Bustamite from Treburland manganese mine, Cornwall, and its paragenesis.

(With Plate XV.)

By C. E. Tilley, Ph.D., F.R.S.
Department of Mineralogy and Petrology, University of Cambridge.

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BUSTAMITE forms an important constituent of the manganese ores of the Treburland mine near Altarnun, Cornwall. The rediscovery of this mineral locality is due to Sir Arthur Russell, who has already presented an account of the rhodonite and tephroite of the mine (Proc. Min. Soc. 1944, p. xix). Since then the writer has noted bustamite and bementite from the same locality (ibid. 1944, p. xxvi), and it is the purpose of the present paper to discuss the composition and paragenesis of this bustamite.

Rhodonite and tephroite form the chief silicate constituents of the manganese ores exposed on the dumps adjacent to the old Treburland mine shaft, but bustamite-bearing assemblages are not uncommon. The minerals associated with bustamite are primarily rhodonite and tephroite, but many of the rocks carry variable amounts of clinopyroxene and less commonly spessartine garnet intergrown with bustamite (pl. XV, figs. 2 and 4).

The mineral is rather readily distinguished from rhodonite by its pale flesh-pink colour and its fibrous character, which is an expression of the better developed cleavages. On exposure, the fresh broken surface of bustamite may lose its delicate pale pink tint, gradually changing to a brownish hue. Coarse-grained specimens of bustamite, an inch or more in length, carrying dispersed clinopyroxene and associated with fine rhodonite and coarse-granular tephroite occur in some abundance.

In their fibrous character and general physical and optical properties the bustamites show much resemblance to wollastonite, with which the mineral has indeed been grouped by a number of investigators. The studies, particularly of Sundius,[1] and later the evidence of X-ray data, support the view that the bustamites are triclinic manganese-wollastonite solid solutions.

The cleavages of the Treburland bustamites can be correlated with those recognized in wollastonite, namely *a* (100), *c* (001), *v* (101), *t* ($\bar{1}01$), if for convenience we retain the old monoclinic orientation of wollastonite. These four cleavages can all be identified in the cross-sections of the fibrous crystals. Twinning, though not common, corresponds as in wollastonite to (100).

Like the analogous iron-wollastonites,[2] the bustamites can be distinguished by their extinction-angles in sections perpendicular to the zone of cleavages; α': (100) = 47° is a common value for the Treburland bustamites, thus con-

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[1] N. Sundius, Amer. Min., 1931, vol. 16, pp. 411–429, 488–518. [M.A. **5**-143.]

[2] C. E. Tilley, Min. Mag., 1937, vol. 24, pp. 569–572.

siderably greater than the value for pure wollastonite, α': (100) = 32°. Sections perpendicular to the acute bisectrix (α) show γ to the trace of cleavage 29–30°, and a strong dispersion of the optic axes $v > r$ is visible. The optic axial angle is always small, though variable: values of 2V 30–35° are common though even lower angles have been recorded.

To obtain closer knowledge of the composition of the Treburland bustamite, the mineral has been isolated and analysed from a coarse clinopyroxene-bustamite assemblage containing only accessory rhodonite and spessartine garnet. The associated pyroxene has also been isolated and analysed. The results of these two analyses have been set down in tables I and II and the analyses computed to molecular percentages of $CaSiO_3$, $MnSiO_3$, $FeSiO_3$, and $MgSiO_3$. Both analyses have been carried out by Geochemical Laboratories.

TABLE I. Analysis of bustamite, Treburland manganese mine, Cornwall.

	Analysis.	Metal atoms on basis of 6 oxygens.		Mol. %.
SiO_2	46·32	1·966	2·00	$FeSiO_3$ ... 15·35
Al_2O_3	1·02	0·051		$MnSiO_3$ ... 47·70
Fe_2O_3	nil	—	2·01	$MgSiO_3$ ... 2·81
FeO	8·63	0·305		$CaSiO_3$ ... 34·14
MnO	26·50	0·950		Ca: (Mg,Fe): Mn =
MgO	0·88	0·056		34·14: 18·16: 47·70
CaO	14·98	0·680		
TiO_2	0·03			
H_2O+	1·05			
H_2O-	0·24			
	99·65			

The optical properties of the two analysed minerals are:

	α.	β.	γ.	2V.	Sp. gr.
Bustamite	1·692	1·705	1·707	2Vα 35°	3·425
Clinopyroxene (Manganhedenbergite)	1·710	1·720	1·736	2Vγ 60°	3·460

The analysis of table I shows that the bustamite is one of the lime-poor varieties, most comparable among existing analysed bustamites with one from Långban

TABLE II. Analysis of manganhedenbergite, Treburland manganese mine, Cornwall.

	Analysis.	Metal atoms on basis of 6 oxygens.		Mol. %.
SiO_2	48·79	1·959	2·00	$FeSiO_3$ ... 20·73
Al_2O_3	1·32	0·063		$MnSiO_3$ ... 16·24
Fe_2O_3	nil	—	2·01	$MgSiO_3$ ... 16·85
FeO	12·36	0·412		$CaSiO_3$ ... 46·18
MnO	9·53	0·323		Ca: (Mg,Fe): Mn =
MgO	5·56	0·335		46·18: 37·58: 16·24
CaO	21·35	0·918		
TiO_2	0·09			
H_2O+	0·84			
H_2O-	0·24			
	100·08			

discussed by Hey[1] and Sundius. From all previously analysed bustamites (Långban and Franklin Furnace) it differs by its higher FeO content.

The change in optical properties with change in composition of bustamites has been carefully studied by Sundius and it will suffice here if we compare our bustamite with those of Sundius, comparing for convenience the value of the β index of refraction. The values are set down below and incorporated in the graph of fig. 1, showing a rather striking correlation of the β index with the sum of (Fe+Mn).

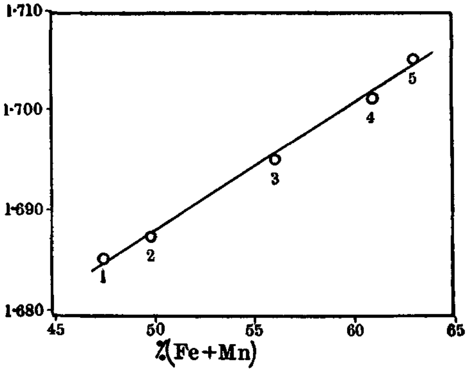

FIG. 1. Variation of refractive index β in the bustamite series, plotted against the sum of Fe+Mn.

	β.	(Fe, Mn).
1. $(Mn_{47\cdot5}\ Fe_{0}\ )\ (Ca_{49\cdot2}\ Mg_{3\cdot2})$	1·685	47·5
2. $(Mn_{49\cdot2}\ Fe_{0\cdot6})\ (Ca_{48\cdot6}\ Mg_{1\cdot5})$	1·687	49·8
3. $(Mn_{55\cdot3}\ Fe_{0\cdot8})\ (Ca_{40\cdot2}\ Mg_{3\cdot7})$	1·695	56·1
4. $(Mn_{57\cdot8}\ Fe_{3\cdot2})\ (Ca_{33\cdot1}\ Mg_{5\cdot9})$	1·701	61·0
5. $(Mn_{47\cdot7}\ Fe_{15\cdot3})\ (Ca_{34\cdot1}\ Mg_{2\cdot8})$	1·705	63·0

1–4, Sundius, loc. cit., p. 518. 5. Bustamite, Treburland mine.

The clinopyroxene associated with the bustamite proves to be a manganhedenbergite, not only richer in iron but also in magnesia. The relationship in composition of the pair can be conveniently represented in a triangular plot (CaO : MnO : FeO+MgO) as in fig. 2, where the points of the two analyses are joined by a tie line. In this plot are also given the composition of analysed manganhedenbergites, schefferites, bustamites, and a number of johannsenites, distinguished as indicated below the figure. The clinopyroxene-bustamite association is a paragenesis of considerable interest.

Bowen, Schairer, and Posnjak[2] have shown that hedenbergite and johannsenite both show inversions to high-temperature forms which are respectively iron-wollastonite solid solutions and a bustamite. Of these, hedenbergite has the higher inversion temperature at 965° C. The determination of the johannsenite inversion was carried out on an Italian johannsenite described by Schaller,[3] the lowest temperature of its inversion being placed at 830° C. The composition of this johannsenite appears to have been close to the ratio CaO : MnO = 1 : 1.

[1] M. H. Hey, Min. Mag., 1929, vol. 22, pp. 193–205.

[2] N. L. Bowen, J. F. Schairer, and E. Posnjak, Amer. Journ. Sci., 1933, ser. 5, vol. 26, pp. 271, 275. [M.A. 5–454.]

[3] W. T. Schaller, Amer. Min., 1939, vol. 23, p. 575. [M.A. 7–222.]

It is clear from the plot that the bulk composition of the assemblage of the Treburland rock, lying on the line BH is within the field both of Fe-Mn-wollastonite solid solutions (bustamites) and of clinopyroxenes (manganhedenbergite-johannsenite solid solutions).

It would appear that at the highest temperatures material of this bulk composition could exist as a single Fe-Mn-wollastonite phase (cf. vogtite in slags), or at lower temperatures as a single clinopyroxene phase.

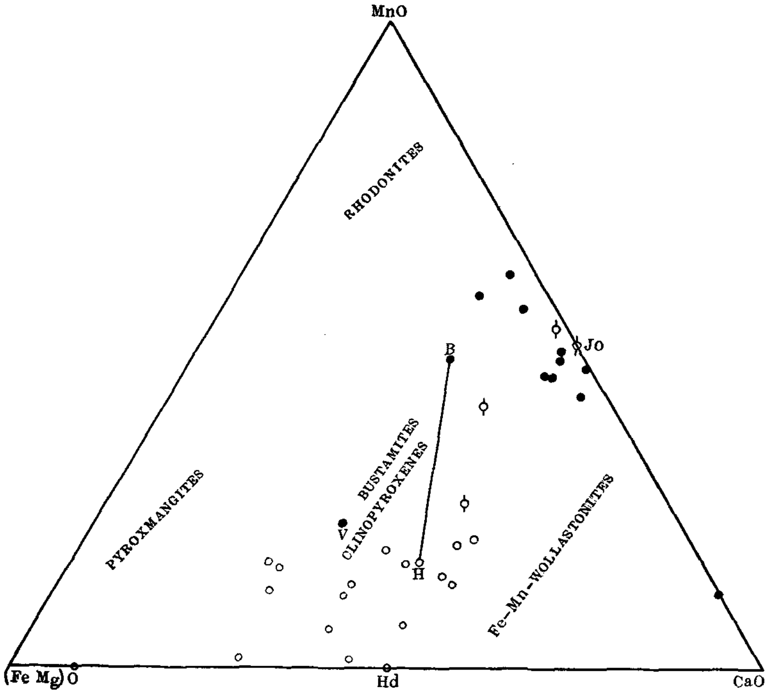

Fig. 2. Plot of the composition (mol. %) of the analysed bustamite (B) and manganhedenbergite (H) from Treburland manganese mine, and of allied minerals. Hedenbergites, manganhedenbergites, and schefferites—circles; johannsenites—barred circles; wollastonite solid solutions, including bustamites—dots. V = vogtite.

At Treburland the temperature conditions of metamorphism appear to have been intermediate—in a temperature region where both phases have crystallized side by side.

The existence of bustamite at ordinary temperatures shows that the bustamite →clinopyroxene inversion may be a sluggish one, and the preservation of iron-bearing wollastonites in rocks (Tilley, loc. cit.) points to a similar conclusion as regards the unmixing of the iron analogues.[1] If the association bustamite-clinopyroxene can be regarded as an equilibrium one at the temperature of its formation we may suppose that the effective metamorphism was accomplished

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[1] This observation in an endogeneous contact-zone (Scawt Hill) has now been extended to a contact skarn carrying iron-wollastonites associated with hedenbergites.

in the solid solution inversion interval which separates an α and β region in the sub-solidus of the complex system represented at Treburland (cf. the inversion relations obtaining in the simpler artificial system $CaSiO_3$–$FeSiO_3$–β-$CaSiO_3$ solid solution–hedenbergite–$FeSiO_3$ solid solution, Bowen *et al.*, loc. cit., p. 213). It is of interest, therefore, to note that the low-temperature phase, the clinopyroxene, is relatively enriched in (Fe+Mg), i.e. in the hedenbergite and diopside components.

The grade of metamorphism of the Treburland assemblages of the system CaO–MnO–SiO_2–CO_2 is revealed by the co-existing phases of fig. 3 (*a*), except

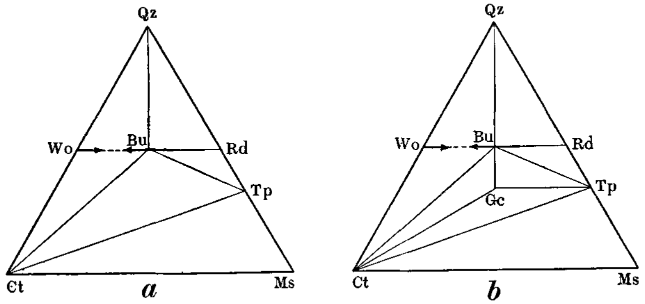

Fig. 3. Assemblages of the system CaO–MnO–SiO_2 in higher grades of metamorphism, 3*a* (Treburland), 3*b* (Franklin Furnace). Qz = quartz, Wo-Bu, wollastonite-bustamite solid solutions, Rd = rhodonite, Tp = tephroite, Ms = manganosite, Gc = glaucochroite, Ct = calcite. (Projected from the quaternary system with CO_2 at the apex of the tetrahedron.)

that we may note that manganosite has so far not been recorded. The bustamite assemblages are:

1. Bustamite-rhodonite-tephroite,
2. Bustamite-tephroite-calcite[1] (manganocalcite).

The existence of wollastonite-bustamite solid solutions is indicated by the thickened line. The hiatus shown along the Wo–Bu join indicates merely that existing analyses do not wholly cover the wollastonite-bustamite region; nevertheless it seems probable that this part of the series is unbroken.

On the rhodonite side it is clear that solid solution is limited, a distinct rhodonite phase with its own range of solid solution extending some way towards Bu from the point Rd.

These assemblages are in part depicted in the photomicrographs of pl. XV. The calcite of fig. 1, associated with tephroite, has ω 1·675 corresponding to 10 mol. % of $MnCO_3$ in solid solution, but this is a maximum figure which takes no account of the probable small content of $FeCO_3$. In fig. 3 calcite, tephroite, and bustamite are seen in association, while in fig. 5 coarse bustamite is associated with granular tephroite.

Glaucochroite, the manganese analogue of monticellite, is recorded among the manganese silicate assemblages of Franklin Furnace, New Jersey, where it is associated, among other minerals, with tephroite. The appearance of glaucochroite in the system doubtless corresponds with an advanced, higher tempera-

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[1] The calcite phase is more strictly a solid solution containing small amounts of $MnCO_3$.

ture, stage of metamorphism, one of increasing decarbonation. As fig. 3 (*b*) indicates, it can be considered as deriving by a reaction between a bustamite phase, tephroite, and calcite, thus:

$$\underset{\text{Bu}}{CaMnSi_2O_6} + \underset{\text{Tp}}{Mn_2SiO_4} + \underset{\text{Ct}}{2CaCO_3} \rightleftarrows \underset{\text{(Gc)}}{3CaMnSiO_4} + 2CO_2$$

The equilibrium assemblages at higher temperatures are then:

Glaucochroite-tephroite-calcite [CO_2],
Glaucochroite-bustamite-calcite [CO_2],
Glaucochroite-tephroite-bustamite [CO_2].

With the incoming of glaucochroite, the high-water mark of metamorphism as revealed thus far in manganese silicate contact-rocks seems to be attained.

In conclusion, the writer desires to express his indebtedness to Sir Arthur Russell, who first introduced him to the Treburland metamorphic rocks.

EXPLANATION OF PLATE XV.

Rocks from Treburland manganese mine, Cornwall.

Magnification 16 diameters.

FIG. 1. Tephroite-calcite-rock.

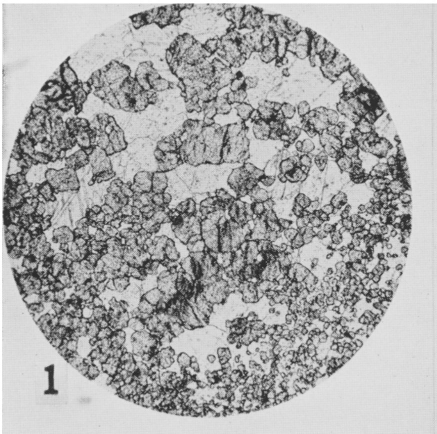
FIG. 2. Bustamite-tephroite-rock with areas rich in clinopyroxene. Two large porphyroblasts of clinopyroxene separated by granular tephroite. Bustamite fringes the clinopyroxene crystal on the left side of the photograph.

FIG. 3. Junction of tephroite-calcite-rock with granular bustamite-rock. Larger crystal of bustamite surrounded by tephroite and calcite (left centre).

FIG. 4. Spessartine-bustamite-rock. Isolated crystals of spessartine garnet in fibrous bustamite.

FIG. 5. Coarse bustamite-tephroite-rock. Above, single crystal of bustamite; below, tephroite, section cut $\perp$ γ showing (010) cleavage; centre, wollastonite-like cross-section of bustamite, some calcite.

FIG. 6. Radiating sheaves of bementite in vein in rhodonite-rock. Idioblastic rhodonites of Pajsberg habit enclosed in bementite.



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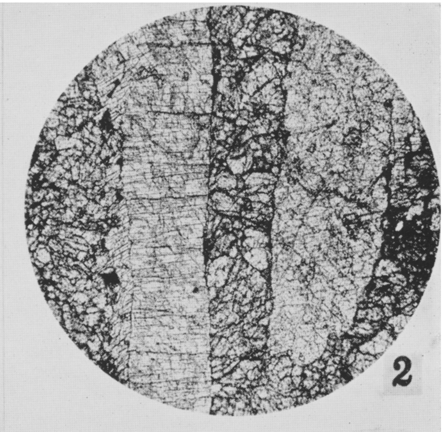

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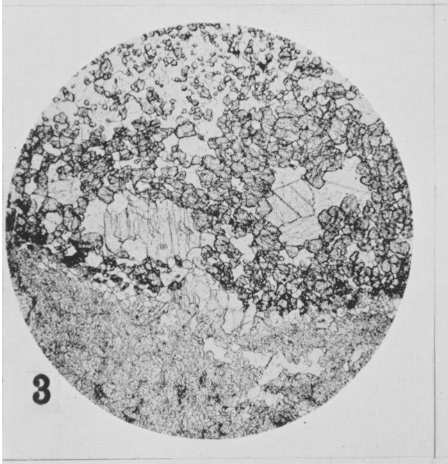

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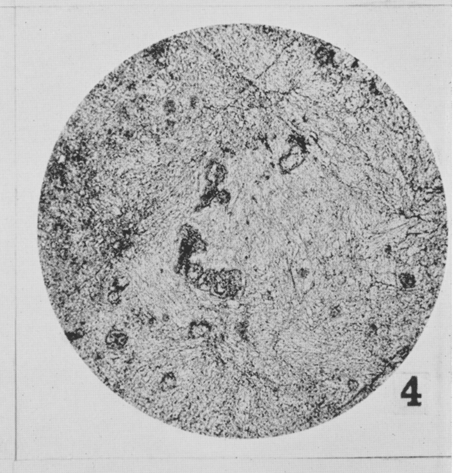

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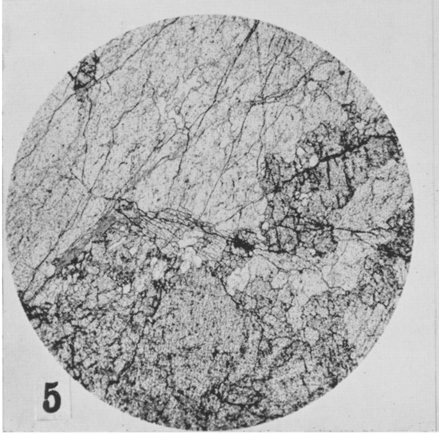

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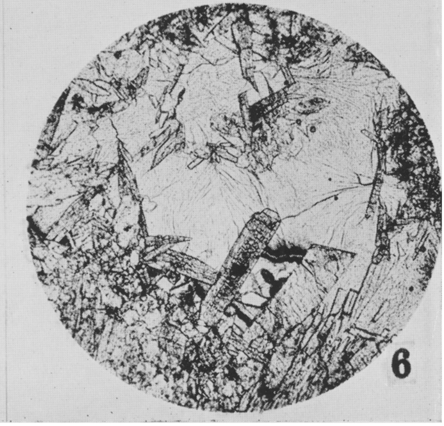

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C. E. Tilley: Bustamite, etc., from Treburland mine, Cornwall.