METABASITE PARAGENESES IN SOUTH-WEST ENGLAND

D. ROBINSON, C. MAZZOLI AND T.J. PRIMMER

basites with diagnostic chlorite ± pumpellyite ± actinolite assemblages are sporadically developed in the Variscan belt of south- England. Consideration of these phases in the NCFMASH system [SiO_2-(Al_2O_3+Fe_2O_3)-FeO-MgO-CaO-Na_2O-H_2O], using the epidote projection, shows in most cases sub-parallel tielines between co-existing chlorite - pumpellyite and chlorite – actinolite assemblages. These relationships are suggestive of equilibrium relationships in the majority of samples and indicate prehnite-pumpellyite and low greenschist facies metamorphism. This is compatible with previously described anchizone and epizone conditions based on illite crystallinity. Application of the chlorite geothermometer suggests temperatures of c. 270 and 310°C for the two faciees respectively. The paragenetic relationships do not support the previously defined higher pressure pumpellyite-actinolite faciees for the Roseland area.

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INTRODUCTION

The metamorphic character of the Variscan Orogeny in southwest England has been documented in a variety of recent studies which concentrated on examination of pelitic rocks. The illite crystallinity and bo parameter of white micas have been widely measured in the abundant pelitic rocks in the region. These studies have shown a range from diagenetic levels through anchizone conditions into epizone metamorphism, with the metamorphism being typically of a low-pressure facies series (Primmer, 1985a, b; Kelm and Robinson, 1989; Warr *et al*, 1991). Low grade metamorphic parageneses in basic igneous rocks are also most useful indicators of the degree of metamorphism. However, the metabasites in south-west England have not proved as useful as the pelitic rocks in determining the metamorphic character of the region because of the widespread prevalence of a non-diagnostic chlorite-albite ± carbonate assemblage (Primmer, 1985a) most probably generated as a result of high CO_2 in the fluid Phase.

The region under consideration here covers the Cornish region of south-west England (Figure 1) in which there are abundant basic extrusive and intrusive volcanic rocks of Devonian and Lower Carboniferous age. The metamorphic character of the region was reviewed by Warr *et al.* (1991), who presented the most comprehensive map of the metamorphic zonation in the region (Figure 1), which is largely based on illite crystallinity data. Epizone and anchizone conditions were established over all of the region studied. The pelitic rocks of the anchizone region are dominated by illite, with illite crystallinity values of > 0.21°2Θ, and chlorite. Epizone areas have also an illite (IC < 0.21) and chlorite assemblage, except for the Tintagel region. Here the slates have a more varied assemblage with muscovite, chlorite, biotite and chloritoid, indicative of greenschist facies, and are possibly of a slightly higher grade than the other areas identified as epizone.

Metabasite rocks are widely distributed in most of the area shown in Figure 1. However, assemblages are typically chlorite-albite ± carbonate and non-diagnostic of grade. As even very low amounts of CO_2 (Xco_2 < 0.1) in the fluid phase drastically inhibit the diagnostic sub-greenschist facies calc-silicate assemblages (Digel and Ghent 1994), it appears that CO_2 must have been present in the fluid phase during the metamorphism. There are, however, sporadic occurrences of intrusive metabasites with diagnostic calc-silicate assemblages and those for which mineral chemical data are available are shown in Figure 1.
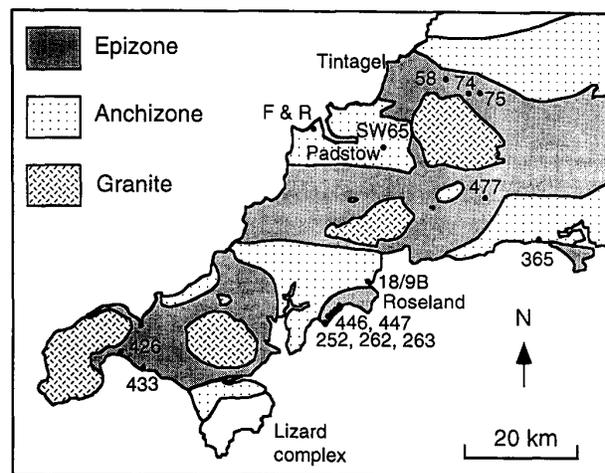

Figure 1. Simplified metamorphic map of southwest England (modified after Warr et al., 1991), *showing metabasite bearing pumpellyite and/or actinolite. F & R - sample from Floyd and Rowhotham (1982); 18/9B - sample from Barnes and Andrews (1981); other samples detailed in Primmer (1985a).*

The scarcity of such phases, a largely petrographic approach, and a minimum of mineral chemical data, has meant that only provisional allocation to a particular metamorphic facies has been possible. For example, in the Roseland area of south Cornwall, Barnes and Andrews (1981) recognised the higher pressure pumpellyite-actinolite facies, while in the Padstow region Floyd and Rowbotham (1982) recognised prehnite-pumpellyite facies and greenschist facies in the region north of Padstow (Robinson and Read, 1981). The most comprehensive assessment of metabasite parageneses was undertaken by Primmer (1985a), who recognised a sub-greenschist assemblage with occasional prehnite, epidote and pumpellyite, and a greenschist assemblage dominated by actinolite and chlorite, associated respectively with anchizone and epizone grade in the pelites (Primmer, 1985 a, b).

Since the above work was undertaken there have been significant advances in the understanding of low grade metabasite parageneses. These have been by 1) application of petrogenetic grids (Liou *et al*.,
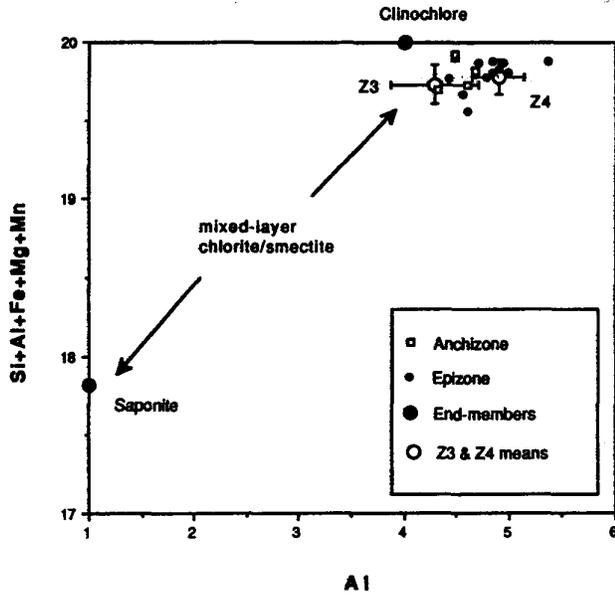
Figure 2. Plot of total non-interlayer cation totals (Si+Al+Fe+Mg+Mn) versus total Al in chlorite. Chlorite formula calculated on the basis of 28 oxygens. Z3 and Z4 - means of zone 3 (prehnite-pumpellyite-abundant zone) and zone 4 (actinolite-abundant zone) chlorites from low grade metabasites in Greenland and Wales (after Bevins et al., 1991).

Figure 4. Plot of MgO/(MgO + FeOₜ) in chlorite versus MgO/(MgO + FeOₜ) in whole rock (molecular proportions). Welsh and Greenland data from Bevins and Robinson (1993).
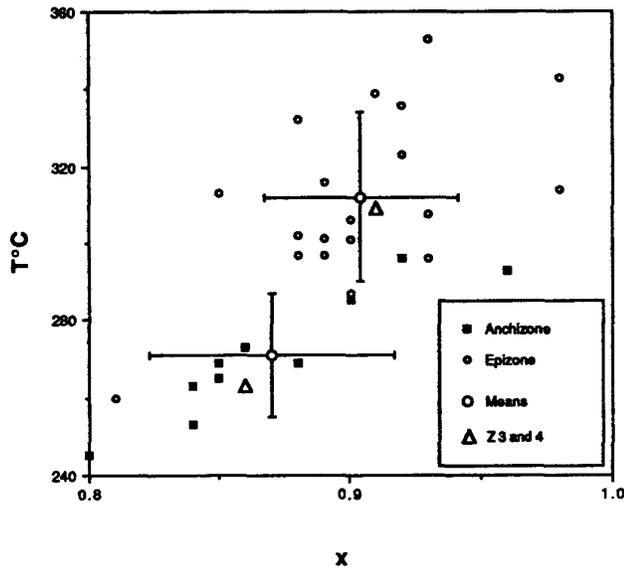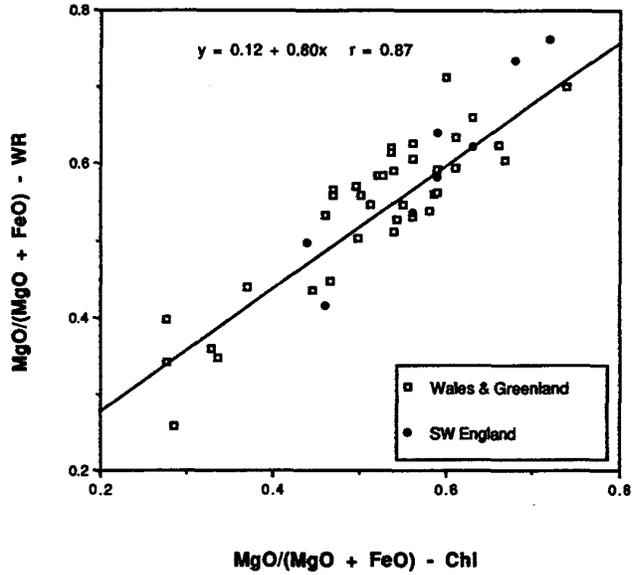

Figure 3. Plot of x (chlorite layers in mixed-layer chlorite/smectite using method of Benison and Schiffman, 1988) determined from microprobe analyses of chlorites in south -west England against temperature determined from tetrahedral Al content (Catbelineau, 1988). Means and one sigma values shown for anchizone and epizone samples. Z3 and Z4 are mean temperatures for zone 3 (prehnite-pumpellyite-abundant zone) and zone 4 (actinolite-abundant zone) chlorites from low grade metabasites in Greenland and Wales (after Bevins et al., 1991).

Figure 5. Pumpellyite - chlorite (dashed tie-lines) and actinolite-chlorite (solid tie-lines) relationships in the epidote projection (after Springer et al., 1991). AF* = 100 (Al₂O₃+ Fe₂O₃ - 0.75CaO - Na₂O) / (Al₂O₃ + Fe₂O₃ - 0.75CaO - Na₂O + FeO + MgO). Labelled tie-lines are specific samples mentioned in the text.

1985; Frey *et al, 1991),* 2) mineral projections (Springer *et al.,* 1992), 3) a greater understanding of those minerals in equilibrium and of the effect of whole rock chemical control on such low grade parageneses (Bevins *et al.,* 1991; Bevins and Robinson, 1993; Robinson *et al,* 1993). It is the aim of this paper to re-assess the metabasite mineral parageneses of the region on the basis of these advances, using new

mineral chemical and whole rock data, as well as previously-published results in order to define more closely the metamorphic conditions of the Variscan Orogeny in south-west England.

SAMPLE AND MINERAL ASSEMBLAGES

As shown in Figure 1, eleven samples are from the epizone areas and four samples from the anchizone regions. Mineral chemical data (Tables 1, 2 and 3) for samples 18/9B and F & R are from the published works of Barnes and Andrews (1981) from Roseland, and Floyd and Rowbotham (1982) from Padstow. The remaining samples

and mineral chemical data are from Primmer (1985a) for which the mineral analyses (Tables 1, 2 and 3) have not been previously published.

All samples contain quartz, albite, epidote and chlorite as part of the assemblages. Those samples from epizone areas (426, 433, 262, 263, 446, 447, 477, 58, 74 and 75) also contain actinolite, with the exception of sample 252 in which pumpellyite is present. Two samples from anchizone areas, SW65 and F & R, do not contain actinolite but have pumpellyite, which is in contrast to sample 18/9B that has both actinolite and pumpellyite, while sample 365 contains actinolite but no pumpellyite. On the basis of IC-determined grade for the region (Warr *et al.,* 1991) as shown in Figure 1, there is a general link between actinolite-and pumpellyite bearing assemblages in epizone and anchizone areas respectively, as originally suggested by Primmer (1985a). However, there are discrepancies in respect of pumpellyite in epizone sample 252, and actinolite in anchizone samples 365 and 18/9B.

In addition to the four ubiquitous phases, albite + quartz + chlorite + epidote the samples contain either pumpellyite or actinolite (except sample 18/9B) and such diagnostic assemblages are indicative of a fluid phase that is in effect pure H$_2$O. Thus, the rocks can be considered in terms of the seven component system SiO$_2$-(AlO$_3$+Fe$_2$O$_3$)-FeO-MgO-CaO-Na$_2$O-H$_2$O (NCFMASH); this system has been widely employed in the study of metabasites from other regions (Springer *et al.*, 1992; Bevins and Robinson, 1993). The system is simplified by assuming all iron in pumpellyite, chlorite and actinolite is FeO. This assumption was examined in the case of pumpellyite by Beiersdorfer (1993), who showed that it was a good approximation and that there was no major effect on the interpretation of chemographic projections. In the samples studied, the four ubiquitous phases along with excess H$_2$O and in most cases one of either pumpellyite or actinolite, indicate that the typical assemblage is trivariant. Pressure and temperature can obviously be assigned as two variables, while in low grade metabasites from the Welsh Basin and Greenland it has been shown that the whole rock MgO/(MgO+FeOt) ratio can be considered as the remaining variable (Bevins and Robinson, 1993). In metabasites from the Welsh Basin and Greenland there is a strong whole rock control on mineral chemistries and assemblages (Bevins and Robinson, 1993), and a similar control

may well be evident in the present samples. In the prehnite--pumpellyite and greenschist facies the whole rock control is demonstrated by a correlation between the MgO/(MgO + FeOt) ratios in co-existing chlorite, pumpellyite, actinolite and that of the whole-rock. For example the control between chlorite and whole rock is evident from the relationship MgO/(MgO + FeOt)rock = 0.80 [(MgO/(MgO + FeOt)]chl + 0.12 (Bevins and Robinson, 1993). Transitional between these two facies it has been shown that the MgO/(MgO + FeOt)chl ratio of c. 0.54 is a critical divide separating rocks into chlorite-pumpellyite (<0.54) and chlorite-actinolite (>0.54) assemblages at the same grade (Bevins and Robinson, 1993).

In recent studies of metabasites in the NCFMASH system the epidote projection has proved to be a most useful aid in the interpretation of low grade metabasite parageneses (Springer *et al.,* 1992; Beiersdorfer, 1993; Bevins and Robinson, 1993). The phases albite, quartz and H$_2$O are regarded as in excess, and projection is made from epidote onto a AF* - [MgO/(MgO+FeO)] plane on which relationships between chlorite, pumpellyite and actinolite may be shown. Full details of the projection are given by Springer *et al.* (1992).

MINERAL CHEMISTRY

Chlorite

All samples contain mafic phyllosilicates, and minerals in this group have traditionally been classified in terms of the Hey (1954) scheme. However, this scheme gives little in the manner of petrogenetic information, so here a scheme after Wiseman (quoted in Bettison and Schiffman, 1988) is utilised, in which the microprobe analyses are recalculated in terms of non-interlayer and interlayer cation totals and the proportion of mixed-layer chlorite/smectite layers within the mineral. For an ideal trioctahedral chlorite such as clinochlore, the non-interlayer cation total is the sum of Si+Al+Fe+Mg+Mn and should total 20, while the interlayer cation total is the sum of Ca+Na+K which ideally is zero. A mixed-layer chlorite/smectite series links the tri-octahedral end-member chlorite with the tri-octahedral end-member swelling smectite (saponite). In saponite the non-interlayer cation total (calculated on the basis of 28

sample	58	74	75	SW65	F & R a	F & R b	262	263	446	447	252	18/9B	365	477	433	426
SiO$_2$	28.39	28.42	27.64	27.25	27.59	26.91	28.78	27.66	27.29	28.05	29.62	28.28	30.17	28.94	28.75	25.7
TiO$_2$	0	0	0	0	0.02	0	0	0	0	0	0	0	0	0.09	0	0
Al$_2$O$_3$	20.03	20.22	19.09	18.5	18.04	17.7	21.52	20.14	19.61	20.77	19.09	18.3	1824	18.16	21.48	21.55
FeO	17.51	22.23	21.96	28.7	29.12	29.02	15.79	23.4	18.94	19.22	20.06	20.61	20.1	24.93	15.51	29.53
MnO	0	0	0.19	0.35	0.27	0.35	0.12	0.3	0.385	0.24	0.24	0.13	0.24	0	0.2	0.52
MgO	20.95	17.93	17.75	12.81	14.06	13.65	23.17	16.62	19.12	19.27	18.77	20.18	19.78	16.38	22.47	12.07
CaO	0.3	0	0	0	0	0.11	0.26	0	0	0.56	0.24	0	0.4	0.1	0.23	0
Na$_2$O	0.15	0	0	0	0.16	0.11	0	0	0	0	0	0	0	0	0	0.11
K$_2$O	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0	0
Total	87.33	88.80	86.63	87.61	89.26	87.85	89.64	86.12	85.35	88.11	88.02	87.50	88.93	88.70	88.64	89.48
Si	5.74	5.77	5.77	5.84	5.82	5.78	5.61	5.71	5.71	5.67	6.00	5.81	6.05	5.98	5.65	5.42
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Al(iv)	2.26	2.23	2.23	2.16	2.18	2.22	2.39	2.29	2.29	2.33	2.00	2.19	1.95	2.02	2.35	2.58
AI(vi)	2.51	2.61	2.48	2.52	2.30	2.27	2.55	2.62	2.54	2.63	2.56	2.24	2.37	2.40	2.64	2.78
Fe$_2$	2.96	3.77	3.84	5.15	5.13	5.22	2.57	4.04	3.31	3.25	3.40	3.54	3.37	4.31	2.55	5.21
Mn	0.00	0.00	0.03	0.06	0.05	0.06	0.02	0.05	0.07	0.04	0.04	0.02	0.04	0.00	0.03	0.09
Mg	6.31	5.43	5.53	4.09	4.42	4.37	6.73	5.12	5.96	5.81	5.67	6.18	5.92	5.04	6.59	3.79
Ca	0.06	0.00	0.00	0.00	0.00	0.03	0.05	0.00	0.00	0.12	0.05	0.00	0.09	0.02	0.05	0.00
Na	0.06	0.00	0.00	0.00	0.07	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00
x	0.88	0.89	0.93	0.9	0.95	0.96	0.92	0.90	0.93	0.85	0.81	0.99	0.83	0.87	0.89	0.93
T°C	302	297	296	285	290	295	323	306	307	313	260	291	251	264	316	353
AF*	0.20	0.21	0.20	0.20	0.19	0.19	0.21	0.21	0.21	0.21	0.20	0.19	0.18	0.19	0.21	0.23
MgO/(MgO+FeO)	0.68	0.59	0.59	0.44	0.46	0.46	0.72	0.56	0.64	0.64	0.63	0.64	0.64	0.54	0.72	0.42

Table 1.

sample	252	18/9B	SW65	F & R a	F & R b
SiO_2	37.12	38.07	37.72	36.81	36.85
TiO_2	0	0.03	0.18	0	0.01
Al_2O_3	21.85	24.84	21.31	26.39	25.26
FeO	8.72	3.64	9.56	2.71	6.01
MnO	0	0.11	0	0.31	0.09
MgO	2.36	2.58	1.7	2.7	1.98
CaO	22.43	22.09	22.09	22.67	22.61
Na_2O	0	0.11	0	0.36	0.17
K_2O	0	0	0	0.06	0
Total	92.48	91.47	92.56	92.01	92.98
Si	6.16	6.18	6.26	5.95	5.99
Ti	0	0	0.02	0	0
Al	4.27	4.76	4.17	5.03	4.84
Fe_2	1.21	0.49	1.33	0.37	0.82
Mn	0	0.02	0	0.04	0.01
Mg	0.58	0.62	0.42	0.65	0.48
Ca	3.99	3.84	3.93	3.93	3.94
Na	0	0.03	0	0.11	0.05
K	0	0	0	0.01	0
AF*	-0.91	-0.88	-0.97	-0.92	-0.76
MgO/(MgO+FeO)	0.33	0.56	0.24	0.64	0.37
Al/(Al+Fe+Mg)	70.44	80.96	70.47	83.18	78.87
Fe/(Al+Fe+Mg)	19.94	8.42	22.43	6.06	13.31
Mg/(Al+Fe+Mg)	9.62	10.63	7.11	10.76	7.82

Table 2.

oxygen) totals 17.92, while the interlayer cations are at a maximum. A measure of the proportion of chlorite layers (x) in the mixed-layer series is determined according to the formula:

$$(K, Na, Ca_{0.5})_{z-y} [(Mg, Fe, Mn)_{6-y}, Al_y] [Si_{8-z} Al_z]_{20} (OH)_4 x[(Mg, Fe)_6(OH)_{12}].$$

This calculation follows the scheme outlined by Bettison and Schiffman (1988), and for a pure chlorite x = 1, and x = 0 for a saponite.

Cathelineau (1988) showed a strong correlation between tetrahedral aluminium and temperature in chlorite from the Los Azufres, Mexico geothermal system. This geothermometer was shown to compare favourably with temperature estimates based on mineral assemblages in low grade metabasites by Bevins *et al.* (1991).

In their study of low grade metabasites from Wales and Greenland Bevins *et al.* (1991) recognised four zonal divisions, of which zones 1 and 2 were related to an absence or sporadic occurrence of prehnite and pumpellyite, zone 3 to abundant prehnite and pumpellyite and zone 4 to dominant actinolite in the absence of prehnite and pumpellyite. The data from that study provide useful constraints on which to examine the chlorite minerals from the Variscan metabasites.

A plot of non-interlayer cation total v. total Al content is shown for chlorite from the present samples in Figure 2. All samples have high cation totals (>19.5) and fall close to the end-member clinochlore. As shown the present data overlap with the means and 1 sigma ranges in chlorite from zones 3 and 4 of the Welsh and Greenland samples and there is no distinction in chemistry between chlorite from the anchizone and epizone. The proportions of chlorite layers (x) in mixed-layer chlorite/smectite, calculated from the phyllosilicate microprobe analyses of 29 samples for which data are available (Barnes and Andrews, 1981; Floyd and Rowbotham, 1982; Primmer, 1985), are shown plotted against the temperature derived

from the chlorite geothermometer (Cathelineau, 1988) in Figure 3. The x values are c. 0.85 (x = 0.87) for the anchizone, and > 0.85 (x 0.91) for the epizone samples. Temperatures are in the range 250 to 350°C and there is a separation between the anchizone and epizone temperatures with respective means of 271°C (±16) and 312°C (±22) (Figure 3). These mean temperatures are almost identical to the values given by Bevins *et al.* (1991) for chlorites from zones 3 (263°C) and 4 (309°C) of metabasites from Wales and Greenland. The values are also in good agreement with temperatures of 270 to 320°C reported for fluid inclusions from the Padstow area (Pamplin, 1990).

As indicated earlier Bevins *et al.* (1991) showed that there is a strong correlation between MgO/(MgO+FeO$_t$) in whole rock and chlorite. This correlation is shown in Figure 4 along with the samples from the present study for which there is whole rock data, and it can be seen that the present data similarly shows this same strong correlation.

Pumpellyite

Pumpellyite compositions are generally Al-rich with a range from 70.5 to 83.2% (Table 2) of this component in the triangular Al-Fe-Mg field. Such compositions are generally similar to those reported from the Roseland (Barnes and Andrew, 1981) and Padstow (Floyd and Rowbotham, 1982) areas, and are often taken as indicative of higher pressure metamorphism. However, reliance on individual mineral compositions as indicators of grade is unreliable as shown later. The pumpellyite compositions show a wide range in MgO/(MgO + FeO,) ratio which are partly controlled by whole rock compositions as also shown later.

Actinolite

In the metabasites of the region amphiboles commonly occur, ranging from ferro-hornblende (Primmer, 1985a) and kaersutite (Floyd and Rowbotham, 1982) to dominant actinolite (Primmer, 1985a). Typically the needle-like actinolite (Table 3) overgrowing pyroxene is related to the regional low grade metamorphism, whereas other amphiboles are pre-metamorphic in origin (Primmer, 1985a) and are not considered here. A similar feature involving pre-metamorphic ferro-hornblende and regional metamorphic actinolite was reported for the Welsh metabasites (Bevins and Robinson, 1993).

Paragenetic Relationships

Three samples from the anchizone, and one from the epizone have pumpellyite and chlorite and their relationships in the epidote projection are shown in Figure 5. The anchizone samples (SW65, F & R and 18/9B) show pumpellyite-chlorite tie-lines that are positive and sub-parallel with $K_{D\ pmp-chl}$ Mg-Fe values of 0.4 -0.72. The epizone sample (252) has a tie line that is oblique, and a $K_{D\ pmp-chl}$ of 0.32 suggesting that this sample is not representative of the same metamorphic conditions, and the pumpellyite may well be a relict phase. For the sample F & R (Floyd and Rowbotham 1982) the radiating pumpellyite grains showed variation from Fe-rich (0.37) to Mg-rich (0.64) analyses; the Fe-rich variety shows similar relationships to other samples, while the slope for the Mg-rich type is steeply negative (F & Ra) and cuts across the other tie lines, suggesting disequilibrium relationships.

All samples from areas of epizone IC values, and one sample (365) from an anchizone area, contain chlorite-actinolite whose relationships in the epidote projection are shown in Figure 5. Here eight samples show negative slopes and have sub-parallel tie lines suggestive of metamorphism at similar conditions. The $K_{D\ act-chl}$ Mg-Fe values lie between 1.30 and 1.53 with a mean of 1.40 (1 = ± 0.16). Of the three remaining samples, two show steeply positive tie lines with $K_{D\ act-chl}$ values of 0.83 and 0.95 (365 & 426), while the final one (477) has a much shallower negative slopes with a $K_{D\ act-chl}$ value of 2.60. The sharply crossing tie-lines for these three samples probably reflects disequilibrium relations between these minerals.

DISCUSSION OF THE METAMORPHIC CONDITIONS

Chlorites from the anchizone and epizone areas of south-west England approach near-ideal end-member clinochlore with a minimum of mixed-layer swelling saponite component. The compositions are compatible with chlorites reported from prehnite-pumpellyite and lowest greenschist facies metabasites in Wales and Greenland (Bevins *et al.*, 1991). Application of the chlorite geothermometer (Cathelineau, 1988) to the available data suggests there is a small increase in temperature of metamorphism between the metabasites from the anchizone (c. 270°C) and epizone (c. 310°C) regions.

The samples from the anchizone areas with chlorite - pumpellyite assemblages appear diagnostic of prehnite-pumpellyite facies with K_D $_{pmp-chl}$ values in the range 0.4 to 0.7, which is similar to the ranges reported by Bevins and Robinson (1993) for metabasites from the diagenetic and anchizone (0.3 -0.6; x = 0.42) and epizone (0.4 - 0.8; x = 0.52) metabasites of the Welsh Basin. However, the MgO/(MgO + FeOt)$_{chl}$ ratio for sample 18/9B at 0.63, lies above the critical value of 0.54 at which a chlorite-actinolite assemblage would be expected if grade had been higher than that of the prehnite-pumpellyite facies.

Eight samples from epizone areas with actinolite-chlorite assemblages have sub-parallel tie lines and a K_D $_{act-chl}$ range of 1.30 - 1.53 with a mean of 1.40. These values are higher than those reported for Welsh metabasites in the transition from prehnite-pumpellyite to greenschist facies of 0.93 -1.40, and a mean of 1.17 (Bevins and Robinson, 1993). The range is, however, similar (1.26 - 1.65), with a near identical mean (1.40) to greenschist facies metabasites from the Welsh Basin (Bevins and Robinson, 1993).

Of the remaining three samples with chlorite-actinolite assemblages, 477 has a shallow slope and high K_D $_{act-chl}$ value (4.3) and although it is situated well within an epizone area, the tie lines are indicative of non-equilibrium relationships between these minerals. Of the final two samples with non-compatible tie lines, sample 426 is close to the edge of the Lands End intrusion and it is possible that there may be some contact effect that has disrupted the regional metamorphic parageneses. Sample 365 lies very close to the anchizone/epizone boundary and has actinolite. The MgO/(MgO + FeO$_t$)rock ratio is 0.63 and thus is above the critical value of 0.54 at which chlorite-actinolite develops rather than chlorite-pumpellyite, and the presence of actinolite in this sample is representative of the lowest grade at which the actinolite-in reaction may occur.

In the Roseland area of Cornwall, the pumpellyite-actinolite assemblage and the similarity of the pumpellyite Al-rich compositions to those in pumpellyite-actinolite and glaucophane schist facies, have been used as evidence for the higher pressure pumpellyite-actinolite facies metamorphism (Barnes and Andrews, 1981). The pumpellyite-actinolite facies was regarded as being of regional extent from the Roseland area southwards to include the Menage Formation just north of the Lizard thrust, as a unit structurally underlying the Lizard Complex (Barnes and Andrews, 1984). However, of the samples from the Roseland area examined here, three out of four have chlorite - actinolite tie lines and K_D $_{act-chl}$ values (446 =1.30; 262 = 1.48; 163 = 1.35 and 447 = 4.35) that are entirely compatible with greenschist facies assemblages (mean K_D $_{act-chl}$ = 1.40) from Welsh metabasites that have been shown to belong to a low-pressure facies series (Robinson and Bevins, 1986; Bevins and Robinson, 1993). Additionally, in the higher pressure pumpellyite-actinolite facies, the actinolite -chlorite tie lines are shallower and K_D $_{act-chl}$ mean value is higher, as for example from the eastern Sierra Nevada in California at 1.76 (Bevins and Robinson, 1994) and for the Loeche area of Switzerland at 1.72 (Coombs *et al*, 1976). The metamorphism in the Roseland area is thus compatible with low pressure greenschist facies conditions rather than the higher pressure pumpellyite-actinolite facies. Finally, it is of note that Floyd and Rowbotham (1982) showed that pumpellyite compositions in metabasites from the Padstow area were similar to those reported by Barnes and Andrews (1981) from Roseland. The Padstow area is, as demonstrated here and by various previous authors (e.g. Floyd and Rowbotham, 1992; Primmer,

sample	58	74	75	262	263	446	447	365	477	433	426
SiO_2	54.45	54.04	54.1	55.4	53.91	54.06	56.03	54.9	55.04	54.14	48.07
TiO_2	0	0	0	0.07	0	0	0	0.05	0.07	0	0
Al_2O_3	2.23	1.67	1.53	2.7	3.44	2.31	1.79	1.76	2.71	1.96	6.61
FeO	10.05	12.48	13.47	8.31	14.38	12.14	9.74	16.34	10.39	9.54	22.06
MnO	0	0	0.04	0.1	0.24	0.34	0.16	0.22	0.24	0.12	0.62
MgO	17.47	15.45	14.82	18	13.79	15.96	17.35	13.39	16.45	18.18	8.58
CaO	12.66	13.31	12.98	12.9	12.49	12.89	12.88	12.64	13.14	12.57	11.95
Na_2O	0.48	0	0	0.44	0.4	0	0	0	0	0	0.87
Total	97.34	96.95	96.94	97.92	98.65	97.70	97.95	99.30	98.04	96.51	98.76
Si	7.76	7.83	7.87	7.78	7.73	7.76	7.90	7.88	7.79	7.76	7.21
Ti	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00
Al	0.37	0.29	0.26	0.45	0.58	0.39	0.30	0.30	0.45	0.33	1.17
Fe_2	1.2	1.51	1.64	0.98	1.72	1.46	1.15	1.96	1.23	1.14	2.77
Mn	0.00	0.00	0.00	0.01	0.03	0.04	0.02	0.03	0.03	0.01	0.08
Mg	3.71	3.34	3.21	3.77	2.95	3.41	3.64	2.86	3.47	3.89	1.92
Ca	1.93	2.07	2.02	1.94	1.92	1.98	1.95	1.94	1.99	1.93	1.92
Na	0.13	0.00	0.00	0.12	0.11	0.00	0.00	0.00	0.00	0.00	0.25
AF*	-0.37	-0.41	-0.4	-0.37	-0.35	-0.36	-0.38	-0.37	-0.37	-0.34	-0.27
MgO/(MgO+FeO)	0.76	0.69	0.66	0.79	0.63	0.70	0.76	0.59	0.74	0.77	0.41

Table 3.

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1985a, b), at prehnite - pumpellyite facies with illite bo values indicative of a low-pressure fades series (Primmer, 1985a; Warr *et al,* 1991). Thus, the use of mineral chemical variation alone as a means of defining grade is an unreliable method, and petrogenetic analysis is required in order to allow the most realistic interpretations of metamorphic conditions.

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