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AN ANDRADITE-SPESSARTITE GARNET FROM PAJSBERG, SWEDEN

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ABSTRACT

Garnet from Pajsberg, Sweden, has been found to have the following molecular per cent composition: andradite, 66; spessartite, 27; almandite, 4; grossularite, 2; and pyrope, 1. Physical properties of the analyzed mineral are: specific gravity minimum 3.96±.01, maximum 4.00±.01, average 3.98; index of refraction minimum 1.888±.003, maximum 1.898±.003, average 1.893; and unit cell size 11.99 Å±.02. A heavier garnet fraction from the same rock has an MnO content of 14.6 per cent, equivalent to 34 molecular per cent spessartite, and physical properties for this fraction clearly indicate that most of the remaining 66 molecular per cent is andradite. The andradite-spessartite garnet occurs with rhodonite, a dark olive green mineral with the hedenbergite structure but of doubtful composition and very small amounts of chlorite, biotite, hematite, barite, and allanite, at a mine that in the past has produced both iron and manganese from an ore body located within a lens of dolomite.

GEOLOGIC OCCURRENCE

The rock specimen described here is No. 2955 of the Stanford Mineralogy Collection. It is apparently a very old acquisition and is labeled simply "Pajsberg, Sweden." According to Dr. P. Quensel of the University of Stockholm (personal communication) the Pajsberg mine is rather small, has not been worked since 1887, and is now flooded. Most of the Pajsberg samples now extant were collected prior to 1887, either by Gustav Flink or by Hj. Sjögren.

The Pajsberg mine is near Lake Yngen, about ten miles south of the famous Långban mines in Vermland, Sweden. There is little detailed information available on the geology of the Pajsberg deposit. The following description is based on the accounts of Igelström (1866), Tagengren (1924), and Quensel (personal communication). The Pajsberg mine was worked for iron ore during 1842 and 1849–1852 and for both iron and manganese ores during 1884–1887, when a total of 3,515 tons of manganese ore was produced. The iron ore is mostly hematite, with some magnetite; the manganese ore is hausmannite. Both the iron and manganese ores lie within a lens of dolomite. The manganese ore body is 6–18 feet thick and about 200 feet long; it is flanked by a larger tabular mass of iron ore. The iron and manganese ores lie in close proximity, but they are sharply divided and appear to be two separate ore bodies.

The Pajsberg ores resemble those of the nearby Långban deposits in this respect. Sjögren (1910, p. 1310) states: "It is characteristic of the Långban deposits that iron ores and manganese ores occur, on the whole, separated and independent of each other, although so close that they are mined in the same workings." The Pajsberg and Långban ores are also similar mineralogically (Tagengren, 1924, p. 22).

Petrography

Megascopically the garnet-bearing rock is fine-grained. The fresh surface has a waxy luster and a color that is a rather uniform dark olive green tinged with brown. The hand specimen is cut by a small veinlet of rhodonite. In thin section it is seen to be composed almost entirely of rhodonite, clinopyroxene, and garnet. The grain size of the rhodonite ranges from less than 0.1 mm. to more than 1 mm. and averages about 0.2 mm. The grain size of the clinopyroxene is more uniform, most crystals being 0.1–0.3 mm. in diameter. Although rhodonite and clinopyroxene are intergrown, the pyroxene grains tend to be grouped in irregularly shaped clusters within the rhodonite. In some instances cleavage is persistent through adjacent grains of rodonite and clinopyroxene. However, universal stage work failed to establish any symmetry between these common cleavages and the optical directions in the two minerals.

Garnet is associated with rhodonite and with clinopyroxene. Most garnet grains are less than 0.05 mm. in diameter; the largest are about 0.2 mm. Patches of a very fine-grained white opaque material are seen in one portion of the thin section, associated principally with garnet and clinopyroxene but also with rhodonite. This white material resembles leucoxene, but the presence of leucoxene here would seem to be anomalous.

Very small amounts of chlorite and biotite also are visible in thin section. The biotite is pleochroic from dark grass green (Z) to straw yellow (X).

Minor amounts of hematite (identity confirmed by means of an *x*-ray diffraction pattern) and barite and a few grains of allanite were recovered from the crushed material, but these minerals were not seen in thin section.

Mineralogy

The optical values given below were measured in sodium light. Specific gravity values were determined in Clerici solution at room temperature by means of the suspension method.

(1) *Garnet*

The specific gravity of the garnet in this rock ranges from less than 3.85 to more than 4.11, but none of the grains has an index of refraction below 1.88. Now it is very unusual for any garnet with a specific gravity approaching or exceeding 4.0 to have an index of refraction as high as 1.88; therefore two portions of the heavier material were selected for detailed study. As the final step in the purification of these fractions, the garnet was ground to dust size and centrifuged in Clerici solution. Few of these smaller particles were zoned.

The first fraction dealt with was large enough for a complete chemical analysis. The physical properties of this garnet, determined on the material analyzed, are as follows: Specific gravity minimum 3.96±.01, maximum 4.00±.01, average 3.98; index of refraction minimum 1.888 ±.003, maximum 1.898±.003, average 1.893; and unit cell size 11.99 Å ±.02. In grains of 200-mesh size the mineral was dark apple green in reflected light and pale green in transmitted light. In dust-size particles,

TABLE 1. ANALYSIS OF GARNET FROM PAJSBERG, SWEDEN

(Stanford Mineralogy Collection #2955)
Eileen H. Oslund, analyst

	Weight per cent	Molecular proportions	Metals		
SiO_2	34.8	.580	2.91	.09	3.00
Al_2O_3	8.0	.078	.78	.69	2.07
Fe_2O_3	22.0	.138	1.38		
TiO_2	.06	.001	.01		
MgO	.1	.003	.02		
FeO	.5	.007	.04	2.93	2.93
MnO	11.4	.161	.81		
CaO	22.9	.409	2.05		
BaO	nil	—	—		
H_2O (−)	.03	—	—		
Total	99.8				

the color, though lighter, was still distinct apple green in reflected light and pale green in transmitted light.

The film on which the unit cell size is based was prepared by means of FeKα radiation, filtered with MnO. Lines on this film are uniformly fuzzy, making it impossible to determine the cell size more exactly than ±.02 Å. Exposure of the mineral to CuKα radiation gave the same results. Failure of garnet of such a narrow range of specific gravity to give sharper reflections suggests a disordered structure, which in this case might be due to solid solution of large molecular per cents of andradite and spessartite.

The analysis (Table 1) gives an SiO_2:R_2O_3:RO ratio of 3.00:2.07 :2.93. Assuming the Fe^{+++} determination to be high, as is often the case in garnet analyses (Fleischer, 1937, p. 752), an adjustment to the ideal

garnet ratio of 3:2:3 is possible, and the components (molecular per cent) become: andradite, 66; spessartite, 27; almandite, 4; grossularite, 2; and pyrope, 1.

Fleischer (1937), in a statistical study of 57 garnet analyses, confirmed Ford's (1915) thesis that there is a direct relationship between chemical composition and physical properties in the garnet group.

The values used by Ford and Fleischer for the pure end members were

TABLE 2. COMPARISON OF OBSERVED AND CALCULATED PHYSICAL PROPERTIES OF PAJSBERG GARNET

	Calculated		Difference
Refractive index	Ford's value	1.862	−.031
Observed = 1.893 (Avg.)	Skinner's value	1.856	−.037
Unit cell size	Fleischer's value	11.914 Å	−.076 Å
Observed = 11.99 Å ± .02	Skinner's value	11.902 Å	−.088 Å
Specific gravity	Fleischer's value	3.94	−.04
Observed = 3.98 (Avg.)	Skinner's value	3.96	−.02

determined by extrapolation from natural garnets of mixed composition. Skinner's (1956) values for index of refraction and unit cell size were determined from synthetic pure end member garnets, and his specific gravity figures were calculated from the volume of the unit cell.

Observed and calculated physical properties for the Pajsberg garnet are given in Table 2. The odd composition of this garnet is probably responsible for the unusually wide divergence between the observed and calculated values. Also, it is interesting to note that of the 57 garnets included in Fleischer's (1935, p. 755, analyses 56, 57) statistical study, only two minerals have the observed value for refractive index as much as .03 greater than the value calculated from the component molecules represented in the analysis. One of these is number 6 in Tables 3*A* and 3*B* of this paper. The other, also predominantly andradite, has this molecular per cent composition: andradite, 92.25; spessartite, 2.69; grossularite, 2.56, and pyrope, 2.49.

The physical properties of the second Pajsberg garnet fraction dealt with in detail are as follows: Specific gravity minimum 4.01 ± .01, maximum 4.11 ± .01, average 4.05; index of refraction minimum 1.884 ± .003, maximum 1.892 ± .003, average 1.888; and unit cell size, 11.95 Å ± .02. The pure dust size material is apple green in reflected light, but as seen beside the fraction described above (specific gravity = 3.96–4.00), this

heavier material has a distinct reddish hue. The color in transmitted light is pale green.

Unfortunately this fraction was too small for a complete chemical analysis, but the MnO content was determined by C. O. Ingamells of the University of Minnesota Rock Analysis Laboratory to be 14.6 per cent. This is equivalent to about 34 molecular per cent spessartite, and

TABLE 3*A*. ANALYSES AND PHYSICAL PROPERTIES OF GARNETS WITH HIGH MOLECULAR PER CENTS OF ANDRADITE AND SPESSARTITE

	1	2	3	4	5	6
SiO_2	34.8	n.d.	38.63	35.24	37.57	34.34
Al_2O_3	8.0	n.d.	8.20	6.48	18.98	7.20
Fe_2O_3	22.0	n.d.	21.90	23.90	3.47	24.01
TiO_2	.06	n.d.	n.d.	nil	n.d.	n.d.
MgO	.1	n.d.	n.d.	2.04	0.23	1.29
FeO	.5	n.d.	n.d.	n.d.	7.45	n.d.
MnO	11.4	14.6	13.00	16.37	16.50	5.94
CaO	22.9	n.d.	19.80	15.20	15.80	27.36
BaO	nil	n.d.	n.d.	.18	nil(?)	n.d.
$H_2O(-)$	.03	n.d.	n.d.	nil	n.d.	n.d.
Total	99.8	—	101.53	99.41	100.0	100.14
Sp. Gr.	3.98 (avg)	4.05 (avg)	n.d.	4.02	—	n.d.
R.I.	1.893 (avg)	1.888 (avg)	n.d.	n.d.	—	1.89
a_0	11.99 Å ± .02	11.95 Å ± .02	—	—	—	—

1. Garnet from Pajsberg, Sweden. Stanford Mineralogy Collection 2955. Eileen H. Oslund, analyst.
2. Garnet from Pajsberg, Sweden. Stanford Mineralogy Collection 2955. MnO determination by C. O. Ingamells.
3. Garnet from Gåsborns, Vermland, Sweden. Igelström, 1883, p. 94. L. I. Igelström, analyst. (Analysis made in 1864.)
4. "Spandite" from Garbham, India. Fermor, 1909, p. 167. J. Coggin Brown, analyst.
5. "Spandite" from Kotakarra, India. The analysis of this garnet was "calculated from analyses of rocks containing it." (Fermor, 1909, p. 168.)
6. Garnet from Franklin Furnace, New Jersey. Palache, 1936, p. 75. Jenkins and Bauer, analysts.

the physical properties determined for this fraction, together with the complete analysis listed above (specific gravity = 3.96–4.00), clearly indicate that most of the remaining 66 molecular per cent is andradite.

Earlier garnet analyses that most nearly resemble the present one are presented in Tables 3*A* and 3*B*. At first glance, number 3 of Table 3*A* appears to be very similar to the Pajsberg garnet (specific gravity 3.96–

4.00), but calculation shows the $SiO_2:R_2O_3:RO$ ratio to be 3.10:1.97 :2.59, and the composition in terms of molecular per cents of the garnet end members is problematical. (This is not surprising, since the analysis dates from 1864.)

"Spandite" is the name proposed by Fermor (1909, p. 179) "for the varieties of manganese garnet that are intermediate, as regards composi-

TABLE 3B. COMPONENTS (MOLECULAR PER CENTS) OF GARNETS LISTED IN TABLE 3A

Analysis Number (As in Table 3A)	Components (Molecular per cents)						
	Andradite	Spessartite	Almandite	Grossularite	Pyrope	$Mn_3Fe_2Si_3O_{12}$ ("Calderite")	Totals
1	66	27	4	2	1	—	100
2	—	34	—	—	—	—	—
3	PROBLEMATICAL						
4	47	19	6	0	8	20	100
5	10	38	16	35	1	—	100
6	68	14	0	13	5	—	100

1. Pajsberg, Sweden. Specific gravity = 3.96–4.00.
2. Pajsberg, Sweden. Specific gravity = 4.01–4.11.
3. Gåborns, Vermland, Sweden.
4. Garbham, India.
5. Kotakarra, India (analysis "calculated").
6. Franklin Furnace, New Jersey.

tion, between spessartite and andradite." Number 4 of Tables 3*A* and 3*B* is the only actual analysis of spandite presented by Fermor; number 5 was "calculated from the analyses of rocks containing it" (Fermor, 1909, p. 168). Of the naturally occurring garnets known to the writer, number 6 of Tables 3*A* and 3*B*, from Franklin Furnace, New Jersey, most nearly resembles the Pajsberg garnet. Despite similarity in chemical composition, however, the Franklin Furnace mineral is brownish black (Palache, 1936, p. 75), in contrast to the apple green color of the Pajsberg garnet.

(2) *Clinopyroxene*

This mineral has the hedenbergite structure, for the powder diffraction pattern corresponds to that of an analyzed johannsenite, with slight differences in spacing resulting from compositional differences.

The physical properties are: $\alpha = 1.727$, $\beta = 1.740$, $\gamma = 1.756$, all $\pm .004$; $\gamma - \alpha = .029$ and dispersion $v > r$, moderate. Most crystals have a specific gravity within the range 3.45–3.49, but a few are outside these limits. Universal stage plots of five grains (with one axis observed in every case) gave these values for 2V: 72(+), 84(+), 88(+), 86(−), and 82(−). For $X \wedge c$ grains 2–5, respectively gave 22°, 23°, 19°, and 18°. At a grain size within the range 0.07–0.15 mm., the pure mineral has a very dark olive green color in reflected light. In thin section the color is greenish yellow. Pleochroism is slight, from greenish yellow to a more definite yellowish hue, with $X > Y > Z$.

Flink (1886, p. 496) gives the following analysis for a dark iron schefferite from Pajsberg: SiO_2, 50.88; Al_2O_3, 1.97; FeO, 17.48; MgO, 9.08; MnO, 6.67; CaO, 12.72 and total, 98.81. This iron schefferite occurs with rhodonite, hematite, and barite and has a yellow-green color in thin section (Flink, 1886, p. 500), which suggests that it might have a composition similar to that of the clinopyroxene described above. Unfortunately, neither refractive index nor 2V values are listed for Flink's analyzed iron schefferite.

One might expect a clinopyroxene paragenetically associated with andradite-spessartite garnet and rhodonite to have the composition of a manganhedenbergite or an iron schefferite. The refractive indices and specific gravity of this mineral favor the former alternative (see for example Tilley, 1946, p. 237; Palache, 1936, p. 62). However, the combination of physical properties displayed by this clinopyroxene, including particularly the values for 2V and $X \wedge c$, leave the composition of the mineral in doubt (see Winchell, 1951, pp. 411–417).

(3) *Rhodonite*

The identity of this mineral was checked by means of an x-ray diffraction pattern. Physical properties are: specific gravity maximum 3.64, minimum 3.61, both $\pm .01$; $\alpha = 1.724$, $\beta = 1.730$, $\gamma = 1.738$, all $\pm .004$; $\gamma - \alpha = .014$, and dispersion $r < v$, very slight. Universal stage plots of four grains gave these results for 2V, (+) in every case: 70, 72, 73 and 84. Both optic axes were observed for grain 2, only one for each of the others.

Specific gravity and index of refraction (β) values determined for this rhodonite suggest that the composition includes 85–90 molecular per cent of $MnSiO_3 + FeSiO_3$ (Hey, 1929, pp. 201–202; Lee, 1955, pp. 21–23). Moreover, the color of the pure mineral, which is a dull pink in grains of 200-mesh size, indicates that the FeO content is relatively high, for iron-poor rhodonites commonly have a bright peach-pink color (Lee, 1955, pp. 19–21).

Conclusion

Despite limited miscibility of the grossularite-andradite with the pyrope-almandite-spessartite series of garnets, Boeke (1913, p. 155) has predicted (empirically) that the andradite end member has a special capacity to contain MnO. Results of this study show that under proper conditions of formation natural andradite may contain more than 27, and probably as much as 34, molecular per cent spessartite.

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References

1. Boeke, H. E. (1913), "Die Granatgruppe": *Z. Krist.*, **53,** 149–157.
2. Fermor, L. Leigh (1909), "The Manganese Ore Deposits of India": *Mem. Geol. Surv. India*, **37,** 610 pp., esp. pp. 161–186.
3. Fleischer, M. (1937), "The relation between chemical and physical properties in the garnet group": *Am. Mineral.*, **22,** 751–759.
4. Flink, G. (1886), "Studien über schwedische Pyroxmineralien": *Z. Krist.*, **11,** 449–530, esp. pp. 495–501.
5. Hey, M. H. (1929), "The variation of optical properties with chemical composition in the rhodonite-bustamite series": *Mineral. Mag.* **22,** 193–205.
6. Igelström, L. I. (1866), "Über das Vorkommen von gediegenem Blei in den Eisen- und Manganerz-Lagerstätten von Pajsberg in Schweden": *N. J. für Min., Geol. u. Paleon.*, p. 225.
7. Igelström, L. I. (1883), "Manganmineralier från Stålmalmsgrufvorna i Gåsborns socken, Vermland": *Ofversigt af Kongliga Vetenskaps-Akademiens Fordhandlingar, Stockholm*, **40,** No. 7, 91–96. (Trans. by Gail Keith Meadows)
8. Lee, Donald E. (1955), "Mineralogy of some Japanese manganese ores": *Stanford Univ. Publ., Univ. Ser., Geol. Sci.*, **5,** 64 pp., esp. pp. 19–23.
9. Palache, Charles (1936), "The Minerals of Franklin and Sterling Hill, New Jersey": *U.S.G.S. Prof. Paper 180,* 130 pp., esp. pp. 62, 75.
10. Sjögren, H. (1910), "The Långban Mines": *Geol. För. Förh,* Stockholm, **32,** pp. 1295–1325, esp. pp. 1310–1313.
11. Skinner, Brian J. (1956), "Physical properties of the garnet group": *Am. Mineral.*, **41,** 428–436.
12. Tagengren, F. R. (1924), "Sveriges Ädlare Malmer och Bergverk": *Sveriges Geologiska Undersökning,* Ser. Ca. No. **17,** pp. 1–406, esp. pp. 21, 22, 211, 212, which were translated by Gail Keith Meadows.
13. Tilley, C. E. (1946), "Bustamite from Treburland Manganese Mine, Cornwall, and its Paragenesis": *Mineral. Mag.* **27,** 236–241.
14. Winchell, Alexander N. (1951), *Elements of Optical Mineralogy, Part II, Descriptions of Minerals*, pp. 411–417, John Wiley & Sons.

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