

KORNERUPINE-GROUP MINERALS IN GRENVILLE GRANULITE-FACIES PARAGNEISS, READING PRONG, NEW JERSEY

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ABSTRACT

Prismatine, the boron-rich member of the kornerupine group, has recently been identified in the Reading Prong in New Jersey from granulite-facies gneisses consisting of the assemblage orthoclase + calcic oligoclase + prismatine + biotite + rutile ± almandine ± sillimanite ± graphite ± ilmenite. The prismatine crystals, as much as 6 cm long, are typically altered to muscovite-rich mixtures. The prismatine probably crystallized during isochemical metamorphism of originally boron-bearing clay-rich sediments. The conditions of peak metamorphism were 670–740°C and between 6.2 and 8 kbar. No evidence remains of the boron-bearing mineral precursor of prismatine, but it is reasonable to assume that tourmaline may have been present at lower grades. A possible mechanism for forming prismatine is the reaction: 1.55 Ti-rich biotite + 1.0 tourmaline + 1.22 almandine + 5.23 sillimanite → 3.0 prismatine + 2.55 (orthoclase + albite) + 0.46 rutile + 0.39 B₂O₃ + 2.05 H₂O.

Keywords: prismatine, kornerupine, boron, granulite-facies metamorphism, Reading Prong, New Jersey.

SOMMAIRE

La prismatine, membre borifère du groupe de la kornerupine, a récemment été identifiée dans le socle de Reading Prong, dans l'état du New Jersey, dans des gneiss équilibrés au faciès granulite, qui contiennent l'assemblage orthoclase mésoperthitique + oligoclase calcique + prismatine + biotite + rutile ± almandin ± sillimanite ± graphite ± ilménite. Les cristaux de prismatine, qui atteignent 6 cm en longueur, sont typiquement altérés à un assemblage polycristallin riche en muscovite. La prismatine aurait cristallisé au cours d'un épisode de métamorphisme isochimique de sédiments originellement borifères et argileux. Les conditions du paroxysme métamorphique étaient entre 670° et 740°C et entre 6.2 et 8 kbar. Il n'y a plus de preuve d'un minéral borifère précurseur de la prismatine, mais il semble raisonnable de proposer la présence de tourmaline aux plus faibles degrés de métamorphisme. La réaction suivante pourrait expliquer la formation de la prismatine: 1.55 biotite titanifère + 1.0 tourmaline + 1.22 almandin + 5.23 sillimanite → 3.0 prismatine + 2.55 (orthoclase + albite) + 0.46 rutile + 0.39 B₂O₃ + 2.05 H₂O.

(Traduit par la Rédaction)

Mots-clés: prismatine, kornerupine, bore, faciès granulite, métamorphisme, Reading Prong, New Jersey.

INTRODUCTION

The kornerupine group consists of rare ferromagnesian aluminosilicate minerals with variable boron content. These minerals are characterized by the approximate chemical formula $(\square, \text{Mg}, \text{Fe}^{2+}, \text{Na})(\text{Mg}, \text{Fe}^{2+})_3(\text{Al}, \text{Mg}, \text{Fe}^{3+})_6(\text{Si}, \text{Al}, \text{B})_5(\text{O}, \text{OH}, \text{F})_{22}$. Occurrences of kornerupine-group minerals have now been recognized from approximately seventy localities worldwide. In a review of the nomenclature of the kornerupine group, Grew *et al.* (1996) revalidated the name *prismatine* for boron-rich kornerupine [B > 0.5 atoms per formula unit of 22(O,OH,F)], applied the name *kornerupine* in the strict sense only to kornerupine with B < 0.5 atoms per formula unit, restricted the term boron-free kornerupine to kornerupine analyzed for B and found not to contain it,

and applied the term kornerupine in the broad sense as a group name to a kornerupine-structure mineral with unspecified boron content.

Through the results of chemical analyses (*e.g.*, Grew *et al.* 1990) and crystallographic studies (*e.g.*, Moore & Araki 1979, Klaska & Grew 1991), the cation proportions in minerals of the kornerupine group are now fairly well understood, but the proportions of anion constituents remain to be worked out. The phase relationships of boron-free kornerupine have been investigated systematically (*e.g.*, Seifert 1975), whereas experimental studies of boron-bearing members of the kornerupine group have been limited to syntheses (Werdning & Schreyer 1978). Natural assemblages and Schreinemaker analysis have also been used to infer phase relationships (*e.g.*, Windley *et al.* 1984, Grew 1988, Lonker 1988).

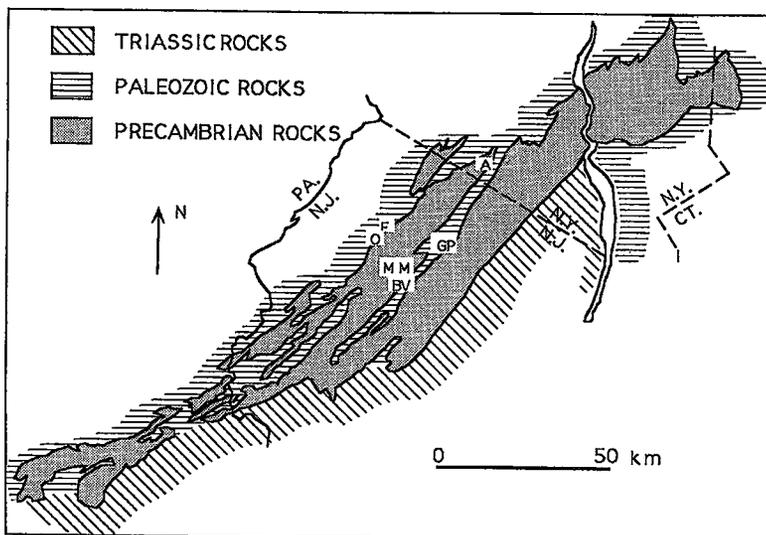


FIG. 1. Geological setting of the Reading Prong. Localities referred to in text as follows: A: Amity, New York; BV: Berkshire Valley, New Jersey; F: Franklin, New Jersey; GP: Lower Paleozoic Green Pond Mountain outlier; MM: Mase Mountain; O: Ogdensburg, New Jersey. Figure 2 is a more detailed geological map of the area around MM and shows the location of prismatic-bearing samples.

In this paper, I describe a distinctive occurrence of kornrupine-group minerals, predominantly prismatic, in which the pelitic host-rock is characterized by the absence of reaction textures, the presence of a very high alkali content, an abundance of mesoperthite, and a lack of quartz. This occurrence, situated within the Reading Prong, a terrane of Middle Proterozoic gneisses and igneous rocks that is exposed from the New York - Connecticut border across southeastern New York and northern New Jersey into eastern Pennsylvania (Fig. 1), adds to the growing number of localities of kornrupine-group minerals reported from the Grenville Province and its southerly extensions (Lonker 1988, Farrar & Babcock 1993, Ackermann *et al.* 1994, Boggs *et al.* 1994). Mineral chemistry, bulk-rock composition, and well-delineated stratigraphy permit construction of a model for the formation of prismatic in the Reading Prong locality.

Although boron-bearing minerals such as sussexite, fluoborite, wawayandaite, and warwickite have been described from the Franklin Marble along the northwestern flank of the Reading Prong (at Amity, N.Y. and Franklin and Ogdensburg, N.J.: Moore 1994) and tourmaline has been encountered sporadically in pelitic gneisses (Jaffe & Jaffe 1973), the development of prismatic shows that boron enrichment within the Reading Prong is more widespread than previously recognized, and suggests that boron-bearing minerals may have been overlooked.

GEOLOGICAL SETTING

The New Jersey locality of prismatic is situated within the Dover 7 1/2' quadrangle, about 1.5 km north of Berkshire Valley at the southwestern tip of Mase Mountain, approximately 770 m north of Taylor Road along a powerline that parallels New Jersey Route 15 (Fig. 2). The locality occurs within the northeast-trending Mase Mountain block, situated just northwest of the Lower Paleozoic Green Pond Mountain outlier (Young 1971). The block consists of a thick sequence of hornblende-granulite-facies gneisses that have been deformed about northeast-plunging axes into overturned tight to isoclinal folds and intruded by late tectonic fayalite-bearing hedenbergite quartz syenite (Young 1972, Young & Cuthbertson 1994). The gneisses probably originated from various pelites, graywackes, mafic lava flows, and volcanoclastic rocks. The sequence was injected by a sill of gabbroic anorthosite that was metamorphosed to biotite-plagioclase gneiss (Young & Icenhower 1989).

The prismatic-bearing rocks occur in the hinge of a major northeast-plunging synform within a 430-m-thick unit composed predominantly of thinly layered graphitic sillimanite - garnet - biotite - quartz - feldspar and biotite- or hornblende-bearing pyroxene-feldspar gneisses. The prismatic crystals are present in several layers within an area approximately

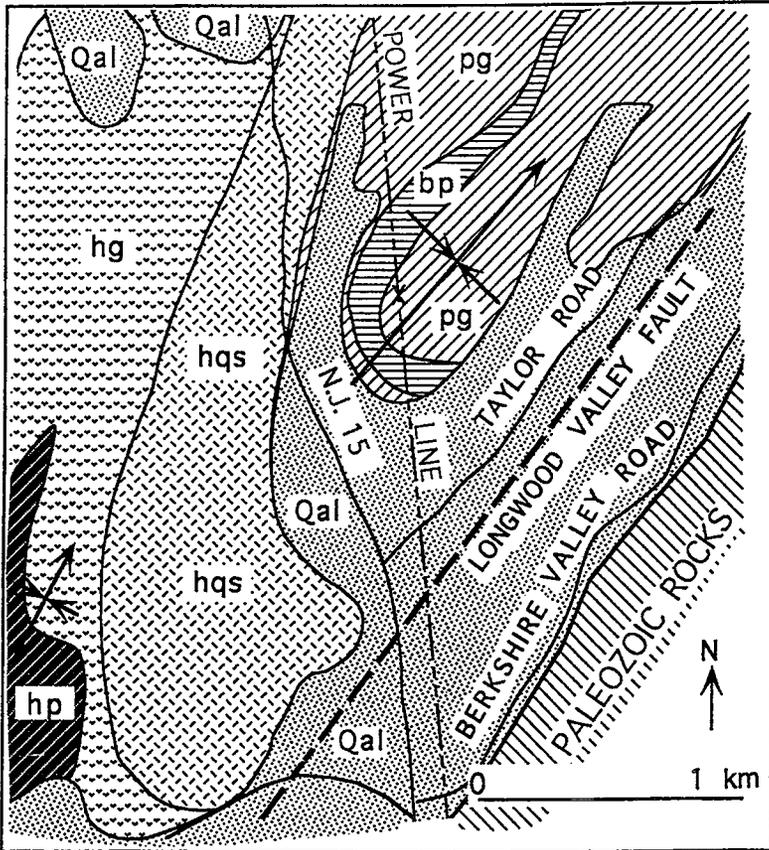


FIG. 2. Local geological setting of prismatic occurrence. Prismatic-bearing outcrops are marked by X along power line. Symbols: hg hornblende granite, hqs hedenbergite quartz syenite (see Young 1972, Young & Cuthbertson 1994), pg assorted paragneisses, bp biotite-plagioclase gneiss (meta-anorthosite sill) (see Young & Icenhower 1989), hp hornblende-plagioclase gneiss, Qal Quaternary alluvium. Berkshire Valley is located at the intersection of N.J. Route 15 and Berkshire Valley Road. Mase Mountain forms a northeasterly trending ridge that terminates in the vicinity of the thickened portion of hqs and the synform along the power line.

5 m × 5 m. The individual layers, typically 1 to 5 cm thick, consist predominantly of feldspar and biotite. Prismatic forms elongate translucent pale yellow-green crystals that weather dull gray to reddish brown and weather out in higher relief than the rock matrix. The crystals, subparallel to the foliation and mineral lineation, are commonly 1 to 2 cm in length, but a few are as long as 6 cm. Well-formed prism faces are readily visible, but the crystal terminations are obscure.

PETROGRAPHY

In thin section, prismatic occurs as very elongate euhedral to subhedral crystals that occur in layers composed of the assemblage orthoclase mesoperthite

(10–70%) + calcic oligoclase (3–68%) + prismatic (6–20%) + titaniferous biotite (1–19%) + rutile (up to 1%) ± almandine ± sillimanite ± graphite ± ilmenite. Although quartz-rich layers are interlayered with prismatic-bearing layers, quartz has not been observed in contact with prismatic. The prismatic displays first-order gray to pale yellow interference colors and indistinct pale tan pleochroism. Larger crystals of prismatic contain small inclusions of rutile, biotite, sillimanite, ilmenite, and perthite. Almost all grains of prismatic are altered to a muscovite-rich fringe. No other products of alteration have been recognized. Characteristic textures are shown in Figure 3.

Coarse biotite displays orange-red pleochroism.

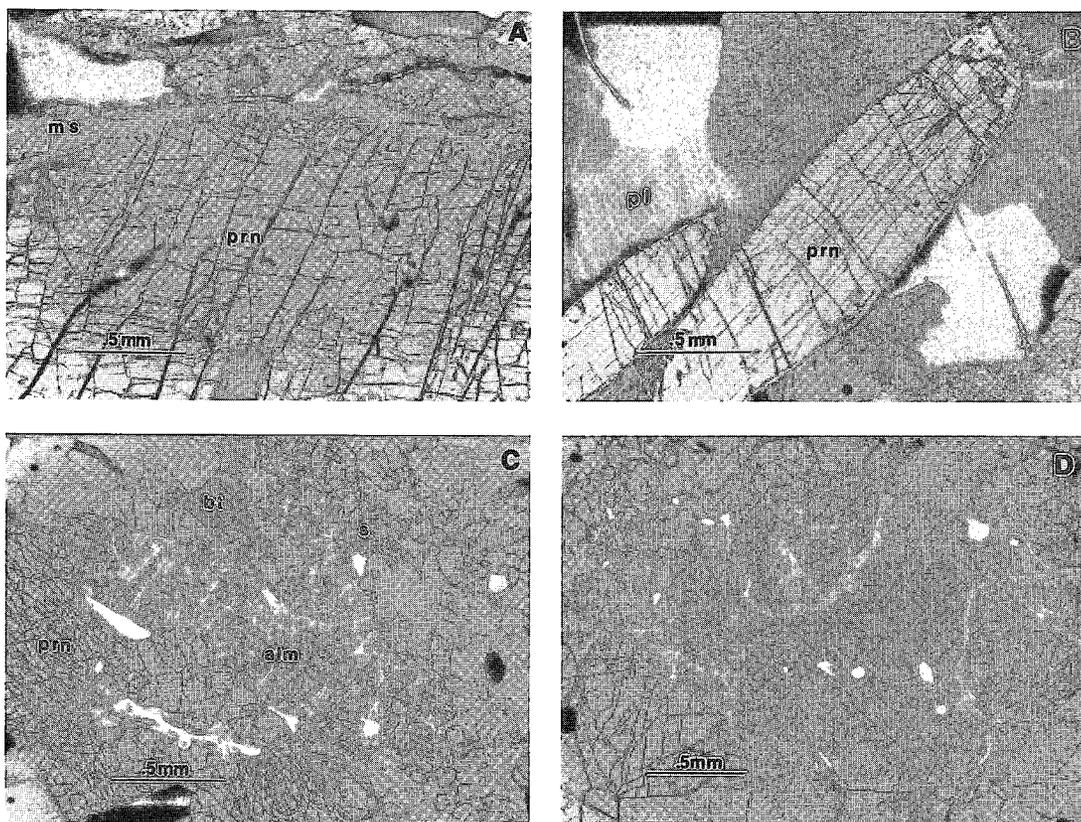


FIG. 3. Textural relationships of prismatic-bearing rocks. A. Sample T2. Biotite, prismatic (prn), and antiperthitic oligoclase. Note muscovite-rich alteration fringe (ms) around prismatic, as well as prominent transverse fractures in prismatic prism. B. Sample T4A. Prismatic prisms (prn) surrounded by antiperthitic oligoclase (pl). C. Sample T3. Almandine (alm), biotite (bt), sillimanite (s), and oligoclase with abundant cross-sections of prismatic (prn). The small dark euhedra are rutile, and the irregular elongate black mineral above the scale bar is graphite. D. Sample T1. Cluster of cross sections of prismatic prisms (high relief) surrounded by perthite grains. Small black grains are rutile.

Almandine is locally present as elongate amoeboid masses containing small inclusions of rutile, biotite, ilmenite, and sillimanite. Feldspar, invariably the most abundant mineral in the prismatic-bearing layers, consists chiefly of orthoclase mesoperthite or calcic oligoclase that is commonly antiperthitic. The range of textures suggests varying degrees of exsolution and recrystallization of an originally ternary feldspar. Rutile occurs as tiny euhedral to subhedral crystals dispersed throughout the prismatic-bearing layers. The muscovite-rich alteration that fringes the prismatic crystals has anomalous yellowish interference colors and resembles the "kryptotile" alteration reported from Waldheim, Germany (Sauer 1886, Uhlig 1910, Schreyer *et al.* 1975).

COMPOSITION OF PRISMATINE AND ASSOCIATED MINERALS

Table 1 summarizes the chemical data for the

kornerupine- group minerals and their host rocks. Table 2 lists representative results of electron-microprobe analyses of the associated minerals. The major-element composition of all minerals was determined by wavelength-dispersion analysis on a Cameca Camebax electron microprobe at the Geoanalytical Laboratory of Washington State University. The analyses were done with a 4- μm beam at a voltage of 20 kV and beam current of 11.4 to 11.8 nA. Analyses along short traverses and at individual spots were obtained for several grains of prismatic, almandine, biotite, sillimanite, rutile, and ilmenite from three representative thin sections (T1, T2, and T3).

In addition, the B_2O_3 , BeO, Li_2O , F, and H_2O^+ contents of two separates of crushed fragments of several small crystals of prismatic from different hand specimens, including those from which thin sections were cut, were analyzed at X-Ray Assay Laboratories. The major- and trace-element composition of a crushed

TABLE 1. CHEMICAL COMPOSITION OF PRISMATINE, KORNERUPINE, AND PRISMATINE-BEARING GNEISSES, READING PRONG, NEW JERSEY

| Grain | P r n | | | | | K r n | | | | P r n-bearing gneisses | | | | | | |
|-----------------------------------|-------|-------|-------|--------|-------|-------|-------|-------|-------|------------------------|-----|--------|-----|-----|-----|-----|
| | T1* | T2* | T3* | Sep.** | T7† | T2‡ | T5§ | T1§ | T1* | T2* | T3* | Sep.** | T7† | T2‡ | T5§ | T1§ |
| SiO ₂ wt% | 30.13 | 30.70 | 30.45 | 30.19 | 29.83 | 28.90 | 53.80 | 56.00 | 53.35 | | | | | | | |
| TiO ₂ | 0.27 | 0.27 | 0.27 | 0.23 | 0.23 | 0.50 | 1.26 | 1.07 | 1.81 | | | | | | | |
| Al ₂ O ₃ | 41.44 | 41.83 | 41.57 | 41.53 | 42.05 | 40.40 | 24.20 | 23.80 | 26.14 | | | | | | | |
| B ₂ O ₃ (d) | | | | | | 3.40 | 0.17 | | | | | | | | | |
| FeO (e) | 7.08 | 7.19 | 8.34 | 8.65 | 8.16 | 9.54 | 6.59 | 3.00 | 1.96 | | | | | | | |
| MnO | 0.05 | 0.03 | 0.04 | 0.03 | 0.04 | 0.03 | 0.05 | 0.01 | 0.01 | | | | | | | |
| MgO | 14.63 | 14.89 | 13.63 | 13.48 | 13.80 | 12.40 | 3.75 | 2.67 | 3.95 | | | | | | | |
| CaO | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.22 | 1.03 | 1.05 | 1.93 | | | | | | | |
| Na ₂ O | 0.11 | 0.10 | 0.09 | 0.11 | 0.09 | 0.41 | 3.64 | 4.87 | 3.25 | | | | | | | |
| K ₂ O | n.d. | n.d. | n.d. | n.d. | 0.01 | 0.62 | 3.66 | 5.28 | 5.89 | | | | | | | |
| H ₂ O* (f) | | | | | | 1.65 | 3.10 | 0.90 | 0.46 | | | | | | | |
| Total (g) | 93.72 | 95.02 | 94.40 | 94.24 | 94.22 | 93.02 | 98.58 | 97.75 | 98.29 | | | | | | | |
| B ppm | | | | | | | 519 | 416 | 2764 | | | | | | | |
| F (h) | | | | | | 4500 | 3080 | 1230 | 1820 | | | | | | | |
| Cl (i) | | | | | | | 338 | 540 | 1240 | | | | | | | |
| Be (j) | | | | | | 75 | 9 | | | | | | | | | |
| Li (j) | | | | | | 511 | 203 | | | | | | | | | |
| Rb (k) | | | | | | | 23 | 141 | 224 | | | | | | | |
| Sr (k) | | | | | | | 74 | 138 | 156 | | | | | | | |
| Y (k) | | | | | | | 21 | 116 | 87 | | | | | | | |
| Zr (k) | | | | | | | 57 | 347 | 243 | | | | | | | |
| Nb (k) | | | | | | | 21 | 36 | 23 | | | | | | | |
| Ba (k) | | | | | | | 251 | 707 | 1030 | | | | | | | |

Structural formulae based on 21.5 atoms of oxygen

| | | | | | | |
|-------|--------|--------|--------|--------|--------|--------|
| Si | 3.797 | 3.817 | 3.828 | 3.808 | 3.759 | 3.935 |
| Ti | 0.026 | 0.025 | 0.026 | 0.022 | 0.022 | 0.051 |
| Al | 6.155 | 6.131 | 6.160 | 6.175 | 6.242 | 6.484 |
| B (l) | 0.739 | 0.729 | 0.737 | 0.740 | 0.739 | 0.039 |
| Fe | 0.746 | 0.748 | 0.877 | 0.913 | 0.860 | 1.082 |
| Mn | 0.005 | 0.003 | 0.004 | 0.003 | 0.004 | 0.003 |
| Mg | 2.748 | 2.760 | 2.554 | 2.535 | 2.590 | 2.518 |
| Ca | 0.001 | 0.001 | 0.001 | 0.003 | 0.001 | 0.031 |
| Na | 0.027 | 0.024 | 0.021 | 0.027 | 0.021 | 0.108 |
| K | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.108 |
| Total | 14.244 | 14.238 | 14.208 | 14.226 | 14.239 | 14.359 |

* Results of electron-microprobe analysis. ** Average partial analysis of two crushed separates of fragments of several crystals of prismatic. † Major elements determined by X-ray fluorescence (XRF). ‡ Composition calculated from mode and mineral analyses. § Average of five spots. ¶ One spot each. †† Average of five spots along traverse. ‡‡ B₂O₃ by inductively coupled plasma - emission spectroscopy (ICP). ††† Total Fe determined as FeO. †††† Wet chemistry. ††††† Exclusive of B₂O₃ and H₂O*. †††††† Fluorine specific electrode. ††††††† by ICP. †††††††† Li by atomic absorption spectroscopy (AA). ††††††††† XRF. †††††††††† Calculated for T1, T2, and T3 using 3.40% B₂O₃. n.d. not detected. Symbols: K r n kornepine, P r n prismatic, Sep. separate.

3-cm single crystal (sample T7) also was determined by X-ray fluorescence and inductively coupled plasma analysis at X-Ray Assay Laboratories. This crystal has a very low B content and is therefore kornepine. The crushed fragments were purified with methylene iodide and a Frantz magnetic separator. Graphite, biotite, and rutile were the obvious contaminants. Although visual estimates suggest that the separates were about 99% pure, the high TiO₂, K₂O, Na₂O, and CaO contents of the kornepine sample (T7) suggest the presence of abundant small impurities of rutile, mica, and feldspar.

Microprobe analyses along a traverse of a prismatic grain in T3 show a slight increase in Al and decreases in Si, Fe, and Mn from core to rim. Both prismatic and kornepine have higher levels of Ti and much higher H₂O contents than most analyzed samples of prismatic and kornepine (e.g., Grew *et al.* 1990).

The unzoned biotite is exceptionally Ti-rich (up to 5.8% TiO₂), and is the most titaniferous biotite yet reported in association with prismatic or kornepine. The rim of a large zoned grain of almandine in T3 that is locally in contact with small biotite flakes (including grain T3-24 in Table 2) is less magnesian than the core. The compositional data indicate that almandine re-equilibrated with biotite upon cooling by exchanging Mg for Fe. The large crystal of almandine shows no evidence of Fe-Mg exchange with prismatic, but is slightly enriched in Ti adjacent to rutile.

The Fe/(Fe + Mg) values of coexisting ferromagnesian minerals exhibit the following ranges: 0.59-0.67 in almandine, 0.27-0.34 in biotite, and 0.21-0.27 in prismatic and kornepine.

TABLE 2. REPRESENTATIVE ELECTRON-MICROPROBE DATA ON MINERALS ASSOCIATED WITH PRISMATINE

| SiO ₂ wt% | Alm | Alm | Alm | Alm | Bt | Bt | Bt | Rt | Ilm | Sil | |
|--------------------------------|--------|--------|--------|--------|-------|-------|-------|-------|-------|--------|-------|
| | Core a | Core a | Rim a | Rim a | b | c | d | e | f | f | |
| | T3-16 | T3-11 | T3-9 | T3-26 | T3-24 | T2-30 | T2-34 | T2-14 | T2-11 | T2-6 | T2-12 |
| SiO ₂ | 39.32 | 39.21 | 39.02 | 38.66 | 37.46 | 36.96 | 37.22 | 37.23 | 0.01 | n.d. | 36.15 |
| TiO ₂ | 0.03 | 0.05 | n.d. | 0.06 | 5.62 | 5.80 | 5.64 | 5.65 | 98.31 | 52.77 | n.d. |
| Al ₂ O ₃ | 22.87 | 22.54 | 22.32 | 22.32 | 15.31 | 14.83 | 15.17 | 15.13 | 0.17 | 0.11 | 62.38 |
| Fe ₂ O ₃ | | | | | | | | | | | 0.45 |
| FeO* | 27.54 | 27.74 | 29.52 | 29.92 | 10.67 | 12.83 | 12.35 | 12.37 | 0.19 | 46.75 | |
| MnO | 0.27 | 0.24 | 0.37 | 0.33 | n.d. | 0.02 | 0.05 | n.d. | n.d. | 0.22 | n.d. |
| MgO | 10.54 | 10.26 | 9.13 | 8.44 | 16.03 | 14.62 | 14.33 | 14.73 | n.d. | 0.18 | 10.10 |
| CaO | 0.63 | 0.59 | 0.60 | 0.59 | n.d. | n.d. | 0.02 | n.d. | n.d. | n.d. | 0.01 |
| Na ₂ O | 0.07 | n.d. | 0.03 | 0.02 | 0.18 | 0.14 | 0.26 | 0.09 | 0.04 | 0.01 | 0.03 |
| K ₂ O | n.d. | n.d. | n.d. | n.d. | 9.77 | 9.75 | 9.81 | 9.94 | n.d. | 0.01 | 0.01 |
| Total | 101.27 | 100.63 | 100.99 | 100.35 | 95.04 | 94.95 | 94.85 | 95.14 | 98.72 | 100.05 | 99.13 |

Structural Formulae

| | O=12 | O=12 | O=12 | O=12 | O=11 | O=11 | O=11 | O=11 | O=2 | O=3 | O=5 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Si | 2.971 | 2.984 | 2.986 | 2.985 | 2.753 | 2.745 | 2.766 | 2.759 | 0.000 | 0.000 | 0.987 |
| Ti | 0.002 | 0.003 | 0.000 | 0.003 | 0.311 | 0.324 | 0.315 | 0.315 | 0.997 | 0.999 | 0.000 |
| Al | 2.037 | 2.022 | 2.014 | 2.032 | 1.327 | 1.315 | 1.329 | 1.322 | 0.003 | 0.003 | 2.008 |
| Fe** | 1.740 | 1.766 | 1.890 | 1.932 | 0.656 | 0.797 | 0.768 | 0.767 | 0.002 | 0.985 | 0.009 |
| Mn | 0.017 | 0.024 | 0.024 | 0.022 | 0.000 | 0.001 | 0.003 | 0.000 | 0.000 | 0.005 | 0.000 |
| Mg | 1.187 | 1.164 | 1.041 | 0.971 | 1.756 | 1.618 | 1.587 | 1.627 | 0.000 | 0.007 | 0.004 |
| Ca | 0.051 | 0.048 | 0.049 | 0.049 | 0.000 | 0.000 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 |
| Na | 0.010 | 0.000 | 0.004 | 0.003 | 0.026 | 0.020 | 0.037 | 0.013 | 0.001 | 0.000 | 0.002 |
| K | 0.000 | 0.000 | 0.000 | 0.000 | 0.916 | 0.924 | 0.930 | 0.940 | 0.000 | 0.000 | 0.000 |
| Total | 8.015 | 8.011 | 8.008 | 7.997 | 7.745 | 7.744 | 7.737 | 7.743 | 1.003 | 1.999 | 3.010 |

a Zoned grain of almandine analyzed at 14 spots. b Spot analysis of biotite adjacent to zoned almandine. c Spot analysis of large unzoned flake of biotite (analyzed at 12 spots) adjacent to prismatic. d Spot analysis of matrix biotite. e Spot analysis. Contains traces of Nb and Ta. f Spot analysis. * Total Fe as FeO. ** Predominantly Fe²⁺ except for sillimanite. n.d. not detected. Symbols: Alm almandine, Bt biotite, Rt rutile, Ilm ilmenite, Sil sillimanite.

CONDITIONS OF METAMORPHISM

ORIGIN OF PRISMATINE

The presence of orthopyroxene and mesoperthite throughout the Reading Prong and of cordierite in the Hudson Highlands (the New York portion of the Reading Prong) has been cited as evidence for peak metamorphic temperatures of 700° to 750°C and pressures of 3 to 5.5 kbar, *i.e.*, hornblende-granulite-facies conditions (*e.g.*, Dallmeyer & Dodd 1971, Young 1971, Jaffe & Jaffe 1973). More recently, Young & Cuthbertson (1994) showed from fayalite + ferrosilite + quartz assemblages that magmatic crystallization of hedenbergite quartz syenite (Young 1972) occurred at a pressure around 6 to 6.5 kbar. This intrusive body occurs within the Mase Mountain block only a few hundred meters structurally below the prismatic locality. Because the quartz syenite is a late tectonic sheet injected during the waning stages of metamorphism and deformation, it is reasonable to infer that the pressure on the prismatic-bearing rocks during peak metamorphism was at least 6 to 6.5 kbar.

Pressures and temperatures also can be estimated from the assemblages in the prismatic-bearing rocks, including the biotite-garnet geothermometer and the garnet - rutile - aluminosilicate - ilmenite (GRAL) geobarometer (Bohlen *et al.* 1983). Although quartz is lacking from the rutile-bearing layers, the coexistence of almandine and rutile was used to establish a minimum pressure of metamorphism around 6.2 to 6.6 kbar, consistent with pressures calculated from the fayalite - quartz - ferrosilite geobarometer. If the temperature of metamorphism was 700°C, then an upper pressure limit of 8 kbar is indicated by the sillimanite-kyanite boundary curve of Holdaway (1971), because sillimanite is widespread, and kyanite has never been reported from the Reading Prong. The minimum pressure at the time of Fe-Mg exchange closure may have decreased to about 5.1 kbar.

The Indares & Martignole (1985) empirical garnet-biotite exchange geothermometer corrects for the high levels of Ti in granulite-facies biotite. For pressures between 6 and 6.5 kbar, the calculated temperature inferred from this geothermometer is about 670°C. Even at 8 kbar, the calculated temperature is only 679°C, probably too low for these granulite-facies rocks. Only the Thompson (1976) and Perchuk & Lavrent'eva (1983) formulations yield temperatures consistent with those previously estimated for metamorphism of the Reading Prong. The geothermometers most applicable to granulite-facies metamorphism suggest peak metamorphic temperatures between 670° and 740°C.

The estimated 6.2 to 8 kbar pressure and 670–740°C temperature for the New Jersey occurrence of prismatic are well within the range of conditions that have typically been inferred for most other localities of prismatic and kornepupine (*e.g.*, Visser 1995).

The most common explanations for the origin of prismatic and kornepupine are high-grade metasomatic introduction of boron into Mg-Al-rich rocks (*e.g.*, Woodford & Wilson 1976, Lonker 1988) and essentially isochemical high-grade metamorphism of initially boron-bearing metasedimentary rocks with or without attendant partial melting, commonly at low activities of H₂O (*e.g.*, Grew 1982, 1988, Nixon *et al.* 1984).

High-grade metasomatism is unlikely for the New Jersey locality because there is no obvious external source of boron. The sequence of gneisses in the Mase Mountain block, in which the prismatic occurs, was intruded by late-tectonic hedenbergite quartz syenite, but the intrusive body is inferred to have been fluid-deficient, and there is no evidence of any metasomatic activity adjacent to it. Nor is there any evidence for metasomatism adjacent to the metamorphosed gabbroic anorthosite sill 75 m structurally below the occurrence of prismatic (Young & Icenhower 1989). Boron mineralization in the Franklin Marble occurs tens of kilometers away.

Essentially isochemical recrystallization of originally boron-bearing rocks under granulite-facies conditions is considered to be more likely. The abundance of oligoclase, orthoclase mesoperthite, biotite, sillimanite, almandine, and prismatic in the prismatic-bearing rocks points to a highly aluminous protolith such as clay-rich sediments, a conclusion confirmed by the chemical composition of the prismatic-bearing rocks. The chemical composition of these rocks is similar to that of many modern river clays and Precambrian shales and mudrocks (Taylor & McLennan 1985). Although the TiO₂ content is relatively high for a sedimentary parent, Ti is commonly enriched in highly aluminous sediments (Force 1976, Garcia *et al.* 1994). The high Na content is anomalous for a clay, but is not unusual for occurrences of prismatic and kornepupine in pelitic rocks. Together with elevated B, F, and Cl contents, the Na-enrichment could indicate either an evaporitic component intermixed with the clay or alteration of clays by volcanogenic fluids.

The bulk chemical composition of the prismatic-bearing rocks also closely resembles, except for their elevated alkali contents, that of many of the stratified tourmalinites that occur in the Broken Hill Group, Australia. Slack *et al.* (1993) suggested that the tourmalinites formed by selective hydrothermal replacement of originally aluminous, clay-rich beds and that the boron was derived by leaching of nearby non-marine evaporites.

Considerable boron can be accommodated in the structure of clay and mica minerals (Harder 1959, Eugster & Wright 1960). However, Leeman & Sisson (1994) have shown that boron becomes severely

depleted in schists and gneisses during the course of prograde metamorphism because of its release from layer silicates during dehydration reactions. Hence, typical granulites contain only 1–15 ppm B. It is probable, therefore, that rocks with high boron content (400–2800 ppm) preserved their original boron in a more stable form such as tourmaline. Although tourmaline is very uncommon in the Reading Prong, Jaffe & Jaffe (1973) did report trace amounts in pelitic gneisses that contain sillimanite, cordierite, almandine, and biotite. Tourmaline may have been an original constituent of a clay-rich sediment, or it may have formed by later hydrothermal replacement of such a sediment, but it could also have formed during low-grade regional metamorphism of originally boron-rich clays and micas. More to the point, there is no textural evidence of the development of prismatic at the expense of other boron-bearing minerals like tourmaline, grandierite, or dumortierite. Both prismatic and almandine do, however, commonly contain small inclusions of biotite, feldspar, and rutile. The prismatic crystals probably developed parallel to the foliation near conditions of peak metamorphism.

The very close association of prismatic and rutile in these layers, coupled with the extreme paucity of rutile elsewhere in the Reading Prong, suggest that both minerals formed as a result of the same reaction. The presence of high-Ti biotite suggests that rutile formed from partial destruction of the biotite. The absence of quartz indicates either that the prismatic-producing reaction produced no quartz or that any excess silica produced went into a melt phase. London *et al.* (1994), however, showed experimentally that granulites containing boron-rich phases probably did not experience a melting episode on grounds that the melt would have dissolved the available boron minerals like tourmaline and left a boron-depleted restite.

I therefore suggest that both prismatic and rutile were produced in a tourmaline-consuming reaction, and that quartz was not a product. A possible reaction might be: 1.55 titaniferous biotite + 1.22 almandine + 5.23 sillimanite + 1.0 tourmaline → 3.0 prismatic + 2.55 (orthoclase + albite) + 0.46 rutile + 0.39 B₂O₃ + 2.05 H₂O. In calculating the reaction, the effects of Mn and F were ignored, Mg and Fe were combined, and the following mineral compositions were used: almandine (Fe,Mg)_{2.90}Al_{2.03}Si_{2.98}O₁₂, titaniferous biotite (K_{0.91}Na_{0.09})(Mg,Fe)_{2.42}Ti_{1.30}Al_{1.33}Si_{2.75}O₁₀(OH)₂, and prismatic (Mg,Fe)_{3.43}Al_{6.15}Si_{3.82}B_{0.74}O₂₁(OH). Ideal formulae were used for sillimanite, tourmaline, orthoclase, albite, and rutile.

This reaction requires that the protolith contained an amount of tourmaline almost half the amount of prismatic produced. Because some of the rocks contain 20% prismatic, the protolith could have contained as much as 10% tourmaline.

The scant experimental data suggest considerably

higher temperatures for many tourmaline-consuming reactions than were achieved in the Reading Prong rocks, and there are no experimental data on the temperatures at which a biotite + almandine + sillimanite + tourmaline reaction might occur. Until much more experimental work is done on tourmaline and prismatic and their reactions with other minerals, any hypothesis about the genesis of the New Jersey prismatic will necessarily remain speculative.

ACKNOWLEDGEMENTS

I am greatly indebted to Edward S. Grew, Richard Herd, and Robert F. Martin for their constructive reviews of various drafts of the manuscript. Discussions about prismatic and kornerupine with Ed Grew have been especially valuable. Virginia Sisson provided helpful comments regarding the parentage of boron-bearing gneisses. Much of the work was supported by a Calvin Research Fellowship. Special thanks are due to my students David Brunsting, Cheryl Essenburg, Christine Potts, and Peter Steen, who enthusiastically helped me to find far more prismatic than I could ever have found by myself.

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Received February 14, 1995, revised manuscript accepted August 30, 1995.