

Staurolite in a garnet-hornblende-biotite schist from the Lanterman Range, northern Victoria Land, Antarctica

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With 2 figures and 2 tables in the text

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Abstract: Staurolite is found as inclusions in a garnet-hornblende-biotite schist of the Late Precambrian (?) Wilson Group near Mount Bernstein (71°37'S, 163°07'E), Lanterman Range, northern Victoria Land, Antarctica. It is partly replaced by a gahnite (52 mole % ZnAl_2O_4)–margarite–muscovite–chlorite assemblage. We interpret the staurolite to be a relic of a staurolite–hornblende–garnet–biotite–quartz assemblage that formed at an early stage in the Cambro-Ordovician Ross metamorphic event at pressures of at least 6 kbar.

The staurolite [atomic $\text{Mg}/(\text{Mg}+\text{Fe}) = 0.20$] is relatively rich in TiO_2 (0.79 weight %) and ZnO (2.78 %) and poor in divalent cations (3.444 per 46 oxygens). In comparison with a staurolite from a tourmaline-talc-phlogopite-chlorite schist from the same area (GREW & SANDIFORD, 1984), the staurolite associated with hornblende contains more Si and less Al. A possible substitution relating the staurolite compositions is ${}^{\text{IV}}\text{Si}^{4+} + \text{O}^{2-} = {}^{\text{IV}}\text{Al}^{3+} + \text{OH}^-$. Garnet [$\text{Mg}/(\text{Mg}+\text{Fe}) = 0.39$ core, 0.33 rim] contains 16 mole % grossular, while hornblende is pargasite with 16.18–18.63 % Al_2O_3 . The Fe–Mg fractionation of the staurolite and garnet is reversed: $K_D = (\text{Mg}/\text{Fe})^{\text{St}}/(\text{Mg}/\text{Fe})^{\text{Gar}} = 0.4–0.5$. We attribute the reversal to reactions involving staurolite in isolation from garnet during the late stage of metamorphism, resulting in Fe-enrichment in staurolite and in relatively little change in garnet composition.

On the basis of pressure-temperature estimates, together with microstructural evidence, we suggest that rapid uplift followed soon after equilibration of the staurolite–garnet–hornblende assemblage, resulting in a pressure-temperature path convex towards the temperature axis. Such uplift was likely to have been induced by erosion of excessively thickened crust (60–75 km) formed during the early stage of the metamorphism.

Key words: Staurolite, crystal chemistry, mineral assemblage, garnet, hornblende, biotite, chemical analysis, genesis, P-T conditions, schist; Antarctica, Victoria Land.

Introduction

A renewed interest in staurolite petrogenesis has led to the report of unusual high-pressure staurolite assemblages, among which staurolite-hornblende has

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figured prominently (e.g. DEMANGE, 1976; GIBSON, 1978; SPEAR, 1982; PURTSCHELLER & MOGESSIE, 1984; SELVERSTONE *et al.*, 1984; WARD, 1984). We report here relics of staurolite in a garnet-hornblende-biotite schist from the Lanterman Range, northern Victoria Land, Antarctica. This staurolite-bearing schist (Sample No. R32094) was collected in November, 1981, 3.5 km northeast of a locality for another relatively high-pressure staurolite assemblage: staurolite–talc–corundum (Sample No. 4017E, GREW & SANDIFORD, 1984). In sample 4017E, staurolite and corundum occur as relics enclosed in tourmaline porphyroblasts in a talc-chlorite-phlogopite schist that is part of a lens of metamorphosed ultramafic rocks. We suggested that the talc–staurolite–corundum assemblage equilibrated at 7–10 kbar and 650–750 °C during an early stage of the metamorphic cycle affecting the Lanterman Range. In the present paper, we present petrologic and chemical data on the staurolite-bearing garnet-hornblende schist. These results provide further evidence for relatively high pressures during the early stages of metamorphism in the Lanterman Range.

Geologic background

The area around Mount Bernstein (71°37' S, 163°07' E), which is in the central part of the Lanterman Range, is underlain by a metasedimentary sequence, the Wilson Group, of probable Late Precambrian age (DOW & NEALL, 1974; WODZICKI *et al.*, 1982; GREW & SANDIFORD, 1982). The dominant rock type in this area is a fine-grained quartz-biotite-plagioclase schist. Metaconglomerate, calc-silicate granulite, muscovite-biotite schist, hornblende schists, and ultramafic rocks are subordinate. Metamorphic grade increases from northeast to southwest. The Lanterman Range is part of a northwest-trending belt of intermediate-pressure metamorphism developed during the Cambro-Ordovician Ross event (GREW *et al.*, 1984). Kyanite and staurolite are found locally in this belt, but andalusite has not been reported. In our earlier paper (GREW & SANDIFORD, 1984), we proposed a 3-stage metamorphic cycle for the Mount Bernstein area:

- 1) an early event at pressures 7–10 kbar and temperatures near 650–750 °C during which kyanite appeared locally in metapelitic schists,
- 2) an intermediate stage at 5–6 kbar and 650–700 °C during which fibrolitic sillimanite developed extensively (locally also prismatic sillimanite and K feldspar), and
- 3) a late stage at 3–5 kbar and 300–370 °C during which the metamorphic rocks were extensively retrograded.

Temperature during the early and middle stages in the vicinity of the locality where R32094 was collected were probably lower than 650–700 °C, for metamorphic grade appears to decrease northeastward from Mount Bernstein.

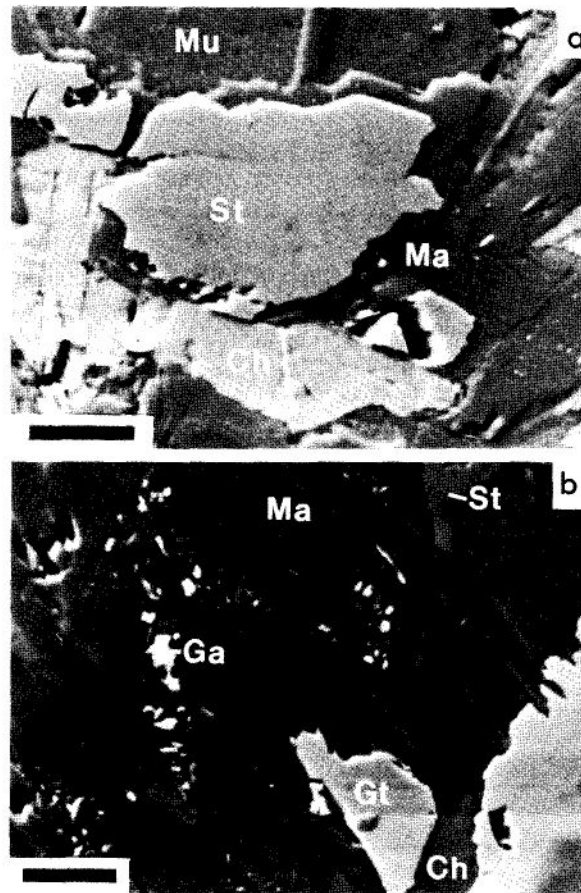


Fig. 1. Scanning electron microscope photographs of staurolite (St), margarite (Ma), muscovite (Mu), chlorite (Ch), zircon (Z), gahnite (Ga), and garnet (Gt) in sample R32094. Length of bar scale approximately 0.1 mm.

Petrography of the staurolite-bearing schist

Sample No. R32094 was collected from a pod 1 × 2 m across, which occurs in a quartz-mica schist containing subordinate garnet and hornblende. Major constituents of sample R32094 are garnet, hornblende, biotite, chlorite, muscovite, and epidote. Rutile, ilmenite, gahnite (approximately $\text{Zn}_{0.49}\text{Fe}_{0.34}\text{Mg}_{0.10}\text{Al}_{2.05}\text{O}_4$), staurolite, margarite, quartz, plagioclase, and zircon are subordinate. Garnet forms aggregates 0.5–2 cm across embedded in a schistose hornblende-rich matrix. Embayed grains of staurolite up to 0.3 mm across are enclosed in margarite (Fig. 1) in the core of one such garnet aggregate. Stau-

rolite is also in contact with chlorite and is separated from garnet by as little as 0.05 mm at one point; contacts of staurolite with other minerals were not found. Muscovite, chlorite, garnet, and gahnite are present in the margarite. Margarite touches garnet, but generally it is separated from garnet by a thin selvage of chlorite or muscovite. Hornblende, biotite, and quartz are found outside the garnet aggregates and as inclusions in garnet. Epidote is present in the garnet aggregates and schist, but not in contact with margarite, while rutile is found only as inclusions in garnet. Chlorite outside of the margarite aggregates appears to be derived from the alteration of biotite.

The precursor to the staurolite-bearing pod can only be inferred from its field association, which suggests that the pod recrystallized from a metasedimentary lens enriched in Ca and Al. However, available information does not preclude a volcanogenic contribution to the original lens.

Mineral compositions

Compositions of minerals in R32094 were determined by M. SANDIFORD on a JXA-5A wavelength dispersive instrument at the University of Melbourne and those in 4017E on a CAMEBAX wavelength dispersive instrument at the Ruhr-Universität Bochum (see GREW & SANDIFORD, 1984).

Staurolite composition appears to vary little from grain to grain and an average of several grains is given in Table 1. Although this staurolite's X_{Mg} [= atomic Mg/(Mg+Fe) ratio] of 0.20 lies in the normal range for staurolite, its TiO_2 content of 0.79 weight % and ZnO content of 2.78 weight % are relatively high (see RIBBE, 1982). Its total cation content per 46 oxygens is low: 29.143 compared to 29.33–29.58 for 20 staurolites analysed by GRIFFEN & RIBBE (1973). By comparison with staurolite associated with talc from the Mount Bernstein area (No. 4017E, GREW & SANDIFORD, 1984), staurolite in R32094 has less Al and more Si. However, the amounts of Al interpreted to be in octahedral coordination, expressed as Al' (= Al + Si – 8) in analyses recalculated to 46 oxygens anhydrous (equivalent to 44 O + 4 OH, see GRIFFEN et al., 1982), differ much less among the staurolites (Fig. 2). Moreover, the increased Si content in R32094 is not associated with an increased content of divalent cations. To a first approximation, the staurolite compositions in the two rocks are related by a substitution involving ^{18}Si and ^{18}Al , and to a lesser extent, ^{27}Al , while Fe, Mg, and Zn are not involved. As differences in Ti and Mn contents are minor (Co content is also expected to be minor in a metasedimentary or a metavolcanic rock), charge balance must involve Li or H, the two most important constituents of staurolite not listed in Table 1. Li most likely enters the tetrahedral Fe site (GREW & SANDIFORD, 1984; DUTROW et al., 1984; crystallographic sites based on the terminology of SMITH, 1968, are given in italics) and consequently substitutions that have been proposed to introduce Li also involve Fe:

Table 1. Compositions of ferromagnesian silicates in sample R32094.

	Staurolite	Hornblende		Garnet		Biotite
				Core	Rim*	
	Weight %					
SiO ₂	28.38	42.82	40.33	39.23	38.89	35.53
TiO ₂	0.79	0.36	0.69	—	—	1.81
Al ₂ O ₃	54.15	16.18	18.63	21.77	21.70	18.98
Cr ₂ O ₃	0.14	0.12	0.12	0.08	0.07	0.13
FeO	9.68	12.35	12.75	24.74	26.35	19.65
MnO	0.31	0.16	0.10	0.54	0.67	0.11
MgO	1.37	11.66	10.40	8.82	7.24	10.83
ZnO	2.78	—	—	—	—	—
CaO	—	11.02	10.77	6.05	6.11	—
Na ₂ O	—	2.06	2.18	—	0.06	0.17
K ₂ O	—	0.30	0.56	—	—	10.03
Total	97.60	97.03	96.53	101.23	101.09	97.24
	Cations					
Oxygens	46	23	23	12	12	22
Si	7.851	6.282	5.983	2.983	2.987	5.327
Al	0.149	1.718	2.017	—	—	2.673
Total	8.000	8.000	8.000	2.983	2.987	8.000
Ti	0.165	0.040	0.077	—	—	0.204
Al	17.504	1.081	1.241	1.951	1.965	0.682
Cr	0.030	0.014	0.014	0.005	0.004	0.015
Total	17.699	—	—	1.956	1.969	—
Fe	2.239	1.515	1.582	1.573	1.693	2.464
Mn	0.074	0.020	0.013	0.035	0.044	0.014
Mg	0.564	2.549	2.299	0.999	0.829	2.420
Zn	0.567	—	—	—	—	—
Total	3.444	5.219	5.226	—	—	5.799
Ca	—	1.732	1.712	0.493	0.503	—
Na	—	0.586	0.627	—	0.009	0.049
K	—	0.056	0.106	—	—	1.919
Total	—	2.374	2.445	3.100	3.078	1.968
Total						
Cations	29.143	15.593	15.671	8.039	8.033	15.768
Mg/(Mg+Fe)	0.20	0.63	0.59	0.39	0.33	0.50
All Fe as FeO						

* Contiguous to biotite.

$${}^{\text{IV}}\text{Li}(\text{Fe}) + {}^{\text{IV}}\text{Si}(\text{Si}) = {}^{\text{IV}}\text{Fe}(\text{Fe}) + {}^{\text{IV}}\text{Al}(\text{Si})$$

implied in the substitution proposed by SCHREYER & CHINNER (1966);

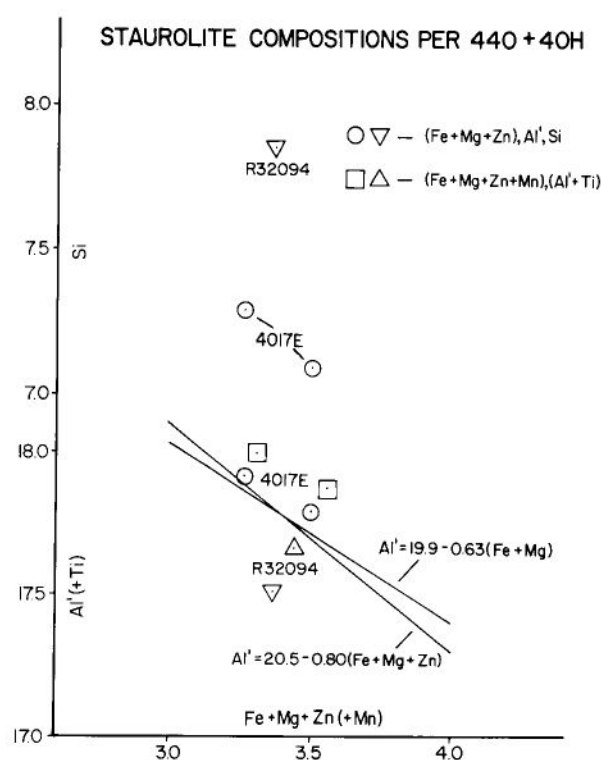


Fig. 2. Compositions of Lanterman Range staurolite recalculated on a Li-free basis per $44\text{O} + 4\text{OH}$. The line Al' (defined as $\text{Al} + \text{Si} - 8$) = $20.5 - 0.80(\text{Fe} + \text{Mg} + \text{Zn})$ is GRIFFEN et al.'s. (1982) "maximum likelihood line" and the line $\text{Al}' = 19.9 - 0.63(\text{Fe} + \text{Mg})$ is calculated from WARD's (1984) least square refinement of compositions of several New Zealand staurolites containing little zinc. Staurolite compositions are taken from Table 1 of this paper and from GREW & SANDIFORD (1984, Table 1). Two sets of points in the Al' vs $(\text{Fe} + \text{Mn} + \text{Mg})$ part of the diagram illustrate the effect of Ti and Mn.

$$^{14}\text{Li}(\text{Fe}) + ^{27}\text{Al}[\text{Al}(3\text{A},\text{B})] = 2^{14}\text{Fe}(\text{Fe})$$

(WARD, 1984; GREW & SANDIFORD, 1984; DUTROW et al., 1984).

A possible substitution not involving Fe is:

$$^{14}\text{Li}(\text{Fe}) + ^{14}\text{Al}(\text{Si}) = ^{14}\text{Si}(\text{Si})$$

However, the differences in Si contents between the staurolites in 4017E and that in R32094 are 0.56 and 0.76 atoms per formula unit, while the Li content in the 4017E (low-Si) staurolites is about 0.2 Li per formula unit (GREW & SANDIFORD, 1984; GREW, HINTHORNE & MARQUEZ, in prep.). Thus the Li contents are not sufficient to account for the difference in Si contents. This conclusion implies that charge balance is largely achieved with hydroxyl, i.e. $^{14}\text{Si}^{4+} +$

Table 2. Compositions of dioctahedral micas associated with staurolite.

Sample no. mineral	R32094 margarite	weight %	4017E muscovite*	
SiO ₂	31.29	30.12	45.69	45.01
TiO ₂	0.14	0.13	< 0.02	0.02
Al ₂ O ₃	48.41	49.06	34.58	35.23
Cr ₂ O ₃	0.01	0.05	≤ 0.02	≤ 0.02
FeO	0.86	0.59	0.29	0.23
MnO	0.01	0.04	≤ 0.02	≤ 0.02
MgO	0.39	0.33	1.15	0.84
CaO	10.98	12.04	0.09	0.09
Na ₂ O	1.75	1.11	0.19	0.17
K ₂ O	<0.01	0.01	11.21	11.21
Total	93.84	93.48	93.20	92.80
Cations per 22 oxygens				
Si	4.219	4.085	6.209	6.114
Al	3.781	3.915	1.791	1.856
Total	8.000	8.000	8.000	8.000
Ti	0.014	0.013	0.000	0.002
Cr	0.001	0.005	0.000	0.000
Al	3.912	3.926	3.747	3.811
Fe	0.097	0.067	0.033	0.026
Mn	0.001	0.005	0.000	0.000
Mg	0.078	0.067	0.233	0.170
Total	4.103	4.083	4.012	4.009
Ca	1.586	1.749	0.013	0.013
Na	0.458	0.292	0.050	0.046
K	0.000	0.002	1.944	1.952
Total	2.044	2.043	2.006	2.011
All Fe as FeO				

* Sericitic aggregate surrounding staurolite grain no. 2 and associated with margarite grains A–C (see Table 2, GREW & SANDIFORD, 1984), chlorite, and pumpellyite.

$O^{2-} = {}^{IV}Al^{3+} + OH^{-}$ (cf. LONKER, 1984, who reports no evidence for this substitution in a suite of staurolites analysed for H₂O). If the hydroxyl content of R32094 is significantly lower than the hydroxyl contents for 4017E, then the oxygen content assumed for the recalculation of the formula must be significantly higher, and as a result, the Al', total (Fe + Mg + Zn) and total cation contents for R32094 will also be higher than those listed in Table 2 or plotted in Fig. 2. Thus the differences in Al' between 4017E and R32094 may be less than those shown in Fig. 2, possibly less than analytical error, and a separate substitution involving Al' may not be needed to relate the compositions of these staurolites.

The composition of the R32094 staurolite lies 0.3 atom per formula unit from GRIFFEN *et al.*'s (1982) "maximum likelihood line", $Al' = 20.5 - 0.80 (Fe + Mg + Zn)$, which is based on 82 staurolite analyses, while the compositions of the 4017E staurolites plot close to this line (Fig. 2). However, if Ti is added to Al' (as recommended by SCHREYER *et al.*, 1984), and Mn to $(Fe + Mg + Zn)$, the deviation for R32094 is reduced to 0.05, but the deviations for 4017E are increased. We question the relevance of this "maximum likelihood line" to variations in staurolite composition, for it ignores Ti and Mn (see also DONNAY & DONNAY, 1983, who emphasized the need to consider Ti and Mn), as well as Li and H. Although the trend for staurolite compositions deduced by WARD (1984) for several Zn-poor New Zealand staurolites [$Al' = 19.9 - 0.63 (Fe + Mg)$], corresponding to the substitution $3 (Fe, Mg, Zn) = 2 Al$, may relate the two staurolite compositions in sample 4017E, it does not relate either of these two compositions with that of R32094 (Fig. 2).

Garnet is calcic (16% grossular) and its core composition is more magnesian ($X_{Mg} = 0.39$) than its rim composition ($X_{Mg} = 0.33$, Table 1). Hornblende is aluminous and approaches pargasite in composition.

Margarite compositions (Table 2) have the same features noted for margarite derived from staurolite in sample 4017E, in particular, an excess of ^{IV}Al and deficiency of Si relative to an ideal binary solid solution of paragonite, $Na_2Al_4(Al_2Si_6)O_{20}(OH)_4$, and margarite, $Ca_2Al_4(Al_4Si_4)O_{20}(OH)_4$ (GREW & SANDIFORD, 1984). We suggested that this excess of Al may in part be due to limited solid solution of ephesite, $Na_2Li_2Al_4(Al_4Si_4)O_{20}(OH)_4$ (e.g. LANGER *et al.*, 1981) in the margarite, for which the staurolite is a possible source of lithium. Ion microprobe analyses of sample 4017E have confirmed the presence of lithium in the margarite, associated staurolite, and paragonite (GREW, HINTHORNE & MARQUEZ, *in prep.*).

In addition, we analysed fine-grained (sericitic) muscovite associated with chlorite, margarite, pumpellyite, and relict staurolite in sample 4017E (Table 2). Phengite content of muscovite could give some indication of metamorphic pressure (see below). The muscovite is compositionally heterogeneous, for in the single sericitic patch analysed, Na_2O varies from 0.17–0.32 weight %, CaO , 0.09–0.84%; MgO , 0.65–2.05%, and FeO , 0.23–0.63%. The CaO is most likely present as finely intergrown margarite (on scale of a few microns, which is too fine to resolve with the electron microprobe) and probably does not represent solid solution towards margarite. Muscovite associated with margarite in other areas contains little CaO (e.g. GIBSON, 1979; GUMOTTI *et al.*, 1979; FREY *et al.*, 1982). Consequently, only analytical spots yielding CaO contents less than or equal to 0.10% can be considered as muscovite free of impurities (two analyses given in Table 2). The phengite content of these muscovites is low, as indicated by their Si contents of 6.144–6.209 atoms per 22 oxygens.

Interpretation of the assemblages

By analogy with the staurolite–talc assemblage in tourmaline-bearing schist at locality 4017 (GREW & SANDIFORD, 1984) we suggest that the staurolite in sample R32094 is a relic of the early, high pressure stage of metamorphism. Textures are consistent with the interpretation that garnet and staurolite were once in equilibrium. Moreover, as inclusions of hornblende, biotite, quartz, and rutile are also present in garnet, the stable assemblage at this stage could have been staurolite–garnet–hornblende–biotite–rutile–quartz. During the middle stage, staurolite appears to have been isolated from hornblende by garnet. During the late stage, staurolite was partially replaced by a gahnite–muscovite–margarite–chlorite assemblage. Ca and K for the micas could have originated from garnet, hornblende, and biotite, while ZnO released by staurolite formed a gahnite-rich spinel.

An anomalous feature of the mineral compositions in sample R32094 is the reversal of the Fe–Mg fractionation between staurolite and garnet, such that $K_D = (\text{Mg/Fe})^{\text{Sta}}/(\text{Mg/Fe})^{\text{Gar Core}} = 0.4$, and K_D for garnet rim, 0.5. Normally K_D is well above unity, that is, garnet is richer in iron than associated staurolite (e.g. ALBEE, 1972; HOLDAWAY, 1978). Other examples of reversed fractionation are: 1) staurolite associated with spessartine-rich garnet (11.9 weight % MnO) in quartz-mica schist (RUMBLE, 1978); 2) staurolite needles in hornblende and garnet in amphibolite from Ötztal, Austria (PURTSCHALLER & MOGESSIE, 1984); and 3) staurolite in a sapphirine-garnet rock from the Limpopo Belt (SCHREYER et al., 1984). Manganese in RUMBLE's (1978) garnet or calcium in the Antarctic (6.1 weight % CaO or 16 mole % grossular) and Ötztal (9.1 weight % CaO or 19 % grossular, PURTSCHALLER & MOGESSIE, 1984) may have been sufficient to disrupt Fe–Mg fractionation in these three samples, resulting in reversals. On the other hand, normal fractionation is reported in other cases where garnet grossular contents range from 6–18 mole % (DEMANGE, 1976; SPEAR, 1982; SELVERSTONE et al., 1984). The garnet in the Limpopo rock contains only 0.31 % CaO and 0.07 % MnO and the staurolite, negligible Li and Zn (SCHREYER et al., 1984). Thus Ca and Mn in garnet and Li and Zn in staurolite cannot be the cause of the reversals in all cases. With the exception of RUMBLE's (1978) sample, a common feature of staurolite-garnet assemblages with the reversed fractionation is that staurolite occurs in relatively small amounts and staurolite grains are significantly smaller than the grains of associated minerals. As a result, reactions involving staurolite and garnet may result in large shifts in staurolite composition and small shifts in garnet composition. Moreover, where staurolite and garnet are isolated from one another, reactions involving staurolite may have little, if any, effect on garnet composition. In sample R32094, where staurolite is not in contact with garnet, staurolite may have become significantly enriched in iron as it reacted to form mica, gahnite, and chlorite, while garnet Fe-enrichment remained relatively modest. In the Ötztal amphi-

bolite, some staurolite is enclosed in hornblende and has had only limited contact with garnet (PURTSCHELLER & MOGESSIE, 1984, Figs. 1–2). Such staurolite may have become enriched in iron by reactions with hornblende at the same time garnet composition remained relatively constant. This explanation would not apply to staurolite enclosed in garnet, also reported in the Ötztal rock by PURTSCHELLER & MOGESSIE (1984), nor to the Limpopo rock. In the latter, several of the analysed garnets are small grains in direct contact with the analysed staurolite, as well as large grains in the main mass of the rock (SCHREYER *et al.*, 1984). In sum, no single explanation may apply to all the reported cases of reversed Fe–Mg fractionation between garnet and staurolite. In the case of sample R32094, reactions of staurolite in isolation from garnet appear to be the most likely cause of the reversed fractionation.

Conditions of metamorphism

In general, the hornblende–staurolite association is characteristic of intermediate or high pressures (≥ 5 kbar) and intermediate temperatures (500–650 °C) of metamorphism. Examples are 560 °C and 5 kbar or more (kyanite only, DEMANGE, 1976), 535 ± 20 °C, 5–6 kbar (SPEAR, 1982), 600–650 °C and 10 kbar (M. L. CRAWFORD, pers. comm. to SELVERSTONE *et al.*, 1984), and a path passing from 520 °C and 9–10 kbar to 550 °C, 7 kbar (SELVERSTONE *et al.*, 1984). However, PURTSCHELLER & MOGESSIE (1984) cite an estimate of 560 °C and 3–4 kbar for the Hercynian metamorphism of the Ötztal staurolite. This pressure estimate is clearly at variance with the presence of kyanite in the Ötztal rock (according to the Al_2SiO_5 diagram of HOLDAWAY, 1971) and of eclogite in the Ötztal area, which was mentioned by PURTSCHELLER & MOGESSIE (1984).

Theoretical considerations also suggest a high-pressure origin of staurolite–hornblende relative to more usual amphibolite–facies assemblages. FROESE & HALL (1983) constructed a reaction grid for quartz-bearing pelitic and mafic rocks in which the reaction chlorite + garnet + plagioclase \rightarrow staurolite + hornblende takes place with an increase in pressure. This reaction extends to higher pressure from an invariant point (No. 13 in FROESE & HALL, 1983), the existence of which is supported by SPEAR's (1982) assemblage chlorite–garnet–hornblende–gedrite–staurolite. SPEAR (1982) estimated that this assemblage crystallized at 5–6 kbar, thereby providing a minimum pressure for FROESE & HALL's (1983) staurolite–hornblende stability field. SELVERSTONE *et al.* (1984) proposed that the following reaction would produce staurolite + hornblende in the presence of quartz: plagioclase + chlorite + epidote \rightarrow hornblende + staurolite \pm kyanite \pm paragonite (garnet may also be a reactant). According to SELVERSTONE *et al.* (1984), this reaction would proceed at a minimum pressure of 6 kbar in mafic rocks of relatively aluminous composi-

tion of which R32094 is probably an example. However, in "typical" mafic rocks, pressures required for this reaction would exceed 6 kbar. It is not clear from these authors' compositional plots why Al_2O_3 is the factor determining the pressure of this reaction. The formation of staurolite + hornblende in both SELVERSTONE *et al.*'s (1984) reaction and FROESE & HALL's (1983) reaction appears to involve a dehydration, and thus water activity may be an important factor controlling the pressure of staurolite + hornblende formation. Host rock Fe^{2+}/Mg and Fe^{3+}/Al ratios may also be critical; staurolite + hornblende could be favored by high Fe^{2+}/Mg or low Fe^{3+}/Al (in SELVERSTONE *et al.*'s reaction, hornblende + staurolite is iron-rich relative to chlorite, and possibly Fe^{3+} -poor relative to chlorite + epidote), and thus either of these conditions, as well as low $P_{\text{H}_2\text{O}}$, could shift the reactions to lower pressures.

In any case, metamorphic pressures of at least 6 kbar are indicated for sample R32094 during the early stage, when staurolite and hornblende are presumed to have been stable. This minimum is consistent with the 7–10 kbar estimated for the staurolite–talc assemblage at locality 4017 and the presence of kyanite at locality 4018 (GREW & SANDIFORD, 1984; GREW *et al.*, 1984). Temperatures of 500–650 °C are not inconsistent with the metamorphic temperatures of 650–750 °C estimated for the early stage near locality 4017 if metamorphic grade decreased from locality 4017 northeast to the locality for R32094 during the early stage, as well as during the middle stage of metamorphism.

We had little success in estimating the temperature of metamorphism directly from mineral compositions in sample R32094. Temperatures calculated from biotite–garnet Fe–Mg fractionation (e.g. FERRY & SPEAR, 1978) exceed 1000 °C. This anomalously high temperature estimate could result either from the high Ca content of garnet (FERRY & SPEAR, 1978) or from incomplete re-equilibration of garnet during the late stage, an effect similar to that discussed for garnet–staurolite Fe–Mg fractionation. Temperatures calculated from garnet–hornblende Fe–Mg fractionation by the method of GRAHAM & POWELL (1984) are 727 and 772 °C for the garnet core and 661 and 700 °C for the garnet rim. GRAHAM & POWELL (1984) report that ferric iron in hornblende should pose no problem in rocks such as R32094 that are not unusually oxidized, and the Mn content of garnet in R32094 is within the limit (Mn less than 10% of divalent cations) that GRAHAM & POWELL (1984) recommended for applying their geothermometer. These somewhat high temperature estimates for R32094 may be due to incomplete re-equilibration during the last stage, indicating that observed garnet–hornblende iron–magnesium fractionation, like those of garnet–biotite and garnet–staurolite, is not an equilibrium one.

The temperatures of 300–370 °C and pressures of 3–5 kbar we estimated for the last stage at locality 4017 may also be applicable for the late stage metamorphism at the locality where R32094 was collected. Margarite provides a constraint on the lower temperature estimate, but in the absence of pumpel-

lyite in R32094, we have no independent constraints on the upper limit for R32094, as we did for the pumpellyite-bearing sample 4017E (see GREW & SANDIFORD, 1984). Our new data on muscovite in sample 4017E (Table 2) can also be used to estimate metamorphic pressures during the late stage. According to the phengite geobarometer experimentally determined by MASSONNE (1981) and MASSONNE & SCHREYER (1983), the muscovite Si contents correspond to water pressures of 1–2 kbar at 300–370 °C. However, MASSONNE & SCHREYER's geobarometer is based on Si contents of muscovite associated with quartz, K feldspar, and phlogopite. The 1–2 kbar estimates for pressure are thus minima, for 4017E is depleted in Si and enriched in Al relative to the assemblage investigated by MASSONNE (1981) and MASSONNE & SCHREYER (1983). FREY *et al.* (1982) noted that the Si contents of muscovite associated with margarite may be low because of the aluminous environment for margarite. Indeed, Si contents of the Antarctic muscovites are comparable to Si contents of muscovite associated with margarite in the absence of quartz in New Zealand (6.166 and 6.130 Si per 22 oxygens, GIBSON, 1979). Pressures for margarite formation in the New Zealand rocks are estimated to be in the range 5 to 9 kbar. Thus the low Si contents of the Antarctic muscovites are probably not due to low metamorphic pressures. Our earlier 3–5 kbar estimate is certainly not unreasonable in light of the compositional data on muscovite.

Tectonic implication

The staurolite–hornblende association in sample R32094 is interpreted to have formed at pressures of at least 6 kbar in the early stage of the metamorphic cycle, at the time talc-staurolite-corundum-chlorite was stable in sample 4017E at 7–10 kbar and 650–750 °C (GREW & SANDIFORD, 1984). The middle stage, during which garnet–hornblende equilibrated in R32094, represents an isothermal decrease in pressure of about 2–3 kbar. The last stage represents a decrease in temperature from 650–700 °C to 300–370 °C and a pressure decrease from 6 kbar to 3–5 kbar. This temperature-pressure path is convex toward the temperature axis (GREW & SANDIFORD, 1984, Fig. 2), a trend characteristic of rapid uplift following metamorphism (HOLLISTER, 1979). Structural and microstructural analysis (SANDIFORD, *in press*) suggests that the 3-staged metamorphic cycle was broadly coeval with a single, prolonged deformational event and with emplacement of granitic rocks, both of which are part of the Cambro-Ordovician Ross orogeny (e.g. GREW *et al.*, 1984). Thus, the uplift indicated by the mineral assemblages was probably induced by surface erosion from an excessively thickened crust. The present-day crust in the Lanterman Range has been estimated to be about 40 km thick (GROUSHINSKY & SAZHINA, 1982). If the depth equivalent of 6–10 kbar is added, we obtain a total crustal thickness of some 60–75 km during the metamorphism. Such crustal thick-

nesses, as well as pressure-temperature-time paths convex towards the temperature axis, are typical of orogenic zones involving continental collision (ENGLAND & RICHARDSON, 1977).

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