older members of the time in 1961 when the fore-runner of the Society, the *Conference of Geologists and Geomorphologists working in South-West England* met at Camborne using mixed boarding, guest house and hotel accommodation and the facilities of the old Camborne School of Mines buildings. The Society had not been in this part of Cornwall before.

On 3 January, under the guidance of Dr A.V. Bromley, twenty-nine members visited the Lizard complex, examining localities at Porthkerris (followed by lunch at the Three Tuns, St Keverne), Coverack and Kennack Sands. The conference began on 4 January with a double lecture by Mr F.W. Dunning (Curator, The Geological Museum) on 'The geological structure of the British Isles - with special reference to controversial areas'. This was a superbly illustrated, dynamic and stimulating introduction. Some thirty-two authors of twenty papers provided the rest of the programme of the conference. The Chairman gave an informal talk on 'W.A.E. Ussher-his ancestral background' after the Annual General Meeting. Following the Conference, at the invitation of the Institution of Geologists, members visited Geevor Mine on 5 January under the direction of Mr M. Mount. Great thanks are due to the leaders and speakers who helped to make the meeting so successful and especially to Dr Keith Atkinson who acted as Conference Secretary.

Now that my two years as Chairman are over, it is a great pleasure to thank Dr Malcolm Hart, Dr Mike Thomas and other members of the committee over the last two years for all they have done to make my task easy. Fortunately, most remain to give continued service to the Society. But to Dr Alf Whittaker now

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retiring as Editor, particular thanks are due; we welcome Dr R.A. Edwards as his replacement. My successor as Chairman, Colin Bristow, needs no introduction to the Society: he has shown great skill recently in organising the affairs of the Institution of Geologists and has been active in our Society for many years. I am sure the Society will flourish in the years to come.

Michael House
April 1978

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W.A.E. USSHER: HIS ANCESTRAL BACKGROUND

by Michael House

Abstract. It is shown that W.A.E. Ussher, after whom the Ussher Society is named, and who contributed much to the geological understanding of south-west England, came from a large and well-known Irish family of Usshers. The family included Archbishop James Ussher whose date for the Creation of 4004 B.C. led to the establishment of the Catastrophist School in geology. W.A.E. Ussher's ancestry is outlined back to the fifteenth century.

The very limited biographical accounts of W.A.E. Ussher, after whom the Ussher Society is named, comment on his geological work in south-west England, but give no detail of his background, and deal not at all with non-geological aspects of his career, or with his geological contributions in other areas of the British Isles. This contribution is intended to outline something of Ussher's ancestral background. Details are mainly taken from The Ussher Memoirs (by W.B. Wright, published in Dublin and London in 1889) and The Dictionary of National Biography (Oxford Univ. Press, 1903). I am indebted to Dr Joyce Bellamy for drawing my attention to the former work which is a rather thorough review of the Irish Ussher Family, and of which W.A.E. Ussher was himself a subscriber. Dr Bellamy has also helped in tracing other biographical material related to him.

The earliest clearly recorded ancestor of the Irish Usshers was Arlantor (or Arland) Ussher, Mayor of Dublin in 1469, who died in 1479. It is descendants from his second marriage, and his sons John and Christopher, which led to the diverse and distinguished family over succeeding generations. Many played an important role in Irish affairs; this is witnessed by the fact that in the period 1579-1757, 34 Usshers received the freedom of the city of Dublin. It is probable that John le Ussher, made Constable of Dublin Castle in 1302, was Arlantor's grandfather or great grandfather. A seventeenth century family tradition states that Arlantor was descended from a John Nevil (of the north of England family) who accompanied Prince John in 1185 to Ireland as Usher of the Court and adopted the surname from this office.

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Arlantor's eldest son, John, had two sons, Arland and Thomas. Arland was Mayor of Dublin in 1528. His descendants use the spelling Usher and need not concern us farther. The second son, Thomas (1496-1566) had at least eight children of which the second son was Archbishop Henry Ussher (c. 1550-1613) whose petition to Elizabeth I was largely responsible for the founding of Trinity College, Dublin (warrant dated 1592), and he was appointed its first fellow. In 1595 he became Archbishop of Armagh and Primate of all Ireland. The fourth son of Thomas Ussher was named Arland, and Arland's second son was Archbishop James Ussher.

Archbishop James Ussher (1581-1656), who has been described as Ireland's greatest scholar, entered T.C.D. in 1593 and was Vice-Provost in 1614 and 1617. He was mainly responsible for establishing the library and for obtaining *The Book of Kells* for it. His major geological contribution was an indirect and negative one. In his *Annals of the Old Testament* he attempted to date from biblical sources the time of the Creation and, in 1654, he affirmed that the Creation was at 9 a.m. on October 26th, 4004 B.C. Acceptance of this date !ed to the establishment of the Catastrophist School in geology. Since it was clear to many that geological processes required greater time than this, it was inferred that fossil faunas must represent earlier creations destroyed by a succession of catastrophes. Such theories were held by notable geologists even after the publication of Darwin's *Origin of Species* in 1859. Elevated to the bishopric of Armagh in 1625, Archbishop James Ussher is buried in Westminster Cathedral.

To trace the ancestry of W.A.E. Ussher we must now return to Arlantor Ussher's sixth child, and second surviving son, Christopher (c. 1465- ! 526) who was Bailiff of Dublin in 1511, and Mayor in 1516 and 1524. Christopher's eldest son John Ussher (c. 1525-1590) was Mayor of Dublin in 1561 and was Collector of Customs for the Port of Dublin. John Ussher is said to have been responsible for the first book ever printed in Irish--an Irish alphabet and catechism dated 1571. In 1582 he is recorded as also pressing for the establishment of a university in Ireland (in order to keep young men from "rebellion in the future and the notions imbibed at Louvain and Douay", the universities where, apparently, many then went). John married a daughter of Sir William Newman (also a mayor of Dublin). Their second surviving son was William Ussher who was knighted in 1603.

Sir William Ussher (c. 1563-1659), who signed his name Vscher, was Clerk of the Council. He married Isabella, the second

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daughter of Adam Loftus, Lord Archbishop of Dublin, Provost of T.C.D., and Lord Chancellor of Ireland. It is recorded that in his house was executed the first Irish version of the New Testament. William had eight children, and following the pattern of choosing partners carefully, the husbands of four of the daughters were knights of the realm. His second son, Adam Ussher, was Ulster King of Arms in 1632. His eldest son, Arther Ussher (c. 1588-1629) had 12 children, and several sons fought for Charles I. Arthur's eldest son William, W.A.E. Ussher's ancestor, was knighted in 1636.

Sir William Ussher Jnr. (1610-1671) was Commissioner of Excise at Dublin. He married twice, and John, the eldest son of the second marriage, continued the lineage we are following. John Ussher (1646-1732) was Master of Chancery, 1698-1721, and married a daughter of the Ulster King of Arms in 1681. Of his six sons, the fifth, Christopher (c. 1690-1763) concerns us here. The sixth son was Samuel whose grandson became Professor of Astronomy at T.C.D. and first Astronomer Royal of Ireland: £5000 to found a chair for Samuel specifically, and also to build an observatory, had been left by Francis Andrews, Provost of T.C.D.. Samuel's eldest son became Admiral Sir Thomas Ussher who conveyed Napoleon from Marseilles to Elba in 1814.

Returning to Christopher Ussher (1690-1763), he was Secretary of the Linen Board in Dublin and his country seat was Mount Ussher, Co. Wicklow. His eldest son, John, was Member of Parliament for Inistiogue (1783-90) and a grandson through his second daughter, Martha, was the Abbé Edgworth, chaplain to Louis XVI, and present at his execution. Christopher left £1000 each to his two sons, William and Christopher (born 1732, W.A.E. Ussher's ancestor), and he wrote in his will that to his two surviving daughters, Catherine and Martha "who are turned Roman Catholiques, and have quitted me and my family and all natural ties to them and their country, I leave them I s. each, with my blessing".

Christopher Ussher (1732-1772), W.A.E. Ussher's great-grandfather, entered the navy and rose to be captain by 1761. He had two sons, Christopher (born 1770) and John (born c. 1771). The latter was a Captain of Militia, settled in Canada, and married a daughter of Samuel Street, for 24 years Speaker of the Legislative Assembly of Canada. Their daughter Mary Jane (born c. 1814) was W.A.E. Ussher's mother.

Christopher Ussher (born 1770) succeeded his uncle John Ussher, M.P., in 1796 and established the Ussher family house at Eastwell, Longhrea, Co. Galway. His eldest son and heir, John (1798-185 I) married his Canadian first cousin, Mary Jane, in 1831. These were W.A.E. Ussher's parents. W.A.E. Ussher was born on 8 July, 1849, and his father died on 24 April, 1851, so Ussher would not really have known him. Eastwell passed to Ussher's elder brother, Christopher (born 1832). Ussher's mother survived until 12 December 1888, and she died at Rookfield, Cary Crescent, Torquay, where Ussher lived for a time during his geological work in south-west England. I am indebted to Patrick Ussher of T.C.D. for informing me that Eastwell has now been pulled down by the Land Commission and that Harry Ussher, the trainer, was the last male representative in Ireland of the Galway branch of the family.

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The role of pressure solution in the formation of small-scale tectonic structures in south Devon (Abstract)

by D.M. Hobson

A succession of grey, fissile mudstones, interbedded with more competent layers, occurs south of Plymouth. Small folds, mullions and tectonic ripples were initiated in these rocks at the same time. Cleavage imposition occurred later in two stages. A period of finite homogeneous strain is recorded by elliptically shaped crinoid ossicles, aligned parallel to cleavage but oblique to local fold axes. In some sandstone layers the strain is expressed as complementary sets of en echelon quartz gash arrays. The cleavage planes were formed later by pressure solution along selected surfaces; many of the crinoid ossicles are truncated against cleavage planes. Particularly intense cleavage development in some tight synclines has resulted in the amplification of the mullions and tectonic ripples. Localised pressure solution has also led to the formation of small boudins, whose axes are aligned parallel to cleavage. However, the traces of bedding planes are at about 50^{o} to the long axes of the boudins. Cleavage striping, also a result of pressure solution, has resulted in the virtual obliteration of some steep fold limbs.

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THE STRATIGRAPHY AND STRUCTURE OF BABBACOMBE CLIFF, TORQUAY, AND ITS SIGNIFICANCE

by Colin T. Scrutton

Abstract. The structure of Babbacombe Cliff, on the N side of the Torquay promontory, is interpreted as a recumbent anticline - syncline couple facing ENE to NE. The Barton Limestone forms the main part of the cliff and is dated *varcus* Zone to Lower *asymmetricus* Zone in age on conodont evidence. It is intruded by anandesitic sill, forming the local base to the succession, and overlain by the Lower Frasnian Babbacombe Slates which crop out at shore level. The slates contain keratophyric extrusives with crude pillow form. This section is the only one so far described in Torquay to show the transition from limestones to shales at the top of the carbonate complex. The structure of the cliff is briefly compared with the structural style developed elsewhere on the Torquay promontory.

1. Introduction

The structure of Babbacombe Cliff on the north side of the Torquay promontory (Fig. l), specifically the area between Withy Point (SX 93176549) and the Oddicombe Cliff Railway (SX 92506575), has never been satisfactorily explained. The bulk of the cliff is composed of limestones with dark grey and black slates cropping out beneath them at shore level and occupying a narrow strip south of the cliff railway. At the south end, Babbacombe Glen (SX 92956538) is largely eroded in shales north of the limestone plateau of Walls Hill. Igneous rocks crop out at various places associated with both the limestones and the argillaceous rocks. Ussher (1903, p. 55, fig 8) sketched the face of the upper third of the cliff opposite the junction of Babbacombe Downs Road and Portland Road (SX 92666557). His section shows a recumbent fold nose facing NE at this point and this outcrop now proves to be an important key to the structure of the whole cliff. The major difficulty to a clearer understanding of the relationships by early workers was uncertainty about the age of slates cropping out along the base of the cliff. Ussher (1903, p. 55) regarded them as occurring within the limestone sequence but Jukes-Browne (1913, p. 26) considered that there was "little doubt that the shales which underlie them (the limestones) at the north end of the cliff are really below them, and are consequently Eifelian". This view was also

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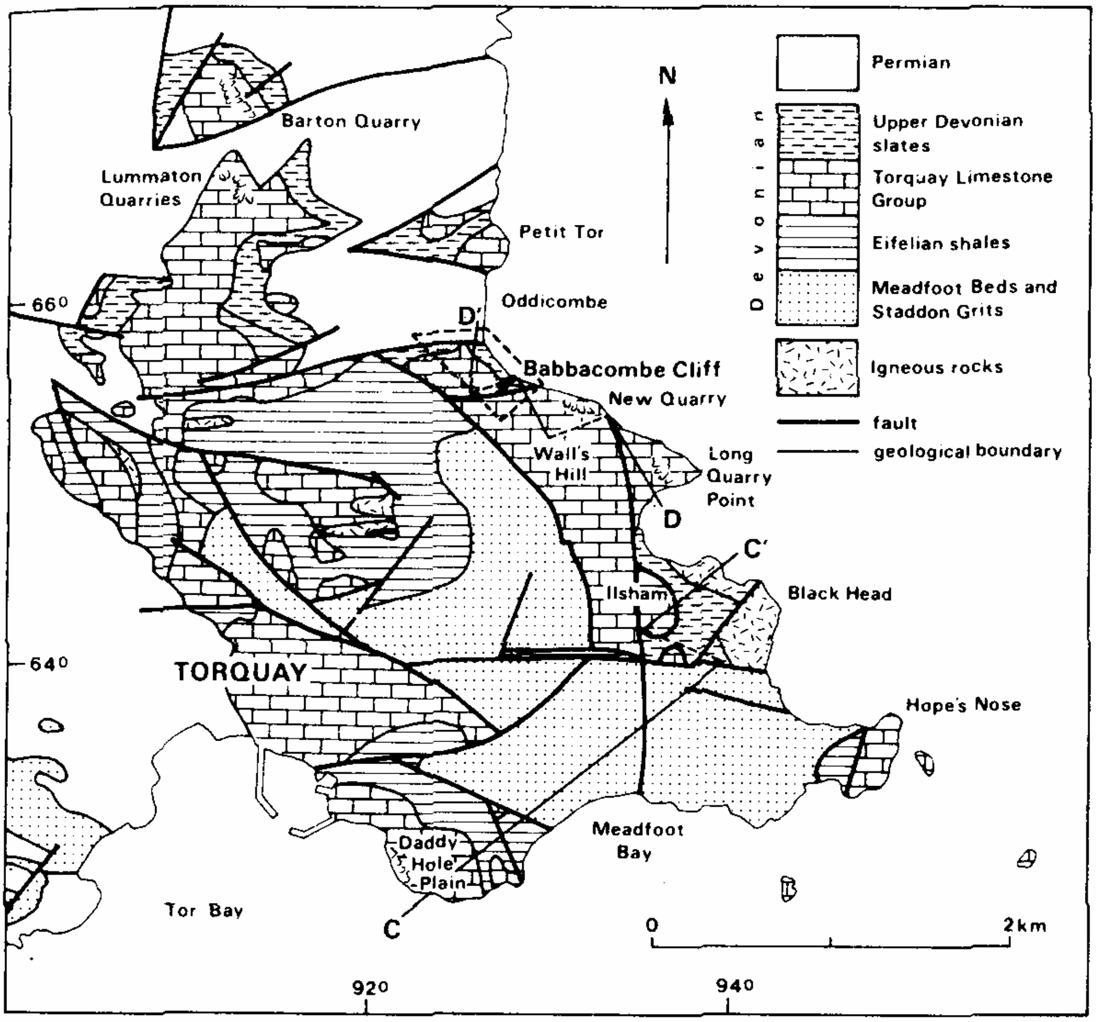

Figure 1. Geological map of Torquay based on the 1:63360 Geological Survey sheets 339 and 350 showing the location of Babbacombe Cliff and of the stepped sections C-C[1] and D-D[1].

taken by Shannon (1928, fig.12) and Lloyd (I 933, p. 47). Lloyd (1933, p. 58, 59, fig. 12) provided an updated but essentially similar view of the same part of the cliff face as Ussher (1903) whereas Shannon (1928, fig. 12) illustrated a sketch of most of the main cliff face but with no clear indication of how the complex outcrop pattern should be interpreted except as a normal succession.

An important advance was made by House (1964, p. 125) who identified a Lower Frasnian goniatite fauna in the dark grey slates at the base of the cliff above and immediately north of Half Tide Rock (SX 92846553). He suggested that if the Middle Devonian age assigned to the limestones above could be confirmed then the section was inverted. Scrutton (1977b, p. 173) showed that the Babbacombe limestones were similar in fauna and texture to the Barton Limestone of late Givetian and early Frasnian age at Lummaton (SX

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913666) and Barton (SX 913671) quarries, although the coral fauna would not exclude a slightly older age. He suggested then that the limestones might be thrust over the Lower Frasnian slates but a recent detailed study of the cliff face indicates quite clearly that the section is indeed inverted as suggested by House (1964).

2. Stratigraphy and structure

From the Oddicombe Cliff railway south to a normal fault striking NE-SW on the north side of Babbacombe Glen, the cliff consists of a recumbent anticline and syncline facing ENE to NE (Figs. 2 and 3). The structure is cut by a number of N-S normal faults, two at the Oddicombe end throwing east and four in the main part of the cliff throwing west. Much of the cliff exposes the inverted limb of the fold pair. The outcrop figured by Ussher (1903, fig. 8) and Lloyd (1933, fig. 12) is the best exposure of the recumbent anticline. The igneous rock in the core of the fold is a carbonated and chloritised flow-banded andesitic sill. The limestone at the contact shows a thin (5 mm) zone of coarse recrystallisation but is otherwise not obviously affected. East and west of the fault block containing this structure, the fold nose is faulted up to about the present cliff top level where outcrops of the andesite are visible. What is probably the same fold nose can be seen high in the cliff above the footpath at SX 92886544 although the sill has not been identified at this point.

The oldest limestones in the cliff are those immediately above and below the folded sill. The limestones are estimated to be about 60 m thick assuming no internal thrusting. They are well-bedded throughout, commonly in the range 5-25 cm but with paler weathering beds exceeding lm in thickness. Fossiliferous bands are medium grey and bioclastic but dark grey, fine-grained, sometimes crinoidal but otherwise unfossiliferous, bands occur particularly lower down the cliff at stratigraphically higher horizons. The fauna is dominated by corals with relatively small, scattered tabular and domal stromatoporoids including *Actinostroma*. Tabulate corals are abundant, particularly *Thamnopora* spp., with *Alveolites* sp., *Favosites* sp. and *Heliolites* sp. in addition. Rugose corals include common *Phillipsastrea hennahi hennahi*, with *Haplothecia pengellyi, Acanthophyllum concavum, Macgeea sp., Thamnophyllum* sp. and according to Jukes-Browne (1913, p.26) *Mesophyllum* spp.. Chaetetes, bryozoa, brachipods and crinoidal debris are also present and some bands contain dense masses of *?Renalcis*. Recently conodonts of the *varcus* and *asymmetricus* Zones have been recovered, the former just stratigraphically above

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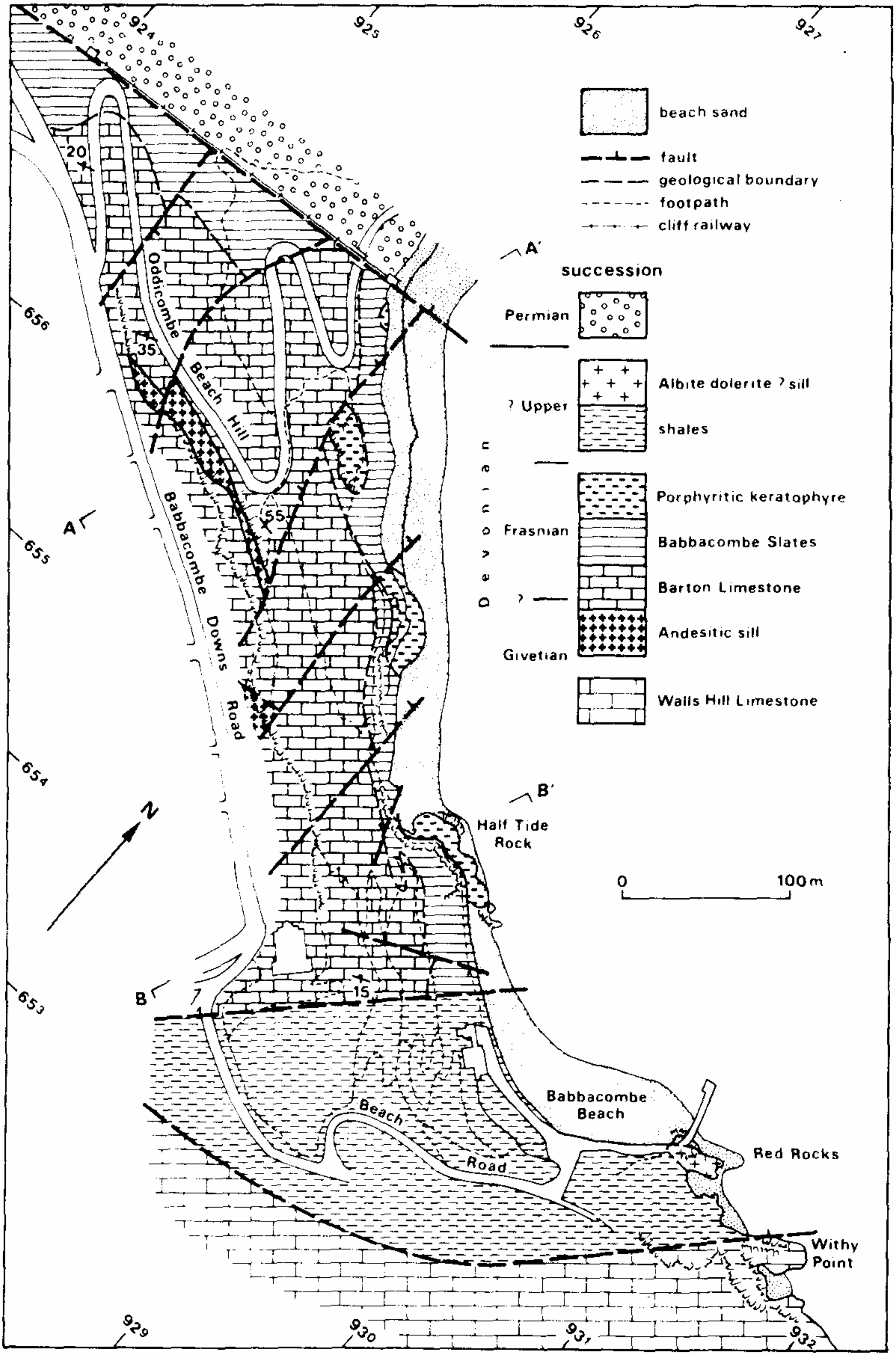

Figure 2. Geological map of Babbacombe Cliff.

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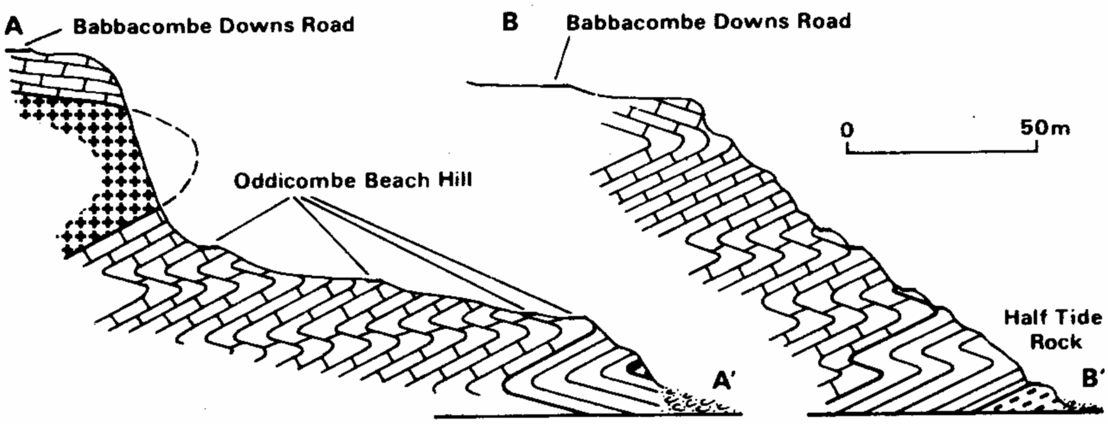

Figure 3. Generalised sections of Babbacombe Cliff. Lines of section are shown on Figure 2.

the intrusion and the latter stratigraphically below the transition to Babbacombe Slates, thus confirming the inverted nature of the limestone sequence below the intrusion (Castle 1978). This evidence also confirms the limestones here as coeval with those of Barton (Castle 1977) and as latest Givetian(?) to lower Frasnian in age. It is uncertain how much of the *varcus* Zone is present at Babbacombe and the succession could be wholly of Frasnian age (Castle 1978).

The top of the limestone, at various levels in the cliff in different fault blocks, passes structurally downwards through dark grey limestone-slate intercalations into the black to dark grey Babbacombe Slates which contain thin, black, fine-grained, pyritic limestone bands. These thin limestones have yielded an *asymmetricus* Zone conodont fauna and from the slates pyritised goniatites have been collected including *Probeloceras forcipiferum*, *Tornoceras* (T.) sp. and *Bactrites* sp. cf. B. *gracilis* indicating the Lower Frasnian *lunulicosta* Zone (House 1964). The slates also contain an igneous rock best seen at Half Tide Rock. It is a vesicular, carbonated, variably porphyritic keratophyre or an intermediate between spilite and keratophyre, in the form of blocks of various sizes, separated by thin layers and wedges of black shale, and occasionally showing crude pillow form; these rocks are clearly submarine extrusives. Farther north on the foreshore and low in the cliffs, the extrusives are repeated by faulting. At beach level around SX 92766561 and in the base of the cliff at SX 92676568 dark grey slates can be seen beneath the keratophyre. On the footpath at SX 92656567 and at the top of the crag above, the slate-keratophyre junction dips respectively northeasterly below the extrusives and

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southwesterly above them, indicating that they occupy the core of a recumbent syncline facing NE.

Cleavage is well developed in the Babbacombe Slates and in the transitional beds passing structurally up into the limestones: it varies between nearly horizontal and dips of up to 20^{o} S. Minor folds can be seen in both the slates and limestones but they are usually flattened and sheared out in the former. In the limestones several minor folds can be seen at the sides of paths above Half Tide Rock and the north end of Babbacombe Beach. Fold axes strike between 1000. and 1700 and are horizontal or plunge up to 25o SE. Bedding in the limestones dips predominantly 10-300 towards 1500 to 1900. Insufficient readings are available to plot sterographically.

South of the NE-SW fault terminating the Barton Limestone outcrop on its south-east side, Babbacombe Glen is eroded in soft dark grey to greyish-green, commonly fissile shales which become reddened near the faulted contact with the Walls Hill Limestone. A heavily carbonated and haematised albite dolerite forming Red Rocks (SX 93096549) is associated with these shales. No fauna has yet been recovered from the shales in the glen and no direct evidence of their age is available. Doleritic intrusions, however, are associated with the later Devonian throughout this area suggesting that this sequence is likely to be Frasnian or Famennian rather than Eifelian in age, postdating the succession in the main part of the cliff to the north.

3. Discussion

The importance of the Babbacombe Cliff section is twofold. Firstly it provides the only outcrop of the transition from the limestone sequence into the overlying argillaceous sediments so far known in the Torquay area. The facies change can be quite precisely dated here and the nature of the transition, presumably reflecting a deepening of the environment at the margin of the carbonate platform (Scrutton 1977a, b), can be examined in detail.

Secondly, an understanding of the structure of the cliff contributes towards the elucidation of the structure of the Torquay promontory as a whole. Although the inland area is heavily built up, good coastal outcrops exist from the area of Torquay harbour (SX 918631) right round the promontory to Oddicombe and provide the best evidence for the overall structure of the area. Some parts of this profile are moderately well known, particularly from the harbour

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round to Hope's Nose (SX 949635), but from Black Head (SX 943643) northwards there is little reliable published information. Sections described and illustrated by Ussher (1903), Shannon (1928) and Lloyd (1933) are nearly all in need of some reinterpretation, and Richter's (1969) contribution, mainly concerned with the area to the south, added only limited new observations on the Torquay promontory. Even so, with the evidence for the structure of Babbacombe Cliff offered here, the major remaining problem on the coast now is the elucidation of the complex relationships between Black Head and Long Quarry Point (SX 938651)

In broad terms the Devonian rocks of the Torquay promontory are disposed in a series of overturned to recumbent folds facing N to E with minor internal thrusting and at least one major thrust carrying the Ilsham limestones over the Black Head dolerite and associated Famennian (House 1963, p.8)slates (Fig. 4). The present outcrop pattern is largely the result of the subsequent block faulting of this fold pile. Earlier workers had considered the structure to be a broad anticline or anticlinorium affected by

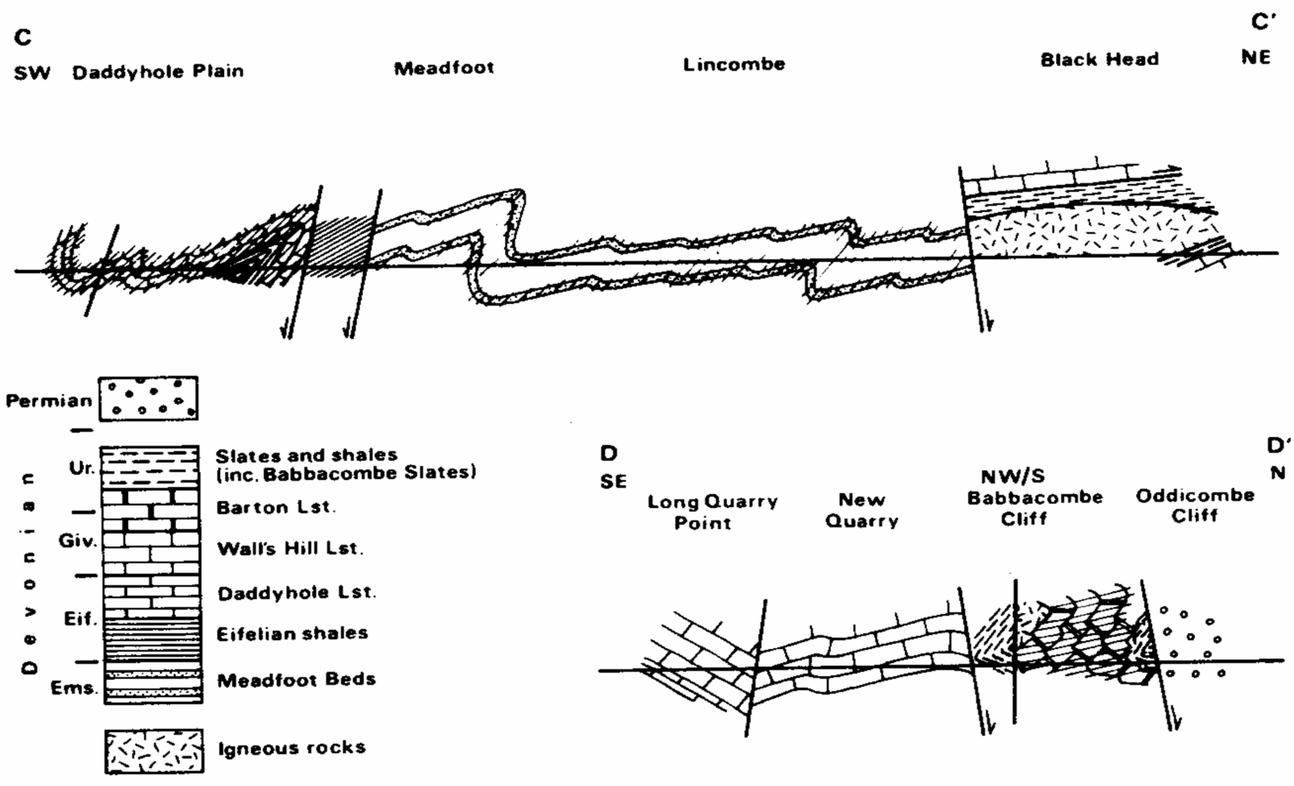

Figure 4. Generalised stepped sections of the Torquay promontory. Lines of sections are shown on Figure 1.

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thrusting and faulting to varying degrees (Ussher 1903, p. 12; Shannon 1928, p. 124; Lloyd 1933, p. 10) but this interpretation is misleading. There is also little evidence to support Vachell's (1963) major overthrust, the Marldon Beacon nappe, as has also been noted by Richter (1969, p. 128). The cleavage at Babbacombe, between 200 S and horizontal, is flatter than elsewhere on the promontory, and the folds face NE to ENE, plunging gently SE to SSE. Structures in the Daddyhole block (SX 925628) have a similar orientation, in contrast to those in the Hope's Nose and Meadfoot area (SX 935633) which face N and mostly plunge gently W. Cleavage in these areas dips Southerly between 30-50o. The most open, upright structures are in the massive stromatoporoid limestones of the Walls Hill block (SX 934652) where a faulted syncline overturned to the N has an axial planar dip of about 750. It appears that lithology and fold style are related to some extent, with the tighter, more overturned folds developed in the less massive limestones and the bands of hard siltstone or fine sandstone in slates of the Meadfoot Beds. The recumbent structures may have a component of gravitational collapse in their formation as they are associated with the top of the limestone sequence where they are succeeded by a thick wedge of incompetent argillaceous rocks.

4. Conclusions

The structure of Babbacombe Cliff, Torquay is interpreted as a recumbent anticline-syncline couple facing ENE to NE. An andesitic sill, occupying the core of the anticline, marks the local base of the succession. It is intruded into the Barton Limestone which forms the main part of the cliff face and contains a rich coral fauna and conodonts indicating a latest Givetian(?) to Lower Frasnian age. The limestones pass stratigraphically upwards into the Babbacombe Slates yielding Lower Frasnian goniatites and conodonts. The slates crop out at shore level and are succeeded by keratophyric extrusives in the core of the syncline.

In the Torquay promontory as a whole, structures face between N and E. The dips of axial planes tends to be high in the massive stromatoporoid limestones with open asymmetrical folds and lower in the bedded limestones and Meadfoot Beds with tighter overturned folds. Axial planes in Babbacombe Cliff appear to be flatter than elsewhere, possibly because the structures there developed at the top of the carbonate sequence beneath a thick succession of incompetent argillaceous rocks.

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Acknowledgements. I am most grateful to Christine Castle for discussions on the stratigraphy of Babbacombe Cliff and for comments on a draft of this paper. I also thank Dr M.H. Battey and Dr B.A.O. Randall (both of the University of Newcastle upon Tyne) for their observations on thin sections of the igneous rocks. Mrs Christine Cochrane (University of Newcastle upon Tyne) drafted the originals of Figs. I-4.

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CONODONT FAUNAS FROM BABBACOMBE CLIFF, TORQUAY

by Christine Castle

Abstract. Conodonts from Babbacombe Cliff indicate the presence of both the *varcus* Zone and the Lower *asymmetricus* Zone in the well-bedded limestones, and of the Lower *asymmetricus* Zone in the Babbacombe Slates. The field relationship of the samples confirms the inverted nature of the succession, which is of a similar age range to that of Barton Quarry and may extend from highest Givetian into the Lower and possibly the low Middle Frasnian.

1. Introduction

Conodonts have hitherto played a very minor part in the Devonian palaeontological record of the Torquay area. Dineley and Rhodes (1956) and Austin (1967) make brief reference to conodonts recovered from Old Wood's Pit and Hope's Nose respectively; Matthews (1970) described conodonts from the Lummaton Shell Bed, and Castle (1977) outlined the faunas present in Barton Quarry. The last two localities mentioned show well the potential of conodonts within the Middle and Upper Devonian of the Torquay area for establishing a biostratigraphy in terms of the standard European conodont zonations as described by Ziegler (1971). Recent work on the Babbacombe area, presented here, further illustrates this potential.

2. Conodont faunas and zones

The succession in Babbacombe Cliff, described by Scrutton (1978), is of well-bedded bioclastic limestones which pass into dark grey to black Babbacombe Slates containing thin, dark, pyritic limestone bands. Conodonts have been recovered from both the well-bedded and the thin limestones.

The oldest fauna found occurs 13 metres above the sill at SX 9268865545, in well-bedded (units 5-40 cm thick) bioclastic limestones with occasional bands rich in corals and small stromatoporoids. The main conodont elements present are *Polygnathus timorensis, Po. linguiformis linguiformis* gamma and *Po. 1.1.* zeta. Ziegler, Klapper and Johnson (1976, p. 113-114) consider the first occurrence of Po. 1. 1. zeta to be in the Middle *varcus* Zone, the last occurrence in the Upper *varcus* Zone. Therefore a Middle and/or Upper *varcus* age is indicated by the fauna.

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At the top of Oddicombe Beach Hill, near the junction with Babbacombe Downs Road, a NW-SE trending roadside exposure (SX 9240565726 - SX 9245265666) shows the succession clearly: well-bedded limestones pass downwards through a transitional zone 3.5-4 m thick of intercalated limestone and shale into dark Babbacombe Slates. A sample of well-bedded limestone from SX 9245065667, l l.7m from the transitional zone, has a conodont fauna of *Ancyrodella rotundiloba binodosa, Icriodus cf. L eslaensis latecarinatus, Po. asymmetricus asymmetricus, Po. cristatus, Po.* aff. *Po. dubius, Po.* aff. *Po. ovatinodosus* and *Po.* aff. *Po. timorensis.* The Frasnian Lower asymmetricus Zone is indicated.

The Babbacombe Slates are seen to the south, above and below the footbridge near Half Tide Rock (Fig. l). Faunas from l-9cm thick, fine-grained limestone bands within the slates (around SX 9281265523) again include *A. rotundiloba binodosa*, this time with *Po. dengleri, Po. dubius, Po. ovatinodosus, Po*. aff. *Po. pennatus* and *Po*. aff. *Po. webbi*. Again, a Lower *asymmetricus* Zone is indicated.

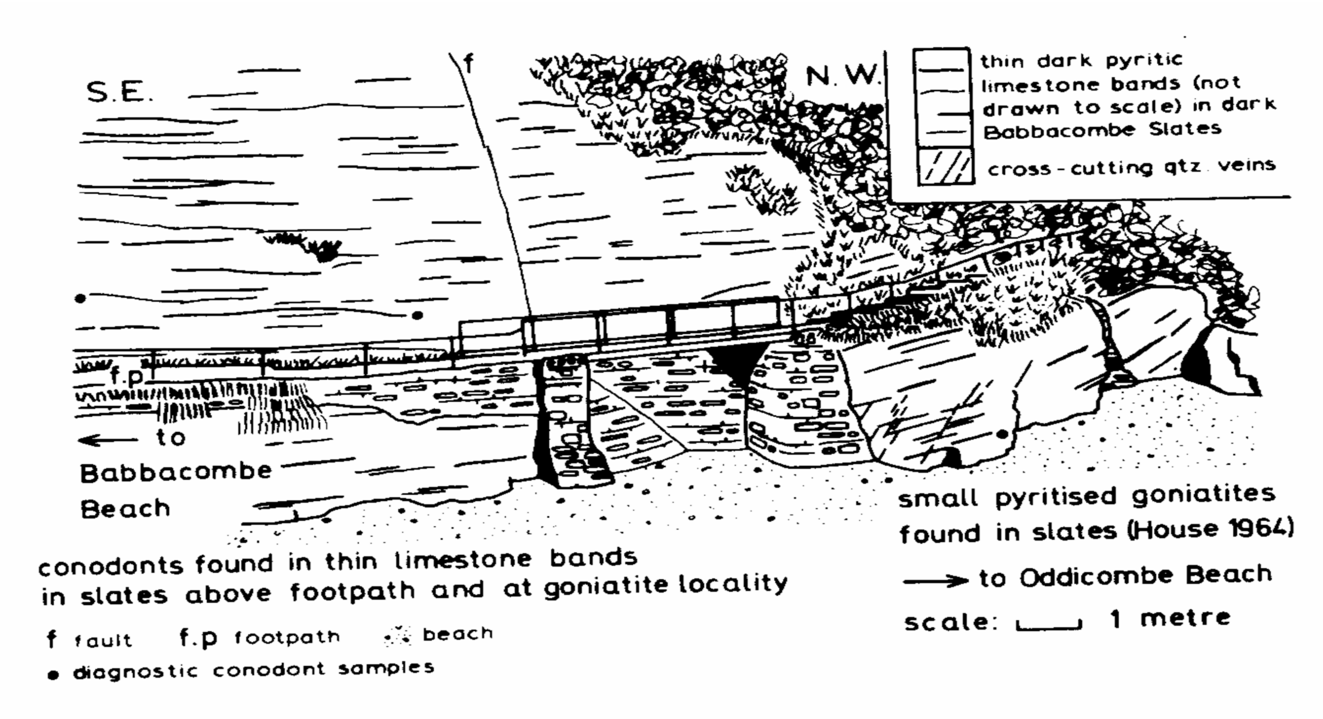

Figure 1. Sketch diagram (after photograph taken from Half Tide Rock) of the cliff section in Babbacombe Slates at the footbridge near Half Tide Rock (around SX 9281265523)

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3. Discussion and conclusions

The presence of a Middle and/or Upper *varcus* fauna above the sill at SX 9268865545 in well-bedded limestones and of Lower *asymmetricus* faunas in limestones on Oddicombe Beach Hill and in thin limestones in the Babbacombe Slates near Half Tide Rock

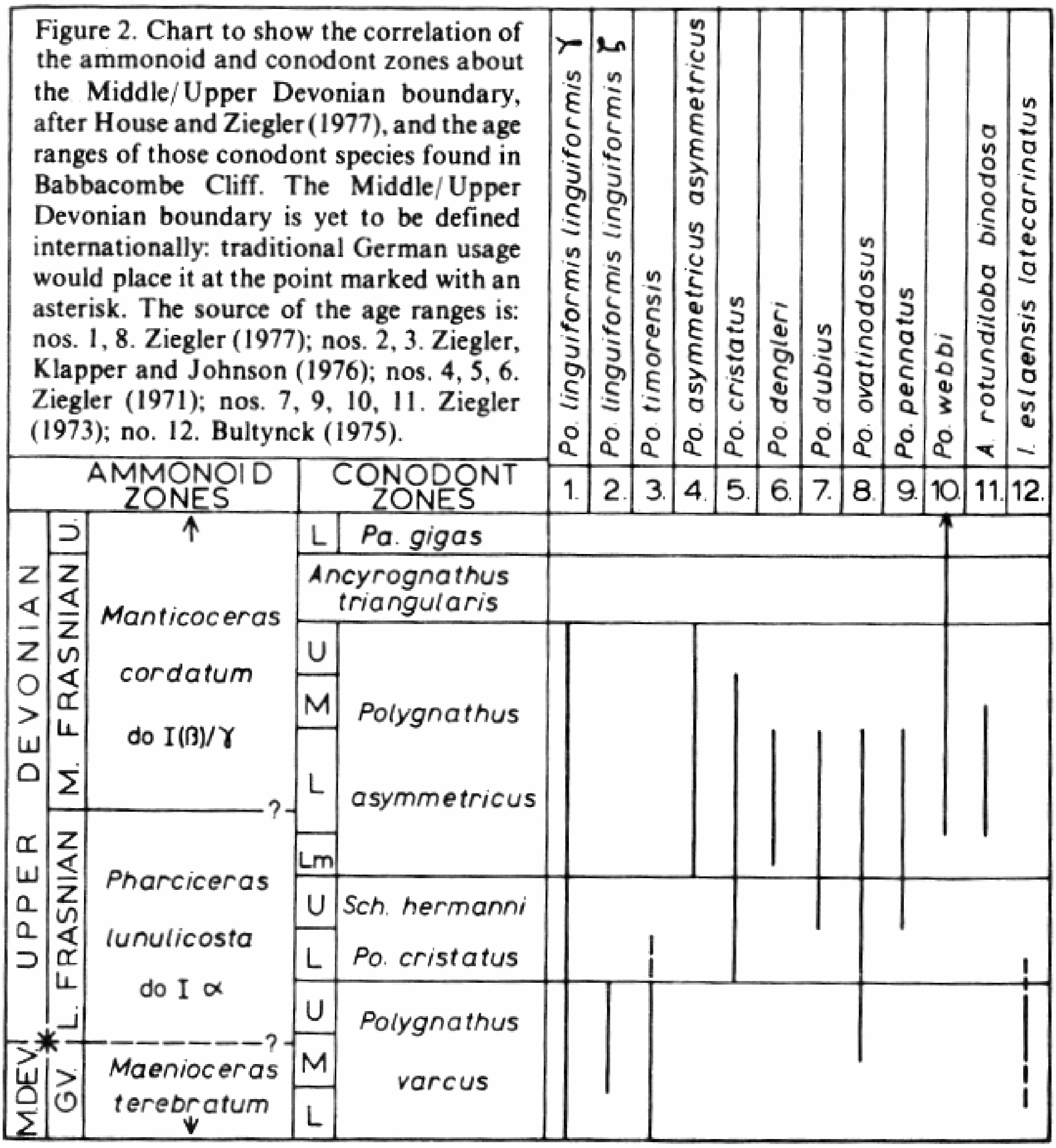

Figure 2. Chart to show the correlation of the ammonoid and conodont zones about the Middle/Upper Devonian boundary, after House and Ziegler (1977), and the age ranges of those conodont species found in Babbacombe Cliff. The Middle/Upper Devonian boundary is yet to be defined internationally: traditional German usage would place it at the point marked with an asterisk. The source of the age ranges is: nos. 1, 8. Ziegler (1977); nos. 2, 3. Ziegler, Klapper and Johnson (1976); nos. 4, 5, 6. Ziegler (1971); nos. 7, 9, 10, 11. Ziegler (1973); no. 12. Bultynck (1975).

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indicates an inverted sequence, dips in the area being low (10-320) and generally to the south and east: that the succession in Babbacombe Cliff is inverted was first suggested by House (1964). Scrutton (1978) considers the structure of the area to be a "recumbent anticline-syncline couple": he takes the conodont evidence to confirm the inversion of the limestone sequence below the sill which is at the core of the anticline and is exposed in higher parts of the cliff.

The slates near Half Tide Rock, previously considered to be Eifelian by Lloyd (1933) among others, were shown to be Frasnian by House (1964) who described a fauna of pyritised goniatites, found near the footbridge (Fig. 1), of the Lower Frasnian *Pharciceras lunulicosta* Zone (do I a). The zone indicated by the conodonts, the Lower *asymmetricus* Zone, is equivalent to possibly the topmost part of the *lunulicosta* Zone and the lower part of the Middle Frasnian *Manticoceras cordaturn* Zone (do I (β)/Y) of the Martenberg ammonoid zonation (House and Ziegler 1977, fig. 4), (Fig. 2). It should be noted that Kirchgasser (1975, fig. 2 and p. 65) considers the *lunulicosta* - *cordatum* boundary to fall within the Lower *asymmetricus* Zone.

The conodonts of Barton Quarry (Castle 1977) span a similar age range to those of Babbacombe, that is, from the *varcus* Zone into the asymmetricus Zone. It is interesting that the Babbacombe succession has not yet produced representatives of the *hermanni-cristatus* Zone which is well represented at Barton. Scrutton (1977, p. 173; 1978) considers the limestones of Babbacombe to be similar in faunal and textural aspect to those of Barton, referring to the former as "Barton Limestone": the conodonts show that the two localities are similar in age.

In conclusion, conodonts from Babbacombe Cliff suggest the presence of both the Middle and/or Upper *varcus* Zone and the Lower *asymmetricus* Zone. The Middle/Upper Devonian boundary is not yet precisely fixed in terms of conodont zones (House and Ziegler 1977, fig. 4 and p. 92) but if the German convention for the Middle/Upper Devonian boundary is accepted, then the Upper *varcus* Zone and higher levels belong to the Upper Devonian (Fig. 2). Thus, the sequence of Babbacombe Cliff can be shown to extend from the Lower into possibly the low Middle Frasnian, and may pass down into the highest Givetian.

Acknowledgements. I am indebted to Dr C.T. Scrutton (University of Newcastle upon Tyne) for discussions on the geology of Babbacombe Cliff; to Professor M.R. House (University of Hull) for his helpful criticism of the manuscript; and to the Natural Environment Research Council for a grant to work on the conodonts of the Torquay area.

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PALAEOCURRENT STUDIES IN THE MIDDLE AND UPPER DEVONIAN BASINAL FACIES OF NORTH CORNWALL

by Anthony P. Beese

Abstract. Preferred orientations of fossils from two facies of the marine Devonian are assessed. After the effects of deformation have been removed, a general change from N - S to E - W in direction of a weak unidirectional bottom current, interpreted as representing turbidite flow, is observed from the Middle to Upper Devonian.

1. Introduction

Fossils showing preferred orientations have previously been recognised in the deformed Devonian strata of south-west England (Gauss and House 1972; House 1975). This paper attempts a reconstruction of original orientations during the Middle and Upper Devonian, and an interpretation of their palaeocurrent significance. Localities chosen were from coastal exposures in the Padstow area (Fig. 1), for which stratigraphical and structural relationships are fairly well known (Gauss and House 1972; Gauss 1973; Beese 1977). Two marine facies were sampled: Middle Devonian grey slates; and Upper Devonian purple and green slates. Localities were selected so that bedding and primary cleavage were nearly parallel, simplifying the 'unfolding' of the structure, All the Middle Devonian (Trevose Slates) localities occur on inverted limbs of north-facing, recumbent folds in the southern part of the area - the normal limbs cut across the cleavage at a high angle; while most of the Upper Devonian (Harbour Cove Slates and Polzeath Slates) localities occur in more gently dipping strata found to the north, where folds are more upright (Fig. 1).

2. Data

The original data were obtained either directly in the field, or, in the case of the ostracods and tentaculitids, by using a binocular microscope on tracings of orientated slate samples after the method of Moors (1969). Each sample represents a single bedding plane or a thickness of less than 50 cm. All observations are referred to Grid North.

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Samples for the Middle Devonian were taken from 250 m of dark grey, calcareous slates of probable Givetian age. At Booby's Bay, orthocones up to 10 cm in length were measured (Fig. 2b - SW 85307580). Orientations of crinoid stem fragments up to 10 cm long were taken at Trevone (Fig. 2c - SW 88947603, Fig. 2d - SW 88957595). Orientations of styliolinids up to 7 mm in length were obtained from three localities: Booby's Bay (Fig. 2a - SW 85367570); Trevone (Fig. 2e - SW 88977604, Fig. 2f -SW 89077597); and Rock (Fig. 2g - SW 93407759). Data for Figs. 2b and 2d are taken from Gauss and House (1972).

Samples for the Upper Devonian were taken from 250 m of upper Frasnian to mid Famennian purple and green slates. Slates totalling 500 m from the lower part of the Frasnian are unsampled owing to their poor faunal content. At Daymer Bay measurements were made on tentaculitids and ostracods, not exceeding 3 mm in length, found in a 3 m purple slate band in green Frasnian slates (Figs. 3c and 3d - SW 92627777). Bactritid orthocone fragments up to

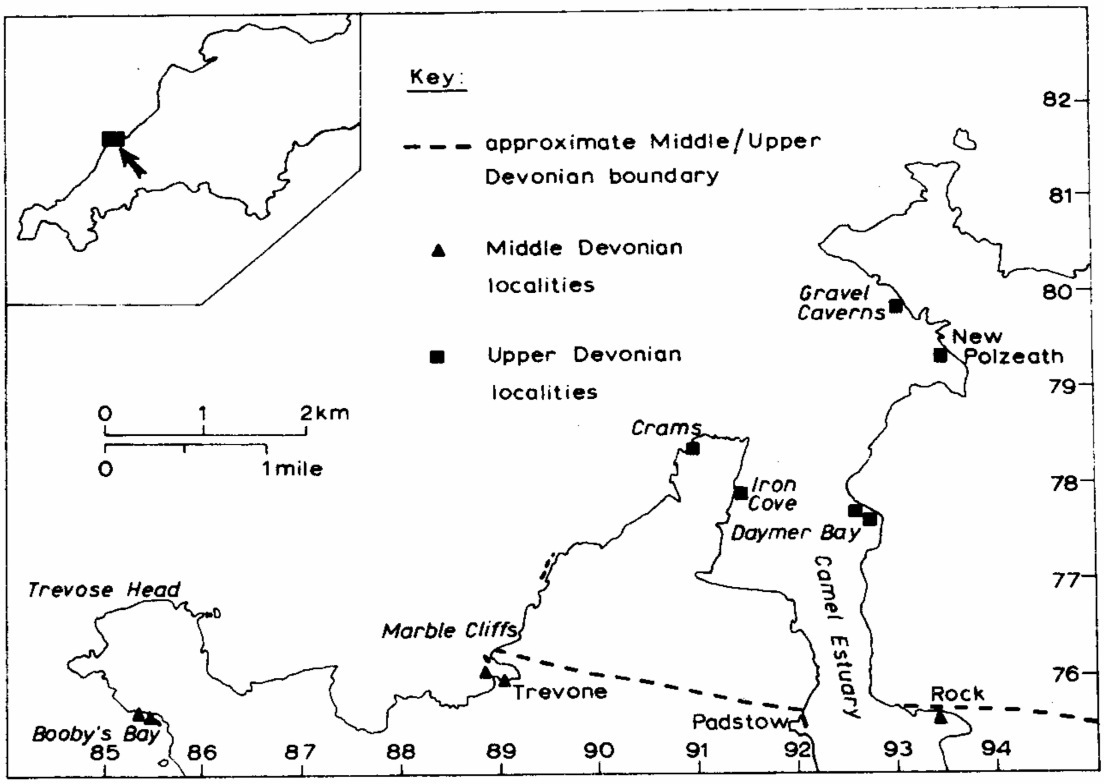

Figure 1. Locality Map

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5cm long were also assessed at Daymer Bay (Fig. 3 b - S W 92777768). Ostracods of Famennian age were taken from various localities within the predominantly purple slates: Iron Cove (Fig. 3e - SW 91387792); New Polzeath (Fig. 3f- SW 93487943); and Crams (Figs. 3g and 3h - SW 90787834).

3. Methods

(i) Structural analysis

Gauss and House (1972) noted the preferred orientations of fossils in the Middle Devonian of the Padstow area, but presented only the raw data, not attempting reconstruction. Recent litho-stratigraphical work (Beese 1977) has clarified some of the complex structural history, and shown that there is a consistent pattern from south to north on both sides of the Camel Estuary. Folds in the southern part of the area are north-facing recumbent folds which cause much of the Middle Devonian succession to be inverted. These are replaced by more upright folds, north of a line joining iron Cove to Daymer Bay (Fig. I), so that the Upper Devonian succession is normal. North of New Polzeath the succession is again inverted (Fig. 3a). In the Padstow area there appears to be no evidence for the major thrust which Gauss (1973) recognised. A few oblique fold axes are similar to those in the Tintagel - Boscastle region (Sanderson 1973; Hobson 1974), for example the fold axis in Fig. 3f. Therefore, secondary rotations of the data are probably insignificant. A possible source of error in the reconstruction of the data may result because the two types of folds are treated as having formed approximately simultaneously. Some of the upright folds, especially those where the cleavage dips more steeply (Figs. 3g and 3h), may be later(see Gauss 1973). Sampling was restricted to areas where the effect of later minor deformations was limited.

Ramsay (1967, p. 486 et seq.) describes the method used in this paper for restoring angular measurements which have been deformed, by correcting each one for the effects of irrotational strain, inclined fold axis, and folding (in that order). To simplify several rotations on each measurement the data were grouped into 12 class intervals of 300 - corrected using the stereographic projection and plotted on rose diagrams (Figs. 2 and 3).

Studies of irrotational strain in the Padstow area are hampered by the lack of suitable strain markers. Gauss (1967; 1973) determined that the greatest shortening was at right angles to the cleavage. All measurements were restricted to bedding nearly

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parallel to cleavage, so that the effect of rotation by flattening can be ignored. Gauss showed that variable amounts of extension occurred in the XY plane, in directions parallel to the fold axes and at high angles to the fold axes. Working on crinoid stems preserved in pyrite, which deform inhomogeneously with their matrix, he recorded extensions of 22 per cent and 31 per cent in two directions at 70o to each other at Booby's Bay. Therefore, the Y/X value is estimated as approximately 0.93. In the area to the north where folds are more upright ostracods preserved in argillite were selected as almost perfect strain markers, deforming homogeneously with their matrix (Daymer Bay - Figs. 3c and 3d). Gooday (personal communication) has identified the ostracods as probably *Entomozoe (Nehdentomis) tenera* and *E. (N.) pseudorichterina*. Sixty measurements were made of their long to short axial ratios, and the angle between their long axes and north. Extension occurs in two directions at 800 to each other. Using Ramsay's graphical method and equation (1967, p. 210):

$$\text{maximum } R_T = R_t R_o$$

for one direction (075° - 095°) in which the maximum axial ratios (R_T) occur an idea of the minimum Y/X value can be obtained ($1 / R_t$). Rabien (1954) gives the maximum value for the original axial ratios (R_o) of the two species as 2.0. The maximum value for R_T is 2.66. Therefore Y/X is approximately 0.75. Using those two values of Y/X, data are corrected by using the graphical solution for changes in angle during deformation (Ramsay 1967, p. 129 et seq). Data corrected for inclined fold axis and folding have the same (Figs. la and 2b), or nearly similar (Figs. 3c and 3d) distribution of maxima as data additionally corrected for irrotational strain. Further variations in other localities cannot be excluded.

The inclined fold axes are taken from the structural map of Gauss (1967). Reconstruction involves rotation of the data around an axis at 90o to the fold axis (Figs. 2 and 3). Folding is corrected by a rotation of the data around the corrected fold axis.

Results indicate that tectonic realignment is of small significance because: (a) original samples show some angular measurements in nearly every class interval (all class intervals for Figs. 2a, b, c, d, e, and g; 3c, f and h), and intermediate submaxima are often developed (Figs. 2a, e, L and 3ci) - an argument used by Moors (1970); (b) maxima for corrected data are consistently parallel to (U. Devonian) and normal to (M, Devonian) tectonic strike (Figs. 2 and 3); and (c) results from Trevone are consistent despite angles between bedding planes differing by as much as 350 (Figs. 2c-f).

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(ii) Palaeocurrent analysis

Complicating factors affecting the final distribution of maxima were considered experimentally by Schwarzacher (1963). In the cases under consideration all the fossils except the ostracods can be described as roughly cylindrical in shape, and all are likely to be drifted. Carapace and valve studies for the ostracods reveal that less than 15 per cent of the ostracods are complete carapaces, suggesting that they have undergone transportation. Mutual interference was negligible in all the samples used, and bottom conditions were smooth since all fossils occur in an argillite matrix. Therefore, rotation parallel to a unidirectional current is to be expected. Krinsley (1960) deduced that orthocone apices point toward the current source.

(iii) Statistical analysis

The statistics used are for circular distributions (Mardia 1972, p. 18 *et seq*). The distributions obtained can be considered as having (a) a unimodal axial component, or (b) two unimodal components 180o apart. In both cases methods of calculation of mean vector (MV) and circular variance (CV) are similar, and the results comparable (Figs. 2 and 3). The circular variance is a function of a mean vector length, approaching a value of I when the distribution is uniform. The Rayleigh Test for unimodal distribution gives a level of significance of 1 per cent for all the fossil distributions, expect the orthocones (Figs. 2b and 3b) which are significant at the 5 per cent level.

4. Results

(i) Results for the Middle Devonian

Directions of maxima are mostly N - S or ENE - SSW and independent of the size of fossil measured (Fig. 2). The styliolinid distributions show development of intermediate submaxima which, according to Schwarzacher (1963), can result from a unidirectional current if fossils are allowed to roll on a smooth sea floor. Results for the styliolinids and orthocones show indistinguishable dominant and secondary modes, and give no obvious idea of current source. The orthocones show the greatest circular variance and a slightly anomalous distribution, possibly because they were affected by buoyancy. Circular variance is least for the crinoids (0.12 -0.17). A suitable interpretation, therefore, would be a weak, unidirectional bottom current operating in a roughly N - S direction.

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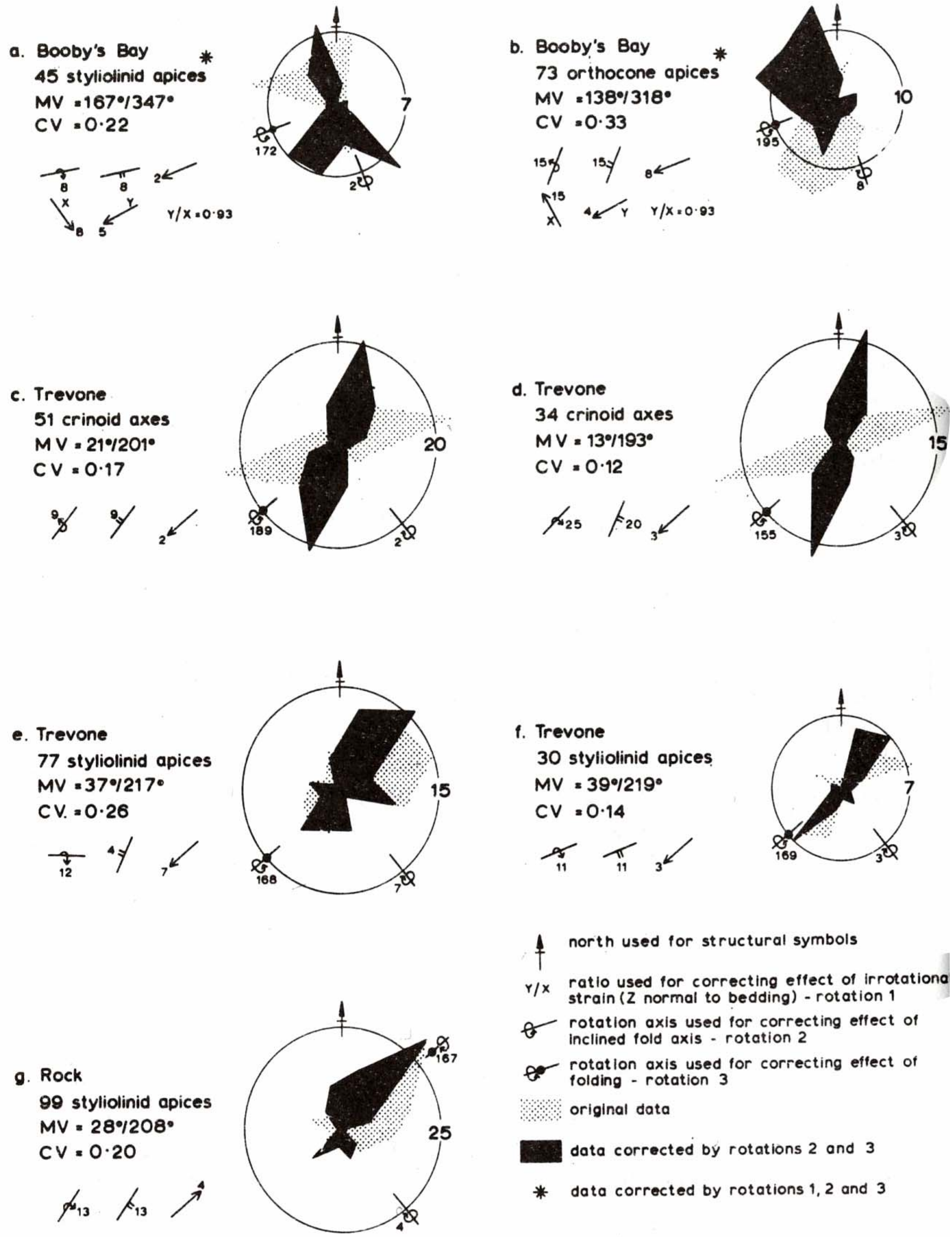

Figure 2. Structural data and rose diagrams for the Middle Devonian examples (data for b and d from Gauss and House, 1972)

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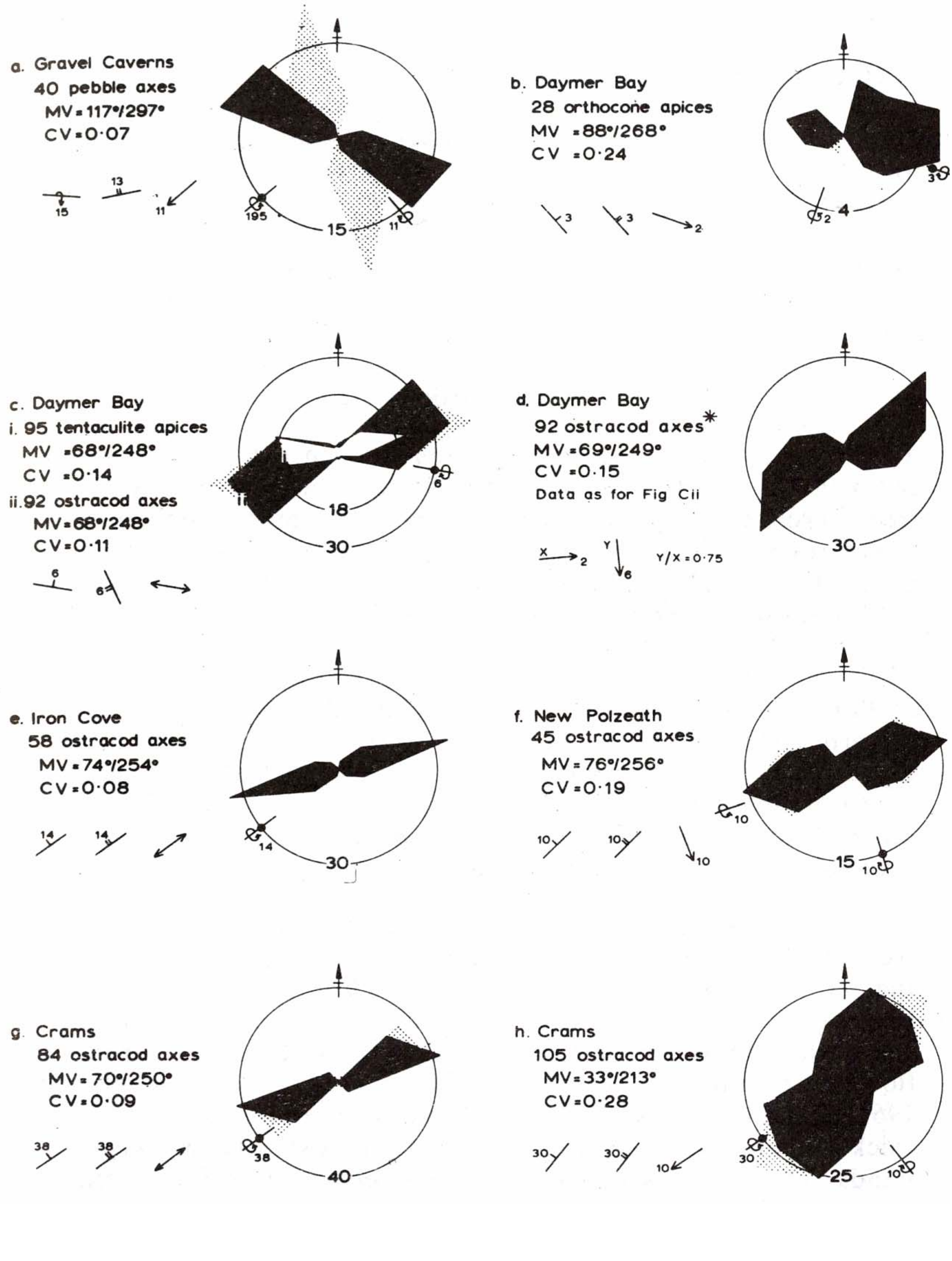

Figure 3. Structural data and rose diagrams for the Frasnian (a-d) and the Famenian (e-h) examples (for key see Fig 2.)

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(ii) Results for the Upper Devonian

Directions of maxima are variable, but generally E - W (Fig. 3). Again results are size independent. The tentaculitids show intermediate submaxima, and indistinguishable dominant and secondary modes; while the orthocones show the greatest circular variance. The ostracods, which show the greatest range in circular variance (0.07 - 0.28), may be indicators of strength of bottom current. Hinge lines of posidoniid bivalves from Crams show a similar preferred orientation to the ostracods (Fig. 3h). Therefore, it is suggested that during the Upper Devonian there was a weak, unidirectional current operating in an E - W direction but variable in both strength and direction.

5. Conclusions

There is little available palaeocurrent evidence from associated sedimentary structures. Tucker (1969) restored current directions from cross-bedding, channel scours and other sedimentary structures seen in an inverted succession of limestones at Marble Cliffs (Fig. 1). He estimated a south-westerly provenance before deformation, agreeing with the NNE - SSW maxima obtained from Trevone (Figs. 2c-f) where the slates are only slightly older. Measurements on rare cross-bedding in a siltstone band south-west of Polzeath (SW 92787826), and on ellipsoidal pebbles at Gravel Caverns (SW 93137978 - Fig. 3a) are the only evidence from the Upper Devonian. The current source suggested by the former, which is of probable mid Famennian age, is NW. Implications of current direction for the latter are complicated, because their deposition was probably by mudflow from a local volcanic rise.

How much do the changes in preferred orientations of fossils from the Middle to Upper Devonian reflect changes in direction of the bottom current or palaeoslope? Throughout both facies lithologies occur which, by comparison with modern basinal sediments, can be interpreted as the result of extreme distal turbidite flow (for example in Gorsline and Emery 1959; Ericson and others 1961). Laminated siltstone and mudstone bands only a few centimetres thick are common. Paler grey bands in the grey slate facies and green bands in the purple slate facies are also frequent; they are generally more than 5 cm thick and have sharp contacts, the basal one often marked by thin siltstone bands. Assuming then, that the preferred fossil orientations represent directions of weak turbidite currents, one can interpret the changes in direction. After the deposition of the Middle Devonian, a period of instability seems to have affected the

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earlier part of the Frasnian with the development of local sea-floor rises or *schwellen* (hence the limestone turbidites of Marble Cliffs, and the volcanically derived pillow lavas and conglomerates of Gravel Caverns). For the Upper Devonian a change in facies could then have resulted from different rates of sedimentation and erosion, and perhaps a different provenance.

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CLAY MINERAL STUDIES OF CRACKINGTON FORMATION SHALES NEAR EXETER

by P. Grainger and M.C. George

Abstract. Shales and their weathered clay products from the Crackington Formation (Upper Carboniferous) near Exeter, have been analysed by X-ray diffraction. The results show an illite-dominated clay mineral suite with subsidiary kaolinite and chlorite. Weathering of the shales to a residual clay soil leaves the clay minerals virtually unaltered, with a slight tendency to reduce the kaolinite and chlorite components. Mapping the analyses of the least weathered samples divides the shales into areas with no chlorite present, and areas with chlorite. Combining these groupings with structural mapping data suggests an east-west anticlinal form along the Alphin Brook to the west of Exeter, with non-chloritic shales exposed in its core.

1. Introduction

A study of naturally unstable slopes in an area of clay soils overlying shales has revealed a distribution of landslips and slope angles related to the underlying structure and lithology. In an attempt to elucidate all the factors controlling slope development in the area, X-ray diffraction analyses of clays and shales have been carried out, and the results form the basis of this paper.

The area studied is immediately west of Exeter (Ordnance Survey sheet SX 89SE) and includes the Alphin Brook valley, followed by the A30 Exeter to Okehampton road, from Ide to Five Mile Hill Cross. Local instabilities have affected the old route of this road for a long time and were a major influence on the design and construction of the new dual carriageway. The area has been mapped as shales and subordinate turbidite sandstones of the Crackington Formation (Namurian), except for a small area of Permian lavas and breccias in the south-east corner. The general structure is of east-west trending folds, asymmetrical or slightly overturned to the south, variably plunging to the east or west. This structure is reflected by the topography of predominantly cast-west ridges and valleys.

The purpose of the mineralogical study of the clays and shales was firstly to determine any chemical changes caused by weathering of

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the shale to a clay soil, and secondly to detect any primary differences in clay mineral suites within the shales, that might account for observed differences in geotechnical properties of the residual soils. A total of 61 samples have been analysed from 32 different localities (Fig. 3), including natural exposures, new road cuttings, and borehole cores.

2. X-ray procedure

X-ray diffraction charts were produced from powdered shale and dried clay samples mounted on glass half-slides. It was decided that best results would be obtained if the platy clay minerals in the powder were preferentially orientated on their basal cleavage. To this end, the crushed shale was vigorously stirred in a beaker with methyl alcohol. After a few seconds to allow large fragments to settle, the alcohol-powder suspension was poured into a second beaker in the bottom of which a clean glass half-slide was lying. After about a minute the bulk of the liquid now containing only the finest fragments, which would, if allowed to settle, increase scatter and background during X-raying, was carefully drawn out of the beaker by means of a hypodermic syringe. The glass half-slide was lifted out of the beaker, care being taken not to disturb the slurry of clay material on its surface, and placed in a warm area to dry slowly. One end of the dried slide was cleared of coating to facilitate mounting in the diffractometer.

The mounted slide was inserted into a Phillips X-ray Goniometer. Cobalt-K a radiation was employed to ensure that the iron present in some of the clays did not fluoresce, as would occur with copper radiation.

Three types of run were generally performed on the samples. (a) $1^{\circ}2\ \theta$ per minute from 3° to about $600\ ^{\circ}2\theta$. (b) ¼ $^{\circ}2\ \theta$ per minute from $3\ ^{\circ}$ to $16\ ^{\circ}2\ \theta$ untreated. (c) 1/4 $^{\circ}2\ \theta$ per minute from $3\ ^{\circ}$ to $16\ ^{\circ}2\ \theta$ glycolated. Run (a) was intended to allow assessment of the total mineralogy of the sample; runs (b) and {c) were for the study of the clay mineral basal reflections alone, including any expanding minerals. After this initial study, certain samples were subjected to heating (at about $600\ ^{\circ}C$) and/or acid treatment in warmed 6N HCl for 24 hours. The resultant samples were X-rayed again to aid kaolinite and chlorite identification.

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3. Results

The clay minerals identified are illite, kaolinite, chlorite and a mixed-layer mineral. Quartz always accompanies the clay mineral suite, but no attempt has been made to establish the proportion present or to identify other minor non-clay minerals.

Of the clay minerals illite dominates and is always present. Variations in the proportion of illite in the total clay content are thus complementary to variations in the amounts of kaolinite, chlorite, and mixed-layer material present. The identification of illite is based on the first basal reflection (001) at about 10 Å, which is not significantly affected by glycolating, moderate heating, or dilute acid treatment (Fig. 1). The other main basal and non-basal peaks were also observed on the longer X-ray scans, (Brown 1961). The width of the 10 Å illite peak (averaging ± 0.2o at half peak height) indicates typical disordered sedimentary illite. This peak is usually skewed with a tail to the higher spacing side. This skewness was shown by glycolation to be partly due to an expanding mixed-layer mineral with a very broad peak centred around 10.5 Å (Fig. la).

Of 25 samples that were treated with glycol to show any expanding minerals, 19 did so, all in this position only. The difference in 10 Å peak areas of the two traces, untreated and glycolated, ranged up to 60 per cent of the non-expanding remaining illite peak. This suggests that a considerable proportion of the total clay content could be of this mixed-layer mineral. As not all samples were glycolated, an attempt was made to assess the presence of mixed-layer material in the traces of untreated samples by measuring the skewness of the 10 Å peaks. The range of skewness values for untreated samples compared to their glycolated counterparts showed a definite positive shift. However, the overlap was such that on any individual sample it would not be possible to be sure of the presence or absence of mixed-layer material without glycol treatment.

Non-swelling chlorite has been recognised in some samples by the presence of a first order basal reflection at 14.1 Å (Fig. la). Heating enhances this peak, whereas prolonged HCl treatment removes it completely. The exact position of the peak suggests an aluminium substitution for silicon of between 1 and 2 out of 4 (Brown 1961). As an indication of relative proportions of clay minerals, the area of the 14 .Å peak has been compared to the area of the illite peak at 10 Å (Tables I and 2).

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The definite presence of kaolinite is shown by the symmetrical, moderately broad peak at 7.15 Å, in some samples where no chlorite occurs (Fig. lb). This peak disappears on heating but is not affected by mild acid treatment. Its shape, and the lack of resolution of the minor kaolinite peaks, indicate a considerable degree of disorder. Where no 14 Å peak is seen, that is no chlorite exists, the areas of the 10 Å and 7 Å peaks are compared, to estimate the relative proportions of illite and kaolinite.

A more difficult assessment is the proportion of kaolinite present where chlorite does occur, since the second order basal reflection (002) of chlorite falls directly on top of the first order (001) kaolinite peak. Furthermore, the ratio of the areas of the 7 Å and 14 Å chlorite peaks is dependent on the composition of the mineral, generally increasing as the iron content increases (Brown 1961), but cannot be measured directly when kaolinite is present. In earlier work on Carboniferous shales in the north of England, Spears and Taylor (1972), faced with the same dilemma, assumed a fixed ratio of one. Thus the relative proportion of kaolinite to chlorite was taken as:

$$\frac{7\text{ Å peak area} - 14\text{ Å peak area}}{14\text{ Å peak area}}$$

By comparison, Bristow (1968), in work on the Petrockstow Basin shows X-ray diffraction traces of Carboniferous shales with the 7 Å, peak about three times as large as the 14 Å, but does not take this to indicate much kaolinite. The ratio of 7 Å: 14 Å total peak areas measured for 29 samples containing chlorite in this study varied from 0.8: l up to 4.8: 1. If the chlorite structure was constant for all samples then the ratio of the chlorite intensities must be at the lower end of this range, that is approximately 1:1 as adopted by Spears and Taylor (1972). In order to test this idea, two samples were treated with warm HCl to dissolve partially the chlorite component. By assuming that the rate of decrease of the (001) and (002) peaks of chlorite was the same, and that the (001) kaolinite peak was unaffected, it was possible to determine the ratio of 7 Å 14 Å chlorite peak areas. These two and a further four samples were subjected to a more prolonged acid treatment which completely removed the 14 Å peak in all cases. The remaining 7 Å peak was taken as kaolinite. The range of values for the ratio of 7 Å: 14 A chlorite peak areas was found to be 0.8:1 up to 2.7:1. The significance of the variations of the chlorite peak ratio is discussed in the following section.

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The conclusions reached as to the composition of the clay fraction for all the samples of clay and shale analysed are summarised in Table 1. It must be emphasised that the measure of relative proportions is based on the assumptions stated earlier and is only an indication of variability, not a rigid quantitative assessment.

Table 1

Average clay mineral compositions

Mineral	Range of Values (% of total clay)	% of samples containing mineral	Average value (% of total clay) All samples	Chloritic samples	Non-Chloritic samples
Illite	45-100	100	77	73	81
Mixed Layer	0-30	-			
Kaolinite	0-45	75	13	7	19
Chlorite	0-35	50	10	20	0

4. Weathering

At several sites sampling was carried out in a vertical or near vertical sequence to assess any changes in mineralogy due to chemical weathering. The unweathered shales can be divided into those containing chlorite and those with none. The significance of this is discussed in the next section. On shales containing no chlorite, the kaolinite to illite (including mixed-layer material) ratio remains fairly constant from fresh shale through to residual soil in any one profile (Fig. 2a). The sites of these profiles are shown on Fig. 3. The only systematic change is a decrease of kaolinite towards the surface, replaced by mixed-layer material at site 20.

In those areas where chlorite does occur, only two profiles have been analysed (Fig. 2b). Site 21, on a steep slope, shows a depletion of chlorite and kaolinite when penetratively weathered. Site 32, in a valley bottom with a considerable cover of transported soil overlying it, shows little alteration, even into the overburden. (This site lies some distance to the west of the main study area but is included for comparison).

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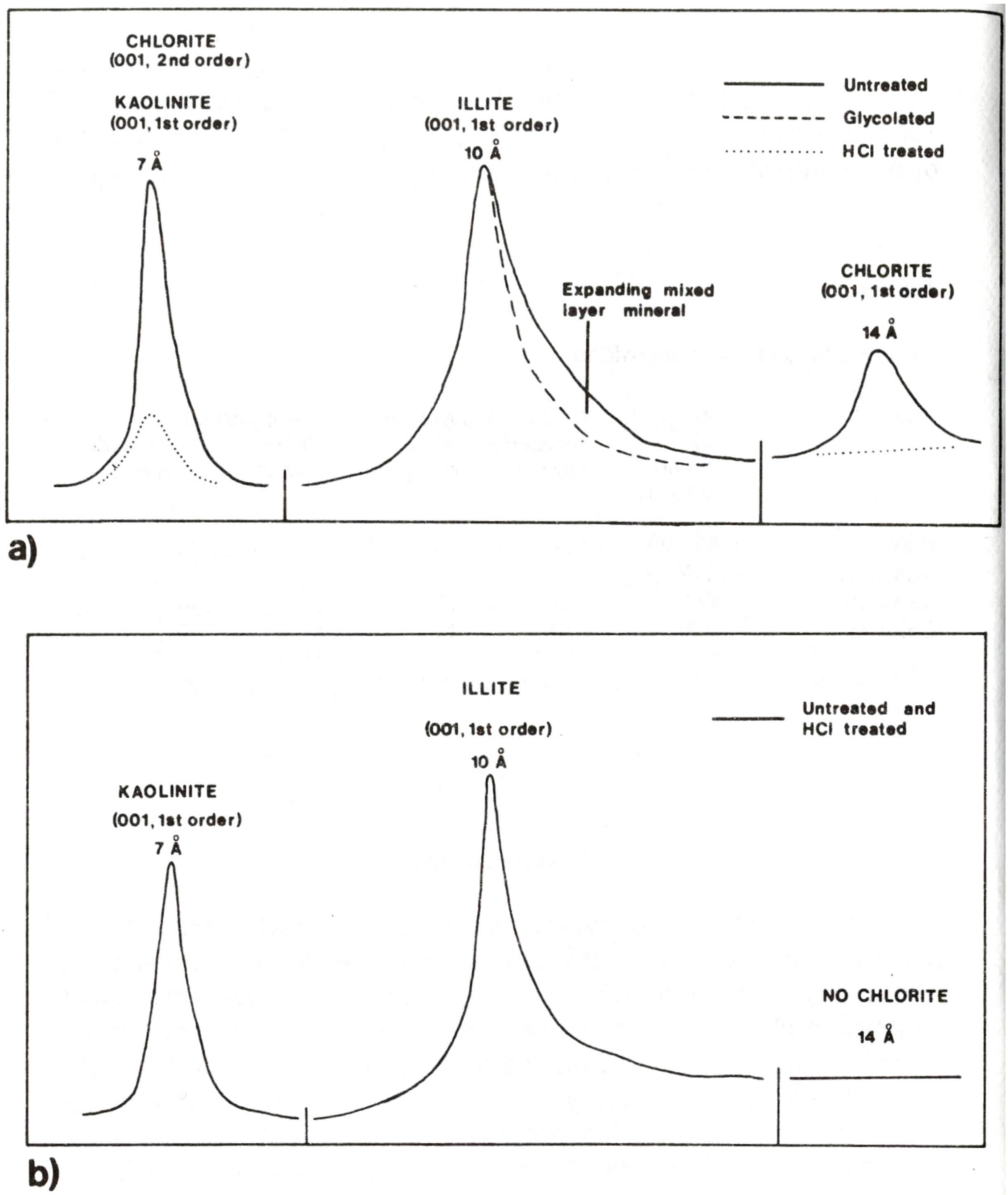

Figure 1. Typical examples of the main X-ray diffraction peaks used for the identification of clay minerals (a) chloritic shale (b) non-chloritic shale

Pure illite residual clays and penetratively weathered shales have been found at several sites, and may indicate the completion of the chemical weathering under present conditions. The half peak width to peak height ratio was taken as a measure of crystallinity, for the illite and kaolinite first order peaks. Illite shows the same average value for samples of residual soil, weathered and unweathered shale,

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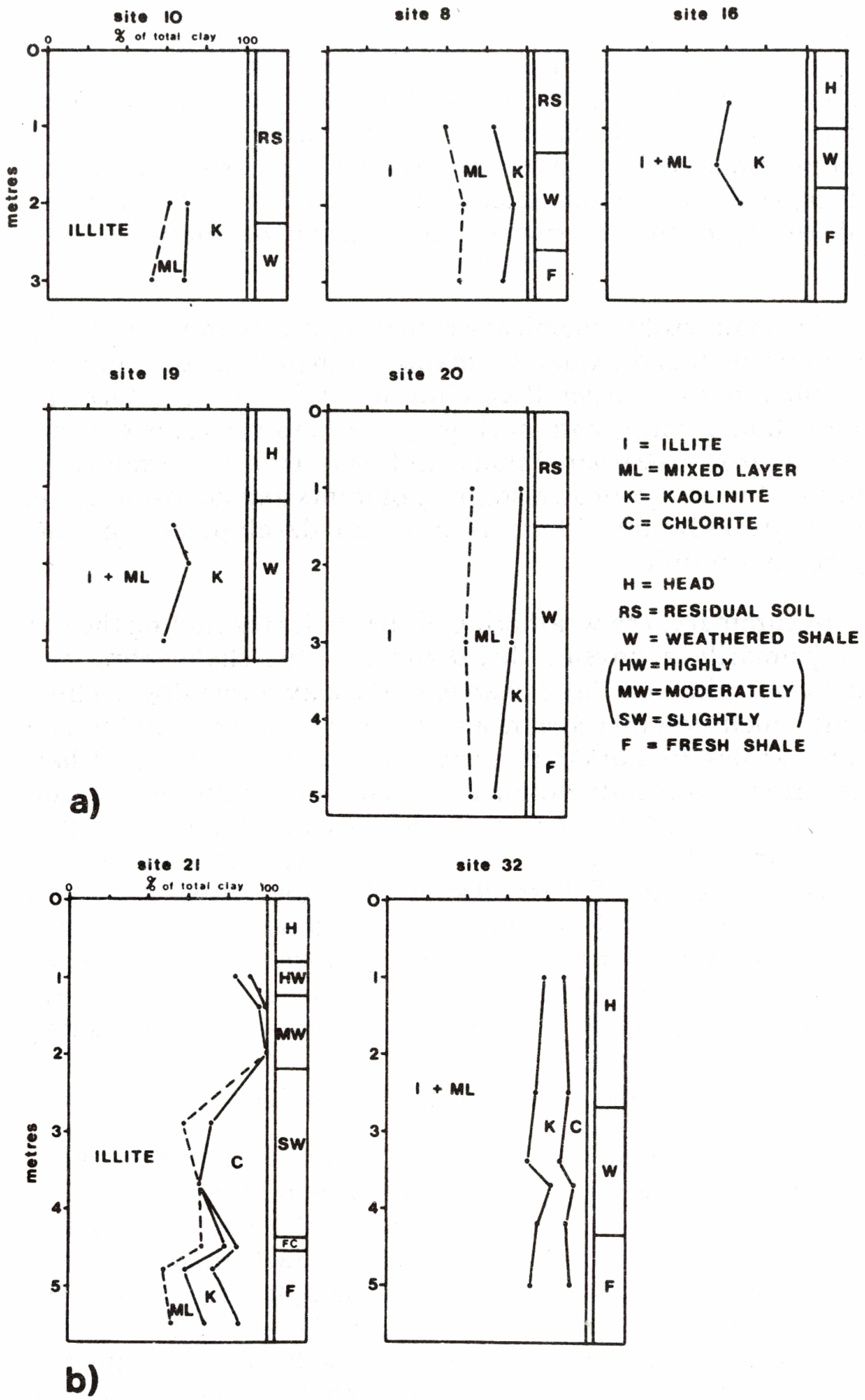

Figure 2. Vertical sections of clay mineral suites through the weathering profile at various sites on (a) non-chloritic shale (b) chloritic shale

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and thus its crystallinity is unaffected by weathering. However, kaolinite appeared more disordered on weathering, in general. As mentioned earlier the 7 Å: 14 Å chlorite peak ratio shows a variation that can be linked with the degree of weathering. The variation is from approximately 2.5 to 3 for fresh shale down to slightly less than I for completely weathered material. This would be consistent with a loss of iron from the chlorite structure during weathering (Brown 1961).

The main visible chemical weathering effects appear to be due to iron movement and oxidation, mainly from primary disseminated and nodular pyrite, rather than chlorite. Oxidation produces the marked colour change from dark grey shales to very pale grey and pale yellow-brown weathered shales and clays. Iron oxide movement is indicated by orange-brown staining of joints and deposition from emerging groundwater. There is iron-pan development in some valley bottom profiles.

In summary, the weathering of the shales (excluding the top-soil) is primarily a physical breakdown of the shale fabric to a residual clay, with very little change in the clay mineralogy. This is the same conclusion that Spears and Taylor (1972) reached for Coal Measures shales in Yorkshire. Any minor changes detected have been towards a more illite-dominated residual soil with kaolinite and chlorite being degraded. Most of the chemical alteration is a result of pyrite decomposition. The lack of any suggestion of kaolinisation, compared to studies of Petrockstow (Bristow 1968), we would attribute to the relatively young age of the landscape in our area. Most of the weathering here could be assigned to temperate postglacial and interglacial conditions during the Quaternary. Kaolinisation is a product of a warmer Tertiary style of weathering.

5. Primary mineralogical variations

Over the area studied the clearest division in terms of basic clay mineralogy of the fresh shales, and in general the persistence of this same mineralogy through to weathered shales, is between chloritic and non-chloritic types (Table 2). Fig. 3a distinguishes those sites where chlorite exists in the freshest sample, from those with none. The distribution of these two types shows a grouping into distinct areas of the map. Combining these results with a summary of structural mapping data suggests a stratigraphical control on the mineralogy. Although complicated by minor folds and faults, the conclusion is that the non-chloritic shales occur at a lower

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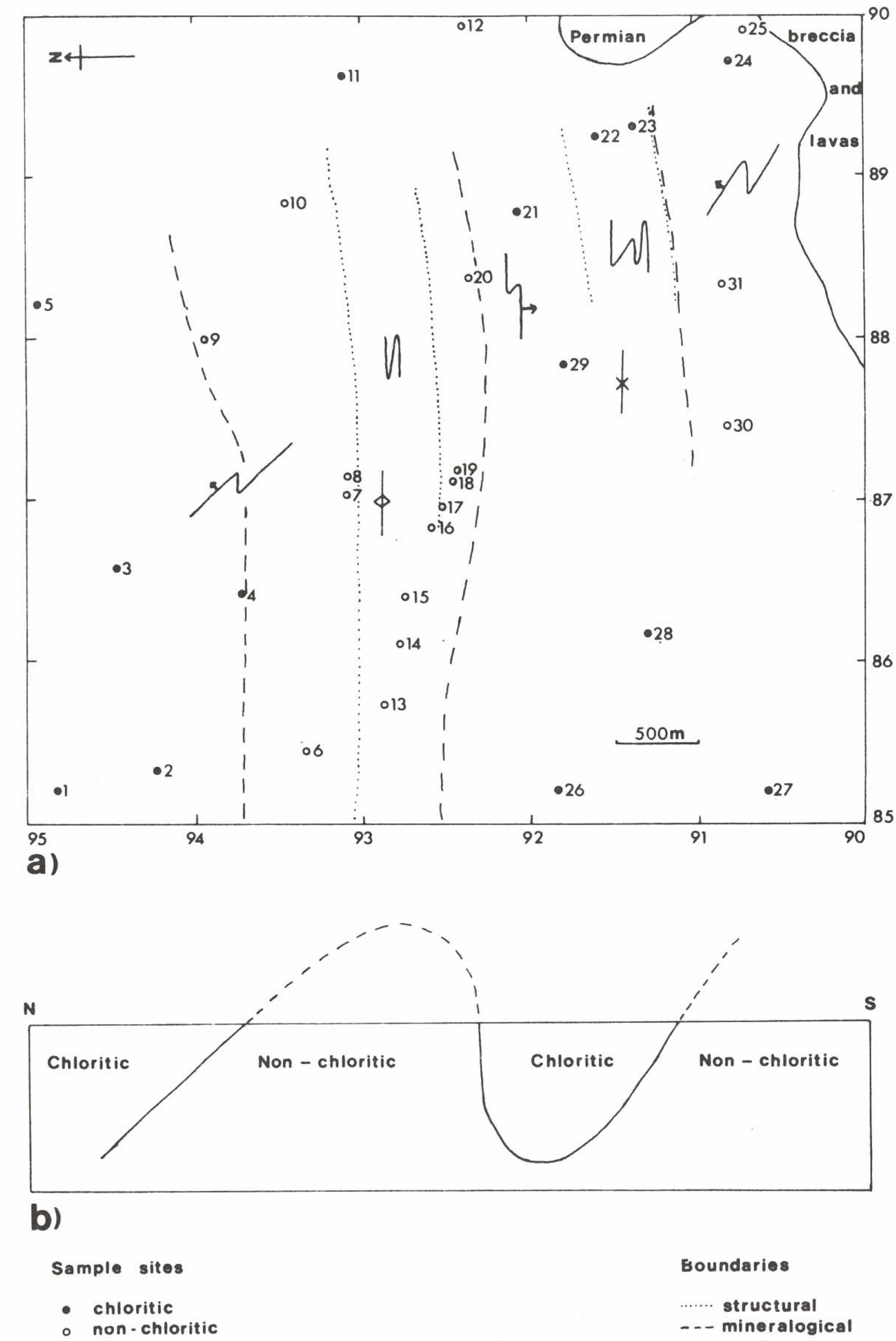

Figure 3. (a) Map of the study area (SX89SE) with sampling sites, approximate zones of consistent fold styles, and mineralogical divisions.
(b) Simplified cross section of major structure.

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Site	Illite & Mixed layer	Kaolinite	Chlorite	% <μ Clay	% 2-6μ Silt	% >6μ Sand
1	88	0	12			
2	62	7	31			
3	77	0	23	27	48	25
4	65	0	35			
5	61	9	30			
6	100	0	0			
7	61	39	0	38	51	11
8	66+22	12	0			
9	100	0	0			
10	52 + 16	32	0			
II	65	0	35			
12	68	32	0			
13	78	22	0			
14	78	22	0			
15	78	22	0			
16	67	33	0			
17	100	0	0	48	47	5
18	63	37	0			
19	58	42	0			
20	73 + 12	15	0			
21	52 + 17	17	14			
22	59 + 0	16	25			
23	46+31	7	16			
24	73 + 17	6	4			
25	65 + 15	20	0			
26	64	8	28			
27	62	16	22			
28	66	0	34	29	42	29
29	88	0	12			
30	95	5	0			
31	100	0	0			
32	76	10	14			

stratigraphical level, exposed in the core of an anticline followed by the Alphin Brook valley (Fig. 3b). To the north these pass up into northward-dipping chloritic shales, and to the south terminate along a distinct east-west line against high angle southward-facing chloritic shales with frequent sandstones around Pocombe Bridge. Farther south again non-chloritic material is thought to represent another anticline.

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Lithologically the shales with no chlorite contain fewer sandstones and siltstone beds and are weaker but less splintery than those with chlorite. These differences are reflected in the grain-size distributions of the residual soils in each area, the results of which are included in Table 2. Also, an inspection of the results of plasticity tests on samples from the A30 site investigation boreholes show an average Liquid Limit of 58 per cent (max. value 82 per cent) in the Alphin Brook Valley, and an average of 42 per cent (max. value 50 per cent) for the area around Pocombe Bridge.

These geotechnical differences in the shales and residual soils give rise to noticeable topographical variations. Slopes average about 10^{o} and rarely exceed 20^{o} in the non-chloritic zone, whereas to the north and south of this the average is nearer 15^{o} with valley sides often exceeding 25^{o}. Soil creep and landslipping activity is concentrated within the central zone due to thicker finer-grained residual soil and higher groundwater conditions.

6. Conclusions

Clay mineral studies of Crackington Formation shales in an area west of Exeter have shown them to be illite-dominated, with subsidiary kaolinite, chlorite and mixed-layer material also present. Weathering to residual clay soils is shown to have little effect on the clay mineral suite, except for minor degradation of chlorite and kaolinite. Areas of ground with no chlorite present are thought to represent the outcrop of strata at a lower stratigraphical level. These areas can also be distinguished by a different lithology which gives rise to different geotechnical and topographical characteristics.

Acknowledgements. We would like to thank Mr J.N. Eathome of the South Western Road Construction Unit for access to the A30 site during construction and for allowing us to examine site investigation reports. We would also like to thank the Professor of Physics in this University for the use of the X-ray diffraction equipment in his Department.

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British Triassic Palaeontology: supplement 2

by G. Warrington

Since the submission of the writer's previous supplement (*Proc. Ussher Soc.*, **4,** 75; 1977) to his paper on British Triassic palaeontology the following works dealing with or including aspects of that subject have appeared:

POOLE, E.G. 1977. Stratigraphy of the Steeple Aston Borehole, Oxfordshire. *Bull. Geol. Surv. G.B.*, No. **57**, 85 pp.

SAVAGE, R.J.G., (Ed.) 1977. *Geological Excursions in the Bristol District*, University of Bristol, 196 pp.

SYKES, J.H. 1977. British Rhaetic Bone-Beds. *Mercian Geol*. **6,** 197-239.

TUCKER, M.E. 1977. The Marginal Triassic deposits of South Wales: continental facies and palaeogeography. *Geol. J.*, **12**, 169-188.

TUCKER, M.E. and BURCHETTE, T.P. 1977. Triassic dinosaur footprints from South Wales: their context and preservation. *Palaeogeog. Palaeoclimatol. Palaeoecol.,* **22**, 195-208.

WARRINGTON, G. 1977. Palynological examination of Triassic (Keuper Marl and Rhaetic) deposits north-east and east of Bristol. *Proc. Ussher Soc***.,** **4**, 76-81.

WARRINGTON, G. and OWENS, B. (compilers). 1977. Micropalaeontological biostratigraphy of offshore samples from south-west Britain. *Rep. Inst. Geol. Sci.,* **No. 77/7**, 49 pp.

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Palynological features of the late Triassic - early Jurassic sequence in west Somerset (Abstract)

by G. Warrington

The Keuper Marl to basal Jurassic (*planorbis* Zone) succession at St Audrie's Bay and Lilstock, west Somerset, has been examined palynologically at 98 horizons in a 119 m sequence; 53 horizons yielded palynomorphs. The lowest assemblage from the Keuper Marl comprises reworked late Permian miospores of unknown provenance but indigenous late Triassic miospores, currently forming the fullest palynological record from the highest Keuper Marl in Britain, occur in the upper 45 m of that unit. The diversity of these assemblages, and their affinity with those of the overlying Rhaetic, increases upwards; in the topmost metre of the Keuper Marl dinoflagellate cysts occur sporadically and, in the Rhaetic, the assemblages are augmented by foraminifera, scolecodonts and significant numbers of organic-walled microplankton (mainly dinoflagellate cysts). An abrupt decrease in diversity occurs at the top of the Rhaetic and assemblages from the Lias comprise relatively few miospore and acritarch taxa in contrast to the profuse and varied assemblages typical of the Rhaetic.

The variations in composition and diversity in the palynomorph associations correspond closely with facies changes; they are thus probably environmentally induced and related to the onset and progress of the transgression which resulted in the establishment of an open sea environment in Britain by Hettangian times.

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THE VARISCAN GRANITES OF SOUTH-WEST ENGLAND: A PROGRESS REPORT

by J.R. Hawkes and J. Dangerfield

Abstract. The field characteristics, distribution and apparent relationships of the principal textural types are described. These types include megacrystic and mesocrystic coarse granites forming about 90 per cent of the major plutons, medium-grained lithium-mica granite of restricted occurrence, and two contrasting varieties of fine-grained granite. Some new chemical data relating to Zr, Ti, Li and Be in the Dartmoor Granite are given. A review of published isotopic age data and ideas related to genesis shows that fundamental questions remain unsettled.

1. Introduction

Several years ago the Geological Survey initiated a petrological study of the Variscan granites in south-west England. The South-West England Field Unit programme has provided a stimulus for mapping the Dartmoor and, more recently, the Land's End, Godolphin and St Michael's Mount granites. Field coverage of these intrusions and of the St Austell, Kit Hill and Hingston Down bodies is complete; also that of the Meldon Aplite dyke. Approximately one fifth of the Bodmin Granite has been surveyed and field work there will be completed in 1978. The Carnmenellis Granite is being examined by the South-West Unit field staff during the re-mapping of the Falmouth Sheet, and it is hoped that all the islands of the Scillies intrusion will be visited in 1979. With the addition of the small bodies of Cligga, St Agnes, and the Seven Stones, a full account of the work is planned for publication in 1981-2.

So far observations have been made at 1684 localities, and it is felt that there is now sufficient field information to present generalized definitions of the Variscan granitic rock types on a province-wide basis, together with provisional comment on their distribution and apparent relationships. The account also contains some new chemical data and discussion of questions relating to the age and origin of the granites.

2. Rock types

Only the main field characteristics of the rock types are considered here. Detailed petrography will be given in a future account.

Apart from certain lithium-rich varieties, the granitic rocks are all composed predominantly of quartz, potassium-feldspar and sodic plagioclase, with variable quantities of biotite, and accessory

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minerals which commonly include muscovite, tourmaline, zircon, topaz and apatite. The following broad divisions are proposed principally on textural grounds:

coarse granite	(megacrystic types)	forming over 90 per cent of
	(mesocrystic type)	the main plutons,
medium-grained	(non megacrystic)	restricted occurrence,
lithium-mica granite	(varieties)	
fine granite	(megacryst-rich types)	forming less than 10 per cent
	(megacryst-poor types)	of main plutons.

The average grain-size of groundmass constituents in the coarse granites is of the order of I mm, but the larger feldspar crystals in these rocks allow a two-fold division into megacrystic varieties and a mesocrystic type.

The megacrystic granites are characterised by feldspar crystals (principally orthoclase perthites) ranging from 15 mm to 170 mm in length and comprising from about 1 to 30 per cent of the rocks by volume. It seems that as the percentage of megacrysts increases, so does their mean length. Field point-counting using a 15 mm grid has established a complete gradation in megacryst content which can be demonstrated along the coast section of the Land's End Granite between Porth Nanven (SW 355 308) and Gribba Point (SW 355 302). On the distribution map (Fig. 1), megacrystic granite is distinguished from poorly megacrystic granite at an arbitrary megacryst content of 10 per cent.

In marked contrast, the mesocrystic type is characterised by feldspar crystals, here termed mesocrysts, which are smaller on average than megacrysts, and commonly arranged to give a rock a distinctive linear texture. The major intrusions where this rock-type is developed have yet to be fully examined; preliminary results indicate a range in mesocryst length from 15 mm to about 40 mm (average 20 mm), and in content of the whole rock from I to 7 per cent. The mesocrysts are generally more closely packed than are the megacrysts of the other coarse-grained varieties, but because of their smaller size constitute a relatively small proportion of the whole rock.

Lithium-mica granites display an even, medium-grained texture (mean grain-size about 0.5 mm) lacking both mesocrysts and megacrysts. Another feature is the presence of very pale brown lithium-mica instead of the dark brown biotite characteristic of other granitic rocks. Less obvious mineralogical differences include the

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albitic composition of all the plagioclase and a relative abundance of accessory topaz. One body, the Meldon Aplite, contains distinctive green crystals of lithium-tourmaline. As in the case of the various biotite-granites, quartz and potassium-feldspar are major constituents.

The fine-grained granites are readily distinguished not only on account of the actual fineness of their groundmass constituents, but also by a variation in average grain-size of the order of one magnitude. Mean groundmass grain-sizes range from around 0.06 mm to 0.6 mm. Rocks of this group can be divided into biotite-rich types bearing numerous megacrysts of feldspar, quartz and biotite, and biotite-poor types in which megacrysts are rare or locally absent. In both, feldspar megacrysts typically range up to about 60 mm in length, but normally are smaller than those in the megacrystic granites, and generally much less abundant. The biotite content varies from 1 per cent up to at least 17 per cent by volume, with values most commonly within the ranges I to 5 per cent and 10 to 15 per cent. In contrast, the average biotite content of coarse granites lies between these ranges.

There remain two groups of transitional rock-types. The first includes finer grained varieties of the megacrystic granite commonly associated with the megacryst-poor fine granites, which can be seen, for example, in coastal exposures of the Land's End Granite north of Morvah and in the River Dart below Dartmeet. The second comprises biotite-rich finer varieties of megacrystic granite which are displayed near the contacts around Mousehole and along the southeastern margin of the St Austell mass.

3. Distribution and apparent relationships

Figure 1 shows the distribution of the principal varieties of granite. An outstanding feature is an alternation in the textural character of the coarse granite forming the major plutons, for which there is no obvious explanation. Dartmoor, St Austell and Land's End are characterised by megacrystic varieties, while Bodmin Moor, Isles of Scilly and Carnmenellis (including Carn Marth and Carn Brea) are composed principally of mesocrystic granite.

The minor bodies, however, do not follow any particular pattern. Seven Stones, Cligga Head and the eastern part of Hingston Down are composed of poorly megacrystic granite; St Michael's Mount and Kit Hill of mesocrystic granite. The Tregonning-

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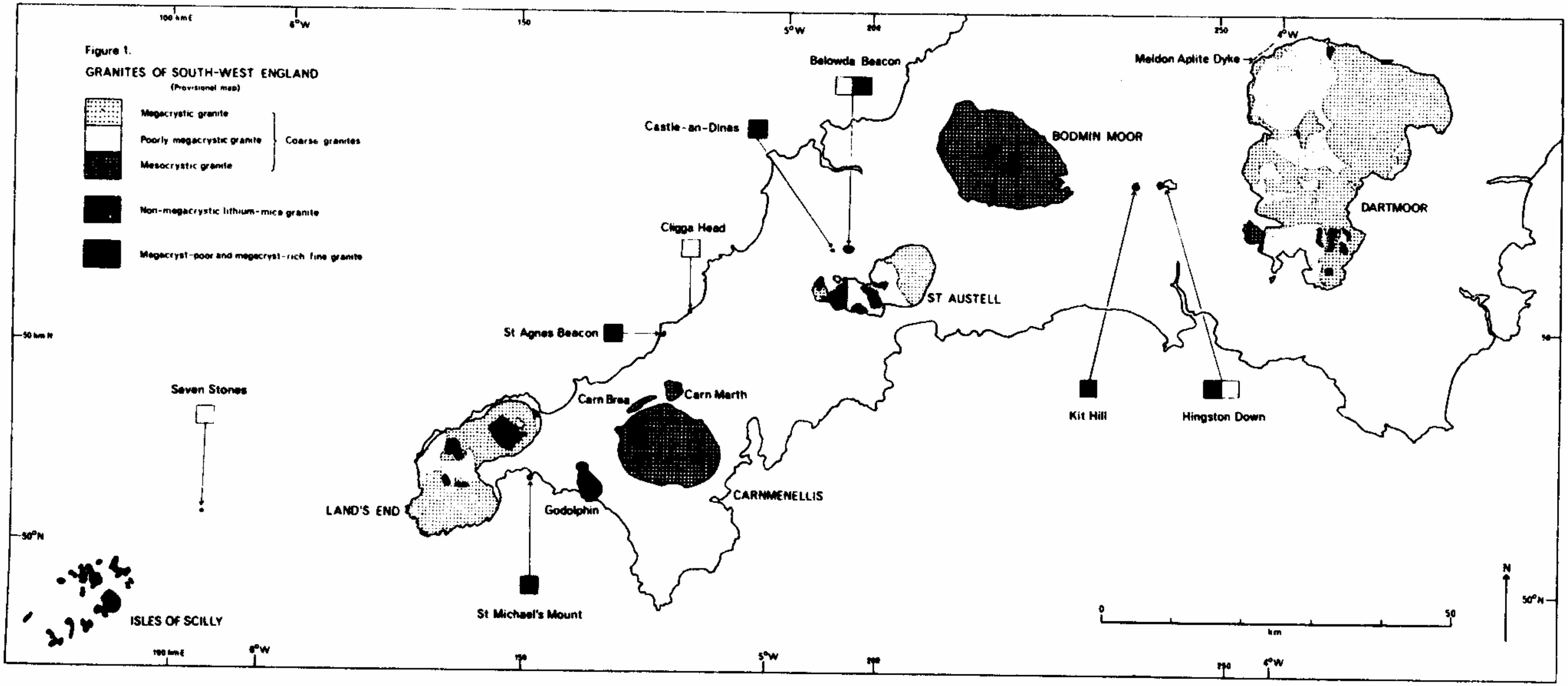

Figure 1.
GRANITES OF SOUTH-WEST ENGLAND
(Provisional map)
Megacrystic granite
Poorly megacrystic granite
Mesocrystic granite
Coarse granites
Non-megacrystic lithium-mica granite
Megacryst-poor and megacryst-rich fine granite
Belowda Beacon
Castle-an-Dinas
Cligga Head
St Agnes Beacon
Seven Stones
Carn Brea
Carn Marth
LAND'S END
Godolphin
CARNMENELLIS
St Michael's Mount
ISLES OF SCILLY
ST AUSTELL
BODMIN MOOR
Kit Hill
Hingston Down
Meldon Aplite Dyke
DARTMOOR
km
N

Godolphin intrusion is mainly a lithium-mica type apparently with an area of megacryst-bearing fine-granite forming Godolphin Hill. The St Agnes Beacon outcrop seems also to be of the latter type, and the western portion of Hingston Down is composed of megacryst-poor fine-granite. The granitic outcrops of Belowda Beacon, Castle-an-Dinas and St Dennis (SW 950 582) are considered to be part of the St Austell mass because the rocks are similar to marginal varieties in the main body, and because the Devonian sediments around and underlying Goss Moor (SX 950 597) are thermally metamorphosed.

The map (Fig. 1) shows that within the Dartmoor and Land's End masses the distribution of the megacrystic granites is somewhat complex, whereas in the St Austell pluton it is relatively simple. Coarse granite with more than 10 per cent of feldspar megacrysts predominates in the first two; the two megacrystic types are almost equally represented in the St Austell body.

Variations within the mesocrystic granite masses, although observed in quarries in the Carnmenellis pluton, have proved unmappable in the area of Bodmin Moor examined so far.

Attention should be drawn to an area of mesocrystic granite which grades into poorly megacrystic material forming the extreme south-west of the Dartmoor mass. So far, no comparable areas of megacrystic granite have been found within the major mesocrystic bodies, but small developments of poorly megacrystic granite do occur in the Bodmin Moor intrusion. Conversely, poorly megacrystic granite of the Land's End mass grades locally into minor developments of mesocrystic material.

Most of the Tregonning-Godolphin body consists of lithium-mica granite. Unfortunately, contacts against other granitic materials are not exposed. Stone (1975) has suggested that the present fabric and mineralogy result from recrystallisation and autometasomatism. Two regions in the St Austell mass are composed of lithium-mica granite; one in the west-central ("chinastone") part, the other, a much smaller body, occurring just ESE of Hensbarrow Beacon (SW 997 575). Biotite in surrounding

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poorly megacrystic granite seems from field observation to have been extensively replaced by paler brown lithium-mica, due perhaps to fluids emanating from these two bodies. It is possible that they themselves originated in the same manner as the lithium-rich rocks of the Tregonning-Godolphin Granite. The Meldon Aplite provides a fourth occurrence of lithium-rich granitic rock, forming a 3.5 kin-long dyke intrusive into country rocks NW of the Dartmoor pluton.

For simplicity the areas of fine granite, irrespective of type, are depicted on the map in solid black (Fig. l). At the scale used, only the principal areas can be shown, but many smaller outcrops have been located within the three megacrystic granite masses. Additionally, fine granites have been recorded at numerous individual localities where they can form small isolated pods, horizontal, inclined and vertical sheets, or irregular masses. Fine granites occur in similar forms within the mesocrystic intrusions and as relatively small inclusions in the lithium-mica granites.

The larger bodies of fine granite transgress from regions of high megacryst content to those with less than 10 per cent. Their distribution is by no means consistent, being associated in the St Austell mass mainly with the poorly megacrystic granite and within the Dartmoor and Land's End plutons mainly with richly megacrystic granite. Some major and most minor outcrops of fine granite are composed predominantly of either biotite-rich, or biotite-poor types. A few areas, particularly the one around Castle-an-Dinas (SW 485 350) on the Land's End mass, exhibit a range of mineralogical and textural varieties. At Porthcurno (SW 3915 2235) on the Land's End peninsula, a gently inclined fine granite sheet, 100 m thick, grades through various types and then imperceptibly into underlying coarse megacrystic granite.

Junctions between the larger bodies and enclosing coarse granite are rarely exposed. On the small scale, however, numerous examples show smooth or irregular, and sharp, gradational or pegmatitic contacts. Interlayering of fine and coarse granite is characteristic of some larger masses and veining of fine granite by coarse megacrystic granite has also been observed.

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4. Chemistry

The broadly similar potassic nature of most granitic rocks was established by the early analyses (Hill and MacAllister 1906; Reid and Flett 1907; Ussher and others 1909; Reid and others 1912; Ghosh 1927; Brammall and Harwood 1932; Ghosh 1934).

According to published data, it seems that there are no major differences in chemistry between the biotite-bearing megacrystic and mesocrystic types. Only the medium-grained lithium-mica rocks constituting the Meldon Aplite Dyke, much of the Godolphin intrusion and the two "chinastone" regions of the St Austell Granite differ significantly in composition. They show especially enrichment in Na and Li relative to K (McClintock 1923; Exley 1959; Exley and Stone 1966; Stone 1975). Spark-source mass-spectrographic analysis of material from Meldon and Godolphin suggests also some relative enrichment in Rb and Cs and marked depletion in rare earths. For example, the lanthanum content of two Meldon specimens lies in the range 0.2-2.0 ppm La; that of a single Godolphin sample in the range 0.6-6.0 ppm La. Other rare earth elements apparently occur in quantities generally of < 1 ppm. These values contrast with spark-source mass-spectrographic results from two biotite-bearing megacrystic granite specimens where lanthanum, for instance, is present in the range 20-200 ppm La. The europium contents of both types of granitic rock are low; respectively<0.3 ppm Eu and 0.2-3.0 ppm Eu. However, because of the extensive replacement of plagioclase by potassium-feldspar, and of the secondary albitic nature of much of the plagioclase (particularly that in the lithium-mica granites), this is an expected feature. It is perhaps worth stressing that europium depletion in granites is more likely to be a direct reflection of mineralogical developments like these which involve the removal of calcium, than an infallible guide to the degree of differentiation undergone by the original magmas.

Textural evidence from the megacrystic and mesocrystic granites of south-west England indicates that quartz and muscovite, as well as the feldspars, owe existence in their observed form largely to metasomatic reactions and transformations, so that none of their contained elements will characterise with certainty the chemistry of the original magmas. Thus, any whole-rock data, including the results of isotopic investigations, may be useful only in illuminating complex events post-dating emplacement.

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With this reservation in mind, limited optical emission spectrographic analysis was performed by the Analytical and Ceramics Unit, I.G.S. on samples from the Dartmoor Granite for Zr, Ti and Li, while the γ - η technique (Bowie and others 1960) has allowed determination of Be. Zirconium and Ti were chosen as possible indicators of early chemistry; Li and Be because of their probable late entry into presently observed mineral species. The data are presented in provisional form as mean and range figures for the principal rock types (Table 1).

It seems from these figures that Zr and Ti show a reasonably systematic variation in sympathy with each other and according to rock type. Lithium apparently has a more random distribution. The Be content of the rocks is surprisingly constant. More detailed comment on this data is beyond the scope of the present paper.

5. Age and origin

Despite numerous isotopic studies, the date of emplacement of the plutons has not been satisfactorily resolved (see Miller and Mohr 1964). A suggestion that their arrival should be equated with the contact metamorphic K/Ar age of c. 295 Ma derived from doleritic dykes at Meldon remains the best informed opinion (Fitch and Miller 1964). There is only one published whole rock Rb/Sr isochron and that yields a somewhat ambiguous age of 288 ± 13 Ma for the St Austell Granite (Harding and Hawkes 1971). Subsequent application of the computational method described by Brooks and others (1972) has made this figure 285 ± 12 Ma, and the $^{87}Sr/^{86}Sr$ ratio 0.7086 ± 0.0034. An attempt to produce another Rb/Sr isochron, this time using 21 samples from the Dartmoor mass (including 6 specimens of fine-grained megacryst-rich granite), has succeeded in emphasizing the difficulties posed by the mineralogical transformations already mentioned, and also more subtle alterations which may have been partly connected with the province-wide elvan volcanism. Whole-rock Rb/Sr data indicate an approximate age of 269 Ma for this activity (Hawkes and others 1975), which ushered in the period of greisenization and primary tin mineralisation. Serious account needs to be taken of other factors. One of these is the deep-seated mantle volcanism represented by the ubiquitous c. 280 Ma-old minette lamprophyres and the penecontemporaneous, though geographically more restricted potassic basalts and biotite-rhyolites. A second factor relates to exposure of the Dartmoor Granite during the latter volcanism (Dangerfield and Hawkes 1969; Hawkes 1974). From about that time, the presently exposed granitic rocks clearly were subject periodically to groundwater circulation. For example,

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Table 1. Mean and range figures (µg;g) for Zr, Ti, Li, and Be in samples from the Dartmoor Granite

	Zr	Ti	Li	Be
Megacrystic granite	165 (56-527)	2899 (1400-6400)	251 (130-400)	12 (6-69)
	20	**27**	**27**	**24**
Poorly megacrystic granite	58(0-320)	1296 (90-4200)	340 (22-827)	14(5-28)
	20	**38**	**38**	**37**
Mesocrystic granite	30(18-58)	984 (527-1600)	222 (35-360)	12(4-19)
	3	**3**	**3**	**3**
Fine granite: megacryst-poor	34(5-142)	827 (337-1357)	284 (12-1052)	16(4-53)
	14	12	12	**10**
Fine granite: megacryst-rich	178 (110-377)	1846 (1000-2596)	370 (130-925)	8(4-11)
	10	**10**	**10**	**10**
Xenoliths	158 (102-222)	2750 (2512-3148)	432 (258-596)	7(5-10)
	3	**3**	**3**	**3**

groundwaters present during both the minette and later elvan volcanic episodes may have become sufficiently hot locally to cause some selective redistribution of Sr and Rb isotopes, as well as those of Ar, K, and possibly other elements now coming under investigation. Significantly, published isotopic data (excepting those from the Meldon Aplite) indicates a spread of ages between c. 303 Ma and c. 265 Ma, with a suggestion of groupings around 295-303 Ma, 277-285 Ma and 265-273 Ma. That results for the Scilly Isles Granite appear the highest (Miller and Mohr 1964) could be due to lack of lamprophyre intrusions. The nearest known minette dyke occurs at Chyweeda, near Leedstown (SW 6125 3261), 70 kilometres away on the mainland.

More recent isotopic age work has centred on lode minerals depicting events post-dating elvan intrusion and primary mineralization. On the basis of ^{40}Ar - ^{39}Ar data from the St Just district, for example, Halliday and Mitchell (1976a) suggested the possibility of hydrothermal degassing of lode material around 210 Ma and 215 Ma which overprints a primary formation age of roughly 270 Ma. New mineral growth may have occurred close to 165 Ma with further hydrothermal activity at about 100 Ma. Adularia from veins in the Lizard Complex also provides indication of hydrothermal events around 210-220 Ma and 160-170 Ma (Halliday and Mitchell 1976b). Activity in the latter period may have been even more widespread in that it could include the outburst of unlocated, but dominantly trachytic volcanism which produced the debris now forming the Middle Jurassic fuller's earth deposit of the Bath district (Jeans, Merriman and Mitchell 1977). Other igneous events, the extrusion of the Lower Cretaceous Wolf Rock Phonolite (see Harrison and others 1977) and intrusion of the Eocene Lundy Granite and associated basaltic and trachytic dykes (see Edmonds and others, in press), are already well known.

Mention is made of all these ages, because one, possibly others, may indicate the timing of relatively high temperature, deep-seated, regional hydrothermal (geyser) activity that caused extensive mineralogical destruction in parts of some granite plutons. Whether the presently observed kaolin results from Tertiary weathering is not an issue here (Sheppard 1977; Bristow 1977), rather the fact that perhaps for a third time after emplacement of the granites, groundwaters throughout the province were involved in mantle-induced heating and thus instrumental in disturbing various of the radiometric clocks in granite minerals.

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These matters are of some importance in considering the origin of the granite magmas, for which of course there are two possibilities: derivation from the mantle, or melting of crustal material. Because of all the foregoing chemical uncertainties, the solitary published initial $^{87}Sr/^{86}Sr$ ratio cannot be taken seriously. In any case, the actual figure (0.7086) favours neither source.

Most authors have opted for a palingenetic origin, mainly on account of the apparent orogenic setting(see, for example, Brammall and Harwood 1932; Exley and Stone 1966). With the advent of plate tectonic theory and its possible application to igneous activity in south-west England, Floyd (1972) again reviewed this problem. He concluded that evidence of an unbroken Moho (Bott and others 1970) and the solitary $^{87}Sr/^{86}Sr$ ratio of 0.7067 (recalculated value, 0.7086) indicated a deep crustal origin. However, in applying his lateral plate model, Badham (1976) argued that the granite magmas were certainly not generated in the crust by the dynamics of perpendicular continental collision. But while suggesting the mantle rather than horizontal compression as a causative influence, he declined to specify the source of the material. Sheppard (1977) has proposed probable crustal derivation with a significant argillaceous component on the basis of high $^{18}O/^{16}O$ ratios in granite samples.

Broadly, the palingenetic view has been that Variscan compression caused partial melting (granulite and amphibolite facies metamorphism) in the lower crust with the evolution of liquids of ternary minimum composition. By assimilation, reaction and crystallization at moderate depths, these fluids are thought to have produced large regions of granodioritic rock, leaving residual material enriched in H_2O and K to migrate still higher, there incorporating predominantly argillaceous sediments and forming the presently exposed granite plutons.

Textural evidence suggests that primary crystallization (at least in the case of Dartmoor) yielded a mush of trondjhemitic composition, the present mineralogy resulting from sustained interaction with contained K-rich aqueous fluids (Edmonds and others 1968). Crystallization was seemingly initiated under isometric or adiabatic conditions, rather than those envisaged in ternary minimum theory (Hawkes 1968). This could imply rapid ascent from deep crustal regions.

If ascent of the magma was comparatively rapid, the age of emplacement at observed levels becomes a particularly critical factor

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in understanding the genetic processes. Thus even the oldest date (c. 303 Ma; K/Ar) implies a largely post orogenic event, which immediately poses two questions. First, would acceptance of a palingenetic origin mean that the plutons had punched their way through an older, perhaps Middle to Upper Devonian granodioritic batholith? Secondly, why should mobile magmas have been generated in the waning stages of the orogeny?

Alternatively, if the concept of comparatively rapid ascent is put into Badham's theory of lateral plate movement, different questions arise. For example, was there a connexion between genesis of the granite magma and the mantle activity responsible for the seemingly later lamprophyre volcanism? Could this mantle activity have been directly responsible for the granitic magma, or instead the cause of melting in the lower crust? What are the comparative ascent rates of granite and lamprophyre magmas? Was eventual extrusion of the lamprophyric material dependent on deep-seated isostatic fracturing related to the rise of the plutons? How could the Westphalian folding in supracrustal rocks be explained in this context? Is the geophysical model misleading in that no orogenic batholith exists after all? Similar questions are posed by the Carboniferous lamprophyres and granites of the Channel Islands-Contentin-Côtes-du-Nord region, where isotopic ages apparently indicate a much closer temporal association of these contrasting rock types (Lees 1974).

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A CLUSTER ANALYSIS OF CHEMICAL DATA FROM THE GRANITES OF S.W. ENGLAND

by M. Stone and C.S. Exley

Abstract. Of the four principal mainland biotite-granite cupolas, Dartmoor has lowest Al_2O_3 and highest femic constituents and Carnmenellis has lowest K_2O and total alkalis. No systematic variation is apparent.

Cluster analysis reveals three distinct groups of granitic rocks; biotite-granites, lithium-mica granites and granite-porphyries. A strong femic ion association (Ti, Fe^{2+} Mg, Ca) reflects variations mainly in the amounts of biotite and is believed to result from the cleansing of contamination products during fractionation. An antipathy between Na and K is interpreted as resulting mainly from ion-exchange and is common to all the cupolas, but the Al-Mn-P association increases in importance in the Li-mica granites. The strong trend of K-enrichment in the granite-porphyries ('elvan') is thought to reflect alkali-ion exchange with or without partial muscovitization during transit or after emplacement. A "flue" hypothesis is consistent with the features of the 'elvans' and their association with vulcanism and mineralization.

1. Introduction

A preliminary compilation of major element data, both published and unpublished, for the granites of south-west England has been obtained from the sources indicated in Fig. I. In a number of instances, several analyses are available of a single rock type from a given area or part of a cupola. These have been averaged to give a mean "type", which should be more representative of the granite than any one of the individual analyses. For example, all the coarse megacrystic biotite-granites of Dartmoor (Edmonds and others 1968) give one average rock type. On the other hand, the single analysis of a granite-porphyry at Gunnislake (Hall 1970) is given equal weighting. Such treatment leads to over-representation of minor but often petrogenetically important rock types. Truly representative (weighted) sampling can, indeed, swamp or hide geologically important patterns or trends. As long as handling bias is known and understood, due allowance can be made in drawing final conclusions.

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A comparison between the means of the coarse- (and medium) grained biotite-granites of Dartmoor, Bodmin Moor, Carnmenellis and Land's End using the Mann-Whitney U-test, shows many significant differences, some of which could be merely a reflection of individual laboratory bias. However, data from similar rocks from Dartmoor, Bodmin Moor and Land's End, but from different sources, show quite good correspondences. Hence, it is considered that differences between cupolas that are highly significant (at the 0.01 significance level) are likely to be real. The results indicate that Dartmoor is more femic than the other three cupolas and is poorer in Al_2O_3 and that Carnmenellis has lower K_2O and total alkalis, but is relatively more sodic. No clear systematic variation is apparent from the data used here.

2. Cluster Analysis

Rock types commonly follow the "continuum of nature" in passing insensibly from one into another. However, owing to processes that bring about their distribution and contrasts, distinguishable rock types may accur in juxtaposition. Cluster analysis provides a multivariate method of grouping (clustering) similar samples and types: the clearer the classification or distinctions, the higher is the degree of clustering. Comparison between samples can be made by using -the distance coefficient or the correlation coefficient (i.e. the correlation coefficient between samples, not variables: the conventional role between sample and variable is here interchanged). The correlation coefficient is used in the present study, although similar results are obtained by using the distance coefficients. The method follows the simple scheme given in Davis (1973) and the Fortran computer program used is a modified version of that given in Davis' book.

A simple cluster dendrogram based upon 26 "samples" is given in Fig. 1. The source of the data and the number of analyses that have contributed to the data for each "sample" are given in the figure. Three principal groupings emerge:

(i) Biotite-granites;

(ii) Lithium-granites plus some late terms (aplites);

(iii) Granite-porphyries ("elvans")

The marked distinction between (i) and (ii) has been observed by Floyd (1967;1968), on the basis of distributions (populations) that appear on some of the plots on probability paper, particularly those for Na, Li and Mg.

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Although the granite-porphyries tend to form a marked cluster, there are some examples scattered amongst the biotite-granites in Fig. 1, in agreement with the observation of Hall (1970) that there is gradation from biotite-granite into granite-porphyry. It is interesting and important to observe that the fine-grained Boswyn granite, which forms two small ovoid masses at the western end of the Carnmenellis cupola is classed with the "elvans' and indeed has a similar chemistry to the potash-rich "elvans".

3. Correlation

Positive correlation between elements can signify geochemical association although its amount can vary according to the amount of "weighting" given to the raw data, and it can be enhanced by spurious data. The effects of the latter can often be reduced by using non-parametric statistics (Chapman 1976).

Comparisons between correlation matrices based upon the Pearson product moment and the Spearman rank correlation coefficients shows broad agreement. Only the significance matrices are given in Table 1; these reveal the following principal features:

(i) A strong association of the femic elements Fe^{2+}, Mg, Ca, and Ti.

(ii) An Al- Mn- P association: this is weak in the Spearman coefficients and hence could be interpreted as spurious in the product moment matrix, but ig known to be a strong association in the lithium-mica granites (Stone 1975). In fact, the data of these minor, but petrogenetically highly important rocks tend to be swamped by those from the more abundant (and volumetrically more important) biotite-granites. The Mn - P association is plotted in Fig. 2; the product moment correlation coefficient is +0.53 (highly significant), but drops to -0.11 (not significant) when the three Li-mica granite plots are omitted, and agrees more closely with the rank coefficient. Clearly, the strength of a geochemical association in numerical terms can be a function of the extent of initial averaging, and the initial sampling plan, if there is one. The need to plot the points in bivariate associations and not merely rely upon the correlation coefficient, in doubtful cases, cannot be overstressed.

(iii) A strong negative correlation exists between Na and K. This pattern is clear in individual cupolas (AI-Turki 1972; Stone 1966, 1975) and has been interpreted in terms of ion-exchange particularly between the feldspars (Exley and Stone 1966).

Both (i) and (iii) are, in fact, common to individual cupolas in S.W. England. Pattern (ii) is associated closely with Na and Li in the Tregonning-Godolphin granite (Stone 1975).

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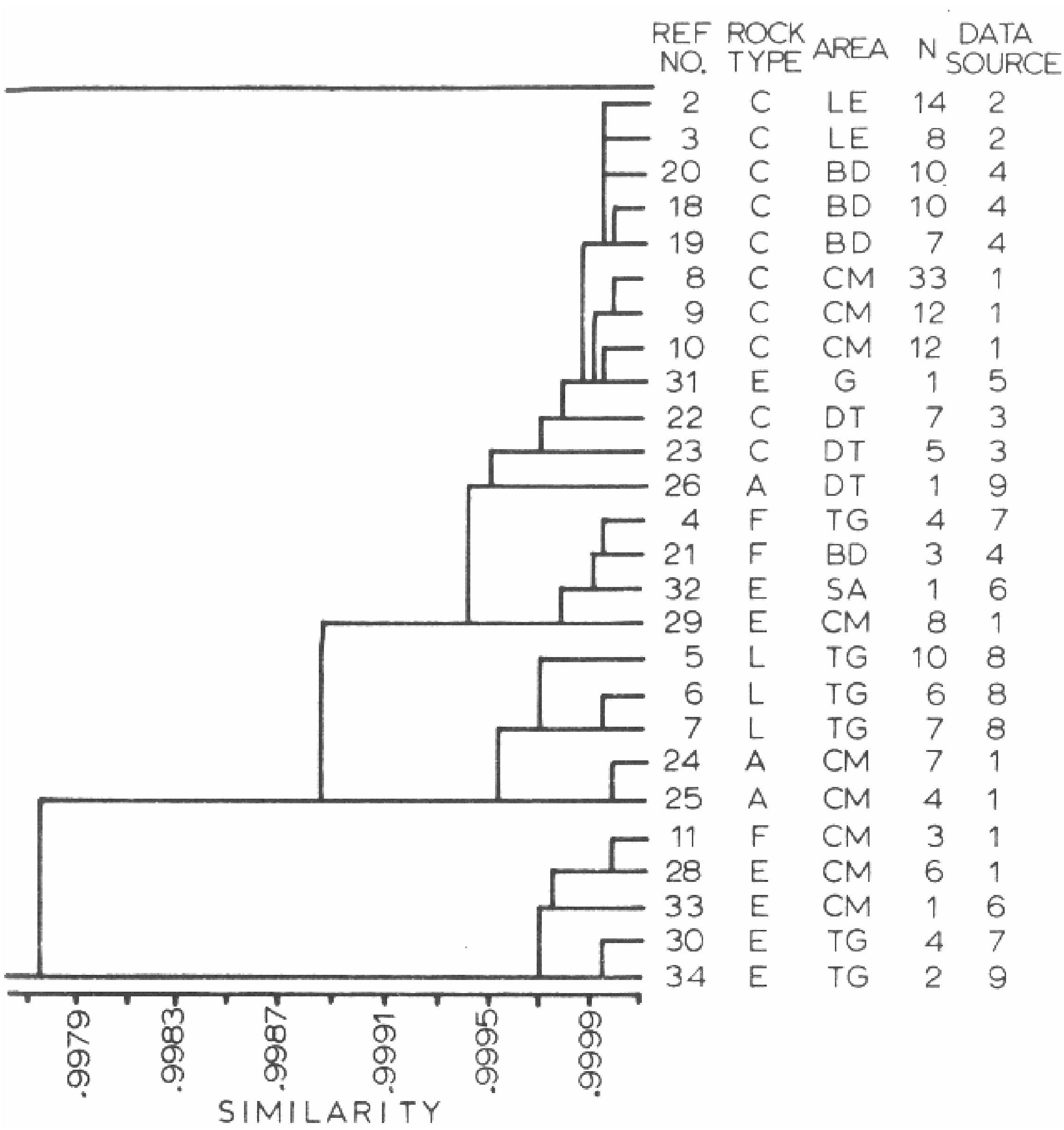

Figure 1. Cluster dendogram of 26 'samples' of granitic rocks from south-west England. Similarities are correlation coefficients. Reference numbers are `sample' identifiers used in computer input and output. Rock types: A - aplite, C - coarse-grained biotite-granite, E-‘elvan' (granite porphyry), F - fine-grained biotite-granite, L - lithium-bearing granitic rocks (not differentiated). Areas: BD - Bodmin Moor, CM - Carnmenellis, DT - Dartmoor, G - Gunnislake, LE - Land's End, TG - Tregonning-Godolphin. Data sources: 1- Al-Turki (1972), 2 - Booth (1966), 3 - Edmonds and others (1968),4 - Edmondson (1972), 5 - Hall (1970), 6- Hawkes and others (1975), 7-Stone (1968), 8 - Stone (1975), 9 - Stone (unpublished).

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SPEARMAN RANK CORRELATION

	Si	Ti	Al	Fe^{111}	Fe^{11}	Mn	Mg	Ca	Na	K	P
Si	-	0	-3	0	0	0	0	0	0	0	-1
Ti	0	-	0	1	3	0	3	3	0	0	-1
Al	-1	0	-	0	0	1	0	0	-3	0	3
Fe^{111}	0	2	0	-	0	0	0	0	0	-3	0
Fe^{11}	0	3	0	0	-	0	3	2	0	0	0
Mn	0	0	0	0	0	-	0	0	0	0	3
Mg	0	3	0	1	3	0	-	3	0	0	-1
Ca	0	3	0	0	2	0	3	-	0	0	-1
Na	0	0	0	-3	0	0	0	0	-	-3	0
K	0	0	0	1	0	0	0	-1	-3	-	0
P	0	0	1	0	0	0	0	-1	0	0	-

The significance matrices result from testing the correlation coefficients against Null hypotheses that the correlation coefficients are zero. The higher the number the more significant is the correlation. 3, 2 and 1 correspond with rejections of the Null hypothesis at the 0.001, 0.01 and 0.05 levels of significance respectively and 0 corresponds only with significance above the 0.05 level. Owing to some departures from the normal distribution and constant sum effects, only levels above 1 are accepted as indicating important correlation. Signs correspond with the signs of the correlation coefficients.

4. Discussion

An explanation for the clustering of the granites into three main rock groups is given by their distribution in some of the chemical variation diagrams, in particular, the Na - K diagram (Fig. 3) and the Quartz (Qz) - Albite (Ab) - Orthoclase (Or) diagram (Fig. 4). In both diagrams, the biotite-granites cluster in the centre, whilst the principal variations are provided by the lithium-mica granites which show a distinctive trend of Na and Ab enrichment (with time) and the "elvans" which show an equally distinctive trend (not with time) of K and Or enrichment.

(a) *Biotite-Granites*. All the coarse- and medium-grained biotite-granites cluster together in Fig. 1. Their tendency to subcluster is related to location and may again reflect laboratory bias, but could reflect real (multivariate) differences. Existing sparse data suggest that fine-grained granites tend to plot on the potash-richer side of their associated coarser biotite-granites: this is an interesting relationship, but requires more data before it can be considered with any confidence.

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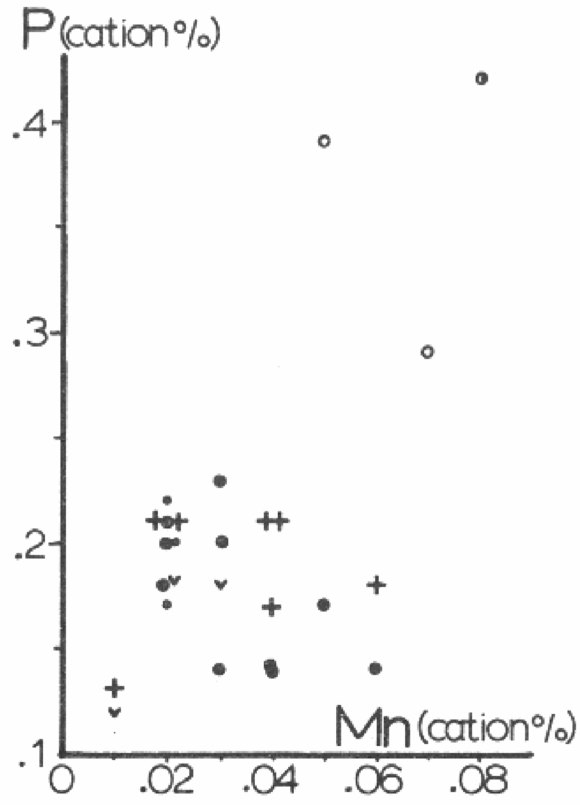

Figure 2. Mn-P variation diagram (cation weight percentages) illustrating the effects of a few data points in converting a poor correlation into one that is numerically highly significant (see text and Table 1). Symbols are as follows: Open circles - Li-mica granites; larger filled circles - coarse-grained biotite-granites; smaller filled circles - fine-grained biotite granites; small v's - aplites; crosses - granite porphyries.

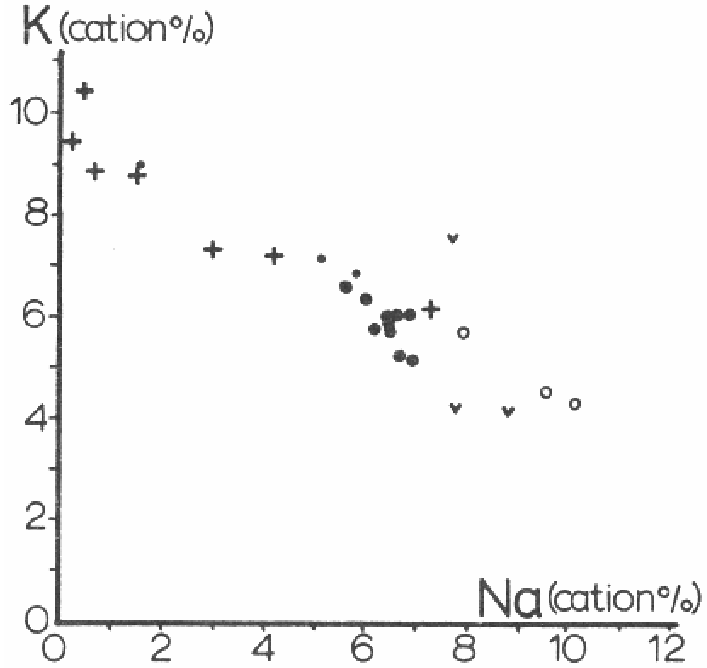

Figure 3. Na-K variation diagram (cation weight percentages). Regression equation (reduced major axis) K=-0.60 Na + 3.20. Product moment correlation coefficient - 0.94. Symbols as in Figure 2.

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The femic association referred to above is predominantly the "biotite" (or "biotite/tourmaline") association, though the high correlation with Ca indicates that it is coupled to the anorthite content of plagioclase. The amount of variation in biotite is not yet known, but is currently under investigation by the authors and others. The strong positive association between Fe^{2+} and Mg reflects decreasing biotite (of constant Mg/Fe ratio) with time and a trend towards more leucocratic products. Such a pattern is observed in the data used here, and particularly in the data from the Carnmenellis

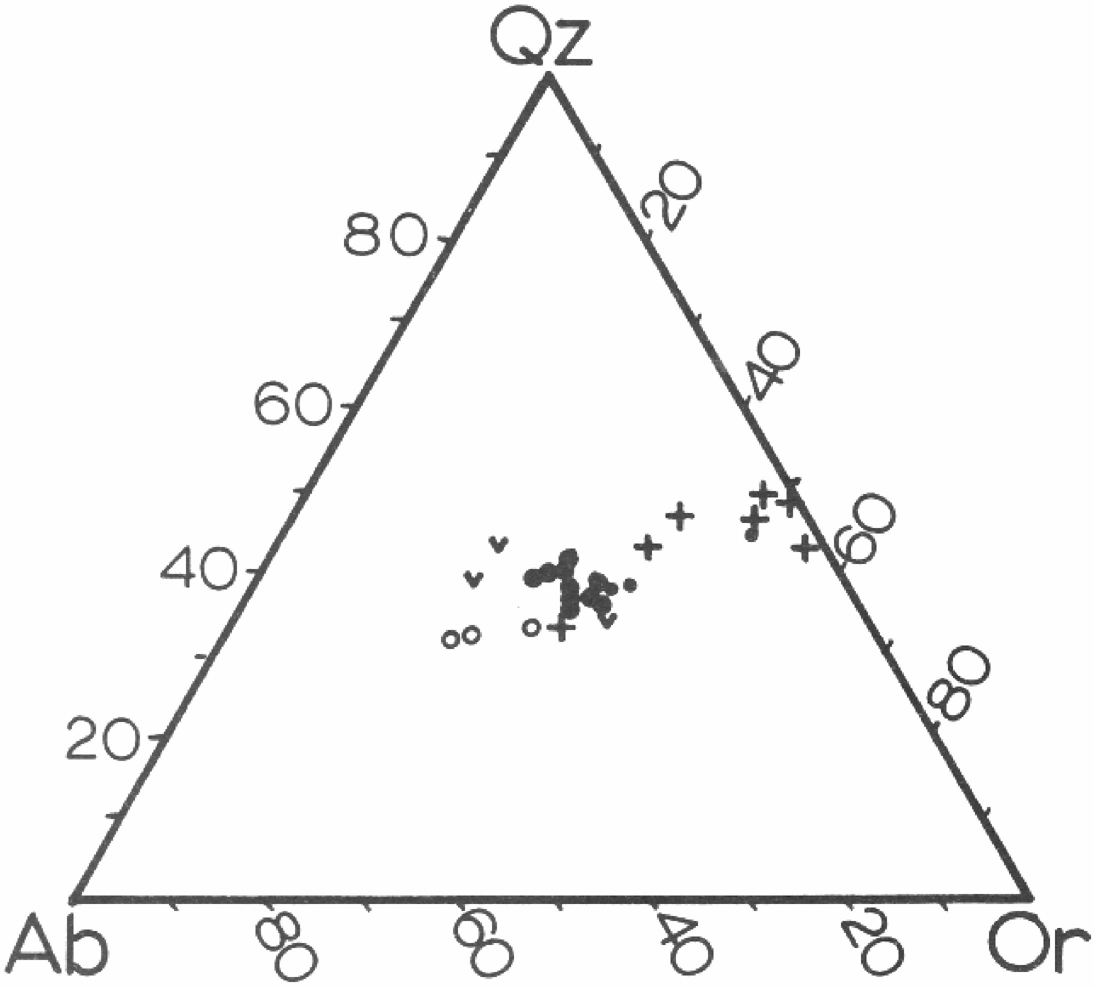

Figure 4. Plots of 26 'samples' used in cluster analysis onto the Quartz (Qz) - Albite (Ab) - Orthoclase (Or) base of the Qz-Ab-An (Anorthite) - Or tetrahedron to show both the trends of the Li-mica granites and the `elvans'. Symbols as given in Figure 2. Plotted points based upon CIPW norms.

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granite (Al-Turki 1972), and is interpreted as the result of cleansing during fractionation of the contamination products of palingenesis. At the present level of exposure, there is locally evidence of contamination in the form of xenoliths and stoped blocks, but these are additional to the ordinary biotite which is scattered through the · granite in an apparently homogeneous way. At the same time, there also occur partly digested xenoliths that grade into schleiren which in turn pass into isolated biotite flakes. This sequence indicates an earlier and very important stage of contamination in which the 'granite fraction' has progressively been 'melted out' of included material to leave 'residual xenoliths' (sometimes 'ghost-like' relics) which subsequently have been transported upwards to their present positions.

(b) *Lithium-mica Granites*. These granites in the Tregonning-Godolphin cupola have clearly differentiated in situ (Stone 1975). They show a marked trend of Na enrichment with time (Fig. 3) and in the quaternary "granite" system, actually lie on the Qz - Ab - Or base of the tetrahedon: their trend is clearly towards a minimum or eutectic (Na-rich, owing to the high contents of F and Li: Wyllie and Tuttle 1964)., (Fig. 4). The compositions of these rocks are such that, in the presence of large amounts of F, they probably crystallized initially over a very small temperature interval, i.e. their compositions are close to the minimum or eutectic and they are composed of about 90 per cent feldspars and quartz. Small fluctuations in temperature and changes in fluorine content and alkalis can result in local remobilization, so that fractionation by melting and reaction with a fluid phase are likely to be important. Rocks transitional between these and the biotite-granites might be found in the megacrystic Li-mica granite of St Austell. However, differentiation of biotite-granite in situ in the small granite dome or "mini-cupola" at Porthmeor Cove (Land's End granite: Grid ref. SW 425 375) does not appear to produce Li-mica granite: a study of this body is now under way for comparison with the roof of the Tregonning granite.

(c) *"Elvans" (mainly granite-porphyries).* The slight pattern of K-enrichment that may be shown by the fine-grained granites becomes a marked reality in the "elvans". There can be little doubt that these rocks have been derived from normal biotite-granites (Figs. 3 and 4). Emplacement of "elvan" dykes as fluidized systems was suggested by Stone (1968) to account for the occurrence of granite fragments and quartz-feldspar aggregates, for textural variation in terms of elutriation and for efficient, sometimes almost complete, alkali ion exchange in some bodies, resulting in almost complete K-enrichment

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and Na-depletion. Fluidization as a mechanism of emplacement is supported by the work of Goode (1973) who has described the occurrence of granite fragments and brecciation in "elvan" dykes whilst the markedly variable petrography and Sr isotope ratios observed by Hawkes and others (1975) support: the idea of a heterogeneous origin rather than a magmatic one. Alkali-ion exchange is suggested by the limited data given in Stone (1968) and is reinforced by the trend shown in the Qz-Ab-Or diagram, Fig. 4. This trend goes from the principal area of concentration of biotite-granites (approximately $Qz_{40}Ab_{25}Or_{35}$) to the quartz-orthoclase sideline at about $Qz_{50}Or_{50}$ and corresponds with a trend of potash feldspar enrichment, but total feldspar reduction. The broad trend of the Perranporth data (Henley 1972) reaches the quartz-orthoclase sideline between $Qz_{40}Or_{60}$ and $Qz_{60}Or_{40}$ (a few samples extend to the greisen region around $Qz_{70}Or_{30}$). This wide spread can be attributed to silica enrichment and muscovitization (Henley 1972; 1974). Henley has suggested that biotite-granite is broken down to quartz - muscovite - potash feldspar aggregates before transport and emplacement, the amount of feldspar depending upon the H^+ and K^+ ion activities, but the observed patterns could also be interpreted readily in terms of partial (sometimes complete) muscovitization during transport (along with alkali-ion exchange) or even after emplacement.

Any hypothesis of fluidization must imply the presence of an opening to the surface or to a fracture system close to the surface of the earth. Such a "flue" hypothesis is consistent with volcanism associated with the later stages of plutonic activity and particularly with mineralization (Hawkes 1974; Cosgrove and Elliott 1976).

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PETROGRAPHIC AND CHEMICAL DISTINCTION BETWEEN THE MEGACRYSTIC MEMBERS OF THE CARNMENELLIS GRANITE, CORNWALL

by Khaled I. Al-Turki and Maurice Stone

Abstract. On the basis of modal and chemical data the megacrystic biotite-granite of Carnmenellis can be divided simply into an outer type and an inner type. The outcrop pattern of the two granite types is consistent with that observed in some centred complexes.

1. Introduction

The location of the Carnmenellis granite is shown in Fig. 1. It forms one of the larger exposed cupolas of the batholith of south-west England. Modern work on the granite began with that of Ghosh (1934) who divided the coarse megacrystic biotite-granite into three types, referred to as types I, II and III. A finer-grained granitic facies, the Boswyn granite, had been recognised earlier as two small masses in the western part of the granite outcrop (Hill and MacAlister 1906).

Ghosh (1934) considered that type I granite is the oldest of the three megacrystic granites and that it is veined by type II; also that type III granite veins type I and is the youngest of the three types because it is the least basic and contains the lowest percentage of accessory minerals. The finer-grained (Boswyn) granite is believed to vein type I granite, but its relations to the other granites are not seen (Ghosh 1934).

Following the work of Ghosh (1934), various attempts have been made to confirm the classification of the coarse megacrystic granites into three types. This is difficult, as the supposed junctions are not easy to recognize and petrographic distinction between the granite types is not always clear. On the basis of petrographic data, Chayes (1955) could find no statistically significant difference between the modes of granite types I and II. Likewise, from a study of the radioactivity of zircon, Cameron (1958) concluded that granite types I and II are identical, but quite distinct from type III and the finer-grained granite. Stone and Austin (1961) considered that the

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three coarse granites are merely local variants of a single megacrystic biotite-granite.

This paper presents and examines new petrographic and chemical data obtained in order to test further the similarities or differences between the granite types.

2. Petrographic and chemical data

Little need be added to earlier petrographic accounts of these granites (Ghosh 1934; Stone and Austin 1961; Exley and Stone 1966), Examination of hand specimens suggests that there may be minor textural variations between the three types of coarse megacrystic biotite-granite. Biotite frequently occurs as isolated grains in type III and as aggregates in the other types. Also, the groundmass of type III commonly appears to be finer-grained than that in the other granites. However, on their own, the recognition of these textural variants as distinctive features is subjective and insufficient to warrant the division of these granites into three distinct petrographic types.

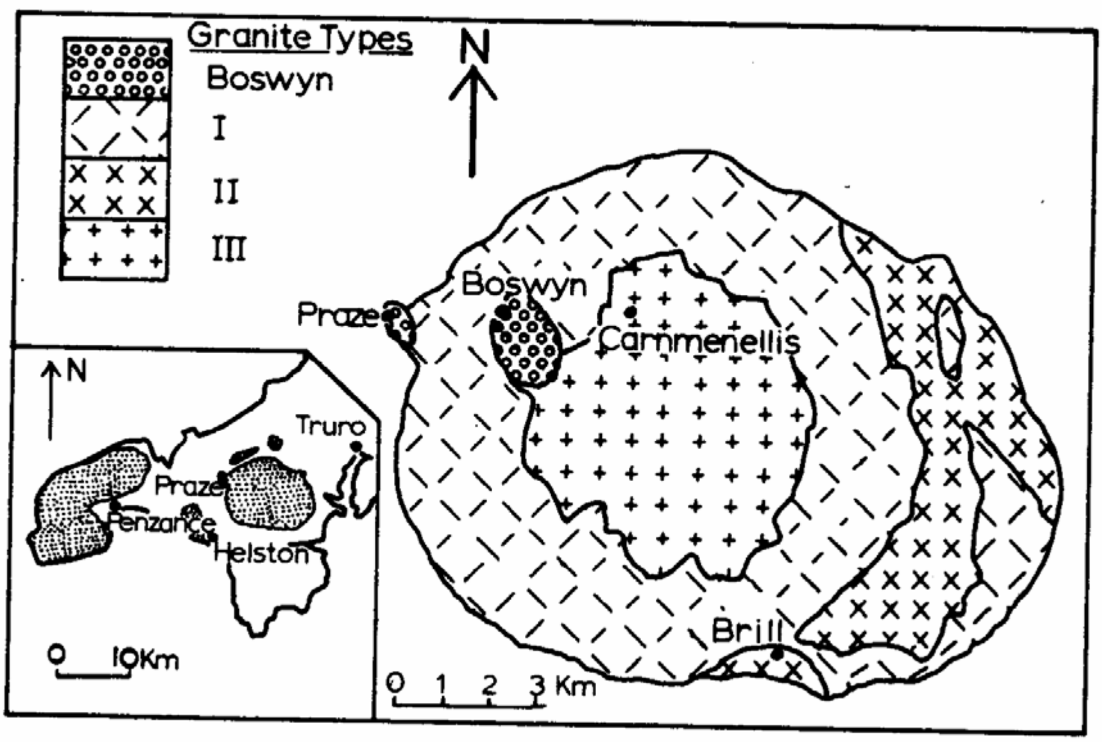

Figure 1. Geological sketch map of the Carnmenellis granite showing distribution of the granite types. (Based upon Ghosh 1934, fig. 1., with permission of the Geological Society of London).

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Table 1. Summary of Modal Analyses of Carnmenellis Granite and tests of differences between means

	(A) GRANITE TYPES						(B) MANN-WHITNEY U-TESTS		
	I		II		III		I-II	I-III	II-III
	Mean	SD	Mean	SD	Mean	SD			
Quartz	32.1	1.46	30.7	1.94	36.0	3.26	NS	*	**
K-Feldspar	33.2	1.39	32.1	1.80	28.3	2.25	NS	**	*'
Plagioclase	23.5	1.84	24.0	3.22	23.8	1.07	NS	NS	NS
Biotite	4.7	1.10	6.1	1.29	3.3	1.17	*	NS	*'
Muscovite	4.9	.84	5.6	1.61	6.7	1.42	NS	**	NS
Tourmaline	0.8	.58	0.5	.25	1.1	.33	NS	NS	**
Apatite	0.3	.20	0.4	.18	.3	.18	NS	NS	NS
Andalusite	0.3	.27	0.4	.32	.3	.29	NS	NS	NS
Others	0.1	.05	0.1	.07	.1	.10			
	99		99.9		99.				
No.of Samples	8		8		7				

SD is one standard deviation NS is not significant
*is significant at the .05 probability level
**is significant at or below the .01 probability level
(Results of Mann-Whitney U-tests based upon tables for small samples in Siegal 1956).

Average modes of the three granite types together with their standard deviations are given in Table 1 (A). The modal analysis of each sample is based upon the combined analyses of several thin sections together with data for potash feldspar obtained from polished slabs etched' in hydrofluoric acid fumes and stained with sodium cobaltinitrite. This increases appreciably the total sampling area for the coarse constituent.

Chemical data for the three megacrystic granite types are given in Table 2: these include all the major elements together with several trace elements. Each column of Table 2 is the average analysis of several samples, as indicated: in some cases, specimens were obtained from separate parts of a single quarry, but are counted here as separate samples. SiO_2, TiO_2, $A1_2O_3$, total iron as Fe_2O_3, CaO K_2O and P_2O_5 were analysed by X-ray fluorescence spectrometry using the method of Leake and others (1969), but standardized against wet-analysed samples of Carnmenellis granite. MnO, MgO, Na_2O, and Li_2O together with Zn were determined by atomic absorption spectrophotometry. Other trace elements were determined by X.R.F. spectrometry after spiking, and FeO was analysed by titration with potassium dichromate as indicated in Shapiro and Brannock (1962).

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Table 2. Summary of Chemical Analyses of the Carnmenellis Granite

Granite Types	I		II		II	
Weight %	Mean	SD	Mean	SD	Mean	SD
SiO_2	72.62	.06	72.63	.15	72.70	.11
TiO_2	.27	.03	.28	.03	.22	.02
Al_2O_3	14.65	.08	14.65	.11	14.77	.19
Fe_2O_3	.54	.23	.50	.21	.48	.14
FeO	1.16	.22	1.24	.13	.77	.26
MnO	.05	.01	.05	.01	.04	.01
MgO	.46	.07	.48	.06	.36	.06
CaO	1.08	.12	1.12	.11	.77	.25
Na_2O	3.23	.24	3.11	.24	3.02	1.24
K_2O	4.30	.37	4.36	.43	4.81	1.21
P_2O_5	.18	.01	.18	.01	.17	.01
ppm						
Li	321	90	341	36	321	144
Rb	429	44	473	35	512	65
Sr	93	18	93	6	91	10
Zr	128	25	138	19	95	9
Ga	41	3	40	3	39	2
Zn	62	14	65	12	80	18
Pb	39	1S	47	24	34	8
No. of samples	33		12		12	

SD is one standard deviation

3. Statistical tests

Large departures from a normal distribution of data can upset their examination by conventional statistical procedures that are based upon an underlying assumption of normality. Many elements are approximately lognormally distributed (Ahrens 1966). Shaw (1961) suggested that the best probability function to use is the lognormal for trace elements and that this is also better than the normal function for major elements. Both the chemical and modal data examined by Rodionov (1965) indicate the predominance of the lognormal distribution. Departures from normality can be indicated by coefficients of variation (S haw 1961; Floyd 1968; Koch and Link 1970), or by estimates of skewness and kurtosis provided that sample sizes are sufficiently large. However, the simplest test for a whole range of sample sizes is the Kolmogorov-Smirnov one sample test (Siegal 1956). This test compares the cumulative distribution of the data with the cumulative normal curve (or, indeed, with any other chosen distribution) and the Kolmogorow-Smirnov statistic (K-S) is found as the largest difference between the two cumulative distributions. The statistic is compared with tabled values for chosen levels of probability.

Table 3 (A) gives the values of K-S for the bulked chemical data of all 57 samples of Carnmenellis granite when compared against the normal and lognormal distributions. The lower the value of K-S, the closer are the data to the distribution with which they are being compared. The Null hypothesis that the data have the

Table 3. Statistical Tests of Chemical Data

	(A) K-S Test for Normality				(B) Mann-Whitney U-Tests		
	1		2		3	4	5
	Ho-Normal		Ho-Lognormal		I-II	I-III	II-III
Si	0.075	NS	0.054	NS	NS	**	NS
Ti	0.123	NS	0.157	NS	NS	**	**
Al	0.193	*	0.187	*	NS	*	*
Fe^{3+}	0.112	NS	0.104	NS	NS	NS	NS
Fe^{2+}	0.12	NS	0.206	*	NS	**	**
Mn	0.215	*	0.181	*	NS	NS	NS
Mg	0.057	NS	0.095	NS	NS	**	**
Ca	0.133	NS	0.211	*	NS	**	**
Na	0.225	**	0.33	**	NS	'*	*
K	0.238	**	0.21	*	NS	NS	NS
Li	0.253	**	0.315	**	NS	NS	NS
P	0.256	**	0.241	**	NS	*	NS
Rb	0.198	*	0.181	*	**	NS	**
Sr	0.141	NS	0.129	NS	NS	NS	NS
Zr	0.085	NS	0.128	NS	NS	**	**
Ga	0.126	NS	0.113	NS	NS	NS	NS
Zn	0.179	NS	0.135	NS	NS	**	**
Pb	0.16	NS	0.083	NS	NS	NS	NS

NS Not significant
*significant at the .05 probability level (two tailed tests)
**significant at or below the .01 probability level (two tailed tests)
Results of significance based upon data in tables in Siegal (1956)

1. Kolmogorov-Smirnov statistic for raw data
2. Kolmogorov-Smirnov statistic for data transformed to natural logarithms
3. Mann-Whitney U-test for comparison of means of granite types I and II
4. Mann-Whitney U-test for comparison of means of granite types I and III
5. Mann-Whitney U-test for comparison of means of granite types II and III

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distributions indicated are tested at the .05 and .01 levels of probability. Rejection of the Null hypothesis is indicated by asterisks. It is clear from this table that normality of distribution improves in some cases but degenerates in others when data are transformed to natural logarithms. Furthermore, some elements, notably Na, Li and P show marked departures from both normal and lognormal distributions. For this reason, and because of the small sample sizes of the modal analyses, nonparametric tests are preferable to those that assume a particular distribution. A powerful test for examining the differences between the means of two sample groups at a time is the Mann-Whitney U-test (Siega11956). This is the nonparametric equivalent of the t-test and is used in testing the data presented in this paper.

4. Results

Both the Kolmogorov-Smirnov one sample test and the Mann-Whitney U-test were performed by using computer programs modified after those given in the I.B.M. Scientific Subroutines Package to handle arrays of analytical data and to give suitable output formats.

Results for the modal data are given in Table 1 (B). The Null hypothesis is marginally rejected only for biotite in the test between the means of granite types I and II. In contrast, there are clearly several rejections that amount to significant differences between type III and each of the other two types: most of these are at the .01 level of significance.

Results of the Mann-Whitney U-test for the means of the chemical data are given in Table 3 (B). The pattern is broadly similar to that of the modal data. It is clear that, with the exception of Rb, there are no significant differences between the element means of granite types I and II. On the other hand, the Null hypothesis is rejected for 10 elements in the tests between types I and III and for 9 elements in the tests between II and III.

Clearly, granite types I and II cannot be distinguished except for their Rb contents and marginally for biotite. However, each of these is quite different, both petrographically and chemically, from type III. These results agree with those of Chayes (1955) and Cameron (1958), but are at variance with the conclusion of Stone and Austin (1961) that the three granite types are merely local variants of a single unit. The outcrop patterns of these two granite types suggest

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that they might be called the outer and inner granites, where the outer granite corresponds with types I and II and the inner granite corresponds with type III. The differences between the outer and inner granites are both petrographic (modal) and chemical, although it does not necessarily follow that the inner granite constitutes a separate intrusive phase. However, the fact that this granite does map out as an approximately equidimensional body totally enclosed within the outer granite does suggest that it may be a separate later phase. The pattern of distribution and approximate shapes of the outer and inner granites are similar to (hose observed in many centred complexes (e.g. Pitcher 1953).

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THE HALVOSSO PEGMATITES

by N.J. Jackson

An area within the Carnmenellis granite noted for its pegmatites has yielded another pegmatite locality. Halvosso Quarry (SW 738 338) is located in the coarse-grained, porphyritic, two-mica granite of Ghosh (1934). The pegmatites occur as lenticular or podiform bodies up to 20 cm in long dimension and commonly localised along joint planes. Two types of pegmatite can be recognised:

1. *simple pegmatite* -- comprising large (up to 5 cm) crystals of perthitic orthoclase, brown tourmaline, zoned pale brown Li mica, and quartz (commonly with doubly terminated crystals).
2. *complex pegmatite* -- contains in addition to the above minerals albite, muscovite, fluorite, blue-green apatite, cassiterite, pyrite, sphalerite and stokesite (Mr R. Barstow, personal communication).

The mineral paragenesis in the pegmatite is: orthoclase + quartz ---------- albite, acicular brown tourmaline, Li mica ------------ muscovite + blue-green apatite ------------- cassiterite ----------- stokesite, pyrite, sphalerite and fluorite. Similar pegmatites in the nearby Trolvis Quarry (Hosking 1954) do not contain Sn-bearing minerals. However, they do contain topaz, betrandite and stilbite which were not identified at Halvosso.

Fluid inclusion studies on samples of clear euhedral quartz and blue-green apatite (Fig. l) suggest that the quartz was formed in the T_h range 280-380°C. The apatite was formed in the Th range 350-380°C but was subsequently fractured and penetrated by fluids which homogenised in the Th range 320-340°C. Both phases were penetrated by low temperature ($T_h < 120$°C) fluids. All the above temperatures are uncorrected for the effects of pressure and therefore could be considerably lower than true formation temperatures. There was no evidence of boiling in any of the samples examined

Recent $^{18}O/^{16}O$ and D/H isotopic studies on the Li mica (Dr S.M.F. Sheppard, personal communication) suggest that there could have been a contribution from magmatic water, although the

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low fluid salinities appear to contradict this. K-Ar dating of the same mica (Halliday 1977) indicates a formation age of 280 Ma.

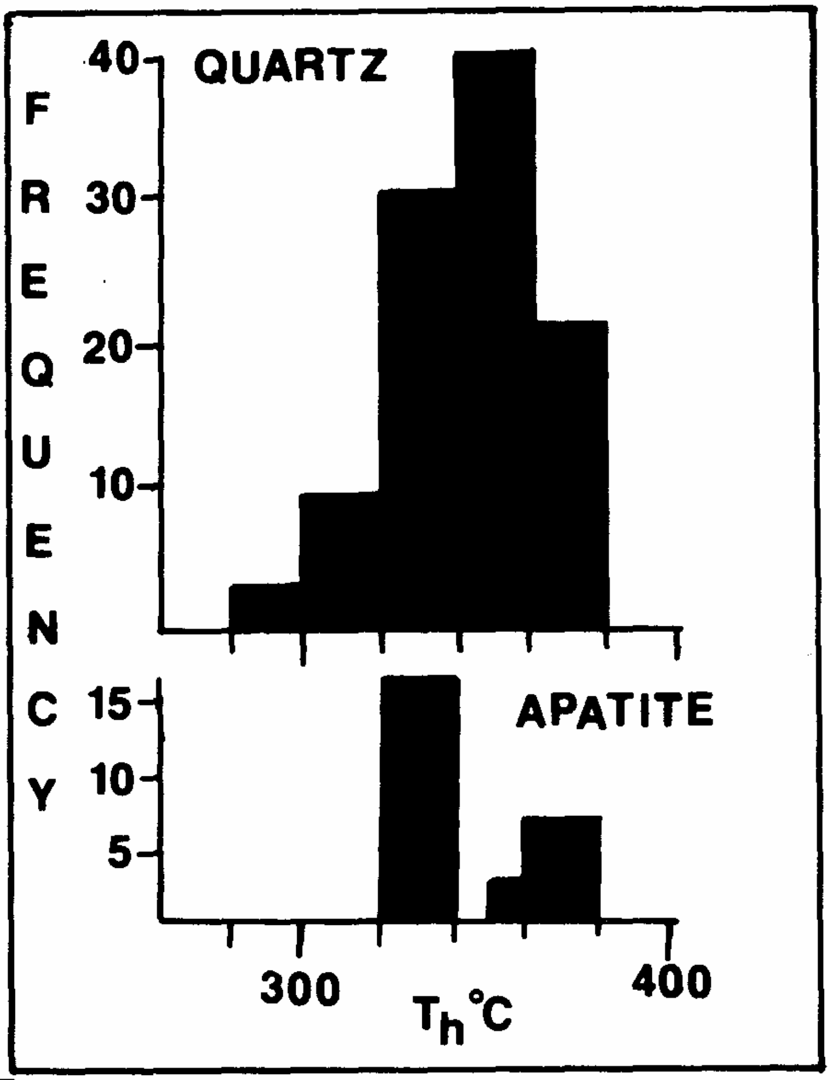

Fig 1. Homogenisation temperatures in the Halvosso pegmatite

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A FIELD STUDY OF THE BASIC CONTROLS OF WEATHERING PATTERNS IN THE DARTMOOR GRANITE

by W.R. Dearman and F.J. Baynes

Abstract. Methods of distinguishing the effects of hydrothermal alteration, chemical weathering and frost shattering, based on field mapping and grading are described and put into practice in interpreting several exposures of rotten granite on Dartmoor, including the classic Two Bridges exposure. The model, considered to be applicable to all granites of south-west England, should aid the interpretation of site investigations carried out for engineering purposes.

1. Introduction

Friable or decomposed granite exposed on Dartmoor may be the result of hydrothermal alteration related to the cooling history of the granite (Dines 1956), chemical weathering developed during Tertiary denudation (Linton 1955) or Pleistocene frost shattering (Waters 1964); it is considered that many exposures show the effects of all three processes (Brunsden 1964). It is often difficult to isolate precisely the effects of each separate process, and this uncertainty has led to disputes over the origin of features characteristic of granite areas over the whole of south-west England such as the china clay (reviewed by Exley 1958 and Bristow 1977) and the tors (Linton 1955; Palmer and Neilson 1962; Eden and Green 1971). Although these disputes generally appear to have been resolved there are still occasions when new data do not fit the accepted hypotheses (Jackson and others 1977) and the interpretation of many classic exposures still remains problematical.

This field study attempts to interpret some of the features to be seen at such problematical exposures. Although civil engineering works are unlikely on the moor in the future, rotten granite has had to be contended with in the past (Sandeman 1901; Kennard and Lee 1947; Knill 1972) and affects present-day quarrying operations in the south-west (Dearman and others 1976). The exercise has therefore been undertaken to aid interpretation of similar features for engineering geological purposes.

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2. Geological and geomorphological history of the area

Three types of granite are recognised within the Dartmoor cupola: porphyritic giant granite containing abundant large feldspar megacrysts, blue granite with fewer and smaller megacrysts, and aplite dykes and veins (Dearman 1964). Intrusion of the granite was followed by extensive tourmalinisation, greisening and mineralisation together with kaolinisation on all scales from the extensive areas of china clay on the moor to slight alteration along joints (Edmonds and others 1969).

The geomorphological history of the area began with uplift and erosion which led to the unroofing of the cupola some time in the Cretaceous (Orme 1964). Since that time, the development of a complex series of plantation surfaces reflects a lengthy denudation chronology, the sequence of events having been ably summarized by Brunsden and others (1964). Precise correlation and dating of the numerous minor erosion surfaces is difficult and there is also the possibility that contemporaneous Tertiary wrench faulting (Dearman 1963) may have altered their relative positions (Shearman 1967). The evidence points to continuous exposure of parts of the granite throughout much of the Tertiary which would have allowed a chemical weathering profile to form (Linton 1955). Unambiguous evidence of chemical weathering is seen in rocks exposed in the contact metamorphic aureole of the granite (Fookes and others 1971; Dearman and Fookes 1972; Dearman and others 1976). During the Pleistocene the rocks at the surface were subjected to gelifraction (frost shattering), geliturbation (frost heave) and solifluction (mass movement) in the periglacial environment (Te Punga 1957; Palmer and Neilson 1962; Waters 1964).

This long and complicated history of hydrothermal alteration, chemical weathering and frost shattering appears to be reflected in the complexity of many of the granite exposures which, none-the-less, may be interpreted using simple field criteria.

Chemical weathering profiles, typically unevenly developed (Thomas 1966), can be expected to show a general increase in intensity of effect upwards towards the ground surface. Classic weathering profiles consist of friable and selectively decomposed material, up to 60-100 m thick, overlying less weathered joint-bounded blocks which show staining and disintegration extending inwards from the joint surfaces (Moye 1955; Ruxton and Berry 1957).

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Hydrothermal alteration also results in the decomposition of minerals but by the action of hot aqueous fluids, generated within the cooling granite intrusion, that were released along joints and other fracture zones. Thus, within the depth range of surface exposures, hydrothermal effects should show no tendency to decrease in intensity with depth.

By mapping the distribution of equal intensities of decomposition at any particular outcrop, it should theoretically be possible to determine whether the observed decomposition is due to weathering (overall increase in intensity upwards) or hydrothermal alteration (no overall increase in intensity upwards). As many of the exposures are very small, something more sensitive than the grades of chemical weathering used for engineering purposes, based on discoloration percentages and "rock-and-soil" ratios (Anon. 1972; Dearman and others 1976) is required that will, for instance, discriminate "soils" with differing degrees of decomposition. The grading system used is given in Table 1; it was found that with practice exposures could be mapped very quickly using these criteria. As with every grading system, it was based on the observed progressive stages of decomposition in both chemical weathering and hydrothermal alteration (cf. Goldich 1938; Exley 1976).

Frost shattering will generally increase in intensity towards the ground surface and will be manifest as an increase in physical disintegration. An intensity grading system was also set up for the effects of this process (Table 2) based on observed increases in the discontinuity spacings in a type section which was uniformly chemically decomposed but physically weathered to differing degrees.

The criteria set out in Tables 1 and 2 have been used to map and thus to provide a field interpretation of exposures at Merrivale quarry (SX 547752), Foggintor quarry (567726), a quarry at (770635) referred to here as Powder Mills quarry, Fernworthy quarry (670837), and Two Bridges quarry (611750).

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Grade	Description
A	All mineral grains are hard and fresh.
B	One feldspar species, usually small crystals assumed to be plagioclase, has decomposed.
C	Plagioclase has decomposed; some of the other feldspars, assumed to be orthoclase, have decomposed to a "gritty", but not "clayey", consistency.
D	Plagioclase has decomposed; most of the orthoclase feldspars have decomposed to a "gritty" or "clayey" consistency.
E	Virtually all of the feldspars have decomposed to a "clayey" consistency.

Table 1. Chemical decomposition grades. The grades are assessed in the field by probing the rock material with a penknife; gritty" feldspars crush under pressure, "clayey" feldspars can be cut and smeared.

Grade	Description
1	Planar through-going tectonic discontinuities spaced at between 600-1000 mm or more.
2	Planar discontinuities dividing up joint-bounded blocks formed by grade I discontinuities and tending to he parallel to them, spaced at between 40-600 mm.
3	Non-planar discontinuities breaking up joint-bounded blocks and tending to be anastomosing. Spaced at between 20-40mm.
4	Non-planar discontinuities dividing the rock into thin flakes which are generally sub-horizontal spaced at between 7-20 mm.
5	Granular disintegration, rock material has separated into separate mineral grains, i.e. discontinuities are spaced at less than 7 mm.

Table 2. Physical disintegration grades, based on a type section at Powder Mills quarry. The grades are assessed in the field by counting the discont-inuities along a line at right-angles to their trend.

3. The field evidence

Only a selection of the field evidence will be presented here by reference to particular aspects of the exposures examined.

Merrivale Quarry: in this deep working quarry the coarse-grained, grey granite with occasional feldspar phenocrysts is fresh (Grade A) except close to the surface where many of the smooth joint surfaces show pitting due to the decomposition of plagioclase (grade B). The distribution indicates that this very localized change is due to chemical weathering.

Several types of jointing are present in unweathered granite: (a) a roughly orthogonal set (horizontal and vertical at 012^{o} and 302^{o}) of widely spaced (3 to 7 m) continuous planar joints with granulated selvedges 50-100 mm wide of fresh, mechanically disintegrated

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granite comprising an interlocking fine gravel. The joints are characteristically stained red (red veins) either as a diffuse tint throughout the granulated zone or as a central fine-grained filling a few millimetres wide. These red-stained, granulated joints may be weathered to a silty sand near the surface, with both the spatial distribution and the associated decomposition tending to suggest that the change is due to chemical weathering.
(b) unstained granulated joints frequently developed as single wavy joints between the stained variety.
(c) unstained planar joints parallel to the (a) types, spacing 2 to 10m, sporadically developed, and becoming more frequent close to the ground surface.
(d) planar joints subparallel to the ground surface, increasing in number upwards until spacings are 300 to 500 mm.

Joint sets a, b, c comprising horizontal and orthogonal vertical members are "tectonic" joints; granulation in sets a and b may be due to shearing associated with wrench-faulting (Dearman 1963) as some are horizontally slickensided; others are vertically slickensided. Red staining is presumed to be hydrothermal in origin on account of the uniformity of development with depth and involvement of the veins in undoubted chemical weathering at the surface. Subtopographic set d was probably formed by stress release.

Foggintor quarry: again provides evidence for a chemical weathering profile with fresh (grade A) grey, coarse-grained porphyritic granite overlain by grade B rock.

Vertical zones of more decomposed (grade D) rock are present in two forms:
(a) as a 1 m thick selvedge to a steep quartz-tourmaline vein which can be traced for the whole length of the quarry, and from top to bottom of the quarry faces. This distribution is typical of a hydrothermal origin, although the decomposition is not necessarily caused by the quartz-tourmaline vein. Edmonds and others (1968) consider that tourmalinisation was a phase separate from kaolinisation, although both processes may have used the same open fracture; this is consistent with the observation that quartz-tourmaline veins occur without associated altered selvedges.
(b) although having slightly different orientations (e.g. 335°), these occur in distinct sets and are similar to the granulated joints of Merrivale. Both stained and unstained types occur, 50 mm thick, and may pass upwards into wider zones adjacent to quartz-tourmaline veins.

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Physical disintegration of grades 2 to 4 only affected granite chemically weathered to grades B, C and D to any great extent; implying that fresh granite is frost resistant.

Powder Mills quarry: is the type section for physical weathering grades. The coarse-grained porphyritic granite is uniformly weathered to grade B apart from what is interpreted as an original granulated horizontal joint which is now grade C, and grades C and D as selvedges to a small vertical quartz-tourmaline vein.

Frost shattering is concentrated in areas of close jointing, and terminates abruptly with grade 4 against grade I across certain inclined joints giving a trough weathering effect (Currey 1969). Only locally is granular disintegration (grade 5) present. The distribution of weathering grades is shown on Fig. 1.

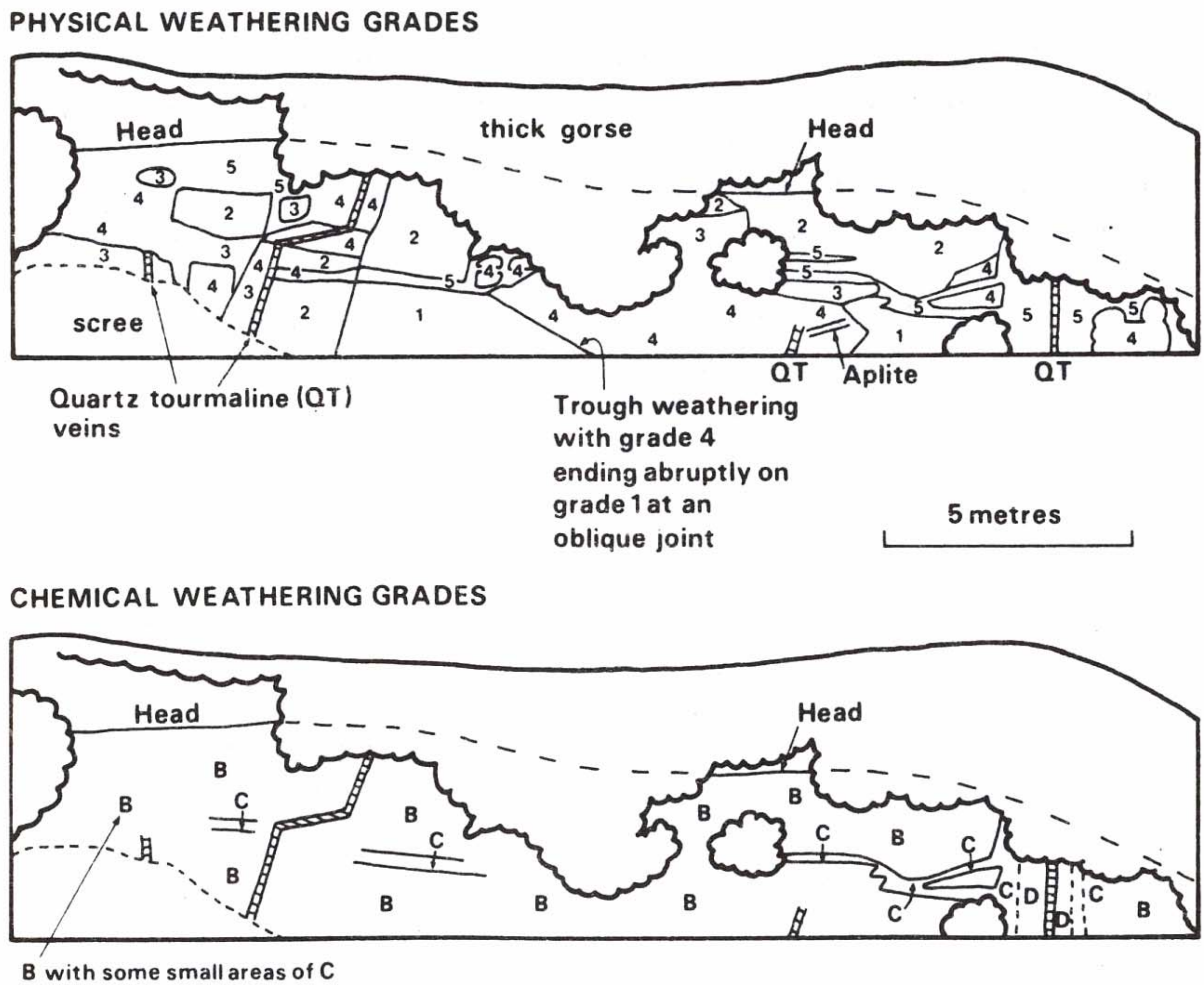

Figure 1. Field sketch of the main face in Powder Mills quarry showing the distribution of physical and chemical weathering grades. The letters and numbers refer to the grades set out in Tables 1 and 2.

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Fernworthy quarry: shows more intensely chemically weathered granite than elsewhere with relict masses of less weathered rock standing as incipient tots (Linton 1955) in grade C and D material. A quartz-tourmaline vein has weathered to a purple friable material; quartz porphyry veins are now thin, clay-rich, white seams, and xenoliths have decomposed. In the north-west face of the quarry, the granite is chemically weathered to grade B, with C and D adjacent to a quartz-tourmaline vein, whereas physical weathering is of the more intense grades 4 and 5. There is much red veining and staining in the southern wall of the quarry, where chemical weathering is most intense (grades D and E). This may imply the former presence of red granulated zones which could have assisted greater chemical weathering.

Two Bridges quarry: providing a striking juxtaposition of fresh and rotten granite, is the exposure on which much of the argument over the origin of rotten granite on Dartmoor has centred (Linton 1955; Palmer and Neilson 1962; Eden and Green 1971).

The grey, coarse-grained porphyritic granite is cut by aplite dykes, thin quartz-tourmaline veins and red veins. Decomposition increases in intensity upwards, but only relatively small proportions of the rotten granite are weathered to grade D, and most of the 'engineering soil' or *in situ* growan is grade C. (Fig. 2). A pronounced feature is the marked differential decomposition which has left masses of strong, nearly fresh granite surrounded or separated by friable decomposed granite. Both steeply inclined and horizontal, narrow decomposed bands can be traced across the quarry and these have red veins or thin quartz-tourmaline veins associated with them. In other parts of the quarry, similar veins are present without associated decomposed selvedges. It is suggested that only where the veins are associated with granulated joints, similar to those seen at Merrivale quarry, does later chemical weathering produce a decomposed selvedge to the red veins and quartz-tourmaline veins.

Numerous red veins cross the large area of growan in the northern end of the pit which is more decomposed near the original ground surface. Hence the origin of the growan is attributable at least in part to chemical weathering.

Frost shattering has affected all granite that was chemically weathered to grades B to D, with some rounding of the edges of joint-bounded blocks.

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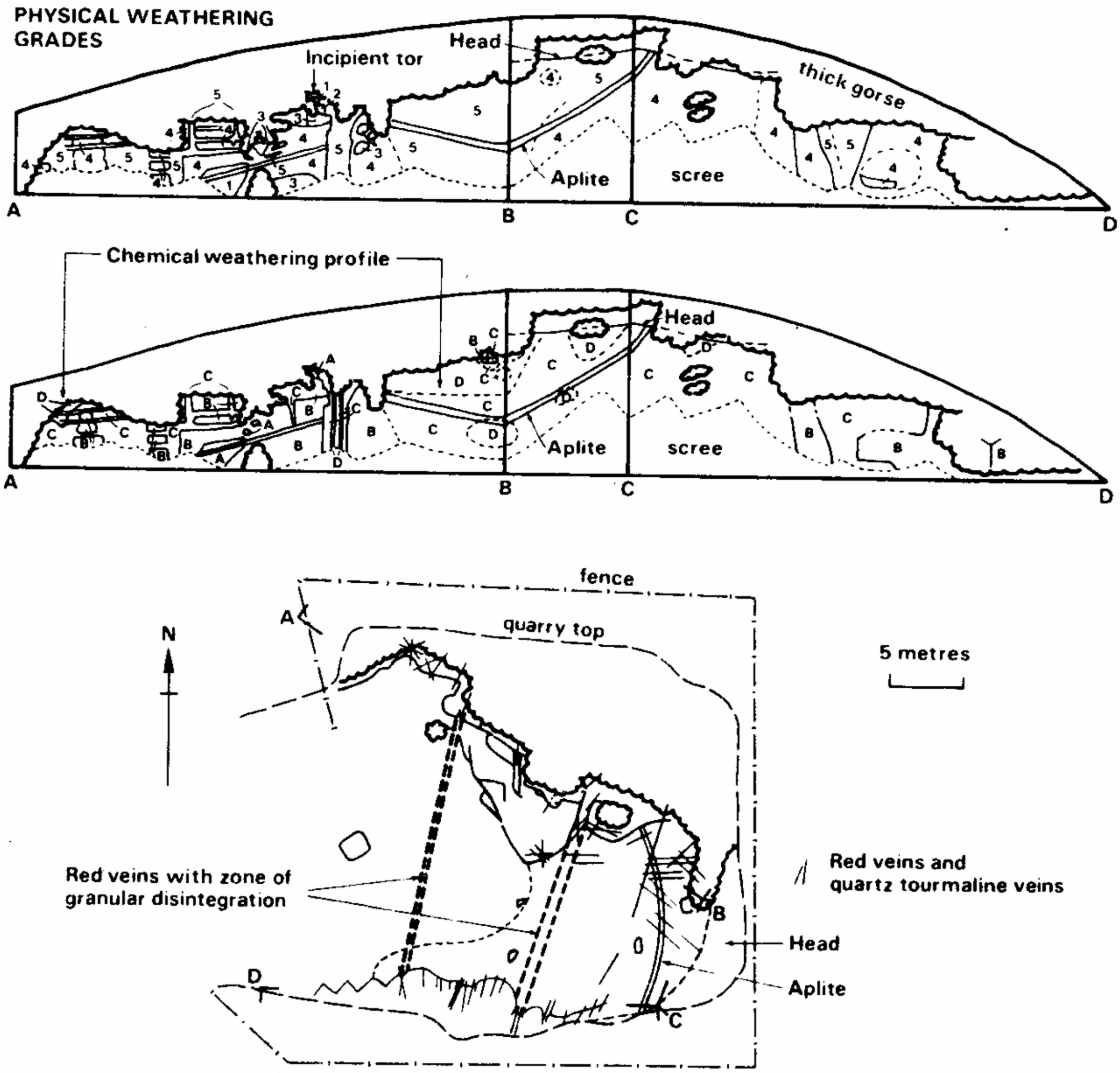

Figure 2. Field sketch of the faces in Two Bridges quarry showing the distribution of physical and chemical weathering grades. The letters and numbers refer to the grades set out in Tables 1 and 2.

4. Summary of weathering effects

The field evidence from well-known, but admittedly selective Dartmoor localities may be summarized as model profiles (Fig. 3) containing all the observed phenomena and their interactions. Conceptually, the main problem is to place these observations in the correct time sequence, but there can be little doubt that this sequence should be formation of structures, hydrothermal alteration and associated effects, chemical weathering and physical weathering, with the probability that structures such as joints may have formed at more than one time. There must also be some uncertainty concerning the timing of the effects of wrench-faulting on the granite, although the main phase of faulting is presumably Miocene in age.

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Prior to chemical weathering (Fig. 3a) the granite contained structurally controlled granulated joints and tectonic planar joints. Also present were aplite dykes, quartz-tourmaline veins and red veins, all of which tended to follow structural weaknesses in the granite. The granite was affected by hydrothermal alteration which ranged from the complete kaolinisation seen in the china clay pits to local kaolinisation exploiting the same weaknesses as the dykes and veins. Near the ground surface local distressing produced further joints parallel to both the original tectonic joints and also sub-parallel to the topography.

Chemical weathering (Fig. 3b), acting downwards from the surface, picked out such features as zones of intense or incipient hydrothermal alteration. In areas of close jointing, weathering extended inwards from the joint planes but corestones were only very occasionally developed.

Erosion and frost shattering during the Pleistocene (Fig. 3c) resulted in the formation of new discontinuities in all but the unweathered rock. In general, remnants of slightly chemically weathered rock within intensely' chemically weathered rock were most susceptible to frost shattering. Solifluction exhumed the consequent irregular bedrock topography to produce tors, whilst at the same time any outcrops of slightly weathered rock assumed rounded forms due to differential disintegration along joint planes.

5. Conclusions

The effects of hydrothermal alteration, chemical weathering and frost shattering can be differentiated by mapping the distribution of grades of equal intensity of effect. Hydrothermal alteration and chemical weathering both produce mineral decomposition, the former occurring as vertical zones in which decomposition is uniform and the latter as sub-horizontal zones in which decomposition increases in intensity upwards. Frost shattering has merely induced a greater percentage of discontinuities. The precise controls on the distribution of chemical weathering profiles are difficult to determine but relate to structural aspects of the granite including those macroscopic features such as jointing and veining which can be studied in the field. As these features also control the distribution of hydrothermal alteration, which in itself may locally intensify the effects of subsequent weathering, many areas may show both effects. Although at any exposure the dominant process may be

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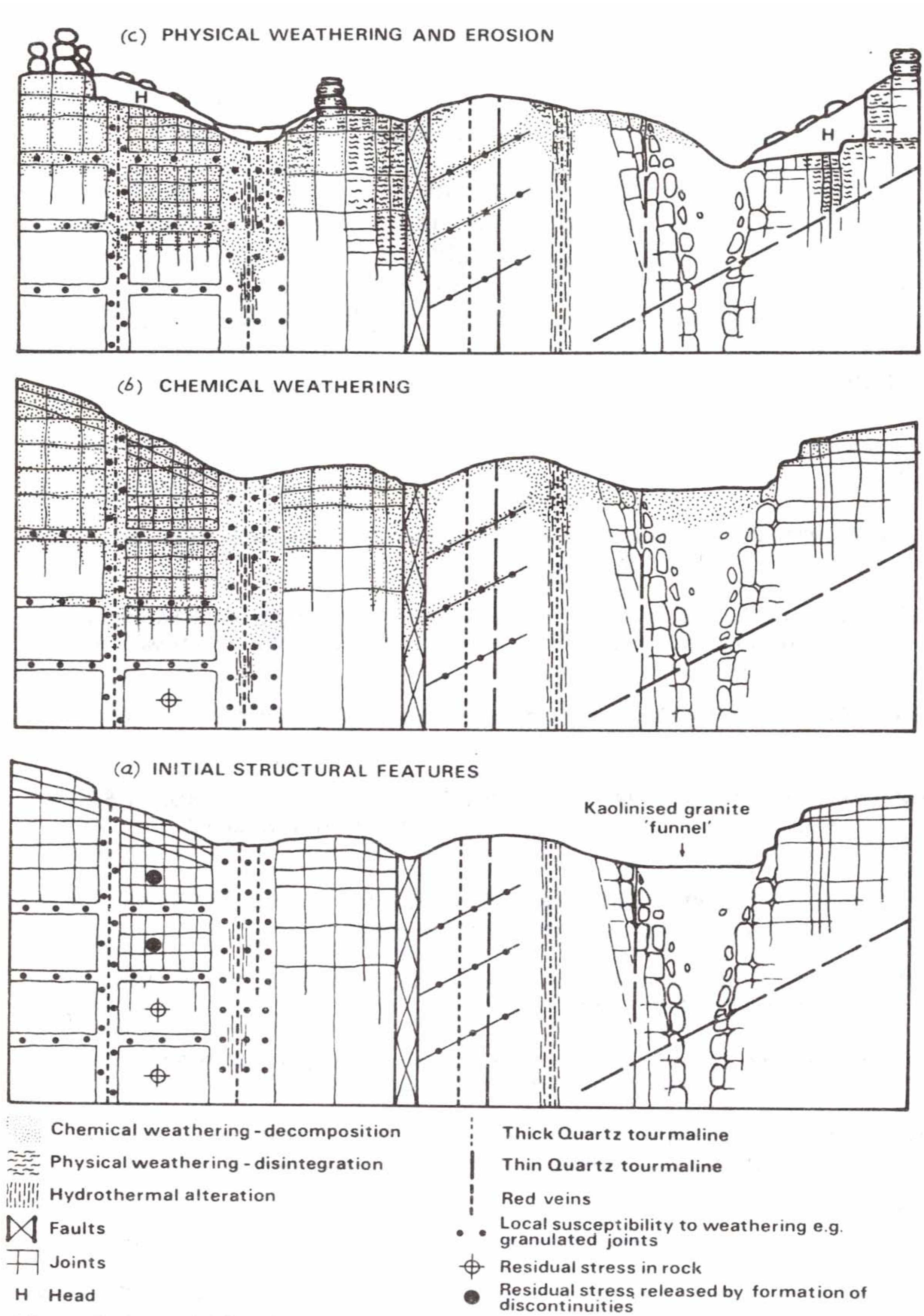

Figure 3. A model for the development of weathering profiles on Dartmoor: (a) the initial granite structures; (b) chemical weathering; (c) physical weathering superimposed on chemical weathering, and the effects of erosion.
Kaolinised granite 'funnel' after Bristow 1977, fig. 1.

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ascertained, the precise extent to which each of the three potential processes has affected the rock is difficult to determine. This difficulty is compounded where small exposures showing a great variety of effects, such as at Two Bridges, are considered.

An understanding of the relationship between the structural control exerted by the granite and the distribution of chemical and physical weathering grades would undoubtedly assist in the interpretation of a site investigation carried out for a civil engineering scheme. This particularly applies to the recognition of rockhead, and also has implications in assessing the possible distribution of engineering soil and rock below this level.

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TORS AND GRANITE LANDFORMS OF DARTMOOR AND EASTERN BODMIN MOOR

by A.J.W. Gerrard

Abstract. The tors of Dartmoor and eastern Bodmin Moor have been classified on the basis of location into summit tors, valley-side and spur tors, and emergent tors outcropping on the sides of low hills. Detailed measurements on 65 tors show that there are also differences between the tors with respect to their size, the intensity of their jointing and the slope angles at their base. Both summit and valley-side tors possess closely spaced vertical joints whereas the vertical jointing of emergent tors is much wider spaced.

It is concluded that the large summit and valley-side tors are located where the joint spacings have permitted differential weathering and erosion to take place. The smaller emergent tors probably represent random outcrops of granite, which, because of the paucity of joints have resisted weathering. Detailed analysis of the jointing is seen as the key to the understanding of the distribution and origin of tors.

1. Introduction

Granite landforms in general and those of south-west England in particular have attracted a great deal of attention. Most of this attention has been focused on tors as individual features rather than on their position in the total landscape. Their significance depends on their form, distribution and setting, and this paper examines some of these factors using the tors of Dartmoor and eastern Bodmin Moor as examples. The granite of both areas is essentially coarse-grained and contains abundant porphyritic orthoclase feldspar. Both areas also possess similar types of tors and it is the origin of these that is now considered.

2. Tor formation

Linton defined a tot as a 'residual mass of bedrock produced below the surface level by a phase of profound rock rotting effected by ground water and guided by joint systems, followed by a phase of mechanical stripping of the incoherent products of chemical action' (Linton 1955, p. 476). Alternatively, Palmer and Neilson attributed the formation of tors to mechanical weathering under periglacial

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conditions. They defined a tor as an upward projection of granite left behind when the surrounding bedrock was broken up by frost action and removed by solifluction (Palmer and Neilson 1962, p. 337).

Much of the early discussion was, thus, concerned with the origin of the incoherent granite which is found beneath soliflucted deposits on most slopes. Great stress has been placed on the lack of clay and the apparent little alteration of the feldspars which suggests a mechanical or periglacial origin (Doornkamp 1974). But Wahraftig (1965), in an examination of the weathered granite in the Sierra Nevada of California, has shown how the alteration of biotite to 14 angstrom clays such as chlorite results in expansion which shatters the rock. The fractures so formed rarely follow grain boundaries, but are irregular and radiate from the expanding minerals and from the cleavage directions in the feldspars. Examination of the incoherent granite on Dartmoor suggests that a similar process may have been in operation producing growan akin to the sandy weathering type described by Bakker (1967). Certainly when rock types other than granite are examined chemical decomposition becomes more certain (Bristow 1968; Fookes and others 1971; Dearman and Fookes 1972; Dearman and Fattohi 1974). However, periglacial processes have also been active in the past and frost action on a previously partially decomposed granite could account for the characteristics of the growan. Earlier ideas concerning the significance of hydrothermal alteration may have to be modified as a result of the recent work of Bristow (1977) and Sheppard (1977).

The theories of Linton and Palmer and Neilson taken singly or in combination explain many of the features of tors but the detailed relationships between tors and joints have still to be determined. An examination of the types of tors present on Dartmoor and eastern Bodmin Moor and the intensity of their jointing may determine some of these relationships.

3. Types of tor

The author has suggested in an earlier paper that the Dartmoor tors may be classified on the basis of location into summit tors, valley-side and spur tors, and small tors found outcropping on the flanks of low convex hills (Gerrard 1974). In this paper, the tors belonging to the last group are termed emergent tors. On Bodmin Moor, Sharp, Bearah, Kilmar, Trewartha and the tors of the Cheesewring are summit tors while Tregarrick and Hawk's Tors are spur tors. Emergent tors are represented by Newel and Hill Tors on Siblyback Moor and by the group of small tors on the northern flank of Craddock Moor.

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	Mean Maximum Height	Mean Maximum Slope Angle at Base
Summit Tors	21.8 m	7.2^{o}
Valley-side Tors	26.5 m	10.4^{o}
Emergent Tors	9.9 m	6.3^{o}

Table 1. Mean maximum heights and mean maximum slope angles of the three tor types.

When the classification was first proposed it was not clear whether the three types of tors possessed any other marked differences apart from their relative position. Since then a detailed analysis of 65 tors on Dartmoor and Bodmin Moor has been undertaken and the results suggest that the tot types proposed possess other major differences, the maximum height of each tor was measured as was the maximum slope angle over a distance of 200 m from the base of each tot and the intensity of jointing. These measurements show that emergent tors are clearly smaller and possess, on average, gentler slopes at their base (Table 1). A series of Mann-Whitney U tests has shown that the differences in height between emergent tors and both summit and valley-side tors are significant at the 95 per cent level, whereas the difference between summit and valley-side tors is not significant. Similarly, the differences in maximum slope between valley-side tors and both the other types are also significant at the 95 per cent level but not the difference between summit and emergent tors.

The average spacings of the horizontal and vertical joints for the three tor types, grouped into one metre classes, are shown in Tables 2 and 3. It is not feasible to list the results for all 65 tors and so a small sub-sample of tors in western Dartmoor has been chosen to illustrate the differences that occur (Table 4). The intensity of the horizontal jointing is very similar in all three types but there are marked differences in the spacings of the vertical joints. The vertical joints are wider spaced on the emergent tors than on either summit or valley-side tors and these differences are statistically significant. There is, perhaps, some justification in linking these two tor types on the basis of joint frequency.

These results suggest that there are relationships between the intensity of vertical jointing and specific tor types. There also appear to be relationships between the jointing intensity and the height and

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	0-0.99 m	1-1.99 m	>2m
Summit Tors	13	14	0
Valley-side Tors	14	10	1
Emergent Tors	13	6	0

Table 2. Relative frequency of the mean spacings of horizontal joints.

	0-0.99 m	1-1.99 m	2-2.99 m	>3 m
Summit Tors	1	10	8	2
Valley-side Tors	1	10	11	3
Emergent Tors	0	1	6	12

Table 3. Relative frequency of the mean spacings of vertical joints.

relative location of the tors in that widely spaced vertical joints seem to be associated with small, simple tors and gentle slopes. Summit and valley-side tors are larger, exhibit much greater complexity of form and possess closer spaced vertical jointing. In some cases the detailed form of these tors is related to variations in the joint spacing. This can be seen in the Twelve Mens Moor area of Bodmin Moor where a remarkable pattern of ridge-like tors and associated depressions occurs. These tors, such as Kilmar, Trewartha and Bearah Tors, are totally unlike the neighbouring tors of the Cheesewring and Sharp Tor. The shape of these former tors might be partly explained by the fact that the approximately N-S joints are wider spaced (up to 6 m) than the E-W joints (2-3 m) and that the E-W joints are not vertical but dip to the north at about 30 degrees. This arrangement would favour rock wall retreat from the north and south and the great mass of clitter on these slopes, especially on the north side of Kilmar Tor attests to this.

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	Height	Width (metres)	Depth	Average Spacing of joints (metres) Horizontal	Vertical
Summit Tors					
Great Staple	9.0	45.0	130.0	1.2	1.2
Kings Tor	14.0	120.0	45.0	1.0	1.2
Pew Tor	7.6	26.5	18.0	2.1	1.0
Roos	4.6	183.0	61.0	1.5	4.6
Valley-side Tors					
Heckwood	2.4	1220	9.0	1.0	3.1
Hucken	4.9	107.0	31.0	I.0	4.6
Ingra	11.0	150.0	15.0	1.5	1.5
Kings Tor A	3.7	27.0	32.0	0.7	3.1
MiddleStaple	4.6	18.3	*18.3*	1.2	2.4
Vixen	20.7	113.0	12.2	1.5	1.5
Emergent Tors					
Blowing House	2.7	26.0	9.1	0.7	3.1
Feather	4.0	33.0	14.0	0.7	Too few
Little Staple Tor	2.4	12.2	14.0	2.0	Too few
Whitechurch Common Tors	2.4	17.4	14.9	0.7	3.1

Table 4. Mean joint spacings and dimensions of a sub-sample of tors from western Dartmoor.

4. Relationships between jointing, weathering and erosion

The previous section has shown how the types of tors are related to the intensity of jointing. An additional factor, possibly of equal significance for the processes of weathering, is the variability of the joint spacing. Theoretically, if the joints are closely and very evenly spaced then sub-surface chemical weathering will attack the rock easily and fairly uniformly creating a uniform weathering front or basal surface of weathering, If the joints are widely and very evenly spaced the amount of weathering will be less but a uniform weathering front will still be produced. However, if the vertical joint spacing is more variable then differential weathering will take place producing an irregular weathering front and creating the basis for tors when the weathered material is removed. The irregular nature of this weathering front can be seen in certain valley-side exposures where relatively sound masses of granite are surrounded by incoherent regolith.

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The variability of vertical jointing on the tors examined is greater on both valley-side and summit tors than on the emergent tors. This variability would seem to have allowed differential weathering to produce ultimately the complex forms typical of summit and valley-side tors.

Periods of regolith formation and removal must also be Seen in terms of the changing conditions of ground surface stability. Weathering profiles will deepen beneath stable slopes and be truncated on unstable slopes. This will also lead to a highly variable weathering front. In general, the weathering front will be nearer the surface in the summit areas where regolith and moisture retention are least and be deeper towards the base of slopes due to the combined action of weathering and the downslope accumulation of material. This latter condition seems to be generally true of both Dartmoor and Bodmin Moor where exposures show that the thickness of weathered granite is greatest low down on the valley-sides. Many of these considerations apply to the processes of mechanical weathering as well as to sub-surface chemical weathering. There should, therefore, be a complex interaction between jointing, weathering and surface erosion processes which is what the results seem to show.

5. Conclusions

It is now possible to suggest a synthesis with which to explain the type and distribution of the tors of Dartmoor and eastern Bodmin Moor. The measurements of joint spacings have shown that the tors examined can be divided into two broad groups, namely, summit and valley-side tors, and emergent tors. The large and often complex summit and valley-side tors with closely spaced but highly variable vertical jointing are located where both chemical and physical weathering would have been able to act differentially and where the intensity of surface processes has been sufficient to remove the products of this weathering. Conversely, emergent tors may well represent chance exposures which, because of their wider spaced and less variable vertical joint spacing and possibly gentler slopes have failed to develop to the size and complexity of the other tors. A detailed analysis of tors and jointing is, thus, seen as the key to the understanding of the granite landforms of Dartmoor and Bodmin Moor.

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SOME TOURMALINISED ROCKS FROM CORNWALL AND DEVON

by Carol J. Lister

Abstract. Contrasts are drawn between tourmaline habits and textures observed in two different luxullianite veins, one in the St Austell granite and one on Dartmoor.

1. Introduction

Luxullianite is one of the less common varieties of tourmalinised granite found in south-west England. Material previously described has generally been taken from loose boulders, rather than observed in situ within the parent granite (Bonney 1877: Wells 1946).

Two *in situ* occurrences of luxullianite type rocks have been described, one from the eastern part of the St Austell granite close to the type locality (Lister 1978), and one from east Dartmoor (Blyth 1949).. In both localities the tourmalinised rock occurs as vertical veins up to 2 metres wide, within potassium feldspar megacryst bearing granite. The Dartmoor vein lies within a larger zone of reddened granite containing pink feldspar megacrysts and large rounded quartz crystals in a finer-grained matrix; this texture is reminiscent of those found in zones of wall rock alteration associated with metalliferous lodes in the vicinity (R. Scrivener, personal communication, 1978). In the St Austell example, however, the reddening is confined to the luxullianite veins.

The mineralogy of the tourmalinised material is superficially similar in each case, with pink alkali feldspar, quartz and tourmaline forming the major components. However, the tourmalines show definite textural differences, reflecting their mode of formation (Blyth referred to "luxullianite" in inverted commas, presumably to imply this textural difference). The tourmalinisation process has in each case been studied by microscopic examination of material transitional between granite and its alteration product; thus it has been possible to observe mineral grains at various stages of transformation, and to suggest possible origins for the tourmaline varieties present.

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2. St Austell luxullianite

In the St Austell luxullianite, two distinct tourmaline phases coexist, namely primary tourmaline which is brown in thin section, and secondary (hydrothermal) tourmaline which is blue and acicular. The brown variety is present in the parent granite as unzoned prismatic crystals up to several millimetres in length, and as clusters of fragmental or interstitial tourmaline in optical continuity. The colour and habit persist from the unaltered granite into the luxullianite veins. The blue acicular tourmaline occurs only in the luxullianite, both as "tourmaline suns" and as oriented hairlike overgrowths upon existing brown tourmalines. By reference to the material transitional between granite and luxullianite, this secondary phase may be seen to arise, at least in part, from the hydrothermal breakdown of biotite with minute tourmaline needles growing between the cleavage planes of biotite crystals (this is described and illustrated by Lister, 1978).

3. Dartmoor "luxullianite"

The Dartmoor "luxullianite" contains tourmalines of quite different habits and textures. All the tourmaline crystals are strongly zoned, comprising both brown and blue tourmaline in the central portions, and often with a dark blue rim. Most are euhedral to subhedral, ranging in size from 0.5 mm to 10 mm; some of the larger crystals are skeletal, or consist of several smaller individuals linked by the subsequent addition of outer zones. By contrast with the St Austell material, acicular "tourmaline sun" development is virtually absent, as is acicular overgrowth (Fig. 1).

Examination of the transitional rock between the reddened granite and "luxullianite' reveals four tourmaline varieties: 1. Pale brown short prismatic tourmalines 0.5 mm to 2 mm in length, are very similar to primary magmatic tourmalines seen elsewhere in the south-west England granites. Towards the centre of the "luxullianite" vein, these become zoned by the addition of a dark blue variety.
2. Pale blue, elongate (up to 3 mm) prismatic crystals, often adopting a radiate configuration, lie within and at the margins of feldspar grains, and are perhaps derived from them (an origin suggested by Wells, 1946, for St Austell radiate tourmaline). These blue tourmalines are not fine and acicular like their St Austell counterparts; rather they resemble the prismatic tourmalines forming radiate structures in quartz-schorl rocks (e.g. Hemerdon,

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Dartmoor). As these incipient "tourmaline suns" do not generally appear to persist into the centre of the "luxullianite" vein,' it is possible that they became incorporated in the larger composite tourmaline crystals as tourmalinisation progressed.

3. Sub-radiate aggregates of brown and blue tourmaline, showing relict biotite structures (Fig. 2), are also present. Within an outer fringe of dark blue tourmaline, the core region consists of parallel dark brown, pale greenish-brown and blue lamellae, cutting straight across the tourmaline alignment. These lamellae are considered to represent residual biotite cleavage planes; indeed, the structure closely resembles some of the biotite replacement phenomena seen in the St Austell transitional zone. In the central part of the "luxullianite" vein, such residual structures are absent, but many of the larger tourmalines still show a rather patchy colour distribution in their cores.

4. Dark blue tourmaline forms continuous zones around the periphery of the tourmaline crystals already described, and this is itself frequently rimmed by a paler blue variety. In many crystals several concentric zones are present, indicating multistage growth, while in St Austell only one stage of secondary tourmaline formation is in evidence. The margins of the Dartmoor tourmalines are nearly all sharp and continuous, lacking the fine hairlike overgrowth common in the St. Austell luxullianite.

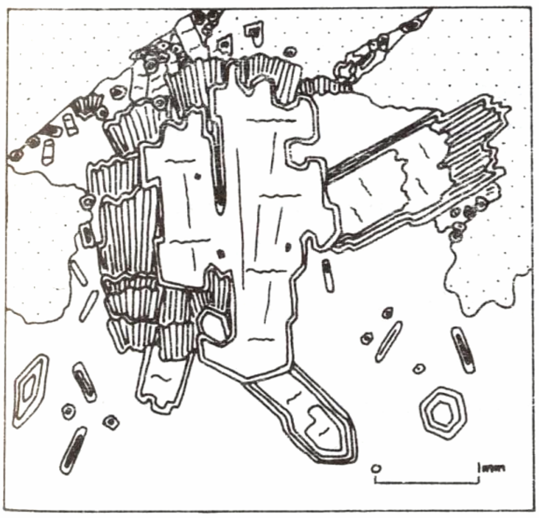

Fig. 1 Large composite and zoned tourmaline from Dartmoor

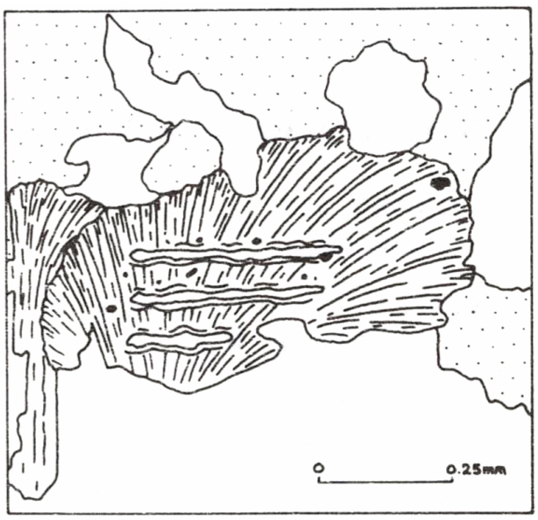

Fig. 2 Residual biotite lamellae within sub-radiate tourmaline

Legend: Feldspar stippled, quartz blank, opaques solid, tourmaline all other symbols.

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4. Conclusions

The tourmalines found in rocks of luxullianite type may be said to develop by various processes, though individual grains all seem to range between schorlite and magnesian schorlite in their bulk composition. Primary brown tourmaline is present in the parent granites in both the examples described. Replacement of biotite also seems an important source, both of radiate structures (St Austell and Dartmoor), and of large patchy tourmaline grains (Dartmoor only). Growth within feldspar (perhaps associated with K-feldspathisation of Na-bearing feldspar) is a further possibility for the origin of radiate configurations in the Dartmoor material; however, these structures do not seem to persist as such with continuing tourmalinisation. Finally, blue tourmaline, either introduced in solution or mobilised within the veins, accretes upon or around existing tourmaline grains, building up zoned crystals in the Dartmoor example and hairlike overgrowths in St Austell.

The formation of the St Austell luxullianite may be explained as a single stage process, producing one type of secondary tourmaline. However, the Dartmoor "luxullianite" appears to represent a somewhat more complex tourmalinisation history.

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Rare earth elements in basic volcanics from S.W. England (Abstract)

by P.A. Floyd

Twelve low-grade or spilitic intrusives (meta-dolerites) and pillow lavas (meta-basalts) from the Upper Palaeozoic volcanics of SW England have been analysed for rare earth elements (REE) by neutron activation analysis. Accuracy was monitored with W-I which gave acceptable replicate results when compared with the recommended values.

The REE were analysed to provide additional information on the genetic relationships within the tholeiitic and alkali basalt groups (defined on other trace element distributions) and also to determine the tectonic environment of the volcanics. Although the REE are generally considered relatively immobile during alteration, minor variations are exhibited when the cores and rims of pillow lavas were comps/red: (i) rims were marginally enriched in total REE, and (ii) La/Yb ratios were increased slightly in the rim portions due to light REE enrichment (largely Sm). Little change was seen with progressive hydration in the intrusives.

The tholeiitic and alkali basalt groups are distinguished by their total REE content and different light to heavy REE fractionation (as measured by the La/Yb ratio). Tholeiitic instrusives and pillow lavas from south Cornwall have light REE enriched normalized distributions, low primitive REE contents and La/Yb ratios (less than 5.6). They compare with some continental tholeiites formed in a rifting environment. The alkali basalts, on the other hand, exhibit a much greater degree of light REE enrichment and at the same level of differentiation can be divided into two groups with varying light to heavy REE fractionation: (i) pillow lavas from north Cornwall with La/Yb of 10-12, and (ii) pillow lavas from east Devon with La/Yb of about 15. Their tectonic characterization is less clear, having lower La/Yb ratios than many (subaerial) continental alkali basalts and are similar to certain oceanic island basalts. No significant Eu anomalies are seen in either magma group

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Preliminary REE fractionation models show that for the few samples analysed: (i) the tholeiitic intrusives can be derived from a parental composition (represented by a chilled margin) by olivine and plagioclase fractionation, whereas the more evolved pillow lavas are not related directly by fractionation to this parental magma, and (ii) variation within the alkali basalt pillow lavas can be accounted for by minor plagioclase fractionation (plagioclase is a major phenocryst phase) and two different parental magmas.

The primitive REE (and other trace element) nature of the intrusive tholeiites from south Cornwall suggest direct derivation from an upper mantle lherzolite with La = 1.3, Sm = 0.72 and Yb = 0.3, by about 40 per cent partial melting (assuming that all REE enter the melt phase).

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Rare earth elements in acid rocks of S.W. England (Abstract)

by G.J. Lees, D.H.M. Alderton, J.A. Pearce and C.S. Exley

When plotted on the conventional 'chondrite-normalised' diagram, rare earth element (REE) concentrations of biotite-bearing granites from Carnmenellis, Bodmin Moor and St Austell suggest that these rocks have been generated by crystal fractionation rather than progressive anatexis. A marked negative anomaly for Eu is found but the fractionated phase responsible remains uncertain; possibilities are feldspar, biotite, apatite, and zircon.

In the St Austell granite the early Li-mica granite and the biotite granite are similar (having total REE concentrations of 51.5 and. 106.7 ppm respectively). The late Li-mica granite and the fluorite granite show a marked depletion (totals of 15.4 and 12.7 ppm respectively) as a result of continued differentiation of the magma and cessation of crystallization of such REE-bearing phases as biotite. Their Eu concentration shows a larger negative anomaly.

in a Bodmin Moor granite, the muscovite has a higher concentration of lighter REE (except Eu) than either of the feldspars, suggesting that sericitization might result in incorporation of REE (except Eu) from altered feldspar in newly-formed mica, and a comparison between fresh and sericitized rock has confirmed this. Altering fluids thus seem able to mobilize and remove REE.

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Rare earth elements in minettes from Jersey, Channel Islands (Abstract)

by G.J. Lees

Rare earth elements (REE) have been determined on three mica-lamprophyres (minettes) from Jersey. The results show very high total contents (306 ppm; 661 ppm; 1563 ppm) and also very strong enrichment in the light REE (un-normalised Ce/Yb: 36; 121; 133). Such features are consistent with the data obtained for other 'incompatible' elements outlined previously by the author (*Proc Ussher Soc*., 1974, 3, 149-155). Modelling shows that the variation in REE between the samples cannot be explained by the fractionation of any of the observed phenocryst phases. Partial melting of a garnet-lherzolite parent, representing an undeleted upper mantle source, will only produce the observed minettes levels of REE concentrations in a hypothetical daughter melt when extremely low degrees of partial melting (below 1 per cent) are envisaged.

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Trace elements as indicators of sediment transport in some estuaries of south-west England (Abstract)

by J.R. Merefield

Studies by X-ray spectrometry on the <60 mesh fraction of recent estuarine sediments in south-west England demonstrate that minor elements may be useful as natural tracers of sediment transport. Skeletal debris contributes a large proportion of Sr to the total found in the sediments. In the Teign estuary this concentration is greatest at the seaward end (c. 86 ppm) and values decrease upstream. Therefore, Sr proves useful as a guide to the net influx of marine sediments. Two distinct populations of Sr values exist in the estuary, suggesting that it is also possible to detect calcite-rich or aragonite-rich shell debris from chemical analysis of the acid extractable fraction. Strontium determinations allow accurate detection of marine sediments in the Teign estuary which is relatively iow in carbonates. In some other estuaries of south-west England considerably higher carbonate and, therefore, Sr contents are found. Work is in hand at these estuaries in order to assess the value of the Sr diagnostic criterion and to test other potential tracers.

Another useful element in the Teign estuary is Ba. High values in the upper reaches (c. 3200 ppm) decrease fairly rapidly towards the mouth. The catchment contains barytes lodes as well as mine dumps and Ba from these is weathered and transported into the estuary, where it acts as an indicator of river input. Data from Sr and Ba may be used to define a mixing zone where both types of sediment occur. The length of this zone is 4.9 km. Its western edge is 2.6 km from the Teign's normal tidal limit, whilst its eastern edge is 2.5 km from the mouth of the estuary.

Evidence suggests that monitoring of recent sediments with trace element analysis could prove a rapid and useful way of obtaining data valuable in general estuarine management.

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RADON IN THE STREAM WATERS OF EAST DEVON

by E.M. Durrance

Abstract. Rn^{222} produced by the radioactive decay of UTM is gaseous at normal temperatures and pressures, and has a half-life of 3.82 days. If lost by diffusion from its *in situ* parent material, radon can become trapped in soil gas or in ground or surface waters. Samples have been taken from 91 stream sites in East Devon and their radon content analysed. The result shows a pattern of low values distributed uniformly over the area with, additionally, high values located around the mouth of the Exe Estuary. The position of these high values is significantly displaced from the known occurrence of uranium bearing sedimentary nodules at Littleham Cove and Withycombe Raleigh. it is suggested that the radon anomaly represents a source of uranium at depth which in the past supplied uranium to migrating ground water and led to the precipitation of uranium complexes at sites in the sedimentary sequence occupied by contemporaneous plant debris.

1. Introduction

Two common isotopes of radon exist: Rn^{222} and Rn^{220}. Both are inert gases at normal temperatures and pressures. Rn^{222} is the sixth member in the disintegration series between U^{238} and Pb^{206}. It decays by alpha particle emission to Po^{218} with a half-life of 3.82 days. Because Rn^{222} exists in a gaseous state rapid loss can occur by diffusion from its parent uranium-bearing minerals. Consequently the gamma-ray emitting decay products of the U^{238} series, especially Bi^{214} which is a daughter product of Rn^{222} may be out of secular equilibrium with the parent uranium. While the loss of Rn^{222} may thus be instrumental in producing errors in the assessment of uranium-bearing deposits by gamma-ray studies, detection of the radon gas can allow the location of uranium-bearing deposits which are blanketed by non-radioactive materials. The 3.82 day half-life of Rn^{222} permits the location at some distance from the parent material. As radon moves most easily as a gas or in solution through permeable materials or along fissures, the location of permeable zones can also be achieved by radon detection.

Rn^{220} is the fifth member of the disintegration series between Th^{232} and Pb^{208}. Like Rn^{222} it decays by alpha particle emission, but its daughter is Pb^{216} and it has a half-life of only 54.5 seconds. The location of thorium-bearing minerals by Rn^{220} detection is therefore

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practical only over very short distances from the parent material. Radon lost by diffusion from uranium- and thorium-bearing minerals may be detected in the atmosphere, in soil gas or in ground or surface waters.

2. Radon detection methods

The detection of radon is achieved simply by taking a sample of gas and measuring its alpha activity. As radon is the only element with radioactive isotopes occurring naturally in a gaseous state at normal temperatures and pressures, the activity must be related to the presence of radon. A simple sequential series of measurements on a single sample allows the differentiation between Rn^{222} and Rn^{220} by virtue of their very different half-lives.

Gas samples for analysis may be obtained directly from the atmosphere, by extraction from a small augered soil hole or by degassing a sample of ground or surface water, Typical equipment used for this purpose is shown in Figs. I and 2. Figure ! shows an EDA Electronics RD200 system with a circulating pump and probe for obtaining soil gas samples, while Fig. 2 outlines the main features of the EDA Electronics RDU200 system for water degassing.

For soil gas, the probe is inserted into the augered hole and the hole sealed. Five pumps are sufficient to bring the soil gas into contact with a scintillation compound coated on the inside of an open, hollow cell. The cell itself is within a light-sealed photomultiplier system and counter. The activity of the cell is recorded over five one-minute periods and the results obtained as counts per minute. Any significant difference between the first and last counts is due to the presence of Rn^{220}.

For water gas, samples of water are collected in glass bottles with glass stoppers or metal caps from either streams or dipped wells and boreholes. Pumping should not be used, as degassing will occur. Care has to be taken that the bottles are completely full to avoid degassing of the sample by agitation during transport. Also the time of sampling should be noted so that a correction for the decay of the radon between sampling and analysis can be applied. For controlled degassing, 130 ml of water is placed in the sample holder of the degassing unit shown in Fig. 2, and a standard vacuum applied to a sealed scintillation cell. The vacuum is then released by bubbling air through the water sample for 3 minutes. A standard volume of water is therefore placed under a standard vacuum and degassed for a

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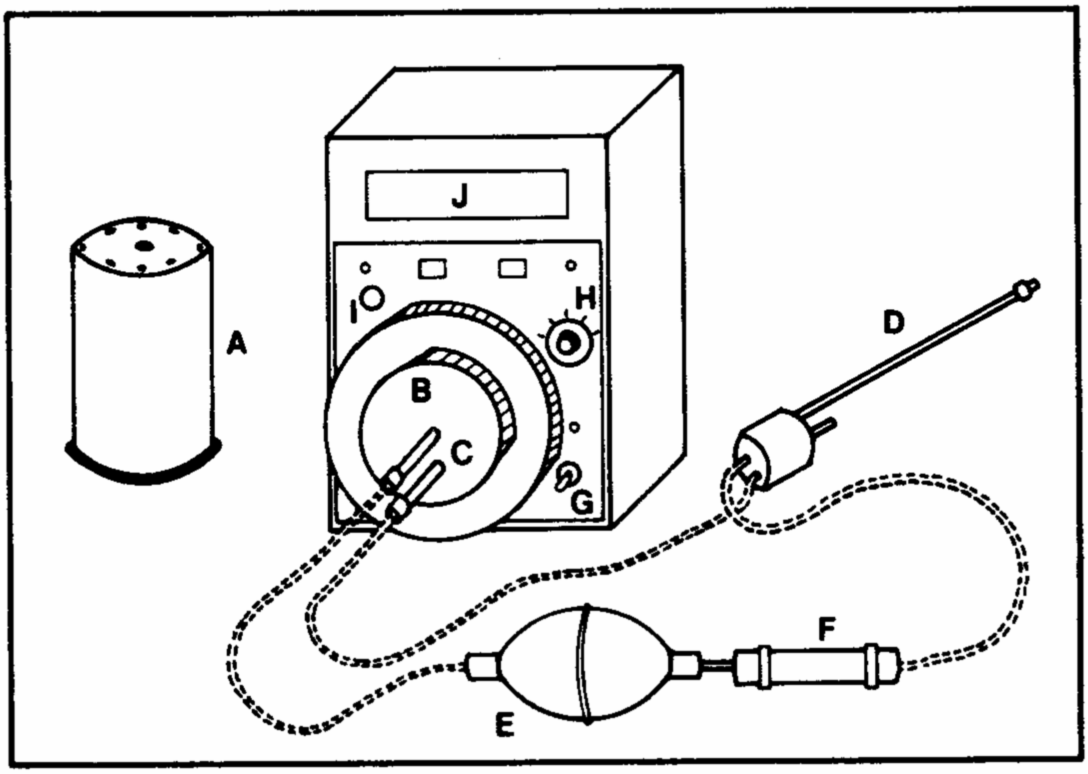

Figure 1. E.D.A. Electronics RD 200 Soil Gas System

A. Open scintillation cell
B. Cell housing in photomultiplier system
C. Circulating inlet/outlet tubes
D. Soil probe
E. Hand pump
F. Filter
G. On/off switch
H. Variable count time
I. Sample warning light
J. Decade counters

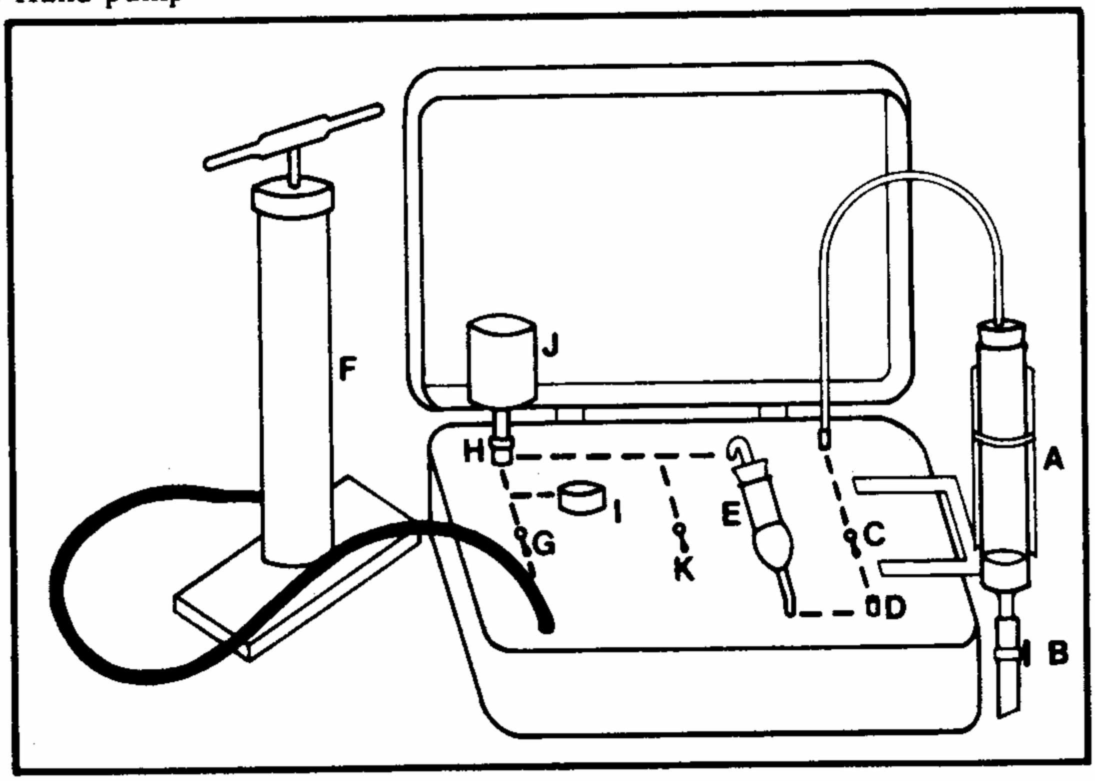

Figure 2. E.D.A. Electronics RDU 200 Water Gas System

A. Sample holder
B. Air inlet
C. Sample hold tap
D. Regulator valve
E. Drying agent
F. Vacuum pump
G. Vacuum tap
H. Spring-linkage
I. Vacuum gauge
J. Sealed scintillation cell
K. Flushing tap

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standard time. The results from different samples may, therefore, be directly compared with one another. The sealed scintillation cell is placed in the photomultiplier system and its activity recorded over three five-minute periods. Of these three counts the first is usually ignored as it is subject to possible error due to light entering the photomultiplier, but the last two are averaged to yield a result in counts per minute. Because of the delay that usually occurs between collection and analysis of the water gas, the presence of Rn^{220} in a sample is not noticeable.

3. Radon diffusion

The loss of radon from uranium-bearing minerals is largely controlled by the form in which the minerals are present. Least loss occurs from compact, well crystallised material, while most loss is from crumbly, incoherent, earthy masses. The movement of the radon away from its source is then controlled by the permeability of the surrounding material, air pressure, and ground water characteristics. Radon concentrations thus decrease with distance from the source both by dilution and by radioactive decay. The distance from the source for any given concentration is, however, unlikely to be regular, as the movement of the radon will be more rapid along fissures. The action of these variables in controlling radon movement results in limiting the use of radon detection methods to uranium or thorium location in a merely qualitative fashion, even when the soil gas or ground water gas methods are used.

When considering the surface water gas method more variables have to be taken into account. Once uranium minerals have been broken down the uranium becomes separated from its long-lived daughter radium owing to the markedly different chemical properties of the two elements. In the secondary environment radon can be regarded as being almost exclusively a daughter of radium except where detrital uranium resistate minerals are introduced into the stream course. In the latter case the minerals are likely to have a lower specific surface area and are therefore unlikely to contribute significant quantities of radon to the stream. Most radon in streams is therefore likely to be derived from the stream bed radium concentration.

Rainfull and run-off are also two important factors which control the radon concentration in streams. Although stream volumes will increase with rainfall and dilute the radon concentration, rainfall will also cause run-off to increase the rate of

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breakdown of uranium-bearing minerals in exterior source areas and aid the transfer of radium and radon to the streams. Once in the streams, radon can be lost by degassing due to turbulent flow. The degree of turbulence will depend upon such factors as discharge rate and bed-form characteristics. The relative magnitude of all these factors is as yet unknown, but they act to produce a complex pattern for the quantitative distribution of radon.

What may be deduced from this interaction of time dependent variables is that even if we consider a simple point source of a uranium-bearing mineral situated near a stream, with a sampling point some way downstream, the radon content of the stream at the sampling point will vary significantly with time. What is more, depending upon the relative positions of the source and sampling point, the changes which occur may be either positive or negative over the same time interval. This means that if a survey extends over a protracted length of time it is impossible to directly compare the data acquired on one day with that on another. Despite these difficulties, however, it is clear that if a random distribution of sampling points is selected, radon distribution in stream waters is likely to show a complex pattern of high and low values in the vicinity of a uranium source, especially when the survey has been conducted over a long period of time. Outside the uranium-bearing zone the radon values should be consistently low. Thus a semi-quantitative approach to the interpretation of radon distribution in stream waters on a regional scale would appear to be straightforward.

4. Uranium in East Devon

The presence of uranium in reasonable quantities in parts of East Devon was first recognised by Carter (1931) who described large nodules from the red marls and sandstones of Littleham Cove, at the western end of Budleigh Salterton beach, which would produce contact autoradiographs. These nodules have since been subject to detailed study by Perutz (1939), Harrison (1962, 1975) and Durrance and George (1976). The occurrence of the nodules is principally in the coastal area of outcrop of the Littleham Mudstones Formation (Henson 1971), but some nodules have also been recorded from the brickworks quarry at Withycombe Raleigh. Small dark nodules also occur in the Keuper Marl Formation but these do not usually produce contact autoradiographs.

Apart from the concentration of uranium in the nodules of the Littleham Mudstones Formation, it would appear that small amounts of uranium may be found throughout the area of the New

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Red Sandstone Series where uranium has been precipitated from ground water solutions at sites in the sediments occupied by contemporaneous plant debris (Durrance and George 1976). Some uranium may also be associated with shales of Carboniferous age. Uranium is not recorded from the Cretaceous Greensand and Eocene Flint formations.

5. Radon survey of East Devon

In order to determine the inland extent of the uranium-bearing nodules in the New Red Sandstone Series of East Devon, 91 stream sites were sampled for radon analysis between July and September 1977. Their location is shown in Fig. 3. The sites were chosen to give a reasonably uniform coverage of the area, yet lie near points of easy access; normally where streams are crossed by road bridges. The position of the sites is therefore irregular. However, an exception concerns the stream flowing from Littleham village to Exmouth, which was intensely sampled to check on the presence of radon in the stream waters of the area where the uranium-bearing nodules are known to occur. At least two samples were taken at each site so that the reliability could he assessed. In all cases the results from each member of a pair of samples was within 10 per cent of the other.

The possibility of either of two patterns emerging in the results of the survey was predicted. Either there would be a completely random distribution of high and low values throughout the area reflecting a relatively widespread distribution of uranium, or there would be a simple pattern of high and low values near the areas where the uranium-beating nodules occur with low values alone occurring outside those areas. In practice neither of these predicted patterns has emerged from the survey. The actual results achieved are shown in Fig. 3. From repeat samples taken over a ten week period from sites at Kenn, Exmouth and Ottery St Mary, it must be emphasised that in areas where higher values are indicated considerable time dependent variation is likely to be present, but low value areas are not affected. The values shown in Fig. 3 are raw data, and have not been processed in any way.

6. Discussion of results

Two features emerge from the map of stream radon distribution. Firstly, as predicted low values (less than 10 counts per minute) are present throughout the area, and secondly, high values (greater than 20 counts per minute) are not confined either to the outcrop or subsurface position of the Littleham Mudstones Formation but are

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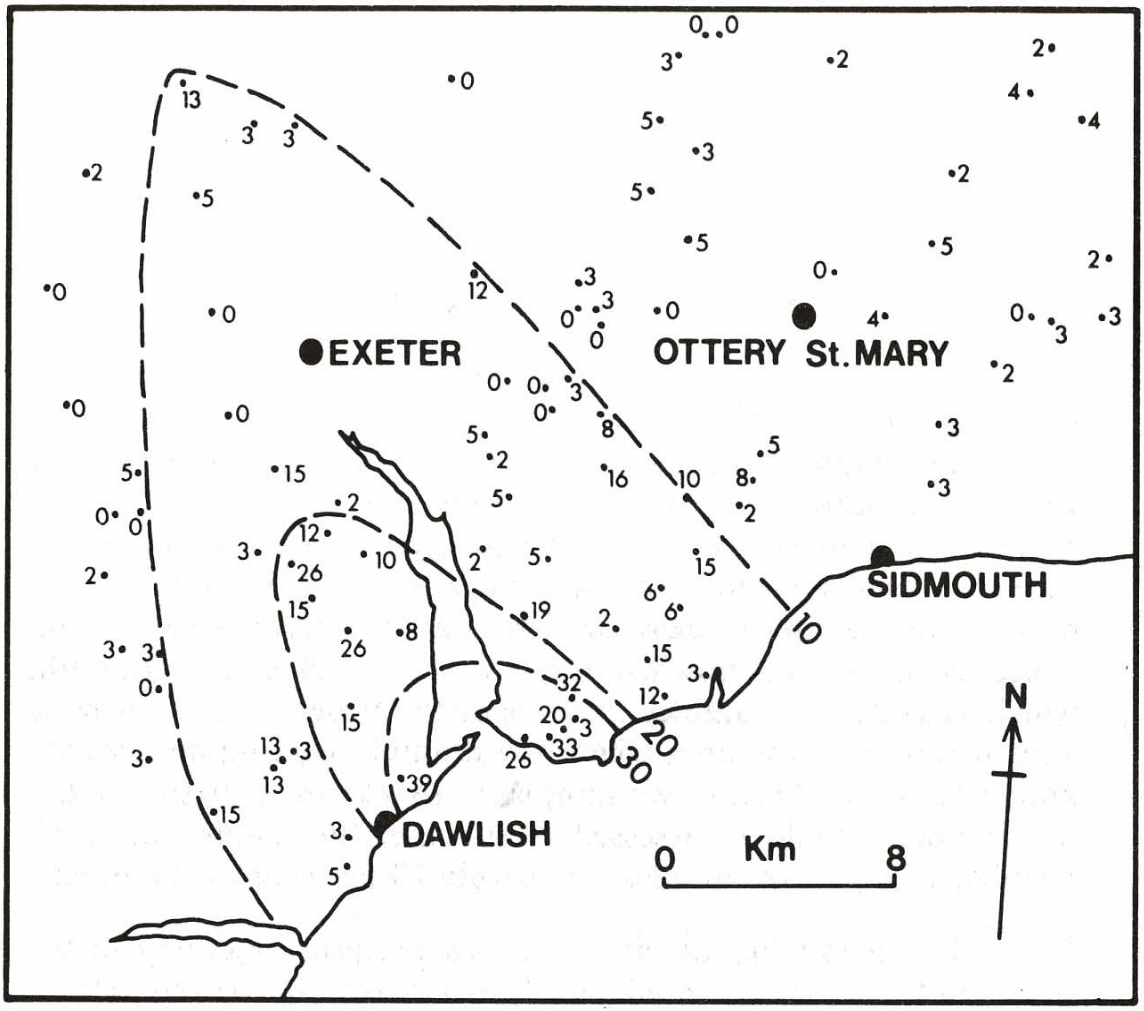

Figure 3. Radon distribution in the stream waters of East Devon

found in areas both to the west and east of the Exe Estuary. From the arguments outlined above, it is clear that low values can be expected even in areas where uranium-bearing minerals are known to occur and, indeed, a value of only 3 counts per minute has been recorded from Littleham village itself which is situated very close to the known occurrence of the uranium nodules. Because individually the values shown in Fig. 3 have no absolute meaning in terms of proximity to a uranium source, simple contouring of the data would have no corresponding geological reality. In order to achieve a realistic visual impression of the results, however, an exclusion system can be used. This is shown in Fig. 3. The lowest value line (10 counts per minute) shown in Fig. 3 has been drawn so that all values outside this line are less than 10 counts per minute. Similar lines at 20 and 30 counts per minute have been drawn. Outside the 20 counts per minute line all values are less than 20 counts per minute, and outside the 30 counts per minute line all values are less than 30 counts per minute. The 10, 20 and 30 counts per minute lines so drawn clearly show a concentric

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arrangement centred about the mouth of the Exe Estuary, with a trend which is elongated roughly north-west to south-east.

Obviously the distribution of the radon is not related specifically to the known occurrence of the uranium-bearing nodules, as none have been recorded from the rocks west of the Exe Estuary. Neither is the radon randomly distributed throughout the area. The actual pattern is simple and like that to be expected from a single source area, but the centre of the anomaly is displaced to the west of the known occurrence of the nodules. Although the streams in the nodule-bearing ground flow to the west, this cannot be the primary cause of the displacement, as high values also occur on the west side of the Exe Estuary where the streams are flowing eastwards. Artificial contamination from a source at the mouth of the Exe Estuary can also be ruled out as the sampling sites lie well above any tidal influence.

From the results of this study a number of questions arise:

1. What is special about the area of the mouth of the Exe Estuary, or are the results merely a reflection of a much more complex pattern which has not emerged from the present level of sampling?
2. Does the area at the mouth of the Exe Estuary represent a localised source of uranium in either the near surface solid or drift formations?
3. Could uranium-bearing minerals be fairly evenly distributed throughout East Devon, but the area of the mouth of the Exe Estuary represent a zone where the breakdown of these minerals and the consequent liberation of radon is greater than elsewhere?
4. Could the area at the mouth of the Exe Estuary be situated over a source of radon from a deep level?

Although no definite answers can be given to these questions it is clear that comment is needed. Firstly, although the intensity of sampling sites could be increased, the coverage shown in Fig. 3 is fairly reasonable encompassing as it does all the solid formations in the area and most of the stream catchments. It is unlikely that further sampling would produce results which would drastically alter the distribution pattern. Secondly, although the high radon values are not confined to specific solid lithologies or to specific areas of valley gravel they are restricted to areas occupied by the New Red Sandstone Series. However, the distribution pattern shown in Fig. 3 is not compatible with the structural disposition of the New Red Sandstone formations. Nevertheless the north-west to south-east elongation of the anomaly could possibly be related to the general alignment of faults in this area which have a similar trend. Thirdly, the

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area of high values does not appear to be unique in any way from a climatological or geomorphological point of view, neither does it show the presence of more intensive faulting than the adjacent areas. In short, there appears to be no reason why the breakdown of uranium-bearing minerals should be more rapid in this area than elsewhere in East Devon. Finally, the possibility exists that the radon is related either directly or indirectly to a deep source of Uranium. This would seem reasonable as the area has been the site of uranium precipitation in the past, as shown by the presence of the nodules in the Littleham Mudstones Formation. Perhaps the restriction of uranium precipitation in important quantities to the Littleham Mudstones Formation resulted from the presence of suitable plant debris nuclei just in this Formation, but that the source of the uranium covered a wider area. Whether or not this source now acts to produce the radon found in the streams is debateable.

Only a tentative interpretation of the radon distribution in East Devon can be made. Possibly a uranium source occupied the area off the mouth of the Exe Estuary. This source was present during the formation of the uranium-bearing nodules at Littleham Cove, when migrating ground water carried the uranium to sites where plant debris caused its precipitation. Some quantities of uranium were also probably deposited at suitable sites elsewhere in the New Red Sandstone sequence. Today, some radon from the uranium source may still find its way to the ground surface and enter the stream waters, but radon from detrital radium produced by the erosion of the New Red Sandstone Series is probably the main contributor to the concentrations found in the stream waters.

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