

A staurolite-talc assemblage in tourmaline-phlogopite-chlorite schist from northern Victoria Land, Antarctica, and its petrogenetic significance

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Abstract. Staurolite and corundum are found as inclusions in tourmaline in a talc-phlogopite-chlorite-albite schist near Mount Bernstein (71°37'S, 163°07'E), northern Victoria Land, Antarctica. These inclusions are interpreted as relics of a staurolite-talc-corundum-chlorite assemblage that was stable during an early stage in the metamorphic cycle and subsequently armored by tourmaline, probably during the middle stage. Pressures and temperatures during the middle stage are estimated to be 650–700° C and 5.5–6.4 kbar. The transition from the early to the middle stage represents a roughly isothermal decrease in pressure of 2–3 kbar. During a late retrograde stage (T=300–370° C, P=3–5 kbar), staurolite was partly replaced by a muscovitic aggregate containing clinozoisite, pumpellyite, and margarite.

The staurolite is unusually Si-poor (26.77, 25.85 weight % SiO₂ or 7.275, 7.091 Si per formula unit for 46 oxygens anhydrous), Al-rich (58.00, 57.85% Al₂O₃, 18.579, 18.702 Al), low in divalent cations (Fe + Mg + Mn + Zn = 3.301, 3.560) and magnesian (atomic Mg/(Mg + Fe) = 0.42, 0.40). Ion microprobe analysis of the first grain indicates about 0.2% Li₂O (0.219 Li) is present. The following substitutions are proposed to explain the unusual chemistry of this staurolite (crystallographic site notation of Smith 1968, in bold letters): Al(Si) + Al(**Al(3A,B)**) → Si(Si) + Fe(Fe), Li(Fe) + Al(**Al(3A,B)**) → 2 Fe(Fe), and 2 Al(**Al(3A,B)**) → 3 Fe(Fe).

According to a pressure-temperature diagram constructed by the method of Schreinemaker for the model system FeO–MgO–Al₂O₃–SiO₂ (H₂O in excess), the talc-staurolite assemblage should be stable only in quartz-free rocks at temperatures near 700° C and pressures of 8 kbar or more. The rarity of the staurolite-talc assemblage even in Mg–Al-rich rocks metamorphosed at the appropriate pressure-temperature conditions is attributed to the appearance of anthophyllite or, in Na₂O-bearing rocks, gedrite. Orthoamphibole-cordierite and orthoamphibole-kyanite assemblages with chlorite or corundum are incompatible with staurolite-talc ± albite. In rocks lacking corundum and formed at pressures above the stability limit of cordierite, staurolite-talc may be metastable relative to orthoamphibole-kyanite, while in corundum-bearing rocks, staurolite-talc may appear under certain conditions, possibly at higher water activities than the orthoamphibole-kyanite assemblage.

Introduction

Staurolite is a characteristic mineral of pelitic and other siliceous and aluminous rocks metamorphosed under intermediate pressure conditions of the amphibolite-facies. These staurolites are not magnesian (atomic Mg/(Fe + Mg) = X_{Mg} < 0.3, eg. Deer et al. 1982) and metamorphic conditions indicated for their formation lie within the stability field for Fe-staurolite + quartz determined in the laboratory, that is, pressures above 1.5 kbar and temperatures between 500° and 700° C (Richardson 1968). On the other hand, Mg-staurolite is stable only in the absence of quartz and at pressures above 10–12 kbar at roughly 720° to 980° C (Schreyer 1968). Magnesian staurolite is rare in nature and staurolites with X_{Mg} near 0.5 have been reported from only three localities: (1) New Zealand, in metabasite metamorphosed at about 12 kbar and 750° C (Ward 1984); (2) Southern Africa, in garnet-gedrite-phlogopite-sapphirine rock metamorphosed at 7 or more kbar and 800° C or more (Schreyer et al. 1984), and (3) Norway, in eclogite formed at pressures possibly as high as 30 kbar (Smith 1984). Another possible paragenesis for magnesian staurolite is a talc-bearing assemblage, for talc is reported to be a low temperature breakdown product of Mg-staurolite (Schreyer 1968). Staurolite has been reported as inclusions in garnet in a talc-kyanite schist from Kazakhstan, but these staurolites are not magnesian (X_{Mg} = 0.16, 0.22; Udovkina et al. 1977, 1978). The occurrence apparently was the first report of staurolite from a whiteschist terrain (see Korikovskiy 1979, p. 125). Staurolite and talc also occur in enclaves from New Hampshire and Massachusetts (Schumacher 1983). However, the absence of staurolite in other talc-bearing rocks is noteworthy, in view of increasingly frequent reports of garnet, kyanite, and chloritoid in such rocks (e.g. Vrána and Barr 1972; Råheim and Green 1974; Chopin 1981).

In the present paper, we report a relatively magnesian staurolite (X_{Mg} = 0.40–0.42), talc, and corundum as inclusions in tourmaline porphyroblasts in a chlorite-talc-phlogopite schist. This paragenesis is a suitable basis for developing a petrogenetic model for the staurolite-talc assemblage and placing constraints on the appearance of Mg-rich staurolites under certain conditions. As far as we are aware, only Korikovskiy et al. (1983) have considered the petrogenesis of staurolite-talc; these authors made use of the Kazakhstan paragenesis reported by Udovkina et al. (1977, 1978). Korikovskiy et al. (1983) suggested that talc-stauro-

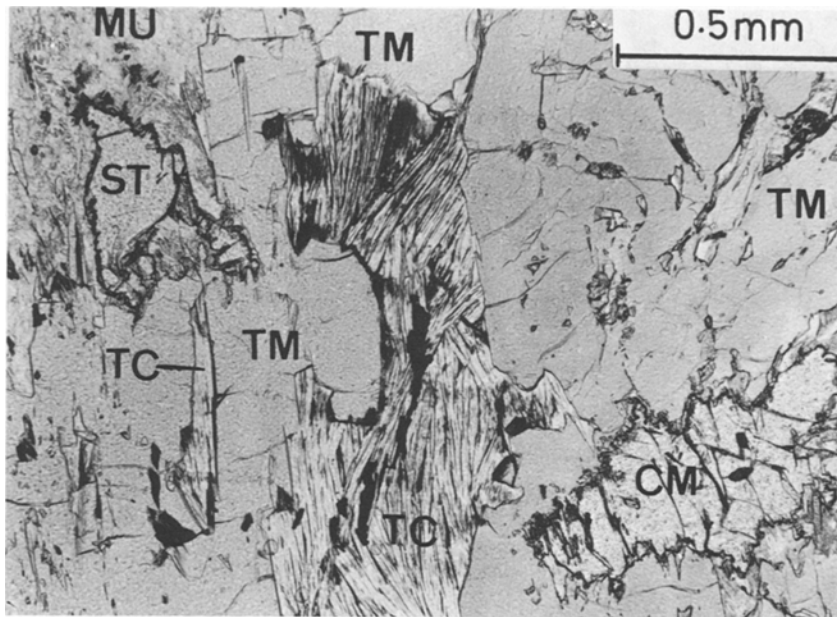


Fig. 1. Photomicrograph (plane light) of tourmaline (Tm), staurolite (St), corundum (Cm), and talc (Tc) in sample 4017E. Length of bar scale = 0.5 mm. Staurolite is surrounded by fine-grained muscovite (Mu)

lite would appear in quartz-bearing rocks metamorphosed at low temperatures and high pressures. Our model predicts that staurolite-talc would form only under a narrow range of conditions at moderate temperatures and pressures in quartz-free rocks, conditions closer to those required for synthesis of Mg-staurolite in the laboratory (Schreyer 1968).

Geological setting and petrography

The staurolite-talc-bearing rock was collected in November 1981, on "Fibrolite Ridge" (informal name), which extends northeast from Mount Bernstein (71°37'S, 163°07'E) in the Lanterman Range, northern Victoria Land. The Mount Bernstein area is underlain by a metasedimentary sequence, the Wilson Group, of probable Late Precambrian age (Dow and Neall 1974; Wodzicki et al. 1982; Grew and Sandiford 1982). The dominant rock type on "Fibrolite Ridge" 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. Sample 4017E was collected about 3.5 km northeast of Mount Bernstein at a locality (No. 4017) 0.5 km northeast of the first appearance of fibrolite in biotite-muscovite-quartz ± garnet schist, and 2.5 km northeast of a locality where K-feldspar is found with prismatic as well as fibrolitic sillimanite and muscovite. Kyanite relics are preserved in plagioclase in a fibrolitic mica schist collected 2 km southwest of 4017E. No staurolite was found in the pelitic schists along "Fibrolite Ridge", although staurolite relics are present in garnet in a garnet-hornblende-biotite schist 7 km northeast of Mount Bernstein (Grew and Sandiford, in prep.).

Sample 4017E is from a lens 4 m thick of ultramafic rocks consisting largely of talc, anthophyllite, clinoamphibole, phlogopite, and chlorite. This sample is a phlogopite schist with a layer 2 to 4 cm thick rich in tourmaline porphyroblasts up to 2 cm in length set in a matrix of talc, phlogopite, and chlorite. Plagioclase, allanite, rutile, apa-

tite, and zircon are found sparingly in the schist matrix. The tourmaline porphyroblasts contain inclusions, not only of talc, chlorite, phlogopite, and the other minerals in the matrix, but also of staurolite, corundum, clinozoisite, pumpellyite, muscovite, paragonite, margarite, and xenotime. In thin section, the tourmaline porphyroblasts are in some places euhedral, in others, embayed. The tourmaline is color zoned, typically darker brown around the margins and pale brown or green in the cores; the green and brown colors having a patchy distribution. The finer inclusions are commonly concentrated into a zone that is roughly concentric with the margins of the tourmaline porphyroblasts.

Staurolite occurs as isolated embayed grains mostly 0.35 to 0.8 mm across surrounded by tourmaline or by a muscovite aggregate commonly containing clinozoisite, pumpellyite, and chlorite (Fig. 1). Corundum also forms isolated embayed grains that are on the average larger (to 2 mm) and in places form aggregates up to 3.5 × 1.5 mm across. Muscovite, clinozoisite, pumpellyite, and chlorite are also found independently of staurolite and corundum. Paragonite was identified (by element scan) in a single grain near corundum. Margarite has been positively identified in flakes 0.05 to nearly 0.25 mm across in a muscovitic aggregate around one staurolite grain (see below) and tentatively in a mica-chlorite-clinozoisite aggregate independent of staurolite. Reconnaissance with the energy dispersive detector on the electron microprobe suggests that none of the minerals found only as inclusions in tourmaline, notably staurolite, corundum, mica, and clinozoisite, are in contact with talc, nor is staurolite found in contact with corundum. However, staurolite and corundum are in places separated from talc by a tourmaline selvage only 0.1 mm thick (Fig. 1).

The precursor to the talc-staurolite-bearing rock is inferred to be an Al-rich zone in an ultramafic rock. Lenses containing talc, magnesite, and serpentine and resembling the lens at locality 4017 are exposed elsewhere along "Fibrolite Ridge". This ridge lies across a northwest-trending belt of ultramafic lenses extending 45 to 50 km in the eastern Lanterman Range (Grew et al., in press). These lenses,

one of which is a relatively fresh garnet-olivine pyroxenite, may be of deepseated (mantle?) origin, tectonically inserted into the metasediments prior to regional metamorphism. The precursor to the staurolite-corundum-bearing layer may have been a garnet-rich zone in the ultramafic, or a reaction skarn between the ultramafic and country rock. The boron which is presently fixed in tourmaline was probably introduced prior or during metamorphism.

Mineral chemistry

Methods

Electron microprobe analyses of staurolite, margarite, and of associated minerals are presented in Tables 1–3. Analyses on sample R32078 were performed by Sandiford on a JXA-5A wavelength-dispersive instrument at the University of Melbourne, while analyses on 4017E were performed on a CAMEBAX wavelength-dispersive instrument by Grew at Ruhr-Universität Bochum. The Melbourne data were reduced by the method of Ferguson and Sewell (1980) and the Bochum data were processed by the MISO program (Abraham and Schreyer 1973; Schreyer et al. 1984).

Staurolite

The staurolite is magnesian ($X_{\text{Mg}}=0.42, 0.40$), poor in divalent cations and Si, and rich in Al (Table 1) in comparison to average staurolite (e.g. Deer et al. 1982; Ribbe 1982). The relatively high X_{Mg} appears to be due to the unusually low Fe contents (only Zn and Co-rich staurolites contain less Fe than grain no. 1), while the Mg contents of the Antarctic staurolites are not unusually high (1.32 vs 0.38–1.13 atoms per formula unit for most staurolites, see Ribbe 1982). Ion microprobe analyses of grain 1 indicate Li_2O is present, possibly 0.2 wt.% (E.S. Grew, G. Werdinger, and J.R. Hinthorne, unpublished data). The two staurolite grains analyzed differ slightly in Si, Fe, and Zn contents as well as in X_{Mg} .

Staurolite compositions recast in cations per 46 oxygens anhydrous (equivalent to 44 O + 4 OH) as recommended by Griffen et al. (1982) lie within 0.1 atom per formula unit of the “maximum likelihood line” Griffen et al. (1982) calculated from 82 staurolite analyses. This line is defined by the relation $\text{Al} + \text{Si} - 8 = 20.5 - 0.80 (\text{Fe} + \text{Mg} + \text{Zn})$ in atoms per formula unit.

The low Si contents of the staurolite (7.091 Si per formula unit is the lowest reported in staurolite) are most likely related to the SiO_2 -undersaturated bulk composition of the host rock. Low Si values are characteristic of magnesian staurolites from silica-undersaturated environments ($\text{Si} = 7.23\text{--}7.57$, $X_{\text{Mg}} = 0.32\text{--}0.56$, Gibson 1978; Ward 1984; Schreyer et al. 1984), but not of such staurolites associated with quartz ($X_{\text{Mg}} = 0.41$, $\text{Si} = 7.98$, Spear 1982). The high Al contents, which are exceeded in staurolite only by the 60.5 weight % value reported by van Knorring et al. (1979), may be due to association with corundum, although not all staurolite associated with corundum is rich in Al_2O_3 (e.g. Spry 1982). Ward (1984) suggests that the high Al_2O_3 content of van Knorring et al.'s (1979) staurolite, which is from muscovite veinlets cutting amblygonite, may be due to substitution of $\text{Li} + \text{Al}$ for $2(\text{Fe}, \text{Mg}, \text{Zn})$. However, staurolites containing 0.06–0.13 wt.% Li_2O (300–650 ppm Li, Schreyer and Chinner 1966; Hietanen 1969) have Al_2O_3 contents of 52.3–54.8 wt.%, values within the normal range for staurolite. Moreover, the Li content estimated for grain

Table 1. Analyses of Staurolite in tourmaline-talc-chlorite-phlogopite schist (No. 4017E)

Grain	1	2
	wt. %	
SiO ₂	26.77	25.85
TiO ₂	0.39	0.39
Al ₂ O ₃	58.00	57.85
Cr ₂ O ₃	0.04	0.14
FeO	8.12	8.51
MnO	0.19	0.25
MgO	3.26	3.22
ZnO	0.46	1.15
CaO	<0.01	<0.01
Na ₂ O	≤0.02	0.04
K ₂ O	≤0.01	≤0.01
Li ₂ O	~0.2	—
Total	97.43	97.40
Cations per 46 oxygens		
Si	7.275 (7.292) ^a	7.091
Al	0.725 (0.708)	0.909
Total	8.000 (8.000)	8.000
Al'	17.854 (17.915)	17.793
Ti	0.080 (0.080)	0.080
Cr	0.009 (0.009)	0.030
Total	17.943 (18.004)	17.903
Fe	1.845 (1.849)	1.952
Mn	0.044 (0.044)	0.058
Mg	1.321 (1.324)	1.317
Zn	0.092 (0.093)	0.233
Li	0.219 (—)	—
Total	3.520 (3.309)	3.560
Total cations	29.462 (29.313)	29.463
Mg/(Mg + Fe)	0.42	0.40

All Fe as FeO. Li_2O by ion microprobe analyses

^a Values in parentheses are calculated assuming no Li present, for comparison with grain 2

1, 0.219 per formula unit, is not sufficient to explain the high Al content (18.579) by this substitution alone, for Al contents of staurolite are generally 17.07–17.60 per formula unit (Ribbe 1982). The following three substitutions applied together account for the unusual composition of the Antarctic staurolite (in parenthesis are the crystallographic sites in boldface using the notation of Smith 1968):

- ${}^{\text{IV}}\text{Al}(\text{Si}) + {}^{\text{VI}}\text{Al}(\text{Al}(\mathbf{3A}, \mathbf{B})) \rightarrow {}^{\text{IV}}\text{Si}(\text{Si}) + {}^{\text{IV}}\text{Fe}(\text{Fe})$
- ${}^{\text{IV}}\text{Li}(\text{Fe}) + {}^{\text{VI}}\text{Al}(\text{Al}(\mathbf{3A}, \mathbf{B})) \rightarrow 2 {}^{\text{IV}}\text{Fe}(\text{Fe})$
- $2 {}^{\text{VI}}\text{Al}(\text{Al}(\mathbf{3A}, \mathbf{B})) \rightarrow 3 {}^{\text{IV}}\text{Fe}(\text{Fe})$ (see Ward 1984).

An alternative to the third substitution is $\text{Al} \rightarrow \text{Fe} + \text{H}$ (see Lonker 1983). The Fe site seems the most likely site for Li in staurolite. The ionic radius of ${}^{\text{IV}}\text{Li}$, 0.59 Å (Shannon 1976), is not very different from the radius of ${}^{\text{IV}}\text{Fe}^{2+}$,

0.63 Å, and ^{IV}Zn , 0.57 Å, which substitutes for Fe on the Fe site (Griffen 1981; cf. radius of ^{IV}Zn , 0.60 Å given by Shannon 1976). We propose the coupled substitutions involving the partially occupied **Al(3A,B)** sites, for increased occupancy of these sites should preserve electrostatic balance on the oxygens **O(1A,B)** and **O(3)**, these oxygens are coordinated to **Fe** and **Si**, respectively, which lose charges through substitutions of $Al \rightarrow Si$, $Li \rightarrow Fe$, or decreased occupancy of **Fe**. Conversion of oxygen to hydroxyl at **O(1A,B)** could also preserve electrostatic balance, but increase in hydroxyl is not consistent with increased occupancy of **Al(3A,B)** (Donnay and Donnay 1983), nor with substitution of Al for Fe + H. Significant entry of ^{VI}Al in the **U(1,2)** site also appears unlikely, for one of the oxygens (**O(5)**) bonded to **U(1,2)** positions is saturated even with zero occupancy of **U(1,2)** (Donnay and Donnay 1983). Moreover, these authors note that the radius of ^{IV}Al is too small for direct substitution of Al for Fe on the Fe site. Alternative substitutions, such as $^{IV}Li(Fe) + ^{IV}Si(Si) \rightarrow ^{IV}Fe(Fe) + ^{IV}Al(Si)$, implied by Schreyer and Chinner (1966), or a modified edenite substitution, $0.5 (Fe + Mg + Zn) + Al \rightarrow Si$ (Schreyer et al. 1984), are not appropriate for the Antarctic staurolite in view of its low Si and Fe + Mg + Zn contents. In sum, a simple formula cannot be deduced for the Antarctic staurolite and the proposed substitutions are at best tentative. Nonetheless, the distinctive compositional features of the Antarctic staurolite indicate that lithium may play an important role in staurolite crystal chemistry, one comparable to that of zinc. Lithium has been ignored in the recent reviews of staurolite (e.g. Griffen et al. 1982; Donnay and Donnay 1983). Yet, the Li contents of staurolites in which both Li and Zn were sought (Table 1 and Hietanen 1969) are 0.07 to 0.22 Li per formula unit, overlapping their zinc contents of 0.05–0.15 Zn. Moreover, staurolite-bearing pelitic schists contain non-negligible amounts of lithium, for example 31 to 310 ppm Li as compared to an overall average of 106 ppm for pelitic schists from the same area (Shaw 1954). Lithium, like zinc, is concentrated mainly in staurolite in such rocks (Hietanen 1969). Thus lithium, like zinc, should be routinely analysed in staurolite, and no staurolite analysis can be considered complete without some indication of its lithium content.

Tourmaline, phlogopite, talc, chlorite, and plagioclase

The color zoning in tourmaline reflects changes in composition. The analysis in Table 2 is for a spot in the darker marginal zone. An analysis of the lighter colored material nearer the core suggests that the core has a higher Fe/Mg and Na/Ca ratio and a lower TiO_2 content than the margin, variations analogous to those Schreyer et al. (1975) reported in a zoned tourmaline of the Waldheim (Saxony) kornerupine rock. An ion microprobe scan at the analytical point in the margin revealed substantial boron, but only a trace of lithium.

Iron-magnesium ratios in phlogopite ($X_{Mg}=0.83$, Table 2) and talc ($X_{Mg}=0.94$) appear to vary little from flake to flake. On the other hand, Na_2O contents range from 0.6 to 1.1 wt.% in phlogopite and 0.1 to 0.5 wt.% in talc. Al_2O_3 contents are as high as 18 wt.% in phlogopite, and range from 0.4 to 1.7 wt.% in talc. In recast talc compositions, Na is about equal or somewhat less than ^{VI}Al and is generally less than ^{IV}Al (e.g. Table 2). The compositions could result from a combination of $Na + ^{IV}Al$ for $\square + Si$,

$^{IV}Al + ^{VI}Al$ for $Si + Mg$, or 2 Al for 3 Mg substitutions into the ideal talc formula (Schreyer and Abraham 1976; Schreyer et al. 1980).

Chlorite varies little in composition from grain to grain (except FeO, which ranges from 7.9 to 8.4%) and is clinochlore (Table 2). Plagioclase is albite and varies in anorthite content from An 1 to 5 (electron microprobe analyses).

Clinozoisite and pumpellyite

The magnesium contents of clinozoisite and pumpellyite in 4017E are variable within a single grain and range from near 0 to about 0.6 weight % MgO (average = 0.3%, Table 2) in a single clinozoisite grain and 2.4 to 3.8 in three pumpellyite grains (an analysis of one grain listed in Table 2). Possibly these two minerals are intergrown on a scale too fine to be resolved with the electron microprobe. Moreover, pumpellyite iron contents vary from 0.6 to 1.7 wt.% Fe_2O_3 , and Al_2O_3 , from 26.4 to 28.3%. These compositions are characteristic of the aluminous variety (Schiffman and Liou 1980).

Margarite

Margarite is sodic and varies in composition from flake to flake (Table 2). Flakes contiguous to staurolite (B and C, Table 2) are more sodic than flakes (A) not in contact with staurolite. The Antarctic margarites contain little Fe, Mg, Ti, or K, and appear to have more than four cations in octahedral coordination per formula unit for 22 oxygens, features characteristic of margarite in general (Frey et al. 1982). Total cations assigned to the interlayer position exceed two per formula unit. Moreover, all the analyses indicate an excess of ^{IV}Al and deficiency of Si relative to an ideal binary solid solution of margarite ($Ca_2Al_4 \cdot (Al_4Si_4)O_{20}(OH)_4$) and paragonite ($Na_2Al_4(Al_2Si_6) \cdot O_{20}(OH)_4$). The deviations for the Antarctic sample are as great as the maximum found for 60 microprobe analyses reviewed by Frey et al. (1982). Moreover, the amounts of Mg and Fe are insufficient to account for incorporation of Na by solid solution towards a hypothetical 5-octahedral endmember $Na_2MgAl_4(Si_4Al_4)O_{20}(OH)_4$ (Chopin 1977; Smith and Kechid 1983). We suggest that some of the Na is entering the margarite as ephesite ($Na_2Li_2Al_4(Al_4Si_4) \cdot O_{20}(OH)_4$) (see Schaller et al. 1967; Langer et al. 1981). Neglecting Li in recasting the formula in cations per 22 oxygens results in an apparent excess of cations in the interlayer site. Moreover, staurolite in grain 2, like that in grain 1, may contain Li and thus be a source of Li for the ephesitic component.

Interpretation of the assemblages

Along "Fibrolite Ridge" east of Mount Bernstein textures in the metamorphic rocks suggest a three stage metamorphic cycle: (1) an early stage during which kyanite formed locally in pelitic rocks, (2) a middle stage, during which fibrolite (and K-feldspar in one fibrolitic schist) developed in the highest grade zones, but at temperatures below that required for breakdown of muscovite + quartz, and (3) a late stage, during which the higher-grade assemblages were altered under low temperature conditions to muscovite, epidote, and chlorite.

Staurolite and corundum in sample 4017E are inter-

Table 2. Analyses of minerals associated with staurolite in tourmaline-talc-chlorite-phlogopite schist (4017E)

	Phlogo- pite ^a	Talc ^a	Chlorite ^b	Tourma- line ^c	Clino- zoisite ^a	Pumpel- lyite ^d	Margarite ^e		
							A	B	C
							wt. %		
SiO ₂	38.53	59.28	29.07	36.22	38.55	37.30	30.12	30.79	32.80
TiO ₂	1.16	0.15	0.07	0.70	—	0.03	0.24	0.34	0.19
Al ₂ O ₃	16.69	1.58	19.60	32.28	31.39	26.64	49.46	48.97	47.34
Cr ₂ O ₃	0.03	≤0.01	0.05	0.03	—	<0.01	0.10	0.15	0.11
FeO ^f	7.64	3.14	8.14	2.26	2.33	1.14	0.33	0.40	0.36
MnO	0.04	0.03	0.04	≤0.01	—	<0.01	<0.01	0.02	<0.01
MgO	20.22	27.64	27.96	10.20	0.29	3.64	0.69	0.71	0.59
CaO	<0.01	≤0.02	0.03	1.12	24.03	23.39	10.95	10.14	8.12
Na ₂ O	0.61	0.42	<0.01	2.27	<0.01	0.09	1.66	2.08	3.23
K ₂ O	9.22	≤0.01	0.03	≤0.01	≤0.01	0.03	0.03	0.03	0.13
Total	94.14	92.24	84.99	85.08 ^g	96.58	92.26	93.58	93.63	92.87
Cations									
Oxygens ^h	22	22	28	24.5	12.5	24.5	22	22	22
Si	5.599	7.864	5.751	5.873	2.986	5.967	4.070	4.152	4.432
Al	2.401	0.136	2.249	0.127	—	—	3.930	3.848	3.568
Total	8.000	8.000	8.000	6.000	—	—	8.000	8.000	8.000
Ti	0.127	0.015	0.010	0.085	—	—	0.024	0.035	0.019
Al	0.458	0.111	2.321	6.042	2.865	5.022	3.946	3.934	3.972
Cr	0.003	—	0.008	0.004	—	—	0.011	0.016	0.012
Fe	0.929	0.348	1.347	0.307	0.136	0.138	0.037	0.045	0.041
Mn	0.005	0.004	0.007	—	—	—	—	0.002	—
Mg	4.381	5.466	8.247	2.466	0.033	0.867	0.139	0.143	0.118
Total	5.902	5.944	11.940	8.904	3.034	6.027	4.157	4.175	4.162
Ca	—	—	0.006	0.195	1.995	4.009	1.585	1.465	1.176
Na	0.172	0.109	—	0.714	—	0.028	0.435	0.544	0.847
K	1.709	—	0.007	—	—	0.007	0.005	0.005	0.023
Total	1.881	0.109	0.013	0.908	1.995	4.045	2.025	2.014	2.046
Total cations	15.783	16.052	19.953	15.812	8.015	16.039	14.182	14.189	14.208
Mg/(Mg + Fe)	0.83	0.94	0.86	0.89	—	—	—	—	—

Dash: not analysed or cations not calculated

^a Average analysis of a single grain^b Average analysis of several grains^c Average analysis of a grain margin^d Single analysis^e Margarite analyses: A. Average of several flakes in muscovite surrounding staurolite grain # 2. B. Average of several flakes contiguous to staurolite grain # 2. C. Single flake contiguous to this staurolite^f All Fe as FeO except for clinozoisite and pumpellyite, for which all Fe as Fe₂O₃^g Trace Li₂O, ion microprobe analysis^h Anhydrous and boron-free (for tourmaline) basis

preted to be relics preserved by tourmaline of a talc-chlorite-phlogopite-plagioclase-staurolite-corundum assemblage. This assemblage was most likely stable during the early stage of metamorphism. The poikilitic tourmaline porphyroblasts could have grown coevally with the minerals in this six-phase assemblage during the early stage. Alternatively, tourmaline may have formed during the middle stage and prevented the talc, staurolite, and corundum from reacting with one another under the changed conditions,

a situation analogous to the preservation by tourmaline of a chlorite-quartz assemblage in a talc-kyanite schist from Sar e Sang, Afghanistan (Schreyer and Abraham 1976).

Margarite undoubtedly formed during the late stage, and in general, it developed only in the vicinity of staurolite. Muscovite, paragonite, clinozoisite, pumpellyite, and secondary chlorite also formed from retrogression of staurolite and corundum during this stage. Mineral assemblages deduced from textural relations include margarite-muscovite-

Table 3. Compositions of Minerals in a fibrolitic garnet mica schist (R32078) used for estimating metamorphic pressure and temperature

	Garnet		Biotite ^b		Plagioclase ^b	
	Core	Rim ^a	Core	Rim	Core	Rim ^c
	wt. %					
SiO ₂	37.38	37.11	35.65	34.71	62.62	62.61
TiO ₂	0.03	0.01	1.63	1.44	0.02	0.09
Al ₂ O ₃	21.19	21.01	19.51	19.41	23.27	23.58
Cr ₂ O ₃	—	—	0.03	0.03	—	—
FeO ^d	33.23	32.41	19.86	19.62	0.01	0.06
MnO	3.17	5.45	0.14	0.20	—	—
MgO	3.83	2.62	9.30	9.18	—	—
CaO	1.05	1.05	0.00	0.00	5.03	5.02
Na ₂ O	—	—	0.23	0.24	8.87	8.87
K ₂ O	—	—	9.55	9.56	0.12	0.22
Total	99.88	99.67	95.91	94.39	99.94	100.44
	Cations					
Oxygens	12	12	22	22	32	32
Si	2.999	3.006	5.401	5.357	11.103	11.055
Ti	0.001	0.001	0.186	0.167	0.002	0.012
Al	2.004	2.006	3.485	3.531	4.863	4.907
Cr	—	—	0.004	0.004	—	—
Fe	2.230	2.195	2.516	2.532	0.001	0.009
Mn	0.215	0.374	0.018	0.027	—	—
Mg	0.458	0.317	2.101	2.112	—	—
Ca	0.090	0.091	0.000	0.000	0.955	0.949
Na	—	—	0.066	0.073	3.050	3.038
K	—	—	1.847	1.882	0.028	0.049
Total	7.997	7.990	15.625	15.686	20.002	20.019
Mg/(Mg + Fe)	0.17	0.13	0.46	0.45	—	—
Ca/(Ca + Na)	—	—	—	—	0.24	0.24

Dash: not analysed

^a Rim to biotite. A rim to quartz contains 32.39% FeO, 4.78% MnO, 3.02% MgO, and 1.08% CaO

^b Average of rim and core used to calculate temperature and pressure

^c Rim to garnet

^d Fe as FeO in garnet and biotite and as Fe₂O₃ in plagioclase

chlorite-pumpellyite and muscovite-chlorite-clinozoisite. As talc was not found in contact with any of the retrograde minerals in 4017E, we conclude that the talc-muscovite (phengite) assemblage was not stable during the retrograde stage.

The formation of margarite and pumpellyite from staurolite is unusual. By analogy with the development of margarite from staurolite and corundum in a tremolite amphibolite (Jan et al. 1971), we attribute these minerals to the local concentration of Ca and Al rather than to unusual pressure-temperature conditions. Possible sources of calcium in the Antarctic rock are plagioclase, which may have been more calcic than An 5 during the early or middle stages of metamorphism, tourmaline, or solutions percolating through the rock during the late stage.

Conditions of metamorphism

Middle and early stages

For a quantitative estimate of the metamorphic temperatures and pressures during the middle stage, we analysed

the minerals in a fibrolite-garnet-muscovite-biotite-plagioclase-quartz schist (No. R 32078, Table 3) collected 2.5 km southwest of locality 4017. Calculated pressures (method of Newton and Haselton 1981) are 6.4 kbar at 700° C and 5.5 kbar at 650° C, while the calculated temperature is 709° C at 6 kbar (method of Ferry and Spear 1978) and 652° C (method of Thompson 1976). The estimated temperatures of 650 to 700° C are consistent with the local appearance of K feldspar in sillimanitic mica schist at this locality. Kerrick (1972) reports an upper temperature limit of 650 to 660° C at pressures of 4 to 6 kbar for the assemblage quartz-muscovite-K-feldspar-sillimanite in the absence of melting (proportion of water in fluid: 1.0 to 0.7) (see Fig. 2).

Relic kyanite in fibrolite schist implies that during the early stage pressures were higher or temperatures lower, or both, than during the middle stage. A petrogenetic model developed in the next section suggests that the staurolite-talc association is probably stable at temperatures in the range 650–750° C at pressures above 6 kbar. For kyanite to be stable at 650–750° C, metamorphic pressures must be at least 6.8 to 8.9 kbar (Holdaway 1971), that is, about 2–3 kbar above the 5–6 kbar estimated for the middle stage.

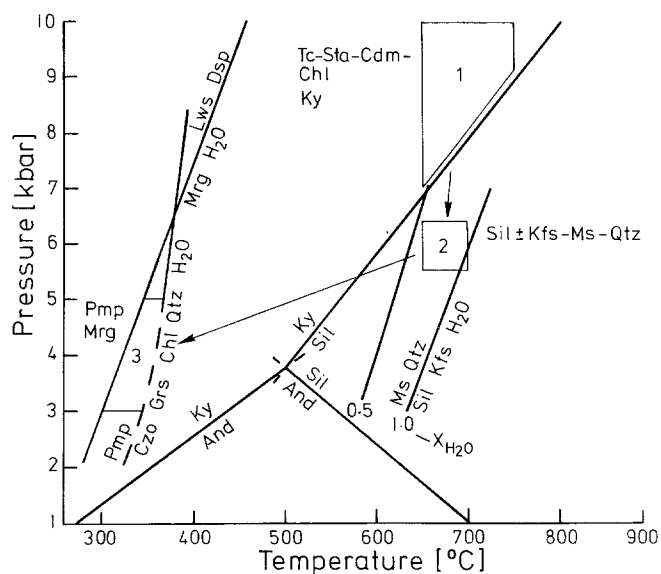


Fig. 2. Schematic diagram illustrating estimated pressure-temperature conditions for early (1), middle (2), and late (3) stages in the metamorphic cycle, and path (arrows) followed by rocks at "Fibrolite Ridge", Lanterman Range, Antarctica. Basis for estimates (boxes): 1. coexistence of talc(Tc)-staurolite (Sta)-corundum (Cdm)-chlorite(Chl) from Figs. 5-6, 2. geothermometric and geobarometric calculations on a fibrolitic mica schist (see text), and 3. presence of aluminous pumpellyite (Pmp) and margarite (Mrg). Critical mineral assemblages are indicated for each stage. Sources of data for experimental and theoretical curves: kyanite (Ky), sillimanite (Sil), and andalusite (And) (Holdaway 1971); muscovite (Ms) + quartz (Qtz) = sillimanite + K feldspar (Kfs) + H_2O at mole fractions of water (X_{H_2O}) in fluid phase of 1.0 and 0.5 (Kerrick 1972); pumpellyite = clinozoisite (Czo) + grossular (Grs) + chlorite + quartz + H_2O (Schiffman and Liou 1980); and lawsonite (Lws) + diaspore (Dsp) = margarite + H_2O (Chatterjee 1976).

Thus estimated conditions for the early stage are 7–10 kbar and 650–750°C and the transition from the early to the middle stages is interpreted to be a nearly isothermal decrease in pressure (Fig. 2).

Late stage

The margarite-muscovite-chlorite-pumpellyite assemblage provides some fairly tight constraints on metamorphic temperatures during the late stage, but less constraint on pressures, which were not sufficient to stabilize talc-muscovite. This association may require pressures above 10 kbar (Chopin 1981), especially in quartz-free rocks. The temperature is constrained by the appearance of both margarite and pumpellyite. The lower temperature limit for margarite is predicted from theoretical calculations to range from 300 to 500°C at water pressures of 3 to 13 kbar (Chatterjee 1976, plotted in Fig. 2). However, a lithium- and sodium-bearing margarite may be stabilized to lower temperatures, the same effect as a decrease in water activity. The reactants on the low temperature side of Chatterjee's reaction, lawsonite + diaspore, do not incorporate significant Li or Na and together are more hydrous than margarite (see Chatterjee 1976). Aluminous pumpellyite breaks down to grossular + clinozoisite + chlorite + quartz + H_2O at 325 to 390°C over a fluid pressure range of 2 to 8 kbar (Schiffman and Liou 1980, plotted in Fig. 2). This experimentally determined high-temperature breakdown of pumpellyite on its

own composition probably represents an upper temperature limit for pumpellyite in the Antarctic assemblage, particularly if water pressure in the natural setting were less than total pressure. Thus the area bounded by Chatterjee's (1976) and Schiffman and Liou's (1980) curves would shift to lower temperatures under natural conditions and the 300°–370° temperature range indicated on Fig. 2 is maximum estimate. Pressure is not constrained by these curves. However, Schiffman and Liou (1980) note that aluminous pumpellyite ($Fe_2O_3 < 10$ wt.%), in contrast to iron-rich pumpellyite, is generally found in medium to high pressure environments. Consequently, the Antarctic pumpellyite, which contains little iron, may have formed at pressures near 3–5 kbar, and the transition from the middle to late stage is associated with a modest decrease in pressure, but a substantial decrease in temperature (Fig. 2).

Petrogenesis of the staurolite-talc association

A pressure-temperature diagram for staurolite-talc

The possibility of a talc-staurolite association has received little attention in the literature. As far as we are aware, talc and staurolite have not been reported in an equilibrium assemblage, possibly 4017E is the closest approach recorded to date. In the rocks from Kazakhstan described by Udovkina et al. (1977, 1978), the major constituents are talc (30–60%, volumetric), garnet (10–35%), kyanite (5–17%), and quartz (1–8%). Staurolite, chloritoid and chlorite are found as inclusions in garnet. Secondary minerals are muscovite (0–1%), biotite, and a more iron-rich chlorite. The X_{Mg} of two analysed staurolites are 0.16 and 0.22. Their SiO_2 contents of 28.30–29.00 wt.% and Al_2O_3 contents of 55.10–51.00% are within the normal range for staurolite (e.g. Deer et al. 1982). Staurolite and talc are not in physical contact and Udovkina et al. (1977, 1978) imply that these two minerals never coexisted at any stage in the metamorphic evolution of the talc-bearing rocks. On the other hand, Korikovskiy et al. (1983) suggested that the Kazakhstan talc-garnet-kyanite rocks went through a talc-chloritoid and a talc-staurolite stage during prograde metamorphism. These authors illustrate in their Fig. 3 a stability field for talc-staurolite-quartz at pressures of 7 kbar and more and temperatures of 450–530°C. Talc also occurs sparingly with staurolite in cordierite-rich enclaves in gedrite-rich rocks from Massachusetts and New Hampshire, USA (Schumacher 1983). However, in one case the talc is secondary, and in the second, talc and quartz are completely enclosed in cordierite, while staurolite is isolated in plagioclase (Schumacher 1983, and pers. comm. 1984). Consequently, neither paragenesis represents a stable talc-staurolite (with or without quartz) assemblage.

On the other hand, Schreyer (1968), Schreyer and Seifert (1969a), and C. Chopin (pers. comm. 1983) report reactions involving Mg-staurolite and talc in the absence of quartz in experimental studies of the $MgO-Al_2O_3-SiO_2-H_2O$ system. This suggests that talc-staurolite may be a stable assemblage under suitable conditions, most likely, in silica-poor, Mg-Al-rich rocks metamorphosed at high water pressures and high temperatures.

The purpose of the present section is to combine available experimental and petrologic data into a pressure-temperature diagram that qualitatively predicts the metamorphic conditions required to stabilize staurolite-talc. We have

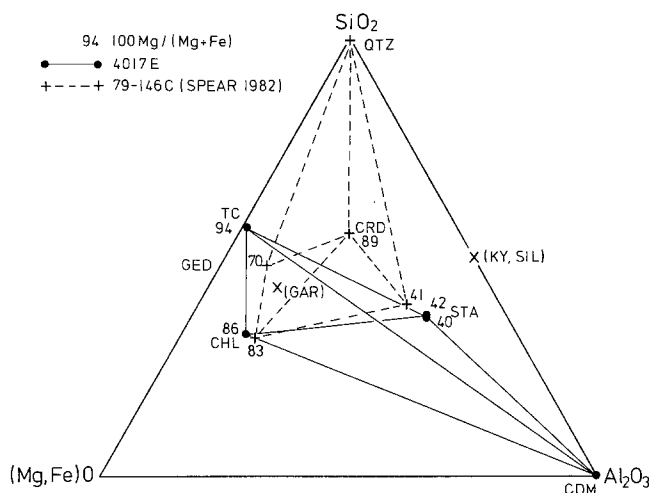


Fig. 3. Plot of mineral compositions in the plane SiO_2 – Al_2O_3 – $(\text{Mg,Fe})\text{O}$. Compositions of minerals in staurolite-bearing rocks from Mount Bernstein area, Antarctica (4017E) and New Hampshire, USA (79–146C) are based on electron microprobe analyses (Tables 1 and 2 this paper; Spear 1982); also shown with () are minerals involved in the petrogenetic grids. Mineral Abbreviations: QTZ, quartz; TC, talc; GED, gedrite; GAR, garnet; CRD, cordierite; KY, kyanite; SIL, sillimanite; STA, staurolite; CHL, chlorite; and CDM, corundum

constructed this diagram by the Schreinemakers method (see Zen 1966) for the model four component system FeO – MgO – Al_2O_3 – SiO_2 (H_2O in excess) for the phases present in sample 4017E and in Udovkina et al.'s (1977, 1978) Kazakhstan rocks, namely staurolite, talc, chlorite, corundum, kyanite, garnet, and quartz, as well as sillimanite and cordierite. This four component system is an acceptable simplification of the mineral compositions in 4017E and the Kazakhstan rocks, for other elements (except possibly MnO in garnet) are subordinate, e.g. CaO in garnet, Li_2O and ZnO in staurolite, and Na_2O in talc. We have assumed that the presence or absence of phlogopite does not materially affect the phase relations among the K-free phases.

As a first step, let us consider the mineral compositions in 4017E in terms of the model system and determine which mineral assemblages might be incompatible with the assemblage in 4017E, namely staurolite-talc-corundum-chlorite. The compositions of staurolite, talc, and chlorite are plotted in terms of Al_2O_3 , SiO_2 and $(\text{Mg,Fe})\text{O}$ (Fig. 3) and projected through corundum onto the MgO – FeO – SiO_2 plane (Fig. 4). Compositions of staurolite and chlorite associated with gedrite, cordierite, plagioclase, ilmenite and quartz from New Hampshire, USA (Spear 1982) are plotted for comparison. Projection through corundum (Fig. 4) of mineral compositions in Spear's (1982) quartz-bearing assemblage is theoretically incorrect. The purpose here is to illustrate the similarity in staurolite-chlorite Fe–Mg partitioning between the two assemblages, that is $K_D = \text{Mg/Fe (staurolite)}/\text{Mg/Fe (chlorite)} = 0.14$ (Spear 1982) and 0.11–0.12 (sample 4017E), and the relative positions of gedrite and the staurolite-chlorite join.

Both figures display the high Mg/Fe ratio in the host rock composition implied by the Antarctic staurolite-talc-corundum-chlorite assemblage. Moreover, the staurolite-talc-corundum-chlorite association is not sufficiently siliceous for either cordierite or an Al_2SiO_5 mineral to appear.

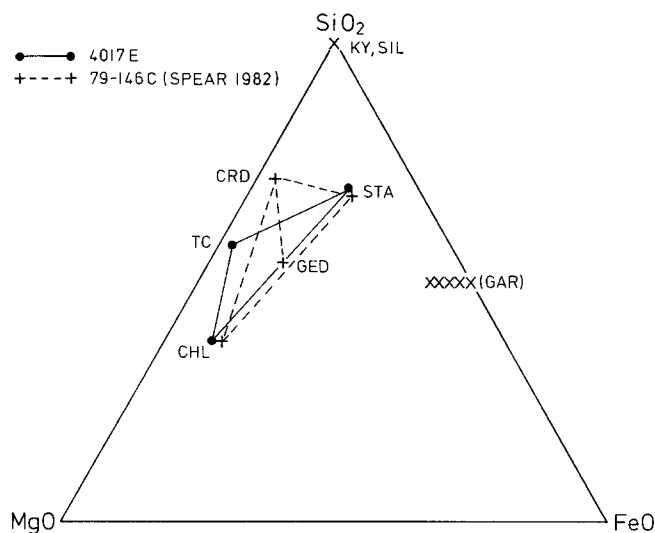


Fig. 4. Projection of mineral compositions onto the plane SiO_2 – MgO – FeO from corundum. This projection is a proper phase diagram only for 4017E, in which corundum is present; the data from Spear's (1982) quartz-bearing assemblage are plotted for comparison only. Symbols and abbreviations are the same as in Fig. 3

The association of chlorite with quartz, cordierite, or Al_2SiO_5 is incompatible with staurolite-talc-corundum, for $\text{Fe}/(\text{Fe}+\text{Mg})$ ratio of talc is less than that of cordierite or chlorite (Spear 1982). Garnet, which has a higher $\text{Fe}/(\text{Fe}+\text{Mg})$ ratio than coexisting staurolite in all but one case (see below), would only appear in a more iron-rich rock, or in a rock lacking chlorite. Cordierite-chlorite and sillimanite- or kyanite-chlorite assemblages are characteristic of amphibolite facies terrains metamorphosed at low (andalusite-sillimanite) or moderate (kyanite-sillimanite) pressures (e.g. Guidotti et al. 1975; Grambling 1981; Spear 1982). These relations also imply that the talc-staurolite association requires unusual P–T conditions, as well as unusually Mg–Al-rich bulk compositions, to be stable.

Given the minerals plotted in Fig. 3 and 4, staurolites associated with talc, corundum, and kyanite would theoretically have the highest X_{Mg} possible under the pressure-temperature conditions under consideration. The X_{Mg} of staurolite in a talc-corundum-chlorite assemblage such as sample 4017E may be close to this theoretical maximum and consequently, the 0.40–0.42 X_{Mg} values obtained on 4017E suggest that Mg-rich staurolites may not be stable at the moderate temperatures (700° C) and pressures (7–10 kbar) estimated for the talc-staurolite assemblage in 4017E. Staurolite with $X_{\text{Mg}} > 0.5$ appears to be restricted to rocks metamorphosed at pressures above the minimum required for Mg-staurolite in the iron-free system, 10–12 kbar (Schreyer 1968), which is the case for the New Zealand (12 kbar, Ward 1984) and Norwegian Mg-rich staurolites (30 kbar, Smith 1984). Pressures during the early stage of metamorphism when staurolite formed in the Limpopo belt may have been well above 7 kbar (Schreyer et al. 1984).

A pressure-temperature diagram for the four component system (H_2O in excess) can be constructed by the Schreinemakers method in 3 stages: 1) Tie to invariant points in the three component MgO – Al_2O_3 – SiO_2 and

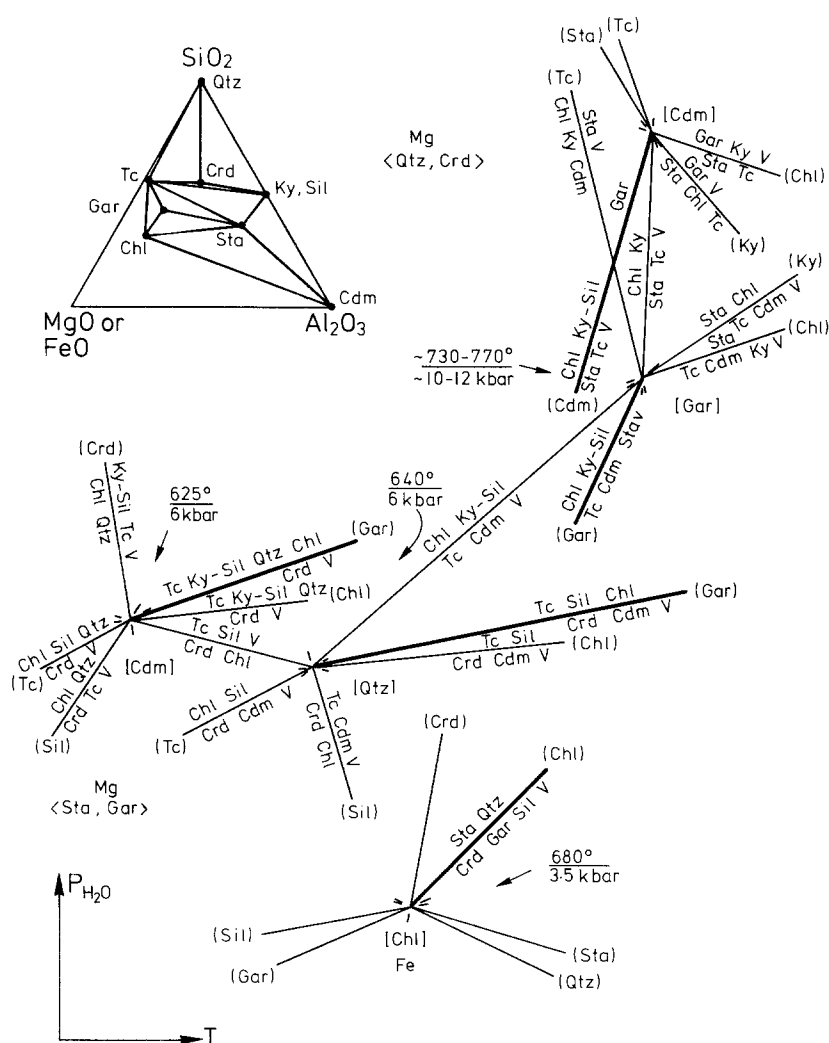


Fig. 5. Pressure-temperature diagram constructed by the Schreinemaker method for the $\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (indicated by Mg) and $\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (Fe) systems (H_2O in excess). Angled brackets $\langle \rangle$ indicate multisystems, square brackets $[]$, invariant points; and rounded brackets $()$, univariant lines; absent phase(s) enclosed. Temperatures in degrees Centigrade and water pressures in kilobars for the invariant points are from Massonne and Schreyer (1983) for [Cdm] and Richardson (1968) for [Chl] in the Fe system; [Qtz] and [Gar] are estimated from Massonne and Schreyer (1983), Seifert (1973), and Schreyer and Seifert (1969b). Diagram is not drawn to scale. Heavy lines indicate univariant curves in the $\text{MgO}-\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (H_2O in excess) system. The labels for these heavy lines (absent phase in parentheses) are the same as the labels in Fig. 6 and refer either to the phase absent at the invariant point or to one of the phases absent from the multisystem to which the invariant point belongs. Mineral abbreviations from Fig. 3; V— H_2O fluid. Ky-Sil indicates either Al_2SiO_5 phase may be involved in the reaction. Composition diagram in corner shows only one set of possible compatibilities

$\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (H_2O in excess) systems and 2) partitioning of Fe among the phases and 3) choice of stable and metastable invariant points. This diagram has been constructed assuming that the curvature in univariant reaction lines does not alter the topology. In the present paper, multisystems, invariant points, and univariant lines are labeled by the phase(s) not participating enclosed in angled $\langle \rangle$, square $[]$, and round $()$ brackets, respectively (Burt 1978).

Appropriate experimental and theoretical studies in the $\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (H_2O in excess) system involve the phases quartz, talc, chlorite, corundum, Al_2SiO_5 , Mg-staurolite, pyrope, and cordierite (Schreyer 1968; Schreyer and Seifert 1969a, b; Chernosky 1978; Seifert 1973; Massonne and Schreyer 1983). The MgO portion of the grid in Fig. 5 is based largely on the discussions of Schreyer and Seifert (1969b) and Massonne and Schreyer (1983). The latter authors located [Cdm], their IP_1 , at 625°C and 6 kbar, and predicted the intersection at [Qtz] in $\langle \text{Gar}, \text{Sta} \rangle$ of the univariant curves talc+sillimanite (kyanite) + H_2O = cordierite + chlorite and cordierite + corundum + H_2O = chlorite + sillimanite determined by Seifert (1973). This intersection (Massonne and Schreyer's IP_2) must lie near 640°C and 6 kbar. It represents the minimum temperature (at $P_{\text{H}_2\text{O}} = P_{\text{total}}$) for the appearance of talc-corundum assemblage, but provides no constraints on pressure. Invariant

points involving Mg-staurolite, pyrope, talc, chlorite, corundum, and kyanite lie at pressures of 10 kbar or more. Schreyer and Seifert (1969b) report the low temperature breakdown of Mg-staurolite to kyanite + chlorite + corundum and Schreyer (1968) mentions a high temperature breakdown of Mg-staurolite to kyanite + talc + corundum. These two breakdown reactions intersect the reaction chlorite + kyanite = talc + corundum + H_2O at the invariant point [Gar] in the $\langle \text{Qtz}, \text{Crd} \rangle$ multisystem. The invariant point is the lower pressure limit of Mg-staurolite (Fig. 5), and probably lies between 10 and 12 kbar and 730° to 770°C (Schreyer and Seifert 1969b). Another invariant point [Sta] involves pyrope instead of Mg-staurolite. One reaction Schreyer and Seifert (1969b) proposed as the low temperature stability limit of pyrope is kyanite + talc + chlorite = pyrope + H_2O which would intersect the univariant reaction (Crd) at this invariant point [Sta]. However, this invariant point must lie at higher pressures than [Gar] and be metastable, for Schreyer and Seifert (1969b) observe that pyrope is unlikely to appear as a low temperature breakdown product of Mg-staurolite. The low temperature stability limit of pyrope defined by kyanite + talc + chlorite would intersect the reaction chlorite + kyanite = staurolite + talc + H_2O at an invariant [Cdm] at pressures above [Gar] (Chopin, unpubl. experimental data). This invariant point would represent the upper pressure limit for staurolite-talc in the

iron-free system. At high temperatures, Mg-staurolite may break down to kyanite + garnet + corundum (Schreyer and Seifert 1969b), suggesting the possibility of a [Chl] invariant point at pressures and temperatures above [Gar] in the quartz- and cordierite-absent multisystem <Qtz, Crd>.

Richardson's (1968) plot for staurolite in the FeO–Al₂O₃–SiO₂ (H₂O in excess) system is also applicable to the proposed diagram. Richardson (1968) located a chlorite- and chloritoid-absent invariant point, which involves the phases Fe-cordierite, sillimanite, Fe-staurolite, almandine and quartz, at about 680° C and 3.5 kbar ([Chl] in Figs. 5–6). This represents a minimum pressure for the set of invariant points in the diagram for the four component system.

The diagram for the MgO–FeO–Al₂O₃–SiO₂ (H₂O excess) system was constructed assuming that the fractionation of iron relative to magnesium among the reacting minerals increased as follows: Talc < cordierite < chlorite < staurolite < garnet (see Deer et al. 1982; Spear 1982). This fractionation constrains the reactions in the four component system to intercept the [Cdm] and [Qtz], [Gar] and [Cdm] invariant points in the iron-free system and Richardson's (1968) chlorite- and chloritoid-absent invariant point [Chl] in the magnesium-free system as shown in Fig. 5. Schreyer et al. (1984) report a reversal in Fe–Mg fractionation between staurolite ($X_{Mg}=0.49$) and garnet ($X_{Mg}=0.56$) that is $X_{Mg}(Sta) < X_{Mg}(Gar)$, or $K_D = X_{Mg}^{Sta} X_{Fe}^{Gar} / X_{Mg}^{Gar} X_{Fe}^{Sta} = 0.75$. This fractionation may be applicable to magnesian staurolite, although Ward (1984) reported a K_D value of 1.06 for staurolite with $X_{Mg}=0.55$ –0.56. A reversal in Fe–Mg fractionation would alter the relative positions of some of the univariant reactions involving staurolite and garnet, for example, (Chl) and (Tc) around the invariant point [Crd, Qtz] in Fig. 6. Other reactions, notably (Cdm) and (Sil) around this invariant point, would not be affected. Consequently, such a reversal in Fe–Mg fractionation should not materially affect the arguments or conclusions presented here.

The next step in constructing the diagram in the four component system is to determine which invariant points are stable and which are metastable. We have not considered all theoretically possible multisystems, but have constructed a diagram that can be fit with the invariant points in the two three-component systems as shown in Fig. 5. With this empirical approach, three alternative constructions are plausible. We present here arguments why we have selected the construction in Fig. 6, which of the three alternatives appears to be the only one consistent with natural occurrences and experiment. One alternative construction differs from Fig. 6 in that the [Gar, Cdm] and [Gar, Qtz] invariant points are stable (and by necessity [Sta, Cdm] and [Sta, Qtz] are metastable), which is the opposite as shown in Fig. 6. The other alternative construction, with [Cdm, Crd] stable, is implicit in Korikovskiy et al.'s (1983, Fig. 3) diagram.

The choice between a construction with [Gar, Cdm] (and by extension [Gar, Qtz]) stable or metastable depends on the relative stability of garnet-cordierite vs talc-staurolite-quartz, which are incompatible assemblages.

The construction illustrated in Fig. 6 predicts a stability range for garnet-cordierite for temperatures above [Tc, Cdm] and [Sta, Cdm], i.e. above 625° C and pressures up to cordierite breakdown. The alternative construction predicts no stability range for garnet-cordierite within the sta-

bility range of staurolite, while staurolite-talc-quartz is predicted to be stable at temperatures above the breakdown of chlorite-quartz and at pressures up to those required for the reaction staurolite + quartz = talc + garnet + kyanite. Korikovskiy et al. (1983, Fig. 3) located a segment of this reaction at 7–8 kbar, 500–530° C. However, garnet-cordierite is a widespread assemblage in upper amphibolite- and granulite-facies rocks and has been synthesized in the four component system at temperatures as low as 740° C ($P=3.25$ –4 kbar) (Hensen and Green 1973; Holdaway and Lee 1977). Rocks containing talc, staurolite, and quartz are very rare and in none of these rocks are the three minerals in stable equilibrium (as discussed at beginning of this section).

In the other alternative construction, the stable portions of the univariant reactions labeled (Crd) issuing from [Tc, Cdm] and [Sta, Cdm] and (Cdm) from [Crd, Qtz] converge at high pressures at a stable invariant point [Crd, Cdm]. In Fig. 6, the metastable portions of these reactions converge at low pressures and [Crd, Qtz] is metastable. The other three univariant reactions issuing from [Crd, Cdm], namely (Gar), (Chl), and (Ky), are the three chloritoid-absent reactions in Korikovskiy et al.'s (1983, Fig. 3) diagram. According to these authors, the reactions (Gar), (Chl), and (Ky) converge below 7 kbar and above 530° C. This intersection is by definition these authors' location for a stable [Crd, Cdm]. In our construction the reactions (Gar), (Chl), and (Ky) are metastable. There are three considerations that argue against a stable [Crd, Cdm]. Firstly, a stable [Crd, Cdm] below 7 kbar implied by Korikovskiy et al. (1983) is inconsistent with C. Chopin's evidence (unpubl. experimental data) for a [Cdm] invariant point at high pressure in the <Qtz, Crd> multisystem in MgO–Al₂O₃–SiO₂ (–H₂O) (in Fig. 5). The (Cdm) reaction in the four component system issuing from [Crd, Qtz] must terminate in this [Cdm] invariant point in the Fe-free system. Korikovskiy et al.'s (1983) construction constrains this reaction to pass through [Crd, Cdm], and thus [Cdm] in <Qtz, Crd> must lie at temperatures below 530° C and pressures above 7 kbar, but probably not much above 10 kbar for temperatures above 0° C. Secondly, this invariant point [Cdm] in <Qtz, Crd> in the iron-free system would be metastable relative to reactions involving quartz, as it would lie along the metastable extension of (Cdm) beyond [Crd, Cdm] in the four component system. Thirdly, a stable [Crd, Cdm] at pressures less than 7 kbar implies that all the invariant points in the four component system shown in Fig. 6 also lie at pressures less than 7 kbar. Thus no cordierite would be expected at pressures much above 6 kbar, while talc-kyanite-garnet-quartz, a breakdown assemblage of cordierite (Fig. 6), would be expected to be stable at pressures as low as 6–7 kbar. Observations are inconsistent with these expectations. Cordierite is common in pelitic rocks metamorphosed at 6–7 kbar (e.g. Newton 1983), while talc-kyanite-garnet-quartz is restricted to eclogite-bearing terrains (Råheim and Green 1974; Udovkina et al. 1977, 1978).

A more rigorous treatment of the above arguments was proposed by Burt (1978), who demonstrated that the labels (that is, absent phases) of the metastable invariant points in a given multisystem constitute a stable assemblage, and the labels of the stable invariant points, a metastable assemblage. In the <Cdm> multisystem, [Sta, Cdm], [Tc, Cdm], and [Qtz, Cdm] are stable invariant points ([Qtz, Cdm] is metastable relative to the <Qtz> multisystem), while [Gar,

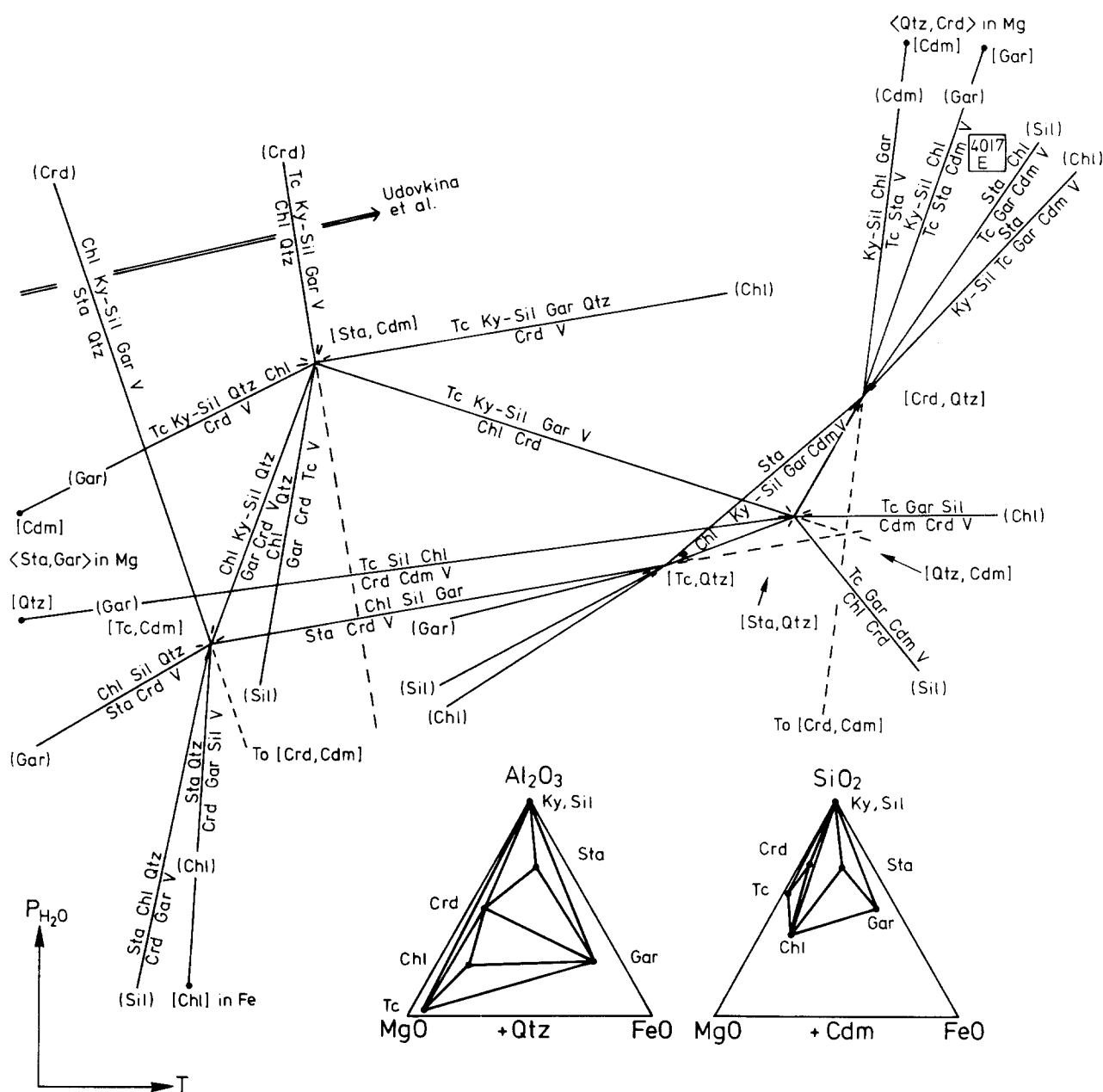


Fig. 6. Pressure-temperature diagram (not to scale) constructed by the Schreinermakers method for the FeO–MgO–Al₂O₃–SiO₂ (H₂O in excess) system. Symbols and abbreviations are the same as those in Fig. 5. The univariant lines which connect to invariant points in the iron-free or magnesium-free system are shown discontinuous, with one segment ending in filled circles representing these invariant points and labeled as in Fig. 5. Arrow refers to *P–T* path for Kazakhstan talc-kyanite-garnet schist (Udovkina et al. 1978) and 4017E lies in area where the assemblage staurolite-talc-corundum-chlorite is predicted to be stable. Some of the univariant curves radiating from [Te, Qtz] and [Te, Cdm] may extend into the andalusite stability field; this has not been indicated. Compositions of minerals are projected through quartz (left triangle) and corundum (right triangle) and one set each of compatibilities are shown. The composition plot on the left applies to reactions involving quartz; that on the right, to reactions involving corundum; and Fig. 3, to reactions in which quartz and corundum are both absent, that is, the three reactions converging at [Qtz, Cdm].

Cdm] and [Cr_d, Cdm] (as well as [Sil, Cdm] and [Chl, Cdm]) are metastable. Thus staurolite-talc-quartz should be metastable, and garnet-cordierite-Al₂SiO₅-chlorite, stable. The Al₂SiO₅ mineral can be either kyanite, sillimanite, or andalusite. In examples of the latter assemblage that have been studied in detail, the garnet contains considerable manganese (Osberg 1971; Grambling 1981), and thus these examples are not strictly applicable to the model four component system. In the <Qtz> multisystem, the predicted metastable and stable assemblages are talc-staurolite-cordierite

and garnet-corundum-chlorite- Al_2SiO_5 , respectively, neither of which has been reported, as far as we are aware. In fact, all four assemblages may be metastable with respect to orthoamphibole-bearing assemblages, and thus a rigorous test of the validity of Fig. 6 by Burt's (1978) approach may not be possible.

Figure 6 is consistent with the observations and reactions put forward by Udovkina et al. (1977, 1978) for the disappearance of staurolite and chlorite in the Kazakhstan kyanite-garnet-talc-quartz rock. The two reactions pro-

posed by Udovkina et al. (1978), that is, staurolite + quartz = kyanite + chlorite + garnet + H₂O and chlorite + quartz = kyanite + garnet + talc + H₂O are the (Crd) reactions radiating from [Tc, Cdm] and [Sta, Cdm], respectively (Fig. 6). Udovkina et al.'s (1977, 1978) interpretation implies that staurolite and talc were never in equilibrium at any stage during the metamorphic cycle, and indeed the locations of these two reactions lie outside the stability field of staurolite-talc. In contrast, Korikovskiy et al. (1983) suggested that the Kazakhstan talc-kyanite-garnet schist passed through a talc-chloritoid and talc-staurolite stage and their Fig. 3 is based on this interpretation. However, the absence of staurolite in other whiteschist terrains (e.g. Vrána and Barr 1972; Chopin 1981) is not consistent with Korikovskiy et al.'s (1983) interpretation. There is no evidence that staurolite is involved in reactions with chloritoid, chlorite, garnet, kyanite, and talc in the transition from talc-chloritoid to talc-kyanite + garnet parageneses. Figure 6 predicts breakdown of staurolite + quartz at temperatures below that of chlorite + quartz to talc + kyanite + garnet. Staurolite is not stable in quartz-bearing rocks at temperatures where chloritoid and chlorite react to form talc + garnet + kyanite.

In Figure 6, we predict that staurolite-talc is stable only at relatively high temperatures and in the absence of quartz. In addition, staurolite-talc assemblages require higher pressures than the minimum pressure (about 6 kbar, Massonne and Schreyer 1983) required for the assemblages talc-kyanite or talc-sillimanite. The minimum pressures and temperatures for talc-staurolite (for $P_{H_2O} = P_{total}$), the invariant point [Crd, Qtz] in Fig. 6, are constrained to lie between [Qtz] and [Gar] in the iron-free system, that is, between 6 kbar and 10–12 kbar and 640° and 730–770° C (At $P_{H_2O} < P_{total}$, the minimum temperatures and pressures required for staurolite-talc-corundum may be less). This range of temperatures overlaps the temperatures of 650 to 700° C inferred for the middle stage of metamorphism at "Fibrolite Ridge". Thus the predicted pressure-temperature stability field for staurolite-talc-corundum-chlorite according to Fig. 6 is consistent with formation of this assemblage in the "Fibrolite Ridge" rock only if we assume an isothermal decrease in pressure during the transition from the early to the middle stages of metamorphism.

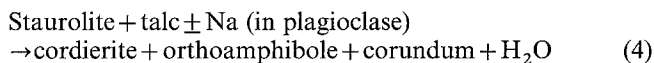
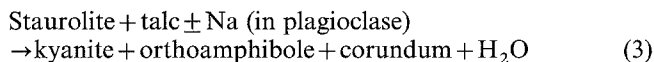
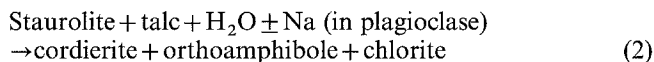
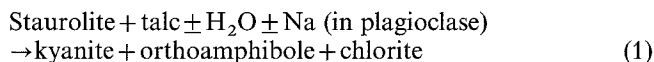
Incompatibility of staurolite-talc with orthoamphiboles

In view of the pressure-temperature range predicted for talc-staurolite, the rarity of this assemblage is puzzling. Admittedly, appropriate bulk compositions (rich in Mg, Al, poor in Fe, Si) of the host rock are unusual. Another possible explanation is that the reactions around the invariant point [Crd, Qtz] are metastable relative to reactions involving orthoamphibole. At temperatures of 600°–700° C, anthophyllite or gedrite might appear, particularly gedrite in rocks containing Na₂O (see Schreyer and Abraham 1976). In sample 4017E, albite is present both as inclusions in tourmaline and in the schist matrix, and thus Na₂O was available in the rock during the entire metamorphic cycle. The absence of orthoamphibole in this rock cannot be attributed to absence of Na₂O.

Assemblages of anthophyllite and gedrite with cordierite or Al₂SiO₅, which are relatively common, restrict talc-staurolite assemblages to very magnesian bulk compositions. The orthoamphibole-cordierite and orthoamphibole-

Al₂SiO₅ tielines are probably in an FeO-richer portion of the FeO–MgO–Al₂O₃–SiO₂ composition tetrahedron relative to staurolite-talc tielines. This geometric relation is required by the analyses plotted in Fig. 3. The orthoamphibole-cordierite and orthoamphibole-Al₂SiO₅ assemblages are generally found in relatively magnesian rocks and in a few cases, in rocks nearly free of FeO (Schreyer and Abraham 1976). Most likely the appearance of orthoamphibole-cordierite or orthoamphibole-Al₂SiO₅ in an iron-bearing rock means that metamorphic conditions were such that this association is stable in a corresponding iron-free rock, thereby precluding the talc-staurolite assemblage. Orthoamphibole-chlorite assemblages with either cordierite or Al₂SiO₅ are incompatible with staurolite-talc. Three of Spear's (1982) rocks (including sample 79–146c illustrated in Fig. 3) contain the assemblage orthoamphibole-cordierite-chlorite. For corundum-bearing rocks, similar arguments apply. If we assume that the composition of a gedrite associated with corundum does not differ significantly from Spear's (1982) composition of gedrite, which is associated with quartz, we can refer to the relations illustrated in Fig. 4. Thus orthoamphibole in corundum-bearing rocks restricts talc-staurolite to magnesian compositions, while orthoamphibole-cordierite and orthoamphibole-Al₂SiO₅ are incompatible with staurolite-talc. In sum, the appearance of orthoamphibole in Mg–Al-rich rocks either restricts the staurolite-talc assemblage to unusually low-iron bulk compositions, or excludes it altogether. It is thus no surprise that talc-staurolite is a rare assemblage.

Under what conditions might an staurolite-talc assemblage be stable relative to an orthoamphibole-bearing assemblage? The following four reactions relating talc-staurolite to orthoamphibole (gedrite or anthophyllite)-bearing assemblages might answer this question:



The amount of water released by these reactions can be estimated by balancing the equations with mineral compositions simplified from Tables 1 and 2 and Spear (1982), and assuming that staurolite contains 3 protons per formula unit of 48 oxygens (see Ribbe 1982; Lonker 1983, reports 1.8 to 3.6), cordierite, 0.5 H₂O per formula unit of 18 oxygens (roughly 1.5 wt.% H₂O, e.g. Deer et al. 1962; Hess 1969), and orthoamphibole, 2 protons per formula unit of 24 oxygens. In reaction (1), the reactants and products contain about the same amount of water, while reaction (2) consumes a small amount and reactions (3) and (4) release a considerable amount. Approximate calculations of the volume change for the reactions involving anthophyllite indicate a large volume increase for the appearance of cordierite (reactions 2, 4) but little change for that of kyanite (1, 3). Consequently, staurolite-talc would be expected at higher pressures than the assemblages cordierite-orthoamphibole-chlorite or cordierite-orthoamphibole-corundum. Schreyer and Seifert (1969a) estimated maximum pressures

of 10 to 12 kbar for orthoamphibole-cordierite in the Na_2O -free system, and this pressure range could be a minimum for staurolite-talc. On the other hand, there is no clearcut difference in either the total volume or water content between kyanite-orthoamphibole-chlorite and staurolite-talc, and consequently we have no means of predicting the relative stabilities of these assemblages in pressure-temperature space. Kyanite-orthoamphibole is a relatively common assemblage and possibly staurolite-talc is metastable relative to this assemblage in corundum-free rocks. However, in rocks containing corundum, the kyanite-orthoamphibole assemblage results from the dehydration of talc-staurolite (reaction 3). This relation suggests the possibility of a window in pressure-temperature-water activity space in which temperatures are sufficiently high to stabilize staurolite-talc relative to kyanite-chlorite (Fig. 6) at water partial pressures (activities) sufficiently high to prevent the breakdown of talc-staurolite to orthoamphibole-kyanite. This window may have been accessible during the early stage of metamorphism in the Antarctic rock, during which burial and temperature increase may have been associated with retention of water in this particular rock. Thus water activity may have remained relatively high at temperatures near 700°C . It is doubtful water activities remained high in the enclosing sediments, for we found no evidence of partial melting on "Fibrolite Ridge" northeast of Mount Bernstein.

In conclusion, the rarity of the talc-staurolite assemblage may be largely due to the appearance of orthoamphibole in magnesian rocks at the pressure-temperature conditions appropriate for stability of the staurolite-talc assemblage. Only in corundum-bearing rocks, where orthoamphibole-bearing assemblages form from dehydration of the staurolite-talc assemblage, is it possible for talc-staurolite to appear, and then only under conditions of relatively high water activities. Such conditions may be attainable only during the early stages of a metamorphic cycle.

Acknowledgments. Logistic support in the field was provided by U.S. Navy Antarctic Development Squadron Six as part of the U.S. Antarctic Research Program. Grew thanks K. Abraham for assistance with the operation of the electron microprobe facility at Bochum. This research was funded by U.S. National Science Foundation Grant DPP 80-19527 to the University of California, Los Angeles, and by the Alexander von Humboldt-Stiftung in Bonn. Sandiford's research was also supported by a Commonwealth Postgraduate Research Award. Comments by C. Chopin, P.C. Grew, W. Schreyer, and J.C. Schumacher on earlier versions of the manuscript have led to a substantial improvement, for which the authors are deeply grateful. We also thank J.C. Schumacher for comments on talc and staurolite from enclaves he is currently studying and C. Chopin for discussions on his experimental work at high pressures on the $\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ system.

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Received February 16, 1984; Accepted July 9, 1984