

Almandine from Botallack, Cornwall.

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WELL-CRYSTALLIZED icositetrahedral garnets from Botallack, Cornwall, are preserved in most British mineral collections, but they have previously not been systematically examined. The original specimens were discovered in 1821 by a St. Just miner who dealt in minerals, and the occurrence is first referred to by Carne¹ in his paper 'On the mineral productions and the geology of the parish of St. Just' as follows: 'About six months ago, a mass of beautiful garnets, of a deep red colour, was found imbedded in the rock, not far from low water mark at the foot of Chycornish Carn, about a quarter of a mile south of Botallack. Some of the crystals were larger than hazel-nuts, and most of them were twenty-four sided. Some specimens of a very superior order were procured, each having from one to two hundred crystals on its face.'

The rocks of the locality are hornfelses in the aureole of the Land's End granite and consist of metamorphosed greenstones in which the garnets occur in veins. Mr. A. Russell, who has succeeded in discovering the original spot² where these garnets were obtained, states that all the garnet specimens have been removed, save for traces. There are, however, numerous specimens of the garnets with their associated matrix in the Carne collection preserved at Cambridge.

The home of these garnets is a biotite-rich layer of the altered greenstones which have suffered strong metasomatic metamorphism with removal of CaO and addition of K₂O and FeO, the biotite layer passing out into a zone rich in grunerite and in places also in cordierite. The associated rock is a metasomatic variant of the cordierite-

¹ J. Carne, Trans. Roy. Geol. Soc. Cornwall, 1822, vol. 2, p. 309.

² Near low water mark on the cliffs close to Zawn a Bal, between the Crowns and Wheal Edward.

anthophyllite-rocks described by Tilley and Flett¹ from Kenidjack.

The petrography of this rock and the significance of the garnet paragenesis will be dealt with in a later communication by Prof. Tilley.

The garnet crystals are icositetrahedra (211) varying in size up to a diameter of 1.5–2 cm., the faces being striated parallel to the intersections of possible dodecahedra. In some examples very small faces of (110) truncate the corners of (211). The crystals are of a dark red colour, and the larger ones are crowded with inclusions most of which are of biotite or more rarely grunerite.

Material for chemical analysis² was obtained by picking out individual crystals which were crushed, most of the inclusions removed by flotation in methylene iodide, and a pure sample finally obtained by hand-picking under a binocular microscope. An analysis was made by the writer and the following results obtained.

SiO ₂	35.58 %
TiO ₂	trace
Al ₂ O ₃	21.94
Fe ₂ O ₃	none
FeO	38.54
MnO	0.70
MgO	0.68
CaO	1.68
H ₂ O (below 105° C.)	0.12
	<hr/>
	99.24

Recalculating this analysis in terms of mineral molecules :

Almandine	89.00 %
Spessartine	1.65
Pyrope	2.29
Grossular	4.51
Corundum	1.79
Quartz	0.06
Water	0.12
	<hr/>
	99.42

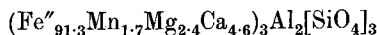
Considering the garnet molecules alone and raising to a summation of 100 we have

Almandine	91.33
Spessartine	1.69
Pyrope	2.35
Grossular	4.63

¹ C. E. Tilley and J. S. Flett, Summary of Progress, Geol. Surv. of Great Britain, 1930, for 1929, pp. 24–40. [Min. Abstr., vol. 4, p. 402.]

² The specimen analysed was from the S. G. Perceval collection in the Department of Mineralogy and Petrology, Cambridge.

This gives us the following formula for the garnet molecule :



The theoretical composition of pure almandine corresponding to the formula $\text{Fe}_3\text{Al}_2[\text{SiO}_4]_3$ is :

SiO_2	...	...	...	...	36.15 %
Al_2O_3	...	...	...	...	20.51
FeO}	...	...	...	...	43.34

The above analysis and calculated formula show the unusually high proportion of almandine in the Botallack garnet. The following analyses are of almandine from other localities and of comparable purity. The percentage of the different garnet molecules has also been calculated from each analysis.

	I.	II.	III.	IV.	V.
SiO_2	38.36	37.39	37.25	38.63	39.66
Al_2O_3	18.03	20.72	19.43	21.81	19.66
Fe_2O_3	2.02	0.83	3.29	1.47	—
FeO	36.53	36.37	35.45	29.38	39.68
MnO	0.50	0.86	1.24	1.90	1.80
MgO	2.29	3.85	1.13	4.81	—
CaO	1.20	0.41	2.51	1.57	—
etc.	1.53	0.16	—	—	—
	<u>100.46</u>	<u>100.59</u>	<u>100.30</u>	<u>99.57</u>	<u>100.80</u>
Almandine ...	86.6	83.9	85.1	72.8	95.7
Spessartine ...	1.2	2.0	3.0	4.8	4.3
Pyrope	8.3	12.9	2.1	17.3	—
Grossular ...	—	—	—	0.2	—
Andradite ...	3.9	1.2	9.8	4.9	—

I. Thackaringa, New South Wales. Anal. W. A. Greig in G. W. Card, *Rec. Geol. Surv. N.S.W.*, 1920, p. 181 [M.A. 1-335]. Sp. Gr. 4.150.

II. Falun, Sweden. Anal. M. Bendig in G. Menzer, *Zeits. Krist.*, 1929, vol. 69, p. 360 [M.A. 4-111]. Sp. gr. 4.188 ± 0.002 .

III. Ceylon. Anal. M. Seebach, *Inaug. Diss. Heidelberg*, 1906; *Centralbl. Min.*, 1906, 774. Sp. gr. 4.040, n 1.7779.

IV. Odenwald. Anal. E. Rost-Hoffmann in G. Klemm, *Notizbl. Ver. Erdk. Darmstadt*, 1919, Folge V, Heft 4, p. 20. Sp. gr. 3.9502, n_{Na} 1.7964. Like the Botallack garnet, this occurs within a thermal aureole.

V. Falun, Sweden. Anal. W. Hisinger, *Journ. Chem. Phys.* (Schweigger), 1817, vol. 21, p. 258.

It will be seen that the Botallack garnet shows a higher proportion of almandine than any of the others quoted with the exception of no. V (Falun) with which comparison is unsatisfactory in that

FeO and Fe_2O_3 are not separated and neither MgO nor CaO determined.¹

The Botallack analysis shows that there is an excess of alumina over that required by the fundamental formula. This is reflected by the presence of corundum in the calculated mineral composition. The ratio $\text{RO} : \text{R}_2\text{O}_3 : \text{SiO}_2$ is 2.76 : 1 : 2.76. This divergence from the accepted 3 : 1 : 3 ratio may perhaps be best explained by the hypothesis that aluminium replaces both iron and silicon in the crystal structure. A similar suggestion has been made by Gossner² who found in three analyses of almandine from Irschenrieth, Ober-Pfalz, that the ratios were :

$$\begin{aligned} & 2.61 : 1 : 2.66 \\ & 2.61 : 1 : 2.71 \\ \text{and } & 2.51 : 1 : 2.69 \end{aligned}$$

These show an excess of silica as well as of alumina. The excess silica in the Botallack analysis is negligible. In the analyses of garnet previously quoted the ratios are :

I	...	...	3.13 : 1 : 3.37
II	...	...	2.98 : 1 : 3.00
III	...	...	2.76 : 1 : 2.94
IV	...	...	2.61 : 1 : 2.89
V	...	...	2.98 : 1 : 3.42

Of these analyses nos. I to IV are the only ones with which we can justifiably make any comparison, as in no. V FeO and Fe_2O_3 are not separated and it is in other ways incomplete. The complete analysis of I also shows the presence of small amounts of alkalis, phosphorus, and titanium. The alkalis and phosphorus are presumably present as impurities or inclusions, which makes consideration of the analysis difficult for our present purpose.

The analysis of the Botallack garnet, the three given by Gossner, and nos. II, III, and IV above are thus deemed suitable for considera-

¹ Other analyses, having a somewhat lower percentage of almandine, but which are for various reasons unsatisfactory for purposes of comparison, are recorded as follows :

Wicklow, Ireland. J. W. Mallet, Journ. Geol. Soc. Dublin, 1850, vol. 4, p. 275.

Redding, Connecticut. Anal. F. L. Sperry in W. E. Ford, Amer. Journ. Sci., 1915, ser. 4, vol. 40, p. 34.

Brena, Sweden. Anal. J. F. Bahr, Öfvers. Vetenskaps-Akad. Stockholm, 1845, vol. 1 (for 1844), p. 93.

² B. Gossner, Beitrag zur Stöchiometrie der Silicate. Zeits. Angewandte Chem., 1929, vol. 42, pp. 175-178. [M.A. 4-198.] Also B. Gossner and E. Ilg, Centralbl. Min., Abt. A, 1932, pp. 1-12. [M.A. 5-528.]

tion, and in all of them, with the possible exception of no. II, alumina is found to be in excess of that required by the fundamental formula $3\text{RO} \cdot \text{R}_2\text{O}_3 \cdot 3\text{SiO}_2$. This can be more clearly shown if the analyses are recalculated in terms of the number of atoms of each kind in the molecule. In column (3) of the following table some Al is allotted where necessary to the Si group, and when this is done the small amount of Fe''' usually present is transferred to the $(\text{Mg}, \text{Fe}'' \dots)$ group, or if no Fe''' is available a corresponding amount of Al is similarly treated. It will be seen that in such a way a close approximation to the ideal composition is obtained.

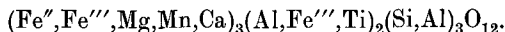
Locality.		(1). Per cent. by weight.	(2). Number of metal atoms on basis of 12 O.	(3). Arrange- ment in groups.	(4). Ideal com- position.	
Botallack	SiO_2	35.58	2.94	$\left. \begin{array}{l} 0.06 \\ 2.01 \\ 0.06 \end{array} \right\}$	3.00	3
	Al_2O_3	21.94	2.13			
	Fe_2O_3	—	—			
		MgO	0.68	0.08	$\left. \begin{array}{l} 2.99 \\ 3 \end{array} \right\}$	3
		FeO	38.54	2.65		
		MnO	0.70	0.05		
		CaO	1.68	0.15		
Irschenrieth, Ober-Pfalz*	SiO_2	36.10	2.92	$\left\{ \begin{array}{l} 0.08 \\ 2.04 \end{array} \right\}$	3.00	3
	Al_2O_3	22.22	2.12			
		Fe_2O_3	1.24	0.08	$\left. \begin{array}{l} 2.95 \\ 3 \end{array} \right\}$	3
		MgO	1.21	0.15		
		FeO	29.75	2.01		
		MnO	6.86	0.47		
		CaO	2.81	0.24		
Irschenrieth, Ober-Pfalz	SiO_2	36.24	2.94	$\left\{ \begin{array}{l} 0.06 \\ 2.08 \end{array} \right\}$	3.00	3
	Al_2O_3	22.25	2.14			
		Fe_2O_3	0.79	0.05	$\left. \begin{array}{l} 2.89 \\ 3 \end{array} \right\}$	3
		MgO	1.31	0.16		
		FeO	28.80	1.95		
		MnO	8.81	0.60		
		CaO	1.49	0.13		
Irschenrieth, Ober-Pfalz	SiO_2	36.79	2.95	$\left\{ \begin{array}{l} 0.05 \\ 2.04 \end{array} \right\}$	3.00	3
	Al_2O_3	22.11	2.09			
		Fe_2O_3	1.85	0.12	$\left. \begin{array}{l} 2.90 \\ 3 \end{array} \right\}$	3
		MgO	1.54	0.18		
		FeO	27.61	1.85		
		MnO	9.05	0.61		
		CaO	1.74	0.14		

* The three almandines from Irschenrieth were analysed by M. Arm and F. Spielberger.

Locality.		(1).	(2).	(3).	(4).
		Per cent. by weight.	Number of metal atoms on basis of 12 O.	Arrangement in groups.	Ideal composition.
Falun	SiO ₂	37.39	3.00	3.00	3
	Al ₂ O ₃	20.72	1.95	2.01	2
	TiO ₂	0.16	0.01		
	Fe ₂ O ₃	0.83	0.05	2.98	3
	MgO	3.85	0.46		
	FeO	36.37	2.43		
	MnO	0.86	0.06		
CaO	0.41	0.03			
Ceylon	SiO ₂	37.45	3.03	3.04	3
	Al ₂ O ₃	19.43	1.85	2.05	2
	Fe ₂ O ₃	3.29	0.20		
	MgO	1.13	0.14	2.84	3
	FeO	35.45	2.40		
	MnO	1.24	0.08		
	CaO	2.51	0.22		
Odenwald	SiO ₂	38.63	3.04			3.04	3
	Al ₂ O ₃	21.81	2.02	2.11*	2
	Fe ₂ O ₃	1.47	0.09		
	MgO	4.81	0.57	2.76*	3
	FeO	29.38	1.93		
	MnO	1.90	0.13		
	CaO	1.57	0.13		

* These discrepancies are larger than in the other cases, and may be due to possible impurities in the material analysed, a fact which Klemm recognizes.

Several interesting features are shown by the analyses when stated in this form. It is evident, for instance, that the Falun almandine is well represented by the formula $(\text{Fe}, \text{Mg}, \text{Mn}, \text{Ca})_3(\text{Al}, \text{Fe}, \text{Ti})_2\text{Si}_3\text{O}_{12}$. It would also appear probable that in many cases a small amount of silicon is replaced by aluminium¹ and that this is accompanied by the entry of small amounts of ferric iron into the (Fe, Mg . . .) group. The composition of such garnets may therefore be expressed as



The refractive index of the Botallack garnet was determined as $n = 1.808 \pm 0.002$. The method used was that of immersion of the grains in solutions of AsBr₃ and AsS in methylene iodide as suggested by Borgström,² and the subsequent determination of the refractive index of the liquid in a hollow prism on a goniometer.

¹ F. Machatschki, Zeits. Krist., 1930, vol. 73, pp. 133, 134. [M.A. 4-277.]

² L. H. Borgström, Compt. Rend. Soc. Géol. Finlande, 1929, no. 2, p. 3. [M.A. 4-449.]

The specific gravity as determined by flotation in saturated solutions of thallium formate is 4.22. According to Ford's¹ diagrams a garnet of the Botallack composition should have a refractive index of about 1.82 and a specific gravity of about 4.2. The figures for pure almandine are given as n 1.830 and sp. gr. 4.250.

Eskola² gives a diagram for the determination of the approximate composition of garnets from a knowledge of the refractive index alone. From this the composition of the Botallack garnet should be about $\text{Fe}_{82}\text{Mg}_{12}\text{Ca}_6$, i.e. almandine 82 % by weight, pyrope 12 %, and grossular 6 %. In this case, there is a rather poor correspondence between the chemical composition and the physical properties as suggested by Ford and Eskola. It is clear that these simple physical data do not at present always afford a reliable means of accurately diagnosing the chemical composition of garnets, and further work in correlating the physical properties with accurate analyses is required.

The writer wishes to express his thanks to Prof. C. E. Tilley at whose suggestion and under whose supervision this work was undertaken.

¹ W. E. Ford, Amer. Journ. Sci., 1915, ser. 4, vol. 40, p. 42. [M.A. 2-37.]

² P. Eskola, On the eclogites of Norway. Vidensk. Skrift. Kristiania, 1921, no. 8, p. 9. [M.A. 2-313.]
