Occurrence of wagnerite in Mg–Al granulites of Sonapahar, Meghalaya

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We report for the first time the occurrence of rare phosphate wagnerite as a stable phase from the Mg–Al granulites of Sonapahar. The wagnerite bearing assemblages consist of the spinel, phlogopite, brucite and corundum. The wagnerite appears in the Mg–Al granulites due to the break-down of spinel and fluorapatite. The mineral chemistry of the phases has been discussed from the EPMA data, which reveals that the fluorine content of the wagnerite is relatively low due to the exchange of F to coexisting phases. The major oxide analysis of the rocks show the low content of Ca, which is the requisite for the occurrences of wagnerite.

Keywords. Mg–Al granulites; wagnerite; phase and mineral chemistry.

1. Introduction

Wagnerite is a magnesium–fluorophosphates bearing (Mg, Fe, Ca, Mn) $[\text{PO}_4(\text{F}, \text{OH})]$ mineral, which rarely occurs in metamorphic rocks all over the globe. However, it has been reported from different localities of the world in wide range of metamorphic conditions such as (a) amphibolite facies rocks (Sheridan *et al.* 1976; Iroisechek-Zumuthor and Armbruster 1985; Leroux and Ercit 1992; Brunet *et al.* 1998; Pitra *et al.* 2008), (b) as low-to-high pressure granulites (Novak and Povondra 1984; Vry and Cartwright 1994; Simmat and Rickers 2000; Ouzegane *et al.* 2003; Ren *et al.* 2003) and (c) high Mg–Al granulites (Simmat and Rickers 2000).

In Indian granulites, it was reported for the first time by Simmat and Rickers (2000) in high Mg–Al granulites of Anakapalle in the Eastern Ghat Belt. High Mg–Al granulites of Anakapalle occur as xenoliths within the basic granulites and experienced Grenvillian ultra-high-temperature (UHT) metamorphism (8 kbar; $T > 900^\circ\text{C}$). The textural

relations suggest that it occurs as inclusions either in garnet and orthopyroxene as a part of the UHT-assemblage. Wagnerite from Anakapalle is characterized by unusually high (OH) content ($\text{F}/(\text{F}+\text{OH}) = 0.47\text{--}0.60$) and low Ca content (0–0.5 weight percentage of CaO).

In this paper, we first report the occurrence of wagnerite in Mg–Al rich granulites of Sonapahar (Rianagdo), 40 km away from Noingstoin town, as a stable phase coexisting with phlogopite, spinel, corundum and brucite with the help of petrography, mineral chemistry and geochemistry (major oxide and trace element data).

1.1 Geological setting

The Mg–Al granulites of Sonapahar belong to the Shillong Meghalaya Gneissic Complex (SMGC) which forms a part of the northeastern extension of Eastern Ghats granulite belt (Crawford 1974). However, Chatterjee *et al.* (2007) considered that the Meghalaya plateau was a part of the

Figure 1. Regional geological map of the western Shillong–Meghalaya Gneissic complex, Meghalaya modified after Chakraborty (1990).

Indian shield since Mesoproterozoic time and was close to the Australo–Antarctica block, evidenced from the Neoproterozoic–Cambrian paleomagnetic reconstruction of the Rodinia supercontinent. They suggested Prydz Bay suture possibly passes through SMGC with the western boundary of the suture between Garo-Goalpara and Sonapahar areas. The Proterozoic metasedimentary Shillong Group and the basement gneissic complex make up most of the plateau (SMGC), with the Shillong Group of rocks, occurring in 240 km long NE–SW trending intracratonic basin. It was metamorphosed to greenschist facies and rest unconformably, as indicated by a basal conglomerate (Nandy 2001), on an assortment of rock types including sillimanite-bearing gneisses, amphibolite, banded iron formation, granulites and granite gneisses known as the gneissic complex. Basic eruptives occur as concordant and discordant bodies within the Shillong Group of metasediments are referred as Khasi green stones (Mazumder 1986). Syn to late-tectonic granites occur as discordant plutons, cutting across the Shillong metasediments and basement gneissic rocks (Medlicott 1869; Mazumder 1986, 1976). The area around Sonapahar (latitude $25^{\circ}41'N$ and longitude $91^{\circ}04'E$) essentially composed of

the upper amphibolite to granulite facies rocks (Lal *et al.* 1978; Chatterjee *et al.* 2007; Dwivedi 2011; Dwivedi and Theunuo 2011). The investigated area includes: (i) cordierite-bearing granulites, (ii) basic granulites, (iii) quartz–sillimanite schist, (iv) granite gneisses, and (v) Mg–Al granulites (figure 1). The Mg–Al granulites (latitude $25^{\circ}40'7''N$ and longitude $91^{\circ}04'7''E$) occur adjoining to quartz-sillimanite schist located near the abandoned sillimanite mines. The different stages of metamorphic deformations, *viz.*, D_1 , D_2 and D_3 have been observed in the study area around Sonapahar, which consists mainly of two generation folds, *i.e.*, F_1 trending E–W and F_2 , which superposing the F_1 fold is trending north–south with the development of crenulations (Dwivedi and Theunuo 2013).

2. Petrography and mineral chemistry

The Mg–Al granulites occur as small lenticular bodies (10–20 m), medium- to coarse-grained and dark grey to yellowish brown in colour. The colourless phlogopite is present in a significant amount and defines the prominent schistosity of the rocks.

The occurrence of Mg–Al granulites can be traced by the appearance of phlogopite flakes on the ground and includes the following mineral assemblages:

- (a) Spinel–phlogopite–wagnerite–brucite–corundum–magnetite–rutile–ilmenite–fluorapatite.
- (b) Spinel–corundum–phlogopite–rutile–magnetite–ilmenite $\pm$ apatite.
- (c) Spinel–phlogopite–rutile $\pm$ apatite–magnetite.

Spinel is dark green in colour and occurs as coarse elliptical porphyroblast in hand specimen. It is commonly xenoblastic to subidioblastic and the grain size ranges from 0.4 to 5 mm in diameter (figure 2a–c). It contains inclusions of magnetite, apatite and rutile. The spinel is in textural equilibrium with brucite, phlogopite, corundum and wagnerite (figure 2a), which suggests the following reaction:

The random distribution of spinel suggests that its crystallization took place after D₂ deformation.

Phlogopite is either feebly pleochroic ($Z = \text{colourless}$; $Y = X$ brown or pale brown; $Z < Y = X$) or colourless and non-pleochroic with high birefringence. It occurs as coarse flakes, which vary in length between 5 and 15 mm (figure 2b). The flakes of the phlogopite define the schistosity and aligned parallel to the S₃ and also along the micro-folded relics of S₂, suggesting that the crystallization began during D₁ deformation. Its formation also outlasted D₂, is indicated by the occurrence of cross-cutting phlogopite flakes overprinting the fabric of the matrix and containing inclusion of spinel and wagnerite (figure 2b).

Wagnerite is yellow in colour and highly pleochroic from dark yellow to pale yellow. It occurs as (2–4 mm in diameter) idioblastic crystal, in equilibrium with spinel and phlogopite (figure 2a–c). Spinel contains the inclusion of apatite (fluorapatite), partially rimmed by wagnerite, corundum and phlogopite, which provide the evidence of appearance of wagnerite by the following reaction:

Brucite is dark brown in colour and occurs in the textural equilibrium with spinel, wagnerite and phlogopite (figure 2a), which suggests the

Figure 2. Photomicrograph of wagnerite bearing Mg–Al granulites, (a) showing the coexistence of wagnerite, spinel, brucite and phlogopite in which wagnerite is partially rimmed by spinel and brucite, (b) wagnerite contains the inclusion of spinel and coexisting with phlogopite, and (c) coarse xenoblast of spinel containing inclusion of fluoroapatite and partially rimmed by wagnerite and corundum.

appearance of brucite may be due to the reaction (1). There is no textural evidence of its formation from retrogression of earlier periclase because the relics of latter have not been observed in the brucite.

Corundum occurs as small granular aggregate and rarely as a coarse prismatic crystal up to 15 mm in length (figure 2c) in the Mg–Al granulites. However, it is present in a significant modal amount in the sillimanite corundum rocks of the investigated area. In the massive sillimanite rocks, corundum

Table 1. *Electron microprobe analyses of coexisting mineral phases and their structural formula from the Mg–Al granulites of Sonapahar.*

Mineral	Spinel				Phlogopite			
Sample	S-12A							
Domain	1/1	1/2	1/3	1/4	1/5	1/6	2/1	2/2
SiO ₂	0.01	0.12	0.04	0.07	0.03	0.09	43.19	42.13
TiO ₂	0.02	0.04	0.00	0.02	0.02	0.00	0.17	0.27
Al ₂ O ₃	66.14	66.30	66.16	66.17	65.89	65.44	13.16	13.71
Fe ₂ O ₃	1.62	0.45	1.06	0.53	1.52	1.10	0.20	0.20
FeO	11.89	12.34	11.58	12.46	11.35	12.17	1.03	1.04
MnO	0.21	0.15	0.14	0.11	0.17	0.20	0.00	0.00
MgO	19.80	19.42	19.80	19.36	20.01	19.31	26.91	26.55
CaO	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00
Na ₂ O	0.00	0.00	0.01	0.00	0.00	0.00	0.91	1.00
K ₂ O	0.00	0.05	0.03	0.00	0.00	0.00	9.15	9.54
ZnO	0.40	2.21	1.98	2.00	1.40	2.58	0.00	0.00
Total	100.10	101.08	100.81	100.73	100.39	100.94	94.72	94.45
	Cation on 4-oxygen basis				11-oxygen basis			
Si	0.00	0.00	0.00	0.00	0.00	0.00	3.01	2.96
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Al	1.97	1.99	1.98	1.99	1.97	1.97	1.08	1.14
Fe ³⁺	0.03	0.01	0.02	0.01	0.03	0.02	0.01	0.01
Fe ²⁺	0.25	0.26	0.25	0.27	0.24	0.26	0.06	0.06
Mn	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.75	0.74	0.75	0.73	0.76	0.74	2.80	2.78
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.14
K	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.85
Zn	0.01	0.05	0.04	0.04	0.02	0.06		
X _{Mg}	0.73	0.73	0.74	0.73	0.74	0.72	0.98	0.97
Mineral	Wagnerite		Brucite					
Sample	S-12A		S-12A					
Domain	3/1	3/2	4/1	4/2				
SiO ₂	0.00	0.00	0.06	0.07				
Al ₂ O ₃	0.00	0.00	0.00	0.02				
P ₂ O ₅	42.21	42.48	0.00	0.00				
MgO	51.11	51.23	61.02	60.66				
CaO	0.28	0.28	0.01	0.00				
MnO	0.18	0.18	0.05	0.05				
FeO	1.08	1.10	0.00	0.05				
TiO ₂	0.00	0.00	0.01	0.01				
H ₂ O calc.	3.52	3.69	–	–				
Na ₂ O	0.00	0.00	0.03	0.00				
K ₂ O	0.00	0.00	0.02	0.01				
F	3.62	3.37	4.98	5.05				
Cl	0.02	0.00	0.01	0.00				
Total	102.02	102.33	66.19	65.92				
O=F,Cl	–1.53	–1.42	–	–				
Total corrected	100.49	100.91	–	–				

Table 1. (Continued.)

Cation on 4.5-oxygen basis			2-oxygen basis	
Si	0.00	0.00	0.00	0.00
P	0.96	0.96	0.00	0.00
Mg	2.06	2.05	2.00	2.00
Ca	0.01	0.01	0.00	0.00
Mn	0.01	0.01	0.00	0.00
Fe ²⁺	0.02	0.03	0.00	0.00
Ti	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00
Sum	3.06	3.06	2.00	2.00
M ²⁺	2.09	2.09	0.00	0.00
OH calc.	0.63	0.66	—	—
Cl	0.00	0.00	0.00	0.00
F	0.37	0.34	0.50	0.51
X _F	0.37	0.34	—	—
X _{Mg}	0.98	0.98	1.00	1.00

occurs as rounded blebs within the coarse needle of sillimanite.

Besides the above-mentioned phases, the Mg–Al granulites contain the common accessory minerals like ilmenite, rutile and apatite.

2.1 Analytical techniques and mineral chemistry

The microprobe analysis of the coexisting phases of Mg–Al granulites (table 1) was done at Faridabad, Geological Survey of India by CAMECA SX100 electron microprobe. For silicate analysis, the accelerating voltage was 15 kV with a beam current of 10 nA and beam diameter of 1 μ m. The standards used for different elements were Al₂O₃ (Al), CaSiO₃ (Si, Ca), TiO₂ (Ti), Cr (Cr), Zn (Zn), albite (Na), orthoclase (K), Fe₂O₃ (Fe), Rhodonite (Mn), peridotite (Mg), BaSO₄ (Ba), NaCl (Na), apatite (P&F).

EPMA analyses of spinel (table 1) show solid solution between spinel (MgAl₂O₄) and hercynite (FeAl₂O₄) and X_{Mg} slightly varies from 0.72 to 0.74. The Al content of the spinel on 4-oxygen basis varies from 1.97 to 1.99 which indicates that 0.01 to 0.03 amount of Fe³⁺ is present in the spinel.

Wagnerite analyses and structural formula on 4.5 oxygen basis are given in table 1. The amount of (OH) group is calculated by subtracting F from the theoretical (OH+F) content, and O=F correction plays no role in the structural formula correction (Pitra *et al.* 2008). The weight percentage analyses of fluorine content varies from 3.37 to 3.62, which is very less in comparison of fluorine analyses of wagnerite from other locality that ranges between

Figure 3. Triangular plots of coexisting mineral phases from the study area.

5.5 and 7. It might be due to using apatite as the standard for F content of wagnerite. Pitra *et al.* (2008) reported that the F concentrations in wagnerite are probably underestimated when apatite is used, but overestimated when topaz is used as a standard, which was also reported by Grew *et al.* (2007). Wagnerite of Sonapahar has low iron content, which varies between 1.08 and 1.10 weight percentage.

Phlogopite: The TiO₂ content of phlogopite is low and varies from 0.17 to 0.27 weight percentage. The X_{Mg} of phlogopite varies between 0.97 and 0.98. Brucite has high X_{Mg} and fluorine content, which varies from 4.98 to 5.05 weight percentage.

The observed mineral assemblages are plotted in triangular (MgO+FeO)–Al₂O₃–SiO₂ diagram (figure 3), which depicts the coexisting phases. The coexisting phases and their tie lines relation also provide the evidence of the reactions 1 and 2.

Table 2. Major oxide and trace element data of the Mg–Al granulites of Sonapahar.

Sample	S-12A	
SiO ₂	34.33	35.06
Al ₂ O ₃	14.34	14.38
Fe ₂ O ₃ ^t	5.79	5.72
TiO ₂	0.51	0.44
MnO	0.05	0.04
MgO	36.09	36.13
CaO	0.32	0.29
Na ₂ O	0.84	0.87
K ₂ O	7.55	7.64
P ₂ O ₅	0.36	0.33
LoI	0.47	0.53
Total	100.65	101.43
Mg#	0.93	0.93
Trace element		
Ni	141	140
Cu	bdl	bdl
Zn	1148	1119
Ga	55	53
Pb	13.3	14.4
Th	bdl	bdl
Rb	267	270
U	1.39	1.4
Sr	189	187
Zr	159	143
Nb	15.9	14.7
Ba	305	111
Cr	280	415
V	237	261
Y	18	18
Sc	60	57
Co	bdl	bdl

bdl = below detection limit.

3. Geochemistry

Analysis of the rock samples for major and trace elements was done at Wadia Institute of Himalayan Geology (WIHG), Dehradun (table 2). Fresh sample chips were powdered manually by agate mortar to avoid contamination. Major and trace elements were determined by the X-ray fluorescence (XRF) method using Siemens SRS 3000/S-8 tiger sequential X-ray spectrometer with windows Rh X-ray tube, on pressed sample pellets. Analytical accuracy on XRF is better than 5% and 12% for major oxides and trace elements respectively. The precision regarding observed standard deviation on repeated measurement is better than 2% (Saini *et al.* 1998).

Major oxides of the Mg–Al granulites display the following compositional variation of enriched

Al₂O₃ (14.34–14.38 weight percentage), MgO (36.09–36.13 weight percentage), Fe₂O₃^t (5.72–5.79 weight percentage), K₂O (7.55–7.64 weight percentage) and low content of SiO₂ (34.33–35.06 weight percentage), TiO₂ (0.44–0.51 weight percentage), CaO (0.29–0.34 weight percentage) and Na₂O (0.84–0.87 weight percentage) and P₂O₅ (0.33–0.36 weight percentage) which is totally different from the major oxide and trace element data pattern of the metapelites and basic granulites of the study area (Dwivedi and Theunuo 2013). The Mg–Al granulites are rich in compatible elements Cr (279–359 ppm), Ni (140–141 ppm), Sc (57–60 ppm), V (237–261 ppm) like basic granulites and low in incompatible elements, U (1.39–1.4 ppm), Th (bdl) and Nb (14.7–15.9 ppm) and abnormally high in Zn content (1119–1148 ppm).

4. Discussion

This is the first report of the wagnerite from the Mg–Al granulites of the Sonapahar, Meghalaya, north-east India. The SMGC rocks are closely related to the Australo–Antarctic plate (Chatterjee *et al.* 2007) and might be the extension of Eastern Ghat granulites belt. The wagnerite bearing assemblages were reported from Sapphirine-bearing granulites in Enderby land, Antarctica (Grew 1981) as well as from the Anakapalle (Eastern Ghat), India (Simmat and Rickers 2000). Pitra *et al.* (2008) concluded that the wagnerite occurrences are limited to low Ca and high Mg-rich rock. The Mg–Al granulites of the study area consist of very low Ca content (0.24–0.34 weight percentage) and high Mg and Al content which is decisive for the formation of wagnerite (Sheridan *et al.* 1976; Novak and Povondra 1984; Iroisechek-Zumuthor and Armbruster 1985; Pitra *et al.* 2008). The high concentration of Zn (1119–1148 ppm), Cr (280–415 ppm) and V (237–261 ppm) in the rock as a whole may be due to these elements are fractionated into the spinel. The wagnerite is only present in Mg–Al granulites with spinel, corundum and brucite and absent in adjoining garnet-cordierite and basic granulites of the SMGC. It is not possible to estimate the *P–T* condition of metamorphism from the given EPMA data of the study area due to an incomplete set of reaction. However, the *P–T* estimates of the adjoining rocks garnet-cordierite (705°C/5.6 kbar) and basic granulites (1021°C/8.45 kbar) of the study area was reported by Dwivedi (2011) and Dwivedi and

Theunuo (2011). Brunet *et al.* (1998) experimentally observed that the $\text{Mg}_2\text{PO}_4\text{OH}$ polymorphs would only form above 10 kbar pressures and suggested that the F or (OH) substitution expands the stability field of wagnerite towards the low-pressure condition. This explains why natural wagnerite is fluorine-rich and common about other polymorphs, and supports the occurrence of wagnerite with spinel, phlogopite and corundum in the investigated area. The low F content in the wagnerite of the present study is due to the migration of the F content to the coexisting phases like phlogopite and brucite, which contain high F contents (4.98–5.08 weight percentage).

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