# Pumpellyite- actinolite grade regional metamorphism in south Cornwall

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Low grade regional metamorphism is described from the Lizard peninsula and the Roseland to Gorran area of south Cornwall. Widespread occurrences of pumpellyite, chlorite, sericite, carbonate, albite and quartz together with actinolite, clinozoisite and prehnite in basic lithologies characterise the M 1 regional event. Microprobe analyses of several of these phases are presented. The $Al_2O_3$-rich nature of the pumpellyite and conodont colour index support the grade of metamorphism indicated petrographically. This event is synchronous with the first deformation and suggests a temperature of about 300°C and a pressure of several kilobars.
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## Introduction

Metamorphic studies in south-west England have largely been restricted to contact effects of the Cornubian batholith. Regional work has been concentrated along the north coast, north of the batholith (Fig. la). Hutchings (1889) and subsequently Tilley (1925) reported chloritoid from the Tintagel area. Phillips (1928) recorded white mica, chlorite and chloritoid plus rare garnet from a belt trending ESE from Tintagel. He noted that the chloritoid overgrows the schistosity in the phyllites whereas subordinate chlorite is parallel to this fabric. Brazier and others (1979) examined illite crystallinity along the coast north of the batholith, their results suggesting epizone grade metamorphism around Tintagel with lower grade rocks (anchizone) to the SW and NE.

An occurrence of meta-anthracite was reported from south Cornwall (Pendower Beach) by Cooke and others (1972). They concluded that this must reflect a temperature of at least 350°C during metamorphism. However, petrographic observations and conodont colour indices at this locality led Brazier and others to suggest a lower temperature. Conodonts from the Lower Carboniferous of north Cornwall suggest slightly higher heating than those in Devonian strata at Pendower Beach.

Two areas of south Cornwall are considered here (Fig. 1), both south of the granite batholith and as far removed from the effects of the granite as is possible in this area. The results reported encompass petrographic work on 500 thin sections from a wide variety of lithologies, supplemented by microprobe analyses of certain metamorphic minerals. The colour of conodonts from Roseland is also considered.

## Summary of Geology

The coastal geology of both areas is summarised in Fig. 1. These areas are characterised by melange which structurally overlies bedded Gramscatho turbidites; in Roseland bedded turbidites also rest structurally above the melange. On the Lizard peninsula, melange is structurally overlain by the Lizard ophi01ite (Strong and others 1975; Kirby 1978). Both areas have a southeasterly inclined penetrative cleavage and a down dip extension lineation (D1) (Barnes and others 1979).

In detail the melange may be sub-divided into: (i) slump breccias of arenite phacoids in a shale matrix. These represent slumped Gramscatho Beds. Both the bedded and slumped arenites have a quartz + feldspar + lithoclast composition. The feldspar grains are predominantly plagioclase, with some orthoclase and microcline. Lithoclasts are predominantly cleaved arenites and acid igneous rocks with some basaltic rock fragments, (ii) arenite slump breccia with a wide variety of other lithologies incorporated within the shale matrix; many of these were lithified prior to incorporation. These include Ordovician quartzite, possible Lizard derived debris (notably serpentinite), keratophyres and greenstones. The latter are tholeiitic in character and may be related to the Lizard or to south Cornish greenstones (Kirby 1979; Floyd and Al Samman 1980). This melange also contains a scattering of relatively small angular lithoclasts, predominantly deformed metasediments. These together with amphibolite and granitic, intermediate and mafic igneous rock fragments, are also the major constituents of rudites which have gradational contacts with this melange in which they may be interbeds rather than phacoids.

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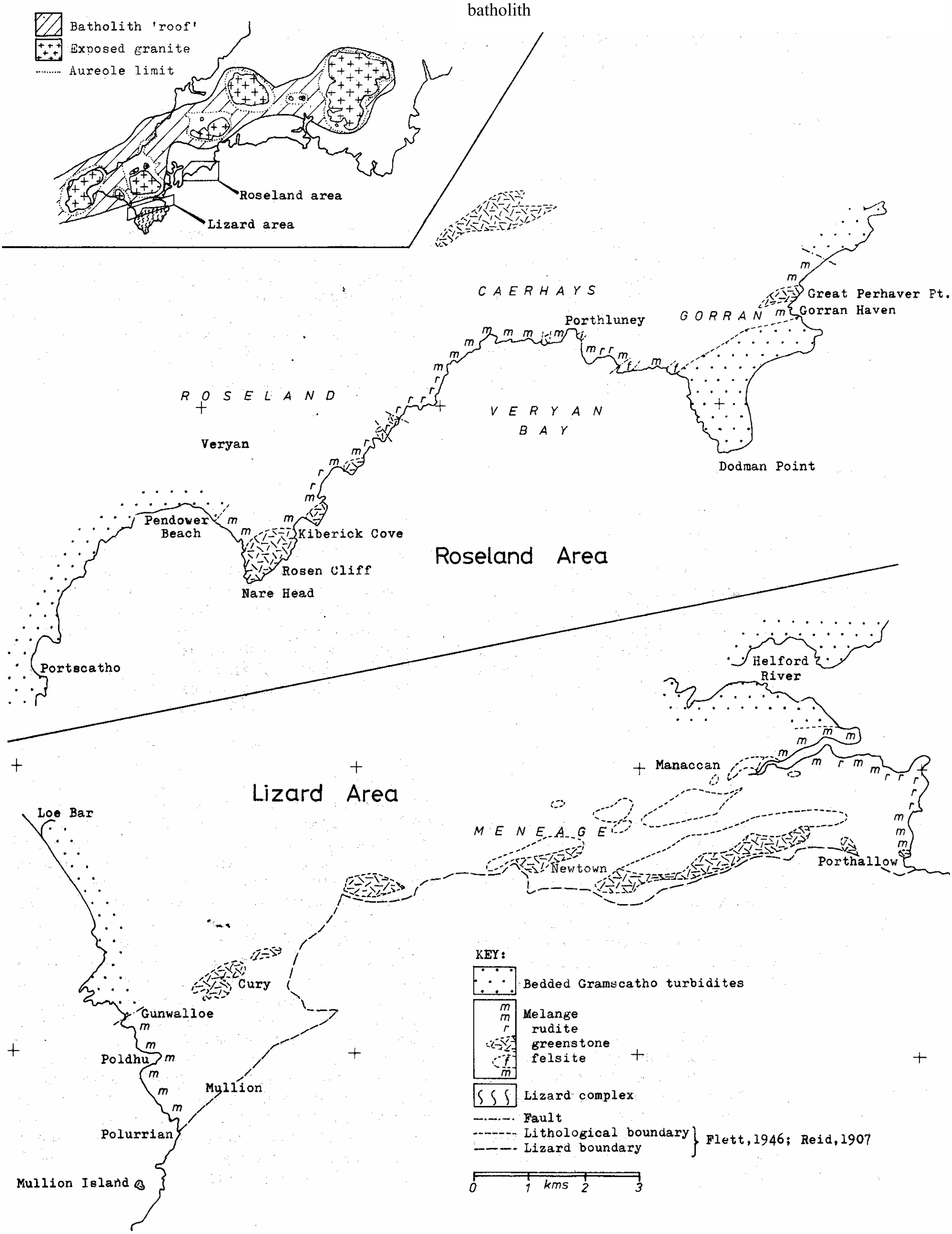
Figure 1. Summary of the geology of the Lizard and Roseland areas. Inset: location of areas studied in relation to the granite batholith

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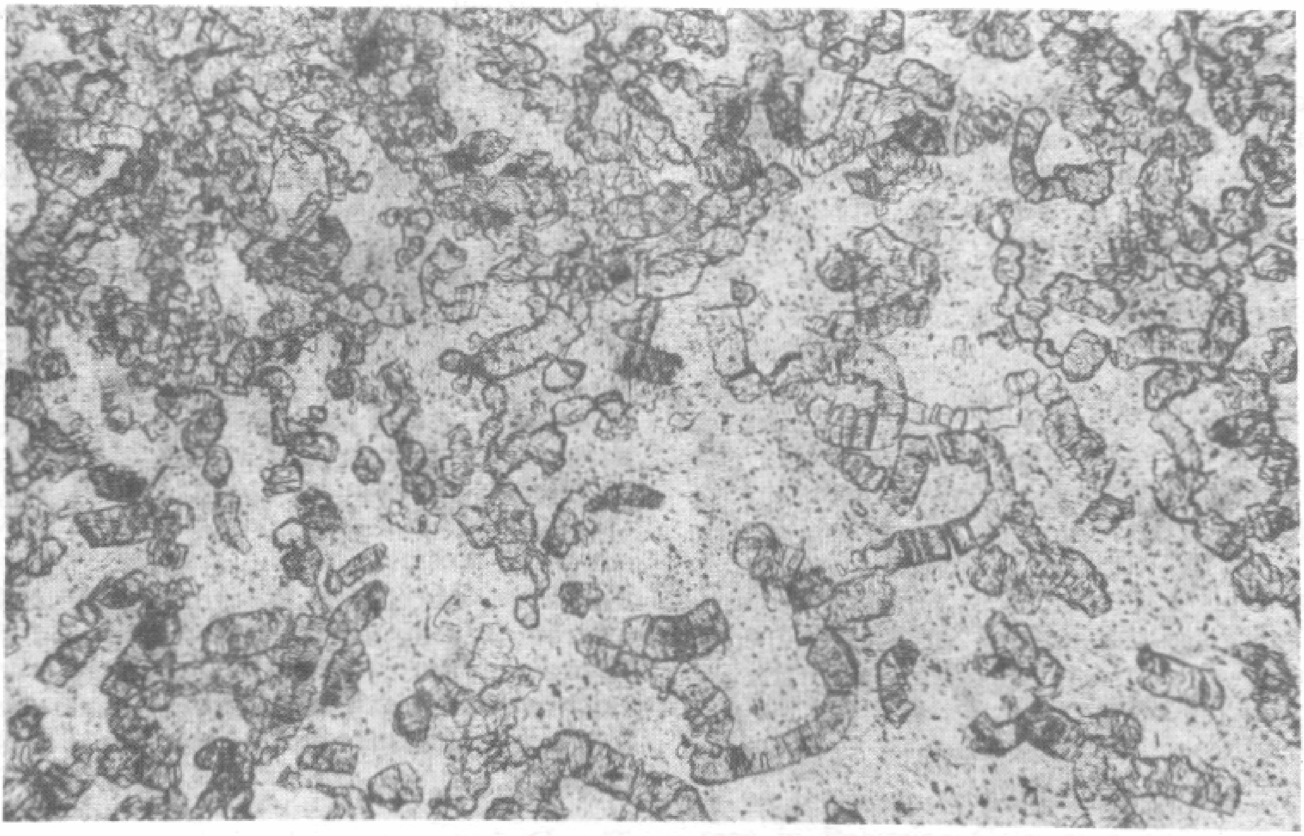
a.



b.

Figure 2. 1.5mm wide photomicrographs in plane polarised light, a. Great Perhaver Point greenstone (18/9B/10). Acicular pumpellyite and albite in veins; granular and 'spongy' pumpellyite in altered feldspar laths, b. Pendower Beach quartz, albite, carbonate, chlorite vein (JA-79-11); vermiform chlorite in dusty quartz.

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## Metamorphism

The lithologies most susceptible to low grade alteration and hence showing the best developed and most diagnostic metamorphic assemblages are the basic volcanics or greenstones. Thus in the following petrographic descriptions emphasis is placed on these rocks. However, in a melange, a metamorphic assemblage seen in only one lithological type may be derived and not representative of the regional metamorphism which has affected the melange as a whole. Thus it is also important to consider assemblages developed in the other lithologies, particularly the bedded greywackes and their slumped equivalents whose sedimentation was approximately contemporaneous with that of the melange as a whole.

The regional metamorphism is .referred to hereafter as M 1 and was synchronous with the first deformation (D I). Syn-D 1 veins and pressure shadows contain M 1 mineral assemblages and these minerals are developed parallel to and in conjunction with the first cleavage (S1). Mineral phases generated during M1 include pumpellyite, actinolite, chlorite, sericite, carbonate, clinozoisite, prehnite, albite and quartz.

## Petrography

*General*

All plagioclase is now albite; microprobe analyses indicate that the anorthite content is generally less than 0.6%. Pumpellyite is seen as spongy aggregates and flecks in albite and more rarely in veins. In the former case it is always very fine-grained (8 gm), very pale green or colourless, and is distinguished from other phases by its relief, low birefringence and oblique extinction of the XZ section. In veins it occurs as acicular crystals up to 50 tan in length. Pumpellyite is absent from specimens containing abundant carbonate, seen as scattered euhedral crystals or aggregates. Actinolite has a pale green to colourless pleochroic scheme and occurs as acicular or platy crystals. Chlorite is usually pale green in colour and forms flaky crystals or fibrous aggregates; in quartz albite veins it is common as vermiform crystals with hexagonal cross-section (Fig.2b). These minerals, together with sericite, vary considerably in grain size and abundance between samples. New quartz and albite is restricted to veins and pressure shadows. Prehnite has only been identified at one locality.

*Roseland Area*

The M1 assemblage in the greenstones is pumpellyite, actinolite, chlorite, sericite, carbonate, clinozoisite and albite together with quartz in veins and pressure shadows. Veins usually contain quartz, albite (often untwinned) and carbonate ± chlorite, pumpellyite and actinolite; other finer and often earlier veins are composed of chlorite ± pumpellyite. Relict feldspar laths contain flecks of pumpellyite, sericite, chlorite and carbonate, sometimes sparse, sometimes abundant. Relict pyroxene is usually fresh, often with an actinolite overgrowth especially where cut by veins. The rock matrix is altered to chlorite, actinolite, carbonate and sericite to varying degrees.

This assemblage is well developed in Nare Head, Great Perhaver Point and inland Caerhays greenstones. Inland exposure in the Roseland area is extremely poor, however the latter greenstone is exposed in quarries and roadsides. In Great Perhaver Point pumpellyite is particularly well developed in fine veins with albite and chlorite (Fig.2a; analyses 1 and 5, Table 1).

The possibility of derived metamorphic assemblages has already been mentioned. Such an assemblage is seen in all of the 'greenstones' exposed around Veryan Bay from Kiberick Cove to Porthluney. With the exception of the Porthluney Cove greenstone these are mostly rudites comprised largely of foliated basic lithoclasts in which coarse-grained amphibole and commonly epidote are well developed. The greenstone in Porthluney Cove is a single 'block' but also contains a derived amphibole with a dark green-blue green-yellow green pleochroic scheme. These derived assemblages are deformed by D1 and to some extent overgrown by the finer grained M1 assemblage. However conditions during MI were not sufficiently intense to cause serious retrogression of the earlier, higher grade, metamorphic assemblages.

The M1 assemblage in the greenstones is corroborated by the metamorphic minerals developed in all other lithological types in both the bedded Gramscatho sequence and the melange. The arenites and rudites are cut by quartz, albite, carbonate, chlorite veins, and plagioclase clasts have flecks of sericite, pumpellyite, chlorite and carbonate. The matrix contains chlorite and carbonate together with strong sericite orientated along S1. Chlorite is often seen with quartz as fibrous pressure shadow fringes around pyrites and resistant clastic grains.

The felsites outcropping in north-east Veryan Bay and at Gorran Haven include both flows and fragmental volcanics. These quartz keratophyres are always extensively altered to sericite, carbonate and chlorite, some of which may have been autohydrothermal in origin.

The Dodman greywacke-shale sequences shows no evidence of a metamorphic grade any higher than that of the melange below it: at least none can be inferred from the lithologies present. The arenites do show significantly higher strain than those to the north and quartz chlorite pressure fringes around quartz and feldspar grains are much better developed. Phyllosilicates in the slates have recrystallised to a coarser grain size, probably as a result of the higher strain.

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| | Pumpellyite | | | Prehnite | Chlorite | | Sericite | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | 18/9B/10 | 25/8C/3 | 18/4C/4 | 30/8C/1 | 18/9B/10 | JA-79-11 | 18/4C/4 | 25/8C/1 |
| $SiO_2$ | 38.07 | 38.14 | 39.05 | 43.29 | 28.83 | 26.33 | 50.30 | 47.20 |
| TiO | 0.03 | 0.07 | 0.01 | - | - | 0.02 | 0.29 | - |
| $Al_2O_3$ | 24.84 | 26.46 | 24.96 | 24.27 | 18.88 | 22.22 | 28.32 | 31.45 |
| FeO | 3.64 | 2.68 | 5.51 | 1.87 | 19.27 | 26.89 | 1.68 | 1.53 |
| MnO | 0.11 | 0.02 | 0.05 | 0.05 | 0.13 | 0.20 | 0.05 | 0.20 |
| MgO | 2.58 | 2.28 | - | 0.55 | 18.80 | 12.40 | 1.95 | 1.33 |
| CaO | 22.09 | 22.09 | 23.16 | 26.11 | 1.59 | 0.02 | 0.06 | 1.07 |
| $Na_2O$ | 0.11 | - | 0.16 | - | - | 0.01 | 0.29 | 0.26 |
| $K_2O$ | - | - | 0.02 | 0.02 | 0.01 | - | 9.17 | 10.00 |
| Total | 91.48 | 92.37 | 93.23 | 96.41 | 87.50 | 88.08 | 91.84 | 93.04 |

| | 1 | Σ | 2 | Σ | 3 | Σ | 4 | Σ | 5 | Σ | 6 | Σ | 7 | Σ | 8 | Σ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Si | 6.21 | | 6.13 | | 6.36 | | 5.95 | 6.00 | 5.91 | 8.00 | 5.54 | 8.00 | 6.86 | 8.00 | 6.43 | 8.00 |
| Al | 4.00 | | 4.00 | | 4.00 | | 0.05 | | 2.09 | | 2.46 | | 1.14 | | 1.57 | |
| Al | 0.78 | 1.88 | 1.02 | 1.94 | 0.79 | 1.55 | 3.88 | 4.02 | 2.47 | 11.81 | 3.05 | 11.73 | 3.41 | 3.81 | 3.48 | 3.94 |
| Ti | - | | 0.01 | | - | | - | | - | | - | | - | | - | |
| Fe | 0.49 | | 0.36 | | 0.75 | | 0.03 | | 3.23 | | 4.73 | | 0.19 | | 0.17 | |
| Mg | 0.62 | | 0.55 | | - | | 0.11 | | 5.74 | | 3.89 | | 0.40 | | 0.27 | |
| Mn | 0.01 | | - | | - | | - | | 0.02 | | 0.04 | | 0.01 | | 0.02 | |
| Ca | 3.86 | 3.90 | 3.91 | 3.91 | 4.04 | 4.09 | 3.84 | 3.84 | 0.35 | | 0.01 | | 0.01 | 1.69 | 0.16 | 1.97 |
| Na | 0.03 | | - | | 0.05 | | - | | - | | 0.01 | | 0.08 | | 0.07 | |
| K | - | | - | | - | | - | | - | | - | | 1.60 | | 1.74 | |

Table 1. Microprobe data for certain M1 mineral phases..

Formula units:
Pumpellyite - 16 cations
Prehnite- 22(O)
Chlorite - 28(O)
Sericite - 22(O)
* Total Fe as Fe O.

*Lizard Peninsula*

(1) East coast and Meneage

The melange in this area contains the same variety of lithologies as the Roseland melange. The contact with Lizard rocks is seen on the south side of Porthallow Cove where pelitic and semi-pelitic schists of Old Lizard Head facies are thrust over the melange. Figure 1 shows the large greenstone 'phacoids' that outcrop immediately north of this boundary, one of which is exposed at Porthallow. Here pillow lavas and tuffs have an M1 assemblage very similar to that described from the Roseland greenstones, with pumpellyite, actinolite, albite, chlorite, carbonate, sericite, clinozoisite and quartz all developed in much the same way. The adjacent rocks, felsite and melange to the south, arenite melange, conglomerate and bedded Gramscatho turbidites, all contain corroborative assemblages identical to those described from the Roseland area.

Inland exposure is very poor; however the greenstones east of Newtown are seen in several small quarries and road cuttings which expose pillow lava and breccia and massive lavas. A relatively small phacoid near Porthallow consists of porphyritic, medium-grained greenstone with fresh pyroxene. The feldspar phenocrysts are totally altered to sericite (analysis 8, Table 1), but the matrix laths contain well developed pumpellyite. Chlorite and actinolite are developed in the matrix. In specimens from the large greenstone stretching east from Newtown fresh pyroxene is common and feldspars contain sericite and pumpellyite. Pumpellyite is also well developed in veins (analysis 2, Table 1) very similar to those described from Great Perhaver. The greenstone matrix contains sericite, chlorite and actinolite. Chlorite is common in veins and infilling vesicles. One locality (G.R. 756232) contains prehnite in addition to the pumpellyite and chlorite. The prehnite (analysis 4, Table 1) occurs in veins and vesicles with chlorite and is also scattered through the rock matrix, as crystals up to 50 µm long.

(2) Polurrian to Loe Bar coastal section

The northern part of this section, from Gunwalloe, is comprised of bedded Gramscatho turbidites; arenite melange is exposed south of here to the Lizard contact seen in Polurrian Cove as a normal fault. With the exception of rare basic phacoids in the melange at Poldhu, lithologies in this section are restricted to greywacke and slate. The arenites have been studied in detail petrographically. They have a quartz-feldspar-lithic clast assemblage identical to that of arenites from other areas described above. Plagioclase grains and basic lithoclasts contain flecks of pumpellyite in addition to sericite and chlorite. However in many specimens

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carbonate is abundant to the exclusion of pumpellyite. The rock matrix contains strong sericite developed parallel to S 1, together with chlorite and carbonate. The basic phacoids at Poldhu vary from a few centimetres to over 1 metre in size. However they are usually totally altered to carbonate plus chlorite and sericite.

Microprobe Data

Selected analyses of various M1 mineral phases from polished thin sections are presented in Table 1, and are discussed below.

*Pumpellyite*

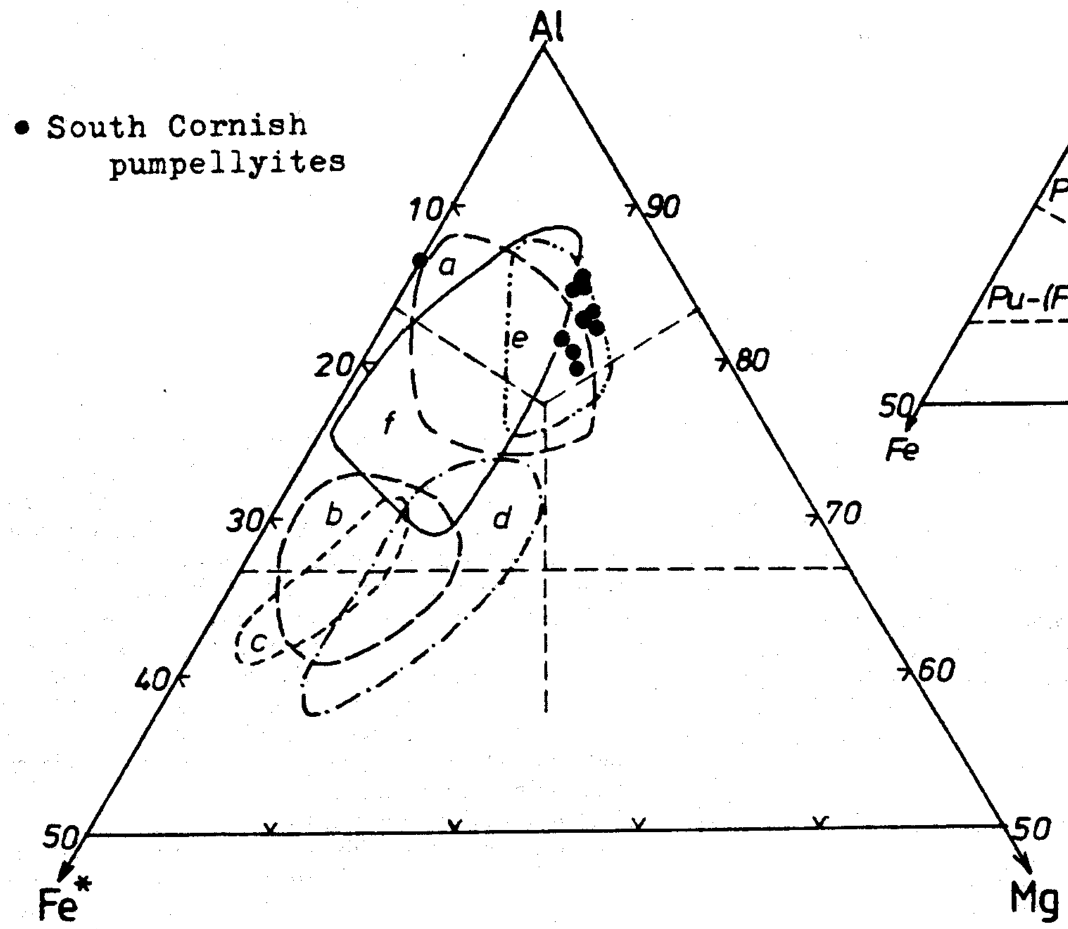
Difficulties were experienced in trying to analyse pumpellyite due to its extremely fine grain size. In a qualitative sense, analyses proved the optical identification of the mineral, but Useful quantitative results were restricted to three samples containing the coarsest grained pumpellyite. Two of these (1 and 2, Table 1) are from chlorite-pumpellyite veins from Great Perhaver Point and Meneage (G.R. 774327) respectively. The third is from a granitic clast from rudite near Portloe in which pumpellyite and sericite (analysis, 7) are very strongly developed in feldspar.

Allman and Donnay (1971) proposed the following pumpellyite formula:
$Ca_2Al_2(OH)_2(Al, Mg, Fe) (OH, O)SiO_4. Si_2O_6$
OH, O)

This was re-written by Coombs and others (1976) as:

$W_4X_2Y_4Z_6O\ (_{20+x}\ ')\ (OH)\ (_{8+x}')$

where W= Ca, Mn; X = $(Mg, Fe^{2+}, Mn)_{2-x}$ $(Fe^{3+}, Al)_x$’; Y=$Fe^{3+}$, Al; Z = Si



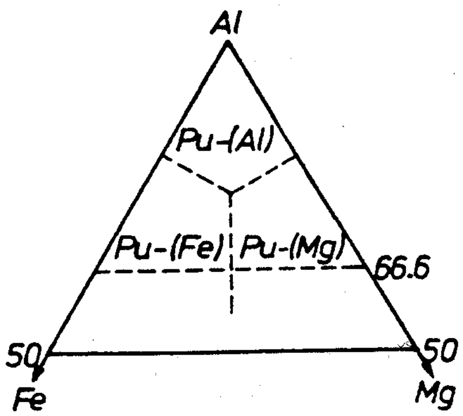




Figure 3a. Compositions of pumpellyites from south Cornwall and other terrains in atomic proportions Al:Fe*:Mg where Fe* = total Fe. Areas a and b - Upper Wakatipu, New Zealand, Kawachi *(1975);* c - Vancouver Island, Surdam (1969); d - Olympic Peninsula (Glassley)976) and Jonestown (Zen 1974); e - California *glaucophane* schists (Ernst and others 1970; Deer, Howie and Zussman 1962; Galli 1972); f- Loeche, Switzerland from Coombs and others (1976). Diagram after Coombs and others (1976, fig. 3).

Figure 3b. Classification scheme after Passaglia and Gottardi (1973).

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Due to uncertainty regarding the oxidation state of Fe and the importance of OH in the formula, these authors used 16 cations to calculate the formula unit. That practice is followed here. Passaglia and Gottardi (1973) (Fig.3b) used the dominant cation on the X site, after allocation of cations to fill the Z and W sites, to classify pumpellyites. South Cornish pumpellyites plot in the Pu-(Al) field (Fig. 3b), The exception is analysis 3 from Portloe, which falls just outside this field. The 'pumpellyite' analysis 3 from Portloe contains no MgO, possibly suggesting an epidotic mineral. However the optical properties clearly indicate that it is pumpellyite. MgO was clearly available during metamorphism, as sericite in the same specimen contains appreciable amounts of Mg (see analysis 7). This deficiency results in a low total in the X site of the pumpellyite.

Figure 3b compares Cornish pumpellyite analyses with those of pumpellyites from other terrains. Areas a, e and f are higher grade terrains (a and f- pumpellyite actinolite; e - glaucophone schist) than b, c and d which are zeolite and prehnite pumpellyite grade. The higher grade pumpellyites are relatively Al rich. This decrease in Fe content with higher grade supports the change from strong to pale coloured noted by several authors (e.g. Iwasaki 1963). Cornish pumpellyites are pale coloured (usually very pale green to colourless) and have high A1 content.

*Micas and Chlorite*

Several microprobe analyses were made of chlorite and sericite. The chlorite analyses (Table 1 Nos. 5 and 6) are from Great Perhaver Point and Pendower Beach respectively. Both occur in veins, the former in the chlorite pumpellyite vein which provided pumpellyite analyses (e.g. 1), and the second from vermiform chlorite (Fig. 2) in a quartz-albite-carbonate-chlorite vein cutting greywacke. The anomalous CaO content of analysis 5 is probably a result of overlap of the electron beam onto adjacent pumpellyite.

The sericite analyses are both of flecks in altered feldspar, 7 from Portloe and 8 from altered feldspar phenocrysts in a Meneage greenstone. These differ from ideal muscovite in that they contain significant amounts of FeO and MgO, showing substitution towards a phengitic composition.

*Conodont Colour Index*

Devonian conodont faunas collected from bedded limestones at Pendower Beach and from limestone phacoids in Porthluney Cove are poorly preserved. However they do provide an independent assessment of the maximum temperatures reached at these localities. All of the forms recovered are black and compare with the highest colour alteration index of Epstein and others (1977). This suggests from their data a temperature in excess of 300°C

## Discussion

With the exception of prehnite and pumpellyite the low grade mineral assemblages developed in the greenstones of south Cornwall have long been known (e.g. Flett 1946; Reid 1907). However they have always been interpreted in terms of spilitic alteration contemporaneous with their formation. There is controversy as to whether spilites are formed by sea floor alteration or low grade regional metamorphism (e.g. Amstutz 1974). The end product is much the same.

In south Cornwall the assemblage pumpellyite, actinolite, chlorite, sericite, carbonate ± clinozoisite is seen to overgrow the primary textures of all basic lithologies and is also seen to alter basic rocks which have suffered a previous higher grade metamorphic event. In addition these minerals, with the exception of actinolite and clinozoisite, are seen in all other lithologies in the melange and also in the bedded sequence. Thus whilst spilitisation may have locally altered the greenstones and keratophyres, the broad assemblage now seen suggests regional metamorphism within the pumpellyite actinolite facies. This interpretation is supported by the chemistry of the pumpellyite, and also from conodont colour. The latter suggests a maximum temperature in excess of 300°C, which compares well with a temperature range of 250 to 350°C proposed by Coombs and others (1976) for pumpellyite actinolite facies rocks in Switzerland. The meta-anthracite occurrence reported by Cooke and others (1972) was suggested to reflect a temperature of at least 350°C. This may not be as far out as was suggested by Brazier and others (1979).

The occurrence of prehnite at one locality in Meneage may suggest a lower temperature local overprint or lower pressure during metamorphism of this area. However it is not incompatible with pumpellyite actinolite facies as its occurrence in this facies is reported by Munha (1979) from south Portugal.

## Conclusions

A pumpellyite, actinolite, chlorite, carbonate, sericite, albite, quartz ± clinozoisite and prehnite mineral assemblage is described from Devonian melange and bedded strata of south Cornwall. It is associated with the first phase of deformation which affected these rocks. A pumpellyite actinolite facies grade of metamorphism suggested by this assemblage is supported by pumpellyite composition and conodont colour index. A temperature of about 300°C and a pressure of at least 3 kilobars during metamorphism is indicated by these results.

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