

# Hydrothermal Högbomite Associated with Vanadiferous-Titaniferous (V-Ti) Bearing Magnetite Bands in Bhakatarhalli Chromite Mine, Nuggihalli Greenstone Belt, Western Dharwar Craton, Karnataka, India

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**Abstract:** Högbomite, a rare exotic mineral, is found to be associated with the vanadiferous–titaniferous (V-Ti) bearing magnetite bands at Bhakatarhalli, Nuggihalli greenstone belt, western Dharwar Craton, India. We report on a second occurrence of högbomite from the Dharwar craton in Karnataka, which is the sixth documented occurrence of this mineral from India. We evaluate the chemical characteristics of högbomite and associated Fe-Ti-minerals in an attempt to identify its formation as a primary hydrothermal mineral in a metamorphosed magnetite layer. We report here the presence of högbomite as a complex oxide of Fe, Mg, Al and Ti with accessory of Zn, V and Sn. Petrographic studies suggest the (V–Ti) bearing magnetite (Mt) contain spinel, högbomite, chlorite, martite, ilmenite (Il) and minor amounts of diaspore. The högbomite displays euhedral to subhedral textures, and is up to 250 µm along the grain boundaries of magnetite and ilmenite. In the samples studied, högbomite is prismatic, irregular and elongated in shape. The genesis of högbomite in veins between magnetite and ilmenite implies its precipitation from fluids without involving complicated reactions. Several models were proposed for the formation of högbomite; however, the subject is still debatable.

**Key words:** Högbomite, western Dharwar craton, vanadium, magnetite, EPMA, India

## 1 Introduction

Högbomite is the name given to a group of minerals which are composed of variable amounts of nolanite-type ( $\text{TM}_4\text{O}_7(\text{OH})$ ; T indicates tetrahedrally, M indicates octahedrally coordinated cations) and spinel ( $\text{T}_2\text{M}_4\text{O}_8$ ) modules (Armbruster, 2002, Hejny and Armbruster 2002). Consequently, högbomite has a variety of polysomes and a widely variable composition. Högbomite is typically considered a metamorphic mineral that is assumed to have formed through a range of possible reactions involving most commonly magnetite and spinel (e.g. Petersen et al., 1988; Rakotonandrasana et al., 2010; Sengupta et al., 2009; Razakamanana et al., 2000). To date, högbomite has been reported from five localities in India: Orissa (Beura et al., 2009), Andhra Pradesh (Grew et al., 1987, 2003), Tamil Nadu (Tsunogae and Santhosh, 2005; Sengupta et al., 2009) and 2 localities in Karnataka (Devaraju et al., 1981). Here we report on a second occurrence of högbomite

from the Dharwar craton in Karnataka, which is the sixth documented occurrence of this mineral from India. We evaluate the mineral chemical characteristics of högbomite and associated Fe-Ti-minerals in an attempt to decipher the formation of högbomite as a primary hydrothermal mineral in a metamorphosed magnetite layer.

## 2 Geological Setting

The Dharwar Craton of South India is one of the major Archean crustal blocks with lithological units as old as 3.6 Ga (Ramakrishnan, 1981). It is bounded by the Narmada–Son—Godavari rift system to the north–northeast, to the west by the western margin of the subcontinent, towards the east by the Eastern Ghat mobile belt, and towards the south it is separated by granulite terrain by the transition zone (Fig. 1). The Craton was divided into the western block and the eastern block by Swaminath et al. (1976), but renamed as the Western Dharwar Craton (WDC) and the Eastern Dharwar Craton (EDC) respectively by Rogers

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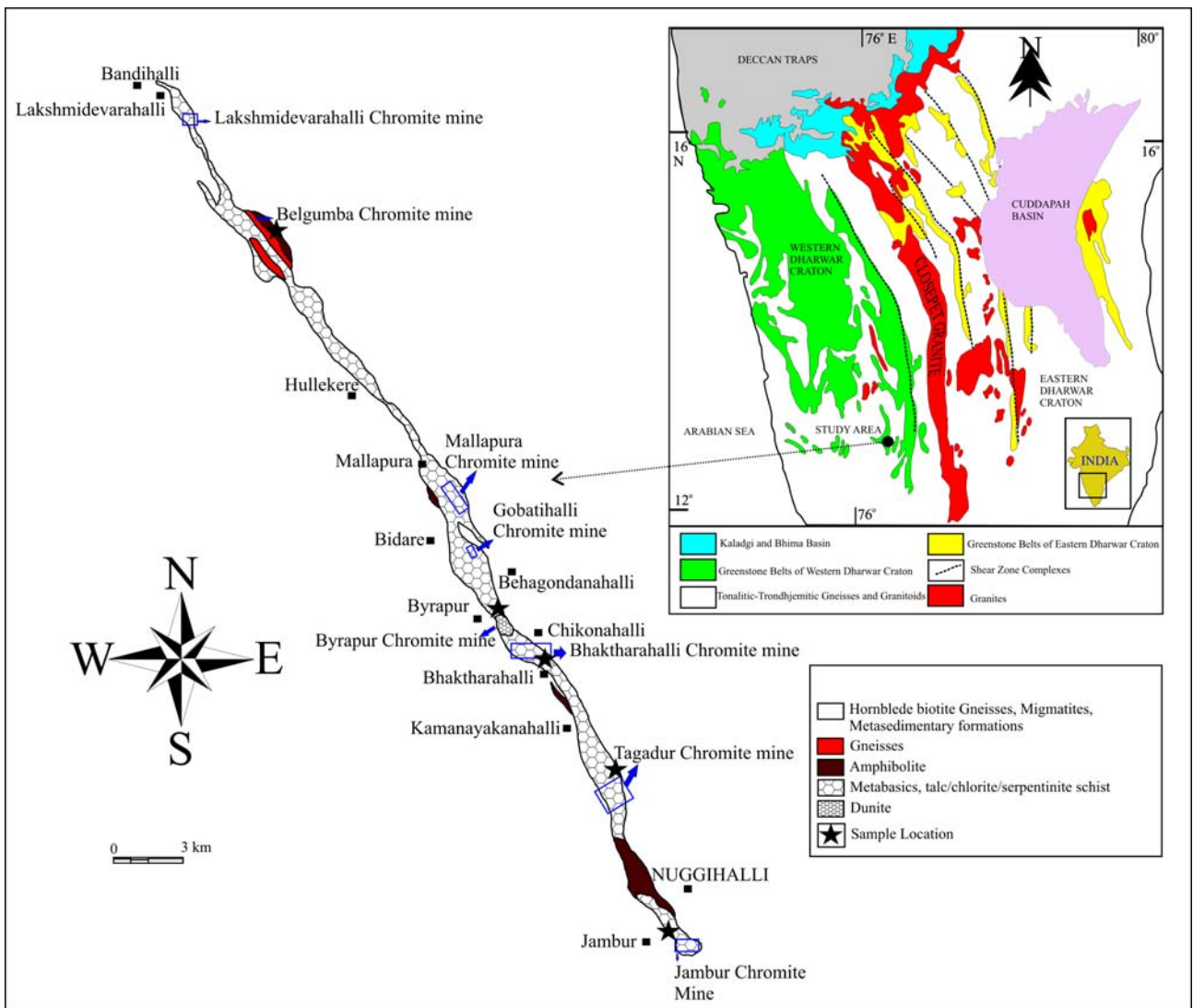


Fig. 1. Geological overview of the South India (in-set) and geological map of Nuggihalli greenstone belt.

(1986). The WDC and EDC are separated by the undefined contact with Chitradurga granite at the eastern margin of the Chitradurga schist belt near to the western margin of the Closepet granite. There are distinct changes in regional geology, lithounits and metamorphic grade between WDC and EDC, which are however, beyond the scope of this paper and have been discussed elsewhere (Raju P.V.S et al., 2011, 2009, 2006). Among the Supracrustal groups of WDC, the oldest identified Sargur Group occurs as enclaves within the gneisses, where as younger supracrustals (3 to 2.5 Ga old i.e., Late Archaean) of the Dharwar supergroup: Chitradurga, Shimoga, Bababudan and Western Ghat belts of WDC have been designated as Dharwar type schist belts by Shackleton (1976) and Goodwin (1977). The Chromite and V-Ti magnetite occur in the form of bands/layers and small lenses associated with the ultramafic-mafic complexes of the Sargur Group of the WDC. The economically

exploitable chromite deposits are known in the Sinduvalli-Talur belt (Mysore District) and the Nuggihalli greenstone belt (Hassan district). The Nuggihalli greenstone belt extends for nearly ~50 km (NNW trend) from Kempinkote in the South to Arsikere in the north. This belt varies from 1 m to 3 m in width, and its maximum width can be observed at the central part of the Nuggihalli. The rock type includes chromite-bearing serpentinised peridotite, talc-tremolite-chlorite schists, amphibolites metasediments (fuchsite quartzite, quartz mica chlorite schist and staurolite-quartz mica schist (Ramakrishnan, 1981). The chromitite occurs as lenses, tabular and as irregular bodies in the Nuggihalli greenstone belt. The chromitite contain chromite at mineable scale from Byrapur, Bhaktharahalli, Tagdur Ranganbetta and Jambur areas (Radhakrishna, 1957) (Fig. 1). In Nuggihalli greenstone belt V-Ti magnetite is reported throughout the belt. The V-Ti magnetite occurs as seams/ lenses/ loads and as narrow

bands, typically associated with pyroxenite-gabbro-anorthosite litho units. The V-Ti bearing magnetite layers and lenses look in-similarity with chromite. The ultramafic bodies with chromite bearing anorthosites are deformed and mostly occur in the gneisses. So far the evidence on the age for these ultrabasic is lacking, except an estimated age of >3.0 Ga (Baidyananda et al., 2003). Recent work done by Mukherjee et al. (2010, 2012) on Nuggihalli greenstone belt provided a Sm-Nd measured age of (3125 ± 125) Ma, and suggested linkage to a stage of supercontinent amalgamation. Mukherjee et al. (2012) also discussed at length the tectono-metamorphic history and whole rock geochemical analyses of the Nuggihalli greenstone belt. These rocks constitute the Aladahalli band which forms an arm of the Nuggihalli belt extending from Byrapur to Ugrahalli, and probably are host rocks for Cu-Ni mineralisation (Subba Rao and Naqvi 1997).

### 3 Analytical Method

Electron Probe Micro Analysis (EPMA) of the oxide minerals of interest were carried out on polished thin sections using the fully automated Cameca SX-100 facility at the National Geophysical Research Institute, Hyderabad. Wavelength spectrometer analyses were performed using an accelerating voltage of 20 kV and a beam current of 20 nA. The measurement time on the peak to background is 60 sec. Zinc was analyzed on LIF crystal, Ni, Cr, V and Mn on large LIF crystal, K, Ca and Ti on large PET crystal, and Al, Si and Mg on TAP crystal. The following materials were used for calibration: sphalerite for zinc, pure nickel for nickel, bustamite for manganese, chromite for chromium, V<sub>2</sub>O<sub>5</sub> for vanadium, orthoclase for potassium, diopside for calcium, rutile for titanium, plagioclase for aluminum and quartz for silica). Tin was not found. Interferences between the Ti-K<sub>beta</sub> X-ray emission line and the V-K<sub>alpha</sub> line, as well as V-K<sub>beta</sub> and Cr-K<sub>alpha</sub> were corrected using the Cameca® overlap correction program and checked by analyzing pure element standards. Mineral standards were analyzed as unknown and re-calibrations were performed when necessary.

### 4 Petrography

The common mineral assemblage in the Fe-Ti-Mg-Al-rich domains comprises spinel, and högbomite associated with diasporite, ilmenite and magnetite are accessory minerals. No obvious mineral fabrics are present in the assemblage. Chlorite and diasporite occur as secondary phases partly replacing spinel and corundum. The högbomite is pale brownish in colour and forms fine- to

medium-grained (50 to 250 µm) euhedral to subhedral grains included in or scattered along grain boundaries of coarse-grained spinel aggregates and ilmenite and magnetite association. Its optical characters (weakly pleochroism, uniaxial negative, parallel extinction, high birefringence, and length slow) are all consistent with the previously reported data for högbomite. It has hexagonal morphology, when cut perpendicular to the 'c' axis (Fig. 2a), is also typical (e.g. Petersen et al., 1988). Högbomite is associated with spinel, diasporite and secondary chlorite. In this study area mostly högbomite grains contain massive Fe-oxide (magnetite-ilmenite association) (Fig.2b). The investigated samples comprise of massive magnetite with more than 80 % of magnetite and ilmenite with a granoblastic texture. Magnetite and ilmenite vary in size typically from about 10 to 200 µm, although individual magnetite grains may approach 1 mm in size. The massive magnetite is intersected by vein-like features that are dominated by ilmenite and högbomite, with a smaller proportion of magnetite, and variable, but always small amounts of what we tentatively call diasporite and corundum (BSE images of Figs. 2c, d). Smooth grain boundaries and the angles between these minerals imply formation under equilibrium conditions. Some of the högbomite is rimmed and partially replaced by chlorite

## 5 Analytical results

### 5.1 Mineral chemistry

#### 5.1.1 Magnetite in matrix and veins

Twenty-three analyses by EPMA (magnetite in the matrix and in vein) (Table 1) shows that there is very few difference in composition of the magnetite in the two textural settings. The compositional ranges overlap widely, but it appears that the magnetite in the veins has slightly higher concentrations of Ti and Cr, while the matrix magnetite has higher vanadium contents.

#### 5.1.2 Ilmenite in matrix and veins

Several differences can be observed between the analyses of ilmenite in the matrix and the veins (Table 2). Vein ilmenite is higher in titanium and some of the grains appear to have slightly higher Zn contents than the matrix ilmenite, while some of the matrix ilmenite has higher Mg and vanadium contents. Ilmenite contains on average less than 1 wt% of MgO, but there are some Mg-enriched ilmenite grains which formed as exsolutions from very large magnetite grains in the magnetite. Some analyses of ilmenite from the matrix demonstrate vanadium contents around 1 wt% which is substantially higher than observed for the vein ilmenite, while others show concentrations overlapping with vein ilmenites. No particular reason or characteristics for the Zn-enriched or

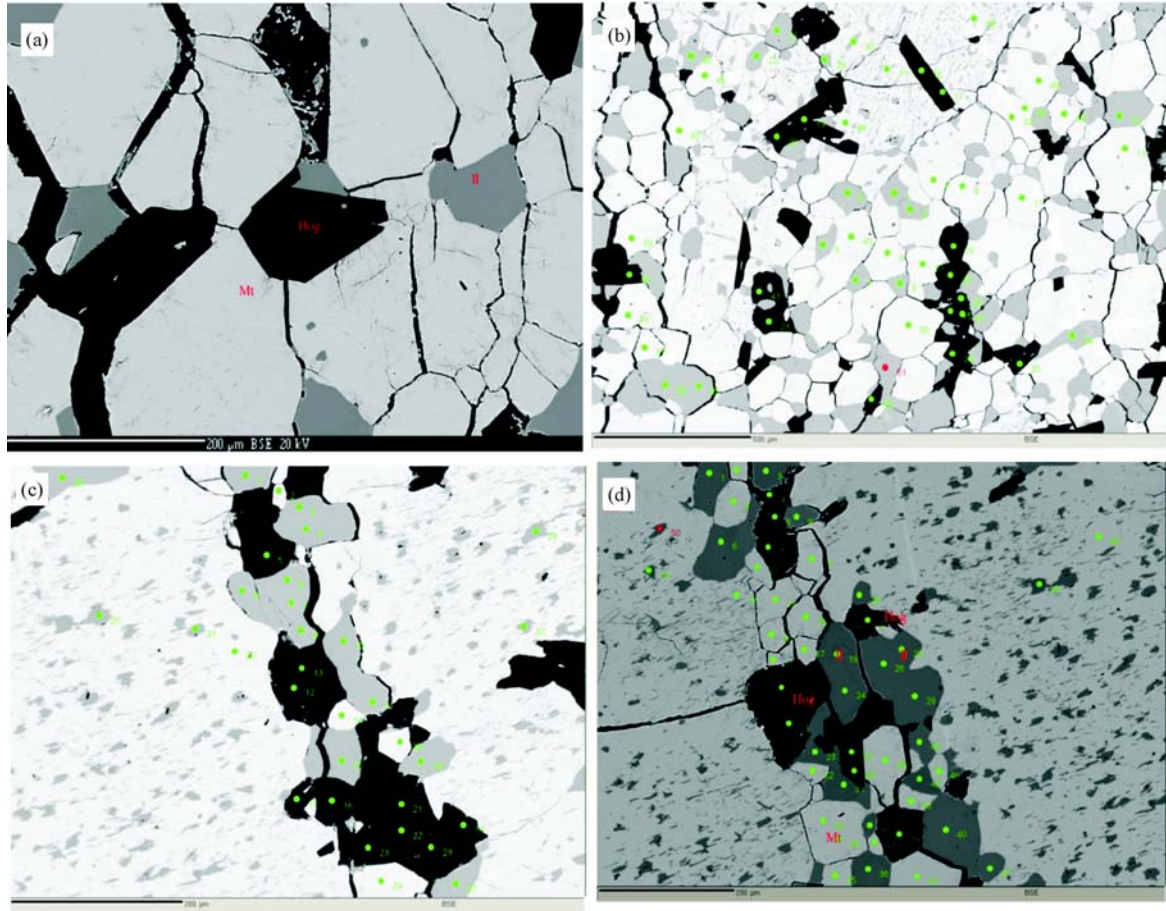


Fig. 2. (a), BSE image of högbomite (hexagonal) associated with ilmenite and magnetite; (b), Högbomite associated with ilmenite and magnetite (the exsolution of ilmenite are in middle). The green dots indicate the spot analyses; (c), Högbomite with association of ilmenite-magnetite in vein form; (d), Högbomite associated with ilmenite-magnetite as a thin the matrix show exsolution lamellae.

**Table 1 Summary of compositional variation of magnetite**

Mineral	N	Minimum	Maximum	Mean	Std.Dev.
<b>Magnetite vein</b>					
TiO <sub>2</sub>	23	0.11	2.29	0.58	0.48
Al <sub>2</sub> O <sub>3</sub>	23	0.11	0.47	0.27	0.09
MgO	23	0.02	0.17	0.07	0.04
Cr <sub>2</sub> O <sub>3</sub>	23	1.53	1.89	1.68	0.08
MnO	23	0	0.06	0.01	0.02
FeO	23	87.23	89.71	88.51	0.75
NiO	23	0	0.25	0.11	0.05
V <sub>2</sub> O <sub>3</sub>	23	0.93	1.11	1.04	0.05
ZnO	23	0	0.12	0.04	0.04
<b>Magnetite matrix</b>					
TiO <sub>2</sub>	23	0.04	1.47	0.26	0.34
Al <sub>2</sub> O <sub>3</sub>	23	0.16	0.77	0.34	0.16
MgO	23	0.03	0.23	0.10	0.05
Cr <sub>2</sub> O <sub>3</sub>	23	0.57	1.77	1.54	0.23
MnO	23	0	0.03	0.00	0.01
FeO	23	85.82	89.31	87.42	0.77
NiO	23	0.01	0.16	0.10	0.04
V <sub>2</sub> O <sub>3</sub>	23	1.01	1.18	1.12	0.04
ZnO	23	0	0.14	0.03	0.04

Unit for oxide is wt%.

**Table 2 Summary of compositional variation of ilmenite**

Mineral	N	Minimum	Maximum	Mean	Std.Dev.
<b>Ilmenite vein</b>					
TiO <sub>2</sub>	28	52.60	55.14	53.64	0.59
Al <sub>2</sub> O <sub>3</sub>	28	0.00	0.05	0.00	0.01
MgO	28	0.55	0.91	0.71	0.10
Cr <sub>2</sub> O <sub>3</sub>	28	0.04	0.27	0.10	0.05
MnO	28	0.91	1.15	1.06	0.07
FeO	28	43.78	46.76	45.45	0.70
NiO	28	0.00	0.11	0.03	0.03
V <sub>2</sub> O <sub>3</sub>	28	0.25	0.60	0.41	0.09
ZnO	28	0.00	1.35	0.25	0.25
<b>Ilmenite matrix</b>					
TiO <sub>2</sub>	22	50.87	54.25	51.84	0.85
Al <sub>2</sub> O <sub>3</sub>	22	0.00	0.00	0.00	0.00
MgO	22	0.58	1.68	0.94	0.32
Cr <sub>2</sub> O <sub>3</sub>	22	0.02	0.22	0.10	0.05
MnO	22	0.93	1.24	1.07	0.08
FeO	22	44.20	46.63	45.28	0.52
NiO	22	0.00	0.08	0.02	0.02
V <sub>2</sub> O <sub>3</sub>	22	0.28	1.11	0.81	0.30
ZnO	22	0.00	0.26	0.09	0.08

Unit for oxide is wt%.

V-enriched ilmenite could be identified. There seems to be a systematic negative relationship between Ti and V (Fig. 3a), but no systematic relationship between Cr and V.

### 5.1.3 Högbomite in matrix and veins

The small number of analyses makes a statistical evaluation difficult, but there is an indication that there may be a negative relationship between Ti and Al or Zn

(Fig. 3b), a negative relationship between Al and V, but a positive relationship between Ti and Cr or total Fe (Fig. 3c). If any difference in composition exists at all, vanadium seems to be the most likely candidate, with vanadium in the vein-hogbomite being slightly lower than in the matrix (Table 3).

### 5.1.4 Others (corundum, diaspore)

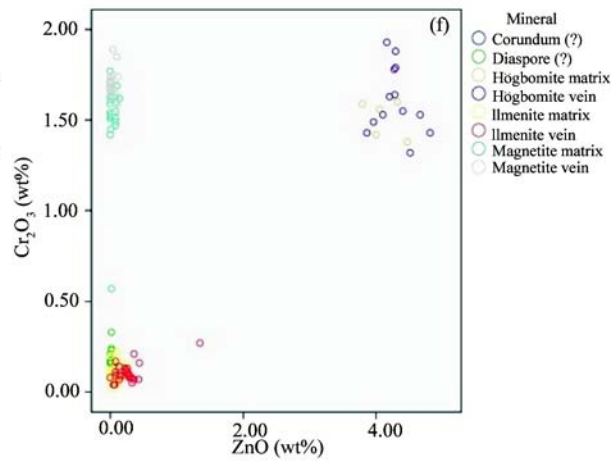
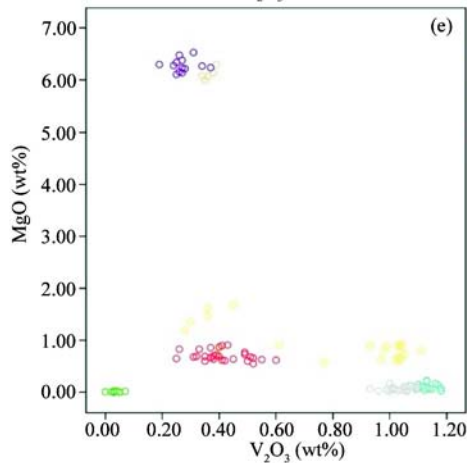
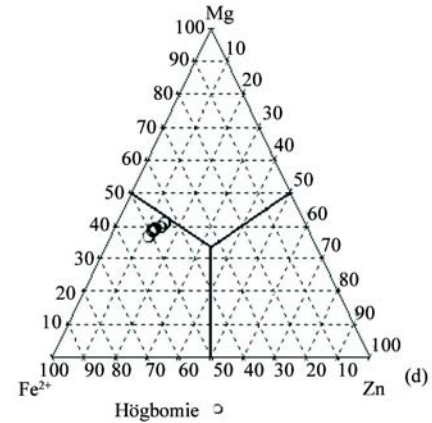
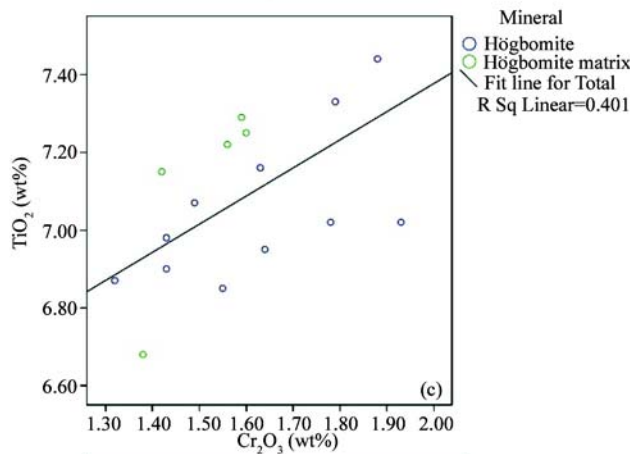
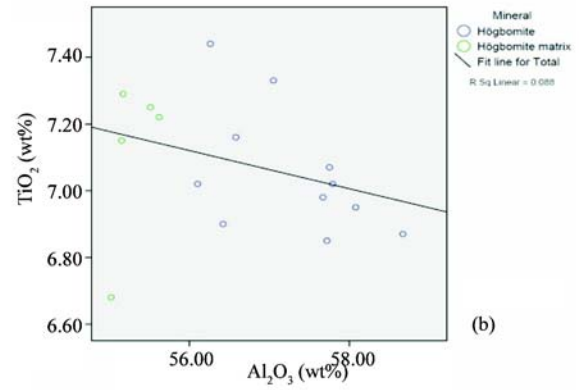
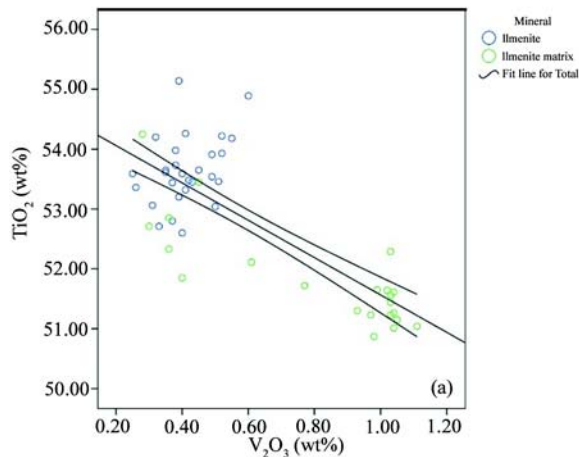


Fig. 3. (a), Binary diagram of  $\text{TiO}_2$  vs  $\text{V}_2\text{O}_5$  in ilmenite and ilmenite matrix; (b), Binary diagram of  $\text{TiO}_2$  vs  $\text{Al}_2\text{O}_3$  in högbomite; (c), Binary diagram of  $\text{TiO}_2$  vs  $\text{Cr}_2\text{O}_3$  in högbomite; (d), Ternary plot of Fe-Mg-Zn in Cation % and högbomite present in ferro-högbomite; (e), Binary diagram of  $\text{MgO}$  vs  $\text{V}_2\text{O}_5$  in magnetite, magnetite matrix, ilmenite vein and matrix, högbomite vein and matrix, corundum and diaspore; (f), Binary diagram of  $\text{Cr}_2\text{O}_3$  vs  $\text{ZnO}$  in högbomite and magnetite.

Some analyses of mineral grains in the veins and matrix gave compositions around 84 wt% Al<sub>2</sub>O<sub>3</sub> (Table 4) with minor titanium, chromium and iron, which agrees well with the theoretical composition of AlO(OH) of 84.98 wt% Al<sub>2</sub>O<sub>3</sub>. We have not confirmed the exact nature of this mineral and therefore call it tentatively diaspore (?). One grain, consisting of diaspore and corundum produced a composition for corundum of almost pure Al<sub>2</sub>O<sub>3</sub> with 0.13 wt% Cr<sub>2</sub>O<sub>3</sub> and 0.77 wt% Fe<sub>2</sub>O<sub>3</sub>.

## 6 Discussions

Comparing the analyzed minerals in the veins and matrix, and looking at "non-essential" elements for magnetite and ilmenite (Cr, V, Zn, Mg), we get an indication where these non-essential elements like to partition into if titaniferous magnetite, ilmenite, and h gbomite coexist.

Despite the Fe-rich environment and the possibility to incorporate both iron and magnesium into the h gbomite structure, h gbomite is the mineral with the highest magnesium enrichment. However, following the guidelines of Armbruster (2002), Fe is the dominant 2+ cation (calculated to achieve charge balance; (Fig. 3d (ternary plot of Fe-Mg-Zn) in cat-%) and the h gbomite encountered in this study is in all likelihood ferro-h gbomite.

Chromium is concentrated in h gbomite and magnetite to similar concentration levels, but the concentrations of vanadium in h gbomite are relatively low, much lower

than for magnetite and some of the ilmenite grains (Fig.4e; (Mg-V). It is noteworthy that both the magnetite and the h gbomite in the veins have slightly lower vanadium contents than the grains in the matrix.

Ilmenite in veins and matrix contains minor concentrations of Zn with a tendency for slightly higher amounts in ilmenite in the veins. However, in the ilmenite-magnetite- h gbomite assemblage, zinc is strongly concentrated in h gbomite (Table 5 Kd values; Fig 3f ;Cr-Zn).

Table 5 is a summary of partition coefficients (wt-% oxide), based on averages and extreme values in the vein assemblage only (in the matrix, MgO and V<sub>2</sub>O<sub>3</sub> in ilmenite vary widely, implying a whole range of processes we do not understand and can not quantify). By using only the vein, we have 1 set of data that seems to represent 1 event and 1 process. \* means the value can not be calculated because the lowest values are below the detection limit.

### 6.1 H gbomite composition

A h gbomite sample has distinctly high Ti and Fe content and low Al content, implying the interference of ilmenite in this analysis. However, there is no textural evidence for the interference, and the analysis was therefore not excluded. Compared to the literature data, the h gbomite in this study is high in Ti and low Al (Fig. 4a; (Ti-Al), about average in MgO and ZnO, low in MnO (Fig. 4b; (Mn-Zn), and unusually high in V and Cr (Fig. 4c; (V-Cr). The latter could be because the fluids were at least in partial equilibrium with the matrix magnetite, which in itself is high in Cr and V compared to most of the environments in which h gbomite has been described. The Mg content of the h gbomite is towards the lower end of the range compared to literature data. Again this can be attributed to the low Mg content of the matrix and consequently the fluid.

The formation of h gbomite exclusively or predominantly through metamorphic reactions requires the

**Table 3 Summary of compositional variation of h gbomite**

Mineral	N	Minimum	Maximum	Mean	Std.Dev.
<b>H�gbomite veins</b>					
TiO <sub>2</sub>	13	6.85	7.44	7.07	0.21
Al <sub>2</sub> O <sub>3</sub>	13	56.10	58.67	57.14	0.85
MgO	13	6.11	6.53	6.31	0.14
Cr <sub>2</sub> O <sub>3</sub>	13	1.32	1.93	1.63	0.21
MnO	13	0.07	0.17	0.12	0.03
FeO	13	20.34	22.05	21.32	0.59
NiO	13	0.15	0.32	0.23	0.04
V <sub>2</sub> O <sub>3</sub>	13	0.19	0.34	0.27	0.04
ZnO	13	3.86	4.81	4.32	0.28
<b>H�gbomite matrix</b>					
TiO <sub>2</sub>	5	6.68	7.29	7.12	0.25
Al <sub>2</sub> O <sub>3</sub>	5	55.02	55.62	55.29	0.26
MgO	5	6.00	6.30	6.12	0.11
Cr <sub>2</sub> O <sub>3</sub>	5	1.38	1.60	1.51	0.10
MnO	5	0.06	0.19	0.12	0.06
FeO	5	19.82	21.40	20.92	0.63
NiO	5	0.18	0.31	0.24	0.05
V <sub>2</sub> O <sub>3</sub>	5	0.34	0.39	0.36	0.02
ZnO	5	3.79	4.47	4.13	0.27

Unit for oxide is wt%.

**Table 4 Summary of compositional variation of diaspore**

	N	Minimum	Maximum	Mean	Std. Dev.
TiO <sub>2</sub>	8	0.02	0.22	0.10	0.07
Al <sub>2</sub> O <sub>3</sub>	8	83.51	85.22	84.38	0.70
Cr <sub>2</sub> O <sub>3</sub>	8	0.16	0.33	0.21	0.06
FeO	8	0.51	0.98	0.68	0.16
V <sub>2</sub> O <sub>3</sub>	8	0.00	0.07	0.04	0.02

Unit for oxide is wt%.

**Table 5 Summary of partition coefficients (wt% oxide)**

		average	extreme 1	extreme 2
MgO	Kd H�g/Ilm	8.90	11.87	6.71
	Kd H�g/Mt	94.48	326.50	35.94
	Kd Ilm/Mt	10.61	45.50	3.24
Cr <sub>2</sub> O <sub>3</sub>	Kd H�g/Ilm	15.44	7.15	4.89
	Kd H�g/Mt	0.96	1.02	0.70
	Kd Ilm/Mt	0.06	0.14	0.02
MnO	Kd H�g/Ilm	0.12	0.22	0.06
	Kd H�g/Mt	14.77	*	1.17
	Kd Ilm/Mt	121.60	*	15.17
V <sub>2</sub> O <sub>3</sub>	Kd H�g/Ilm	0.66	1.48	0.32
	Kd H�g/Mt	0.26	0.40	0.17
	Kd Ilm/Mt	0.40	0.65	0.23
ZnO	Kd H�g/Ilm	17.29	*	2.86
	Kd H�g/Mt	112.05	*	32.17
	Kd Ilm/Mt	6.48	*	*

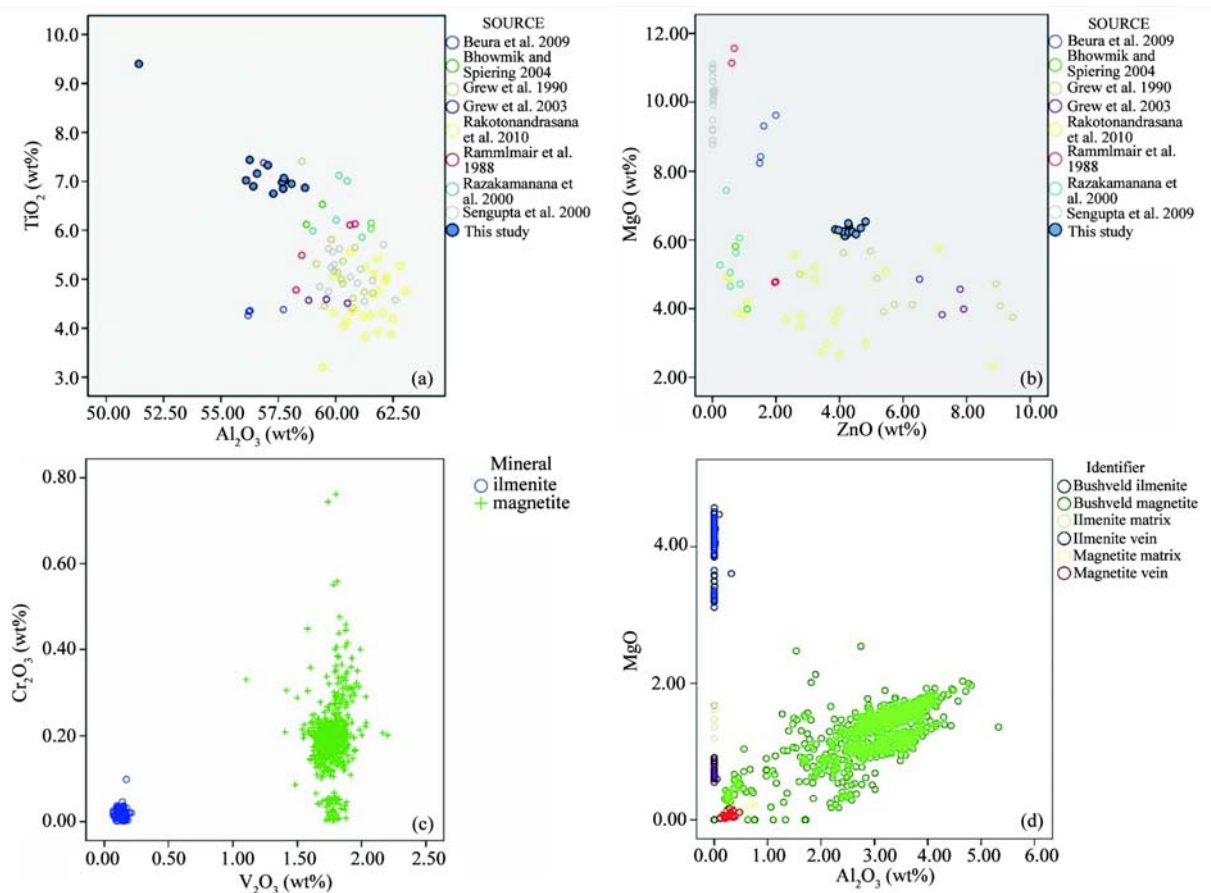


Fig. 4. (a), Binary diagram of TiO<sub>2</sub> vs Al<sub>2</sub>O<sub>3</sub> of högbomite analyses compared to the literature data; (b), Binary diagram of ZnO vs MgO of högbomite analyses in comparison to the literature data; (c), Binary diagram of Cr vs V in ilmenite and magnetite data from magnetite layer of Bushveld complex; (d), Binary diagram of Mg vs Al the ilmenite and magnetite data from Bushveld complex.

availability of Al (and also of Mg). Our magnetite does not contain an obvious source of Al. It is inferred that the concentration of Al in magnetite obviously depends on the intrinsic conditions in the melt during crystallization (i.e., whether the silicate melt was saturated in plagioclase component at the time of magnetite formation or not). Comparison of the Bushveld data (Fig. 5d) with the data in this study shows that the Bushveld magnetite (with an average Al<sub>2</sub>O<sub>3</sub> content of close to 3 wt% and a maximum of 5.3 wt%; average MgO content of 1.2 wt% and up to 2.5 wt%) in solid solution after exsolution of Al- and Mg containing phases (Butcher and Merkle 1987) appears still higher than in our data set with less than 0.5 wt% and 0.07 wt% respectively. This affords the possibility that the magnetite could have expelled substantial amounts of Al and Mg, which could have contributed to the högbomite formation. Textural considerations imply that the högbomite in this study did not form by any of the commonly proposed metamorphic reactions (e.g. Petersen et al., 1988; Rakotonandrasana et al., 2010; Sengupta et al., 2009; Razakamanana et al., 2000). Because the

composition of metamorphic fluids and the minerals they interact with are too complex to exclude any combination of processes, any element not present in the pre-reaction minerals can always be assumed to be provided by the fluids. However, in an environment like a meta-igneous magnetite, Zn in any of the primary minerals present will be extremely low. Would högbomite form through a purely metamorphic reaction in such an environment, Zn contents in högbomite should be very low. The analyses reported by Sengupta et al. (2009) from the Sittampundi Complex agree well with this argument. The substantial amount of Zn in our högbomite therefore requires an external source for the Zn, and consequently of the fluid itself. That the vein ilmenite has a tendency towards higher Zn than the matrix ilmenite is consistent with such an interpretation.

## 6.2 Vanadium in ilmenite

The graphical presentation (Fig. 4d) of 813 electron microprobe analyses of ilmenite and magnetite from the Main Magnetite Layer of the Bushveld Complex, South

Africa. We use 813 analyses as being representative of the distribution of vanadium and chromium between magnetite and ilmenite in magmatic bodies. Although the absolute values vary as a function of silicate melt composition, temperature, and oxygen fugacity, magnetite tends to be enriched in chromium and vanadium relative to coexisting ilmenite (e.g., Tugarinov et al., 1975; Schuilig and Feenstra, 1980, Grammatikopoulos et al. 2002).

As described, ilmenite exsolutions in large magnetite grains in the matrix differ from this expected scheme by being clearly enriched in vanadium (Cr-V) of (ilm + mt), while other ilmenite grains show lower vanadium contents, at concentration as would be expected. We took utmost care to ensure that no analytical artifact is responsible for this anomaly and could reproduce these elevated vanadium contents.

We were able to find two references to a comparable situation (Schuilig and Feenstra, 1980; Beura et al., 2009), but in neither case are the information on the analytical technique detailed enough to exclude an analytical artifact (e.g., insufficient peak overlap correction). Schuilig and Feenstra (1980) performed experiments and achieved preferred partitioning of vanadium into ilmenite under highly oxidizing conditions (close to the magnetite-hematite buffer). This affords the possibility that partitioning of vanadium into ilmenite instead into magnetite could occur in nature as well.

Although the exact average oxidation state of vanadium in mafic melts varies, an average oxidation state approaching 4+ appears to be normal in terrestrial melts (Papike et al., 2004, 2005), which facilitates partitioning of vanadium preferentially into magnetite. Canil (2002) suggested that vanadium partitioned more strongly into a spinel structure at lower oxygen fugacities and hence lower average oxidation state, but it is known that this is not the only controlling factor (Righter et al., 2006). It appears that only at oxygen fugacities higher than normally encountered in silicate melts (close to the magnetite-hematite buffer) vanadium partitions preferentially into ilmenite (Schuilig and Feenstra, 1980). Although a scenario could be constructed in which secondary oxidation of a magmatic vanadiferous assemblage of ilmenite and magnetite may create the conditions conducive for incorporation of vanadium into ilmenite, it is difficult to argue that such a distribution would survive regional metamorphism in which magnetite and ilmenite re-form and vanadium partitions into ilmenite exsolutions from the magnetite on cooling.

We have not determined the oxidation state of vanadium in a system or rock where vanadium preferentially partitions into ilmenite and therefore refrain from any speculation about the incorporation of vanadium

into the ilmenite structure.

## 7 Conclusions

(1) The Cr-V and inverse relationship between magnetite and ilmenite in the matrix implies very oxidizing localized conditions during metamorphism (and equilibration between magnetite and ilmenite), but less oxidizing conditions during the formation of the veins (implying a different event).

(2) Textures imply equilibrium precipitation from fluids.

(3) The occurrence in veins and the composition of hōgbomite implies precipitation from fluids without involving complicated reactions.

(4) This is the second report on the occurrence of hōgbomite from Dharwar Craton and also the sixth such Occurrence from India.

(5) Typically the hōgbomite group minerals are present along the grain boundaries of ilmenite and magnetite.

(6) This study may help use hōgbomite-bearing assemblages to understand the evolutionary history of ancient orogenic or hydrothermal systems.

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