

## AN OCCURRENCE OF THE ASSEMBLAGE GRANDIDIERITE, KORNERUPINE, AND TOURMALINE IN ANTARCTICA

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**Abstract** Grandierite, kornerupine, and tourmaline occur in high-grade pelitic gneisses from the Larsemann Hills, East Antarctica. The three minerals contact to each other and show a special order:  $\text{Trn}_1 \rightarrow \text{Gdd} \rightarrow \text{Trn}_2 \rightarrow \text{Krn} \rightarrow \text{Trn}_3$ , suggesting the occurrence of the assemblage is controlled by the temporal changes of the chemical potentials of  $\text{B}_2\text{O}_3$  and  $\text{H}_2\text{O}$ . The discovery of the assemblage is a good constraint on the setting and composition feature of metamorphism in the area.

**Key words** grandierite, kornerupine, tourmaline, boron, evolution.

A long column mineral (Plate 1), which was described as "tourmaline" by Stüwe *et al.* (1989c), is distributed throughout the Larsemann Hills, East Antarctica. While grandierite was discovered in some samples with "tourmaline" and it is the first report of grandierite in Antarctica (Ren and Zhao, 1992a). Further work reveals that the so-called "tourmaline" is in fact kornerupine. Nevertheless, fine-grained tourmaline does exist in small amount in the area.

Grandierite is a much rare mineral and so far over 20 localities of the mineral have been found in the world (Grew *et al.*, 1990), and only one in China (Tan and Li, 1990). Kornerupine is also a rare mineral (Grew *et al.*, 1990). While the assemblage of grandierite, kornerupine and tourmaline is even rarer (Vrana, 1979; Lonker, 1988). Due to the unique formation condition of grandierite and kornerupine, their presence is significant to the study of metamorphism and anatexis (Lonker, 1988).

### Geological Setting

It was generally accepted that the Larsemann Hills are located on the mid-late Proterozoic mobile belt (Stüwe *et al.*, 1989a,c). But recent studies show that the main metamorphism, at least one of the high grade events, occurred c. 550Ma ago (Ren *et al.*, 1992b; Dirks *et al.*, 1993). The area is underlain dominantly by aluminium rich

metasediments (gneisses) in which the borosilicate minerals are present, minor basic granulites and felsic orthogneisses. The main metamorphic event is low-pressure granulite facies metamorphism and can be subdivided into four substages ( $M^1-M^4$ ). The assemblage of  $M^1$  is biotite-sillimanite-feldspar-garnet, hornblende-plagioclase, which are responsible for the regional foliation, then comes the granulite facies associations ( $M^2$ ), such as sillimanite-garnet-cordierite-spinel, clinopyroxene-orthopyroxene-plagioclase, with the temperature 750°C, pressure 4.5 kbar. Further decompression (uplifting) is accompanied by intensive partial melting ( $M^3$ ), some megacrystals are formed, e. g. garnet, pyroxene euhedrals mantled by K-feldspar leucosome (Stüwe and Powell, 1989b) and idiomorphic kornerupine, cordierite (Ren *et al.*, 1992b). Eventually, as the result of isobaric cooling, the geotherm tended to normal ( $M^4$ ), which is manifested by the corona texture such as the biotite and sillimanite around ilmenite, hornblende and plagioclase around pyroxene.

### Borosilicate Minerals and Their Petrography

Besides borosilicate minerals, biotite, cordierite, K-feldspar, plagioclase, sillimanite, ilmenite and minor quartz, spinel, corundum, gibbsite, rutile, monazite and zircon are also present in the boron rich rock, and minerals in the rock distribute generally inhomogeneously, such as the chamber of minerals in the cordierite and kornerupine gneisses and the approximate monomineral rock of kornerupine, sillimanite and ilmenite-magnetite can be easily discovered. Identification and some features of the borosilicate minerals are described as follows.

1. *Grandidierite* is variable in amount in each sample, from 0.5 to 3% in volume. The mineral is deep green and tabular, prismatic in shape. Some properties under microscope: strong pleochroism,  $N_g = N_m =$  colorless,  $N_p =$  deep bluish green, top interference color of II grade, two groups of cleavage, parallel extinction, both positive and negative elongation.

Grandidierite occurs intimately with sillimanite and can only be found in the magnesio-(iron) rich but silica poor rocks (Grew, 1983). So does it in this area. Except for the grandidierite inclusion in kornerupine (Plate 2), the mineral is always associated with sillimanite and the transition from sillimanite to grandidierite can be observed (Plate 3). Grandidierite is often surrounded by cordierite, sometimes adjacent to biotite, together with quartz and rutile, while quartz may be present as the corona of grandidierite (Ren and Zhao, 1992a).

Electron microprobe analysis of grandidierite is shown in Table 1, with the ideal formula  $MgAl_2Al[SiO_4][B_2O_3]O_2$ , Mg can be replaced by  $Fe^{2+}$ , Mn and  $X_{Fe} = Fe^{2+} / (Fe^{2+} + Mg)$  is between 0.204 and 0.258, while that of Rogaland, Western Norway can reach 0.811 (Huijsmans *et al.*, 1982), implying the approximate ideal solid solution between Mg

and Fe end members of grandierite. The infrared spectrum of the mineral is shown in Figure 1, among them  $1462\text{cm}^{-1}$ ,  $1410\text{cm}^{-1}$  and  $1311\text{cm}^{-1}$  are the absorption bands of boron.

Table 1. Microprobe analysis of grandierite, kornerupine and tourmaline in the Larsemann Hills.

	Gdd	Gdd*	Krn	Krn*	Trn <sub>1</sub>	Trn <sub>2</sub>	Trn <sub>3</sub>
SiO <sub>2</sub>	20.80	20.83	30.37	30.76	35.74	36.26	34.92
Al <sub>2</sub> O <sub>3</sub>	50.40	50.19	38.35	42.49	30.81	30.07	31.74
TiO <sub>2</sub>	—	0.04	0.27	0.24	1.36	0.19	0.74
MnO	—	0.07	0.11	0.09	—	—	—
Fe <sub>2</sub> O <sub>3</sub>	n. d.	2.54	n. d.	1.97	n. d.	n. d.	n. d.
FeO	5.82	3.61	10.36	9.67	5.98	6.01	5.26
MgO	9.37	10.45	13.75	11.65	8.72	9.10	8.79
K <sub>2</sub> O	0.03	0.01	0.02	0.01	—	—	—
CaO	0.04	0.68	0.07	0.07	0.82	0.97	0.66
Na <sub>2</sub> O	—	0.40	—	0.04	1.70	1.69	1.47
H <sub>2</sub> O	n. d.	0.75	n. d.	—	n. d.	n. d.	n. d.
B <sub>2</sub> O <sub>3</sub>	n. d.	9.56	n. d.	3.17	n. d.	n. d.	n. d.
Si	1.04	1.036	3.837	3.892	5.894	6.03	5.831
B	n. d.	0.818	n. d.	0.693	n. d.	n. d.	n. d.
Al <sup>4</sup>	—	—	0.163	0.415	0.106	—	0.169
Al <sup>6</sup>	2.975	2.937	5.547	5.923	5.881	5.894	6.075
Ti	—	0.015	0.026	0.023	0.168	2.024	0.093
Mn	—	0.003	0.012	0.009	—	—	—
Fe <sup>3+</sup>	n. d.	0.096	n. d.	n. d.	n. d.	n. d.	n. d.
Fe <sup>2+</sup>	0.244	0.149	1.095	1.211	0.924	0.836	0.735
Mg	0.700	0.773	2.590	2.197	2.143	2.258	2.189
K	0.004	0.006	0.008	0.001	—	—	—
Ca	0.002	0.036	0.009	0.009	0.145	0.173	0.118
Na	—	0.036	—	0.010	0.542	0.545	0.476
OH	—	0.251	n. d.	0.098	n. d.	n. d.	n. d.

Note: \* Gdd cited from Tan and Li(1990), Krn from Jiang *et al.* (1992).  
n. d. not determined.

2. *Kornerupine* aggregate is bundle or radial (Plate 1) while the single crystal is prismatic, the largest may be up to 15cm long, 10 to 80% of the rock volume in amount. *Kornerupine* in the Larsemann Hills was once mistaken as *tourmaline* (Stüwe *et al.*, 1989c; fig. 5c). But the composition (Table 1) and X-ray data ( $d(I)$ : 3.345(28), 2.996(77), 2.607(100), 2.094(45), 2.073(43), 1.672(37), 1.493(51), 1.408(29) show that the mineral is *kornerupine*, not *tourmaline*. Microscopic features are: strong pleochroism, Ng= light bluish green, Np= colorless to light yellowish brown, developed prismatic cleavage, interference color up to yellow of I grade, parallel extinction, negative elongation, biaxial crystal and optically negative.

*Kornerupine* is coarse grained and poikilitic with *cordierite* and *plagioclase*, great amount of inclusions of *biotite*, *tourmaline*, *grandierite* (Plate 2), *sillimanite*, *ilmenite*, *zircon* and *monazite* are present in *kornerupine*.

The molecule formula of kornerupine can be written as  $(\text{Mg}, \text{Fe}^{2+}, \text{Na})(\text{Mg}, \text{Fe}^{2+})_3(\text{Al}, \text{Fe}^{3+}, \text{Mg})_6(\text{Si}, \text{Al}, \text{B})_5(\text{O}, \text{OH}, \text{F})_{22}$  (Moore and Araki, 1979). Kornerupine is with higher aluminum content and lower silicon in composition than tourmaline (Table 1). Boron is not necessarily in kornerupine (Grew *et al.*, 1990), but the boron absorption bands can be discerned in the infrared spectrum of kornerupine; the antisymmetrical vibration of  $\text{BO}_4$ ,  $913\text{cm}^{-1}$ ,  $879\text{cm}^{-1}$  and the symmetrical vibration of  $\text{BO}_4$ ,  $782\text{cm}^{-1}$ ,  $731\text{cm}^{-1}$ , suggesting that kornerupine in the Larsemann Hills is boron-bearing.

3. *tourmaline* On the basis of optical feature, composition of the mineral and textural relationship with others, at least three types of tourmaline have been discerned. (i) Tourmaline one ( $\text{Trn}_1$ ) is brownish green under microscope, it is often prismatic rounded or hexagonal section if included in K-feldspar. It generally occurs as inclusions in cordierite, kornerupine, sillimanite and K-feldspar. The mineral is the earliest of all the tourmaline

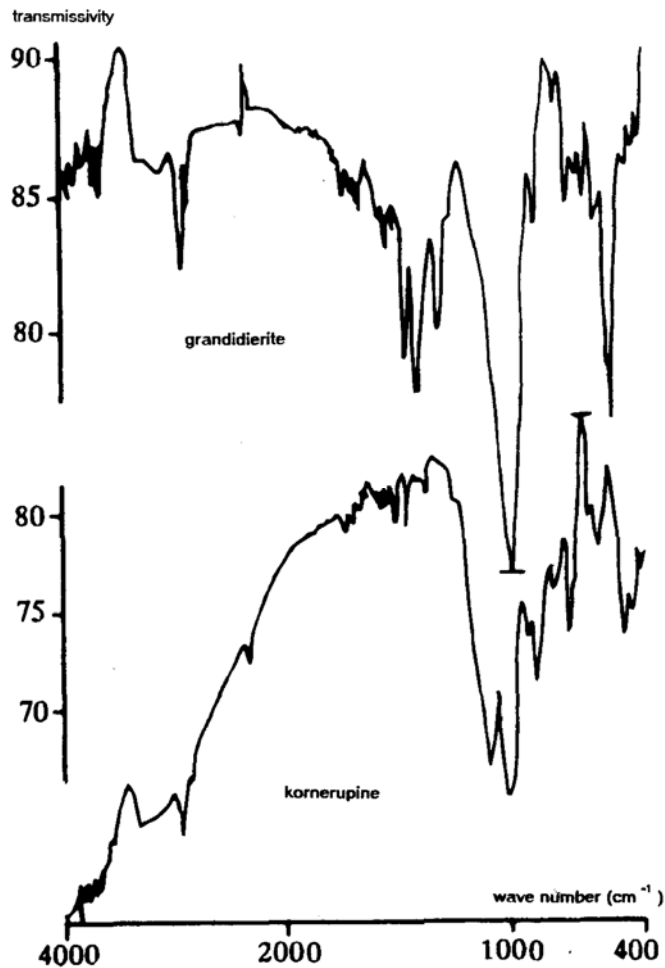


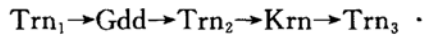
Fig. 1. Infrared spectrum of grandierite and kornerupine.

types and is distinguished by its richest Ti. (ii) Tourmaline two ( $\text{Trn}_2$ ), bluish green in

color and subhedral to anhedral in shape, the tourmaline being accompanied by biotite, quartz and plagioclase, is generally included in kornerupine (Plate 2). The composition is characterized by the poorest in Ti, Al and richest in Si (Table 1). (iii) tourmaline three (Trn<sub>3</sub>) is green and occurs along the rim or crack of kornerupine, sometimes as isolated fine grains near kornerupine. The mineral is poor in Fe, Ca but Ti between that of Trn<sub>1</sub> and Trn<sub>3</sub> (Table 1).

### Evolution of the Borosilicate and Their Relationship with Metamorphism

Generally speaking grandidierite can be formed in the silica poor rocks, kornerupine in the relative silica rich rocks, while tourmaline may be present in both rock types but the three minerals generally do not contact to each other, suggesting the spatial variation of B<sub>2</sub>O<sub>3</sub> potential (Lonker, 1988). It was also pointed out that as composition of the fluid inclusion in the borosilicate is mainly CO<sub>2</sub> and H<sub>2</sub>O, the spatial distribution of the minerals is controlled by the activities of CO<sub>2</sub> and H<sub>2</sub>O (Grew *et al.*, 1991). Although the assemblage of the borosilicate minerals in the Larsemann Hills change from one place to another, it is an essential feature that all the three borosilicate minerals crop out in the same locality, even contact to each other. This can not be explained by the spatial variation of volatile components. It is more likely that certain borosilicate mineral is formed in certain stage of metamorphic evolution, i. e., it is a temporal order of minerals. On the basis of composition and texture of minerals, the order of the borosilicate minerals in the Larsemann Hills can be obtained as follows:



In light of the textural relation between the borosilicate and the non-borosilicate minerals, the order above corresponds with the whole metamorphic story (Ren *et al.*; 1992b). Tourmaline one (Trn<sub>1</sub>) corresponds with the early high amphibolite facies metamorphism substage, grandidierite and tourmaline two (Trn<sub>2</sub>) with the granulite facies, while tourmaline three (Trn<sub>3</sub>) with the final cooling of amphibolite facies metamorphism substage. On the other hand, the order reflects the changes of volatile composition, B<sub>2</sub>O<sub>3</sub> and P<sub>H<sub>2</sub>O</sub> in particular. In granulite facies metamorphism, P<sub>H<sub>2</sub>O</sub> is low, and tourmaline tends to decompose, resulting in the high ratio of B<sub>2</sub>O<sub>3</sub>/H<sub>2</sub>O, therefore grandidierite can be formed (Manning and Pichavant, 1983). When more components involved in partial melting, reactivation of silica and water dilutes the concentration of boron and tourmaline two (Trn<sub>2</sub>) is formed, composition of Trn<sub>2</sub> is consistent with the process in that with poor Ti, Al components (Fortey and Cooper, 1986) (Table 1). When water activity is enhanced, components migrate easily and megacrystal of kornerupine forms. In the final cooling period, kornerupine is decomposed into tourmaline three (Trn<sub>3</sub>). That is, the occurrence of borosilicate minerals are controlled by the temporal, not spatial, changes of activities of B<sub>2</sub>O<sub>3</sub> and H<sub>2</sub>O. This can account for the contact and order of the minerals in the study area.

As regards the metamorphic condition, the occurrence of grandidierite rarely exceptionally reflects the low-pressure/high temperature setting (Lonker, 1988). The granulite facies metamorphism in the area, 4.5 kbar, 750 °C, is consistent with this point. Large crystals of kornerupine have been reported in many localities (Wilson, 1978), suggesting the intensive activity of volatile components in the uplifting of the terrane. Therefore, the occurrence of the borosilicate minerals is helpful to our understanding of the geological circumstance in the area.

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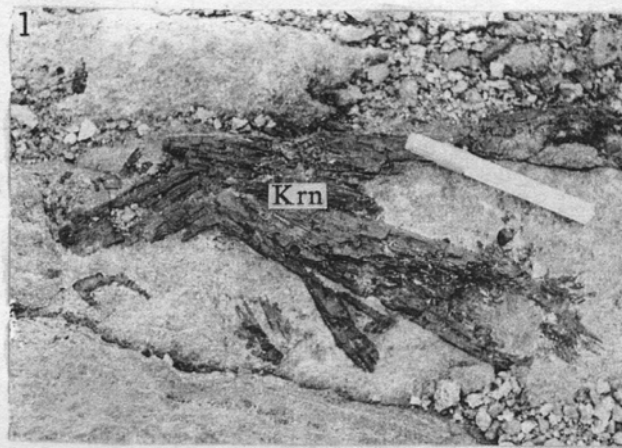


Photo 1. Prismatic kornerupine in the Larsemann Hills.

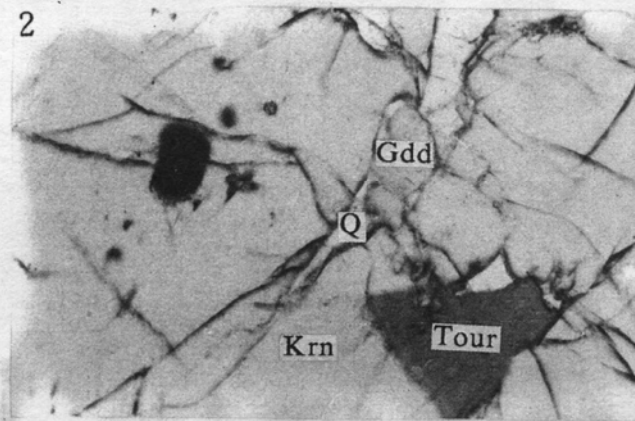


Photo 2. Grandidierite and tourmaline inclusions in kornerupine.  $10\times 10(-)$ .

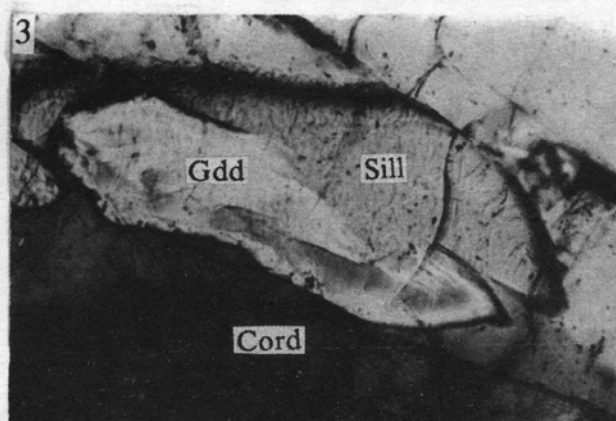


Photo 3. Sillimanite is locally changed into grandidierite.  $10\times 20(-)$ .