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Occurrences of grandidierite, serendibite and tourmaline near Ihosy, southern Madagascar

TOURMALINE is a nearly ubiquitous accessory mineral in metapelites at low and medium grades of metamorphism, whereas the high-temperature borosilicates kornerupine, grandidierite, and serendibite are very rare and occur at the high-grade conditions of the granulite and pyroxene-hornfels facies (de Roever and Kieft, 1976; Grew, 1988; Lonker, 1988, etc.). Grandidierite and serendibite have been found near Ihosy, in southern Madagascar, the former in a seven-phase anatectic gneiss, the latter in a calcsilicate gneiss.

Grandidierite in anatectic gneiss

In the Precambrian Ihosy formation, banded cordierite–garnet gneisses, leptynites, two-pyroxene metabasic granulites, calcsilicate gneisses and marbles indicate conditions of the hornblende intermediate-pressure granulite facies. A widespread anatectic event produced migmatitic gneisses with seven phases: quartz, K-feldspar, plagioclase, garnet, cordierite, sillimanite, and biotite (with green spinel included in cordierite and garnet) and aluminous residues rich in biotite (biotite–cordierite–garnet or sillimanite, ± quartz) and sometimes containing sapphirine and kornerupine (Mégerlin, 1968; von Knorring *et al.*, 1969; Nicollet, 1985, 1988, 1990). Monazite and zircon from a granodiorite dyke produced by the anatectic event yielded a U–Pb age of 561 ± 12 Ma (Andriamarofahatra *et al.*, in preparation).

Dark green tourmaline and blue grandidierite (included in cordierite) occur as very rare crystals in the anatectic gneisses. However, these two borosilicates are never found in the same thin section. In a quarry, 1 km from Ihosy, grandidierite is somewhat more abundant (up to ten crystals per thin section) in coarse-grained quartzo-feldspathic segregations. In these lenses, the same minerals as in the seven-phase gneisses are 1 cm or more in dimension. Grandidierite is included in cordierite and garnet. Within the cordierite, small anhedral grains (≈0.1 mm) of the borosilicate are in sharp contact with biotite, sillimanite, green spinel, and opaques; it has been observed by other authors that grandidierite and sillimanite are closely associated (e.g. van Bergen, 1980; Grew, 1983). The garnet may contain large polymineralic inclusions composed of slender prisms and needles of grandidierite (≈0.5 mm long) with hexagonal basal sections, K-feldspar, plagioclase, quartz, green biotite, and apatite (Fig. 1). The borosilicate shows the usual blue pleochroism. With a X_{Fe} [Fe/(Fe + Mg)] between 0.25 and 0.29 (Table 1), the mineral is moderately Fe rich (cf. Huijsmans *et al.*, 1982; de Roever and Kieft, 1976; Semroud *et al.*, 1976; van Bergen, 1980; Haslam, 1980; Grew, 1983). Tourmaline in the banded gneisses has a composition intermediate between dravite and schörlite (Table 1); X_{Fe} is similar to that of the grandidierite. Green biotite included in garnet (Fig. 1) is less titaniferous and magnesium rich than the brown mica in the matrix, as a result of equilibration with adjacent garnet during cooling.

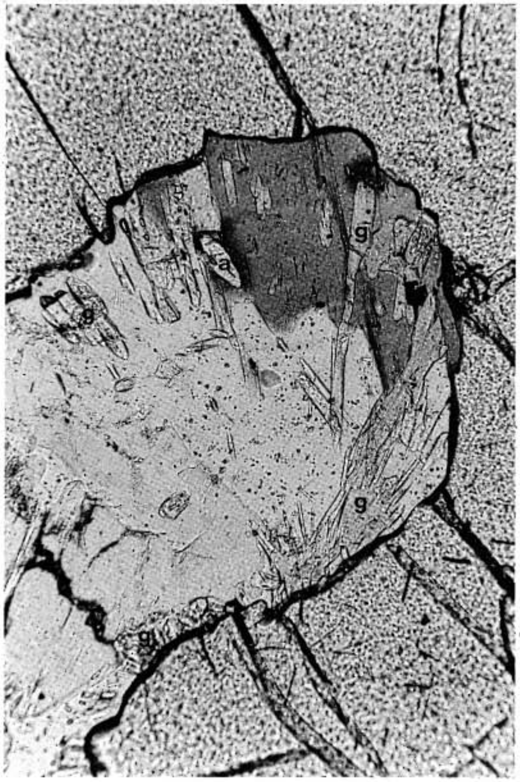

FIG. 1. Sheaf-like aggregate of grandidierite (*g*) with quartz, plagioclase, K-feldspar, green biotite, apatite (*a*) included in garnet. Note that prisms of the borosilicate grow on the garnet. The width of the photomicrograph is approximately 1.0 mm; plane-polarized light.

Table 1 : Electron microprobe analyses

	1	2	3	4
SiO_2	20.56	35.43	24.91	35.83
Al_2O_3	51.96	33.87	36.36	32.41
FeO_t	7.17	6.14	1.76	0.65
MnO	0.15	0.02	0.11	0.02
MgO	9.81	7.67	14.91	12.91
CaO	-	2.27	15.49	4.67
Na_2O	-	1.41	0.31	0.51
K_2O	0.02	0.05	-	0.03
TiO_2	0.02	0.16	0.02	-
Total	89.69	87.02	93.86	87.02
Oxygens	15	24.5	18.5	24.5
Si	2.006	5.733	2.976	5.689
Al	5.975	6.461	5.122	6.067
Fe^{2+}	0.585	0.831	0.176	0.086
Mn	0.012	0.003	0.011	0.003
Mg	1.426	1.850	2.656	3.055
Ca	-	0.394	1.953	0.795
Na	-	0.442	0.072	0.157
K	0.006	0.010	-	0.006
Ti	0.002	0.020	0.002	-
XMg	0.71	0.69	0.94	0.97

1 - Grandidierite, seven-phase anatectic gneiss (234)
2 - Tourmaline, seven-phase anatectic gneiss (Ih 5)
3 - Serendibite, calcsilicate gneiss (230)
4 - Tourmaline, calcsilicate gneiss (230).
B_2O_3 not determined ; all Fe as FeO.

Metamorphic pressures and temperatures are estimated in the seven-phase gneisses to have been near 700 °C and 4–5 kbar and the application of the seven-phase thermodynamic model of Lee and Holdaway (1977) indicates that P_{H_2O} was 0.35–0.4 P_t (total pressure) (Nicollet, 1985, 1988). Relations between grandidierite-bearing rocks and partial melting have often been noted (e.g. de Roever and Kieft, 1976; van Bergen, 1980). The grandidierite gneiss from Ihosy and the *P–T* conditions of its formation are quite similar to those described by Lonker in Canada (1988). At both localities, it may be suggested that the grandidierite was generated through low P_{H_2O} partial melting of tourmaline-bearing pelitic rocks.

Serendibite in calcsilicate gneiss

Ten kilometres southeast of the preceding outcrop (Vohimena's hill; 46°15′30″ E, 22°27′30″ S), a serendibite-bearing calcsilicate gneiss is in contact with an olivine marble. The serendibite-bearing gneiss contains anorthite (An_{90-100}), scapolite

(Me_{75-83}), aluminous diopside, green amphibole, colourless spinel, large poikilitic blue tourmaline, and a little calcite. Tourmaline includes several minerals, especially clinopyroxene, spinel, and a few small crystals of serendibite. Scattered grains of the latter in one crystal of tourmaline are in optical continuity, suggesting that tourmaline is a breakdown product after serendibite. The serendibite is colourless to very light green. The mineral is much less coloured than the prussian blue crystals in a calcsilicate rock associated with clintonite clinopyroxenites from Ianapera, in SW Madagascar (Nicollet, 1988, 1990). The Ihosy serendibite has low birefringence and fine polysynthetic twinning. It may be mistaken for sapphirine, but it is distinguishable from the latter by a larger extinction angle and by its occurrence in calcic rocks. The ferromagnesian minerals in the rock are magnesium rich. Tourmaline (Table 1) is a magnesian uvite and the X_{Mg} ratio of the spinel is greater than 0.9. Hornblende and clinopyroxene are close to their Mg end-members ($X_{Mg} \approx 0.97$). The Fe–Mg partitioning between tourmaline and serendibite (K_d) is $\approx$0.4 as in the more iron rich pair from Ianapera; it is lower than the K_d of coexisting tourmaline and serendibite from Melville Peninsula, Canada ($K_d = 0.61$: Hutcheon *et al.*, 1977).

The *P–T* conditions of the crystallization of this rock are similar to those estimated for the neighbouring seven-phase anatectic gneisses (Nicollet, 1988).

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