

## A zincian högbomite and some other högbomites from the Strangways Range, Central Australia

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**SUMMARY.** Zincian högbomite has formed by hydrous alteration of spinel and biotite in a lens of highly aluminomagnesian sapphirine-bearing granulite-facies rocks. The högbomite forms chestnut-brown {0001} flakes 1 mm across.  $\epsilon = 1.827$ ,  $\omega = 1.852 (\pm 0.002)$ . Analysis: BeO 0.10, SiO<sub>2</sub> 0.65, Al<sub>2</sub>O<sub>3</sub> 59.69, TiO<sub>2</sub> 5.37, Ga<sub>2</sub>O<sub>3</sub> 0.23, Nb<sub>2</sub>O<sub>5</sub> 0.01, Fe<sub>2</sub>O<sub>3</sub> 5.24, SnO<sub>2</sub> 0.06, NiO 0.04, ZrO<sub>2</sub> 0.03, MgO 7.69, Sc<sub>2</sub>O<sub>3</sub> 0.01, CoO 0.11, ZnO 3.08, FeO 17.52, In<sub>2</sub>O<sub>3</sub> 0.05, MnO 0.12. The pattern of *d*-spacings is anomalous. Other högbomites from the region have exsolved from cordierite or titaniferous opaque oxides.

### *Geological setting*

WHILE studying the paragenesis of several new occurrences of sapphirine from the Strangways Range, in central Australia, högbomite has been recognized in several places. The purpose of this paper is to give details of a zincian högbomite, and to record some other högbomites.

The western half of the Strangways Range, which is about 60–100 km north-north-east of Alice Springs, consists of Precambrian igneous and sedimentary rocks that have been metamorphosed to granulite facies on at least two occasions ( $\approx 1860$  Myr and  $\approx 1430$  Myr; Iyer *et al.*, 1976), and retrogressed along certain linear belts to schists of amphibolite and greenschist facies. Gabbroic and granitic rocks have intruded the region on several occasions during its long and complex evolution.

Granulites are the main rocks in the polymetamorphic terrane, and there is a great variation in intensity and complexity of metamorphism from place to place. Rocks of upper amphibolite facies are dominant in the south and south-west. In appropriate magnesian-aluminous rocks in the granulite terrane in the north-east, the assemblage orthopyroxene–sillimanite developed during the peak of the second granulite metamorphism (Woodford, 1974), whereas orthopyroxene–cordierite or gedrite–cordierite are common products of the first granulite metamorphism in the south and south-west.

### *Zincian högbomite from Johannsen's Phlogopite Mine*

Högbomite has been found in several places, but is best developed at Johannsen's Phlogopite Mine, 57 km north-north-east of Alice Springs (fig. 1). Several shafts have been sunk on phlogopite zones developed by pegmatization of highly magnesian, aluminomagnesian, and aluminoferroan ultramafic rocks. These are set within an extensive tract of cordierite–hypersthene–quartz granulites and related siliceous rocks.

Several phlogopitic rocks from a large sapphirine-rich outcrop near the phlogopite mine yield a Rb–Sr age of  $1470 \pm 60$  Myr (Iyer *et al.*, 1976). Several phases of further metamorphism and hydration have resulted in a large number of rock types, and the mineral parageneses are of

great variety and complexity. Indeed, in many rocks, especially the ultramafic ones, mineral phases (or relics thereof) representing at least two (and in some cases, five) distinct metamorphic events may be recognized.

Högbomite is most commonly found as a product of hydrous alteration of highly aluminomagnesian rocks. At a locality about 67 m south-east of the main shaft (now abandoned), a lens of sapphirine-bearing spinel-anorthite-cordierite rock (about  $5 \times 3$  m) is set within masses of cordierite-anthophyllite and gedrite-bronzitites. This lens is replaced on the north-west, north, and north-east sides by a högbomite-bearing hydrous reaction zone, 0.3–1 m wide. The högbomite forms clear chestnut-brown {0001} euhedral flakes up to 1 mm across. The refractive indices of the högbomite are  $\epsilon = 1.827 \pm 0.002$ ,  $\omega = 1.852 \pm 0.002$ . Interference figures are uniaxial negative with no separation of isogyres.

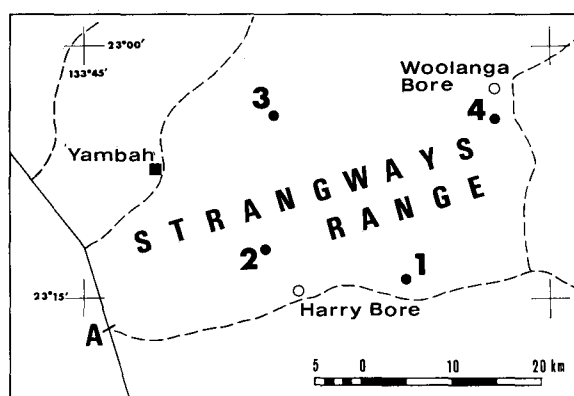


FIG. 1. Högbomite localities, Strangways Range, central Australia: 1—Johannsen's Phlogopite Mine; 2—Harry Creek copper prospect; 3—North-east of Yambah Station; 4—Woolanga bore region. A is 58 km north of Alice Springs.

The högbomite is only developed in the plagioclase-free rocks, and has not been found in rocks containing sapphirine. Figs. 2 and 3 show the normal occurrence. A typical host rock (Sample 110) is a phlogopite rock (with decussate rather than schistose texture) containing relic clots (5 to 10 mm diameter) composed of coarsely intergrown grains of green spinel, opaque oxides, and colourless corundum plates. In this sample a magnesian chlorite (a pale green to very pale fawn sheridanite) forms a fine decussate intergrowth of plates (mostly about 0.3 mm long), which cut across or form pseudomorphs of larger kinked and bent pale brown phlogopite grains (commonly 3 to 4 mm long).

In some samples from the same outcrop (e.g. no. 112) the same grain-boundaries-högbomite relationships are present and the biotite is heavily kinked, but chlorite is absent. It is clear, then, that the development of chlorite is not essential to the paragenesis of högbomite. The chlorite of no. 110, however, is highly magnesian and aluminous and would be stable at high  $P$ - $T$ , and should not be confused with greenschist facies chlorites from the region (for analysis see Table III).

In an adjoining more calcic layer, euhedral staurolite prisms and a calcic amphibole have developed. The petrography suggests that these minerals are isofacial with the högbomite. It is believed that they developed during a high amphibolite facies hydrous retrogression of granulites that had already suffered at least three metamorphic episodes, according to related studies now in progress.

The largest crystals of högbomite are large sheaves of euhedral plates set in a matrix of magnesian chlorite (fig. 2). Smaller less well-developed grains are included in single flakes of biotite, and somewhat resemble coarse exsolution features.

Most of the högbomite, however, is found as euhedral tablets at spinel–biotite and opaque–oxide–biotite grain boundaries. Högbomite has not formed, however, at the following grain boundaries: opaque–oxide–corundum, spinel–corundum, and corundum–biotite.

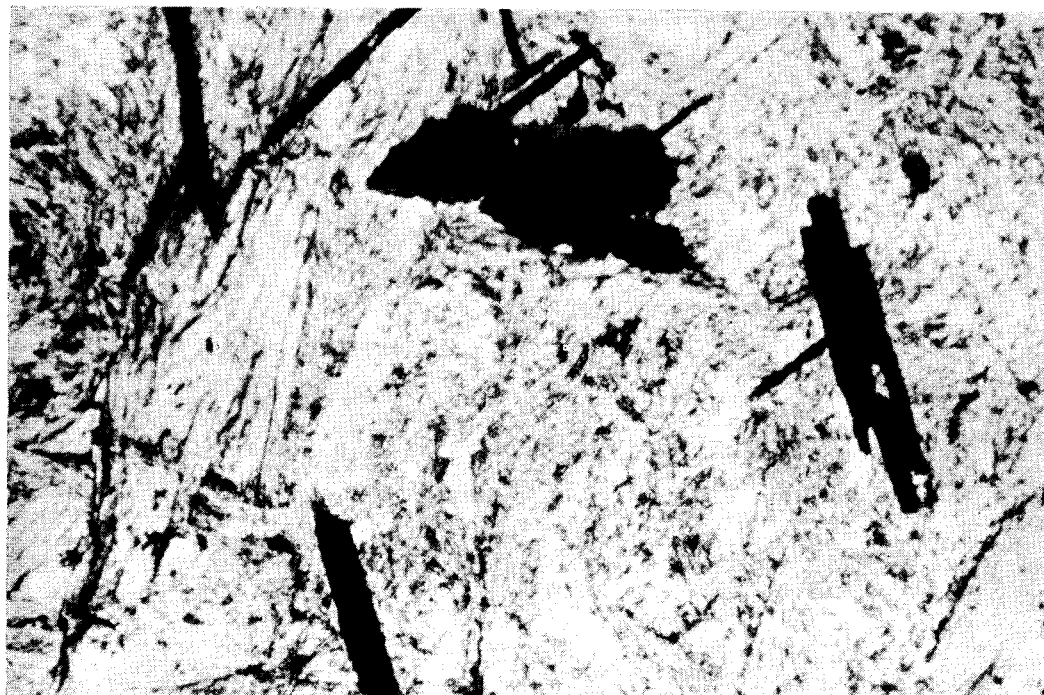


FIG. 2. Tabular crystals of högbomite (black) set within a matrix of sheridanite, a chlorite that has almost wholly replaced phlogopite. The large crystal on the right is 0.8 mm long. Sample 110.

Högbomite, whose chemical composition may be regarded as a 'titaniferous pleonaste' (titanian ceylonite), is well developed in this sample at the expense of green spinel and a titaniferous mineral such as titanian opaque oxide or biotite. (The biotites and phlogopites at this locality normally contain an abundance of exsolved rutile needles.)

#### *Chemical and X-ray data*

*Högbomite.* A chemical analysis of the högbomite from sample 110 was done by Dr. G. Langthaler and is set out as no. 1 in Table I. Details of analytical techniques are shown in the Appendix. Only eight other full chemical analyses could be found, and five of these are set out in Table I. The Strangways Range mineral contains 3.08 % ZnO and thus is a zincian högbomite. Notable zinc has been found in several total rock analyses from the vicinity of Johannsen's Phlogopite Mine, and gahnite has been found near by in several granulites. Thus it is likely that the spinel that has been replaced is either a zincian ceylonite or gahnite. Its refractive index is  $1.788 \pm 0.002$ .

McKie has pointed out that högbomite forms a series of polytypes, designated  $nH$  or  $nR$ , with hexagonal or rhombohedral lattices and hexagonal unit cell dimensions of  $a$  5.72 Å,

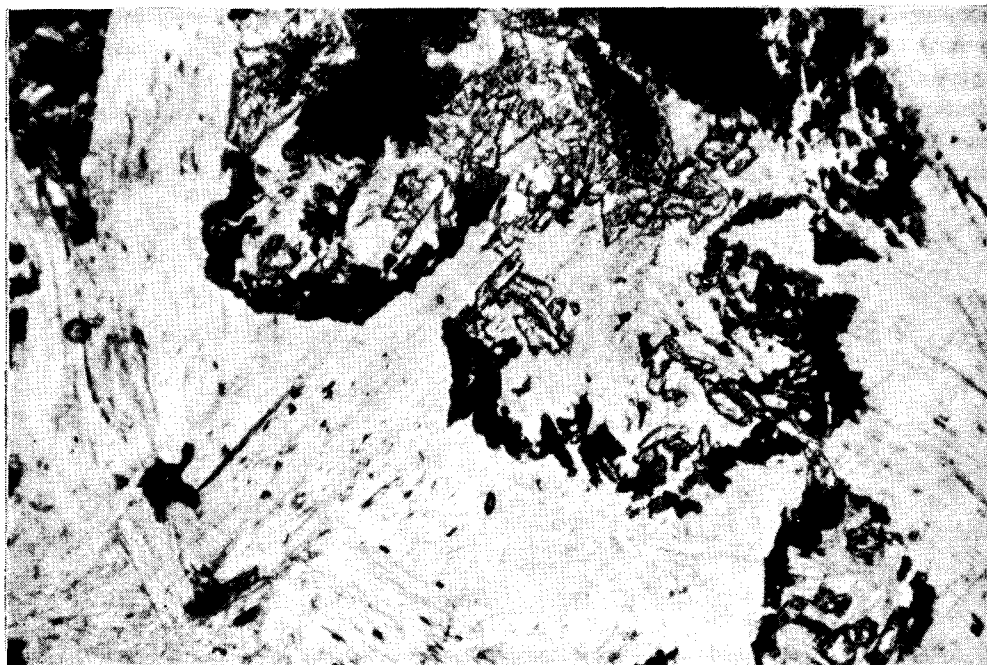
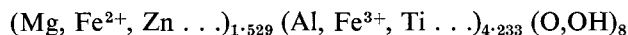
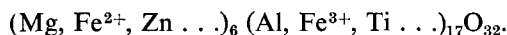


FIG. 3. H gbomite (black angular grains) outlining original ilmenite-corundum-spinel crystal groups and aggregates. Spinel relics—dark grey (top, left, and right of centre); corundum relics—high relief, colourless; ‘ilmenite’ relics (now magnetite)—ragged opaque masses adjoining spinel (top, left of centre), and opaque mass included in corundum (top, right of centre). Matrix (decussate texture) is largely sheridanite (a chlorite), and some relics of non-chloritized phlogopite. The six-sided h gbomite-rimmed feature is 1 mm across. Sample 110.

$c\ 4.6 \times n\ \text{\AA}$ . X-ray determination of the polytype represented by the Strangways Range h gbomite has not yet been done. However, if the cations are appropriately grouped according to ionic radii, the unit sub-cell of:



may be rewritten, and suggests a 4-polytype, thus:



X-ray powder data for the Strangways Range zincian h gbomite (Table II) are very anomalous, for the  $d$ -spacings are much closer to those of the 4H polytype taaffeite than to those of the 18R polytype h gbomite, which has similar  $\text{Fe}^{2+}$  to that of the new zincian h gbomite (for other comparative data, see McKie (1963)); 20 out of 23  $d$  spacings of the zincian h gbomite closely resemble those of taaffeite, whereas only about 5 resemble those of the 18 R-h gbomite. Indeed, a routine survey of the powder data (in the absence of the chemical data) would probably identify this mineral as taaffeite rather than h gbomite.

As the h gbomite contains only 0.10 % BeO (the characteristic element of taaffeite is Be) the chemical reason for the anomalous powder data is unknown, and must await a single-crystal determination of the polytype status of this new h gbomite.

*Chlorite (sheridanite).* A chemical analysis of the chlorite, which is closely associated with some (but not all) of the zincian h gbomite, is set out with some optical and X-ray data in

TABLE I. *Chemical and sub-cell data for högbomites*

			r Å							
			vi	iv	1	2	3	4	5	6
BeO	0.10	Be <sup>2+</sup>	0.35	0.27	0.0128					
SiO <sub>2</sub>	0.65	Si <sup>4+</sup>	0.400	0.26	0.0346			0.043	0.044	
Al <sub>2</sub> O <sub>3</sub>	59.69	Al <sup>3+</sup>	0.530	0.39	3.7520	3.614	3.788	3.458	3.533	3.76
TiO <sub>2</sub>	5.37	Ti <sup>4+</sup>	0.605	?	0.2153	0.208	0.200	0.264	0.326	0.34
Ga <sub>2</sub> O <sub>3</sub>	0.23	Ga <sup>3+</sup>	0.620	0.47	0.0080					
Nb <sub>2</sub> O <sub>5</sub>	0.01	Nb <sup>5+</sup>	0.64	0.32	0.0003					
Fe <sub>2</sub> O <sub>3</sub>	5.24	Fe <sup>3+</sup>	0.645	0.49	0.2102	0.379	0.321	0.344	0.209	
SnO <sub>2</sub>	0.06	Sn <sup>4+</sup>	0.690		0.0013					
NiO	0.04	Ni <sup>2+</sup>	0.700		0.0016					
ZrO <sub>2</sub>	0.03	Zr <sup>4+</sup>	0.72		0.0006					
MgO	7.69	Mg <sup>2+</sup>	0.720		0.6111	0.731	0.929	0.710	0.983	1.26
Sc <sub>2</sub> O <sub>3</sub>	0.01	Sc <sup>3+</sup>	0.730		0.0003					
CoO	0.11	Co <sup>2+</sup>	0.735		0.0048					
ZnO	3.08	Zn <sup>2+</sup>	0.745		0.1211	0.444	Nil			
FeO	17.52	Fe <sup>2+</sup>	0.770		0.7812	0.381	0.499	0.780	0.447	0.32*
In <sub>2</sub> O <sub>3</sub>	0.05	In <sup>3+</sup>	0.790		0.0013					
MnO	0.12	Mn <sup>2+</sup>	0.820		0.0054	0.037	0.007	0.004	0.004	
H <sub>2</sub> O+		OH <sup>-</sup>	}		8.000			0.381	0.427	
H <sub>2</sub> O-		O <sup>2-</sup>				8.000	8.000	7.619	7.573	8.00
Sum	100.00 <sup>+</sup>	Group A (Be <sup>2+</sup> – Fe <sup>3+</sup> )	4.2332		4.201	4.309	4.109	4.112	4.10	
		Group B (Sn <sup>4+</sup> – Mn <sup>2+</sup> )	1.5287		1.593	1.435	1.494	1.434	1.58	
		ε A + B			5.7619	5.794	5.744	5.603	5.546	5.72
		Polytype			? 4	?	?	18R	5H	5H
			Σ		1.827	1.809	1.812	1.828	1.800	1.783
			ω		1.852	1.837	1.850	1.848	1.820	1.805

1. Zinc-högbomite, Strangways Range, central Australia. Anal. G. Langthaler.

2. Zinc-högbomite, USSR. Anal. 3 of Moleva & Myasnikov, 1952.

3. Högbomite, USSR. Anal. 2 of Moleva & Myasnikov, 1952.

4. Högbomite, Transvaal. Variety B of Nel, 1949.

5. Högbomite, Transvaal. Variety A of Nel, 1949.

6. Högbomite, Tanzania. McKie, 1963.

Cations in högbomites calculated to Σ (O + OH) = 8 (the sub-cell), and arranged in increasing order of ionic radius for six-fold coordination (quoted from Shannon & Prewitt, 1969).

+ Recalculated to 100.00 from 100.26, omitting nil H<sub>2</sub>O+, 0.10 H<sub>2</sub>O- and 1.34 corundum; Nb, Sn, Zr, Sc determined by XRF (A. S. Bagley).

\* Total Fe as FeO.

TABLE II. *Comparison of X-ray powder data for högbomite, taaffeite, and the new zincian högbomite*

Högbomite-18R			New Högbomite			Taaffeite-4H			Högbomite-18R			New Högbomite			Taaffeite-4H		
d (Å) I	hkl		d (Å) I	hkl		d (Å) I	hkl		d (Å) I	hkl		d (Å) I	hkl		d (Å) I	hkl	
4.63 w		0.0.0.18				4.57 m	0004					1.925 vw			1.925 m	2026	
			4.37 vw			4.35 mw	1012					1.715 vvw			1.720 vvw	2028	
			3.81 vvw			3.85 vvw	1013								1.684 vw	2135	
			3.36 vw			3.36 m	1014		1.665 mw	1.2.3.23		1.651 vvw					
3.01 mw		1.0.1.22				2.95 mw	1015		1.618 w	1.2.3.26		1.597 w			1.596 mw	2136	
2.93 m		0.1.1.23	2.940 w			2.86 m	1120										
2.87 s		1120	2.857 mw			2.70 vvw	1122		1.589 vw	2.1.3.28		1.575 vvw			1.576 vw	2029	
2.69 ms		0.1.1.26															
			2.670 vvw														
			2.599 m			2.61 ms	1016		1.572 mw	[2.0.2.41							
									1.558 mw	1.2.3.29		1.554 vw			1.554 w	3034	
2.55 mw		0.1.1.28										1.551 vw					
2.49 mw		0.1.1.29															
2.44 vvw		1.1.2.18	2.426 s			2.43 vws	1124		1.538 w	2.1.3.31		1.524 vvw			1.522 w	2137	
2.42 m		2028															
			2.386 vw			2.38 vw	2022										
2.36 mw		1.0.1.31							1.505 w	2.0.2.44							
2.30 vw		2.0.2.14	2.315 vw			2.31 vwb	[2023					1.474 mw			1.476 ms	2.0.2.10	
							1017										
			2.180 vw			2.18 mw	2024		1.462 mw	0.2.2.46							
2.14 vvw		2.0.2.20							1.443 mw	2.0.2.47					1.455 vvw	?	
2.081 m		0.2.2.22							1.434 s	2210		1.430 m			1.428 s	2240	
2.048 mw		2.0.2.23	2.053 w			2.05 s	2025		1.403 vw	0.2.2.49							
1.990 mw		0.2.2.25										1.385 w			1.387 m	2.0.2.11	
1.963 w		2.0.2.26															

Högbomite—18R and the new högbomite = 4 and 1, resp., of Table I. Data for taaffeite—4H is from Anderson *et al.* (1951).

TABLE III. *Chemical analysis and X-ray and optical data for chlorite (sheridanite)*

SiO <sub>2</sub>	27.45	Si	5.249	8.000	$\alpha \approx 1.593$ ; $2V\gamma \approx 10^\circ$ Cell dimensions, assuming Miller indices of sheridanite: $a = 5.306$ , $b = 9.230$ , $c = 14.228$ ; $\beta = 99.800$ Elements determined by classical and atomic absorption. Analyst: G. Langthaler Sheridanite is closely associated with the Zincian högbomite in No. 110.
TiO <sub>2</sub>	0.10	Al <sup>iv</sup>	2.751		
Al <sub>2</sub> O <sub>3</sub>	23.03	Al <sup>vi</sup>	2.440		
Fe <sub>2</sub> O <sub>3</sub>	1.49	Ti	0.015	12.100	
FeO	8.38	Fe <sup>3+</sup>	0.214		
MnO	0.05	Mg	7.942		
MgO	27.87	Fe <sup>2+</sup>	1.340		
CaO	0.04	Mn	0.008		
Na <sub>2</sub> O	0.06	Ca	0.008		
K <sub>2</sub> O	0.45	Na	0.023		
H <sub>2</sub> O+	11.09	K	0.110		
H <sub>2</sub> O—	0.15	OH	16.000	16.000	
Sum	100.16	0	28.000	28.000	

Table III. The unusually high  $K_2O$  content is not due to contamination but may be attributed to biotite-replacement origin of the chlorite.

*Other högbomite occurrences in the Strangways Range*

*Harry Creek copper prospect.* A suite of rocks very similar to those at Johannsen's Phlogopite Mine occur at this locality (fig. 1). The essential difference, however, is that the original granulite facies metamorphism of these polymetamorphic rocks was lower. Rocks of basaltic composition are amphibolites (hornblende–diopside–plagioclase), and orthopyroxene only occurs in some of the cordierite–spinel–gedrite rocks. Sapphirine has not been found. Some retrograde staurolite is present in cordierite.

Högbomite is not common. It occurs as a few small chestnut-brown grains exsolved from opaque iron oxides. Some of the original iron oxides must have been very rich in both  $Al_2O_3$  and  $TiO_2$ , for some opaque masses have given rise to exsolved or secondary plates of corundum or grains of pale green spinel and högbomite or both. Some of the spinels have been found to be rich in zinc. Chemical analyses of these högbomites are not available.

In one of the spinel–cordierite rocks (no. H240) very small magnetite cubes and staurolite prisms have exsolved from large magnesian cordierite grains. In some cases högbomite is set between these exsolved grains in such a way as to indicate that the magnetite and staurolite are isofacial with the högbomite.

It will be recalled that at Johannsen's Phlogopite Mine staurolite is found in rocks from the same outcrop as the zincian högbomite. At that locality it is suspected that högbomite is isofacial with staurolite.

*North-east of Yambah Station.* About 14 km north-east of Yambah some coarse sillimanite–magnetite–cordierite rocks are found to contain a secondary hypersthene–sillimanite assemblage. The opaque Fe oxides commonly have exsolved pale green spinel and corundum, and a few small grains of chestnut-brown högbomite have developed within the spinel, presumably by exsolution.

*Woolanga bore region.* Recent work has revealed högbomite in the Woolanga bore region (fig. 1). Its occurrence is similar to that of the Harry Creek copper prospect, and probe analyses of two zincian högbomites have been recorded (Woodford and Wilson, 1976). The analyses are incomplete, but high ZnO values (5 to 10 %) are estimated.

*Conclusions*

The högbomites of the Strangways Range have formed in two distinct ways: by exsolution from highly metamorphosed aluminous, iron–titanium oxides; and by a hydration of (mainly) spinel and biotite under moderate to high amphibolite facies conditions.

*Acknowledgements.* The chemical analyses were done by Dr. G. Langthaler, the X-ray analyses by A. S. Bagley, and the mineral separates were prepared by N. Fanning.

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**APPENDIX.** The chemical analysis of h gbomite was done on 0.2 g by Dr. G. Langthaler. The great resistance to dissolution of this refractory mineral was overcome by use of twice the normal amount of sodium carbonate. This is preferred to the use of potassium pyrosulphate as this interferes with the gravimetric determination of  $\text{SiO}_2$  and also the use of atomic absorption where  $[\text{SO}_4]$  ions interfere.

After separation of  $\text{SiO}_2$  (determined gravimetrically) part of the filtrate was used for atomic absorption determinations for which standards were buffered with exactly the same concentration of sodium salt as that of the sample solution.  $\text{MgO}$  was determined gravimetrically, and  $\text{Al}_2\text{O}_3$ , because of its high concentration, was found to be best determined colorimetrically. Total Fe was determined both colorimetrically and volumetrically. Some minor elements were estimated by atomic absorption and others (e.g. Zr, Ga) by X-ray fluorescence.

The most unusual feature about this analysis was the procedure for eliminating oxidation of the finely ground sample during estimation of ferrous iron. A common method for solution of the sample employs a teflon vessel with a stream of  $\text{CO}_2$  passing through while the whole vessel is maintained at a temperature of 250 °C. The  $\text{CO}_2$  normally used is that stored in commercially supplied pressure cylinders. However, it has been found that gases stored in this fashion are sufficiently contaminated with air to produce significant oxidation of ferrous iron in finely ground samples of some minerals. Dr. Langthaler has overcome this by using  $\text{CO}_2$  derived directly from frozen  $\text{CO}_2$  ('dry ice'). The sample is finely ground by pestle and mortar operated in a sealed plastic bag filled with  $\text{CO}_2$ .

*Errata:* Table I, line 22, for  $\epsilon A+B$  read  $\Sigma A+B$   
line 24, for  $\Sigma 1.827 \dots$  read  $\epsilon 1.827 \dots$