PROCEEDINGS
OF THE
USSHER SOCIETY

VOLUME ONE

PART FOUR

Edited by
M. R. HOUSE

REDRUTH, OCTOBER 1965
PRICE: 7/6

THE USSHER SOCIETY

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Correspondence and requests for membership and publications should be addressed to:

Dr. F. J. W. Holwill,
Department of Geology,
Imperial College of Science and Technology,
Prince Consort Road,
London, S.W.7.

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CONFERENCE OF THE USSHER SOCIETY
HELD AT ST. AUSTELL, 1965

Hospitality was offered to the conference this year by English Clays, Lovering & Pochin Ltd. to whom the Society is greatly indebted. Mr. C. M. Bristow of the company kindly acted in an organizing capacity. At the meeting, Dr. R. C. Mackenzie of The Macaulay Institute for Soil Research, Craigiebuckler, Aberdeen, gave the Invitation Address.

On Tuesday, 5th January, there was a field excursion to the china-clay country led by Mr. C. M. Bristow and Dr. C. S. Exley. A traditional beer and pasties lunch was generously provided by the hosts, English Clays, Lovering & Pochin Ltd. Fortunately freezing conditions had improved the ground for walking on the quarry floors.

There was a half-day excursion to the St. Austell coastal exposures led by Mr. M. C. McKeown and later Dr. E. M. L. Hendriks led a brief excursion to the Roseland area.

PROGRAMME

Contributions which are printed in the text are marked with an asterisk.

6th January, 1965

73. *INVITATION ADDRESS. Dr. R. C. Mackenzie : "The origin of the clay minerals in soils."
74. *Dr. P. Floyd : "The petrochemistry of kaolinite formation in Gwavas quarry, Newlyn, Cornwall."
75. *Mr. G. M. Power : "The spectrographic analysis of small quantities of tourmaline from S.W. England ; a preliminary report."
76. *Dr. C. S. Exley : "Some structural features of the Bodmin Moor granite mass."

77. *Mr. C. M. Bristow : "A geophysical survey of cavities in a Devonian limestone at Buckfastleigh."

78. *Mr. B. Booth : "Some aspects of the petrochemistry of the Land's End granites."

79. *Dr. W. R. Dearman and Mr. M. A. H. El Sharkawi : "A newly discovered emanative centre associated with the Dartmoor granite."

80. *Mr. R. Lane: "The Hangman Grits - an introduction and stratigraphy."

7th January

81, 82. *Dr. A. C. Bishop, Mr. J. D. Brawshaw, Mr. J. T. Renouf and Mr. R. T. Taylor: "Preliminary results of recent research on the geology and structure of Western Brittany."

83. *Prof. S. Simpson : " Time of implacement of dykes in Bigbury Bay."

84. *Mr. M. A. P. Smith: "Repeated folding between Hayle and Portreath."

85. Dr. H. G. Reading: "Recent finds in the Upper Carboniferous of Bude and Westward Ho ! and their significance."

86. *Mr. J. P. B. Lovell : "The Bude Sandstones from Bude to Widemouth, North Cornwall."

87. *Dr. M. J. Ripley : "Structural studies between Holywell Bay and Dinas Head, North Cornwall."

88. *Mr. E. C. Freshney : "Low-angle faulting in the Boscastle area.'

89. Dr. K. F. G. Hosking : "The significance of certain major, minor, and trace element patterns in the stream sediments of the Carnmenellis granite mass."

90. *Dr. C. J. R. Braithwaite : "A possible re-interpretation of the structure of the Plymouth Limestone."

91. *Dr. W. R. Dearman and Mr. M. A. H. Sharkawi : "The relationship between iron metasomatism and emanative centres on Dartmoor."

8th January

92. Dr. K. F. G. Hosking : "Chemical characteristics of the cement of the Gwithian raised beach and of certain deposition pipes of the St. Agnes Pliocene deposits."
93. *Mr. C. T. Scrutton : "The ages of some coral faunas in the Torquay district."
94. *Dr. D. Richter : "Observations on the vulcanicity and tectonics of the Torquay area."
95. *Mr. G. F. Mitchell and Dr. A. R. Orme : "The Pleistocene deposits of the Scilly Isles."
96. *The Rev. B. B. Clarke : "The upper and lower surfaces, and some structural features of the frost soils of the Camel Estuary."
97. *Dr. C. J. R. Braithwaite : "A preliminary report on the petrology of Middle Devonian limestones in South Devon."
98. *Dr. W. R. Dearman : "Bismuth and Molybdenite from Meldon Quarry, near Okehampton, Devon."

99,100. *SPECIAL SUBSEQUENT CONTRIBUTIONS : Prof. S. Simpson "Ph.D. and M.Sc. theses submitted since 1950 on the geology of Devon and Cornwall". Dr. W. R. Dearman "Map showing geological research in S.W. England - 1965".

73. Invitation Address.

THE ORIGIN OF CLAY MINERALS IN SOILS :

by R. C. Mackenzie, The Macaulay Institute for Soil Research, Craigiebuckler, Aberdeen.

Since sediments and sedimentary rocks consist to a large extent of land-derived materials, frequently little altered by diagenesis but usually somewhat sorted, the importance in geology of an appreciation of the origin of clay minerals in soils is evident. But before considering this aspect it is necessary to consider what is meant by the term clay mineral, how these minerals may be identified and determined, and the factors involved in soil formation.

THE NATURE OF CLAY MINERALS

The term **clay** is used in so many disciplines that it is impossible to give an all-embracing definition which would cover all `clays'- and yet, despite the fact that the word has several connotations, the nature of clay is generally appreciated even by the layman. A recent assessment of this problem of definition (Mackenzie, 1963) has led to the conclusion that natural largely inorganic materials possessing plasticity, having particles of very small size, and having the property of hardening on firing (or two of these three criteria, since there are exceptions) would, in most disciplines at least, be termed clays.

Clay minerals are even more difficult to define in a manner that is generally acceptable, and although many definitions have been proposed none is perfect. However, the empirical :

> "Clay minerals are the minerals that normally predominate in the colloidal fraction of clay rocks, soils, etc."

(Mackenzie, 1963) is reasonably satisfactory and will presently suffice.

Fortunately, international agreement on the classification and nomenclature of clay minerals is gradually being reached and certain recommendations are currently being considered by the International Mineralogical Association. Since the matter is sub judice it would be improper to elaborate here, but to clarify matters so far as this paper is concerned it seems adequate to describe briefly the structures of the main groups of clay minerals (Fig. 1) and to give tables showing the interrelationships of clay minerals (Table 1) and of the common accessory minerals (Table 11).

Most of the clay minerals belong structurally to the phyllosilicate class and may be regarded as consisting of sheets of silica tetrahedra condensed with octahedral sheets of gibbsitic or brucitic type. The kaolinite (gibbsitic)

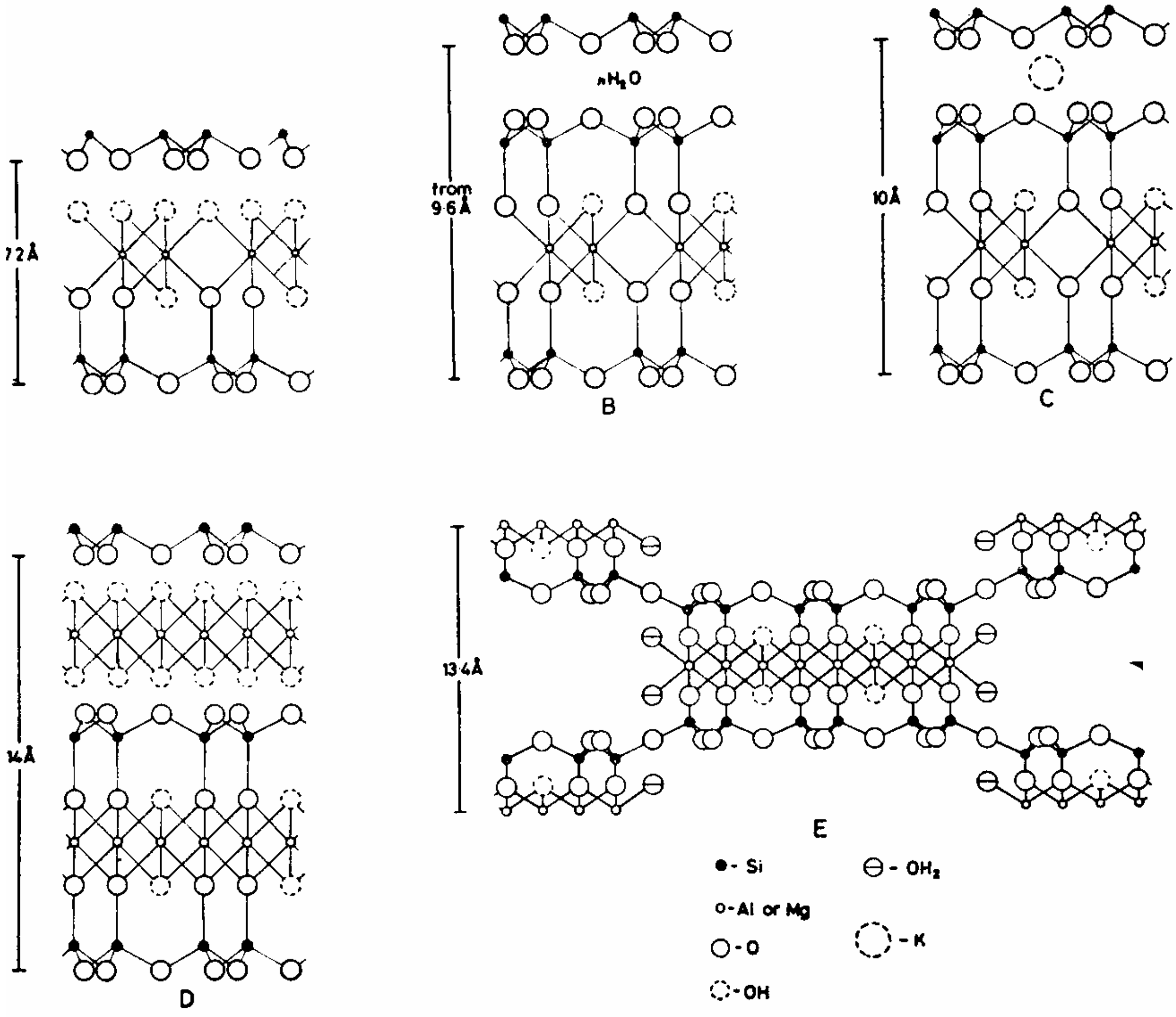


FIGURE 1. Diagrammatic projections of the structures of A - kaolinite, B - montmorillonite, C - mica, D - chlorite, E – sepiolite (after Mackenzie and Mitchell, 1965).

and serpentine (brucitic) groups of minerals have these sheets in 1: 1 proportion in each layer (Fig. IA) and are known as the 1: 1 minerals ; the layers are generally strongly bound, possibly through hydrogen bonds. Pyrophyllite (gibbsitic) and talc (brucitic) have the sheets condensed in the ratio 2 tetrahedral : 1 octahedral, and two oxygen surfaces face each other (Figs. 1B, 1C). Interlayer binding is therefore not so strong and in certain instances) -e.g. the montmorillonite minerals or smectites (Fig. 1 B) -water and other polar liquids can penetrate between the layers and force them apart. Large amounts of isomorphous substitution of ions obeying the Goldschmidt rule (e.g. Al-for-Si, Mg-for-Al, etc.) may also occur in these 2 : 1 layer minerals and consequently several groups may be distinguished from differences in properties attributable largely to variations in surface charge density of the layers. When gibbsitic sheets are present only two out of each three octahedral sites are occupied and these minerals are termed dioctahedral ; when the octahedral sheets are brucitic, on the other hand, all three sites are filled and the minerals are trioctahedral. Unsatisfied charges arising from isomorphous substitution by ions of different valency, and not internally compensated for in the layer itself, are neutralised in 2: 1 minerals by interlayer cations which may (as in montmorillonite) or may not (as in mica - Fig. lC) be readily exchangeable with other ions in solution. Exchangeability is dependent upon the surface charge density of the layer and also upon the type of ion - thus K^+ tends to become `fixed', or nonexchangeable (as in micas) because its size is such that it readily fits into `holes' in the sheet surfaces.

Because of the layer structure of these minerals it is possible, and indeed fairly common, to get individual crystals consisting of layers of more than one type. Such interstratification of layers may be random or regular-the most familiar example of the latter is the chlorite group where 2 : 1 type layers are regularly interstratified with brucitic, or even gibbsitic (Muller, 1963), layers (Fig. 1D).

Even the chain-lattice minerals (Fig. lE) contain units of the layer type and hence have affinities with the phyllosilicates. Two groups are recognised - palygorskite and sepiolite - differing essentially in the size of the phyllosilicate unit, although there may also be other distinctions (Mackenzie and Mitchell, 1965).

Structural details for all these clay minerals are given in standard text-books, such as that of Brown (1961).

INVESTIGATIONAL METHODS

The clay fraction of a soil is defined, by international agreement, as that fraction having particles less than 2µ equivalent spherical diameter and is normally separated by a sedimentation or elutriation method, using Stokes' law to determine the conditions (see, e.g., Mackenzie, 1956a). Because of the small size of the particles, normal petrological techniques are of relatively little use and most information has to be obtained by indirect methods, either instrumental or chemical.

The most common and generally applicable approach is to employ X-ray diffraction techniques (Brown, 1961), but no one method is entirely adequate and the results obtained must be assessed in the light of the findings of other techniques such as differential thermal analysis (Mackenzie, 1957a), infra-red spectroscopy (Farmer and Russell, 1964), electron microscopy (Bates. 1958), electron diffraction (Zvyagin, 1964) and selective chemical techniques (Mitchell, Farmer and McHardy, 1964). It is only by use of all these techniques cumulatively that one can hope to gain even a reasonably accurate picture of the mineralogy of any clay (Mackenzie, 1961).

It is interesting to note that chemical methods, including even total analysis, are finding increasing use in clay mineralogy since they frequently enable refinement of a mineralogical analysis based solely on the results of instrumental techniques (Mackenzie, 1960 ; Mackenzie and Robertson, 1961 ; Jackson and Mackenzie, 1964).

Class	Type	Charge on layer-unit-cell	Group	Series	Species	Difference from the type species
Layer-lattice	1:1	0	Kaolinite	Dioctahedral	Kaolinite	
					Nacrite	Structural
					Dickite	Structural
					Halloysite	Structural
			Serpentine	Trioctahedral	Antigorite	
					Chrysotite	Structural
					Amesite	Fe^{2+} for Mg*
					Cronstedtite	Fe^{2+}, Fe^{3+} for Mg
	2:1:1	Variable	Chlorite	Dioctahedral	Sudote	
				Trioctahedral	Clay chlorite	
	2:1	0	Pyrophillite-Talc	Dioctahedral	Pyrophyllite	
				Trioctahedral	Talc	
		0.7	Smectite	Dioctahedral	Montmorillonite	
					Beidellite	Al for Si
					Nontronite	Fe for Al
					Volkonskoite	Cr for Al
				Trioctahedral	Saponite	
					Sauconite	Zn for Mg
					Hectorite	Li for Mg
		1.3	Vermiculite	Dioctahedral	Dioctahedral vermiculite	
				Trioctahedral	Trioctahedral vermiculite	
		1.9	Mica or Illite	Dioctahedral	Illite	
				Trioctahedral	Ledikite	
		0.2	Hormite	Di-trioctahedral	Palygorskite	
Chain-lattice	(2:1)				Sepiolite	
				Trioctahedral	Xylotile	Fe for Al

TABLE I. Classification of crystalline clay minerals (after Mackenzie and Mitchell, 1965, with modifications).
* This notation indicates isomorphous substitution.

Degree of Order	Group	Cation	Hydration State	Mineral and Formula
Crystalline	Oxides	Silicon	Anhydrous	Quartz, SiO_2 Cristobalite, SiO_2 Tridymite, SiO_2
		Aluminium	Monohydrates	Diaspore, α-AlOOH Boehmite, δ-AlOOH
			Trihydrate	Gibbsite, δ-$Al(OH)_3$
		Iron	Anhydrous	Hematite, α-Fe_2O_3 Maghemite, δ-Fe_2O_3 Magnetite, Fe_3O_4
			Monohydrous	Goethite, α-Fe-OOH Lepidocrocite, δFeOOH
		Manganese	Anhydrous	Pyrolusite, βMnO_2 Nsustite, δ-MnO_2 Birnessite, δ-MnO_2 Hausmannite, Mn_3O_4 Bixbyite, $(Mn, Fe)_2O_3$
			Monohydrates	Manganite, MnOOH Groutite, MnOOH
	Carbonates	Calcium Magnesium	Anhydrous	Calcite, $CaCO_3$ Dolomite, $CaMg(CO_3)_2$ Magnesite, $MgCO_3$
		Iron	Anhydrous	Chalybite, $FeCO_3$

	Sulphides	Iron	Anhydrous	Pyrite, FeS_2
		Manganese	Anhydrous	Haucerite, MnS_2
	Silicates other than phyllo-silicates	Various	Various	Generally remnants of primary minerals
Highly-disordered or amorphous	Oxides	Silicon	Hydrated	Opaline silica, $SiO_2.nH_2O$
		Aluminium	Hydrated	Kliachite, $Al_2O_3.nH_2O$
		Iron	Hydrated	Limonite, $Fe_2O_3.nH_20$
		Manganese	Hydrated	Wad, $MnO_2.nH_20$
	Silicates	Aluminium	Hydrated	Allophane, $mAl_2O_3.nSiO_2.pH_2O$
		Iron	Hydrated	Hisingerite. $mFe_2O_3.nSiO_2.pH_2O$
	Phosphates	Aluminium	Hydrated	Evansite, $mAl_2O_3.nP_2O_{5.}pH_20$
		Iron	Hydrated	Azovskite, $mFe_2O_3.nP_2O_5.pH_2O$

TABLE II. Principal accessory minerals likely to occur in soil clays (after Mackenzie, 1956b and Pedro, 1965, with modifications).

* It is doubtful whether any of these end-members exists as a valid species except under exceptional conditions favouring the stability of that end-member. In general, however, much of the highly dis-ordered material associated with soil clays can be regarded as mixed gels of several of these end-members.

SOIL FORMATION

Interpretation of soil-clay mineralogical information in terms of the mode of origin of the different minerals demands an understanding of the conditions of soil genesis.

It is generally conceded that five factors govern soil formation:

1 - Climate
2 - Flora and Fauna (the Biotic Factor)
3 - Parent material
4 - Relief
5 - Time

but since these are largely interdependent it is often extremely difficult to assess the effect of one factor in isolation. However, certain limited conclusions may be drawn, such as, for example, the influence of parent material under a sensibly constant regime of the other variables.

Latitude	Great Soil Group	Climate	Vegetation
High	Tundra	Arctic	Lichens and mosses
↓	Podzol	Cold Temperature	Conifers
	Brown Forest	Temperate	Deciduous
	Chernozem	Warm Temperate	Steppe
	Red and Yellow	Sub tropical-tropical	Desert
Low	Laterite	Tropical	Tropical Forest

TABLE III. Some important Great Soil Groups and their relationship to climate and vegetation.

Interplay of climate and vegetation over a wide range, with little variation in the other factors, has led to the distinction of major groups of soil, as defined by their profile characteristics, termed the Great Soil Groups. Omitting minor variants, some general relationships are shown in Table III. It is of interest to note that in the sequence shown the intensity of chemical weathering increases, generally, toward low latitudes and the intensity of physical weathering towards high - although excessively dry, warm areas are an exception. A high intensity of chemical weathering leads to highly hydroxylated secondary minerals in the clay, whereas clay fractions formed under conditions where physical weathering predominates tend to contain minerals with much smaller amounts of hydroxyl groups. Consequently, the change from predominantly physical to predominantly chemical weathering towards low latitudes is well illustrated in Fig. 2 where the peaks on the differential thermal curves in the 300-600° C. region represent hydroxylation. One point that must not be forgotten, however, is that time is also a factor here since the high-latitude soils auoted are the youngest and the tropical the oldest.

From the viewpoint of clay formation, parent materials fall into three distinct categories :

a - igneous and metamorphic rocks
b - sedimentary rocks
c - unconsolidated deposits

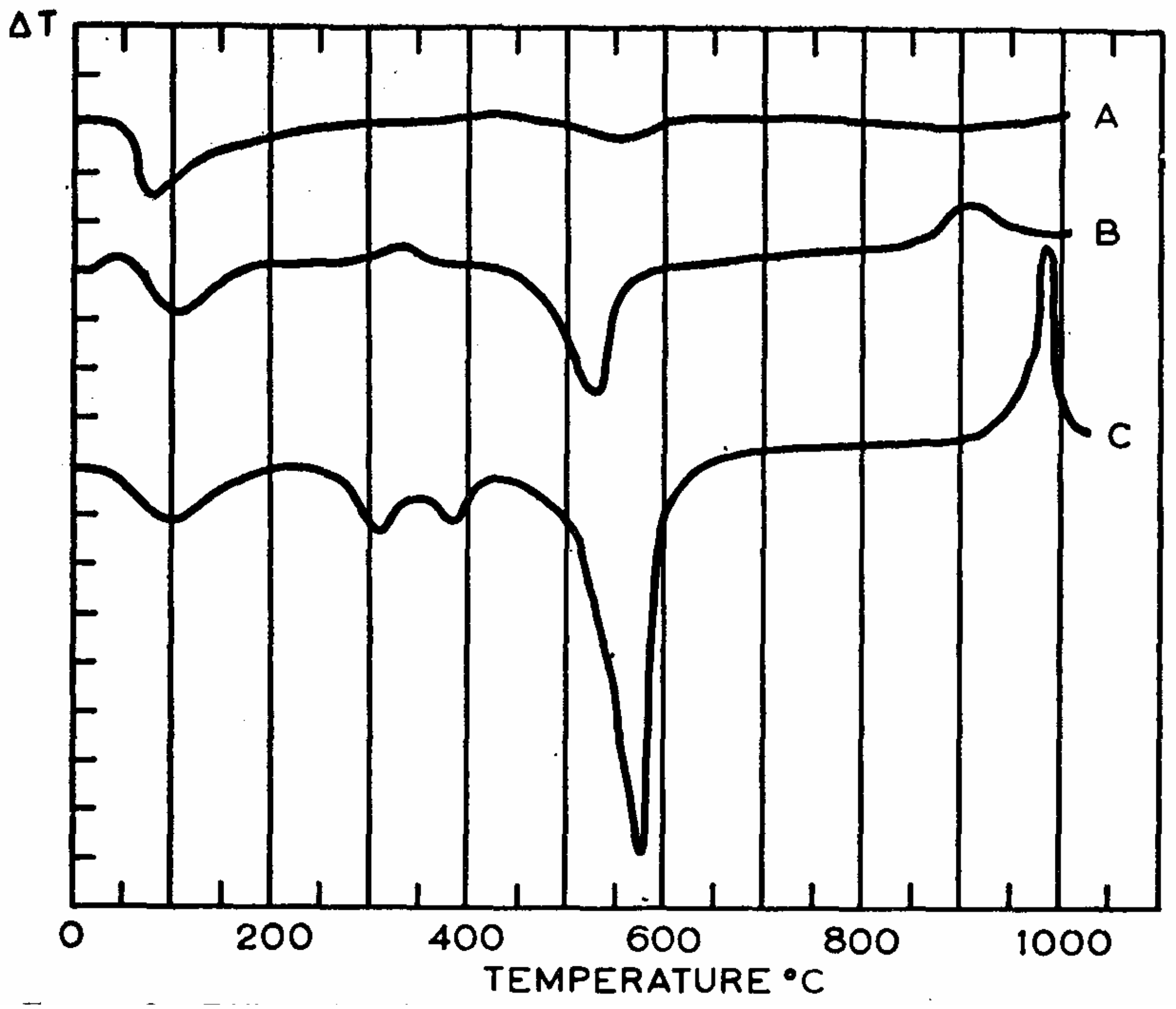


FIGURE 2. Differential thermal curves for soil clays from A- Sweden, B - Scotland, C- West Africa.

and the last category may indeed be conveniently sub-divided into two - unconsolidated materials that are in, or almost in, situ (e.g. tropical deeply weathered deposits and glacial till) and those which have been transported over considerable distances (e.g. loess and alluvium). For the latter, the parent rocks may be very difficult, or even impossible, to trace, and indeed may be so diverse that little information on their influence on clay mineralogy can be garnered. Soils developed on the former type of unconsolidated deposit may, however, yield much information of value. Thus, in Scotland soils are developed largely on glacial till which can often be shown on mineralogical and petrological evidence to have been moved only ½ -1 mile in the direction of ice-movement. In consequence, these present an admirable opportunity for assessing the changes occurring in the sequence rock. → till → soil, which will be considered below in relation both to igneous and metamorphic and to sedimentary rocks.

ORIGIN OF MINERALS IN THE CLAY FRACTION

Three modes of origin can be recognised :

a - inheritance from the parent material
b - alteration and degradative alteration of primary minerals
c - synthesis

all of which may - and probably generally do - operate simultaneously.

Although separation of the effect of each is therefore somewhat difficult the fact that one or other can be assessed to be predominant freauently enables some assessment of their relative influence.

(a) Inheritance from the parent material

Inheritance is of particular importance with sedimentary rocks and unconsolidated deposits. Igneous rocks are certainly known to contain clay minerals either in vesicles or disseminated through the rock - good examples of the former being the occurrence of saponite in andesitic lava in Kincardineshire, Scotland (Mitchell, 1954) and in basalt from the Island of Skye (Mackenzie, 1957b), and of the latter an unpublished observation of the author's of trioctahedral smectite in apparently fresh nepheline basanite from South Dean Law, Roxburghshire, Scotland. But although such minerals may well be inherited by the soil their importance is very minor, and the bulk of the clay fraction undoubtedly originates from the weathering of other primary minerals. In consequence, in this context only sedimentary rocks and unconsolidated deposits will be considered.

The limit to inheritance is set by the pedological conditions obtaining in the soil - which in turn are largely determined by climatic and biotic factors. But in temperate regions, and indeed anywhere that chemical weathering is not excessive, many clay minerals are reasonably stable and the clay mineralogy of the soil is then largely determined by that of the parent rock or deposit - i.e. inheritance is dominant. Many examples can be quoted, but the case of terra rossa is perhaps the most striking. It has been shown by Yaalon (1955) that the clay mineralogy of such soils is a reflection of the clay mineralogy of the parent limestone and extensive investigations have shown kaolinite, illite, montmorillonite and palygorskite to be predominant at different localities (Munoz Taboadela, 1953 ; Cecconi, 1953 ; LippiBoncambi, Mackenzie and Mitchell, 1955 ; Yaalon, 1955). The presence of palygorskite in such association is interesting since this mineral has never yet been synthesized in the laboratory. Large areas of soils characterized by the presence of large or small amounts of palygorskite occur widely in the Middle East (Iraq, Iran and parts of Egypt and Israel) and all are associated with carbonate rocks of some sort. It may be, therefore, that this mineral can only be formed in a carbonate environment.

In Scotland, where glacial till is the parent material of most soils, both the till and the soil developed thereon are generally highly illitic, especially when the parent rock is acidic-intermediate igneous or metamorphic (Table IV). It is clear therefore that the illite in the soil is then inherited from the till.

The origin of this illite in the till raises many questions. Despite the occurrence of micas in the parent rocks the weight of the evidence available suggests that much of the illite has been formed at the expense of other minerals, particularly felspars. This is therefore an alteration reaction, but since it does not occur in the soil as such it is perhaps more apposite to consider it briefly here rather than in the next section. There is no clear evidence as to when the felspars were converted into illite but it would certainly appear that this could not have happened entirely by weathering in the till since the end of the Ice Age : possibly, therefore, the main alteration occurred during attrition by the ice and during the period of melting. It is now established that simple grinding can decompose certain minerals and cause the formation of others (e.g, the effect of grinding on micas - Mackenzie, Meldau and Farmer, 1956) so such a transformation would not be exceptional, but it is worthy of note that it is not consistent with the text-book equation :

$$2KAlSi_3O_8 + 2H_20 + CO_2 = Al_2SiO_5(OH)_4 + K_2CO_3 + 4SiO_2$$

which does not seem particularly apposite to soils except perhaps under tropical conditions. And even then illite or mica might well be an intermediate :

$$\underset{\text{orthoclase}}{3KAlSi_3O_8} + H_2O + CO_2 = \underset{\text{mica}}{KAl_3Si_3O_{10}(OH)_2} + K_2CO_3 + 6SiO_2$$

$$\underset{\text{mica}}{2KAl_3Si_3O_{10}(OH)_2} + 4H_2O + CO_2 = \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + K_2CO_3$$

although considerable structural alteration would be necessary and the equations are deceptively simple.

As distinct from this, the clay mineralogy of till derived from sedimentary rocks, and of the soils developed therefrom, is profoundly dependent on the clay mineralogy of the parent rock - as is well illustrated by soils developed on till derived from sandstones and shales of the Carboniferous Limestone Series in Ayrshire (Mitchell and Mitchell, 1956). The sandstones of this Series are predominantly kaolinitic and the shales illitic and this distinction is clearly evident in the soils developed on the tills derived from these two facies (Table IV). Similarly, in soils developed on tills derived from Silurian shale the high chlorite content (Table IV) is inherited from the shale.

Till derived from :	Clay Minerals in Soils :
Lava (Carboniferous)	Vermiculite>illite = kaolinite chlorite
Andesite and trachyte	Illite>kaolinitewermiculite
Granite and gneiss	Illite>>kaolinite
Quartz schist	Illite>>kaolinite
Quartzite	Illite>kaolinite>vermiculite
Slate (Dalradian)	Illite> kaolinite>vermiculite
Old Red Sandstone sediments	Illite>kaolinite>vermiculite
Shale (Silurian)	Illite>chlorite>kaolinite
Shale (Carboniferous Limestone Series)	Illite>kaolinite>vermiculite
Sandstone (Carboniferous Limestone Series)	Kaolinite>vermiculite>illite

TABLE IV. Clay minerals present in Scottish soils on till derived from different rock types (after Mackenzie, 1965).

Such results indicate that inheritance may occur through several weathering and depositional cycles from sedimentary rocks and that it is of considerable importance in determining the clay minerals present in soils. But the same is true of the accessory minerals and it is interesting to note that in Scottish soils both quartz and felspar may be inherited through from the parent rock.

Soil on till derived from	Horizon	Depth cm.	Illite	Vermiculite	Kaolinite	Chlorite	Quartz
Lava (Calciferous Sandstone Series)	A_2g	5-20	45	20	30		+*
	Bg	20-51	50	10	30		+
	Cg	51-81	60	5	30		+
	A_2g	23-46	5	65	15	10	5
Downtonian Sandstone	Bg	46-66	40	30	15	10	5
	Cg	66-86	70	0	15	10	5

+ * indicates trace.

TABLE V. The illite-vermiculite balance in the clay fraction of some Scottish very poorly drained soils (all values in %) (after Mitchell and Mitchell, 1956).

Other examples of inheritance covering Tundra, Podzolic, Alpine, Prairie, Chernozem and Desertic soils have been cited by Jackson (1959). The minerals inherited depend upon the parent material, the climate and the intensity of chemical weathering. Thus, in cold or hot, dry climates even ferromagnesians and felspars may occur in large amount in the clay fraction, although these same minerals are probably the least stable in finely divided form under moist conditions.

(b) Alteration of primary minerals

Probably the most easily appreciated examples of alteration relate to the micas, and the changes occurring during the transition from biotite to vermiculite and from muscovite to illite have been the subject of much study -and much controversy. The significance of the term illite in particular raises considerable argument. By some it is regarded as a non-swelling mineral of the mica type with less K_2O and more H_3O^+ (Brown and Norrish, 1952) or water (Rosenqvist, 1963) than muscovite. By others it is considered to consist of random interstratification of layers of the muscovite type with layers of the montmorillonite type, and by still others to cover also minerals with particles having a nucleus of muscovite but “splayed” or “frayed” at the edges because of K^+ removal and consequent expansion. There is little doubt that the name has been used for all three types and consequently it may at best be regarded as a useful field term for clay mica - and generally a dioctahedral clay mica. Certainly many clay micas which cannot be shown definitely to be interstratified (but this would not preclude the presence of a few randomly interleaved montmorillonite-type layers) have a K_2O content of about 6.5% and an H_2O content of about 7.5% compared with 10-11.5% and 4.5-5%, respectively, for muscovite.

The apparent relationships in the series mica, hydrous mica, smectite are clearly shown in Fig. 3 (Mackenzie, 1955) but it must be stressed that this cannot strictly be regarded as representing a transformation series since changes in K_2O and H_2O content are necessarily associated with fundamental changes in the lattice. Thus, not only may there be alteration in the amount of isomorphous substition of Al-for-Si, Mg-for-Al, etc., but some of the H_2O^+ may be present as H_3O^+ (Brown and Norrish, 1952) and changes in the oxidation state of some ions may occur - as was clearly demonstrated by Walker (1949) in his classical studies on the biotite → vermiculite transformation. Yet these fundamental changes can readily occur, over long periods of time, in the soil, since oxygen will be readily available, particularly in surface horizons, and there will be interchange between ions in the lattice and those in solution. For these reasons simplified series purporting to show how interstratified minerals and vermiculite or smectite may in the soil be derived from micas by K^+ removal (see Jackson et al., 1952) may be perfectly valid, despite their a priori improbability. Indeed, the fact that this change does occur is well exemplified by the illite (ledikite)-vermiculite balance found in many Scottish soils - particularly of wet acid type (Table V). This transformation to vermiculite appears to occur under acid conditions on tills derived from basic or basic-to-intermediate igneous rocks.

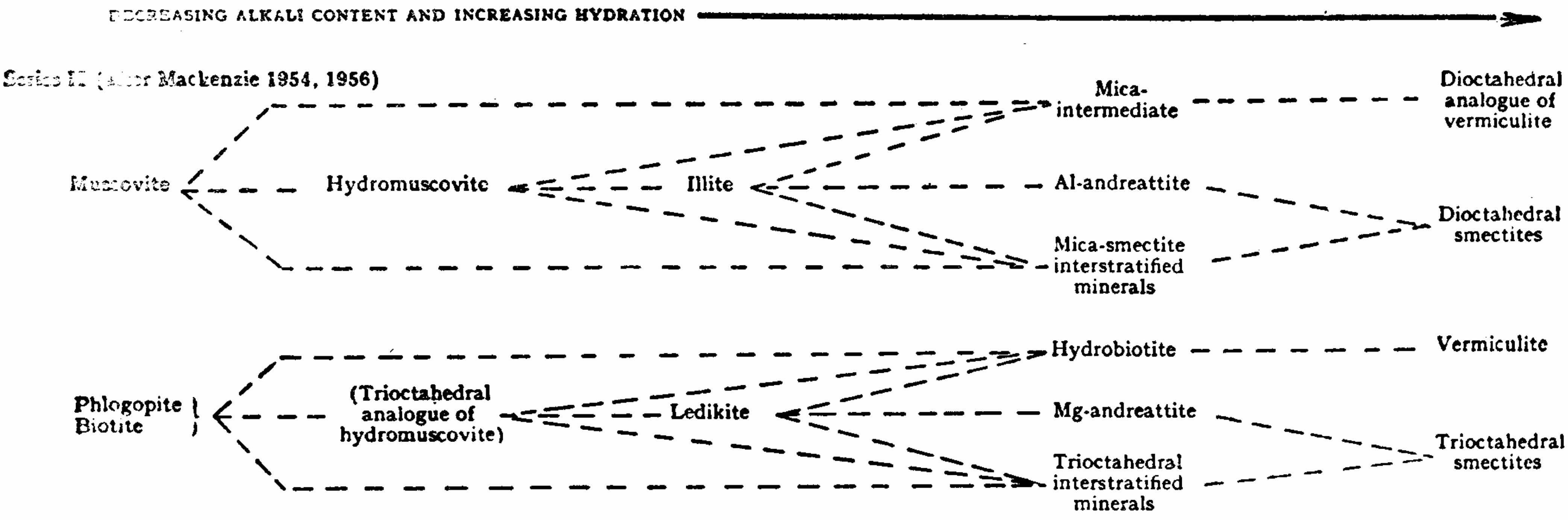
Under strongly acid conditions on tills derived from acid rocks illite is particularly unstable and is either altered to an interstratified mineral + kaolinite or part is completely decomposed leaving kaolinite in apparently enhanced concentration (Table VI). Kaolinite seems reasonably stable under these conditions.

Whichever process operates this might be termed degradation since the changes occurring are much more fundamental than those envisaged above. Into this category also would come tropical deep weathering which leads generally, irrespective of rock type, to a residue consisting, typically, of kaolinite or halloysite along with sesquioxides, and which is therefore highly aluminous. The origin of such high-alumina clays has recently been the subject of several papers (Ginzburg, Nadzhakova and Nikitina, 1962 ; Keller, 1964a, 1964b), and the processes leading to their formation have been considered at length : suffice it to say here that there is still some argument on fundamental aspects and that several mechanisms are possible. These soils are strongly depleted of bases through intense leaching and if this is prolonged and pH conditions are suitable they may be transformed into bauxite.

Horizon	Depth cm.	Kaolinite	Illite	Vermiculite	Quartz	Goethite	Hematite
A1	25-33	45	40	10	+*		
A2	33-38	40	45	10	+	2	+
B1	38-51	35	50	10	+		+
B2	51-74	20	60	10	+		+
C	74-91	10	75	10	+		+

+ * indicates trace.

TABLE VI. The clay mineralogy of a peaty podzol with iron pan developed on till derived from Old Red Sandstone rocks (all values in %) after Mitchell and Mitchell, 1956).



* Names in brackets indicate that the mineral in question has not yet been observed experimentally, although theoretically it should exist (brackets have been removed where the mineral has been described since these series were formulated).

FIGURE 3. Diagrammatic representation of the relationships between various 2 : 1 layer-lattice minerals (after Mackenzie, 1955).

In tropical conditions where leaching is not intense, i.e. where the land is level and the water table is high, ` black cotton soils ' are common ; these are not so depleted of bases and are frequently characterized by a high montmorillonite content.

In order better to understand some of these processes of alteration much experimental work has been carried out in the laboratory in an attempt to simulate the action of water and very dilute acids on minerals and rocks in the field. The classical researches of Correns and his collaborators at Gottingen (see Correns, 1961) gave valuable information upon the decomposition of primary minerals under various conditions, but little upon the secondary products formed except that they appeared to be amorphous. Of more general interest from the viewpoint of secondary minerals are the intensive studies of Pedro (1961, 1964) who made ingenious use of a Soxhlet extractor to speed up the types of reaction which occur in tropical soils. The experiments were so arranged that the temperature of the percolating water never exceeded 65° C. and that part of the bed of rock fragments was above the 'water-table' and part below. The results obtained indeed closely parallel those observed in the field. Thus, as is found in nature, basalt, trachyandesite and granite all yielded essentially the same products (ochreous crusts containing hematite and boehmite above the water-table, and crusts with gibbsite and boehmite below) and the decomposition series was found to be

basalt > trachyandesite > granite.

Furthermore, felspars and amphiboles were shown to be readily decomposed and quartz to be resistant. The material collected in the effluent was amorphous.

The last observation is of considerable interest, since despite this and the earlier observations of Correns and collaborators, there has been little record of any amorphous material occurring in tropical soil clays until the observations of Watson (1965). However, it is only relatively recently that the importance of highly disordered or non-crystalline inorganic material in clays has been generally recognised (Mitchell, Farmer and McHardy, 1964) and it may in earlier studies have been overlooked - or, of course, it may have been removed in drainage water or even have crystallized (Watson, 1965). This problem obviously warrants further study.

The surface layer of the soil maintains plant and animal life and micro-organisms and fungi abound. It has been known for some time that certain minerals are susceptible to attack by mico-organisms, but it is only recently that the mechanism has been elucidated, when Duff, Webley and collaborators (Duff Webley and Scott, 7962; Henderson and Duff, 1963) at the Macaulay Institute showed that acids produced by bacteria and fungi as part of their metabolism (e.g. 2-ketogluconic acid) were particularly important. These acids can chelate many elements in the mineral leaving behind a residue of amorphous silica. It is highly probable that exudates from plant roots have a similar effect and consequently in these circumstances the biotic factor has a determinative effect on the clay minerals formed.

(c) Synthesis

Although synthesis is the reverse of degradation there is no anomaly in the fact that these two processes occur simultaneously in the same soil (Gradusov, 1964) and that at times it is difficult to separate them. For example, the amorphous silica left after microbial attack on minerals is not necessarily deposited as such but more probably co-precipitates with alumina and iron oxides to give mixed gels. Such gels may therefore be regarded as the products of synthesis.

They are amorphous in the sense that they do not diffract X-rays or electrons, but this merely implies that regions with regularity of arrangement of ions are small, and indeed a certain short range order is known to be present (Egawa, 1964; Leonard et al., 1964). It might, therefore, be more appropriate to term such materials highly-disordered, poorly ordered or non-crystalline. Transition to a crystalline phase may well be regarded as a further step in synthesis and is known, in several instances at least, to occur on ageing. Thus, the highly allophanic soils of New Zealand and Japan are developed on volcanic ash and contain in their clay fraction a large amount of non-crystalline mixed gels (allophane). It has recently proved possible to trace the ageing of allophane from extremely disordered forms showing only as shapeless clumps under the electron microscope through apparently more ordered forms showing fibres and even tubes (still amorphous to electrons - Mitchell, Farmer and McHardy, 1964) to halloysite and even perhaps to kaolinite - although this latter step is not so well proven as the earlier ones (Fieldes, 1955 ; Sudo, 1959 ; Garcia Vicente and Besoain, 1961 ; Kanno, 1961 ; Aomine and Wada, 1962).

Volcanic ash soils are, however, rather a special case, and it is apposite to enquire about the importance of highly-disordered inorganic materials in other soils. It is now known that they are of considerable importance, but the evidence for this has accumulated only during the last few years. Previously, for almost 30 years - i.e. since the advent of X-ray powder diffraction techniques - it was customary to regard all inorganic components of soil clays as being crystalline, and it was only when marked discrepancies between the behaviour of many soil clays and that expected for the crystalline components became evident that attention was diverted to the possible existence of significant amounts of non-crystalline material. Such studies have been in progress on Scottish soil clays for several years by Mitchell, Farmer and collaborators (Mitchell, Farmer and McHardy, 1964 ; Follett et al., 1965a, 1965b) and have yielded valuable information. The major difficulties associated with such studies concern identification and determination, and considerable time has been spent in developing and assessing the value of selective chemical reagents. From these studies it has been found that cold and hot extractions with 5°4, sodium carbonate solutions are reasonable for assessment of highly disordered alumino-silicate material with minimum attack on crystalline components and that sodium dithionite removes both crystalline and amorphous iron oxides. Despite the fact that small amounts of crystalline materials may be decomposed by these reagents the sum of the amounts extracted gives some measure of the material synthesized in the soil in question. Examination of the various size fractions of several horizons in soil profiles on till derived from granite and from gabbro have shown interesting trends. Thus, although the highest percentage of extractable material is always associated with the clay fraction the absolute amount of such material associated with the sand fraction may be quite appreciable because of the larger proportion of this fraction in many soils. Furthermore chromatographic development is clearly evident in freely-drained soils, suggesting translocation of, particularly, alumina and iron oxides down the profile. The amounts of extractable material associated with the granitic soil are much less than those associated with the gabbro soil and it is rather staggering to find that in the illuvial horizon of the freely-drained soil on till from gabbro about l4% of the total soil is extractable. In the soil on granitic till the maximum amount is about 6% - clearly illustrative of the variation in the importance of degradation and synthesis in the two regimes.

The mode of occurrence of this material has also been the subject of recent study. It is clear from this that the extractable iron oxides do not occur entirely as discrete oxides but that part at least is in mixed gels with silica and alumina and that these gels tend to bind particles together and to be associated with particle surfaces (Follett et al., 1965a, 1965b). Its removal undoubtedly permits better dispersion of the clay, but the important aspect from the pedological view-point is that, occurring as it does as surface ‘coatings’ on crystalline particles, it can determine the overall surface properties of the soil even when the amount present is not particularly large.

Although the amounts of this material detected in some soils are considerable, this need not be surprising. The soil is a dynamic system and absorbs much energy in its upper layers. The entropy of the system therefore tends to increase and one would naturally expect an increasing degree of disorder in the minerals present as one moves upwards towards the soil surface. The downward translocation of such material and an increase in its degree of order with depth because of conditions of lower entropy would also be expected. Physico-chemically, therefore, the soil behaves in a perfectly logical manner.

This is perhaps sufficient detail concerning synthesis in the field. But many attempts have been made to synthesize clay minerals in the laboratory. Most have been successful, but here only two series of experiments need be mentioned : those of Caillere and Hénin (1962 ; Hénin and Caillere 1963) and those of Roy (1962). The former showed that synthesis of clay minerals was possible from very dilute solutions such as might be expected in the soil solution, and the latter established the stability regions of various minerals in terms of temperature and pressure. Both therefore have to be considered in assessing field results.

CONCLUSION

Despite the complexity of the soil as a system and the inter-relationship of the various factors determining its development, mineralogical studies if carried out sufficiently intensively and in sufficient detail can frequently enable some assessment of the mode of origin of clay minerals in the soil. But studies on the natural material are incomplete without parallel laboratory studies and each complements the other. Many problems remain to be solved, but at least a commencement has been made in understanding how clay is formed at the earth's surface ; what is likely to be its fate during transport, sedimentation and diagenesis is the province of the geologist, but must be understood to assess the 'life-cycle' of any particular clay particle.

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74. The petrochemistry of kaolinite formation in Gwavas quarry, Newlyn, Cornwall : by P. Floyd.

Randomly scattered throughout the basic hornfelses of Gwavas quarry are small columnar zones of soft kaolinized rock. These white coloured zones are of variable width (from 20'-40') and grade into the adjacent greenish hornfelses.

Kaolinite is usually the major product of extensive hydrothermal argillization of alkali felspars in granitic rocks. It is unusual to find kaolinization of basic rocks where there is little or no associated sulphide mineralization. Progressive chemical and mineralogical alteration of the basic hornfelses was traced in a 24' wide kaolinized zone. The unaltered rocks of the quarry are essentially hornblende - plagioclase hornfelses composed of interlocking plagioclase laths and scattered hornblende prisms and fibres. The plagioclase is albitic, shows little or no sericitization and is heavily clouded by dusty opaque inclusions and small amphibole granules. Other minerals include biotite, ilmenite, tourmaline, sphene and apatite. Chemically, the hornfelses show relatively high SiO_2 (60%) and Na_2O (6-7%) coupled with low CaO, MgO and total Fe. The chemistry belies the dominance of felsics over mafics. K_2O is variable and dependant on model biotite.

At the kaolinized zone margin (12' from centre of zone) a number of mineralogical changes occurred, although no clay was developed. Biotite has totally replaced hornblende as the dominant mafic present. Plagioclase has undergone some granular recrystallization and is also heavily sericitized. Much of the plagioclase is replaced by anhedral quartz blebs. Increasing argillization is observed towards the zone centre with kaolinite replacing plagioclase and also biotite flakes. Some large kaolinite pseudomorphs after biotite show a typical sheaf-like development with splayed ends. Although kaolinite and sericite increasingly replace plagioclase, until there is little left, there appears to be a definite antipathetic relationship between these replacing minerals. On extensive kaolinization, minerals other than plagioclase and biotite are replaced, viz. : chloritized biotite is replaced parallel to the cleavage : quartz veins and quartzose patches are embayed and decimated ; ilmenite is replaced leaving a relict network of partially limonitized granules. Fig. 1 shows at what stage the progressive replacement of all the initial minerals in the marginal zone took place.

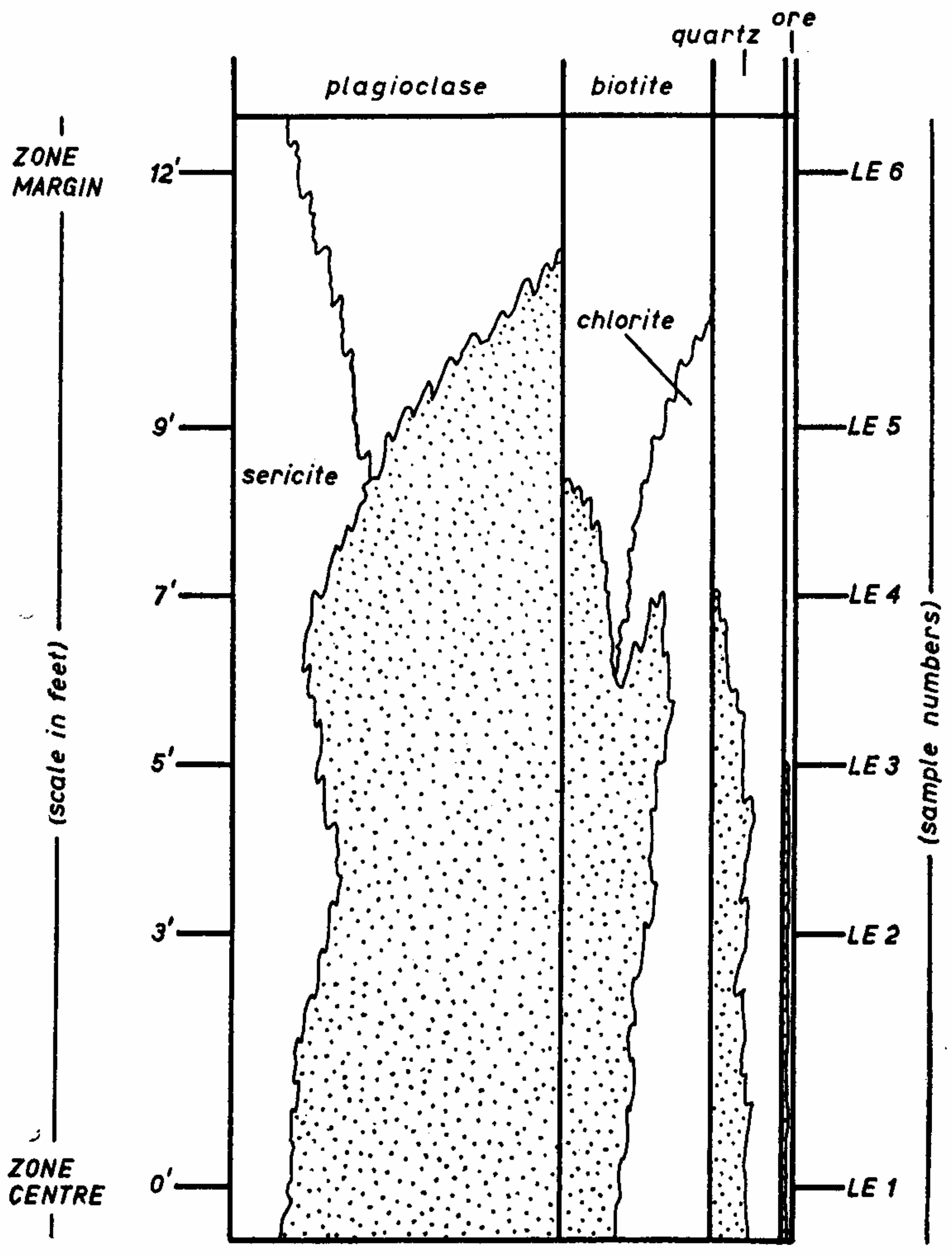

FIGURE 1. Diagrammatic representation of the progressive replacement of the initial minerals of the marginal zone by kaolinite. On increasing argillization the order of replacement is plagioclase, biotite, chloritized biotite, quartz and finally iron ore. The stippled areas represent kaolinite. Relative proportions of the various minerals only approximate.

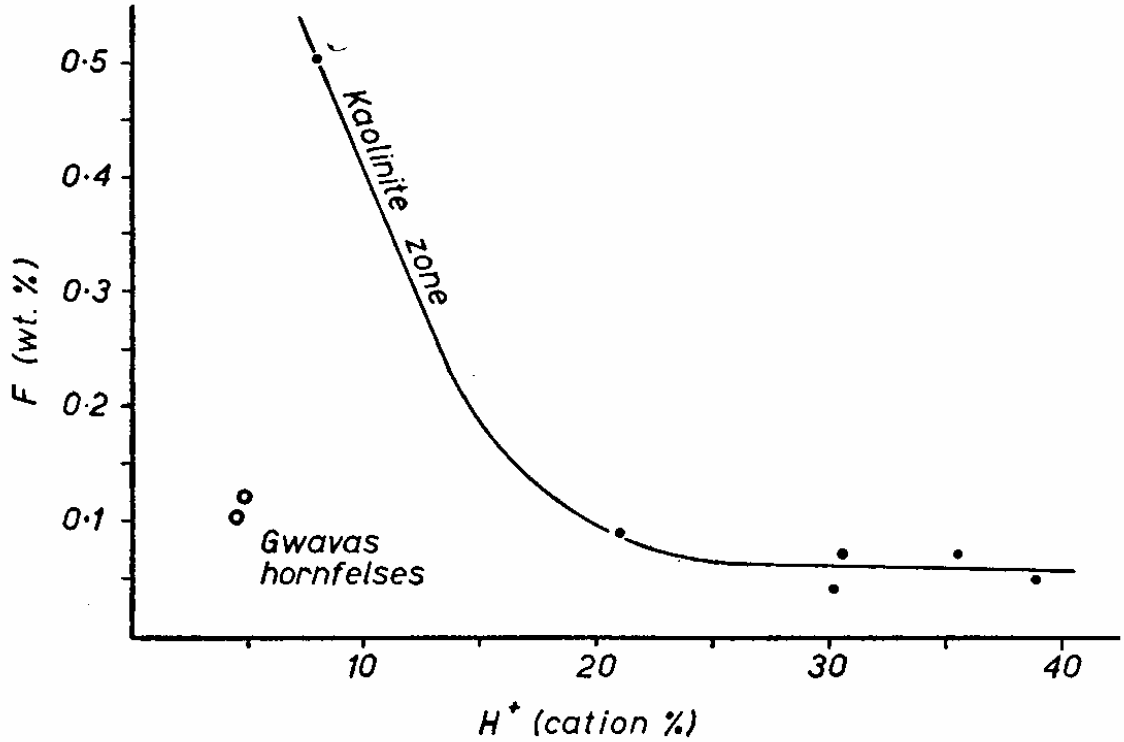

FIGURE 2. Graph showing the slight antipathetic relationship between F - and H^+ ions in kaolinized and unaltered Gwavas hornfelses. The very high F^- value in the kaolinite zone is due to the development of a "fluorine front" in the zone margin.

The progressive variation in the major cation chemistry of the kaolinized zone was determined by analysing 6 specimens at intervals of 2' across the zone. All the cations showed a decrease towards the zone centre, with the exception of K^+, Al^{3+} and H^+. K^+ remained relatively constant and had a value similar to an average of biotite-bearing hornfelses outside the zone. $A1^3+$ on the other hand, showed a slight increase from 16 to 23 cations as the zone centre was approached. An Al^{3+} "high" at 3' coupled with a coresponding Si^4+ "high" can be correlated with an increase in sericite content at the expense of kaolinite. H^+ shows a steady increase (except for a "low" at 3') and can be directly correlated with progressively increasing kaolinite. Volatiles, like CO_2, show little variation in the zone compared with unaltered hornfelses. F-, however, had been expelled to form a "fluorine front" of some magnitude (8 times that of zone average) at the zone margin. The F^- is sited in the biotite by replacement of $(OH)^-$ groups. Fig. 2 shows the antipathetic relationship between F^- and H^+ ions in the kaolinized zone and unaltered Gwavas hornfelses.

75. **The spectrographic analysis of small quantities of tourmaline from S.W. England ; a preliminary report :** by G. M. Power.

In order to carry out a study of the variation in chemical composition of tourmaline with geological environment a spectrographic method of chemical analysis has been developed. The following elements may be determined in triplicate, Ti, Mn, Fe, Ca, Mg, Na, Sc, Cr, V, Sr, Ba, Pb, Cu, Ga, Ni, Co, and Zr using only 0.07 grammes of material, and if another 0.1 grammes is available K, Li, Rb, Cs, and F may also be determined. Other methods of analysis usually require larger amounts of material to determine such a wide range of elements.

It is suggested that spectrographic methods of analysis may validly be adopted for separate mineral analyses where the mineral is present in near accessory amounts in the original rock or where the application of other analytical methods presents technical difficulties, e.g. the resistance to solution of tourmaline. The fall in precision of major element determinations is more than offset by the time saved in mineral separations and the additional information provided on trace element abundances.

The method of analysis used was based on firmly established methods (Ahrens and Taylor, 1961) with palladium or indium being used as internal standards. To minimise matrix effects working curves were prepared for the trace elements from a series of 'addition' standards. These were obtained by adding weighed amounts of trace elements in the form of simple 'Specpure' compounds to a natural tourmaline sample whose own trace element content could thus be determined by an addition method (Ahrens and Taylor 1961, p.159). Certain major constituents were determined from a series of completely synthetic mixtures prepared from 'Specpure' compounds whilst others present in quantities less than 2% were determined by the addition method.

Samples from veins, pegmatites and aplites have so far been analysed. Examination of a large number of thin sections of different specimens was made prior to selection of these first samples for analysis. The tourmaline was usually yellow but some yellow crystal grains with blue rims were found in the samples from veins. Absence of inclusions and zoning and uniformity of colour were the criteria on which selection was based as far as possible.

It may be seen from the table that all the analyses so far obtained are within the chemical limits of the iron-rich variety of tourmaline, schorl. With the exception of analysis 1, copper and lead are almost constant in concentration in all the samples. Barium was not detected in any.

The tourmalines from aplites and pegmatites appear to be similar in chemical composition though there may be a real difference in strontium content. Tourmaline from veins seems richer in titanium and calcium and poorer in iron than the former. Vein tourmaline is, however, markedly richer in chromium and vanadium than that from the other sources.

A sample of blue, acicular, zoned tourmaline from a reddened granite on Staple Tor, Dartmoor had by far the highest concentrations of chromium, vanadium and strontium recorded and was also relatively high in manganese, calcium and titanium content.

	Veins			Aplites		Pregmatics		Reddened Granite
	1	2	3	4	5	6	7	8
Total Iron as FeO	11.5	10.6	11.9	12.3	12.4	12.3	12.1	10.9
MnO	0.12	0.15	0.07	0.1	0.12	0.15	0.38	0.3
TiO_2	0.49	0.58	0.63	0.33	0.3	0.68	0.33	0.67
CaO	0.31	0.8	0.55	0.35	0.21	0.3	0.46	0.67
Na_2O	2.15	1.95	2.15	2.05	2.05	2	2.06	1.85
Cr.	23	44	28	Tr.	Tr.	N.D.	N.D.	50
V.	40	84	146	Tr.	Tr.	N.D.	N.D.	155
Sr.	55	25	64	19	20	N.D.	N.D.	180
Cu.	84	17	12	12	9	8	16	12
Pb.	6	6	5	8	12	7	9	6
Sc.	*	38	63	63	27	53	25	77

* Not determined. Tr.=Element detected but less than 5 p.p.m.
N.D. = Element not detected.

TABLE I. Partial chemical analyses of tourmaline from veins, aplites and pegmatites (with oxides expressed as weights per cent and trace elements as parts per million).

1. Tourmaline vein, N. Side Great Zawn, Porthmeor, near Zennor, Land's End granite.

2, 3. Tourmaline veins, Pedn-men-Du, Sennen, Land's End granite.

4, 5. Aplite veins, N. side Great Zawn, Porthmeor, near Zennor, Land's End granite.

6. Pegmatite, Knills Steeple, near St. Ives, Land's End granite.

7. Pegmatite, Tremearne, Tregonning Godolphin granite.

8. Reddened granite, Staple Tor, Dartmoor granite.

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AHRENS AND TAYLOR, 1961. Spectrochemical Analysis. Second edition. 1961. Pergammon Press, London-Paris.

76. Some structural features of the Bodmin Moor granite mass: by C. S. Exley.

The Bodmin Moor mass, like others, displays sub-horizontal jointing which, prominent at or near the surface, almost disappears at depth although the responsible elements in the fabric may still remain. Like tiles on a roof, the slabs produced by weathering dip towards lower ground less steeply than the hillsides so that the present granite surface consists of a series of structural ridges (e.g. Brown Willy) and domes (e.g. Hawk's Tor). These features are the equivalent of folding in sediments but result from flow orientation in the original fabric.

There is no evidence yet that compositional or textural variations exist on this small scale but there is some evidence that both coarseness of grain and megacryst-development follow synforms and antiforms on a large scale apparently unrelated to the present relief.

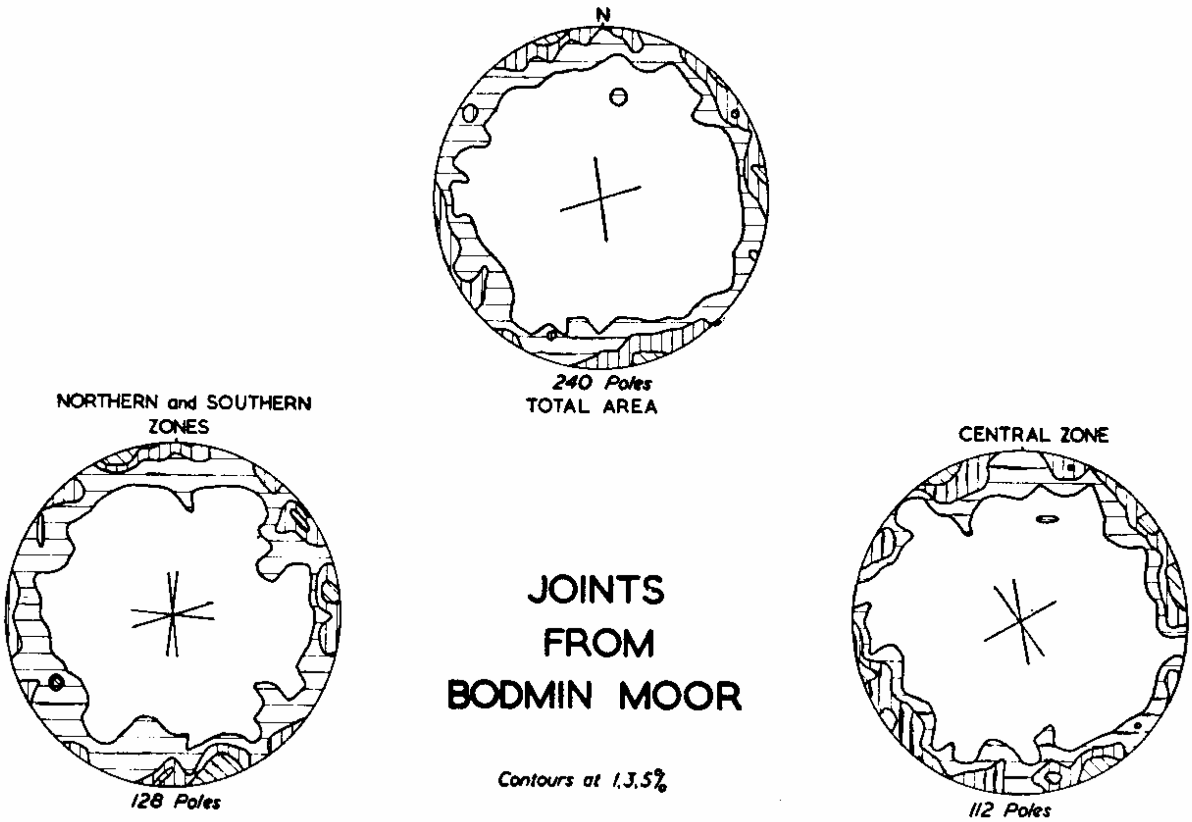

FIGURE 1.

The joint pattern for Bodmin Moor resembles closely those of north-east Dartmoor (Blyth 1962), St. Austell (Exley 1959) and Carnmenellis (Austin 1960). The mean tension- (Q-) joints strike 0772° (Dartmoor), 073° (Bodmin Moor ; see Fig. 1), 067° (St. Austell) and 053° (Carnmenellis), revealing a progressive shift in

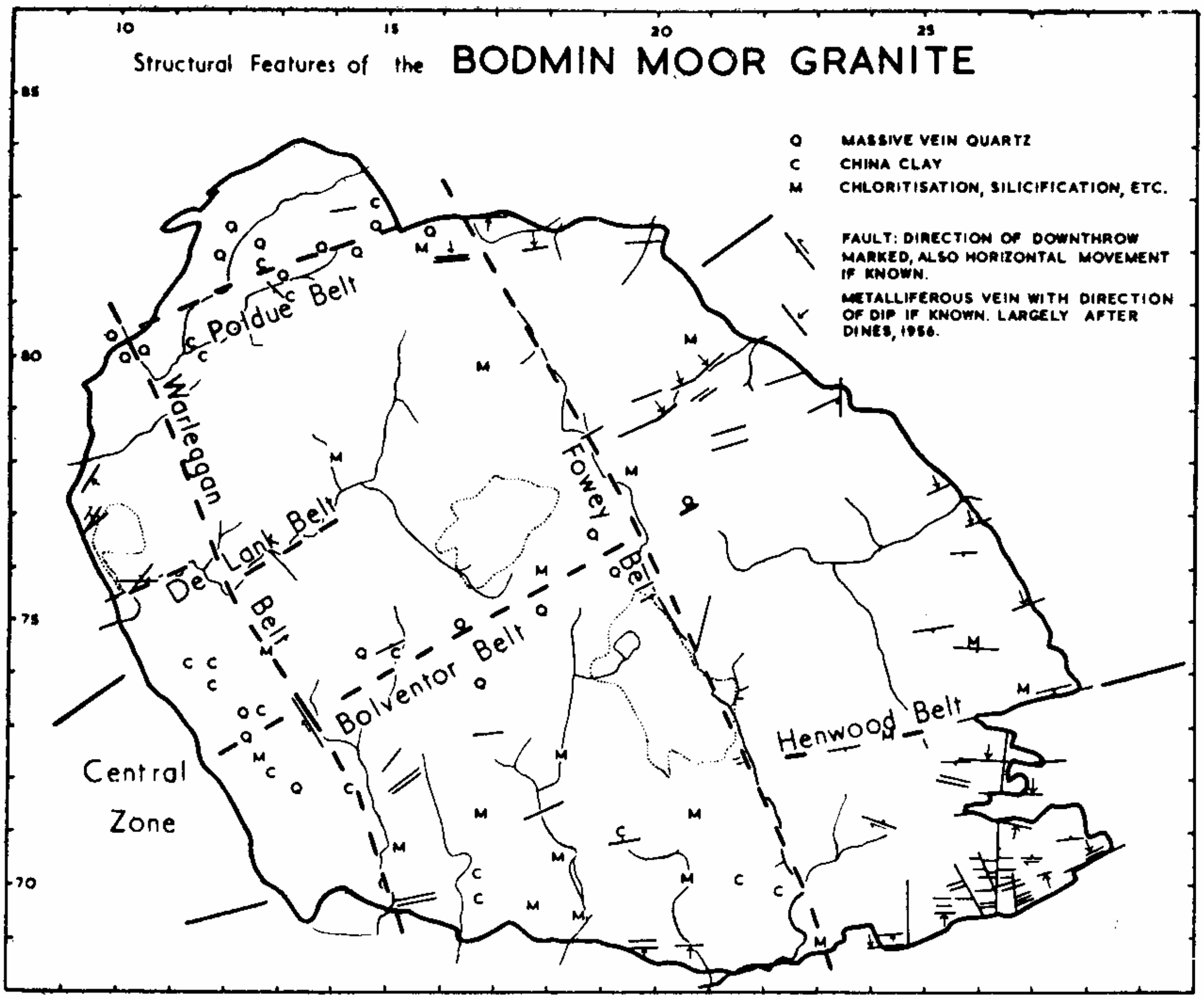

FIGURE 2.

orientation as between the eastern and western granites. The mean compression- (S-) joints strike 171° (Bodmin Moor), 168° (St. Austell) and 155° (Carnmenellis) ; the angle between the compression and tension directions is similar (about 100°) in these three granites. Blyth (1962) suggests that joints striking 164° on Dartmoor may be Riedel shears associated with Tertiary shearing but these could also correspond to the compression-joints of the other granites.

While the over-all joint pattern of Bodmin Moor thus corresponds with the general pattern of the south-west and is a response to stresses of “Armorican” orientation, it contains an apparent anomaly. Joints in the “northern” and “southern zones” (Fig. 2) consist of two pairs whose mean directions strike approximately N.-S. and E.-W. Joints in the “central zone”, however, have mean directions whose strikes are approximately N.N.W.-S.S.E. and E.N.E.-W.S.W. (Fig. 1). This change in orientation is suggested by Dines' (1956) map of mineral lodes and is confirmed by detailed joint measurements. The exact shape of the arbitrarily defined "central zone" is unknown and further work on the joint pattern is required before an explanation of this anomaly can be offered.

Lack of marker horizons and the unknown cumulative effects of small movements along joints make difficult the detection of major dislocations and estimates of movement along them. From the evidence obtained so far (using physical features, chloritization, silicification, slickensides, foliation, etc.) it seems likely that the Bodmin Moor granite is fractured on a relatively large scale along at least six important "belts" and probably along as many less important ones (Fig. 2). Of the former, the Poldue, De Lank, Bolventor and Henwood Belts follow the E.N.E.-W.S.W. trends of the fold-axes and tension-joints usually regarded as being Amorican in central and east Cornwall and south Devon. The Warleggan and Fowey Belts, however, strike approximately 150° and are of special interest in view of Dearman's (1963) dextral wrench-fault hypothesis. While such faulting is present along the northern margin of Dartmoor (Blyth 1962 ; Dearman 1962) there is no evidence that any occurs on Bodmin Moor. Thus neither the Warleggan nor the Fowey Belt displaces the granite margin materially at either end and the horizontal displacement discernible along the Warleggan Belt is very variable, ranging from 1,000 yards where it crosses the De Lank Belt to 200 yards where it intersects the Bolventor Belt. The abrupt change of direction of the granite margin near the northern end of the Fowey Belt is undoubtedly due to a northerly downthrow along the Poldue Belt.

Therefore while it is possible that these two belts are due to Tertiary stresses, since they displace others and their strikes might be regarded as having a Tertiary orientation (Blyth 1962), it is probable that movement along them was mainly vertical, not very great, and that they were of Armorican origin.

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77. A geophysical survey for cavities in Devonian Limestone at Buckfastleigh : by C. M. Bristow.

The William Pengelly Cave Research Centre for Speleological Research is situated in Higher Kiln Quarry, just west of Buckfastleigh parish church. This quarry and some adjacent fields came on the market two years ago and was purchased by the Society for the Promotion of Nature Reserves because the quarry contains the entrances to five caves, some of which have features of outstanding speleological interest, notably the interglacial fauna in Joint Mitnor bone cave.

It is likely that all the caves are really part of one large phreatic cave system which is now partially blocked by cave fill. As the adjacent fields, which form part of the purchase, are at least in part underlain by limestone, it has been supposed that there are further unexplored caves under these fields. As various development proposals concerning these fields had been made, it was necessary to try and establish if there are more caves underneath.

Of the great variety of geophysical methods now available, it was decided to use the resistivity method, because the considerable difference in resistance between an air filled cavity (high) and the surrounding damp limestone (low) is one of the most outstanding physical features of a cave. It is also by far the cheapest in equipment cost.

For this work a single-probe technique was used with one of the current electrodes situated at least 600' away from the station electrode. Potential drop between two electrodes 20' apart, situated radially at mean distance of from 20' to 150' from the station electrode were made. The resistances obtained from the geophysical instrument were then computed and plotted as graphs. An air filled cavity will produce a readily recognisable high resistance anomaly on the graphs ; these can be plotted on sections as arcs centred on the station electrode with a radius corresponding to the mean distance of the potential electrodes from the station electrode at which the anomaly occurs.

By carrying out a test in the opposite direction so that the same ground is covered again, it is possible to pick up the same anomaly and plot another arc. The intersection of the arcs indicates the position of the high resistance feature and hence the cavity both in plan and depth. The tests were carried out on north-south lines, with 150' between each test station. The use of overlapping single probe tests with a graphical solution has never been attempted before, as far as the author is aware.

Higher Kiln Quarry has been opened in Middle Devonian limestone similar to other Middle Devonian limestone in South Devon. The limestone is interbedded with one or more layers of volcanic ash and the limestone is underlain by more massive volcanic rocks which are exposed in a number of places along the hillside. The limestone appears to have a general northward dip. It is probable that the underlying tuff is relatively impermeable ; solution of the overlying limestone has given rise to an extensive cave system in the hill in which the quarry is situated.

A survey along the lines described above was carried out in the fields behind Higher Kiln Quarry over Easter, 1964.

When the curves had been computed and plotted, the first outstanding feature was the number of low resistance curves in the southern half of the area. The low resistance is probably caused by volcanic rocks coming to the surface, this was subsequently confirmed during an independent geological examination of the area. This low resistance material can be seen to pass northwards under the limestone.

Passing north the much higher resistances of the limestone were encountered with a number of exceptionally high resistance anomalies. These are interpreted to be caused by air filled cavities. When arcs are drawn and intersections found the positions of possible cavities can be predicted. The predicted positions agree well with the positions of the know cavities, thereby providing confirmation that the method works. The positions of the unknown predicted cavities lies in lines which suggest that they can be linked to known caves by blocked passages.

Further work is planned to position the cavities more precisely so that an attempt to enter them can be made.

78. Some aspects of the petrochemistry of the Land's End granites: by B. Booth.

The Land's End granite cuts the Mylor Series and associated basic intrusives discordantly producing an aureole up to 2¼ miles wide on the surface ; this reflects the shallow slope of the granite margin. The metamorphic grade ranges up to that of the amphibolite facies.

Granite/hornfels contacts are always sharp and dip outwards at angles of 15° to 25° ; chilled margins occasionally develop which are variable in width with an observed maximum of 24 inches. Where the chilling is absent the coarse porphyritic granite abuts directly against the hornfels. Granite apophyses up to several hundred yards long penetrate the hornfels on the north coast and exhibit differentiation along their length as follows :-(a) Coarse porphyritic granite, (b) Coarse non-porphyritic granite grading into, (c) Fine granite. (d) Rhythmically banded pegmatite and tourmaline-aplogranite. (This occurs for a few yards beneath and parallel to the hornfels roof.) (e) Aplogranite with development of distorted tourmaline pegmatites. (f) Aplite veins. (g) Quartz-tourmaline veins. (h) Tourmaline and/or Quartz veins. The marginal granite often shows stoping effects and rotation of hornfels blocks, while veining of the adjoining hornfels by this phase is frequent.

Every stage of contamination is displayed in this granite, and assimilation effects are seen at Sennen Cove where highly contaminated rocks with up to 28 per cent of biotite occur.

On account of their mineralogical similarities xenoliths have been grouped as follows : (1) Spotted cordierite hornfels xenoliths. (2) Xenoliths with irregular margins, showing planar orientation of biotite giving a schistose appearance, and rarely containing potash feldspar megacrysts. (3) Homogeneous, rounded xenoliths containing potash feldspar megacrysts. (4) As above but lacking potash feldspar megacrysts and occurring as coarse and fine varieties. (5) Schlieren, streaked out xenoliths, or biotite veins of Brammall and Harwood (1930, p.224). (6) Contamination patches - dispersed xenoliths now recognised only by andalusite-muscovite, cordierite, or biotite-rich areas. Transitions between many of these groups occur.

Chemical evidence shows a wide variation within the granite and when the data are plotted on Harker variation diagrams the following facts emerge :

1. As Si^{++++} increases Fe^{++} ,Fe^{+++} , Ca^{++}, Ti^{++++}, and P^{+++++} decrease.
2. There is a reciprocal variation between K^{+} and Na^{+} with increase in Si^{++++} percentage.

In many ways these data resemble those obtained from Dartmoor by Brammall and Harwood and according to them suggest differentiation as the cause of the variation ; but, as Chayes (1964) points out, " strong negative correlations of the typical Harker diagram could be generated by any process which would greatly enlarge the variance of silica relative to other oxides ".

Close chemical examination of serial specimens taken across a fresh granite/hornfels contact in Geevor Mine shows both the marginal chilled phase and the hornfels adjacent to the granite to be soda-rich ; this is interpreted as being due to metasomatism by earlier soda-rich magma.

It therefore appears that an earlier, relatively soda-rich aplo-granite exists which contains about I per cent (by weight) total iron. The main porphyritic biotite granites contain from 2.1 to 3.4 per cent (by weight) total iron and it is suggested that most of this additional iron, which appears as biotite, was donated by assimilated pelitic rocks which have also added much alumina and potash to the granite.

Conclusions. Contact evidence suggests that granites which were leucocratic in aspect and probably soda-rich in composition were intruded as partly crystalline magmas which owed their liquid state to their high volatile content. Emplacement was by forceful injection aided by overhead stoping and assimilation, and they were enriched in iron, alumina and potash by assimilated material. Early orthoclase crystals were orientated by magmatic flow under regional stress and these crystals formed the nuclei for the later metasomatic potash feldspars.

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79. A newly discovered emanative centre associated with the Dartmoor granite : by W. R. Dearman and M. A. H. El Sharkawi.

The distribution pattern of the cassiterite-bearing areas in South-west England bears no obvious relationship to the shapes of the various granite outcrops. It is clear, as Dines (1956 p.7) has pointed out, "that the mineral bearing solutions emanated from the still liquid core of the granite only in certain restricted places and that the ores . . . are located around certain restricted 'emanative centres' . . .". Ore minerals are essential to the concept of an emanative centre, while for the closest delimitation of a centre the mineral paragenesis should be dominated by cassiterite or equivalent high temperature ore minerals. Crystallization of cassiterite is presumably conditioned by, among other factors, a granite or killas environment.

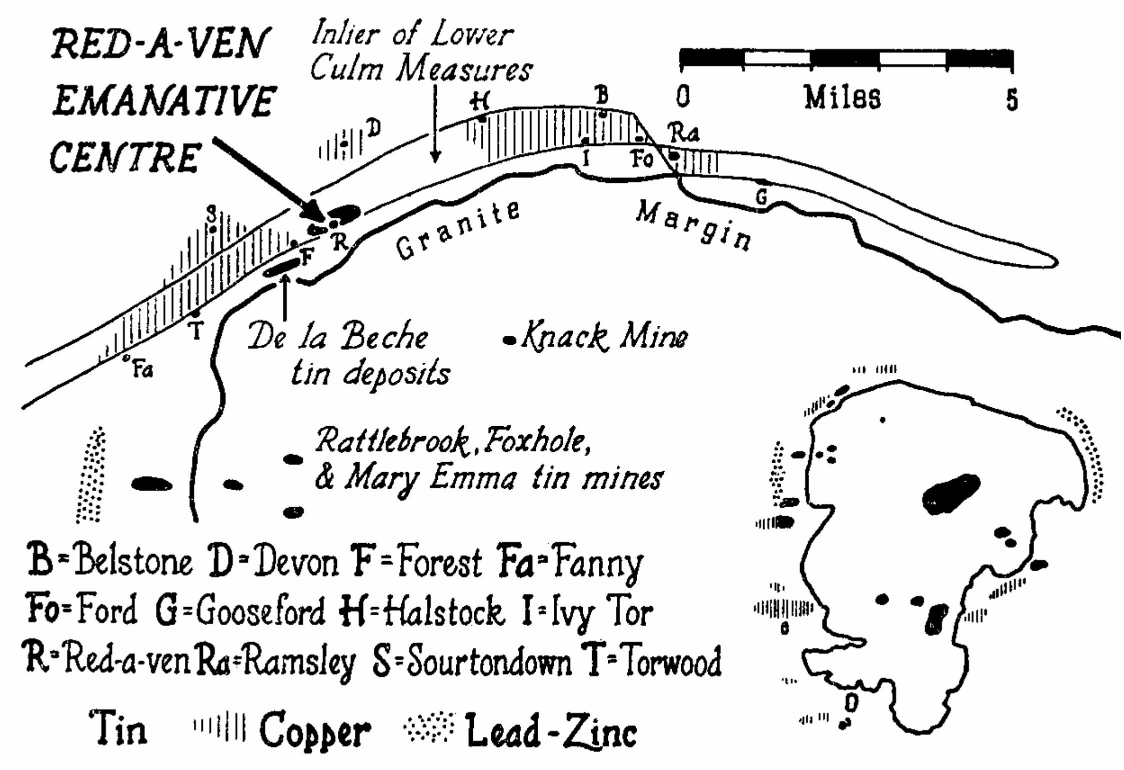

FIGURE 1. Map of the mines and mineralized areas of north-west Dartmoor showing the position of the Red-a-ven emanative centre. Inset bottom right : Map of the mineral deposits of Dartmoor, after Dines 1956, fig. 3b, with some additions.

In his sketch-map showing the distribution of deposits of tin, copper, and lead-zinc in and about the outcrop of the Dartmoor granite, Dines (1956 fig. 3 b) has omitted some of the smaller tin occurrences. These have been added in Fig. 1 so that the copper deposits on the north-west margin of the granite are no longer completely isolated from centres of tin mineralization. The copper deposits here are, for the south-west of England, very unusual impregnations of sulphides in contact altered and metasomatized calcareous cherts and limestones (Dines 1956, p.750). Abundant tourmaline, both in the adjacent granite and in the shales, tuffs and basic intrusives of the Culm Measures, is represented in the calcareous rocks by local developments equally rich in datolite and axinite. Tourmaline is therefore represented by its calcium counterparts, and it has been discovered recently that the place of cassiterite is taken by tin concealed in grossularite, in andradite, and in a tin-sphene (Sharkawi and Dearman 1965).

The greatest amounts of tin have been discovered in the neighbourhood of the Red-a-ven Mine where a very strong lenticular tin anomaly in the soil (Sn more than 3,000 parts in a million) probably reveals the shape of an underlying mineralized limestone horizon in the Lower Culm Measures. Thin beds of wollastonite hornfels with garnet and tin-sphene contain more than 6% SnO_2 locked up in these silicates, equivalent to more than 130 lbs, of cassiterite per ton.

The deposit at Meldon contains at least two of these thin but very rich beds within a well-defined horizon having a strike length of 1,000 yards. Beyond this, an aureole of weaker tin mineralization stretches for at least one mile west and five miles east (Fig. 1).

The high concentrations of boron and tin in the neighbourhood of the Red-a-ven Mine suggest that the area can justifiably be designated as an emanative centre. Away from the tin centre, the overlying copper zone is represented by the rich deposits at Belstone Consols and Ramsley Mine to the east, and perhaps by those at Forest, Torwood and Fanny Mines on the west.

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80. The Hangman Grits - an Introduction and Stratigraphy :

by R. Lane.

In North Devon the Hangman Grits occur in coastal outcrop between Combe Martin and Heddon's Mouth, where cliffs up to 700 ft. in height are backed by 1,000 ft. hill summits. The outcrop trends inland to the south-east forming some of the higher parts of Exmoor.

The formation is largely arenaceous and very quartzitic. A lithological range from clay-shale to pebble-grade conglomerate is present. The sandstones are largely buff in colour with extensive red haematite staining. Strong units of purple silt and fine sandstone occur. The major part of the 5,000 ft. sequence appears to be non-marine with littoral deposits near the top, i.e. a fauna of thick-shelled, worm-bored, lamellibrancs and gastropods, together with marine and continental fossils occurs in the upper strata. The Grits conformably overlie the Lynton Beds and are themselves overlain by the Ilfracombe Beds. They are largely of Couvinian age.

The only significant work on the Hangman Grits of North Devon is that of Evans (1922 and 1929). It is intended to retain his broad stratigraphic units, however, a more accurate and detailed investigation necessitates some modification of his subdivisions. The basal member of his succession, the Trentishoe Grits, is a 3,500 ft. thick, monotonous, purple and buff succession of quartz-sandstones and shales. The Rawns Beds which follow consist of a lower, thin-bedded, succession and thick, massive grits above, totalling 330 ft. The Sherrycombe Beds have a lower argillaceous group, followed by 55 ft. of fossiliferous strata, overlain in turn by variegated, barren sandstones, some 270 ft. in all. The term for the next unit, the Stringocephalus Beds of Evans, is a misnomer since the eponymous brachiopod does not appear to be present. These beds contain two major fossiliferous bands with laminated quartz-sandstones above, totalling 330 ft. The junction with the Wild Pear Beds above is a faulted one.

The formation is entirely unfolded throughout and dips uniformly to the south. A steep southerly dipping cleavage has been imparted to the incompetent beds. Normal dip faulting is frequent and a strong pattern of dextral tear-faulting gives the east-west strike its apparent N.W.-S.E. trend.

The only important inter-stratal features are ripple-marks, sole markings are rare. The former plainly indicate reversible N.W.-S.E. currents. Among the intra-stratal features primary current lineation is interesting and the readings taken indicate transport directions aligned N.E.-S.W., which appears to be anomalous. It is hoped that cross-bedding measurements will help resolve this problem. The most unusual structure is the very large-scale convolute bedding in the laminated sandstones. Beds up to 8 ft. in thickness are affected and the folds seem to show a preferred orientation, however, the base of these beds always remains unaffected. Some channelling exists and an almost complete lack of graded bedding is noteworthy.

Plant fragments are common at many horizons in the sandstones. Evans has recorded *a Coccosteus* scale from the Rawns Beds. The littoral-marine fauna comes from the middle Sherrycombe Beds, where the following genera have been recognised : *Myalina, Naticopsis, Bellerophon,* a spiriferid, *Tentaculites, Thamnopora, Caulostrepsis,* an *Arthrodire* plate, Polyzoans and plant remains, the 'Stringocephalus Beds' contain *Myalina, Naticopsis* and Polyzoans. The articulated bi-valves which have apparently been identified as the inequivalve *Stringocephalus* are in fact sections through equivalve *Myalina* shells which have undergone distortion.

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81 and 82. Preliminary results of recent research on the geology and structure of Western Brittany : by A. C. Bishop, J. D. Bradshaw, J. T. Renouf and R. T. Taylor.

The area described lies within the department of Finistere and comprises the Presque'ile de Crozon, the Presque'ile de Plougastel and the south-western part of the Pays de Leon.

The Pays de Leon from Brest westwards to Le Conquet has a complex structural history. Brioverian sediments intruded by granite, have been regionally metamorphosed and rocks of almandine amphibolite facies produced. The metamorphic grade decreases southward and only scarcely metamorphosed Brioverian is found south of the Elorn.

In Plougastel and the Crozon the folded Brioverian is unconformably overlain by a succession of quartzites (the Gres Armoricain), siltstones and shales that range in age from Lowest Ordovician to Lower Devonian. The succession, in which there are a few breaks, does not exceed 3,000 m. in thickness. It was folded as a unit after the deposition of the Devonian and thrown into simple asymmetical folds overturned to the south. The Palaeozoic sediments are unmetamorphosed and it is believed that the Elorn River follows an important structural line separating the metamorphics of the Pays de Leon from the Palaeozoic area to the south.

83. Time of emplacement of dykes in Bigbury Bay :
by S. Simpson.

All the Geological Survey Memoirs dealing with the Lower Devonian outcrops from the North Cornish coast to Start Bay describe basic igneous rocks which they refer to as “much altered greenstones” or “green sheared porphyritic diabase”. Some of these igneous rocks are considered possibly to be tuffs or lavas, but the majority are considered to be intrusive. Ussher points out (1912 p.41) that the igneous rocks tend to follow the strike of the sedimentary rocks and he evidently thought that sills were frequent. The Bigbury Bay sections show such intrusions within both the Dartmouth Slates and the Meadfoot Beds, but as Fyson (1959) has described, some of the intrusions trend sharply across the strike of the sediments.

In the cliffs north and south of the mouth of the Avon, such basic igneous rocks occur as sheets striking E.N.E. and dipping very steeply. They are thus roughly parallel to the prominent cleavage and also to the bedding, the two being usually almost parallel with one another in this area. In spite of the close similarity of attitude of the igneous sheets and the bedding, there is no example of a truly concordant relationship and in most cases the igneous sheets clearly cut across the bedding and are uninfluenced by it. The implication is that the igneous sheets are dykes, and that they are nearly parallel to the bedding because the bedding had been folded before the

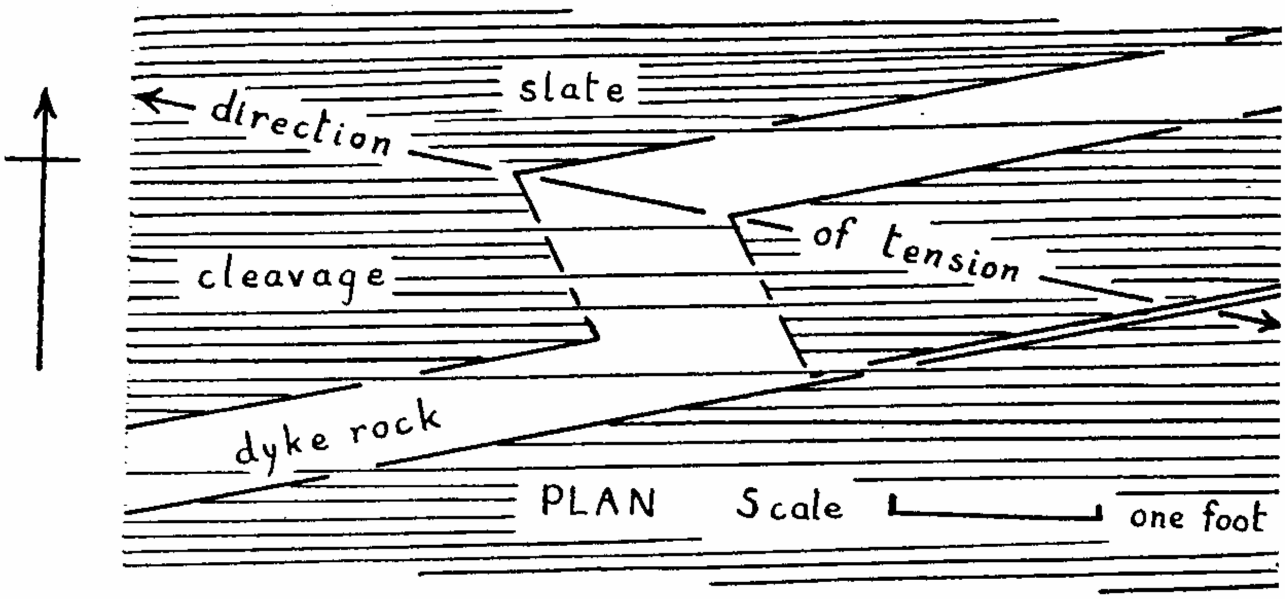

FIGURE 1

intrusion of the dykes. The dykes have however been affected by intense cleavage. This cleavage appears to be the first (slaty) cleavage which can be detected in the area (Marshall, 1959). Thus the igneous material has been emplaced after a tectonic episode not previously recognised.

Detailed observations of the dykes yield a number of facts which tend to confirm that the magma was emplaced in brittle rocks during dilation. While the predominant trend of the dykes is E.N.E., this is in places interrupted by a sharp deviation into a N.W. direction persisting only for a very short distance before the original trend is resumed. The S-shaped pattern implies tension and dilation in a roughly E.-W. direction. That the change in direction is not due to folding is evident from the way is which at the points of intersection of the two directions thin unfolded offshoots are usually given off (see accompanying figure).

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FYSON, W. K., 1962. Tectonic structures in the Devonian rocks near Plymouth, Devon. **Geol. Mag.,** Vol. 99, p.208-226.

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USSHER, W. A. E., 1912. The geology of the country around Ivybridge and Modbury. **Mem, Geol, Surv.**

84. Repeated folding between Hayle and Portreath : by Margaret A. P. Smith.

Three phases of folding have been recognised in the finely banded Mylor slates and siltstones between Strap Rocks, north of Hayle, and Portreath. The relation between the three phases is best seen at Godrevy Point, which is illustrated here (text-fig. I a).

The earliest folds (F_1) are isoclines, initially recumbent in attitude (text-fig. lb). Associated with these E.N.E.-W.S.W. trending, N.N.W.-facing folds is a slaty cleavage (S_1) sub-parallel to bedding except in the fold hinges.

The isoclines have been refolded about approximately horizontal N.E.-S.W. axes into open folds (F_2), concentric in sandstones, more angular in slates (text-fig. lc). An axial plane strain-slip cleavage (S_2), dipping steeply S.E. is developed (text-fig. If). The sense of movement on the cleavage is not constant, but does not appear to be simply related to the position in a fold, since antithetic movement occurs on step limbs. Second folds have been formed on two scales : the steeper limbs of the larger F_2 folds are themselves folded into smaller, similarly oriented parasitic folds.

Superimposed on the earlier structures are folds (F_3) and cleavage (S_3) of the third phase of deformation which was essentially one of vertical flattening (text-figs. lc and lg). This phase of folding has been described previously by Stone (1962) from the south coast near Porthleven. The sub-horizontal cleavage clearly cuts both limbs of the earlier folds. In cutting steeply dipping strata it is accompanied by small-scale recumbent folding or crumpling of the sedimentary banding, silty bands folding concentrically, their thickness controlling the scale of the deformation. In flatter beds, where S_3 and S_1 are more nearly coincident, deformation results in shearing rather than folding. The orientation of F_3 folds is entirely dependent on the attitude of the bedding cut by the sub-horizontal S_3, and so the trend of F_3 fold axes everywhere approximates to the strike.

Two late, steep strain-slip cleavages (N.N.W.-S.S.E. and E.-W.), both occasionally with associated folding, cut F_1, F_2 and F_3 structures. One, at least, (the N.N.W.-S.S.E. cleavage) is widespread in the south-west of Cornwall, and could be connected with the emplacement of the granites, but evidence is inconclusive.

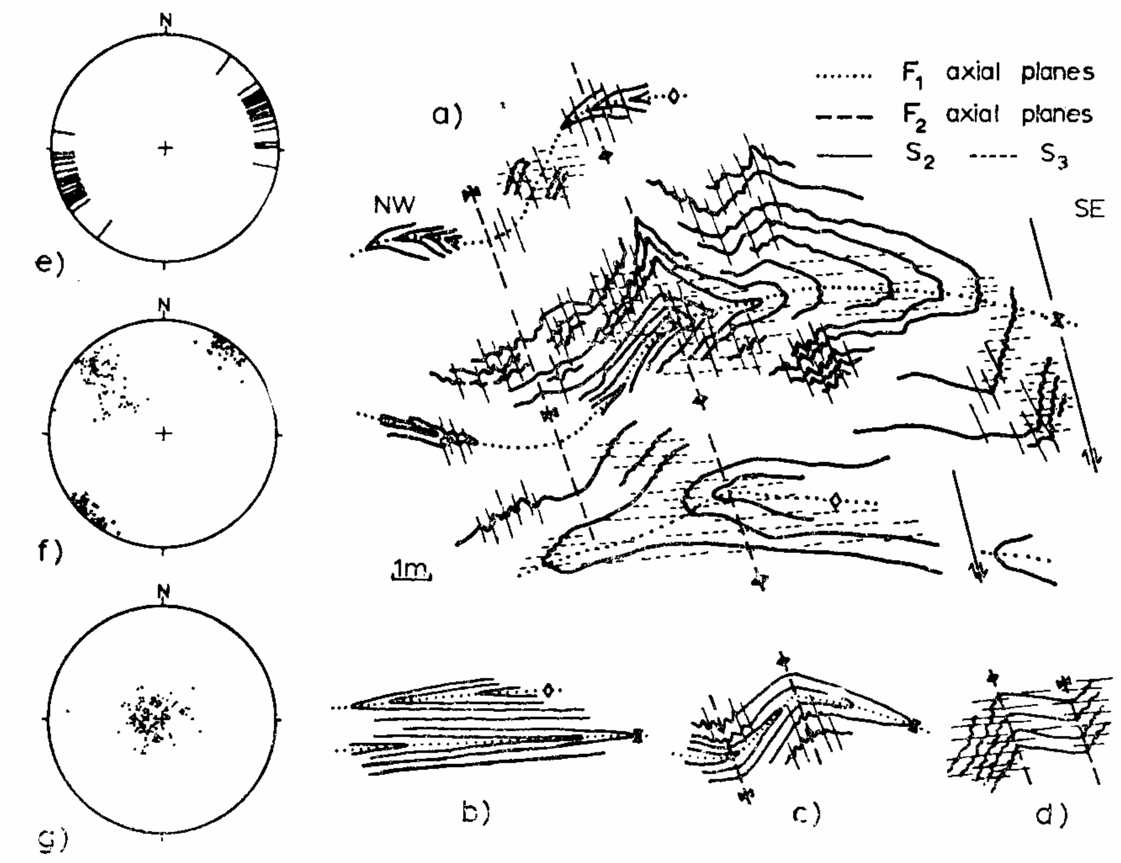

FIGURE 1.

a, Diagrammatic representation of the structure at Godrevy Point, showing F_2 and F_2, folds superimposed on F_1, isoclines, a strongly developed axial plane cleavage S_2 and a transecting, flat-laying cleavage S_3. **b-d,** Schematic development of the structure shown in **a. b,** F_1 isoclines, **c,** F_1 refolded by F_2, **d,** steep limb of F_2 flattened into small F_3 rumples. **e,** Trends of F_1 fold axes. **f-g,** Lower hemisphere stereographic projections. **f,** dots - poles to S_2 cleavage, crosses – F_2 fold axes. **g,** dots - poles to F_3 cleavage.

That the F_1, F_2 and F_3 phases of deformation pre-date the granite emplacement can be shown by xenoliths in the Tregonning-Godolphin granite. Some of the xenoliths are disoriented and contain undoubted F_3 folds in banded Mylor meta-semi-pelites (Stone, personal communication).

The nomenclature used here (F_1, F_2 and F_3) necessarily differs from that employed by Stone *(op, cit),* since three, not two, phases of folding are now recognised. The third phase, F_3 corresponds to Stone's F_2 but it is not clear whether his F_1 "upright sub-isoclinal folds" are equivalent to F_1 or F_2 above.

Reference :

STONE, M., 1962. Vertical flattening in the Mylor Beds, near Porthleven, Cornwall. **Proc. Ussher Soc.** Vol. 1, p.25-27.

86. The Bude Sandstones from Bude to Widemouth, North Cornwall : by J. P. B. Lovell.

Introduction and past research. The Upper Carboniferous Bude Sandstones are a sandstone-shale formation exposed along a six-mile stretch of coast in north Cornwall, from Widemouth in the south to Duckpool in the north, with Bude at the centre of the outcrop. The work here described was carried out on the southern three miles, from Bude to Widemouth. Owen (1934 and 1950) described the Bude Sandstones, and from the abundance of plant remains and the presence of channels suggested that the Bude Sandstones were deltaic deposits. The most complete succession measured by Owen, from Bude to Widemouth, totalled 3.679 feet. Ashwin (1958) was the first to realise that the Bude Sandstones were turbidity current deposits, and he recorded current directions from sole marks. On the basis of structural geometry he nearly doubled Owen's (1934) estimate for the thickness of the Bude Sandstones, and considered that they overlay the Welcombe Beds to the north. This was in contrast to Owen's (1950) view that the Welcombe Beds were higher. Reading (1963) supported Ashwin in considering that turbidity currents were a major factor in deposition of the Bude Sandstones and emphasised that there was no unequivocal evidence for cyclic sedimentation, or for shallow water or coastal plain deposition,

Methods and structure. The structural section (Figure 1) was constructed with the aid of 5 feet to 1 inch sections measured through all possible unfaulted exposures. The location of these is shown at the foot of Figure 1. On these detailed sections were recorded field estimates of the proportion of sand, silt and mud grades, the nature of the bases of the individual beds, and all observed sedimentary structures. The unbroken lines on Figure 1 represent observed shale or slump bed horizons or faults, the broken lines their postulated extension. The lines representing the faults are drawn more heavily, and some beds are marked to demonstrate the structure more clearly. The structural picture is accurate over those sections of the coast where firm correlation across folds is possible. Between Upton Cross and Church Races correlation has been made by observation of cliff and foreshire across a tectonized zone in which accurate observation is impossible. No correlation could be made across the faults at Higher Longbeak and Lower Longbeak ; the interpretation here given assumes a minimum dislocation.

A crustal shortening of 35%-45% has taken place in the north-south line covered by the section. The former extent of the beds was some 27,300 feet ; they now occupy 17,500 feet. Nearly all the major folds axes are aligned east-west and the axial planes dip north, at a progressively shallower angle from north to south. Movement has taken place by bedding plane slip in most cases, giving rise to concentric folds. Secondary folds are considered to be side effects of the main pressures ; no certain evidence was seen for two phases of folding, as suggested by Zwart (1964). Three phases of faulting are distinguished. The first was reverse faulting probably associated with the folding movements, the second wrench faulting, the third normal faulting.

FIGURE 1. Cliff profile of the Bude Sandstones from Bude to Wanson Mouth.

Sedimentology and stratigraphy. Eight facies, defined on field appearance, were used in constructing stratigraphical sections at 5 feet to 1 inch.

These facies include sandstones, grey siltstones and sandstones, slump beds and black shales. The sandstones are in places thin, parallel-bedded, graded, parallel- and cross-laminated, and are interbedded with the black shales. Elsewhere the sandstones are medium- and thick-bedded, poorly graded or ungraded, often lenticular and channelled, and no to 20 feet thick. The thin-bedded sandstones have sole marks and internal structures which are at present regarded as characteristic of distal turbidites. The thick-bedded sandstones lack sedimentary structures indicative of traction currents. This negative evidence, together with the presence of partings and mudflakes within each unit, suggests deposition from successive powerful turbidity currents whose products became amalgamated into one apparently "massive" sandstone ; this may represent a proximal environment. Sole marks indicate that the turbidity currents flowed towards the south and west, a direction opposed to that shown by Macintosh (1964) for the Namurian Crackington Measures which outcrop to the south.

The grey siltstones and sandstones at Bude present a further problem. These are highly carbonaceous, well laminated, and in some cases possess structures indicative of a turbidity current origin. Frequently they do not, and though they may have been turbidites initially, reworking by other currents has taken place. It is uncertain whether the currents responsible were oceanic bottom currents operating in some depth of water, or tidal or other shallow water currents. The slump beds contain contorted boulders of intrabasinal sediments, and, like the turbidites, may be regarded as periodic interruptions of the slow sedimentation of the black shales in quiet water.

No body fossils have been found in this section of the Bude Sandstones, but the discovery at Sandy Mouth by Reading (in press) of goniatites, identified by Dr. W. H. C. Ramsbottom as Lower Westphalian (G_2), dates part of the formation to the north. Correlation with the northern succession indicates a total thickness of about 4,000 feet for the Bude Sandstones.

It is suggested that the environment of deposition was a basin, inimical to marine faunas, in which mud and plant fragments descended gently to the bottom from the surface waters. Into this basin flowed sporadic turbidity currents from the north and east, depositing either thin bedded units in the more distant level parts of the basin, or thick "massive" sandstones nearer the source. Varying turbidity current strengths and frequencies complicated this picture. The turbidity current deposits were occasionally reworked by other currents operating within the basin.

Acknowledgments. The author would like to acknowledge gratefully the help and advice of Dr. H. G. Reading. He would like to thank the University of Oxford for support as a Burdett-Coutts Student during the academic year 1963-4, and for a grant towards the cost of producing Figure I.

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_________ in preparation. Recent finds in the Upper Carbonifer ous of South West England and their significance.

87. Structural studies between Holywell Bay and Dinas Head, North Cornwall : by M. J. Ripley.

This account is concerned only with the folds (F1) related to the slaty cleavage. Several later fold episodes can be recognised. The trends and plunges of the F1 folds are variable but two well defined sets can be recognised which are termed main and crossfolds. The former trend between N.E./S.W. and W.N.W./E.S.E. and plunge at angles of up to 30° but usually less than 10°. The latter, which are not well developed, trend N./S. Both fold sets, which are thought to be contemporaneous, share a common axial plane in localities where they can be seen in juxtaposition. Their axial planes show a progressive change in attitude from a general southerly dip of 45°, in Holywell Bay, to horizontal at Creepinghole Point. This latter orientation is maintained as far north as Dinas Head although there are numerous localized variations resulting from subsequent folding episodes.

The mean interlimb angle of the main folds also shows a progressive change from south to north being about 15° at Holywell Bay and increasing to approximately 90° at Booby Bay. There is however, a decrease north of Boobys Bay to approximately 50°. It must be noted that there can be considerable variation in this angle along a line normal to the fold axes on the axial plane. Thus a relatively open fold can become sub-isoclinal, along this direction, in an area where the mean interlimb angle is as high as 70°.

Apart from the cross-folding the F1 folds have a complex developmental history which can be summarised as follows.

1. Formation of early F1 folds. The slaty cleavage, main and cross-folds are essentially of this age.
2. Intrusion of basic dykes.
3. Translation along well defined discrete slaty cleavage planes with the formation of insignificant late F1 folds. These are not considered in this account. This movement was probably pre-dated by further slaty cleavage formation which post-dated the dyke intrusion.

The dykes which have been recognised in many localities between Flory Island and Holywell Bay, belong to a dyke suite of which similar examples have recently been found in many areas of south Devon and Cornwall. They cut across the early F1 folds and are unfolded, although they are cleaved, the cleavage lying parallel to the axial plane slaty cleavage of the F1 folds in the adjacent sediments. They must therefore have been intruded after the folds had developed but before the associated slaty cleavage had been finally imprinted on the sediments.

Distorted chlorite lenses in the dykes are invariably elongated sub-parallel to the main F1 fold axes indicating that the maximum extension during the late F1 movements took place in this direction. This probably explains the anomalous plunge directions, sub-normal to the main F1 axes, of many of the boudins in this area.

The present long axes, of suitably orientated, distorted crinoid ossicles, frequently trend slightly to the south of the long axes of the chlorite lenses in the nearby dykes. Consequently it is suggested that since these two long axis trend directions are similar, the ossicles must have suffered far greater elongation during the late F1 movements than they did during the early F1 folding. This leads to the probability that since the Fl folds attained their present form before the intrusion of the dykes the more competent beds, in which the ossicles occur, underwent most of their plastic distortion after the folds had been generated.

88. Low-angle faulting in the Boscastle Area : by E. C. Freshney.

Faults dipping at angles of between 15° and 30° in a northerly direction are common in the Carboniferous and Devonian rocks south of Wanson Mouth [SS195011]. These faults appear to belong to the system previously described by Dewey (1909) and Wilson (1951), although these authors described a purely local extent to them. Batstone (1957) suggested that they had a much wider extent and significance.

The faults now described cause repetition of parts of the Carboniferous sequence within its own outcrop and within that of the Devonian. The succession Trambley Cove Beds, meta-volcanics, Barras Nose Beds, which may belong to the Carboniferous, is repeated three times between Boscastle and Trevalga and each time between low-angle north-dipping faults. Green slates with two limestone beds, one of which is dated as Upper Viséan (Selwood 1961) and the other as Tournaisian (Mitchell 1965), occur at Gull Rock, Buckator [SX117932], inserted between low-angle faults into basal Namurian rocks. The effect of the low-angle faults in the main body of the Namurian north of Rusey [SX123938] is to produce a stratigraphical younging of the beds northwards in spite of their dominantly south-facing attitude, and also to cause repetition of the goniatite zones. Of these faults the best known is the Rusey Fault, with its thick smash zone and banded quartz breccia : a low angle fault zone is cut by at least two later steep normal faults trending at 280° and by an even later north-west to south-east dextral tear fault. These have broken up a once continuous band of breccia and fault zone into a series of fragments exposed both at the bottom and at the top of the cliff.

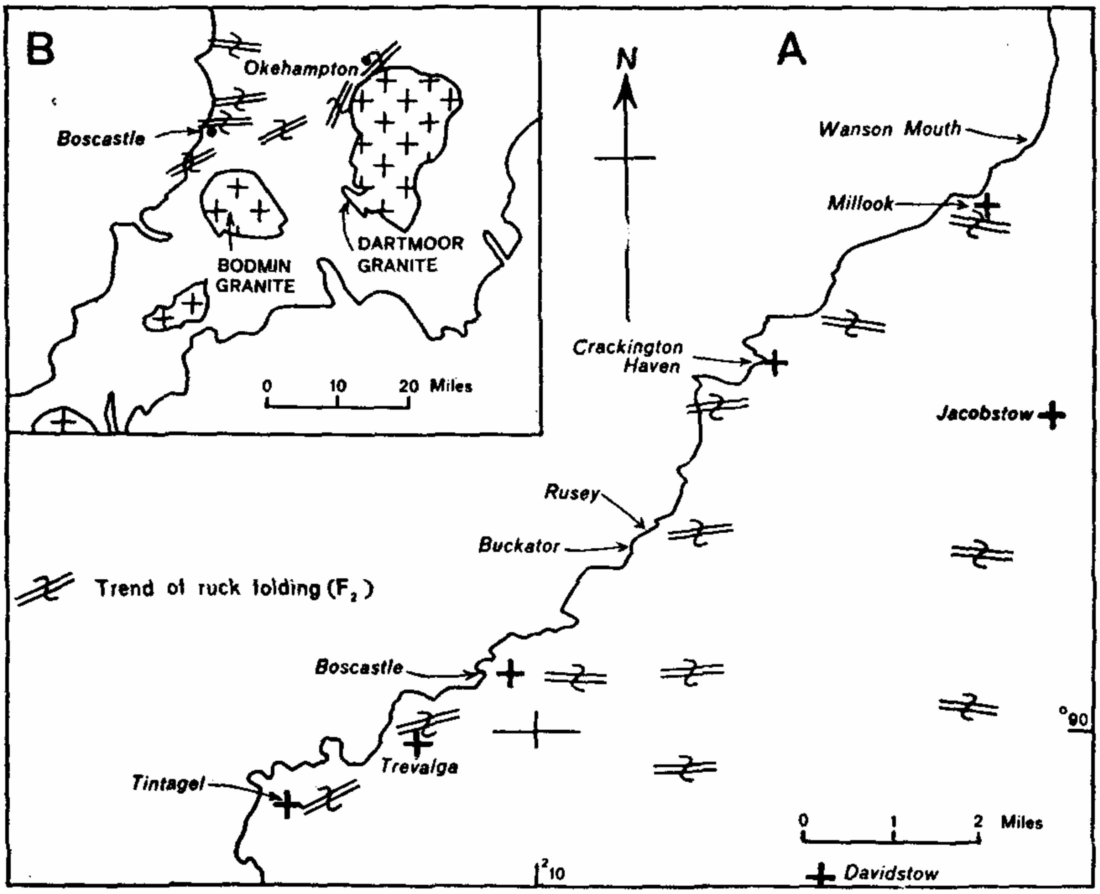

FIGURE 1. A, Sketch-map showing trends of late ruck-fold axes (F2) in the Boscastle area. (Data for Tintagel area supplied by Mr. M. C. McKeown.) B, Sketch-map showing trends of late ruck-fold axes (F2) in the area to the north of the Bodmin-Dartmoor granite. The fold trends in the Okehampton area are from Dearman (1959 and 1964). The outline map of Devon and Cornwall is corrected for the effects of Tertiary faulting after Dearman (1963).

The quartz breccia dips at approximately 30° in a northerly direction, and this inclination probably represents some steepening caused by involvement in the normal faults. Across the fault there is little stratigraphical change (cf. Zwart 1964 ; Freshney and others 1965), for goniatites (identified by Dr. W. H. C. Ramsbottom) indicative of the H, subzone and of the H_1" and F„ subzones have been found respectively to the north and to the south of the fault. In the fault zone, however, there occur masses of chert, crinoidal siltstone and thick goniatite-bearing limesone, all of which are probably Lower Culm (Dinantian) in age. The rocks on both sides of the fault consist mainly of black and grey slates with siltstones and occasional sandstones, although there is an abrupt upward change in the metamorphic grade and in the style and amount of structural deformation on crossing the fault from north to south.

To the north of the Rusey Fault the Namurian rocks show evidence of at least two phases of folding ; first phase recumbent folding (F1) is dominant and is associated with an incipient slaty cleavage, whereas second phase ruck folds (F2), with axial planes dipping south, cut F1 (Dearman and others 1964; Freshney and others, in preparation). This late ruck folding (F2), with its attendant strain-slip cleavage, occurs only sporadically and always adjacent to a low-angle fault.

To the south of Rusey the same two phases of folding are present, but the later folding (F2) is dominant, and in many places the strain-slip cleavage almost obliterates the early cleavage, which has itself become fully slaty, the recumbent (F1) folds being tight to isoclinal. There is an increasing development of metamorphic minerals southwards from Rusey, the rocks being particularly characterized by elongate rust spots after pyrite, and some of the basal Carboniferous and Upper Devonian slates have become phyllitic and are feldsnathic.

In many instances it can be seen that the ruck folding (F2) intensifies towards the low-angle faults, and finally becomes tight drag folding adjacent to the fault. In the great majority of cases the ruck folding and drag folding indicate movement down the plane from a southerly or south easterly direction (cf. Zwart 1964). Fig. 1A demonstrates the trend of the maxima of stereogram plots of ruck-fold axes in different parts of the Boscastle area. It can be seen that the dominant trend of movement on these faults is almost north to south both north and south of Rusey and as far down he coast as Boscastle. Farther south-west the trend becomes increasingly north-west to south-east. The swing in the trend of the ruck-fold axes amounts to 30°, which cannot be explained as being due to flexing caused by subsequent formation of the Davidstow hemidome, for it can be shown stereographically that for the low dips and plunges involved in the hemidome, the swing in trend of a lineation such as a fold axis, consequent upon the generation of the hemidome, would amount to less than 5°. It therefore seems probable that the axes are normal to original radiating transport directions. The arcuate nature of these faults and their contained nappes is expressed by the swing of the repeated outcrop of the stratigraphical units around the hemidome.

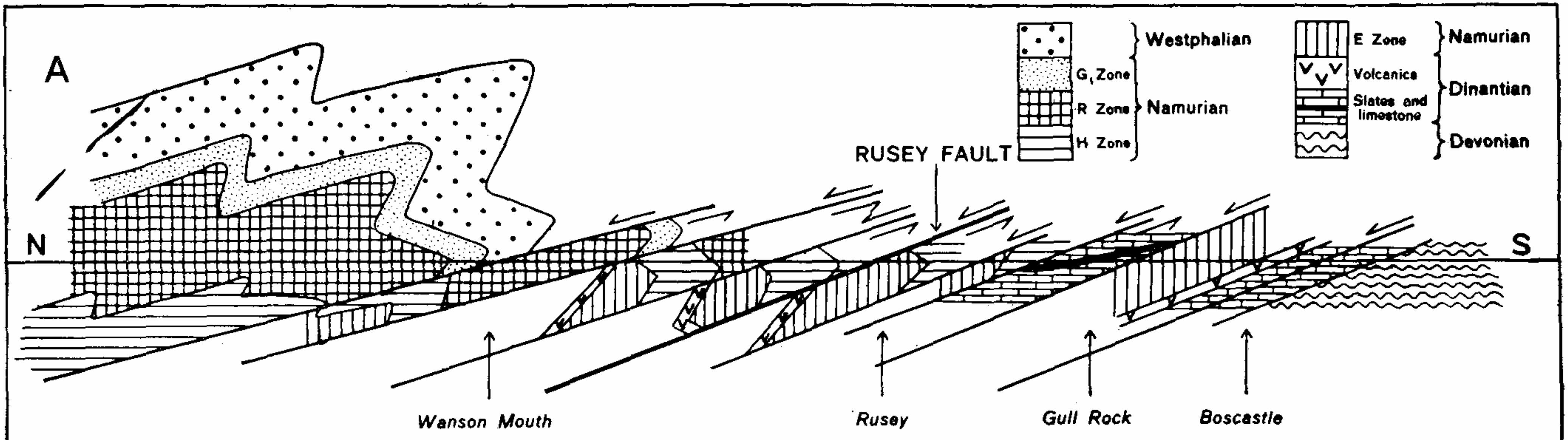

Fig. 2A. Diagram to show the effects of low angle normal faults on folded Carboniferous and Devonian rocks between Widemouth and Boscastle.

Fig. 2B. Diagram to show the postulated mechanism of formation of low-angle faults.

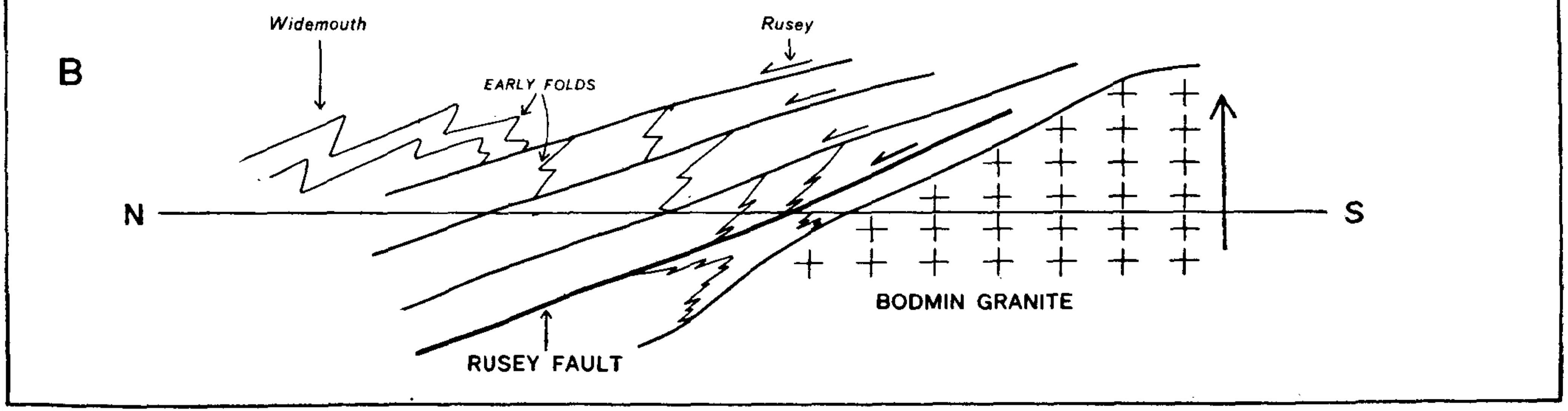

FIGURE 2.

It is suggested that the low-angle faults and the associated ruck folding (F2) were superimposed on pre-existing folds overturned to the south and with axial planes dipping at varied angles to the north. The present recumbent folds (F1) in the area south of Wanson Mouth represent minor folds on the overturned limb of one of the major folds. This limb was sliced by the low-angle faults, producing an extension of the apparent thickness of the recumbent limb, and also causing repetition and cutting out of parts of the succession (Fig. 2A). It may be that some of the more marked low-angle faults, such as the Rusey Fault and another major fault at Trambley Cove [SX074903], existed at the time of the early recumbent folding and during the formation of the southerly directed overfolds, when they would have moved as thrusts from the north. It is possible that the later radial movement on these faults from a southern or south-eastern origin took place as part of the accommodation of the Bodmin-Dartmoor granite (Fig. 2B). Faults similar in nature to these separate the various structural units described by Dearman and Butcher (1959) in the area to the north and west of Dartmoor, and these authors have already suggested movements of this type. Ruck folding possibly associated with these low-angle movements has been described at Lydford by Dearman (1964) and to a lesser extent at Meldon (Dearman 1959). East of Meldon the granite margin appears from geophysical evidence (Bott and others 1958) to be steep, and accommodation of the granite seems to have been effected by shouldering aside of the country rock producing steep isoclinal folds (Wright in Edmonds and others, in preparation). Fig. 1B shows the trend of rucking across the northern side of the Bodmin-Dartmoor granite and it appears that the rucks tend to conform to the probable subsurface shape of the granite, although some variations are to be expected due to the later disturbance of the granite outcrops by wrench faulting (Dearman 1963).

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90. A possible re-interpretation of the structure of the Plymouth Limestones : by C. J. R. Braithwaite.

Little has been written on the structure of the Plymouth limestones. Ussher (1907, p.58) briefly described sections through Mount Wise and Cattedown, showing a northern area of gently undulating southerly dipping beds and a steep overturned syncline at the southern end of the Cattedown section. The only account of structure in the southern part of the outcrop is that of R. N. Worth (1892). This also drew attention to the shallow syncline on the northern margin (Richmond Walk) and further noted undulating folds at Turnchapel which have not otherwise been recorded. These views persisted until 1951 when P. W. Taylor published an account of structure based partly on palaeontological evidence. This interpreted the outcrop as a faulted syncline, overturned to the north, and has been accepted in subsequent accounts by Dineley (1961) and Fyson (1962). The resent investigation indicates that the limestones are a single southerly inclined sheet with gently undulating dip, locally overfolded and thrust along its southern margin.

The limestones displayed a variety of responses to stress. The particular mode of deformation in a given area seems to be governed both by the lithology and overall thickness of limestone present. Cleavage is best developed in the fine argillaceous facies where there is a high insoluble residue. This cleavage is in all cases a fracture cleavage whose orientation is related to fold attitude. For this reason it has been possible to use the relationship between bedding and cleavage for determining "way-up" (c.f. Wilson, 1961). It is noted that a comparable relationship has been found in adjacent areas by Middleton (1954), and Holwill (1962). The more massive (and generally purer) limestones have been initially deformed in broad open warps such as those seen in the Cattedown (491537, grid references to area SX) and Richmond Walk (460543) areas. These folds are associated with normal faults in a number of cases. Most of the northern boundary of the limestones is thought to be faulted. No trace was found of the overturned syncline indicated by Ussher at the southern end of the Cattedown section.

In the southern part of the area, for example in Hooelake quarry (496528), thick-bedded argillaceous limestones are in undulating folds on the gently dipping northern limb of an asymmetric faulted syncline. Northwards in the quarry dark thin-bedded argillaceous limestones, lithologically somewhat similar to those in the northern part of Prince Rock quarry occur, within which one chevron fold and two thrust similar folds can be recognized. These folds have continued in thrusting. It is thought that this markedly different style is the result of there being a thinner development of the competent limestones in incompetent slates. The folds in the thick-bedded limestones are associated with faults resembling the extension style of fracture cleavage. It is noted that the interpretation of this area differs radically from Taylor (1951).

The author has been unable to find evidence for Taylor's eastward continuation of the buff shales south of Richmond Walk quarry, nor for the extensive easterly continuation of the belt of shales north of Oreston (500531), which are said to form together the core of his syncline. In addition, it has not been possible to repeat Taylor's observations of bedding/cleavage relationships in the Mount Batten area (487533). The observed relationship suggests that the beds are not in fact inverted. Similarly, the limestones on Drake's Island (468529) which are presumably in Taylor's inverted area (though they are not included on his map) are thought to be upward facing, and evidence from West Hoe (also in the "inverted" area) also indicates that beds are right way up.

Present evidence suggests that the deformation of the limestones may be seen as a cycle. Initial movements resulted in the relatively intense deformation of the thin-bedded limestones in the southern area, gentle folds in the more massive limestones and greater thicknesses of thin-bedded limestones to the north, and the initiation of fracture cleavage. It is thought that this mode of deformation gave way to thrusting which has similar orientation to the cleavage planes but probably flattens along the base and upper surface of the limestone sheet where Middle Devonian shales could deform more easily.

It is thought that the overburden load on these rocks was light, otherwise one might have expected to see greater plastic deformation and less brittle fracture. Continued or renewed stresses are thought to have been taken up in wrench faults such as those inferred on Mount Batten and a fault running from Oreston to Colesdown Hill (523543) which does not seem to have been postulated hitherto.

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91. The relationship between iron-metasomatism and emanative centres on Dartmoor : by W. R. Dearman and M. A. H. El Sharkawi.

The most prominent emanative centre on Dartmoor is that associated with the Birch Tor and Vitifer and the Golden Dagger group of mines in the central part of north Dartmoor (Fig. 1). In an area measuring three miles by two miles the dominant lode trend is E.N.E., and two small mines, Great Eleanor and Barracott near North Bovey, may be considered to extend an area of intense cassiterite-specularite mineralization another two miles in that direction. The mineralized tract continues to the granite margin in a broad arc swinging to E.S.E. near the granite margin, a change in direction probably due to stepping of groups of E.N.E. lodes by the Tertiary dextral wrench faulting that has affected the north-eastern tract of granite (Blyth, 1962). In this eastern extension specularite is the sole ore mineral, although at the granite margin in Great Rock Mine a little pyrite is also present (Dines, 1956, p.727). Here the lodes in granite have been traced into the killas as narrow strings.

Thus, there is an asymmetrically mineralized belt, here almost entirely within the granite outcrop, in which a tin-iron centre is flanked on one side by a zone in which iron alone has been introduced. The gangue in both cases is tourmaline and quartz.

The same asymmetrical arrangement of introduced tin and iron has been recognised along the northern margin of Dartmoor in bedded copper deposits confined to the calcareous horizon in the Lower Culm Measures. Descriptions of individual mines have been given by Dines (1956, p.750), and it is sufficient to note here that true lodes were not formed in this setting, the deposits being metasomatic replacements in limestones. In this calcareous environment, tin has accumulated in such calc-silicate minerals as grossularite, andradite, and also in sphene. Iron contributed to the formation of skarns by metasomatism of earlier formed contact metamorphic calc-silicate hornfelses and both ferrous and ferric skarns resulted from this activity. Boron contributes to a gangue of datolite and axinite.

Skarns are well developed at the following localities : Red-aven Mine ; in the floor of the main bay of the British Railways Meldon Quarry near the offices ; at Belstone Consols ; and also at

Ramsley Mine. The intervening ground is too poorly exposed for a useful determination to be made of the distribution of rock types in the calcareous rocks. Skarns have not been found west of Red-a-ven Mine.

Tin is concentrated at the Red-a-ven emanative centre at Meldon, so that the region of strongest tin-metasomatism is off-centre within a wide zone of iron-metasomatism. The shape of the mineralized belt has been controlled by lithology and structure mainly within the narrow inlier of the Lower Culm Measures parallel to and some distance from the granite contact.

There are some remarkable similarities between the two groups of deposits described above, even though the settings are so different. Tin is present in both in combination with oxygen, its association with iron emphasizing that geochemically tin is a siderophile element. Incidentally, ferric iron is an essential condition for the camouflaged retention of tin in the garnet, ferrous silicates being tin-free.

The structural factors which have controlled deposition in the Lower Culm must obviously be related to the anticlinal structure of the inlier, with the skarns occupying a slightly undulatory

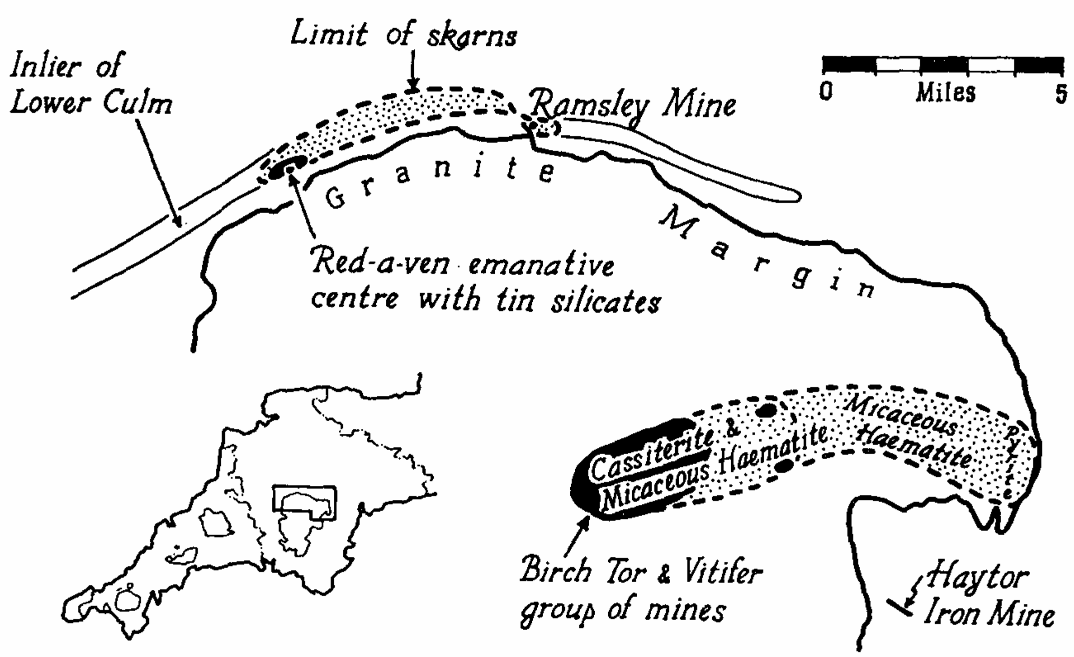

FIGURE 1. Map illustrating the relationship between emanative centres and iron-metasomatism in the mineral deposits of north Dartmoor. Black areas : tin with iron ; stippled areas : iron. Inset : map of S.W. England showing granite outcrops and the area of the main map.

structural culmination stretching from the Red-a-ven to Ramsley Mine. It is likely, although difficult to demonstrate satisfactorily, that the highest point in the six miles long culmination was at the present position of the Red-a-ven emanative centre. This must have been a highly strained region where the main arch of the Culm inlier, rising to enter the granite aureole just over one mile to the west, levelled out to swing in a broad arc round the granite. There is evidence from granite dyke intrusion for a six per cent north to south extension of the sediments on the Red-a-ven, distinguishing the area as one of local stretching and hence active fissuring. Deformation at the point of inflexion of the major fold culmination could therefore have determined the position of the emanative centre, with lateral spread of metasomatizing fluids being directed along the length of the culmination.

The cassiterite-specularite deposits are confined within the granite, the tin-iron lodes cropping out within a 600 feet height range, iron alone through at least 400 feet. With the granite-killas junction apparently acting as a lithological trap for the mineralization, the present asymmetrical shape of the deposits could have resulted from denudation of the top 400 feet of granite from the other half of a symmetrically mineralized tract lying west-south-west of the Birch Tor emanative centre. Four hundred feet added to the present topographic levels would place the granite surface at a minimum height of 2,000 feet above sea-level, a height actually reached near the granite margin south of the Red-a-ven emanative centre.

The similarities between the two groups of tin-bearing deposits appear to be confined to mode of origin combined with obvious geochemical affinities, while resemblances in shape of outcrop are apparently coincidental.

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93. The ages of some coral faunas in the Torquay area :

by C. T. Scrutton.

The rugose coral faunas of Triangle Point (SX929628), Dyer's Quarry (SX922628) and Saltern Cove (SX896585) only are considered here.

The succession in the Daddy Hole area can be demonstrated on the flanks of the anticline in Daddy Hole Cove (SX927628) Eifelian shales pass up through red shaley limestones into dark, crinoidal, thin bedded limestones. Higher in the sequence, the limestones become more massive and paler in colour, with an increasing content of stromatoporoids.

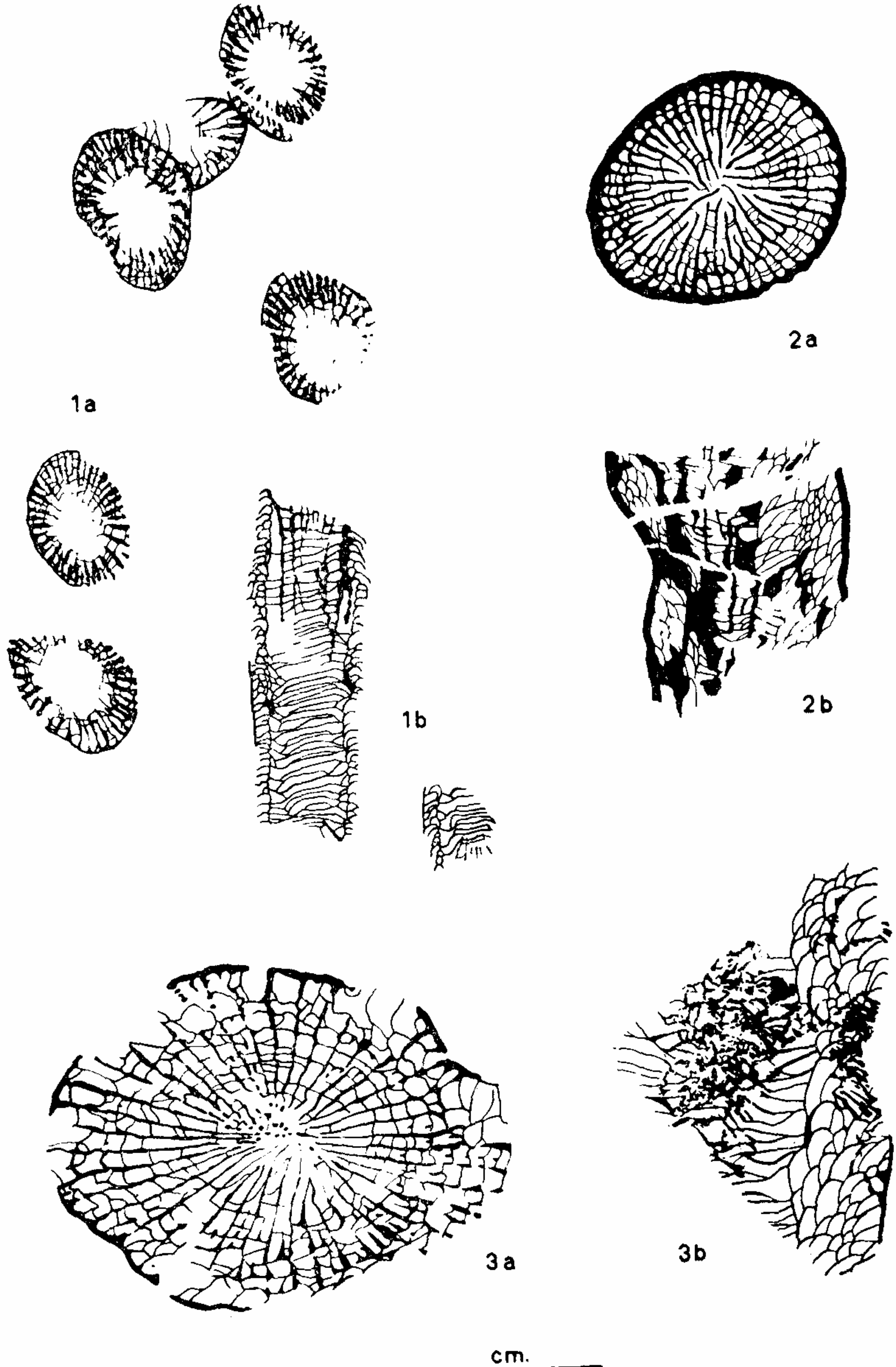
Triangle Point is part of the inverted eastern limb of the Daddy Hole anticline, cut off from the main mass by east-west faults. The dark, thin bedded limestones exposed here contain bands rich in corals, chiefly *Grypophyllum denckmanni* Wedekind *(sensu* Engel and Schouppe, 1958, p.103) with subsidiary *Acanthophyllum* sp. and *Plasmophyllum (Mesophyllum)* sp., tabulate corals, mainly *Alveolites* and *Thamnopora* and occasional small stromatoporoids. The fauna indicates a low Givetian age.

Dyer's Quarry, at the western end of the Daddy Hole limestone mass, has a rich coral fauna preserved in thin bedded, dark, crinoidal limestones exposed in the base of the quarry. *Thamnophyllum* cf. *trigeminum* Penecke and *Plasmophyllum (Mesophyllum)* cf. *maximum* (Schluter) are very abundant and appear to be preserved in their position of growth. *Stringophyllum (Striraoophyllum)* cf. *schwelmense* (Wedekind) is also fairly common with subsidiary *Plasmophyllum (Plasmophyllum)* sp., *Acanthophyllum* sp. and tabulates. The horizon indicated is lower Middle Givetian, somewhat higher than that at Triangle Point.

FIGURE l. **Peneckiella** cf. **minor** (Roemer). la, cross-section, OUM D500/ pl ; lb, longitudinal-section, OUM D501/pl. Thick bedded limestone, immediately above igneous rock ; Saltern Cove, near Paignton, South Devon. Frasnian.

FIGURE 2. **Grypophyllum denckmanni** Wedekind. 2a, cross-section, OUM D502/pl ; 2b, longitudinal-section, OUM D502/p2. Thin bedded, crinoidal limestone, Triangle Point, Torquay, South Devon. Low Givetian.

FIGURE 3. **Stringophyllum (Stringophyllum) schwelmense** (Wedekind). 3a. cross-section, OUM D503/pl ; 3b, longitudinal-section, OUM D503/p2. Thin bedded, crinoidal limestone, base of Dyer's Quarry, Torquay, South Devon. Lower Middle Givetian.


1a
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cm.

The evidence at Dyer's Quarry and Triangle Point suggests that the bulk of the dark, thin bedded limestones, formerly considered to be Eifelian (Lloyd, 1933, p.52), are Givetian in age and that little or no limestone deposition took place in this area before the end of the Eifelian.

Saltern Cove, exposing the Upper Devonian, lies to the south of the Paignton anticline. A short thickness of Famennian mudstones in Waterside Cove overlies Frasnian red, shaley mudstones containing the Saltern Cove goniatite horizon of *holzapfeli* zone age (House, 1963, p.8). In Saltern Cove proper, the Frasnian can be traced southwards in the foreshore until limestone bands appear in the red shales near the southern end. Immediately above the igneous rock forming the southern horn, about 20 feet of massive, reddish limestone is developed.

In the base of the massive limestone is a distinctive band, rich in *Peneckiella* cf. *minor* (Roemer), which can also be found west of the cliff face fault further north in the cove. Higher limestone horizons also contain scattered *Pencckiella* with *Tabulophyllum* sp., *Macgeea gallica* Lang and Smith, several disphyllids and many tabulates. The fauna is Frasnian in age, possibly equivalent to the Middle Frasnian *cordatum* zone.

The Saltern Cove beds probably represent the highest limestone coral fauna known in the Devonian of south Devon. They appear to be separated, however, from the main development of the massive, Middle and Upper Devonian limestones by a succession of shales and tuffs.

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94. Observations on vulcanicity and tectonics of the Torquay area: by Dieter Richter.

Vulcanicity. In the area enclosed by the lines Totnes-Torquay, Totnes-Torcross and the coast line, igneous rocks have a wide distribution and are present in the Lower, Middle and Upper Devonian. The largest coherent igneous complex is constituted by the Ashprington Volcanic Series. New observations at the margins of the complex show interfingering with normal sediments of both Middle and Upper Devonian age. Limestone can also be seen within the complex. It appears that during much of the Middle and Upper Devonian effusive igneous activity interrupted the normal accumulation of sediments, and that only at times of reduced activity could the biogenic limestones accumulate.

Structure. In the south, a broad anticline with its axis at Stoke Fleming brings Lower Devonian to the surface. North of the line from Brixham to Dittisham, Middle and Upper Devonian come in and constitute a synclinal tract between the Lower Devonian to the south and that of the Paignton area to the north. Many subsidiary folds occur, especially in the Middle and Upper Devonian limestones.

The argillaceous rocks are strongly affected by minor folding and have a first, slaty cleavage. Folds tend to be overturned towards the north. They trend E.-W., whether large or small scale, and are horizontal or slightly plunging. South of the line from Brixham to Stoke Gabriel, a second strain-slip cleavage appears occasionally. It is steeper than the first cleavage and the thrusting sense of movement tends to reduce the angle of dip of bedding and first cleavage. The first cleavage forms a fan, dipping south and becoming steeper from Torquay to Slapton and then dipping north at Torcross and further south. The second cleavage fans similarly but the centre, in the Stoke Fleming area where cleavage is vertical, lies north of that of the first cleavage fan. Locally south-facing minor folding presents an interesting problem. The first cleavage is folded in these structures which appear to be younger also than the second cleavage.

The latest structural process was the kinking of cleavage seen at several places south of Brixham and Stoke Gabriel. There are two groups : one consists of flat-lying kink bands affecting mainly the first cleavage, but sometimes also the second, and having a southward thrusting sense of movement ; the other has near vertical kink bands trending north-south and a clockwise sense of movement.

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LLOYD, W., 1933. The Geology of the Country around Torquay [2nd edn.,. **Mem. Geol. Surv.**

95. The Pleistocene deposits of the Scilly Isles : by G. F. Mitchell and A. R. Orme.

Barrow (1906) described a sequence of pre-Holocene deposits overlying the Scilly granites. He recognised some plateau gravels, containing much non-granitic material, for which he suggested an Eocene age. He also described an old beach conglomerate overlain in succession by a lower head, a` glacial deposit' of gravels with striated erratics deposited from floating ice, and an upper head. For these he suggested a Pleistocene age.

Doubts have since been expressed about the nature and origin of the 'Eocene gravels' and the 'glacial deposit'. The former was attributed by Dollar (1957) to the Pliocene and by Mitchell (1960) to Lower Pleistocene fluvial aggradation. Mitchell further implied that the latter deposit was derived by solifluction from the former. A recent thorough re-examination of the islands by the authors has led to a reinterpretation of these anomalous deposits and the following extended sequence is suggested.

(1) Prolonged deep weathering, aided by structural weaknesses aligned most commonly in north-easterly and north-westerly directions and accomplished by weakly acidic circulating groundwaters, has selectively rotted the granite, locally to below present sea level. The weathering, possibly initiated during Tertiary times, continued at least to the Holsteinian interglacial. The later stripping of the resultant growan by subaerial - particularly periglacial - and marine processes has revealed a remarkable number of tors and probably explains the general distribution of the various islands.

(2) A wave-cut platform, since raised 10-25 feet above mean sea level, is generally poorly developed on well-jointed granite and is often no more than a wave-washed land surface, steepening locally to 8°, mantled by storm boulders. It is best seen, however, where

the sea excavated the rotten granite to the base of the weathering profile and, exceptionally, where it trimmed a washing surface across the growan.

(3) An old beach deposit, containing boulders and fallen blocks of granite, pebbles of flint, chert, red sandstone, red and green fine-grained igneous rocks embedded in ferricrete sands, and inter-digitated with head, was later stranded on the rock platform during a falling sea level associated with changing climate and early solifluction. On Annet the raised beach is strongly cryoturbated.

(4) The main or lower head consists entirely of angular granite blocks and frost chips with occasional basal facies of quartz sands washed from the growan. Quartz sands at higher levels may be cemented by manganese. The deposit is quasi-bedded and contains some beach cobbles in its lower levels and some rotten granite blocks indicating the close contemporaneity of the beach and earlier soliflual phases.

(5) A gravel with numerous striated foreign stones, similar in content to the raised beach, was later deposited across the plateaus of the northern isles, north of a line from Chapel Down on St. Martin's to Gweal Hill on Bryher. The gravels, which lack any matrix, may be traced continuously downslope into lenses of similar material occurring between the upper and lower heads of coastal sections. The lenses are clearly soliflual deposits derived from the plateau debris (Barrow's ‘Eocene gravels’) which is interpreted as fluvioglacial outwash from a once nearby ice-sheet. In addition, a brown compact clay, displaying polygonal cracks when dry and containing similar foreign stones dispersed at all angles, occurs at Bread and Cheese Cove on St. Martin's. This closely resembles the Eastern General till of Waterford and Cork and may conceivably be an *in situ* till.

(6) The upper head, consisting of several facies, some erratics (in contrast to the lower head) and, conspicuously, some large granite blocks which may indicate an inversion of the former weathering profile, was later deposited. It is generally weathered to several feet with an underlying iron pan.

Representative coastal sections are well displayed beneath Chapel Down on St. Martin's, in Chad Girt on White Island, beneath Castle Down on Tresco and Shipman Head Down on Bryher, and below the Garrison and Porth Hellick Down on St. Mary's. The implications of a nearby Pleistocene ice-sheet and the relation of sea-level oscillations to changes in climate and process are being examined.

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BARROW, G., 1906. The Geology of the Isles of Scilly. **Mem Geol. Surv.**

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MITCHELL, G. F., 1960. The Pleistocene history of the Irish Sea. **Adv. of Science,** Vol. 17, p.313-25.

96. The upper and lower surfaces, and some structural features of the frost soils of the Camel Estuary : by B. B. Clarke.

The term frost soil covers material formed by physical weathering under glacial conditions : brash, formed by frost shattering of the bench surfaces, slaty heads, solifluxion gravels and clays. These are exposed at the edges of the 15 and 25 ft. benches. The former, although fragmentary, is considered to have been cut by the sea at a different time from the 25 ft. as, where the benches are cut in slate with well developed horizontal jointing, the step up from one to the other is cliff-like.

The succession observed is :

	Maximum Thickness	Distribution	Arkell's terms at Trebetherick
5 Brown solifluxion clay	4'6"	persistent	Solifluxion pebble bed and younger head –Cymrian
			Trebetherick boulder gravel
4 Fine slaty head	12'	patches only	
3 Coarse slaty head	3'	fairly persistent	Main head – Cornovian
2 Frost shattered brash	3'	fairly persistent	
1 S. Saviour's Pt. breccia-conglomerate	1'	rare	

Slate fragments in the frost soils are sharp edged in contrast to the beach pebbles which are rounded though seldom ovoid. The breccia-conglomerate is considered to be an old head because the slate in it is sharp edged, the rounded quartzites being beach pebbles gathered up from the bench during solifluxion. The deposit is eroded away except for two patches north of S. Saviour's Pt., hence the disconformity above it. The fine slaty head is a laminate solifluxion deposit formed in wet conditions ; the coarse is a fairly dry solifluxion deposit. The two are separated by a smooth sloping surface. The brown solifluxion clay rests on fine and coarse slaty head, brash, or on the bench itself. There is thus a disconformity at the base probably representing a considerable time interval. In the whole series there are four solifluxions formed during glacial stadials and two disconformities probably due to interglacial erosion. No evidence of precise age has yet been found (see Zebera 1958 for solifluxion horizons and structures).

The impressive, generally smooth, surface below the solifluxion clay is strikingly similar to the present day land surface, and is considered the result of weathering of the periglacial cover.

The following structures are observed : 1 Frost wedges (Frostkeilen) with straight or bulging sides and long tapering roots extending down into the solid, considered to be the first effect of oncoming glacial conditions, 2 Frost cracks occurring in the clay, filled with white silt stained brown at the edges and with matching sides, 3 Brodelboden with slate fragments oriented in broad swirling sweeps in two dimensions and several feet in radius, 4 Puckering (Brodelung). The generally smooth upper surface of the coarse slaty head is in places depressed or pushed up, due to frost heaving of the surface layer and puckering during downsettling. Puckers occur singly or several together. 5 Expansion flues due to water from unfrozen lower layers escaping through holes or cracks in the frozen layer and orienting the slate towards an upward projecting point. Slate lends itself to revealing these structures by its clearly defined orientation.

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ARKELL, W. J., 1943. The Pleistocene rocks of Trebetherick, North Corn wall. **Proc. Geol. Soc.,** Vol. 64, p.141-165.

ZEBERA, K., 1958. Die Tsecho-slowakei in der Alteren Steinzeit.

97. A preliminary report on the petrology of Middle Devonian limestones in South Devon : by C. J. R. Braithwaite.

Two previous accounts have briefly considered the petrology of these limestones, those of Sorby (1879) and Shannon (1928).

Because the structure of the area and general lack of correlation usually prevent observation of any but vertical lithological changes, the petrology is an account of the variation.

Despite metamorphism, many features of original depositional textures are apparent. Present studies indicate that none of the limestones in South Devon result primarily from mechanical weathering of pre-existing carbonate rocks. Outcrops are almost entirely surrounded by terrigenous sediments ; carbonate grains are of internal origin and, if derived, are from within the area of carbonate deposition. Recrystallization of many fragments leaves their exact origin in doubt but, except possibly for equivocal pure limestones, the bulk are bioclastic. Organisms are rarely in the growth position ; the sediments are mechanically deposited and not bioconstructed, but there is a scarcity of current influenced fabrics such as cross bedding or ripple lamination.

None of these limestones are free from subsequent growth of calcite. This is most easily seen as a rim growth in optical continuity with single crystal fragments, either forming a rim cement, or growing at the expense of surrounding muddy material so that boundaries are limited by and adjusted to contact with surrounding grains.

A few sections offer evidence that rim cementation has taken place relatively early in diagenesis at or near the sediment surface, and intraclasts are also taken as indicating early lithification.

Because of subsequent changes and adjustment to grain boundaries, the recognition of drusy calcite cement is commonly difficult. Not all of the normally applied fabric criteria are applicable to these sediments, and one relies heavily on grain size changes and the shape of cavities. Nevertheless, both primary and secondary cavities can be recognised.

Shelly fragments are usually replaced, two distinct mechanisms being indicated. Either the original material undergoes molecular replacement, or it may be completely dissolved and replaced by growth of drusy calcite into the resulting cavity. It is to be noted that the calcite which most often shows planar boundaries and “equilibrium” texture is the fine grained result of recrystallization of Stromatoporoidal tissue.

There seems to be no close correlatior. between the degree of alteration of fossils and the containing sediment type. It follows in this case, however, that with complete shell removal molds are less easily preserved in coarse sediments than in muddy ones. The degree of preservation of different fossil groups has depended not only on their resistance to recrystallization, but on their inherent competence to resist tectonic deformation and “metamorphism”.

Within the bounds of the present study there is insufficient evidence to suggest a constant order of recrystallization.

In some sediments metamorphism has reduced the original fabric to a consertal mass of grains of varying diameters. Under these circumstances it is difficult to distinguish between textures resulting from the primary growth of grains, and those consequent upon re-adjustment. This is also the case when fine grained "pure" limestones are altered to a mass of approximately equidimensional grains with sub-planar boundaries which are presumed to be near equilibrium. When coarser grains are present in these, they are invariably irregular in outline and are themselves subject to granular recrystallization.

A number of insoluble residues of limestones in the Plymouth area have been examined. Grains of quartz and felspar are relatively common as detrital minerals, but are accompanied by tourmaline, zircon, epidote, garnet, kyanite and glaucophane, together with other unidentified minerals. This suite is thought to be significant of the provenance of these sediments.

In thin sections quartz grains are present which can be shown to be authigenic. Some are probably early diagenetic, while others are best considered as "metamorphic". Authigenic felspars, presumably diagenetic, are common in a number of limestones, and those examined have been shown to be almost pure albite. Both of these minerals may be idiomorphic, but often are not.

Many of the limestones are dolomitized, with isolated crystals showing good shape and appearing, by virtue of their strong colour, pseudopleochroic. There is local evidence for replacement of dolomite by calcite, but no general study either of dolomitization or de-dolomitization has been made to date.

The present study has suggested that these carbonates are divisible into a relatively few main types, there being no clear regional distribution. They range from carbonate mudstones, which are themselves divisible into argillaceous types and pure limestones (stratigraphically separate), through Wackestones to Packstones (Dunham, 1962), the last group including pelsparites and a number of biosparites of varying grain size and allochem composition (Folk, 1959).

It is suggested that current interpretation of the limestones as a reef formation is erroneous. Alternatively, it is postulated that they are bioclastic accumulations from and within areas of prolific growth of carbonate secreting organisms, which at no time formed a growth lattice having topographical expression comparable to modern reefs. A number of separate ecological habitats are recognised, but often no explanation can be offered of their limiting factors. These observations, together with some ancillary study of surrounding sediments, suggest that the area was one of shelf sea sedimentation, perhaps on a hinge zone, with a low lying land mass to the south and possibly deeper waters to the north.

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98. Bismuth and Molybdenite from Meldon Quarry, near Okehampton, Devon : by W. R. Dearman.

In the south-west of England mining region, bismuth is known to have been found both in cross-courses and in lodes of normal trend. But, according to Dines (1956, p.30), the mode of occurrence of bismuth in the latter setting is not known since it was usually detected as small particles in mill concentrates.

Quartz veins with bismuth and molybdenite were found, in 1949, in the main south bay of British Railways Meldon Quarry, situated two miles south-west of Okehampton on the northern border of Dartmoor. The veins were confined to strike joints within a massive basic dyke of the so called Dy`xe Two facies. Dipping south, counter to the dyke and associated sediments, the quartz veins had the attitude of typical east-west lodes (Dearman, 1959, fig. 10). Similar joints elsewhere in the quarry have become small-scale normal faults, another feature in common with the lodes.

Formation of quartz veins was the final episode in a sequence of changes produced by the passage of hydrothermal fluids along joints in the dyke (Table 1). The earliest veins were formed by wall-rock reaction with a minimum of associated joint infilling and consequently have very irregular, gradational margins ; such veins are particularly characteristic of the phase of boron metasomatism and introduction of sulphides. The latest veins cutting across earlier veins are dilational joint infillings with a minimum of marginal reaction.

In the coarse-grained quartz veins the walls of vughs are formed by crystal faces of quartz. These openings may be completely infilled with bismuth, often in single crystals ; alternatively individual globules up to 5 mm. in diameter and other masses with recognizable crystallographic forms may occur. Invariably the bismuth has a very thin lead-grey coating with a yellowish or irridescent tarnish, even where it is in contact with quartz. This coating is a sulphide since it gives a positive reaction with sodium azide reagent. It is presumably bismuthinite but so far it has not been possible to obtain a confirmatory X-ray powder photograph.

Bismuth may be associated with very thin fibres of bismuthinite and hexagonal flakes of molybdenite. In the larger cavities these minerals are often coated with pale brown siderite, black tourmaline, biotite, and crystals of sphene.

TABLE 1. Successive vein developments in Dyke Two.

Contact Metamorphism …	Progressive conversion of pyroxene to amphibole to biotite with formation of albite-biotite rock forming the main mass of Dyke Two.
JOINTING	
Hydrothermal fluids passing along joints and reacting with the wall rocks …	Amphibole veins with pyrite and a white reaction selvedge in which biotite is converted to amphibole and ilmenite to sphene.
JOINTING	
Introduction of Boron and Sulphides of Fe, Cu, As, Zn Pb …	Tourmaline-sulphide veins with reaction selvedge containing chlorite after biotite and sphene after ilmenite.
JOINTING	CUT BY
Formation of leucocratic veins carrying varied assemblages of tourmaline, calcite, fluorite, siderite, sphene, orthoclase, and sulphides with some marginal reaction. These CUT earlier amphibole veins.	Biotite veins. Pyrite - pyrrhotite - chalcopyrite - quartz veins with coarse selvedge of biotite with partial conversion to chlorite. Pyrrhotite-quartz veins, non-reactive. Quartz veins, non-reactive, with bismuth, bismuthinite, molybdenite, chalcopyrite, arsenopyrite, fluorite, calcite, siderite, and a little tourmaline.

Molybdenite has also been found in calc-silicate hornfels from the normal limb of the anticline in the north bay of Meldon Quarry. There it is associated with datolite, grossularite and diopside in irregular veins cutting calc-flintas. The grossularite is tin-bearing, and it is interesting to note that in a wollastonite hornfels from the dumps of the Red-a-ven Mine (Dearman and Sharkawi, 1965) grossularite and sphene are both stanniferous while the associated lollingite contains intergrowths of bismuthian.

In one specimen from Dyke Two, molybdenite appears to be genetically associated not with a quartz vein but with a tourmaline-sulphide vein. Such veins are the non-calcareous analogues of the irregular datolite veins in cale-flintas, and although non-reactive dilation veins of datolite-grossularitezeolite have been found at Red-a-ven Mine they have not been observd to contain either bismuth or molybdenite in hand specimen.

The presence of bismuth and molybdenum minerals in both calc-silicate hornfelses and in basic Dyke Two suggests that the associated veins are hypothermal in origin. Abundant boron and camouflaged retention of tin in calc-silicates would appear to confirm this. In the zonal scheme of the general order of deposition of Cornish lode minerals proposed by Hosking and Trounson (1958, Table II), it would appear that bismuth and bismuthinite should be added to their Zone 2 (Cassiterite ; Arsenopyrite ; [Molybdenite ?] ; Wolframite ; Scheelite) and that the question mark after molybdenite could be removed.

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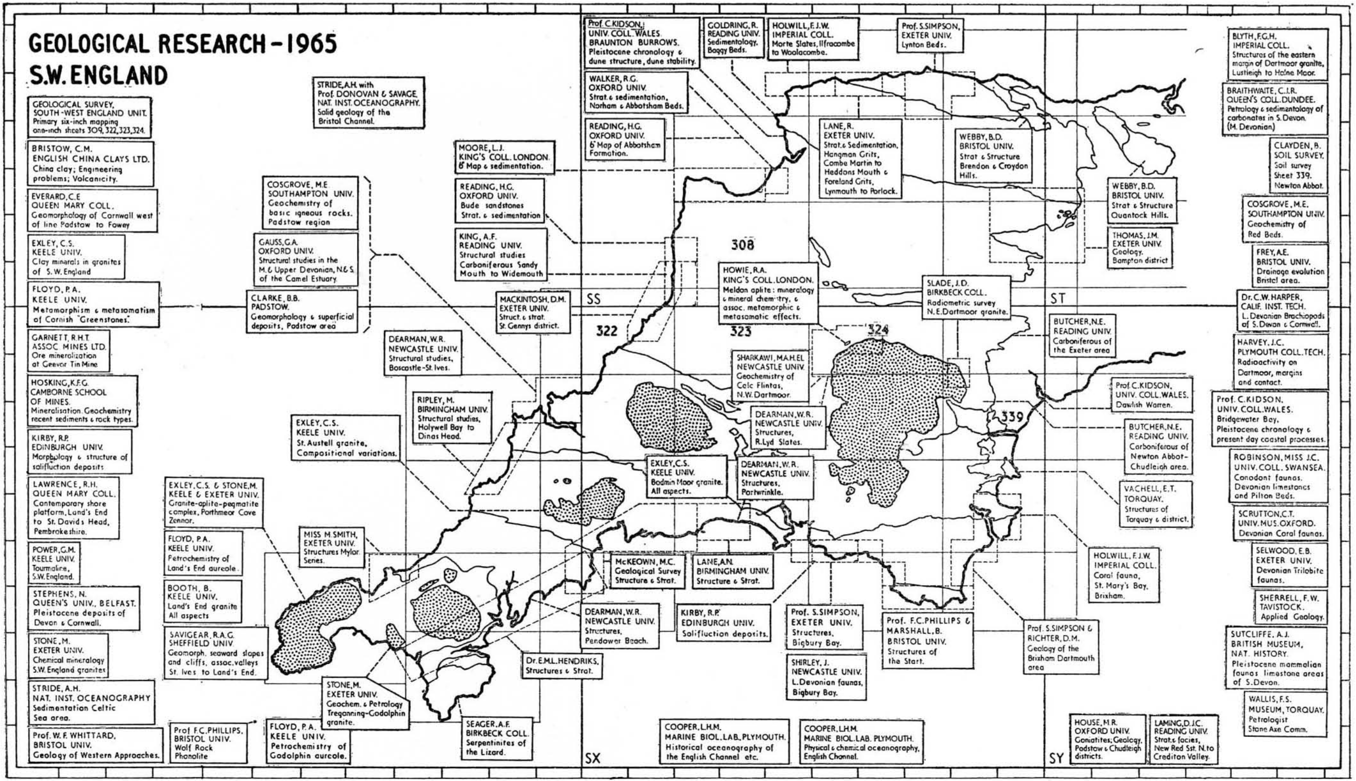

CONTRIBUTION 100. Map showing geological research in S.W. England — 1965, by W. R. Dearman.

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