METAMORPHISM IN SOUTH-WEST ENGLAND

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CONTENTS

I. INTRODUCTION

The metamorphic history which we shall study here is concerned essentially with the evolution of a part of the western, or Armorican, development of the Variscan Fold Belt. Three phases will claim attention. At intervals during the deposition of the Devonian and Carboniferous sediments there was widespread spilitic igneous activity, and related material mainly of picrite-minverite-albite dolerite affinities was later emplaced as a series of minor intrusions. These basic rocks are now in a condition which would justify the use of the name meta-dolerite. They have long been known as greenstones in the local geological literature, and we shall continue to use this convenient name. The contact-metamorphic effects of the greenstones are nowhere extensive but they present points of special interest. A phase of regional metamorphism, of low to moderate grade, was followed by the emplacement of granite masses which now outcrop from Dartmoor to the Scilly Islands (see also Smith *et al.* 1965).

Though the general chronological succession of these events is clear, there is still disagreement over their precise dating. Some structural interpretations invoke major movements at the end of the Devonian or in the early Carboniferous (e.g. Hendriks 1959). Others find little support for, or evidence of, a multiplicity of orogenic phases such as have been claimed for the more eastern part of the fold belt (Simpson 1962), and hold that the Variscan orogeny in Devon and Cornwall 'took place at essentially one time, at the end of the Carboniferous period' (Butcher 1962). The study of radioisotopes has yielded an age of 280 $\pm$ 10 m.y. for the granite intrusions (Long 1962), corresponding to a time of intrusion believed to be close to the Carboniferous-Permian boundary Butcher 1961). Dodson, determining whole-rock potassium-argon ages of fine-grained slates and phyllites, believes that there is evidence for an important phase of movement, effecting recrystallisation of the sediments, at about 350 m.y., near the Devonian-Carboniferous boundary (Dodson 1962; 1963).

In the rocks of the Lizard there may be recorded metamorphic events related to an earlier orogeny, though this appears to be of Caledonian age (Miller and Green 1961) and not Precambrian as was formerly considered probable. The special problems of this area, with its complex intrusions, are considered in a separate chapter of this volume.

II. THE COUNTRY ROCK

The country rock of south-western Cornwall, adjacent to the granite masses of Land's End, Godolphin, and Carnmenellis, consists of Mylor Beds. These are a predominantly dark pelitic succession of alternating argillaceous and silty rocks usually with a characteristic fine banding. More psammitic intercalations occur at intervals, but there are no limestones and no contemporaneous igneous material. These rocks are the typical 'killas' of the mining region. Their age is uncertain, but they may be Lower Devonian and be succeeded by the possibly Middle Devonian Gramscatho Beds, a succession of shales, siltstones, and grits predominantly paler in colour than the Mylor Beds but again without notable limestone horizons, lavas, or pyroclastic deposits. The Gramscatho Beds occupy a broad tract of country running east-west through Truro, and are of interest to us here chiefly as being the country rocks of the small granite intrusions of St. Agnes and Cligga Head.

Undoubted Lower Devonian rocks run eastwards from Newquay to Dartmouth. The variegated, dominantly pelitic, succession of the Dartmouth Slates is followed by the more uniformly grey slates and siltstones of the Meadfoot Beds which are notably calcareous in places. Higher in the succession the lithology becomes predominantly psammitic ('Staddon Grits'). The contact zone of the St. Austell granite lies wholly within these Lower Devonian rocks, which are also of concern to us because of the problem of age-relationship between them and the more highly metamorphosed rocks of the Start Point area.

Middle Devonian rocks extend from Trevose Head south-eastwards past Bodmin, forming the country rock of the Bodmin Moor granite on its south-western contact; the southernmost portion of the Dartmoor granite also is emplaced in a belt of rocks of this age. Limestones become important in this part of the succession, though the massive limestones of Ashburton and Plymouth lie outside the aureole of metamorphism. West of Plymouth calcareous material is present mainly as lenticles or thin bands within the shales.

The remainder of the aureole of the Bodmin Moor granite, and of the southern part of the Dartmoor mass, lies within Upper Devonian sediments. Contemporaneous volcanicity reached its peak during Upper Devonian times, and considerable areas of spilitic lavas with rarer acid flows and some associated tuffs extend south-eastwards from Tintagel and St. Minver around the west and north of the Bodmin Moor intrusion. The greater part of the aureole of the Dartmoor granite lies within rocks of Carboniferous age, but there is no very sudden change of lithology and contemporaneous volcanicity continued for a time. A Transition Series, gradational in lithology between the Upper Devonian and the Lower Culm Measures, is recognised on the north-west border of Dartmoor (Dearman and Butcher 1959). Some of the shales in a shale-siltstone development are blue-black, and limestones occur as thin sheets and lenticles. The lower part of the Carboniferous succession includes massively bedded black shales, a prominent horizon of agglomerates and tuffs, and a series of lenticular limestone. Above, a marked change in lithology from calcareous to arenaceous brings in coarse greywackes and medium-grained sandstones.

III. CONTACT-METAMORPHISM BY BASIC INTRUSIONS

The earliest metamorphic effect which we have to notice is a minor, though widespread, contact-metamorphism adjacent to the basic intrusions, the greenstones. At almost every well-exposed contact some degree of thermal spotting of the country rock can be seen, extending to a distance of from one to several feet from the margin of the igneous rock. The spots vary in size up to several millimetres diameter. The earliest effects seem to be due to local concentration of chloritic material, but the larger spots are sometimes suggestive of the incipient formation of chiastolite or cordierite. The ease with which they develop, and to some extent the nature of the spots, is related to the composition of the rock. Dewey (1915) found the most characteristic spotting in pale green or purple slates rather than in the grey or black; Agrell (1939) has described the development of large compound spots with chlorite, sericite, and calcite or quartz, in black slates.

More striking than this minor thermal metamorphism, and to some extent superimposed upon it, is a metasomatic change which converts the country rock to adinole by the development within it of abundant albite. This change, too, is partly controlled by the composition of the original sediment, and perhaps also by its grain size, and albite may develop preferentially in some layers parallel to the bedding. A completely metasomatised rock is usually a very fine grained, pale greyish white, splintery rock in which sedimentary banding can still be seen. Such a high degree of alteration usually extends only a few inches from the contact; an instructive and accessible exposure on the foreshore of St. Ives Head is figured by Robson (1945). The most impressive development of adinole in Cornwall is that at Dinas Head, on the west side of Trevose Head (Padstow Memoir, sheets 335/6; Dewey 1915; Agrell 1939), where albite-rich metasomatised rocks reach a thickness of about 100 ft. Later movements have unfortunately partly destroyed the original contact-relationships of this zone with the adjacent albite-dolerite, but detailed examination has provided no evidence to favour a suggestion that this great thickness might be partly accounted for by the presence of keratophyric tuffs in the sedimentary succession. Some of the adinoles at this locality carry abundant carbonate. In certain bands within about twenty feet of a contact there occur pseudomorphs in quartz and chlorite after euhedral crystals which have the habit of andalusite. Their appearance is consistent with the superposition of the metasomatic change upon an earlier thermal metamorphism, though the development of andalusite crystals of this size at a contact with a minor sill (some of the pseudomorphs are more than an inch long) must be quite exceptional. This, together with the great extent of metasomatic alteration, may point to the presence of a plug-like igneous mass rather than a simple sill.

The discovery, on occasions, of perfectly preserved fossils in an adinolised sediment (Padstow Memoir, p. 26; Agrell 1939, Pl. 11), as well as the retention of shape of the pseudomorphs, strongly suggests that the metasomatism involved a volume-for-volume replacement; calculations on this basis indicate the addition essentially of Na_2O and SiO_2. A puzzling accessory mineral in many of the adinoles at Dinas Head is a magnesium-rich tourmaline; it is difficult to believe that boron has been contributed in quantity directly by a doleritic intrusion and it may well have been derived from a granitic source (Agrell 1941).

IV. HERCYNIAN EARTH-MOVEMENTS

The region of Devon and Cornwall did not experience the full impact of the earth-movements which built up the eastern part of the Variscan Fold Belt. The most widespread effect associated with the deformation and folding was the imposition of slaty cleavage on the finer-grained sediments. The areal distribution of a good cleavage is somewhat sporadic, its development being related to the nature of the original sediment and to its position in the structure of the fold belt (Phillips 1962). We cannot pursue this latter point further here, but may note that absence of cleavage from apparently potentially cleavable sediments cannot safely be accepted as evidence of deposition after the close of all effective movement (Simpson, 1959, 1959 a; Butcher 1959). In some areas a second cleavage (' false cleavage ', ' strainslip cleavage ') is superimposed on the slaty cleavage and the rock then loses its commercial value.

Slates have been worked locally at very many places in the south-west. De la Beche wrote in his 1839 *Report* of extensive quarrying of roofing slate south of Dartmoor. In Cornwall the most productive area has been west of Bodmin Moor, from the Delabole area and Tynes southwards to Penquean and Pawton. The grey-green and blue-grey slates from the Delabole quarries have had an established reputation through three and a half centuries. These slates are fine-grained quartz-muscovite-chlorite schists and are associated in the Upper Devonian succession with other schists and phyllites of slightly varying mineralogy. Porphyroblastic chlorite is often prominent, and may be accompanied by chloritoid (Tilley 1925). A large area of such rocks is shown on the one-inch sheet 336 (as ' ottrelite schist ') west of Delabole; together with highly micaceous ' silvery schists ' outcropping nearer the margin of the Bodmin Moor granite these were earlier supposed to mark a wide extension of the thermal aureole of this granite. The rocks, however, are typical products of low-grade regional metamorphism which preceded the emplacement of the granite (Tilley 1925; Phillips 1923).

Glossy grey phyllites are developed in south Cornwall at Dodman Point, and have been traced offshore to the east (Whittard 1962). The highest grade regionally metamorphosed rocks within our area (remembering that we are excluding the Lizard) are the schists of Start Point and Bolt Head (Kingsbridge Memoir, sheets 355/6; Tilley 1923). These are mostly quartz-muscovite-chlorite schists, often with albite, and are much more coarsely crystalline than the phyllites and schists of north Cornwall. They have a strongly lineated structure related to folding about approximately east-west axes (Phillips 1961; Marshall 1962).

Contemporaneous volcanic rocks within the sedimentary succession show rather intense deformation over the greater part of Devon and Cornwall. At low grades they are brecciated and sheared, passing into highly schistose green, brown, and purple rocks with abundant chlorite, actinolite, and epidote. The term ' schalstein ' is used in most of the memoirs of the Geological Survey to describe these altered and now fragmental rocks. Sometimes a distinction can be drawn between lavas and tuffs, but it is not always possible to decide whether some have not arisen by the tearing apart, during movement, of thin sheets of highly vesicular lavas. Many are rich in carbonates; in the Ashprington area, south of Totnes, contemporaneous limestone interdigitates with calcareous tuffs (Torquay Memoir, sheet 350). Keratophyric tuffs may develop abundant sericite.

An horizon of Green Schists of igneous parentage is developed between the Start Point and Bolt Head mica schists. These are chlorite-epidote-albite schists, passing with a slight increase of grade into hornblende-epidote-albite schists. In associated schists of mixed parentage, derived from basic tuffs and developed typically on the margins of the Green Schist horizon, garnet is not uncommon. It has an appreciable manganese content (Tilley 1923), as also does the garnet developed occasionally in some of the phyllites of north Cornwall (Phillips 1928).

The intrusive greenstones, generally much more massive in habit than the contemporaneous igneous rocks, are mostly less radically affected by movement. It is possible, too, that some were emplaced at a stage when the main deformation had ceased (Dearman and Butcher 1959). The rocks tend at first to break up into lenticles within which the igneous textures are still preserved. If there is a marginal development of adinole this may remain adhering to the fragments—the occasional discovery of well-preserved fossils within adinolised sediment emphasises the resistant nature of the metasomatised rock. Original pyroxene breaks down into chlorite and epidote. With further crushing the feldspar becomes granulitised and the igneous textures are obliterated. Ultimately there may be some degree of recrystallisation, with the development of fibrous amphibole. Deformed thermal spots in a phyllite at Tintagel are elongated in a direction parallel to a rough lineation in the adjacent sheared greenstone (Wilson 1951, Fig. 8).

It is evident from this account that regional metamorphism in the south-west attained only a low grade. The occasional appearance of garnet is accounted for by its content of manganese. Biotite shows only incipient development in pelitic scists, and the facies aspect is that of the quartz-albite-muscovite-chlorite subfacies of the Greenschist Facies, verging on the quartz-albite-epidote-biotite subfacies (Fyfe, Turner and Verhoogen 1958).

V. AUREOLES OF THERMAL METAMORPHISM

1. Extent and nature of the zone of contact metamorphism

Each of the outcropping granite masses is surrounded by an aureole of metamorphism. The breadth of the altered zone on a map is determined partly by the nature of the country rock and partly by the angle of slope of the granite surface at the contact. Calcareous rocks, most sensitive to alteration, may show some reconstruction at a considerable distance from a visible contact, as on the north-west of Bodmin Moor and at places around Dartmoor. In typical killas faint thermal spotting may first be visible a mile or more from the outcrop of the granite. If a reasonable average slope of the contact surface is accepted to be about 35° this corresponds to a normal thickness of the zone of alteration, at right angles to the granite, of 3,000 ft. The sheet memoirs of the Geological Survey quote a figure of 2,500-4,000 ft. for the Land's End granite, 2,000-3,000 ft. for Bodmin Moor, and 3,500 ft. for the southern part of Dartmoor. On the north-west border of Dartmoor the thickness is stated to be 1,500 ft. (Dearman and Butcher 1959). When the contact slopes very gently, extending below the present surface at no great depth (Bott, Day and Masson-Smith 1958) a small granite outcrop may be surrounded by a wide zone of alteration. The granites of Kit Hill and Hingston Down have a combined aureole six miles wide, leaving only a few miles of unaltered rock at the surface between it and the Dartmoor aureole in the east on the one hand, and between it and the Bodmin Moor aureole in the west on the other. The wide area of alteration on the north-west of the St. Austell granite, extending past Castle an Dinas and Belowda Beacon, is similarly indicative of the shallow depth of the granite surface. Records of thermal spotting in slates several miles from the nearest granite outcrop indicate the undulating nature of this surface (Hosking 1962).

There are many good exposures of actual contacts on the coast and adequate exposures inland mostly in stream sections. Around Land's End, where a discontinuous fringe of contact rocks is preserved, there is a good exposure at Priest's Cove, south of Cape Cornwall, and several others at intervals northwards to Wicca Pool. The southern end of the Godolphin granite has been exposed by marine erosion and contacts may be examined at the east end of Praa Sands beach, in Rinsey Cove, and west of Megiliggar Rocks (Hall 1930). The small mass of Cligga Head provides a coastal section at its southern contact. Of the inland masses, contacts of the Carnmenellis granite, and of its satellites Carn Brea and Carn Marth, have been seen most frequently during mining operations. The margin of the St. Austell granite is not well exposed, but the Memoir on sheet 347 recorded a contact visible in a quarry on the western edge near Meledor. On the west side of the Bodmin Moor granite exposures of contacts can be found west of St. Breward; the eastern margin is inadequately exposed. Good exposures of actual contacts on Dartmoor can be cited at Leusdon Common and in the River Mardle near Holne.

By examining exposures such as these one is left in no doubt about the sharpness of the contacts. Permeation of igneous material into the country rock is very limited. Veining extends only for a short distance; quarries working road-metal in the aureoles, as at the Gwavas quarry of Penlee Quarries Ltd., can be extended back towards the granite without encountering troublesome veins of 'spar'. There is nothing of the nature of a migmatitic border or zone of feldspathisation—these granites " were almost dead when they arrived in their present position " (Read 1949).

2. **Thermal metamorphism of pelitic rocks**

Faint spotting at a distance from the granite is most readily developed in the finest-grained, most highly pelitic, types of killas. Sandstones may show no spotting whatever even at a stage at which there has been considerable recrystallisation. The first-formed spots in the pelitic rocks do not appear to correspond to any neocrystalline development, but often represent recrystallisation of chlorite or sericitic material. Much of the killas is highly aluminous (Fig. 1) and the first new mineral to be specifically identifiable is often andalusite, which has a widespread occurrence. In the form of chiastolite it is much more restricted, developing typically in a particular type of dark Culm shale at many points in the Dartmoor aureole; it occurs sporadically also in older rocks, both on the south of Dartmoor and in the aureoles of some of the Cornish granites, as on Hingston Down and on the east of the St. Austell granite near Porcupine.

Andalusite is often accompanied by red-brown biotite, which may be the earliest new mineral to develop in pelitic rocks which are chloritic rather than aluminous. Andalusite-biotite hornfels is common in the middle zones of many of the aureoles. At a rather higher grade cordierite is developed in most of these pelitic rocks, and if the composition is appropriate may form more than three-quarters of the hornfels.

The textures of these aureole rocks are highly variable, depending both upon the original lithology and the extent to which the rock has been affected by deformation prior to thermal metamorphism. If there is no marked sedimentary banding, and the parent material has not been much deformed, the biotite may develop a typical criss-cross (decussate) texture (Harker 1950, Figs. 2 and 10). Sedimentary banding, arising for example from alternations of silty and argillaceous laminae, is often preserved as an evident foliation even when the rock has been converted to a medium-grade hornfels. The varying compositions of the laminae give rise to varying mineral assemblages in the hornfels, and it is not until the amplitude of diffusion increases notably, quite close to the contact, that this banding tends to be effaced. The limited diffusion in the earlier grades is indicated by the occasional appearance of corundum in silica-poor laminae closely adjacent to free-silica assemblages. A cleavage or schistosity may sometimes be initially accentuated by the growth of micaceous minerals parallel to the planes of fissility, but may later be effaced in a hornfels which still reveals sedimentary banding.

The highest grades of alteration are found in the dark brown or blue-black xenoliths of killas ('heathen' of the quarrymen) enclosed in granite, which are seen in many quarry-exposures. Those at Lamorna were described by J. A. Phillips in 1880. They have been specially studied in the Bodmin Moor granite by Ghosh (1927) and in the Dartmoor granite by Brammall and Harwood (1932). The commonest types are biotite-rich, but assemblages with sillimanite, cordierite, corundum, and spinel occur, and Brammall records rare dumortierite. Sedimentary banding may still survive for a while, but there is considerable reciprocal reaction between the magma and the xenoliths, which may ultimately become granitised and dispersed. In the ACF diagram, Fig. 1, the analyses of 14 xenoliths are plotted for comparison with those of 27 unaltered, or slightly metamorphosed, country rocks.

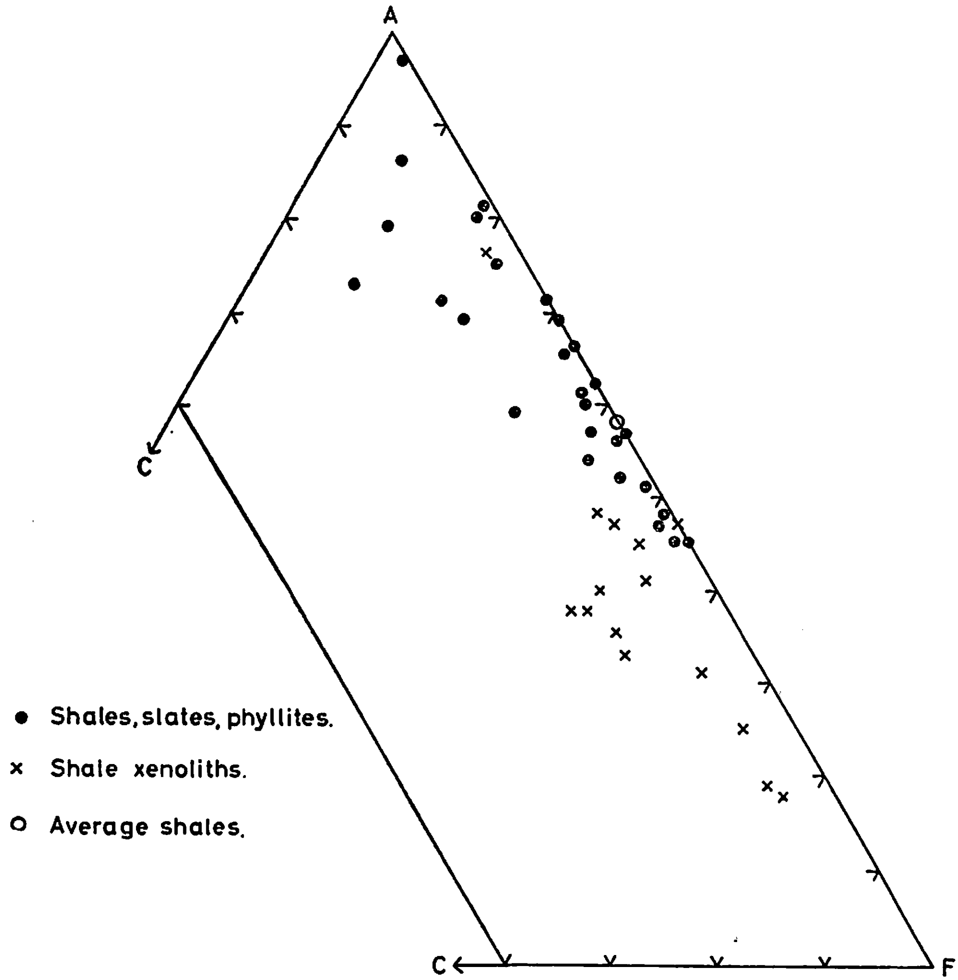

Fig. 1. ACF diagram of shales from country rock and from xenoliths.

3. Pneumatolysis

Introduction of boron into the country rock from the granite is most frequently indicated by the characteristic development of tourmaline. Some small amounts of tourmaline might be formed by reason of an original boron content in the sediment, but there is often a high concentration close to the actual contact. Bawden (1962) found that in the unaltered sediments the boron content ranged from 60 to 460 p.p.m. Near the Godolphin granite the boron content of the thermally altered sediments remained reasonably constant to within a few inches of the contact, but in a tourmaline-rich hornfels the concentration increased by a factor of four or five.

The relationships of the tourmaline crystals to the textures and mineralogy of thermally altered rocks abundantly demonstrate that the development of tourmaline is mainly later than the normal contact-metamorphism. Spotting may still be visible in a slate in which the original minerals have been partly replaced by tourmaline, though it is ultimately obliterated. The aluminous silicates are attacked in turn—biotite, andalusite, cordierite, feldspar—so that the distribution of the newly-formed tourmaline often follows closely original sedimentary lamination. The elongated crystals of tourmaline may have a preferred orientation within the plane of the laminae, producing a fissile tourmaline-quartz schist. The fissility may be increased by the presence of some biotite, and to these rocks the old name 'cornubianite' is applied in many of the sheet memoirs. This appropriate name was redefined in this sense by Bonney in 1886, but it has been used later for a quite different type of metamorphic rock and must now be regarded as obsolete.

Other structures are produced if the tourmaline-forming agents find an easier passage through a tough hornfels than is provided by the bedding-lamination. If the parent rock is jointed, or cleaved, tourmaline may form abundantly along these divisional planes, preserving and emphasizing the original structure of the slate. These contrasting effects are well illustrated in the Bodmin Memoir, sheet 347, Figs. 4 and 3 of Pl. 3, in the former only the original bedding is evident, in the latter a strainslip cleavage is pseudomorphed.

Though tourmalinisation will ultimately destroy all the dark mica, the killas close to the contact frequently contains abundant white mica. De la Beche, in his 1839 *Report*, wrote that "The mica also in many cases appears to have been formed in the altered rock from matter received from the adjoining granite". It seems clear that a process comparable to greisening is indicated, with the transfer of fluorine and possibly of alkali metals to the country rock. A preliminary spectrographic study by Bowler (1958) concluded that there was evidence that F, Rb, Cs and possibly K and Li were available to metasomatise the country rock.

4. Contact-alteration of other types of sediment

Little change is seen in the more highly siliceous members of the sedimentary succession until quite close to the granite contact. The characteristic brown mica develops in the cementing material of argillaceous sandstones; the more pure arenaceous beds eventually undergo recrystallisation; cherts may retain original features until recrystallised to a fine-grained quartzite. A further lithological type which is scarcely subject to any thermal change is the adinolised sediment adjacent to basic intrusions.

It is quite otherwise, however, with sediments which are appreciably calcareous. The major limestone horizons do not extend into the zones of influence of the granites, but at intervals throughout the sedimentary succession, from the Meadfoot Beds of the Lower Devonian to the Upper Devonian and Lower Carboniferous, there are impure calcareous horizons. These may consist of alternations of laminae of calcareous siltstone with argillaceous material or of calcareous lenticles in a matrix of shale or siltstone. These show the effects of thermal metamorphism at a considerable distance beyond the limits of visible change in the killas. They are converted to compact, hard, usually fine-grained siliceous rocks for which the name 'calc-flinta' was introduced in the Geological Survey memoirs (being already in use in Scotland). Earlier terms such as 'porcellanised rock', 'hornstone', and 'ribbon-jasper' convey some suggestion of the somewhat flint-like character of these rocks, a feature which gave rise to the local term 'Sampson-stone' and which made these rocks formerly an important source of road-metal.

A broad zone of calc-flintas is developed in the Meadfood Beds on the north of the St. Austell granite, extending eastwards from St. Columb Major for about ten miles. Closely similar rocks in the Upper Devonian are associated with the Bodmin Moor granite, both on the north-west around Camelford and on the south-east near St. Cleer, and again around Dartmoor extending upwards into the Lower Carboniferous. A typical calc-flinta is banded, on a scale between some tens of inches and a fraction of an inch, the bands differing in grain and also in colour—white, grey, yellow, green, brown, pink, and even almost black. The predominant colour of an individual band is usually due to the presence of some particular lime-silicate mineral in abundance. The pale bands contain such minerals as zoisite or clinozoisite, tremolite, wollastonite, or an almost colourless pyroxene; if garnet or idocrase is present in excess the colour may be pink to yellowish brown; green colours arise from the development of such minerals as epidote, green pyroxene, or a pale amphibole. Darker bands with green amphibole correspond to laminae of calcareous mud in the original sediment.

If the calc-flintas have been within the range of pneumatolytic action a different suite of minerals is characteristic, as illustrated by the occurrences bordering the St. Austell granite. Tourmaline is uncommon, except in some of the non-calcareous pelitic bands. The most abundant calcium-boron mineral is axinite, or much more rarely datolite. Other minerals indicative of the action of emanations are fluorite and occasionally scapolite (Barrow and Thomas 1908, 1909). These minerals are found not only in the body of the rock but also (as in the Camelford area, for example, and in places around Dartmoor) well-developed in pre-metamorphic joints which had become infilled with calcite. In contrast with the typically fine-grained calc-flintas, these pneumatolytic minerals may develop in very coarse aggregates.

The occasional development of sulphides such as sphalerite or pyrrhotite is a link with the more extensive metasomatism which occasionally leads to the formation of a true skarn. The pyroxene tends towards hedenbergite and the garnet towards andradite; the identification and analysis of these minerals in the Dartmoor aureole by Busz in 1900 is a classical contribution. In a few places the replacement of the calcareous rock by iron was almost complete. Impersistent beds of magnetite up to five feet thick, with only small amounts of gangue, were found in the Brent district several centuries ago (Fitch 1932). The magnetite deposits of Haytor have been formed in a similar manner by the metasomatic replacement of calcareous beds in the Culm; the ore is characteristically associated with actinolite and garnet.

The presence of appreciable manganese in the parent sediment leads occasionally to the development of rhodonite, which has been described from a number of localities in both Devonian (e.g. St. Cleer) and Carboniferous (e.g. Meldon). At Treburland. near Altarnun, rhodonite occurs in association with a number of manganese silicates including manganhedenbergite, bustamite, and tephroite, and the paragenesis affords some information on the temperature at which metamorphism was effected (Russell 1946; Tilley 1946).

Non-calcareous pelitic laminae within the calc-flinta successions develop biotite and are converted to a dark, flinty, quartz-biotite hornfels. In marked contrast, another type of lime-free band is pale grey or white and consists almost entirely of quartz and alkali feldspar. In the formation of these it is probable that there has been considerable hydrothermal silicification. The action of siliceous solutions following upon pneumatolysis is indicated by the well-known ' haytorite " pseudomorphs after datolite, but there is unfortunately no direct chemical information on this point. There seems to be in the literature only *one* published analysis of a calc-flinta from south-west England (Bodmin Memoir, sheet 347, p. 101), and even this is clearly not typical of many of these lime-silicate rocks in containing only 4% CaO. A chemical study of these rocks would be informative.

5. **Thermal metamorphism of igneous rocks**

The contemporaneous igneous rocks were mostly greatly altered and in the condition of schalsteins before being subjected to thermal alteration. Calcite was abundant, in the vesicles if these features had not been completely obliterated by shearing or in streaks and bands in a foliated schistose rock. The most abundant ferromagnesian mineral was chlorite, associated with iron oxides, decomposed feldspar, and secondary quartz, and these altered rocks reacted in many respects in a similar manner to the banded sediments which yielded the calc-flintas. An accessible and instructive locality is situated on the east side of the main road at Peek Hill on the flank of the Dartmoor granite. As thermal metamorphism proceeds, biotite begins to replace chlorite, particularly in amygdales. The calcareous bands yield epidote and amphibole, diopside, and grossularite, Recrystallised plagioclase feldspar, at first albite, becomes increasingly lime-bearing. With active pneumatolysis the characteristic mineral is usually axinite, occasionally datolite, rarely scapolite, which develops in the calcareous bands, and tourmaline developing from the biotite.

The intrusive greenstones by reason of their more massive habit have, as we have pointed out, in many places suffered much less deformation than have the contemporaneous lavas and tuffs. An original ophitic texture may be largely retained, with the primary pyroxene partially converted to pale amphibole. The earliest new hornblende is green; it may gradually pseudomorph the pyroxene and preserve for a time the ophitic texture. In higher grades of alteration the amphibole is brown. The plagioclase, at first cloudy with alteration, gradually clears and recrystallises, and more lime enters into it as the grade increases. Sphene develops from ilmenite. Ultimately the igneous texture is obliterated; the feldspar forms a granoblastic mosaic and the toughness of the hornfels at this stage of alteration makes it valuable as roadmetal. The rock worked by Penlee Quarries Limited at Newlyn has an average crushing strength of over 30 tons per sq. in., and the added advantage that it retains a tar coating tenaciously.

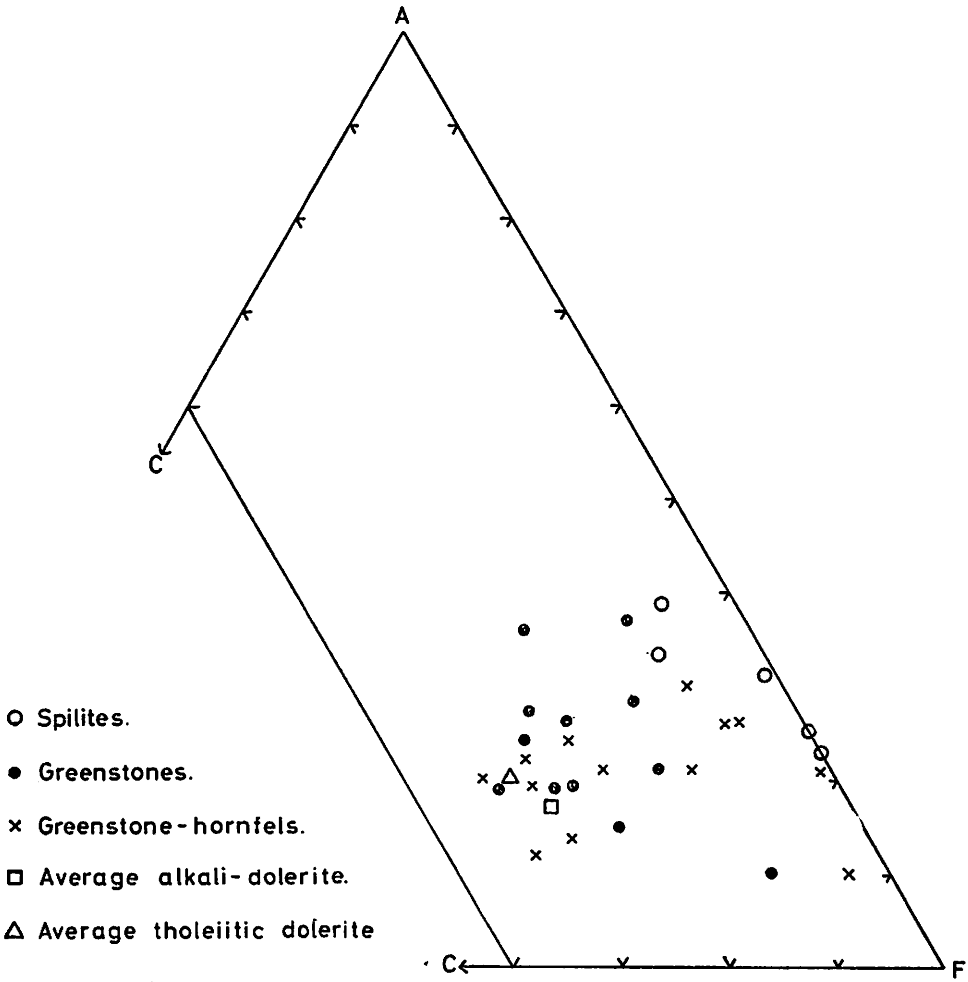

Fig. 2. ACF diagram of igneous rocks and related hornfels.

Greater decomposition of the primary ferromagnesian mineral may have given rise to abundant chlorite in the parent rock, and this may be replaced by a brown mica during contact alteration. The development of this mineral in greenstone-hornfels presents some points of interest. Its formation in preference to a calciferous amphibole would be promoted by loss of lime during weathering before metamorphism, and at first the necessary alkali might be derived from feldspar. Eventually, however, biotite may appear in great abundance, and begin to replace earlier hornblende. A metasomatic introduction of potassium seems to be indicated and has been generally accepted (e.g. Fitch 1932; Tilley 1935; Hawkes 1958; Floyd 1962). Different textural relationships in biotite-bearing greenstones near the Carnmenellis granite were described by Ghosh (1928). From these he inferred that the biotite was an indication of contamination of the basic magma by the country rock at the time of emplacement. Biotite-rich margins might well arise in this way in sills injected whilst the sediments were still largely unconsolidated (Dearman and Butcher 1959).

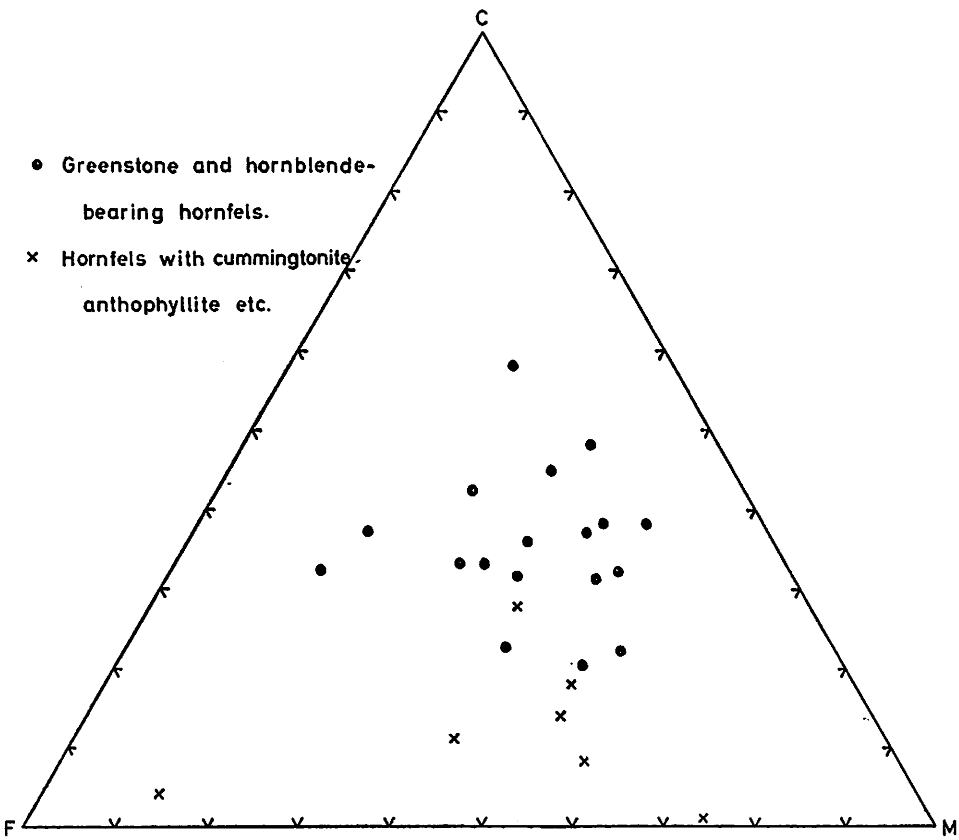

Fig. 3. CFM diagram of greenstones and related hornfels.
[C = $CaO - 3P_2O_5 - CO_2$; F = $FeO - Fe_2O_3 - TiO_2$; M = MgO]

Where the greenstones have been highly sheared before thermal alteration a banded structure is commonly preserved in the resultant hornfels. If the lime is retained, the rocks behave in much the same manner as the schalsteins; lime-silicates such as epidote, grossularite, and diopside may be abundant. The presence of such minerals as axinite, andradite, and hedenbergite is again indicative of pneumatolysis and metasomatism, and as in other calcareous types these minerals may appear at a considerable distance from the contact. Removal of the lime in solution may promote the formation of non-calciferous amphiboles such as anthophyllite and cummingtonite and of cordierite, when the rock is later subjected to thermal metamorphism. An interesting group of dolerite-hornfels of this type from the aureole of the Land's End granite was first fully described by Tilley and Flett (1930); similar types have been described later from other parts of this aureole (Lacy 1958) and occur in minor amounts in other aureoles. Whilst the loss of lime might be due to weathering it seems that this alone could not produce material of the composition of the hornfels. It is suggested that the loss of lime must have occurred during the period of thermal metamorphism as part of a complex metasomatism which involved also the addition of silica and iron oxides (Tilley 1935). The CaO - FeO - MgO relationships of these interesting rocks are shown in Fig. 3. Though many of the Land's End greenstones are highly sheared, the presence of unsheared pillows completely metasomatised shows that shearing is not an essential factor in the process; It may be significant that the Land's End area is one in which, during the formation of the mineral lodes, mineralising agents must have been very active (Lacy 1958).

VI. CONCLUSION

The general aspect of thermal metamorphism in the south-west is that of the albite-epidote-hornfels and hornblende-hornfels facies of contact metamorphism (Fyffe, Turner and Verhoogen 1958). The spotted slates and pelitic hornfels of the outer zones of the aureoles are characteristic of the former, as are the meta-dolerites with albite, chlorite, actinolite, and epidote. The meta-dolerites with hornblende and plagioclase, and the sillimanite-bearing pelitic hornfels, mark an increase of grade to the hornblende-hornfels facies. Diopside appears in calcareous assemblages, but the higher temperatures characteristic of the pyroxene-hornfels facies are scarcely attained even close to the granite contact.

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