

# Metamorphism and mineral chemistry of greenschists from Trebarwith Strand, Cornwall

DOUGLAS ROBINSON  
DAVID READ

---



Douglas Robinson and David Read 1981. Metamorphism and mineral chemistry of greenschists from Trebarwith Strand, Cornwall *Proc. Ussher Soc.*, 5, 132-138.

Variscan regional metamorphism of the Tintagel Volcanic Formation has produced typical greenschists with abundant chlorite plus biotite, celadonic muscovite, albite, epidote plus accessories. The mineral chemistry of the layer silicates, as determined by electron microprobe, is closely comparable to mineral compositions from greenschists of the biotite zone in eastern Otago, New Zealand. The chemical relationships are suggestive of equilibrium such that the presence of porphyroblastic minerals overgrowing the dominant foliation is interpreted as the result of regional metamorphism continuing after cessation of deformation.

*Douglas Robinson, Department of Geology, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR; David Read, Department of Geology, University College, Gower Street, London WC1E 6BT.*

## Introduction

The rocks exposed between Padstow and Bude on the Cornish coast, south-west England are largely of Upper Devonian and Carboniferous age. The succession is dominantly clastic in character, but in the northern part of this coastal section the Tintagel Volcanic Formation (TVF) is exposed (Freshney and others 1972). The area suffered deformation and low-grade regional metamorphism during the Variscan orogeny; subsequently an over-printed contact metamorphism was established in the aureoles surrounding the intrusive Hercynian granites (Phillips 1962). The regional metamorphism produced slates and phyllites from pelitic rocks while greenschists were derived from the TVF.

The metamorphism of the area has been relatively neglected but in the early works of Tilley (1925) and Phillips (1928) a variety of metamorphic minerals was described including muscovite, biotite, chlorite, chloritoid, feldspar and epidote. A study of illite crystallinity by Brazier and others (1979) was indicative of a narrow zone of greenschist facies in the Trebarwith Strand to Boscastle area with a lower grade 'anchizone' to both the south and north. A distinctive feature seen in both the pelites and greenschists of the area is the development of porphyroblastic minerals growing across the foliation in a random orientation. This textural relationship was given as evidence by Freshney and others (1972) for more than one episode of metamorphism and in particular the development of such textures was thought to be the result of an overprinted contact metamorphic event possibly arising from the

intrusion of the Bodmin granite. The presence of these rocks some 6km from the granite, and well outside the aureole, was attributed to subsequent tectonic movements.

## Samples

Two samples (SW and SW13A) of fine to medium grained greenschist were collected from the outcrop at Trebarwith Strand. Both samples have a very strong foliation which is mainly formed by the alignment of the dominant mineral chlorite. Also both samples have muscovite, quartz and feldspar present with disseminated sphene and opaques plus small amounts of epidote. In addition sample SW13A has 'knots' of porphyroblastic feldspar (up to 2mm in size) growing across the foliation. Laths of biotite up to 0.5mm in length are also present; some occur parallel to the foliation but most are arranged in random orientation.

## Experimental

Whole-rock and mineral chemical analyses have been undertaken on the samples. Whole-rock major and trace element analysis was undertaken using a Siemens SRS200 automatic X-ray fluorescence spectrometer with on-line PDP 11/04 computer control. The general methodology

Table 1. Whole rock analyses

	SW	SW13A
SiO <sub>2</sub>	42.82	44.05
Al <sub>2</sub> O <sub>3</sub>	15.86	18.91
TiO <sub>2</sub>	2.1	3.09
F <sub>2</sub> O <sub>3</sub>	7.43	2.79
FeO	4.34	9.64
MgO	8.06	5.16
CaO	9.07	4.92
Na <sub>2</sub> O	0.23	1.91
K <sub>2</sub> O	4.03	2.77
MnO	0.15	0.09
P <sub>2</sub> O <sub>5</sub>	0.19	0.39
H <sub>2</sub> O	4.11	4.18
CO <sub>2</sub>	<u>3.01</u>	<u>1.88</u>
	99.4	99.78
Rb	75	58
Sr	106	103
La	12	16
Ce	22	36

of Harvey and others (1973) was followed for major elements and that of Robinson and Bennett (in press) for trace elements. FeO, H<sub>2</sub>O and CO<sub>2</sub> were determined by standard, wet-chemical techniques. Mineral analyses were made using a Cambridge Geoscan electron microprobe with an energy dispersive system (Dunham and Wilkinson 1978).

## Whole-rock chemistry

The whole-rock analyses are presented in Table 1. Both samples are obviously hydrous and have in excess of 4% H<sub>2</sub>O + and both also show CO<sub>2</sub> greater than 1%, indicative of carbonate content. A pointer to a pelitic origin can generally be taken when K<sub>2</sub>O is in excess of Na<sub>2</sub>O combined with MgO greater than CaO; which can be seen in the case of sample SW13A but not SW. Compared to the greenbeds in the Scottish Dalradian (Van de Kamp 1970) the samples described here are poorer in SiO<sub>2</sub> and Na<sub>2</sub>O but richer in K<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub>. Van de Kamp (1970) showed some distinctive trace element ratios between Dalradian greenbeds and pelites. In the case of Rb/Sr the samples have values of 0.71 (SW) and 0.56 (SW13A) which are intermediate between Dalradian pelites (L37) and greenbeds (0.14). The La/Ce ratios of 0.55 (SW) and 0.44 (SW13A) are similar to the Dalradian pelites (0.4) but more than double that of the greenbeds (0.2).

The variation in chemistry is perhaps best explained in terms of a volcanoclastic origin for these samples With a mixture of volcanic and detrital material. As such they would have a very similar origin to greenschists described by Brown (1967) from the Otago schists of New Zealand.

## Mineral chemistry

### *Chlorite*

Chlorite is dominant in both samples and mean analyses, based on a total of 32 point analyses, are presented in Table 2. Total iron is presented as FeO, and in this state the total occupancy of the Y cations is near the ideal number of 6 in the unit formula Y<sub>6</sub>Z<sub>4</sub>O<sub>10</sub>(OH)<sub>8</sub>. The chlorites lie in the ripidolite field using Hey's (1954) classification, as is normal with metamorphic chlorites (Miyashiro 1973). The Si contents (Table 2) similarly are in the normal range of 2.5 to 3.0 per O<sub>10</sub>(OH)<sub>8</sub> for metabasites. The two chlorites show different Mg/(Mg+Fe) ratios of 0.69 (SW) and 0.48 (SW13A) probably reflecting whole-rock variation where values are 0.58 and 0.46 respectively. An appreciable range in Mg/(Mg+Fe) was recorded by Brown (1967) in chlorites from greenstones of low greenschist facies in eastern Otago (Fig. 1a). Although the chlorite from SW lies outside the range shown by Otago chlorites (Fig. 1a) it still lies in the typical metabasite range of 0.5 to 0.9 (Miyashiro 1973). The small range in Al/(Fe+Mg) seen in Otago chlorites (Brown 1967) is similarly matched in the range and absolute values recorded here (Fig. 1a). X-ray diffraction analysis of magnetically separated chlorite from both samples has shown that all the diagnostic reflections expected for the 11b polytype (Hayes 1970) are present. This is the polytype of common metamorphic and igneous chlorites.

### *Muscovite*

Muscovite is subordinate to chlorite in both samples. The mean analyses are presented in Table 2; total iron is given as F<sub>2</sub>O<sub>3</sub> as in this state the octahedral occupancy lies close to the ideal value of 2.0 per O<sub>10</sub>(OH)<sub>2</sub>. The muscovite compositions depart considerably from an idealized muscovite in which one in four of the tetrahedral sites are occupied by Al, and Al is dominant in the octahedral position. The muscovites do, however, have a true mica structure in that they possess a high inter-layer occupancy of greater than 0.90 (Table 2). The higher Si occupancy in the tetrahedral position and greater substitution of Al by Fe and Mg in the octahedral position shows that the compositions lie in the series between an ideal trisilic muscovite - K Al<sub>2</sub> (Si<sub>3</sub>Al) O<sub>10</sub>(OH)<sub>2</sub> -- and the tetrasilic celadonite K(MgFe<sub>2</sub> (Fe<sub>3</sub>+Al). Si<sub>4</sub> O<sub>10</sub>(OH)<sub>2</sub>. Such celadonic muscovites (phengites of some authors) are typical of low-grade metamorphic rocks where observed solid solution reaches up to 50 mol.% of the tetrasilic variety (Miyashiro 1973).

Although the controls on the amount of substitution are complex and cover factors such as host-rock composition (Guidotti 1969), pressure/temperature (Cipriani, Sassi and Scolari 1971) and PH<sub>2</sub>O (Ernst 1963) the muscovite compositions fall within the compositional limits of muscovite from Otago (Brown 1967) as shown in Fig. 1b.

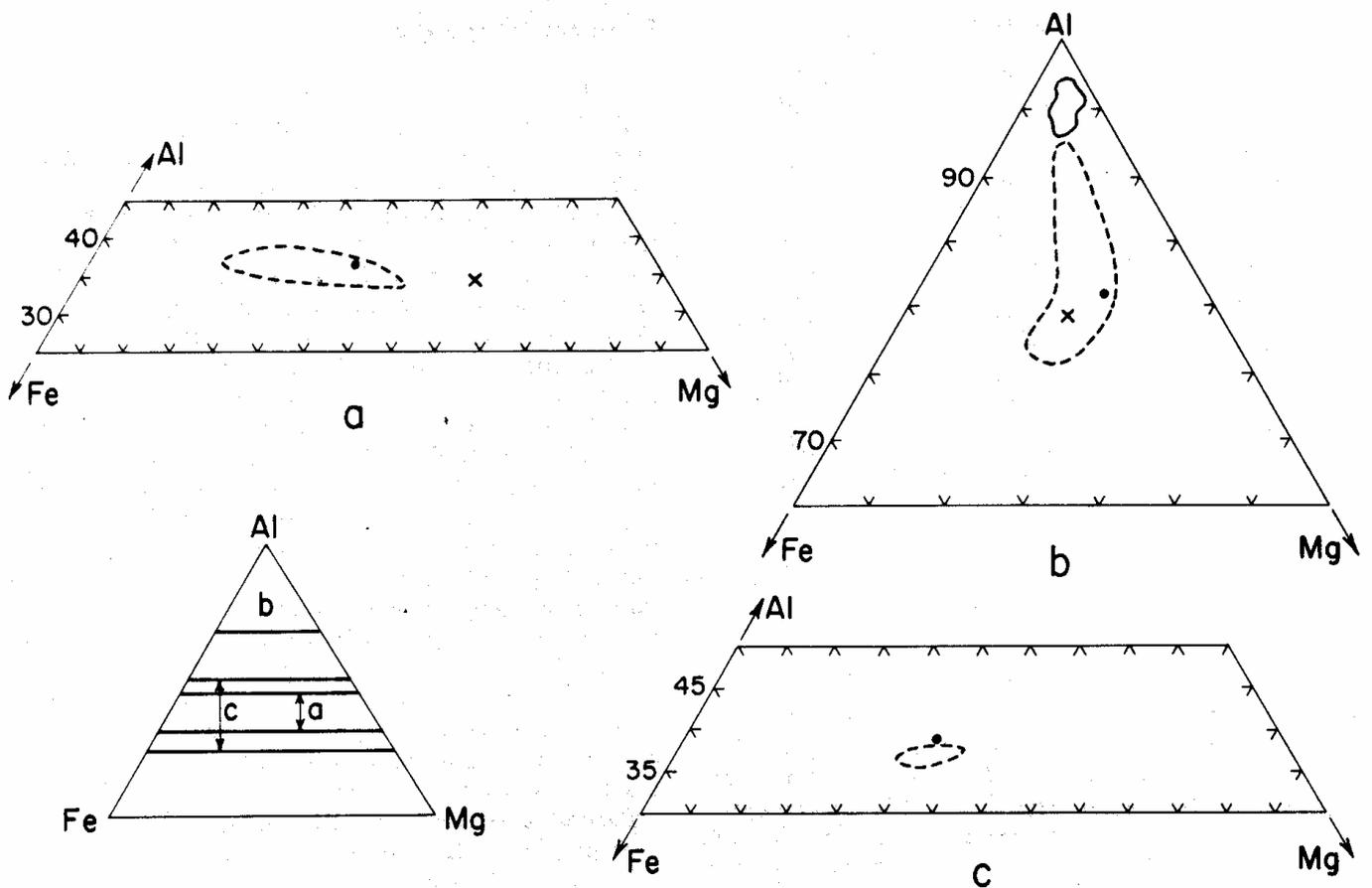


Figure 1. Mineral compositions in atomic % on a segment of Al-Fe-Mg diagram. (a) Chlorite; (b) Muscovite; (c) Biotite. Compositional fields enclosed by dashed lines represent the mineral ranges in eastern Otago (Brown 1967). Area enclosed by solid line is the compositional field of muscovites from higher grade terrains in Sierra de Guadarrama and western Maine (Ruiz and others 1980).  
 • Sample SW13A  
 X Sample SW

As shown also in Fig. 1b the substitution seen in muscovites from low-grade areas is substantially greater than muscovites from higher-grade regions such as Sierra de Guadarrama and western Maine (Ruiz and others 1980).

#### Biotite

Biotite was only recorded in sample SW13A where it occurs both oblique and parallel to the foliation. Analyses of both types show virtually no compositional differences (Table 2). The Al/(Mg+Fe) ratio of the biotites is similar to those from Otago (Brown 1967) as seen in Fig. 1c, but is lower than biotites from other areas as compiled by Brown (1967) and Ruiz and others (1978).

#### Feldspar

In sample SW 13A feldspar occurs as granular crystals set within the matrix and also as porphyroblasts

overgrowing the foliation. The granular crystals are virtually pure albite, while the porphyroblastic crystals, although dominantly albitic, have some 10% of the potassic end-member (Table 2).

#### Epidotes

The epidotes, as is common in low-grade metamorphism, show substantial replacement of Al by Fe (Table 2). In sample SW13A substitution by Fe<sup>3+</sup> is 30% while in sample SW it reaches some 42%. No noticeable zoning was recorded in the epidote crystals. High levels of substitution were also recorded by Raith (1976) in epidotes from greenschist facies rocks in Austria. He recorded an average Fe<sup>3+</sup> substitution of 42% in magnetite-bearing rocks belonging to the greenschist facies.

### Discussion

The mineral assemblage chlorite-muscovite-albite is not totally diagnostic of the grade of metamorphism. The presence of biotite - in the absence of K-feldspar and with celadonic muscovite present (Winkler 1976) - should be unequivocal. It should be recalled, however, that the biotite grows oblique to the foliation and Freshney and others (1972) have, on the basis of this fabric, interpreted it as belonging to a quite separate and later contact metamorphic event. This event was suggested to be associated with a phase of metasomatic introduction of  $K_2O$ , which was supported by the tentative identification of porphyroblasts of orthoclase feldspar. The present identification of porphyroblasts of albite feldspar with only a small component of the orthoclase end-member throws doubt on this interpretation. The mineral chemistry relationships are now examined as an aid to establishing the grade of metamorphism and origin of the biotite.

The relation between Al:K:(Mg+Fe) in muscovite, chlorite and biotite is shown in Fig. 2. Although the muscovite and chlorite lie in the compositional fields of the same minerals from the chlorite zone of Otago, they do fall in the more restricted field of muscovites and biotites from the biotite zone (Brown 1967) - shown stippled in Fig. 2. Similarly the biotite in SW13A lies close to the biotite composition from Otago (Fig. 2). The typical greenschist assemblage for biotite grade in pelitic rocks at high  $PH_2O$  is shown in Fig. 3 after Ernst (1963). The muscovites recorded here show lower levels of substitution than the maximum recorded by Ernst (1963). Lower celadonic values could be realized through a reaction such as celadonic muscovite + chlorite  $\rightarrow$  idealized-muscovite + biotite + quartz +  $H_2O$ , and it is seen (Fig. 3) that muscovite in SW13A with biotite shows a lower celadonic content than that in sample SW without biotite. Such differences in celadonic content of

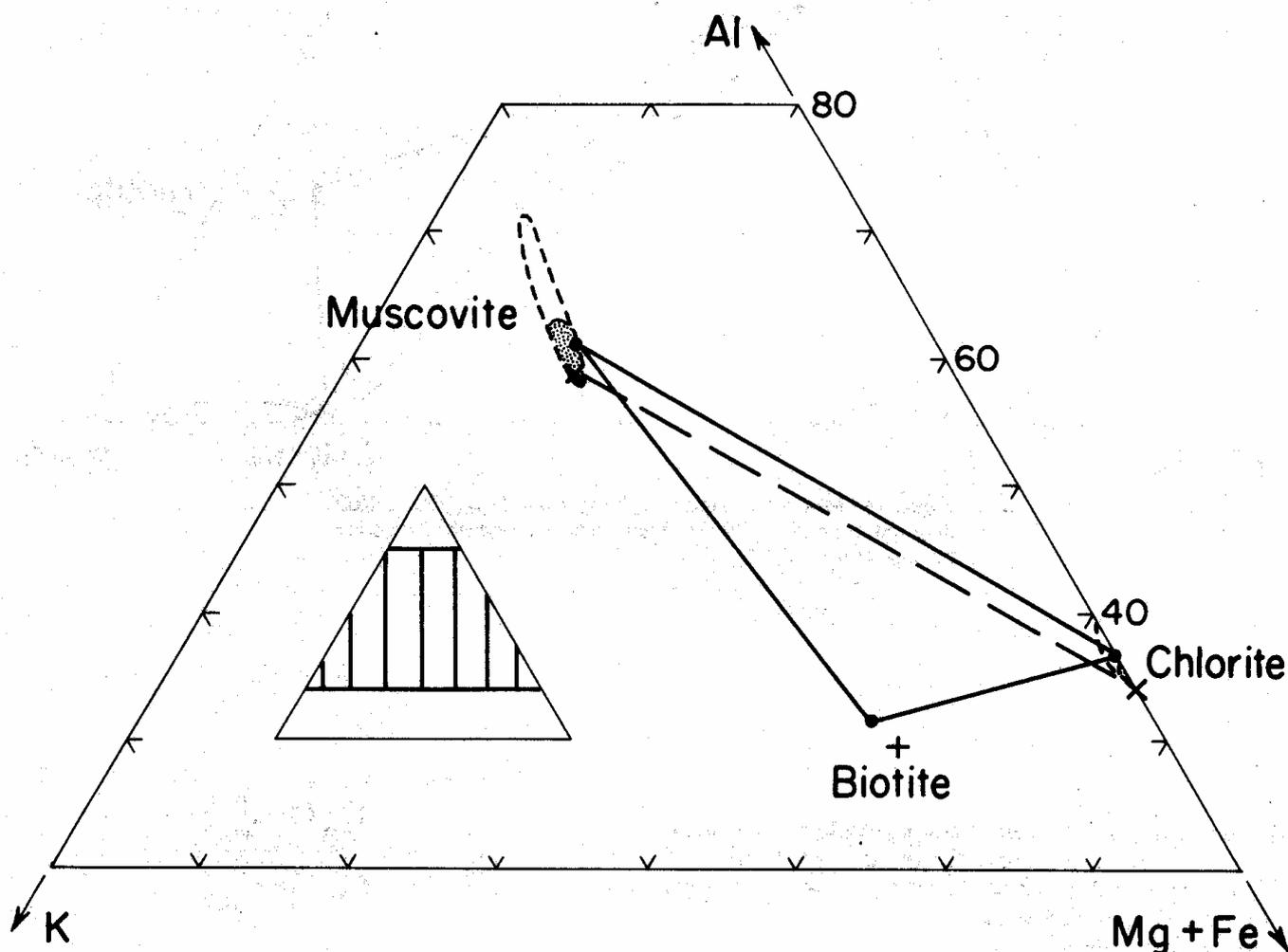


Figure 2. Coexisting minerals in segment of Al-K-(Mg+Fe) diagram, atomic %. Dashed line encloses compositional fields of muscovites and chlorites from the chlorite zone in eastern Otago; stippled areas represent the mineral compositional fields for biotite-bearing rocks of the biotite zone in the same area.

- Sample SW13A
  - x Sample SW
  - + Biotite composition from eastern Otago
- Eastern Otago data from Brown (1967).

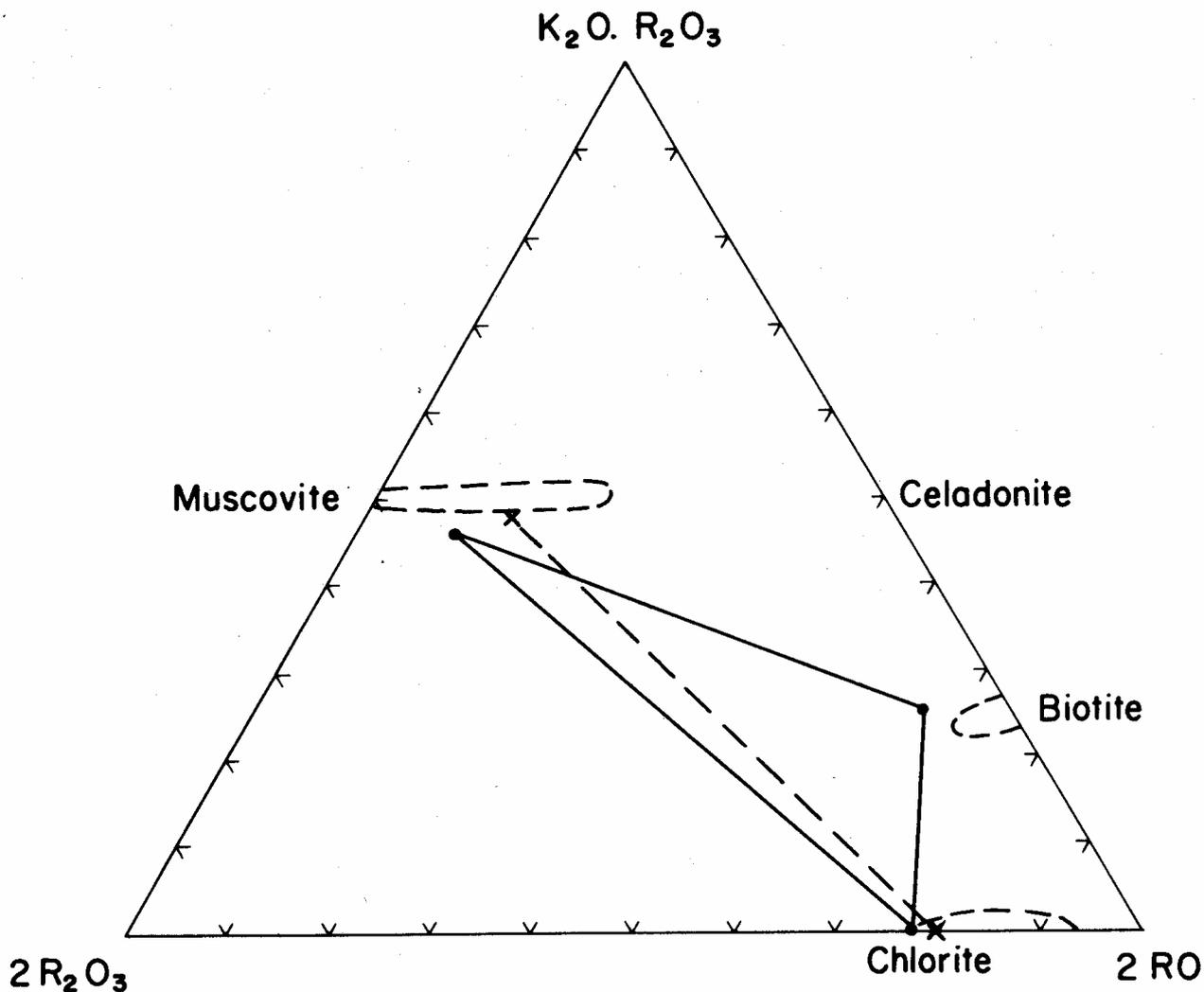


Figure 3. Mineral compositions on  $K_2O, R_2O_3-2R_2O_3-2RO$  diagram after Ernst (1963). Areas enclosed by dashed lines are schematic from fig. 2b of Ernst.

- Sample SW13A
- x Sample SW

the muscovites do not reflect simple Whole-rock control, as the relative molecular proportions of  $Al_2O_3:MgO+FeO$  is greater (after allowing for removal of all  $Na_2O$  as albite) in sample SW than SW13A. The chlorite in sample SW 13A with biotite also shows a less mafic and more aluminous character than in sample SW.

The distribution of Mg and total Fe+Mn between coexisting chlorite and biotite in eastern Otago was shown by Brown (1967) to have a relatively uniform distribution coefficient,  $K_D$ , of near unity.

$$K_D = \frac{X_{Mg}^C (1 - X_{Mg}^B)}{X_{Mg}^B (1 - X_{Mg}^C)}$$

where  $X_{Mg}^C = \frac{Mg}{Mg+Fe+Mn}$  in chlorite

and  $X_{Mg}^B = \frac{Mn}{Mg+Fe+Mn}$  in biotite

Table 2. Electron microprobe mineral analyses and unit formula

	Chlorite		Muscovite		Biotite			
	SW(12)	SW13A(20)	SW(9)	SW13A(3)	SW13A(13) <sup>1</sup>	SW13A(2) <sup>2</sup>		
SiO <sub>2</sub>	27.21	24.01	48.49	46.04	35.81	35.38		
Al <sub>2</sub> O <sub>3</sub>	20.36	20.90	26.85	29.17	17.06	16.88		
TiO <sub>2</sub>	nd	nd	0.30	0.58	2.04	2.08		
*Fe <sub>2</sub> O <sub>3</sub>			5.30	7.09				
+FeO	17.13	26.69			20.98	21.91		
MgO	21.50	14.05	2.88	1.91	9.35	9.20		
CaO	nd	nd	nd	nd	nd	nd		
Na <sub>2</sub> O	nd	nd	nd	0.12	nd	nd		
K <sub>2</sub> O	0.06	nd	10.82	10.65	9.77	9.06		
MnO	nd	0.09	nd	nd	nd	nd		
	<u>86.26</u>	<u>85.74</u>	<u>94.64</u>	<u>95.56</u>	<u>95.01</u>	<u>94.51</u>		
Si	2.79	2.62	Si	3.29	3.12	Si	2.76	2.77
Al	1.21	1.38	Al	0.71	0.88	Al	1.24	1.23
Σ	<u>4.00</u>	<u>4.00</u>	Σ	<u>4.00</u>	<u>4.00</u>	Σ	<u>4.00</u>	<u>4.00</u>
Al	1.25	1.31	Al	1.44	1.45	Al	0.31	0.32
Fe <sup>2+</sup>	1.47	2.44	Ti	0.02	0.03	Ti	0.12	0.12
Mg	3.28	2.29	Fe <sup>3+</sup>	0.27	0.36	Fe <sup>2+</sup>	1.35	1.42
K	0.01	0.00	Mg	0.29	0.20	Mg	1.08	1.07
Mn	0.00	0.01	Σ	2.02	2.04	Σ	2.86	2.93
	<u>6.01</u>	<u>6.05</u>	Na	0.0	0.02	K	0.96	0.90
			K	0.94	0.92			
			Σ	0.94	0.94			
	Epidote		Feldspar					
	SW(3)	SW13A(10)	SW13A(9) <sup>3</sup>	SW13A(3) <sup>4</sup>				
SiO <sub>2</sub>	36.99	38.44	68.23	65.44				
Al <sub>2</sub> O <sub>3</sub>	18.95	23.99	19.42	21.20				
TiO <sub>2</sub>	nd	nd	nd	nd				
*Fe <sub>2</sub> O <sub>3</sub>	20.80	13.30	nd	0.72				
+FeO								
MgO	nd	nd	nd	nd				
CaO	22.02	22.47	0.07	0.20				
Na <sub>2</sub> O	nd	nd	11.99	10.70				
K <sub>2</sub> O	nd	nd	nd	1.66				
MnO	98.56	98.20	99.71	99.92				
Si	3.00	3.03	Si	11.96	11.58			
			Al	4.02	4.42			
Al	1.79	2.23	Fe <sup>3+</sup>	0.0	0.10			
Fe <sup>2+</sup>	1.27	0.79	Ca	0.01	0.04			
Σ	3.06	3.02	Na	4.08	3.67			
Ca	1.91	1.90	K	0.0	0.38			
			Ab	99.8	89.7			
			An	0.2	1.0			
			Or	0.0	9.3			

Number of cations based on a total cationic charge of 28-chlorite; 22-muscovite and biotite; 2S-epidote; 64-feldspar. Figures in brackets refer to the number of point analyses for which the mean is presented. Superscripts 1 and 2 for biotites refer to analyses for grains oblique and parallel to the foliation respectively. Superscripts 3 and 4 for feldspars refer to analyses of granular and prophyroblastic grains respectively.

\*Total iron as Fe<sub>2</sub>O<sub>3</sub>; + Total iron as FeO; nd - not detected.

The  $K_D$  of the chlorite/biotite pair in SW13A is 1.2, which is not dissimilar from the values used by Brown (1967) to suggest equilibrium between these two minerals. The distribution coefficient for Mg and all octahedral cations in coexisting muscovite and chlorite is similar in both samples at 0.14 (SW) and 0.17 (SW13A). Calculated  $K_D$  for Brown's (1967) Samples 5 (0.20) and 199 (0.16) are very similar to our values but dissimilar to his samples 13 (0.35) and 49 (0.38).

These initial chemical data and mineral relationships, especially when compared with the greenschist assemblages in Otago, suggest that equilibrium is not an unreasonable interpretation. The metamorphism, therefore, can be taken as greenschist facies, and as such agrees with the findings of Brazier and others (1979) based on illite crystallinity. The grade within the greenschist facies can be taken as that of the biotite zone. The interpretation presented here suggests that the biotite is a stable phase belonging to the regional metamorphic event and not the result of a later contact metamorphic event. Thus the growth of biotite would have occurred after the deformation event, which gave rise to the foliation in these rocks, and under static conditions.

*Acknowledgements.* Professor J. Zussman, University of Manchester is thanked for allowing the use of the electron microprobe and Mr D. Plant for help with the analyses. Dr S.C. Matthews is thanked for his constructive criticism of the text.

## References

- Brazier, S., Robinson, D. and Matthews, S.C. 1979. Studies of illite crystallinity in southwest England. Some preliminary results and their geological setting. *N. Jb. Geol. Paläont. Mh., II*, 641-662.
- Brown, E.H. 1967. The greenschist fades in part of eastern Otago, New Zealand. *Contr. Mineral. Petrol.*, 14, 259-292.
- Cipriani, C., Sassi, F.P. and Scolari, A. 1971. Metamorphic white micas: definition of paragenetic field. *Schweiz. Miner. Petr. Mitt.*, 51, 259-302.
- Dunham, A.C. and Wilkinson, F.C.F. 1978. Accuracy, precision and detection limits of energy-dispersive electron-microprobe analyses of silicates. *X-ray spectrom.*, 7, 50-56.
- Ernst, W.G. 1963. Significance of phengitic micas from low-grade schists. *Am. Mineral.*, 48, 1357-1373.
- Freshney, E.C., McKeown, M.C. and Williams, M. 1972. Geology of the coast between Tintagel and Bude. *Mem. Geol. Surv. Gt. Br.* 92pp.
- Guidotti, C.V. 1969. A comment on: "Chemical study of minerals from the Moine schists of the Ardnamurchan area, Argyllshire, Scotland" by B.C.M. Butler and its implications for the phengite Problem. *J. Petrol.*, 10, 164-170.
- Harvey, P.K., Taylor, D.M., Hendry, R.D. and Bancroft, F. 1973. An accurate fusion method for the analysis of rocks and chemically related materials by x-ray fluorescence spectrometry. *X-ray spectrometry*, 2, 33-44.

- Hayes, J.B. 1970. Polytypism of chlorite in sedimentary rocks. *Clays Clay Miner.*, 18, 285-306.
- Hey, M.H. 1954. A new review of the chlorites. *Min. Mag.*, 30, 277-292.
- Miyashiro, A. 1973. *Metamorphism and metamorphic belts.* George Allen and Unwin, London, 492pp.
- Phillips, F.C. 1928. Metamorphism in the Upper Devonian of north Cornwall. *Geol. Mag.*, 65, 541-556.
- Phillips, F.C. 1962. Metamorphism in south-west England. In: Coe, K. (Ed.): *Some aspects of the Variscan fold belt*, 109-128; Manchester (University Press).
- Raith, M. The Al-Fe(III) epidote miscibility gap in a metamorphic profile through the Penninic series of the Tauern window, Austria. *Contrib. Mineral. Petrol.*, 57, 99-117.
- Robinson, D. and Bennett, M.C. 1981. Routine XRF analysis of 19 trace elements in international standards. In press.
- Ruiz, L.J., Aparicio, A. and Cacho, G. 1978. Chemical variations in biotites during prograde metamorphism, Sierra de Guadarrama, Sistema Central, Spain. *Chem. Geol.*, 21, 113-129.
- Ruiz, L.J., Aparicio, A. and Cacho, G. 1980. Chemical variations of muscovites from the Sierra de Guadarrama metamorphic area, Sistema Central, Spain. *Geol. Rundschau*, 69, 94-106.
- Tilley, C.E. 1925. Petrographical notes on some chloritoid rocks. II. Chloritoid phyllites of the Tintagel area, Cornwall. *Geol. Mag.*, 62, 314-318.
- Van de Kamp, P.C. 1970. The green beds of the Scottish Dalradian Series: Geochemistry, origin, and metamorphism of mafic sediments. *J. Geology*, 78, 281-303.
- Winkler, H.G.F. 1976. *Petrogenesis of metamorphic rocks.* Springer-Verlag. New York. 320pp.