SYNOPSES

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Paragenesis of hydrothermal mineralization in amphibolites and granulites around Porthkerris Point, the Lizard, Cornwall

A. F. SEAGER
Department of Geology, Birkbeck College, University of London

A STUDY of the post-metamorphic hydrothermal mineralization in the gabbros of the Lizard has already been published (Seager, 1971). The present paper extends the investigation of mineralization in the peninsula to an adjacent area, on the NE. coast around Porthkerris Point. Table I gives the more important events of the paragenesis. Calcite and adularia are the only common minerals; all others are scarce or rare.

The calcite that precedes and succeeds adularia is called early calcite and late calcite, respectively. Both early and late calcite occur in several generations differing in habit, fluorescence, and phosphorescence. Ortho-serpentine is present as inclusions along a growth horizon approximately 0·5 mm thick in some specimens of early calcite. After the growth of natrolite a phase of dissolution occurred, which particularly affected analcime (Seager, 1978). Subsequently there was a widespread deposition of adularia, which shows varied replacement relationships with analcime. Adularia also formed encrustations upon early calcite and replaced it superficially and along grain boundaries. During the second phase of dissolution early calcite was strongly attacked, converting the encrustations of adularia on calcite to epimorphs. In the subsequent period of mineral formation, several generations of late calcite were precipitated. These crystals developed varied habits, on which many forms have been recorded. Stilbite is a relatively scarce mineral that occurs as small scattered bladed crystals, or as encrustations upon late calcite. The solutions associated with the deposition of stilbite formed solution channels in calcite, and appear to have caused some metasomatism in that mineral.

TABLE I. *Paragenesis of the hydrothermal mineralization at Porthkerris**

Green and white botryoidal prehnite	Early calcite
Analcime	
Natrolite	
Dissolution and removal of some analcime	
Adularia	
Quartz	
Dissolution of some early calcite	
Late calcite	
Stilbite	
Dissolution channels in calcite formed during growth of stilbite	

* This is an abbreviated version of the table of paragenesis in Miniprint section.

Discussion. The character and mineral content of the veins indicate their hydrothermal origin, and the cross-cutting relationship to the foliation proves that mineralization post-dates metamorphism. Several aspects of the paragenesis have significance for the interpretation of the geological history of the area. There is a noteworthy alternation of periods of mineral formation and dissolution in amphibolites and granulites at Porthkerris. This phenomenon, the sequence of mineral formation and the modes of crystal growth of several minerals show a striking similarity to the paragenesis in the gabbros of Dean quarry (Seager, 1971). The most satisfactory explanation is that the mineralization in both areas took place simultaneously, by precipitation from the same series of hydrothermal solutions. These two parageneses were based on studies in limited areas, because suitable specimens were obtainable there. However, there is ample evidence that hydrothermal mineralization is widespread in the Lizard complex. Many occurrences of minerals of the prehnite-zeolite-calcite suite have been recorded from metabasic rocks (Holyer, 1972). Prehnite, analcime, natrolite, and calcite occur in the Traboe hornblende-schists on the west coast, approximately 16 km from Porthkerris, on the opposite side of the peninsula. These minerals also occur in a gabbro quarry on the east coast at Porthoustock, and natrolite has been found at the contact of an epidiorite dyke with serpentinite. Adularia occurs at many localities around the coast of the Lizard peninsula, in the Traboe and Landewednack hornblende-schists, gabbros, and rocks of the Old Lizard Head Series. The serpentinites have been examined by the present author for evidence of hydrothermal alteration, which appears to be widespread; it is present in many outcrops around the coast, and at quarries inland. The veins consist mainly of hydrous magnesium minerals and calcite, rarely containing hematite or silica minerals. No trace of prehnite, zeolites, or adularia has been found. Thus post-metamorphic hydrothermal mineralization is present in the major rock suites on a scale that appears to justify the description of regional mineralization in the Lizard complex.

Some evidence is available of the date of hydrothermal mineralization in the Lizard peninsula. Adularia occurs *within* the parageneses of the mineralization in the gabbro at Dean quarry and in the granulites and amphibolites around Porthkerris. Close minimum ages of crystallization for adularia from these localities have been determined as 201 ± 4 Ma and 211 ± 2 Ma respectively (Seager *et al.*, 1975, 1978). Halliday and Mitchell (1976*a*) dated specimens of adularia from these and other localities in the Lizard complex, and suggested that its crystallization took place during a hydrothermal event at 210-20 Ma. The adularia, which is common to the two parageneses quoted above, thus appears to have been formed during the same event. Adularia from Holseer Cove yields evidence of another hydrothermal event at 160-70 Ma (Halliday and Mitchell, 1976*a*). A specimen of adularia from Dean quarry, which appeared to have suffered hydrothermal alteration, gave an apparent age of 147 ± 3 Ma. If partial overprinting is present, it would have taken place in Cretaceous or Tertiary times (Seager *et al.*, 1975, 1978). Adularia is the only mineral from the hydrothermal suite that can be used for dating in the Lizard. Since adularia occurs within the paragenesis, no hydrothermal events that preceded its crystallization have been dated, and there is little evidence of the date of subsequent events. It is tentatively suggested that the parageneses established at Porthkerris and at Dean quarry may indicate that hydrothermal activity extended over a distinctly longer period than the formation of adularia. It is most desirable that means be sought to date the several phases of hydrothermal activity, in order to place events in the Lizard in their regional setting.

Many aspects of primary mineralization in south-west England have been reviewed by Hosking (1964). It was noted that mesothermal veins (with which he included some epithermal veins) are widespread, but are usually comparatively small and uneconomic, mineralization having occurred during two or three periods separated by large intervals. Most activity was related to the Late Jurassic and/or Tertiary igneous phase. The Jurassic and Tertiary activity wrought mineralogical changes largely by remobilization of earlier components, rather than by introducing large quantities of 'new' ore components. The crosscourses may contain a mesothermal suite of minerals, barren quartz, or fault clay. The clay-filled crosscourses were the last to be formed.

A study of uranium mineralization in south-west England led Darnley *et al.* (1965) to conclude that there were periods of uranium mineralization at *c.* 290 Ma, *c.* 225 Ma, and *c.* 50 Ma and probably at *c.* 165 Ma. The younger ages were derived from lower-temperature minerals in NS veins. There are several different vein fillings at Geevor mine, west Cornwall, and the time interval between their formation may be of the order of tens or one or two hundreds of millions of years. ^{40}Ar-^{39}Ar step heating studies suggest that a hydrothermal event occurred at Geevor mine close to 210 Ma, and a K-Ar age determination of a quartz-tourmaline-cassiterite stringer gave an age about 165 Ma (Halliday and Mitchell, 1976*b*).

Several aspects of the hydrothermal activity in the Lizard appear analogous to that in adjacent areas. The alternating periods of mineral formation and dissolution suggest that mineralization occurred in pulses. The periodic access of solutions to veins has been demonstrated elsewhere in Cornwall. The growth of adularia in the Lizard at 210-20 Ma virtually coincides with a period of uranium mineralization and another hydrothermal event at Geevor mine in Late Jurassic times. Adularia was preceded by the formation of prehnite, analcime, natrolite, and some calcite, as well as a phase of dissolution, which may be Late Jurassic or earlier in age. There were two periods of dissolution and one of mineralization after the formation of adularia, the overprinting of which may indicate a Cretaceous or Tertiary event.

Hydrothermal solutions, which introduced little or no new material, but altered and redistributed existing minerals, could account very satisfactorily for the type of mineralization found in the Lizard, in which the mineral composition of veins is closely related to the chemistry of the country rock. If some means can be found of dating other stages of mineralization in the Lizard complex, it may be possible to use the detailed parageneses already established for the mineralization at Dean quarry and at Porthkerris in a comparative study of phases of hydrothermal activity throughout south-west England.

The full text appears in the Miniprint section, pp. M49-59.

REFERENCES*

Darnley (A. G.), English (T. H.), Sprake (O.), Preece (E. R.), and Avery (D.), 1965. *Mineral. Mag.* **34,** 159-76 [M.A. 17-121].

Halliday (A. N.) and Mitchell (J. G.), 1976(*a*). *Earth Planet. Sci. Lett.* **29,** 227-37 [M.A. 77-1290].

Hosking (K. F. G.), 1964. *In* Hosking (K. F. G.) and Shrimpton (G. J.) (eds.), *Present views of some aspects of the geology of Cornwall and Devon.* R. geol. Soc. Cornwall, 201-45 [M.A. 17-650].

Seager (A. F.), 1967-8 [1971]. *Trans. R. geol. Soc. Cornwall,* **20,** pt. 2, 97-113 [M.A. 72-3370].

—— 1978. *Mineral. Mag.* **42,** 245-9.

* Additional references are given in Miniprint section.

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Pyroxenes of basic rocks and rodingites from an ophiolite mélange, south-eastern Turkey

ROBERT HALL

Department of Geology, Queen Mary College, London University, London E1 4NS

OPHIOLITIC rocks occur as a tectonic mélange in the Mutki area of the Eastern Taurus Mountains of south-eastern Turkey. They form the upper part of a Tethyan ophiolite-flysch complex, which is thrust southward over sedimentary rocks of the Arabian foreland (Hall, 1976). The tectonic mélange has a matrix of serpentinite and includes blocks of basic volcanics, gabbros, picrites, and rodingites, most of which have suffered metamorphism and metasomatism. The volcanic rocks have been metamorphosed under conditions transitional between the glaucophane-lawsonite schist facies and the greenschist or greenschist-amphibolite transitional facies of Turner (1968). The picrites have escaped any significant metamorphism, while the gabbros have been partially or completely recrystallized under greenschist facies conditions. Both picrites and gabbros have also suffered calcium metasomatism resulting in the alteration of some of the gabbros to rodingites. Pyroxenes from eight separate blocks from the mélange have been analysed by microprobe (fig. 1) to determine if the pyroxene

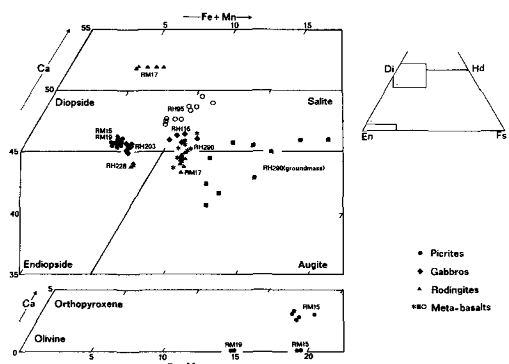

FIG. 1. Composition of clinopyroxenes, orthopyroxenes, and olivines from the mélange rocks.

chemistry is consistent with an igneous origin (as suggested by textural evidence) or if there have been changes due to metamorphism and metasomatism.

None of the blocks examined is completely unaffected by alteration or recrystallization, yet

PARAGENESIS OF HYDROTHERMAL MINERALIZATION IN AMPHIBOLITES AND GRANULITES AROUND PORTHKERRIS POINT, THE LIZARD, CORNWALL

A. F. Seager

Department of Geology, Birkbeck College, 7/15 Gresse Street, London W1P 1PA

The paragenesis of hydrothermal mineralization in the gabbros of Dean quarry, on the east coast of the Lizard peninsula, has been described (Seager, 1971). North of the gabbros the Landewednack hornblende-schists and Traboe hornblende-schists (Flett, 1946), crop out between Porthallow (SW 72 and part of SW 82, 797232) and Porthoustock (806218). Nearly 1 km east of Porthallow is the headland of Pedn Tiere: for 0.5 km southwards, to Porthkerris Point and Porthkerris Cove, there are good exposures in disused quarries, from which most of the specimens for this study were obtained, although the section has been examined to the faulted junction with gabbro at Porthoustock, 1 km further south. These hornblende-schists were divided into four metamorphic assemblages by Green (1964*a*); two of them fall in the almandine-amphibolite facies and two in the granulite facies. One assemblage in the almandine-amphibolite facies corresponds to the Landewednack hornblende-schists, and the other three assemblages constitute the Traboe hornblende-schists, interpreted by Green as a high-temperature aureole of the Lizard peridotite. It has been stated that a transition exists between the Landewednack and Traboe hornblende-schists in the neighbourhood of Porthallow and Porthkerris (Green, 1964*b*). The coastal region around Porthkerris Cove and Porthkerris Point will be referred to as 'Porthkerris'.

Vein systems follow joints, many of which intersect the foliation at large angles, indicating that mineralization was subsequent to metamorphism. The veins are typically less than 10 mm thick and contain cavities lined with crystals. Adularia and calcite are abundant, but all other minerals are scarce or rare.

Description of mineralization

Botryoidal prehnite

Only about 250 mm^2 of a botryoidal prehnite vein surface has been found; this colourless to pale green prehnite is associated with analcime and calcite, enabling their relative periods of formation to be determined. The analcime is clearly later than prehnite, growing over the botryoidal masses.

Botryoidal prehnite is adjacent to calcite (figs. 1*a*, *b*). The calcite (fig. 1*a*) exhibits irregular solution-ridges, and a solution-gap (arrowed) has been formed between calcite and prehnite. The junction has been exposed in part by the natural solution of calcite (fig. 1*a*) and elsewhere by the mechanical removal of calcite. Although the calcite is bounded by sculptured solution-forms, reflections indicate the presence of the domains of three crystals of calcite. The botryoidal prehnite adjacent to the solution-ridges has plane facets, some parallel, others with re-entrant angles, which suggests that the prehnite grew around euhedral calcite. The other two crystals of calcite both show a dual relationship to prehnite. The shape of the prehnite surface on two botryoidal masses suggests that it was growing simultaneously with calcite, but on two other masses the artificial removal of calcite revealed the normal morphology of the surface of botryoidal prehnite, indicating that calcite was definitely later than prehnite in these areas. The calcite on this specimen appears to have been growing before, during, and after the formation of prehnite. All of this calcite is believed to be early calcite: there are no signs of growth zoning, change of colour or transparency, or zoning of fluorescence. The existence of prehnite veinlets in this calcite also suggests that no late calcite is present.

Minute, irregular, apparently discontinuous veinlets of colourless, transparent prehnite are left as projections in several areas where the calcite surface has been lowered by solution. Much of this prehnite seems to grow along grain boundaries, which probably accounts for its irregular morphology. Only a minute quantity of this variety of prehnite has been found.

In some of the very transparent botryoidal prehnite, there are small white, subtranslucent spheres around the point from which the individual crystals radiate (fig. 1*b*). On old fractures a cream-coloured to pale yellow pulverulent material, with much space between the particles, is found at the centre of each botryoidal mass and extends radially along inter-crystal boundaries in a few cases (figs. 1*b*, *c*). The pulverulent material is dark (fig. 1*c*), due to its low reflectivity. On fresh fractures the core is largely hollow, with a small quantity of white or yellowish powder which appears to be a decomposition product, but powder photographs show only the presence of prehnite. The high proportion of pore space indicates that some prehnite has been removed by dissolution. This probably commenced at the nucleation points of the botryoidal aggregates, due to their higher surface free energy.

Euhedral tabular prehnite

A specimen *c.* 90 x 140 mm has a vein of prehnite which follows two joint directions. The vein has extensive cavities in which euhedral crystals of prehnite are developed (fig. 1*d*). The crystals are thin-tabular on {001} and bounded predominantly by {110}; {010} is often well developed, but may be absent, and small faces of {100} occur on some crystals. Forms are referred to the axial ratios $a:b:c$ = 0.843:1:3.378. The faces of {100} and {010} are rough. The basal pinacoid is striated in the direction [010] and the striations appear to be composed of minute elements of {108}. Small faces of {011} are present, as well as very narrow, rough, striated faces of one or possibly more forms {*hhl*}, the symbols of which could not be determined. The crystals are white or pinkish, the largest being approximately 2 x 2 mm.

A grain of colourless, highly corroded quartz, about 5 x 3 mm, occurs within the vein, and is bounded by euhedral prehnite on both sides. The quartz appears to be later than the prehnite, but there is no other indication of its position in the paragenesis.

No evidence has yet been obtained to indicate the relative age of the various forms of prehnite. Euhedral tabular prehnite has been assigned to a similar position in the paragenesis as botryoidal prehnite, as it probably formed in a similar temperature range.

Early calcite

The relative dating of periods of calcite formation at Porthkerris is not easy, since adularia and calcite are the only common minerals and little of the calcite is seen in contact with the scarcer minerals. Initially, a simple division will be made of calcite which pre-dates or post-dates adularia, to be called 'early calcite' and 'late calcite' respectively. There appear to have been several generations of early calcite, indicated by its relationship to other minerals and variation in its crystal habit. For example, some crystals of calcite grew before analcime; a euhedral crystal with brilliant faces was exposed within a broken crystal of analcime, and such calcite grew from the vein wall. Some crystals of calcite may have grown simultaneously with analcime. It is difficult to determine how many generations of calcite preceded adularia, because the early calcite suffered severe dissolution at a later date, so that it is often impossible to determine crystal forms and habits. The difficulty is increased by the frequent overgrowth of late calcite on early calcite. Some early calcite has superficial films of hematite, ranging from a fairly thick encrustation to a fine impalpable pink layer. Similar fine layers occur as phantoms within transparent early calcite, and hematite, with a trace of ortho-serpentine, is also present in pink, turbid growth zones. The hematite films were probably deposited before analcime, because some calcite with thick films occurs in close association with analcime, on which these films are absent. A hematite film makes a clearly visible marker horizon between the early and late calcite, when the latter forms orientated overgrowths on the former. A few specimens of early calcite have loosely to densely packed inclusions along a growth horizon approximately ½ mm thick. The inclusions in some specimens proved to be an almost pure ortho-serpentine, but in others a clay mineral was also present. The inclusions may be pale pea green in colour but can vary, even along the length of a zone, from buff to pale pink to deep orange. Hematite and a little ortho-serpentine were present in the orange-coloured specimens. Cleaved crystals of calcite containing a zone of these inclusions showed that the early phase of growth had a high degree of structural perfection; at the zone of inclusions, and for a small distance beyond it, a moderately fine-grained mosaic structure developed. There is a transition to a mosaic structure with a much larger grain size in the outer part of the crystal, with many of the sub-grain boundaries orientated at large angles to the growth surface. As growth proceeded from the zone of inclusions, grains in unfavourable orientations were eliminated through geometrical selection (Grigor'ev, 1965).

Analcime

Analcime is a relatively scarce mineral, which has been found mainly in the area of Porthkerris Point. The only form developed is the trapezohedron {211}. Most crystals are white and sub-translucent, but colourless, very transparent analcime has also been found. Crystals up to 20 mm diameter are known, but they are usually smaller. Sections through some crystals of analcime show early calcite in contact with the wall rock and analcime partly or completely enclosing the calcite. Some specimens have bright orange adularia and snow-white, partly altered analcime; the adularia grows around and on the surface of analcime, without penetrating it (figs. 1*e*, 2*a*). Where crystals of analcime and late calcite are in

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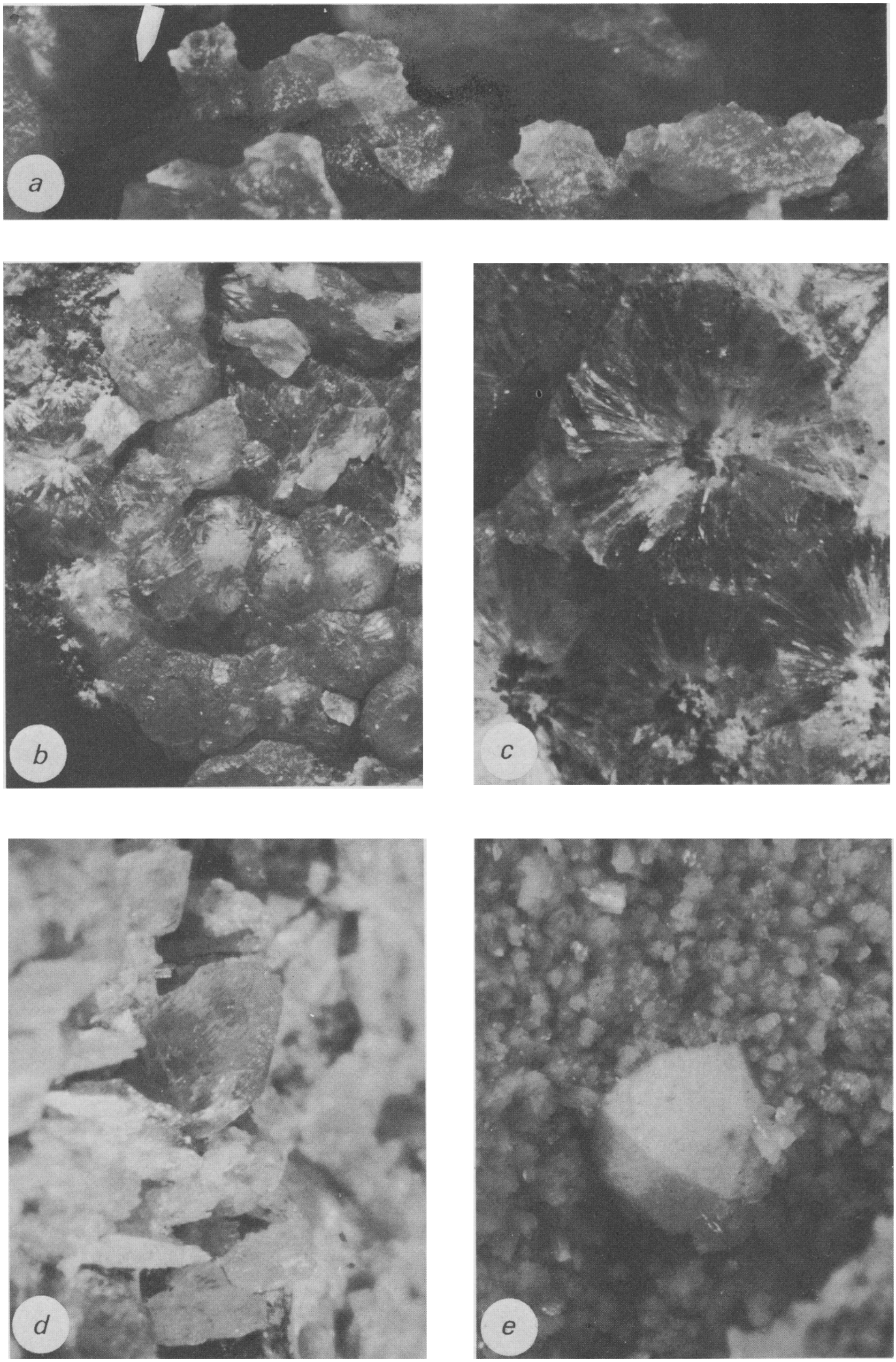

contact, the former are euhedral and evidently earlier. Stilbite occurs very sparingly on analcime.

Most of the analcime has suffered some degree of dissolution or decomposition. No evidence has been found at Porthkerris of the details of the process: whether the mineral was dissolved or whether decomposition occurred with the removal of soluble or insoluble products. No alteration products of analcime have been found in the crystals or traced with certainty in the vein system, with the possible exception of minute amounts of ortho-serpentine in analcime. Montmorillonite is an abundant alteration product of analcime in the gabbro at Dean quarry (Seager, 1971), so it has been sought specifically within the analcime at Porthkerris, but has not been found. A remarkable feature is the high resistance to attack of the surface of the crystals. There is obviously some difference in the physical or chemical properties (or both) of the last portion of the crystal to grow, comprising an outer layer or series of layers with a maximum thickness of about 1 mm. Dissolution of analcime leads to the formation of cavities, which differ markedly in character between those in the surface layers and those in the deeper interior. In the former the attack is frequently differential along successive growth horizons, leaving a series of very thin plates parallel to faces of the trapezohedron. In the deeper interior there may be small to large irregular cavities, boxworks of thin films or fine granular material. Where crystals of analcime have been broken from the surface of the wall rock part of this outer layer of the analcime crystals usually remains attached to the rock as a coherent white rim (fig. 2*b*). These broken crystals demonstrate two other features. Although the surface of the amphibolite or granulite around the analcime may be thickly covered with crystals of adularia, as on this specimen, the rock surface beneath the analcime is completely free of them, nor are any embedded in the crystal which has been removed, adding further proof that adularia post-dates analcime. Only part of the analcime had been broken off the matrix on one specimen, and through the portion which remained there projected an uncorroded crystal of early calcite.

Detailed evidence has been obtained that analcime suffered dissolution before the deposition of adularia. An account of this study has been published separately (Seager, 1978).

Natrolite

Natrolite was found on two small specimens near Porthkerris Point. Divergent prisms of natrolite, which grew towards analcime, terminated against it, showing that the latter preceded natrolite. Some calcite is also present; this has retreated from the contact, through dissolution, and has the appearance of the early calcite associated with botryoidal prehnite (fig. 1*a*). A radiating group of natrolite prisms terminates in plane surfaces, which appear to represent the former contact with euhedral calcite. The virtually identical morphology of the dissolution ridges in calcite associated with natrolite and botryoidal prehnite suggests that the calcite has the same age and origin in both occurrences. The calcite which preceded natrolite thus appears to be early calcite.

Adularia

This is an extremely common vein mineral at Porthkerris; crystals have a very simple habit, with the prism {110} terminated by the basal pinacoid. Carlsbad twinning is often present with partial interpenetration on {100}; the prominent re-entrant angles formed by {001} thus presenting a 'swallow-tail' appearance. Crystals range up to about 2 mm in length, elongated in the direction [001], and the ratio of length to breadth is approximately 3:1. Some crystals are absolutely colourless and pellucid, so fresh, in fact, that growth layers can easily be seen on faces of both forms. When coloured, there seems to be a continuous gradation from the faintest tint to a fairly deep pinkish-orange or orange; deepening colour is associated with decreasing transparency, the darkest crystals being quite turbid.

Fig. 1 (opposite). *a*: Dissolution-ridges in calcite, showing gap at former calcite-prehnite junction (arrowed). x17. *b*: Botryoidal prehnite with white cores (below centre), a fractured group (left), and a solution-gap between prehnite and calcite (dark band, centre top, with calcite on the right).x6. *c*: Broken botryoidal masses of prehnite with porous cores (the cores look dark, due to low reflectivity). x19. *d*: Part of a vein of tabular euhedral crystals of prehnite. x16. *e*: Trapezohedron of analcime surrounded by orange adularia, three crystals of which grow on the analcime. x18.

Evidence has been sought to determine whether one or more generations of adularia are present. In several specimens small crystals have been observed on the sides of larger prisms, but it has not been possible, so far, to prove that they belong to a later generation of adularia crystals, rather than a fresh nucleation towards the end of a single phase of deposition. There does not seem to be any indication that other mineral species have formed within this phase of deposition, which would give grounds for its subdivision. A single phase of deposition appears to be confirmed by the fact that, on one vein surface, small, colourless crystals of adularia pass laterally into large, turbid orange ones by imperceptible gradations. Partial analyses were carried out by A. J. McCord. Calcium and sodium were determined by flame atomic absorption spectrophotometry, and potassium by flame emission spectroscopy. The results, given in weight %, show that the adularia has a characteristically high potassium content.

	K_2O	Na_2O	CaO
Pale pink, slightly turbid crystals (L.47/1)	16.7	0.09	<0.01
Colourless, transparent crystals (L.47/29)	16.7	0.11	<0.01

Veins containing adularia cut the foliation of the country rock at large angles, and in at least one case intersect a vein of quartzo-feldspathic gneiss in the amphibolite or granulite. The hornblende-schists are injected by veins of pinkish, acid, feldspathic rocks, the age and origin of which are problematical† (Flett, 1946).

†The occurrence of pegmatite gneiss veins at Porthkerris is recorded in a marginal note on a manuscript copy of the 1:10560 geological map in the library of the Geological Museum.

Adularia occurs principally on the rock forming the vein walls (figs. 1*e*, 2*a*), and rarely nucleated on the surface of analcime (fig. 1*e*). Adularia displays a variety of relationships with analcime, including superficial replacement (Seager, 1978).

Adularia also exhibits varied relationships with early calcite.

1. Adularia nucleated on early calcite, forming complete encrustations or scattered crystals. The latter show evidence of directional deposition on some specimens.
2. Veins sensibly free of voids contain early calcite, bordered on one or both sides with bright orange, turbid adularia: veinlets of adularia also cut the calcite.
3. Adularia has been deposited metasomatically along grain boundaries in early calcite, forming thin irregular veins.
4. A few examples have been found in which adularia has replaced the surface of euhedral early calcite to a depth of a fraction of a millimetre, incorporating the dust-like film of hematite previously formed on the calcite.

On a broken crystal of early calcite (fig. 2*c*) the two faces on the right (medium and dark grey), which have a film of hematite, have been superficially replaced by adularia. The upper face still retains the original growth striations of the calcite. The crystal was probably completely encrusted with euhedral adularia growing outwards from the calcite surface, as part of a broken encrustation still remains towards the bottom and lower right-hand side of the crystal.

Part of another crystal of calcite has been superficially replaced by adularia (fig. 2*d*), preserving the growth striations of the calcite and incorporating the fine film of hematite upon it. Only a thin fragmentary shell remains, the cavity within demonstrating the dissolution of early calcite after formation of adularia, and the subsequent growth of euhedral late calcite. On specimens showing the encrustation of early calcite by adularia, the former mineral has suffered dissolution in varying degrees. It seems probable that this process has been more extensive in some areas, leaving epimorphs of adularia, or their broken remnants. The plane inner surfaces of the epimorphs indicate that the early calcite was still euhedral when enclosed by adularia, and had not suffered dissolution at that time. In some specimens a few euhedral crystals of adularia project into the interior of the epimorph from its smooth inner surface. Early calcite may be surrounded by adularia growing on the rock matrix, and some specimens show partial retreat of calcite from the contact by dissolution. It is also possible to find rock surfaces otherwise thickly invested with adularia which have scattered areas completely free of that mineral (fig. 4*a*). Many of these areas are bounded by steep, plane surfaces of adularia. From the evidence of the partial dissolution of early calcite described above, these are believed to represent areas in which the calcite has been completely removed at some period after the formation of adularia.

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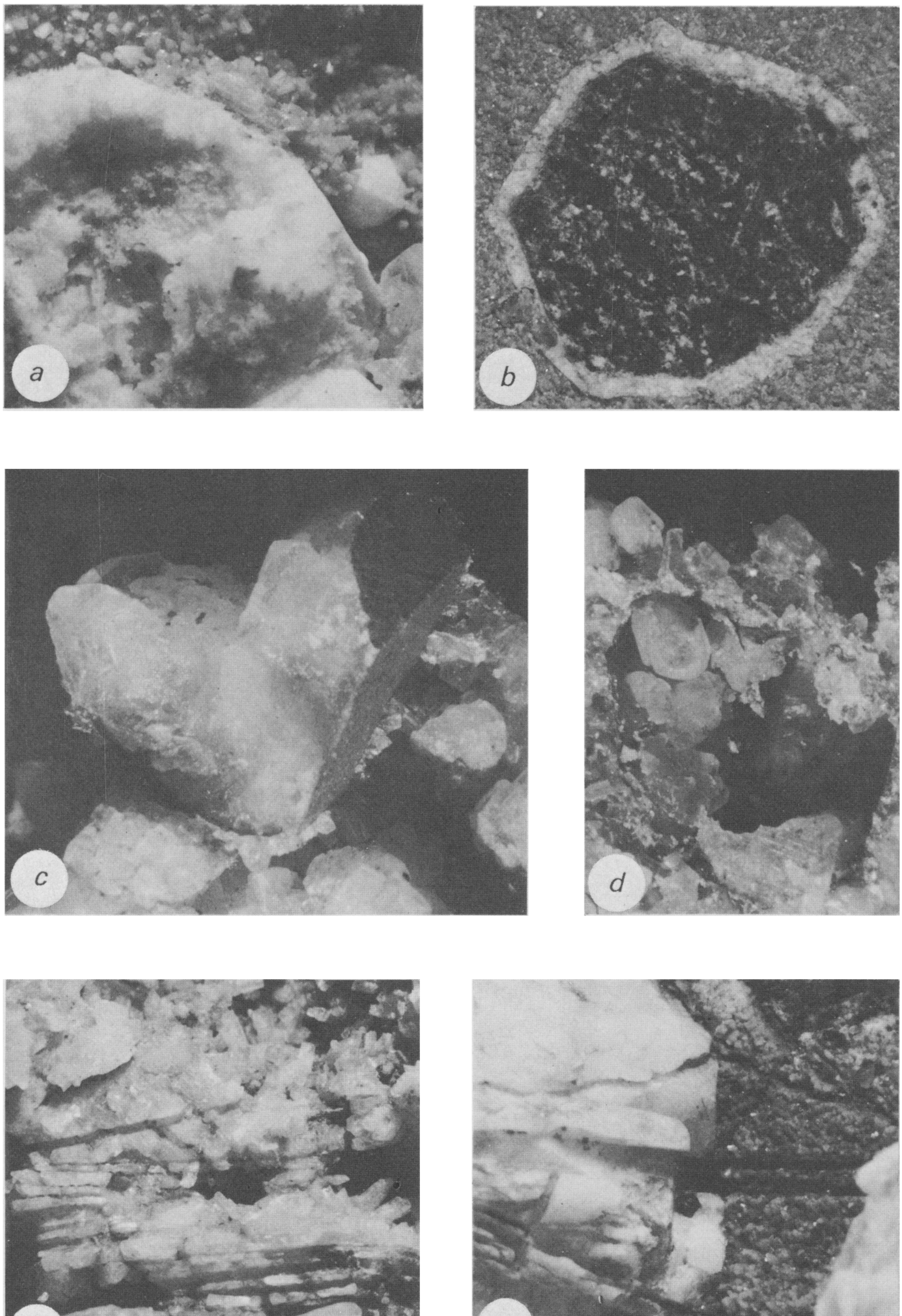

'Hacked' structures

These structures are planar cavities, which appear to be due to the former presence of crystals of thin tabular habit around which other minerals have grown, subsequent removal of the tabular crystal leaving planar cavities. Hacked structures traverse, without deviation, several crystals of one mineral in different orientations, or crystals of two or more minerals. These structures can thus be distinguished from other types of planar cavity, such as preferential dissolution along cleavage planes of calcite or {211} planes in analcime.

Hacked structures in the veins of Porthkerris occur frequently in adularia, occasionally in analcime, and rarely in early calcite and quartz. In the commonest and simplest type of occurrence, small euhedral crystals of adularia form an almost uniform thin layer over the surface of the wall rock, interrupted by a rectilinear pattern of dark lines where adularia is absent and the rock is exposed. The lines may form parallel, sub-parallel or divergent groups, and other lines or groups of lines may be present nearby in completely different orientations. In another specimen of adularia the crystals causing the hacked structure have not reached the rock surface, since adularia is present in the deepest part of the grooves, but the morphology of the adularia has been determined by the crystals formerly present (fig. 2*e*). Adularia also occurs in groups of very thin parallel or sub-parallel plates, the spaces between which vary from *c.* 1 mm to <0.1 mm. These plates show no sign of the typical prismatic habit of adularia, although such crystals may be present in close proximity to the plates. It is inferred that the thin plates of adularia grew in the spaces between the tabular crystals.

Hacked structure also occurs in analcime (fig. 2*f*). There are two 15 mm crystals of analcime, 8 mm apart, with small crystals of adularia between them. Hacked structures are present in several orientations in the adularia, exposing the rock beneath. One of the noteworthy features is the hacked structure, 16 mm long, which passes from the adularia to the analcime without any interruption or deflection. This penetrates the analcime to a depth of about 1 mm and extends to a height of 10 mm above the rock surface.

It has been difficult to establish whether hacked structures exist in the early calcite. Few crystals show structures like them, and subsequent dissolution tends to obliterate many features. One crystal of early calcite has adularia upon it which exhibits well-developed hacked structure, and there are grooves and ridges in the calcite substrate parallel to those in the adularia. This is believed to be an example of hacked structure, because the grooves and ridges in the calcite are not parallel to the traces of any cleavage directions or glide planes which could have produced features similar in appearance by etching. The grooves in the calcite are quite shallow, and do not reach the wall rock.

The shape and disposition of the cavities in hacked structures could be due to a mineral which grew in parallel, sub-parallel, divergent or less regular groups of thin platy crystals, which will be called the unknown tabular mineral. These aggregates must have had a minimum length of several tens of mm and height of *c.* 10 mm. It is envisaged that the aggregates nucleated on the vein wall, but, as they grew, the ends of some of the plates could have risen above the surface of the vein. Some aggregates may have grown until they approached the opposite wall of the vein or made contact with it. Dissolution of the unknown tabular mineral in contact with the vein wall would produce one of the commonest types of hacked structure in adularia (fig. 2*f*). The complete penetration of adularia and partial penetration of analcime in this fig. may have been due to the unknown tabular mineral having nucleated on the rock between the crystals of analcime, the raised ends of the plates partly penetrating this mineral. However, it seems more probable that these structures were caused by the unknown mineral growing from the opposite wall of the vein. This certainly seems to be the explanation of some hacked adularia (fig. 2*e*), in which penetration is not complete, and adularia is present at the deepest part of the grooves.

A search has been made for traces of the unknown tabular mineral, or for any evidence from which it could be identified. One specimen has two sheaves of crystals apparently of appropriate morphology, 20 and 25 mm in length, and both proved to be quartz which had grown upon adularia (fig. 3*a*). Since the form of the sheaves was atypical of quartz, they were initially assumed to be pseudomorphs after the unknown tabular mineral, but the sheaves later proved to be virtually single crystals of quartz. Both sheaves had some adularia with hacked structure immediately adjacent to them; cavities in the adularia appeared to be aligned with those in the quartz, and plates of quartz with ribs of adularia. The quartz sheaves thus appear to exhibit hacked structure caused by growth of the unknown tabular mineral from the opposite wall of the vein. Supporting evidence is found in the fact that the smaller quartz sheaf (fig. 3*a*) is only 7 mm from the hacked adularia shown in fig. 2*e*, to which the same origin has been ascribed. The quartz sheaves must have grown after adularia, upon which they were situated, but prior to removal of the unknown tabular mineral, which caused their hacked structure. It has proved impossible, so far, to find any trace of the unknown tabular mineral, or to identify it by indirect evidence. It is suspected by the author that the original mineral may have been prehnite, somewhat resembling in form the 'pale brown tabular prehnite' described from the gabbro of Dean quarry, in the Lizard (Seager, 1971), but this has not yet been verified.

Hacked structure has been found in early calcite, analcime, adularia and quartz, which were formed in that order. It has not been observed in prehnite, but this mineral has been found in such small quantities that the absence of hacked structure cannot reasonably be used as positive or negative evidence of its occurrence in prehnite, and it is advisable to regard the question as being unsettled. The unknown tabular mineral has affected early calcite, but there is no evidence to show whether it actually preceded all early calcite. The tabular mineral could have grown before, during or after the formation of prehnite and has been placed provisionally at the head of Table I.

Late calcite

The term 'late calcite' embraces all calcite which was deposited later than adularia. Late calcite is a relatively abundant mineral, the crystals of which are usually colourless and transparent, but it may be white and turbid, or tinted yellow or orange. Crystals rarely exceed 10 mm in size. The {01$\bar{1}$2} parting is developed occasionally. Much of this calcite is fluorescent and some is phosphorescent.

Late calcite grew crystallographically orientated on early calcite, or nucleated independently elsewhere in the veins. Some crystals of early calcite which have hematite coatings were only partly overgrown by late calcite, making the distinction of generations obvious. When a hematite coating is absent there may be no clear indication that one generation of calcite has overgrown another. If the early calcite has some adularia upon its surface, but is not entirely encrusted, late calcite may still have grown upon the early calcite in crystallographic continuity, but shows gross imperfections where the adularia is present. Late calcite formed by independent nucleation often occurs on adularia lining the vein walls. Some late calcite grew up to analcime and partly enclosed it, but does not seem to have nucleated upon it.

Morphology of the late calcite

A considerable number of forms and habits have been developed, but it is difficult to determine the forms in many cases due to solution, weathering, striations or overgrowths. It has not yet been possible to place all the varied habits in a paragenetic sequence, owing to lack of association. Scalenohedra dominate the habit of most crystals. In the simplest habit a single scalenohedron is terminated by small faces of {10$\bar{1}$1}; some crystals have two scalenohedra as the only forms developed, and others have two or more scalenohedra in combination with several rhombohedra. One such crystal has {21$\bar{3}$1} and {31$\bar{4}$2}, a terminal rhombohedron {10$\bar{1}$1} with larger faces of {50$\bar{5}$2}, interrupted with fine striations of {70$\bar{7}$5} and coarser striations of {40$\bar{4}$1}. A very similar crystal (lacking {70$\bar{7}$5}) has the terminal edges of {10$\bar{1}$1} bevelled by {11$\bar{2}$3}. Each of these crystals has an additional scalenohedron, to which a symbol could only be assigned tentatively, but in both cases the form appeared to be {32$\bar{5}$1}.

Fig. 2 (opposite). *a*: Broken crystal of analcime, surrounded by adularia, none of which penetrates it. Interior of analcime converted to a boxwork. x9. *b*: Surface of analcime-adularia vein. A crystal of analcime has become detached, leaving only a 'rim' of its more coherent outer layer, exposing foliated wall rock within. Adularia is absent beneath the analcime, but completely surrounds it. x4. *c*: Broken crystals of early calcite. The two faces on the right have a thin red film of hematite and are replaced superficially by adularia. Euhedral adularia grew outwards from the surface (bottom and lower right). x10. *d*: The cavity formed by dissolution of early calcite contains some late calcite. The grey striated area at lower edge represents the morphology of early calcite, preserved through superficial replacement by adularia, which incorporated the very thin film of hematite coating the early calcite. On same specimen as crystals in *c*. x8. *e*: Hacked structure in adularia, beyond which are crystals of normal habit. x6. *f*: Hacked structure in analcime (white) and adularia, showing the continuity of the structure across different minerals. The wall rock is exposed where adularia was prevented from growing. x2.

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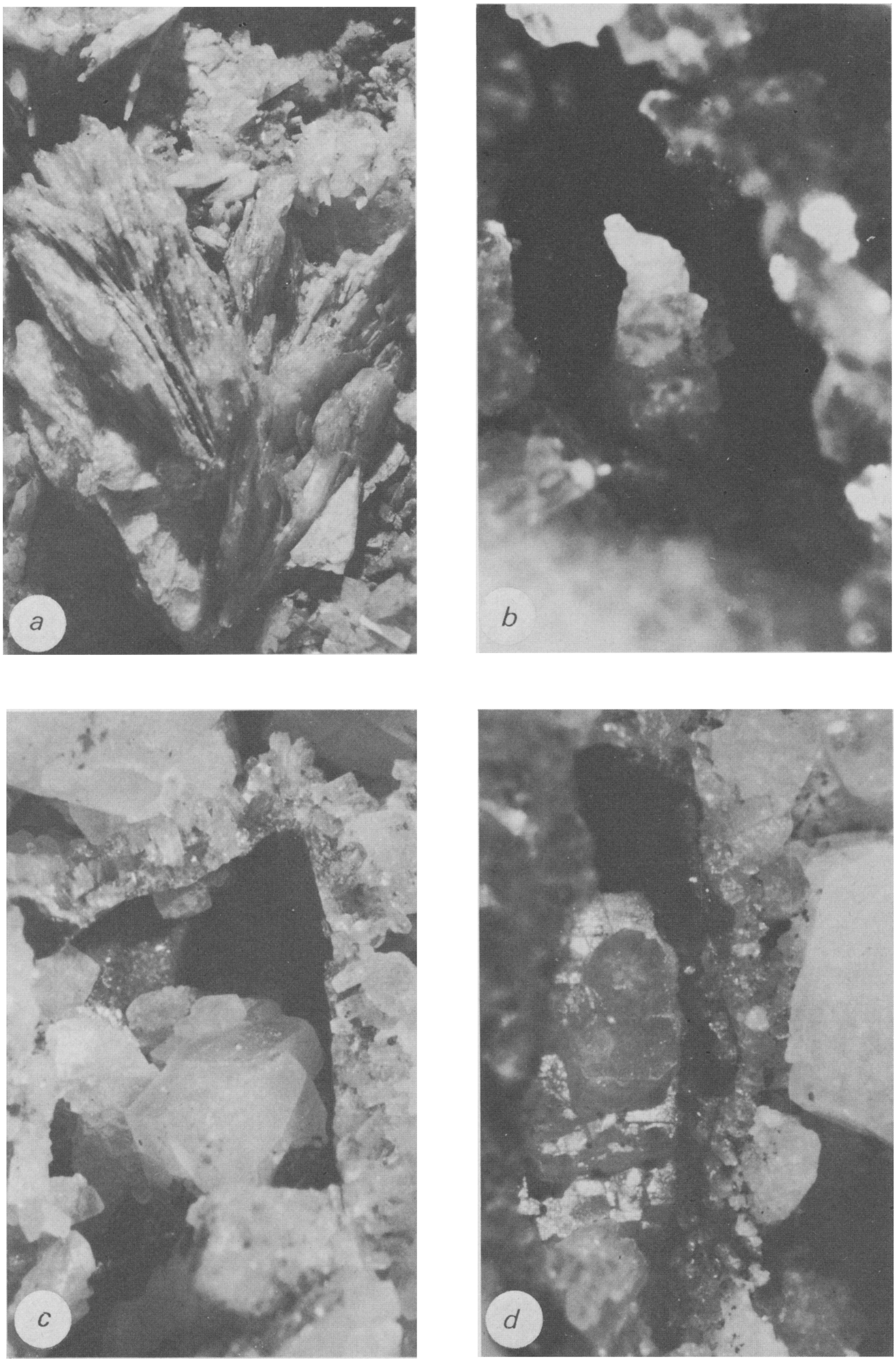

One specimen is of particular interest, as two generations of late calcite are present, one in partial overgrowth upon the other. The earlier calcite is colourless and the later is yellowish-brown. The colourless crystal is similar to some of those described above, being scalenohedral in habit: the only forms exposed are $\{21\bar{3}1\}$ and another scalenohedron which gave readings close to $\{31\bar{4}2\}$, with the rhombohedra $\{10\bar{1}1\}$ and $\{50\bar{5}2\}$. On the crystal forming the overgrowth the dominant scalenohedron is $\{21\bar{3}1\}$, and $\{31\bar{4}2\}$ appears to be absent. Rhombohedron faces are smaller but more numerous: $\{10\bar{1}1\}$, $\{01\bar{1}2\}$ and $\{02\bar{2}1\}$ are of modest size, $\{50\bar{5}2\}$ only appears as extremely narrow faces (and is completely absent on some other crystals on the same specimen), and there is a very small etched face which probably represents $\{40\bar{4}1\}$. Other habits and forms have been found, but need not be described here. Some calcite is partially encrusted with stilbite, and is associated with analcime. It is difficult to determine the forms on this calcite, because the faces that are exposed when the stilbite is removed are rough, dull and often small. However, the faces of one form, $\{02\bar{2}1\}$, are plane and strongly reflecting, the stilbite only encroaching upon them slightly from the edges.

Microcrystalline calcite

A microcrystalline form of calcite occurs occasionally. The pale buff crystals have a fairly uniform length of approximately 0.1 mm. It is difficult to establish the morphology, as the crystals are rather rough and the surfaces may be somewhat curved. They resemble a rhombohedron $\{02\bar{2}1\}$, but this form has not been proved. The crystals show a faint creamy white fluorescence, similar to the late calcite with which they are associated. The microcrystalline calcite has three modes of occurrence.

Firstly, individual crystals of this calcite occur upon minute thin red tabular crystals of hematite, which have been deposited directionally upon adularia.

Secondly, scattered, randomly orientated crystals occur sparsely on the much larger crystals of late calcite. Most of this appears orange, but the colouration is largely due to a film within the crystals and the outer layers are not so strongly coloured. When micro-crystals of calcite are removed they leave slight depressions in the surface of the larger crystals, with a little red crystalline hematite at the interface.

Thirdly, 'drifts' of micro-crystals are accumulated against obstructions in the vein, such as the projection of late calcite above adularia. The deposition of the micro-crystals is directional, but the drifts consist of randomly orientated crystals, which form aggregates with much space between them. These minute crystals are, however, more firmly attached than they appear, and need appreciable force to separate them. It is suggested that the micro-crystals originated elsewhere and were deposited like a sediment by solutions flowing along the vein (indicated by directional deposition and the accumulation in drifts). Then a slight growth of calcite caused the micro-crystals to adhere to each other and to be partially embedded in the larger crystals of calcite. This appears to be supported by the similar fluorescence shown by the micro-crystals and the larger crystals of late calcite. It has not yet been proved that the latter belonged to the last generation of macrocrystalline calcite to form. However, the marked difference in the size and habit of the micro-crystals suggests that a major change had occurred in the nature of the solutions. Since no calcite has been observed upon stilbite, nor stilbite upon microcrystalline calcite, the latter is placed provisionally as the last phase of calcite deposition and assumed to precede stilbite.

Fig. 3 (opposite). *a*: Sheaf of divergent plates of quartz. This occurs on the same specimen as the hacked adularia in fig. *2e*. x4. *b*: Broken adularia epimorph (out of focus) partly surrounding a cavity containing an irregular dissolution remnant of early calcite. x42. *c*: Colourless prisms of adularia grew outwards from a thin film of hematite and formed an epimorph on early calcite, subsequently removed. Euhedral crystals of late calcite in random orientation have formed within the epimorph. x10. *d*: Shows similar phenomena to *c*, but one crystal of late calcite fills most of the epimorph. Near right hand edge of cavity is a thin dark line of hematite, representing the trace of the surface of the original crystal of early calcite. The hematite film formed on the surface of early calcite (fig. *2c*) also occurs on this specimen. In *d* some adularia has also grown into the cavity from the hematite film. x17.

Distinction of early and late calcite

Various criteria have been given for the distinction of early and late calcite, particularly paragenetic relationships to other minerals, but if the appropriate mineral is absent it may be difficult or impossible at present to distinguish between early and late calcite. If the latter has overgrown early calcite, the presence of two or more generations could be overlooked, since most of the calcite is colourless. The forms have not all been determined, but, if they had, morphology alone would not solve this particular problem. The distinction of generations of calcite becomes even more difficult in cleavage masses. However, the use of ultraviolet light of different wavebands has proved helpful. Many crystals of early calcite were found to show no fluorescence or phosphorescence, but these properties varied markedly in different specimens of late calcite. The work is not complete and generalizations are liable to be invalidated, but to date it seems that most, if not all, of the late calcite is fluorescent, with variation of intensity and colour, usually in many shades of mauve, purple and orange, but some specimens exhibit white fluorescence. In addition, some calcite exhibits phosphorescence. This tentative statement has been included to assist in the interpretation of the crystals of calcite with a partially hollow interior, which are described later.

Some relationships of calcite and adularia

Useful paragenetic information is provided by the late calcite formed within the adularia epimorphs. The crystals are euhedral, often doubly terminated scalenohedra with other forms. When remnants of early calcite are present they provide a striking contrast to the later generation, because the former exhibit highly curved solution forms (fig. *3b*), whereas the late crystals are euhedral (fig. *3c, d*). The prisms of adularia which formed the epimorph grew outwards from the surface of the early calcite (fig. *3c*). After the latter was removed, late calcite grew inside and outside the cavity. A thin hematite film lines the epimorph, but is barely visible in this fig. However, the trace of the dark film is easily seen in some broken epimorphs (fig. *3d*). The film demonstrates the former location of the surface of the early calcite, and the fig. shows the cavity formed by its dissolution, as well as the presence of a little euhedral adularia projecting into it. In some specimens the early calcite is completely removed from the adularia epimorph, which has no further growth of adularia within (fig. *4a*). The dark spots on the euhedral adularia consist of rosettes of hematite platelets, none of which occur on the wall rock exposed within the epimorph. The rosettes (fig. *4b*) formed after the growth of adularia, as they leave no indentation when removed, but prior to the complete removal of the adjacent crystal of calcite, because they are not present on the wall rock.

Some of the specimens from this locality are weathered, and calcite is particularly susceptible to attack, but weathering cannot be responsible for all the dissolution of calcite, since highly corroded crystals of early calcite can be found in close proximity to euhedral late calcite, which is little affected.

Late calcite has been used to decipher another stage of the paragenesis, the development of hacked structure. Where the original tabular mineral has been removed from wall rock on which adularia was present, the surface of the rock is exposed as dark lines, with linear groups of adularia crystals between them (fig. *2f*). Crystals of late calcite have nucleated on these rock surfaces (fig. *4c*), proving that the tabular mineral which caused the hacked structures was removed after the formation of adularia but before the deposition of late calcite.

Stilbite

Stilbite occurs as thin colourless bladed crystals, tabular on {010} and elongated in the direction [100]. The crystals appear to be rectangular plates, since they are bounded by {010}, {001} and $\{\bar{1}01\}$. {110} has not yet been observed at Porthkerris. The dimensions of the larger crystals are of the order of 0.2 mm long and 0.05 mm wide, but many are much smaller. This is the stellerite habit, and is similar to one illustrated by Kostov (1968), if the prism faces are omitted from his drawing.

Stilbite is a fairly scarce mineral which has been found within some hematite epimorphs (formed on early calcite) and on adularia. It occurs more abundantly on some specimens which have analcime associated with late calcite. Stilbite is present as scattered crystals on the analcime, but forms a relatively thick encrustation on the late calcite, thick enough to flake off coherently. Although stilbite failed to nucleate on the faces of $\{02\bar{2}1\}$, it encroached slightly upon them by growth from neighbouring faces (fig. *4c*). Stilbite has been found in solution cavities in early calcite occurring with analcime. Late calcite also has some

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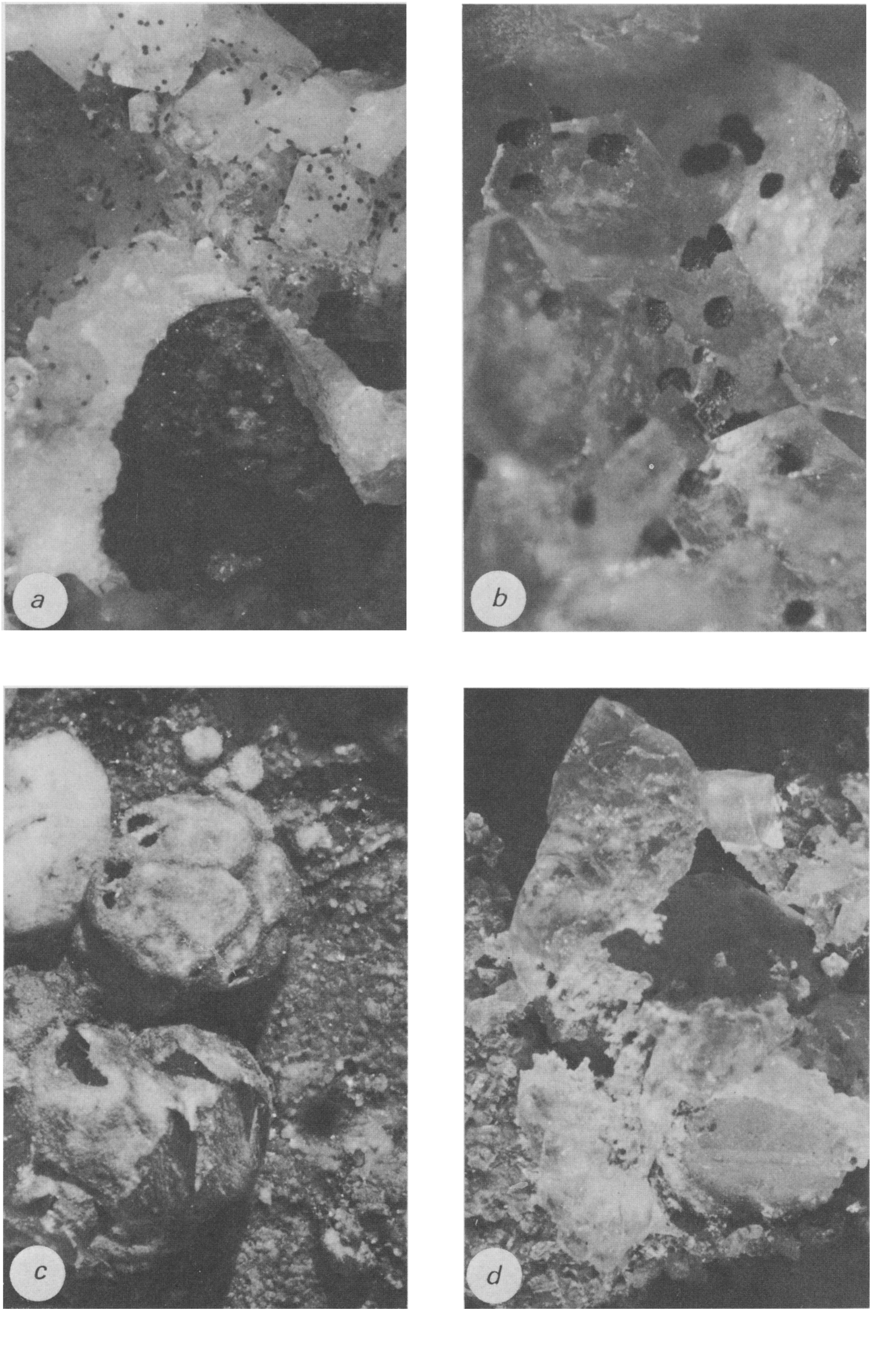

solution channels; they are generally irregular in cross section and orientation, but a few are orientated crystallographically within the calcite. Examples are the development of a rectilinear channel, 9 mm in length, along a glide plane, in which stilbite is present, and of a planar channel along a cleavage plane. Some solution channels follow slightly irregular courses approximately parallel to the rock matrix. Two characteristic features of the solution channels are their lustre and topography. At high magnification under a binocular microscope the surfaces are noticeably dull but have a number of very minute reflecting areas, which are presumably etch pits. Adjacent calcite cleavages, which have probably been dissolved by surface weathering, are much smoother and more highly reflecting. The topography of the channels is not smooth but 'hummocky'. When a sufficient area is exposed it can be seen that all the 'hummocks' are parallel and have a crystallographic orientation, and this topography probably represents a solution form. The extremely low reflectivity makes it very difficult to determine the form, but it seems to approximate to a rhombohedron $\{0k\bar{k}l\}$. The solution channels are either free of minerals or contain some stilbite: since they are present in early and late calcite, and have the same characteristics in both, it seems reasonable to assume the channels were all formed simultaneously by the same process. No evidence has been found of a period of dissolution between the formation of late calcite and stilbite, so dissolution probably began during the formation of stilbite, accounting for the absence of other minerals in the channels. Deformation of late calcite, producing $\{01\bar{1}2\}$ glide planes, must have occurred before or during the growth of stilbite, since it is found in solution channels along these planes. The calcite immediately adjacent to the channels exhibits a white fluorescence in ultraviolet light and phosphorescence. Since the surfaces of the channels appear to be solution forms rather than growth forms, the fluorescence implies metasomatism by solutions passing through the channels.

Crystals of calcite with a partially hollow interior

On several specimens the crystals of calcite have cavities of differing extent. The appearance of the cavities varies with crystallographic orientation and the degree of dissolution. When the c-axis of the crystals makes a large angle with the matrix, the central part or 'core' of the crystal may be surrounded by a zone which has suffered greater dissolution, beyond which is the outer zone which has been less affected. The crystals thus have a depressed annular zone between the more elevated core and exterior. Specimens have also been found on which there is a crystal of calcite surrounded by an annular cavity, beyond which is more calcite, euhedral on the exterior, and approximately concentric with the core. The cleavages on the inner and outer masses of calcite are parallel, so it is assumed that more intensive dissolution has completely removed the intermediate annular zone. The core is growing on the amphibolite or granulite, which is also exposed at the base of the annular cavity, where no adularia is present, but adularia is abundant on the rock surrounding the outer zone of calcite. The absence of adularia at and near the centre indicates that the core of the crystal is composed of early calcite. An examination of one of these crystals in ultraviolet light showed that the core was non-fluorescent in long wave and short wave radiation. The lamp used gave maximum emission at 365 nm and 254 nm respectively. The outer zone fluoresced dull salmon pink in long wave U.V. and gave a brighter fluorescence of the same colour in short wave radiation. The relationship of calcite to adularia seems to provide evidence that the core is composed of early calcite and the outer zone of late calcite. This interpretation appears to be corroborated by the fluorescence.

When the c-axes of crystals lie approximately parallel to the wall rock, partial cavities have been formed between the inner and outer zones of the crystal. In these cavities there are often small amounts of a pale orange substance, which could have been present in the crystal orginally or entered the cavity subsequent to its formation. Eventually a zone of orange inclusions was found in early calcite, similar in appearance to the ortho-serpentine, hematite, etc. described above. This zone was present in the calcite bounding one end of the cavity, the colouration within which had presumably been caused by release of inclusions through dissolution. In some specimens the sides of the cavity are not parallel, suggesting that a change of habit occurred during growth (*fig. 4d*). The outer zone of the crystal shown there appears to be late calcite.

It seems to be possible now to explain the origin of these cavities. At some period after the growth of late calcite, solutions were present which had a moderate solvent action on calcite. If these solutions passed through the vein wall, or penetrated flaws in the crystal, they would dissolve preferentially the zone of early calcite with a fine-grained mosaic structure (due to the presence of inclusions) and perhaps continue through the zone of coarser mosaic structure beyond. Since no dissolution seems to have occurred between the growth of late calcite and the advent of the solutions forming stilbite, it is assumed that these cavities were formed during or after the growth of stilbite.

The paragenesis

The paragenesis of the hydrothermal mineralization at Porthkerris is given in Table I. Most of the information required for its determination has been given already. The placing of some events, for which the evidence was meagre, will be discussed here. A single specimen was found in which the sole minerals were euhedral prehnite and an anhedral grain of quartz. An assumption had to be made about the period of formation of the prehnite, and one needs to be made for the quartz, owing to lack of evidence. Since quartz is a scarce vein mineral here, it has been tentatively assumed that the grain with euhedral prehnite was formed at the same time as the quartz sheaves. It would not matter greatly if these assumptions were wrong, since these varieties of quartz and prehnite have little bearing on the main deductions to be drawn from the paragenesis.

It has been demonstrated that there was a major episode of dissolution after the encrustation of early calcite by adularia, but prior to the formation of late calcite, during which much early calcite was removed from within adularia epimorphs and from the surface of veins. Since no evidence has been found that calcite was dissolved at an earlier stage, it seems reasonable to assume that the partial dissolution of calcite adjacent to botryoidal prehnite also took place during this period. The unknown tabular mineral was removed after the formation of the quartz sheaves and before the growth of late calcite, so that it seems reasonable to assign it to this period of dissolution. An event which has not yet been placed in the paragenesis is the partial removal of the centres of

Fig. 4 (opposite). *a*: Epimorph of adularia on presumed early calcite, since removed, exposing the wall rock. The latter is encrusted with adularia outside the epimorph, but within it adularia is absent. On the adularia are rosettes of hematite crystals, which are not present on the rock. x11. *b*: Rosettes of hematite on limpid adularia. Same specimen as *a*. x44. *c*: Late calcite encrusted with minute crystals of stilbite, which do not nucleate on faces of $\{02\bar{2}1\}$. The stilbite-free faces are larger on the crystals in the lower half of the fig. Some of the encrustation has been removed mechanically, revealing dull, rough faces of calcite beneath. The surfaces coated with stilbite are whiter. Note hacked structure in adularia in the top right hand quadrant, and stilbite-covered calcite in a groove formed by removal of the tabular mineral. x5. *d*: Early calcite (dull grey in fig.) overgrown by late calcite. Dissolution has removed some of the calcite at the interface and formed a cavity between early and late calcite. Part of the cavity can be seen in the fig., appearing black, but it also extends between the two generations of calcite. Adularia is present on the matrix. x9.

Table I. Paragenesis of the hydrothermal mineralization at Porthkerris

? Unknown tabular mineral	
Green and white botryoidal prehnite	↑ Early calcite,
? Euhedral tabular prehnite	with zoned
Ferruginous films on some early calcite	inclusions of
Analcime	↓ ortho-serpentine, etc.
Natrolite	
Dissolution and removal of some analcime	
Adularia	
Quartz in form of sheaves	[bracketed]
? Quartz in euhedral prehnite vein	[bracketed]
Hematite rosettes	[bracketed]
Dissolution of some early calcite: from adularia encrustations; from surface of veins; ? beside botryoidal prehnite	[bracketed]
Dissolution of unknown tabular mineral, causing development of hacked structures	[bracketed]
? Dissolution of nuclei of botryoidal prehnite	[bracketed]
Late calcite	
? Microcrystalline calcite	
Formation of $\{01\bar{1}2\}$ glide planes in calcite (before or during growth of stilbite)	
Stilbite	
Dissolution channels in calcite formed during growth of stilbite	
Dissolution of the interface between early and late calcite (during or after growth of stilbite?)	

? Indicates a slight uncertainty in the placing of an event.
Bracketed events are believed to belong to one phase of activity.

botryoidal masses of prehnite. Since the botryoidal groups are entirely enclosed and no other mineral has been formed in the cavities, there is no means of proving the period of dissolution. It is suggested that it probably occurred in the period under discussion, in which the adjacent calcite appears to have been partially removed and dissolution seems to have been most severe and widespread.

A problem arises in the interpretation of the evidence for the period of dissolution of early calcite. There is very strong evidence for placing it as shown in Table I. The *single* discordant fact is that a number of epimorphs of adularia on early calcite have some euhedral adularia which grew inwards from the surface of the epimorph. This might have arisen in three ways.

1. Formation of adularia epimorphs, some metasomatic growth of adularia within them, followed by the sequence in Table I (quartz in form of sheaves, etc.).
2. Adularia epimorphs formed, followed by the sequence in Table I to dissolution of nuclei of botryoidal prehnite. Slight growth of adularia. Late calcite.
3. Adularia epimorph formed on calcite, then slight dissolution of the latter while adularia was still being precipitated, forming growth within epimorph.

The second mechanism is regarded as highly improbable, because it requires two phases of growth of adularia, and no additional growth of that mineral has been found on or in hacked adularia or the adularia exposed on vein surfaces where early calcite has been removed. It is not easy to distinguish between the first and third mechanisms. It must be emphasized that the additional growth of adularia seems to be an uncommon event, limited to some adularia epimorphs, and has not been observed at any other contacts of euhedral calcite and adularia. The first mechanism is probably less likely to have operated than the third, because of the apparent lack of any structural control by calcite and the comparative freedom with which adularia crystals appear to have grown inwards, being little smaller than those on the exterior.

Discussion

The typical open character of the veins, the mineral species present, and their euhedral character and sequential deposition, indicate that the veins are hydrothermal in origin. Since they intersect the foliation of the amphibolites and granulites, as well as that of the gneiss intrusive into them, mineralization must post-date the metamorphism.

Several aspects of the paragenesis have significance for the interpretation of the geological history of the area. One is the repetition of sequences of mineral formation and dissolution. The latter are emphasized by underlining in Table I. Another is the evidence that individual veins were only accessible to solutions at particular times. This is not only shown by the absence of certain minerals from individual veins but is also very clearly illustrated by the dissolution phenomena. Some crystals of early calcite have been preserved, but others were partially or completely dissolved. In the specimens having late calcite overgrowing early calcite, some show the dissolution of the intermediate zone but others are completely unaffected. There is also a great deal of variation in the preservation of analcime. Paradoxically, that enigmatic substance, the unknown tabular mineral, which was once so widespread at Porthkerris, seems to have been removed in its entirety.

There is a very striking similarity between the mineral paragenesis in the amphibolites and granulites at Portherris and that in the gabbros at Dean quarry (Seager, 1971). The similarity lies not only in the sequences of mineral formation but also extends to the intervening episodes of dissolution and even to the details of unusual growth phenomena and crystal habits of several mineral species. The chief difference between the two parageneses is that more mineral species have been observed in the gabbro, in which the mineral veins are usually much thicker and mineralization is more abundant. The most satisfactory explanation of the remarkable similarity between the two parageneses is that the mineralization in both areas was caused by the same series of hydrothermal solutions, which must have acted simultaneously.

Studies of a limited area in the gabbros and of another in the granulites and amphibolites have been published by the author, because it was possible to obtain suitable specimens from these localities to establish parageneses. However, there is ample evidence to show that hydrothermal mineralization is widespread in the Lizard complex. The following account is intended to be illustrative rather than comprehensive, and to demonstrate the relationship between the type of mineralization and the nature of the country rock.

The amphibolites and granulites of Porthkerris are metabasic rocks and Green (1964*a*) has shown that the four mineral assemblages comprising the Landewednack and Traboe hornblende-schists are 'chemically very closely similar'. The Lizard gabbro is not dissimilar. In these rock suites the mineral association prehnite-zeolites-calcite has been developed, which is very characteristic of the hydrothermal alteration of basic igneous rocks and their chemical equivalents. It can be demonstrated that this type of mineralization is not confined to the areas just mentioned, by reference to the detailed account of mineral occurrences in the Lizard given by Holyer (1972). It is particularly significant that prehnite, analcime, natrolite and orthoclase (var. adularia)[†] occur in Traboe hornblende-schist at several localities on the west coast, near the schist-serpentinite junction, approximately 16 km from Porthkerris on the opposite side of the peninsula. Natrolite was also found on the surface of an epidiorite dyke in serpentinite on the east coast (south of Carleon Cove), demonstrating that such zeolites do occur in other metabasic rocks of suitable composition elsewhere in the Lizard. Orthoclase (var. adularia) was also recorded from many coastal localities, in hornblende-schists, gabbros and rocks of the Old Lizard Head Series. From the gabbro quarry at Porthoustock, on the east coast between Dean quarry and Porthkerris Point, prehnite, analcime, natrolite, calcite and pectolite were recorded. This suite of minerals also occurs in Dean quarry (Seager, 1971).

The serpentinites, which occupy approximately half the area of the Lizard complex, have been closely examined by the present author for signs of hydrothermal activity. This appears to be very widespread, extending from the east coast to the west, and it can also be traced inland (unpublished data). The veins contain mainly hydrous magnesium minerals and calcite, less often hematite or silica minerals, but no trace has been found of the prehnite-zeolite-adularia suite characteristic of several metabasic rocks.

The evidence cited above, which could be amplified, indicates the presence of widespread post-metamorphic hydrothermal mineralization, on a scale which appears to justify the description of regional mineralization in the Lizard complex.

Some evidence is available of the date of hydrothermal mineralization in the Lizard peninsula. Adularia occurs *within* the parageneses in the gabbro at Dean quarry and in the granulites and amphibolites in the neighbourhood of Porthkerris (Table I and Seager *et al.*, 1975, 1978). Close minimum ages of crystallization for extremely fresh adularia from these localities have been determined as 201 $\pm$ 4 Ma and 211 $\pm$ 2 Ma respectively (Seager *et al.*, 1975, 1978). Dating studies of adularia from these localities and several others within the Lizard complex (Halliday and Mitchell, 1976*a*) associate the crystallization of adularia with a hydrothermal event at 210-220 Ma. The adularia which is common to the two parageneses quoted above has thus been formed simultaneously. Evidence of another hydrothermal event at 160-170 Ma has been obtained from the adularia of Holseer Cove (Halliday and Mitchell, 1976*a*). A major hydrothermal event *c.* 180-220 Ma, associated with the early stages of plate separation in the North Atlantic and mineralization of economic importance in western Europe and eastern North America, has been postulated by Mitchell and Halliday (1976). However, it appears possible that still younger events have occurred in the Lizard. A specimen of adularia from Dean quarry, which appeared to have suffered hydrothermal alteration, gave an apparent age of 147 $\pm$ 3 Ma. If partial overprinting is present, it would have taken place in Cretaceous or Tertiary times (Seager *et al.*, 1975). Evidence has also been given of another event younger than 160 Ma (Seager *et al.*, 1978).

All the dating of post-metamorphic minerals and hydrothermal events in the Lizard complex depends, at present, entirely upon adularia, making use of its crystallization and partial or complete overprinting. Since adularia occurs within the hydrothermal paragenesis, no events which preceded its crystallization have been dated at all, and little evidence is available of the date of subsequent events. It is tentatively suggested that the parageneses established at Porthkerris and at Dean quarry (Seager, 1971) may indicate that hydrothermal activity extended over a distinctly longer period than the formation of adularia. If this hypothesis is correct, it offers several interesting fields for

[†] The Revd. V. A. D. Holyer has kindly shown his specimens to the author. The orthoclase has the unusual habit which appears to be characteristic of adularia throughout the Lizard complex. The adularia from many localities has been shown to be triclinic in part (Halliday and Mitchell, 1976*a*).

investigation. It will be necessary to determine the number of phases of hydrothermal activity and date them, in order to place events in the Lizard in their regional setting.

Many aspects of primary mineralization in south-west England have been discussed by Hosking (1964). It was observed that the patterns of intensity of mesothermal and hypothermal mineralization are distinctly different from each other. Epithermal deposits were included with mesothermal ones in part of the discussion. It was noted that mesothermal veins are widespread but are usually comparatively small and uneconomic, mineralization having occurred during two or three periods which were separated by large intervals. Most activity was related to the Late Jurassic and/or Tertiary igneous phase. Gelatinous silica and opal are currently being deposited in some of the quartz veins of the St. Austell granite and it was suggested that they may, perhaps, be the end products of the Tertiary phase of mineralization.

It was indicated that the Jurassic and Tertiary activity wrought mineralogical changes in the lodes largely by remobilization and subsequent redeposition of earlier components, rather than by the introduction of large quantities of 'new' ore components. The crosscourses, which intersect the hypothermal lodes almost at right-angles, may contain a mesothermal suite of minerals or barren quartz or simply fault clay. The clay-filled crosscourses were undoubtedly the last kind to be developed, as some intersect and displace both the other types.

A study of uranium mineralization in south-west England was made by Darnley *et al.* (1965), who concluded that there were at least three periods of formation at *c.* 290 Ma , *c.* 225 Ma and *c.* 50 Ma , and probably at *c.* 165 Ma. The older uranium ages were yielded by high temperature minerals from veins of the main ENE trend, but the younger ages were derived from lower temperature minerals in NS veins. Attention was drawn to the number of different vein fillings which could be seen at Geevor mine in west Cornwall. Evidence had been lacking until then of the time interval between different stages, but the results there showed that it may be of the order of tens or one or two hundreds of millions of years. Recent ^{40}Ar-^{39}Ar stepheating studies suggest that a hydrothermal event occurred at Geevor mine close to 210 Ma and a K-Ar age determination indicated that a quartz-tourmaline-cassiterite stringer formed at about 165 Ma (Halliday and Mitchell, 1976*b*), corroborating some of the $^{206}Pb/^{238}U$ ages.

Several aspects of the hydrothermal activity in the Lizard appear analagous to that in adjacent areas. The alternating periods of mineral formation and dissolution suggest tnat mineralization occurred in pulses. The growth of adularia in the Lizard at 210-220 Ma virtually coincides with a period of uranium mineralization and another hydrothermal event at Geevor mine in Late Jurassic times. Adularia was preceded by the formation of prehnite, analcime, natrolite and some calcite, as well as a phase of dissolution, all of which must be Late Jurassic or earlier in age. There were two periods of dissolution and one of mineralization after the formation of adularia, the overprinting of which may indicate a Cretaceous or Tertiary event. The periodic access of solutions to veins is also known elsewhere in Cornwall.

Hydrothermal solutions which introduced little or no new material, but altered and redistributed existing minerals, could account very satisfactorily for the type of mineralization found in the Lizard, in which the mineral composition of veins is closely related to the chemistry of the country rock. If some means can be found of dating other stages of mineralization in the Lizard complex, it may be possible to use the detailed parageneses already established for the area in a comparative study of phases of hydrothermal activity throughout south-west England.

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REFERENCES

Darnley (A.G.), English (T. H.), Sprake (O.), Preece (E. R.) and Avery (D.), 1965. *Mineral. Mag.* 34, 159-76 [M.A. 17-121].
Flett (J.S.), 1946. *Geology of the Lizard and Meneage*, 2nd edn. Mem. Geol. Surv. G.B.
Green (D. H.), 1964(*a*). *J. Geol.* 72, 543-63 [M.A. 17-311].
—— 1964(*b*). *In* Hosking (K. F. G.) and Shrimpton (G. J.) (eds.), *Present views of some aspects of the geology of Cornwall and Devon.* R. geol. Soc. Cornwall, 87-114 [M.A. 17-649].
Grigor'ev (D. P.), 1965. *Ontogeny of minerals.* Transl. from the Russian (1961), translation edited by Y. Brenner. Jerusalem. (Israel Program Sci. Transl.), 1965 [M.A. 17-452].
Halliday (A. N.) and Mitchell (J. G.), 1976(*a*). *Earth Planet. Sci. Lett.* 29, 227-37 [M.A. 77-1290].
—— —— 1976(*b*). *Proc. Ussher Soc.* 3, 426.
Holyer (V. A. D.), 1972. *The Lizard*, 4, no. 4, 11-20.
Hosking (K. F. G.), 1964. *In* Hosking (K. F. G.) and Shrimpton (G. J.) (eds.), *Present views of some aspects of the geology of Cornwall and Devon.* R. geol. Soc. Cornwall, 201-45 [M.A. 17-650].
Kostov (I.), First English edition 1968. [Author's translation edited by P. G. Embrey and J. Phemister]. *Mineralogy.* Oliver and Boyd, Edinburgh and London [M.A. 19-261].
Mitchell (J. G.) and Halliday (A. N.), 1976. *Trans. Inst. Min. Metall.* (Sect. B: Appl. Earth Sci.), 85, 159-61 [M.A. 76-3318].
Seager (A. F.), 1967-8 [1971]. *Trans. R. geol. Soc. Cornwall*, 20, pt. 2, 97-113 [M.A. 72-3370].
—— 1978. *Mineral. Mag.* 42, 245-9.
——, Fitch (F. J.) and Miller (J. A.), 1975. *Geol. Mag.* 112, 519-22 [M.A. 76-1239].
—— —— —— 1978. *Geol. Mag.* 115, 211-4.