THE RELATION BETWEEN CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES IN THE GARNET GROUP

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In 1915, W. E. Ford[1] showed that the optical and physical properties of a garnet were directly dependent on its chemical composition, so that its refractive index and specific gravity could be calculated quite accurately from the chemical analysis. In the period of twenty-one years since Ford's paper was published, a great many analyses of the garnets have appeared, and the optical and physical properties of many of those analyzed have been determined. As these analyses had been compiled and studied in the course of the revision of the sixth edition of Dana's System of Mineralogy, it seemed worthwhile to bring Ford's work up to date.

It should be pointed out that Ford's calculations were based on the assumption that all garnets conformed to the ideal group formula, $3RO \cdot R_2O_3 \cdot 3SiO_2$, the analyses studied being recalculated to fit this ideal formula. In recent years, however, x-ray work has led to the belief that isomorphous replacement in a mineral group need not be restricted to atoms of the same valence, an outstanding example being the replacement of Si by Al in the amphiboles.[2] If such replacements occur in the garnet group, Ford's method of calculating compositions would be open to serious objection.

This objection has recently been raised by Alderman,[3] who analyzed a garnet, very nearly pure almandite, and found that the analysis showed considerable deviations from the ideal garnet formula, the molecular ratio obtained being 2.91:1.06:2.92 instead of 3:1:3. Alderman cites several other analyses whose molecular ratios deviate considerably from the ideal. He believes that in these cases, Al replaces both Si and ferrous iron. While such replacements appear possible from a consideration of the atomic radii, there are no theoretical grounds on which to decide whether or not they might be expected to occur in any

[1] Ford, W. E., *Am. J. Sci.*, vol. **40**, p. 33, 1915.
[2] Cf. Warren, *Zeits. Krist.*, vol. **72**, p. 493, 1930.
[3] Alderman, *Min. Mag.*, vol. **23**, p. 42, 1935.

particular mineral. However, a study of the analyses in the literature should shed some light on the frequency and extent of such replacements.

Such a study shows that most of the garnets analyzed conform very closely to the ideal ratio, and that those which do not, including those cited by Alderman, show only limited deviations. Furthermore, with few exceptions, those showing noticeable deviations fall into two groups: garnets containing an appreciable amount of TiO_2, and garnets rich in FeO. There is considerable uncertainty at present as to the rôle of titanium in garnets. The problem has been discussed by Kunitz,[4] who came to the conclusion that Ti replaces Si in these garnets. In nearly all the recent analyses, however, the molecular ratios are high for RO_2 and RO, and low for R_2O_3, which makes plausible the suggestion of Zedlitz[5] that part of the titanium is present in the trivalent state. (Any Ti_2O_3 present would cause a corresponding amount of Fe_2O_3 to be reported as FeO.) In view of this uncertainty, the titaniferous garnets have been excluded from the following discussion.

With only a very few exceptions, the garnets of the second group deviate from the ideal group formula in the same way. All give molecular ratios high in R_2O_3 and low in RO. Every one of the analyses cited by Alderman falls into this group. While this might be taken, following Alderman, to indicate that Al replaces Si and ferrous iron, there is an alternative explanation. It is well known that the accurate determination of ferrous iron in a refractory mineral is extremely difficult.[6] The analysis of an almandite garnet for FeO is very likely to give a low result because of incomplete solution of the mineral or partial oxidation during the necessary preliminary grinding. Thus part of the FeO is likely to be reported as Fe_2O_3. Without denying the possibility that replacements such as those suggested by Alderman may occur in the garnet group, it seems more plausible to ascribe the reported deviations from the ideal group formula to analytical error, particularly in the FeO determination.

It would seem, therefore, that the method of calculation used by Ford is justified. It has been used in the present work, with two modifications. For reasons stated above, the titaniferous garnets have been omitted. However, since so many analyses give small amounts of TiO_2, the upper limit allowed has been somewhat arbitrarily set at 0.50% TiO_2, and these small amounts have been calculated as SiO_2. No correction has been applied for the TiO_2 present, but the error thus introduced is apparently

[4] Kunitz, *Neues Jahrb. Min., Geol., Beil.-Bd.*, **70A**, p. 395, 1936.

[5] Zedlitz, *Zentrabl. Min*, **1935A**, p. 68.

[6] Cf. Hillebrand and Lundell, *Applied Inorganic Analysis*. John Wiley and Sons, New York, **1929**, pp. 769–785.

small. There are as yet insufficient data to evaluate accurately the effect of TiO_2 on refractive index and specific gravity in the garnets, but to judge from the data given by Kunitz,[4] the presence of 0.50% TiO_2 in andradite garnets raises the refractive index approximately 0.004 and the specific gravity approximately 0.005.

The second modification in the calculations was used for analyses high in FeO, with ratios deviating from the ideal. In line with the reasoning given above, sufficient of the Fe_2O_3 reported in the analysis was calculated to FeO to correct the molecular ratio to $3:1:3$. This has the effect of increasing the calculated almandite and grossularite content while decreasing the andradite content. In most cases, the values calculated for refractive index and specific gravity are changed only slightly by this procedure, owing to the fact that the changes are nearly compensatory in effect.

Table 1 below gives a summary of 57 analyses published since 1915 with the calculated compositions and the observed and calculated refractive indices. The values used for the component molecules were those given by Ford:—Pyrope (Py) 1.705, grossularite (Gr) 1.735, spessartite (Sp) 1.800, almandite (Al) 1.830, uvarovite (Uv) 1.870, andradite (An) 1.895. It is apparent that there is excellent agreement between the observed and calculated values, the results in Table 1 furnishing a striking confirmation of Ford's values for the refractive indices of the component garnet molecules. For all 57 analyses, the average difference between observed and calculated refractive indices, disregarding plus and minus signs, is 0.006. In seven cases, Nos. 13, 23, 35, 52, 54, 56, and 57, the difference is greater than 0.010. If these are omitted, the average difference for the remaining fifty analyses is 0.0035, and the algebraic sum of the differences is very nearly zero.

Of these seven analyses, No. 13 is particularly interesting, because its composition is unique. The grossularite-andradite garnets have generally been considered to be only partly miscible with the almandite-spessartite-pyrope garnets, the limit of miscibility usually being placed at 20–30% Gr-An (cf. the diagrams given by Ford). This garnet lies far outside this range. Heritsch makes the interesting suggestion that it may be a double salt like dolomite. If this were the case, it might explain the difference between the observed and calculated values of the refractive index. It should be noted, however, that the unit cell calculated for this garnet by the additive rule agrees very closely with that observed by Heritsch (see No. 4 of Table 2).

TABLE 1. CALCULATED AND OBSERVED REFRACTIVE INDICES, AND COMPOSITIONS OF 57 GARNETS

	Gr	An	Al	Py	Sp	Uv	n calcd.	n obsd.	Diff.
1.	96.60	—	2.06	1.02	0.32	—	1.737	1.734	+.003
2.	96.75	2.27	0.59	—	—	0.39	1.740	1.737	+.003
3.	83.96	10.80	3.63	0.72	0.89	—	1.756	1.748	+.008
4.	87.88	2.03	8.07	1.31	0.71	—	1.745	1.750	−.005
5.	10.31	1.26	27.31	59.83	0.68	0.61	1.746	1.750	−.004
6.	87.29	12.71	—	—	—	—	1.755	1.750	+.005
7.	85.21	12.88	0.52	1.07	0.32	—	1.756	1.752	+.004
8.	80.85	7.88	3.82	7.32	0.14	—	1.749	1.756	−.007
9.	18.74	2.94	28.89	48.72	0.72	—	1.753	1.756	−.003
10.	—	5.75	41.66	52.24	0.35	—	1.767	1.758	+.009
11.	15.17	3.33	36.53	43.78	1.19	—	1.763	1.766	−.003
12.	8.43	5.93	40.98	43.16	1.50	—	1.771	1.766	+.005
13.	35.19	11.24	45.13	7.51	0.92	—	1.794	1.777	+.017
14.	14.17	—	55.35	27.44	3.04	—	1.781	1.782	−.001
15.	24.50	—	54.87	18.05	2.58	—	1.783	1.785	−.002
16.	12.07	—	61.08	25.13	1.72	—	1.786	1.786	.000
17.*	27.29	6.77	50.32	15.53	0.10	—	1.789	1.787	+.002
18.	26.28	6.46	49.12	13.99	4.15	—	1.791	1.787	+.004
19.	7.86	6.22	52.46	32.07	1.39	—	1.786	1.789	−.003
20.	19.58	5.18	57.56	16.09	1.60	—	1.794	1.791	+.003
21.	23.96	1.50	54.17	15.29	5.09	—	1.788	1.792	−.004
22.	9.16	2.61	41.12	6.95	40.16	—	1.802	1.794	+.008
23.	1.36	3.26	10.68	0.85	83.85	—	1.805	1.794	+.011
24.	5.07	—	4.14	1.02	89.77	—	1.797	1.796	+.001
25.	16.44	—	63.99	15.69	3.88	—	1.794	1.797	−.003
26.	22.89	1.22	56.51	1.61	17.76	—	1.802	1.797	+.005
27.	6.95	10.76	61.10	19.80	1.39	—	1.805	1.797	+.008
28.	1.30	1.07	6.53	1.98	89.12	—	1.800	1.800	.000
29.*	—	2.11	73.20	20.37	4.32	—	1.805	1.804	+.001
30.	3.07	0.89	16.89	2.23	76.92	—	1.802	1.805	−.003
31.	5.54	—	32.86	—	61.60	—	1.806	1.805	+.001
32.*	—	2.11	74.89	17.50	5.41	—	1.808	1.806	+.002
33.	10.61	—	73.74	11.03	4.62	—	1.805	1.808	−.003
34.*	6.70	—	52.57	1.91	38.82	—	1.810	1.808	+.002
35.	5.05	—	90.43	2.85	1.67	—	1.821	1.808	+.013
36.*	8.64	—	73.21	10.04	8.11	—	1.807	1.810	−.003
37.	0.67	—	33.84	1.20	64.29	—	1.809	1.811	−.002
38.*	—	5.42	37.86	—	56.72	—	1.816	1.812	+.004
39.	1.26	2.29	15.15	2.03	79.26	—	1.804	1.813	−.009
40.	—	0.82	29.24	0.59	69.35	—	1.809	1.813	−.004
41.*	—	2.88	77.36	14.25	5.51	—	1.812	1.813	−.001
42.*	0.82	—	45.44	1.21	52.54	—	1.812	1.814	−.002
43.*	2.08	—	57.42	3.02	37.48	—	1.813	1.815	−.002
44.	2.74	2.51	83.82	3.50	7.42	—	1.822	1.816	+.006

TABLE 1 (*Continued*)

	Gr	An	Al	Py	Sp	Uv	n calcd.	n obsd.	Diff.
45.*	—	1.39	36.58	3.36	58.67	—	1.809	1.817	−.008
46.*	0.74	—	74.08	5.21	19.97	—	1.817	1.817	.000
47.	—	—	62.98	4.19	32.83	—	1.815	1.818	−.003
48.*	1.01	—	74.12	4.97	19.89	—	1.817	1.818	−.001
49.	—	4.52	74.84	3.89	16.76	—	1.823	1.818	+.005
50.*	0.89	—	85.84	8.76	4.51	—	1.817	1.819	−.002
51.	—	1.48	75.00	7.90	15.63	—	1.816	1.821	−.005
52.	5.20	7.52	—	0.17	0.07	87.04	1.864	1.847	+.017
53.	7.32	1.27	—	2.05	—	89.37	1.857	1.855	+.002
54.	17.05	73.70	7.19	—	2.06	—	1.861	1.88	−.02
55.	—	95.23	1.36	3.36	0.05	—	1.888	1.887	+.001
56.	12.78	68.05	—	5.30	13.87	—	1.851	1.89	−.04
57.	2.56	92.25	—	2.49	2.69	—	1.884	1.92	−.04

Analyses marked* are those in which some Fe_2O_3 has been calculated as FeO. 1. Graham and Poitevin, *Mus. Bull. Geol. Surv. Canada*, 1918, No. 27, p. 45; from Black Lake area, Quebec, G. 3.60. 2. Herdsman quoted by Pabst, *Am. Mineral.*, vol. 21, p. 9, 1936; from Georgetown, California, G. 3.506. 3. Agar and Krieger, *Am. J. Sci.*, vol. 24, p. 77, 1932; from West Redding, Conn., G. 3.62. 4. Hezner quoted by Grubenmann (*Festschrift Dozenten Univ. Zurich*, 1914), *Neues Jahrb. Min. Geol.*, 1916, Bd. I, p. 295; from Maigelstal, Switzerland, G. 3.611. 5. Eskola, *Vid. Skrifter, Mat.-Nat. Klasse*, 1921, No. 8, p. 27; from Rodhaugen, Sondmore, Norway, G. 3.782. 6. Eakins quoted by Cross and Shannon, *Proc. U. S. Nat. Mus.*, vol. 71, art. 18, 1927; from Italian Mt., Gunnison Co., Colorado, G. 3.629. 7. McConnell, *Am. Mineral.*, vol. 18, p. 25, 1933; from Sierra Tlayacac, Mexico, G. 3.567. 8. Bendig quoted by Gottfried, *Chem. Erde*, vol. 5, p. 106, 1930; from Passa del Termine, Adamello, Italy, G. 3.512. 9. Bennett quoted by Tilley, *Min. Mag.*, vol. 24, p. 422, 1936; from Weissenstein, Fichtelgebirge, Bavaria, G. 3.760. 10. Cornelius and Dittler, *Neues Jahrb. Min. Geol.*, Beil.-Bd., 59A, p. 53, 1929; from Val Codera, Sondrio, Italy, G. 3.84. 11. Eskola, *op. cit.;* from near Aurlandsfjord, Norway, G. 3.83. 12. Eskola, *op. cit.;* from Silden, Nordfjord, Norway, G. 3.882. 13. Heritsch, *Zeits. Krist.*, vol. 86, p. 253, 1933; from the Lieserschlucht near Spittal, Carinthia, G. 3.877. 14.–16. Eskola, *op. cit.;* 14. from Tvedestrand, Norway, G. 4.02. 15. from Susselbakke, Mysen, Norway, G. 3.94. 16. from Haugen, Bamle, Norway, G. 3.984. 17. Pabst, *Am. Mineral.*, vol. 16, p. 327, 1931; from Russian River, Cal., G. 3.821. 18. Novacek (*Vestnik Kral Ces. Spol. Nauk*, 1931), *Neues Jahrb. Min. Geol.*, 1934, Bd. I, p. 363; from Ronov, Czechoslovakia, G. 3.980. 19. Thomassen quoted by Eskola, *op. cit.;* from Aardal, Sogn, Norway, G. 3.917. 20. Thomassen quoted by Eskola, *op. cit.;* from Vanelvsdalen, Sondmore, Norway, G. 3.995. 21. Novacek, *op. cit.;* from Ronov, G. 3.981. 22. Fairchild quoted by Ross, *U.S.G.S. Prof. Paper* 179, p. 63; from Ducktown, Tenn. 23. Shannon, *J. Wash. Acad. Sci.*, vol. 17, p. 444, 1927; from Amelia, Va., G. 4.153. 24. Shannon quoted by Ross and Kerr, *Am. Mineral.*, vol. 17, p. 16, 1932; from Bald Knob, N. C. 25. Eskola, *op. cit.;* from Taatø near Kragerø, Norway, G. 4.00. 26. Fairchild quoted by Ross, *op. cit.;* from Ore Knob, N. C. 27. Eskola, *op. cit.;* from Romsdalshorn, Norway, G. 3.97. 28. Otto, *Min. petr. Mitt.*, vol. 47, p. 99, 1935; from Amelia, G. 4.253. 29.–30. Novacek, *op. cit.;* 29. from Krizova hora, Czechoslovakia, G 4.153. 30. from Budislav, Czechoslovakia, G. 4.181. 31. Strock, *Am. Mineral.*, vol. 15, p. 40, 1930; from Avondale, Pa., G. 4.117. 32. Novacek, *op. cit.;* from Krizova hora, G. 4.164. 33. Blix quoted by Du Rietz, *Geol. För. Förh.*, vol. 57, p. 190, 1935; from Muruhatten, Sweden, G. 4.145. 34. Shannon and Gonyer, *J. Wash. Acad. Sci.*, vol. 17, p. 534, 1927; from Gwynns Falls, Md. 35. Alderman, *Min. Mag.*, vol. 23, p. 42, 1935; from Botallack, Cornwall, England, G. 4.22. 36. Novacek, *op. cit.;* from Tabor, Czechoslovakia, G. 4.116. 37. Haschka quoted by Novacek, *op. cit.;* from Susice, Czechoslovakia, G. 4.168. 38. Kokta quoted by Novacek, *op. cit.;* from Drahonin, *Moravia*, G. 4.229. 39. Shannon

Am. Mineral., vol. **11**, p. 35, 1926; from Montgomery Co., Md. 40. Novacek, *op. cit.;* from Puklice near Jihlava, Czechoslovakia, G. 4.211. 41. Burri and Parga-Pondal, *Schweiz Min. petr. Mitt.*, vol. **16**, p. 226, 1936; from Hoyazo, prov. Almeria, Spain, G. 4.201. 42.–43. Novacek, *op. cit.;* 42. from Zoptau, Moravia, G. 4.232. 43. from Hoslau-Nacetin, Czechoslovakia, G. 4.240. 44. Bendig quoted by Gottfried (*Sitzber. Heidelberg Akad. Wiss.* **1930**), *Fortschr. Min.*, vol. **18**, p. 174, 1934; from Adamello, Italy, G. 4.152. 45.–46. Novacek, *op. cit.;* 45. from near Marsikov, Moravia, G. 4.219. 46. from Svatava near Cernovice, Czechoslovakia, G. 4.249. 47. Shannon, *Am. Mineral.*, vol. **7**, p. 171, 1922; from Avon Idaho. 48. Novacek, *op. cit.;* from Krizova hora, G. 4.253. 49. Bendig quoted by Gottfried, *op. cit.* #44; from Adamello, Italy, G. 4.006. 50.–51. Novacek, *op. cit.;* 50. from Kladno, Czechoslovakia, G. 4.233. 51. from Pribyslavice near Caslav, Czechoslovakia, G. 4.246. 52. Lokka quoted by Eskola, (*C. R. Soc. Geol. Finlande*, No. 7, p. 26, **1933**), *Min. Abs.*, vol. **6**, p. 46, 1933; from Outokompu, Finland, G. 3.75. 53. Borgström, (*Geol. För. Förh.*, vol. **23**, 569, 1902), *Zeits. Krist.*, 37, 284, 1903; from Kuusjärvi, Finland, G. 3.772. 54. Kunitz, *Neues Jahrb. Min. Geol., Beil.-Bd.*, **70A**, p. 395, 1936; from Risör, G. 3.762. 55. Sanero (*Per. Min. Roma*, vol. **6**, p. 213, 1935), *Neues Jahrb. Min. Geol.*, **1936**, Bd. I, p. 155; from Val d'Aosta, Italy, G. 3.826. 56.–57. Jenkins and Bauer quoted by Palache, *U.S.G.S. Prof. Paper* **180**, 1936; from Franklin, N. J.

In all, eighty-five analyses were found, published since 1915 and accompanied by specific gravity determinations. The differences between calculated and observed values were greater than 0.1 in nine cases, the observed values being low in each case. For the remaining seventy-six, the average difference between calculated and observed values was 0.026, disregarding plus and minus signs, and the algebraic sum of the differences was practically zero. The values used for the garnet molecules were:—Pyrope 3.510, grossularite 3.530, spessartite 4.180, almandite 4.325, andradite 3.835 and uvarovite 3.775. The first three of these are identical with the specific gravities given by Ford, but those given here for almandite and andradite are somewhat higher. The recent determinations on garnets high in almandite and andradite agree very well with the new values. The specific gravity of the uvarovite molecule was calculated from two analyses only (Nos. 52 and 53 of Table 1).

As a check, the specific gravities of the garnets were also calculated from the x-ray data in the literature through the relation

$$G = \frac{Z \times \text{mol. wt.} \times 1.65 \times 10^{-24}}{a_0{}^3}$$

where Z, the number of molecules in the unit cell, is eight for the garnets. Table 2 gives the compositions and the observed and calculated unit cells for nineteen garnets. A large number of x-ray determinations by Stockwell and some by Menzer have been omitted because the sample used for x-ray study was not analyzed. It is well known that even garnets from the same locality may vary considerably in composition. However, Nos. 18 and 19 of Table 2 were included although the analyses were not made on the material that was used for x-ray study, because they are close to pure andradite and pyrope, respectively, and because the analyses of garnets from these localities show little variation.

TABLE 2. CALCULATED AND OBSERVED UNIT CELLS, AND COMPOSITIONS

	Gr	An	Al	Sp	Py	a_0 obsd.	a_0 calcd.	Diff.
1.	1.40	—	12.89	85.71	—	11.562	11.581	$+.019$
2.	5.60	—	84.88	—	9.53	11.506	11.510	$+.004$
3.	—	85.63	8.78	1.30	4.29	11.932	11.965	$+.033$
4.	35.19	11.24	45.13	0.92	7.51	11.668	11.675	$+.007$
5.	89.29	6.86	0.55	0.24	3.05	11.840	11.839	$-.001$
6.	—	1.18	81.50	1.95	15.37	11.497	11.495	$-.002$
7.*	—	2.75	79.83	15.76	1.66	11.521	11.524	$+.003$
8.	3.70	1.66	1.54	92.27	0.83	11.603	11.604	$+.001$
9.*	27.29	6.77	50.32	0.10	15.53	11.58	11.618	$+.04$
10.	—	0.82	29.24	69.35	0.59	11.627	11.565	$-.062$
11.	—	1.48	75.00	15.63	7.90	11.579	11.515	$-.064$
12.*	0.74	—	74.08	19.97	5.21	11.552	11.514	$-.038$
13.*	1.01	—	74.12	19.89	4.97	11.606	11.515	$-.091$
14.*	—	2.11	74.98	5.41	17.50	11.550	11.502	$-.048$
15.*	—	2.11	73.20	4.32	20.37	11.569	11.500	$-.069$
16.	23.96	1.50	54.17	5.09	15.29	11.622	11.584	$-.038$
17.*	0.89	—	85.84	4.51	8.76	11.535	11.498	$-.037$
18.	0.73	96.91	1.60	0.07	0.69	12.030	12.030	$.000$
19.	0.62	4.67	14.67	0.25	74.28			
			Uv 5.52			11.510	11.513	$+.003$

Analyses marked * are those in which some Fe_2O_3 has been calculated as FeO.

Accuracy of observed a_0 stated to be ± 0.01 or better, except for No. 9 which is given ± 0.03, and Nos. 10–17, for which the probable error is not stated. 1.–2. Stockwell, *Am. Mineral.*, vol. **12**, p. 327, 1927; Nos. 9 and 20; 1. on same material as analyzed by Penfield, *Dana's System*, 6th Ed., p. 442; from Branchville, Conn. 2. on same material as analyzed by Sperry quoted by Ford, *op. cit.*, from Redding, Conn. 3. Zedlitz, *Zentralbl. Min.*, **1933A**, p. 225; analysis of somewhat impure material by Machatschki and Weinzödl, from Mixnitz, Styria. 4. Heritsch, *Zeits. Krist.*, vol. **86**, p. 253, 1933; from the Lieserschlucht near Spittal, Carinthia. 5.–8. Menzer, *Zeits. Krist.*, vol. **69**, p. 369, 1928; 5. from Xalostoc, Mexico, 6. from Falun, Sweden, 7. from Engsö, Sweden, 8. from Tsilaisina, Madagascar. 9. Pabst, *Am. Mineral.*, vol. **16**, p. 327, 1931; from Russian River, Cal. 10.–17. Novacek (*Vestnik Kral. Ces. Spol. Nauk*, **1931**), *Neues Jahrb. Min. Geol.*, **1934**, *Bd.* I, p. 363; from Czechoslovakian localities. 18. Menzer, *op. cit.*; composition from an analysis by Scherf quoted by Rakusz, *Centralbl. Min.*, **1924**, p. 353; from Dobschau. 19. Menzer, *op. cit.*, composition from analyses by v. John, *Jahrb. k.k. geol. Reichsanst.*, vol. **42**, p. 53, 1892, and Seebach, *Centralbl. Min.*, **1906**, p. 772; from Meronitz, Bohemia.

The values of a_0 for the garnet molecules which were used to obtain the calculated unit cells in Table 2 are given below in Table 3. Those given by Stockwell[7] are included for comparison. The differences are slight, since both sets of values are based primarily on the work of Menzer and of Stockwell. Examination of Table 2 shows that there is good agreement between calculated and observed values of a_0 except for the eight determinations by Novacek. These are believed to be in error. When the calculation above is reversed, and specific gravities

[7] Stockwell, *Am. Mineral.*, vol. **12**, p. 327, 1927.

are calculated from his analyses and his values for a_0, the values calculated for specific gravity are considerably lower than those he observed, indicating that his values for a_0 are too high.

The specific gravities calculated from a_0 by the relation given above are listed in Table 3. Comparison with those derived from the specific gravity data in the literature shows that the agreement is excellent for almandite and andradite, fairly good for spessartite, and rather poor for grossularite and pyrope. Those calculated from the x-ray data are higher. The discrepancy may be due to errors in the specific gravity determinations, which tend to be too low, but further x-ray work on analyzed garnets is needed.

TABLE 3. UNIT CELLS AND SPECIFIC GRAVITIES OF THE GARNET MOLECULES

	a_0	a_0 Stockwell	Mol. Wt.	G. calcd. from a_0	G. from sp. gr. data
Grossularite	11.840	11.840	450.4	3.582	3.530
Andradite	12.045	12.040	508.1	3.838	3.835
Uvarovite	12.05[a]	—	500.2	—	3.775
Almandite	11.495	11.493	497.6	4.325	4.325
Spessartite	11.590	11.577	494.9	4.196	4.180
Pyrope	11.440	11.430	403.1	3.554	3.510

[a] Calculated from specific gravity = 3.775.

A number of different physical properties of the garnets have been suggested as the basis of determinations of the chemical compositions without analysis. Since x-ray patterns cannot usually be made, refractive index and specific gravity are the properties most helpful and easiest measured. Philipsborn[8] gives tetrahedral diagrams in which refractive indices and specific gravities are plotted. However, these are rather inconvenient to use, and do not give a corresponding gain in accuracy. The three-component diagrams given by Ford appear to be the most suitable for every-day use. The helpful table prepared by Heritsch,[9] showing the range of composition of garnets from various rock types, may be used as a guide in the determination. Occasionally, a qualitative test for manganese is a necessary supplement. Trials with Ford's diagrams, redrawn using the new values for the specific gravities of almandite and andradite, gave the following results: The agreement between deduced and actual compositions was excellent for the garnets from limestone contact zones (largely grossularite-andradite), but was

[8] Philipsborn, *Sächs. Akad. Wiss., Mat.-Phys. Klasse*, vol. **40**, p. 34, 1928.

[9] Heritsch, *Neues Jahrb. Min., Geol., Beil.-Bd.*, **55A**, p. 74, 1926.

only fair for the garnets from pegmatites (largely almandite-spessartite), because the refractive indices and specific gravities of almandite and spessartite are so little different. This method of determination is unsatisfactory for garnets from schists and eclogites because these garnets usually contain four components (almandite, pyrope, grossularite, andradite) in significant amounts. However, the use of either of the three-component diagrams almandite-pyrope-grossularite or almandite-pyrope-andradite will give a good approximation of the almandite content, though giving no accurate idea of the amounts of the other components.

SUMMARY

Examination of the garnet analyses published in 1915 has verified the direct relationship between chemical composition and physical properties found by Ford to exist in the garnet group. The refractive indices, specific gravities and sizes of unit cells have been calculated for the different garnet molecules.