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Gahnite in the Metamorphosed Stratiform Massive Sulfide Deposits of the Mineral District, Virginia, U.S.A.

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With 7 Figures

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Summary

Ferroan-gahnite, $(Zn,Fe)Al_2O_4$, is a common accessory mineral found in association with the metamorphosed volcanogenic massive sulfide ore bodies of the Mineral District, Virginia. Gahnite is present throughout the mineralized zones that contain pyrite, sphalerite, chalcopyrite, and sulfosalts. Although constituting only 1–2 modal percent of most samples and displaying not well-defined distribution pattern, gahnite is especially abundant at the margins of the mineralized zones and locally constitutes as much as 35 modal percent. The compositions vary slightly from one deposit to another but all lie within the range of 68 to 88 mol.% gahnite ($ZnAl_2O_4$), 8 to 25 mol.% hercynite ($FeAl_2O_4$), and 1–17 mol.% spinel ($MgAl_2O_4$). Gahnite occurs within a wide variety of mineral assemblages, with or without coexisting sphalerite.

The reflectance and unit cell dimension are sensitive to composition and decrease with increasing gahnite component. The approximate 8% reflectance at 540 nm is intermediate between most silicates and ore minerals such as sphalerite and magnetite and thus provides a ready method for recognition in reflected light. The gahnite is believed to have formed during amphibolite grade regional metamorphism as a result of either sphalerite desulfidation or the reaction of original zinc oxide phases.

Zusammenfassung

Gahnit in metamorphen schichtgebundenen Sulfid-Lagerstätten des Mineral-Distriktes, Virginia, U.S.A.

Eisenhaltiger Gahnite $(Zn,Fe)Al_2O_4$ ist in den metamorphen vulkanogenen massiven Sulfiderzkörpern Virginias als akzessorisches Mineral weit verbreitet. Er kommt durchwegs in den Pyrit, Zinkblende, Kupferkies und Sulfosalze enthaltenden mineralisierten Zonen vor. Obwohl die meisten Proben nur 1–2 Modal % Gahnit enthalten, und keine klar definierte Verteilung zu erkennen ist, tritt er besonders häufig an den Rändern der mineralisierten Zonen auf und erreicht lokal 35 Modal %. Die Zusammensetzung schwankt leicht von Vorkommen zu Vorkommen, liegt aber stets zwischen 68 und 88 Mol.% Gahnit ($ZnAl_2O_4$), 8 und 25 Mol.%

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Hercynit ($FeAl_2O_4$) und 1 und 17 Mol.% Spinell ($MgAl_2O_4$). Gahnit ist Bestandteil sehr verschiedener Mineralparagenesen mit und ohne Zinkblende.

Introduction

Gahnite, nominally $ZnAl_2O_4$, is a relatively uncommon member of the oxide spinel series. It occurs in moderate to high grade metamorphic rocks and exhibits considerable solid solution toward other members of the series, such as hercynite ($FeAl_2O_4$), spinel ($MgAl_2O_4$), and galaxite ($MnAl_2O_4$). Most gahnite occurrences consist of isolated and widely dispersed crystals, but its association with the massive sulfide ores at Broken Hill, N.S.W., was noted early in the present century (*Andrews* et al., 1922). In recent years, gahnite has been reported as a frequent and sometimes locally abundant phase in and immediately associated with several additional metamorphosed stratiform volcanogenic massive sulfide ores (*Sunblad*, 1982; *Spry* and *Scott*, 1983; *Craig*, 1983). Although gahnite has long been used as an ore guide at Broken Hill, only recently has its potential utilization as a general exploration guide to metamorphosed massive sulfide ore deposits been pointed out (*Sheridan* and *Raymond*, 1977; *Spry* and *Scott*, 1982).

Samples and Analytical Techniques

The present study was based upon the examination and analysis of 580 polished sections and 50 thin sections from located samples and diamond drill cores that penetrated the mineralized zones and associated host rocks of four of the stratiform sulfide deposits – Cofer, Arminius, Sulphur, and Julia – of the Mineral District. The polished sections were prepared and examined according to the conventional techniques described by *Craig* and *Vaughan* (1981). Because many of the samples were originally selected for an examination of the ore mineralogy, there is a strong bias of samples to represent mineralized zones rather than the surrounding strata.

Chemical analyses of gahnites and associated sulfide and silicate minerals were performed on an ARL-SEMQ electron microprobe at VPI & SU using synthetic sulfides and well characterized natural grains of the following as standards: gahnite, fayalite, norbergite, tephroite, rutile, albite, orthoclase, anorthite. Unit cell dimensions were determined using an automated Norelco diffractometer employing Ni-filtered CuK_α-radiation and using CaF_2 as an internal standard. Reflectance measurements on the gahnite were performed at 460, 546, and 650 nm using a McCrone MPA1 photometer and magnetite, galena, and pyrite reflectance standards calibrated against a primary Zeiss reflectance standard.

General Geologic Setting and Ore Mineralogy of the Deposits

The mineral District is contained within the Chopawamsic Formation that consists of a complex pile of interbedded felsic and mafic volcanics and sedi-

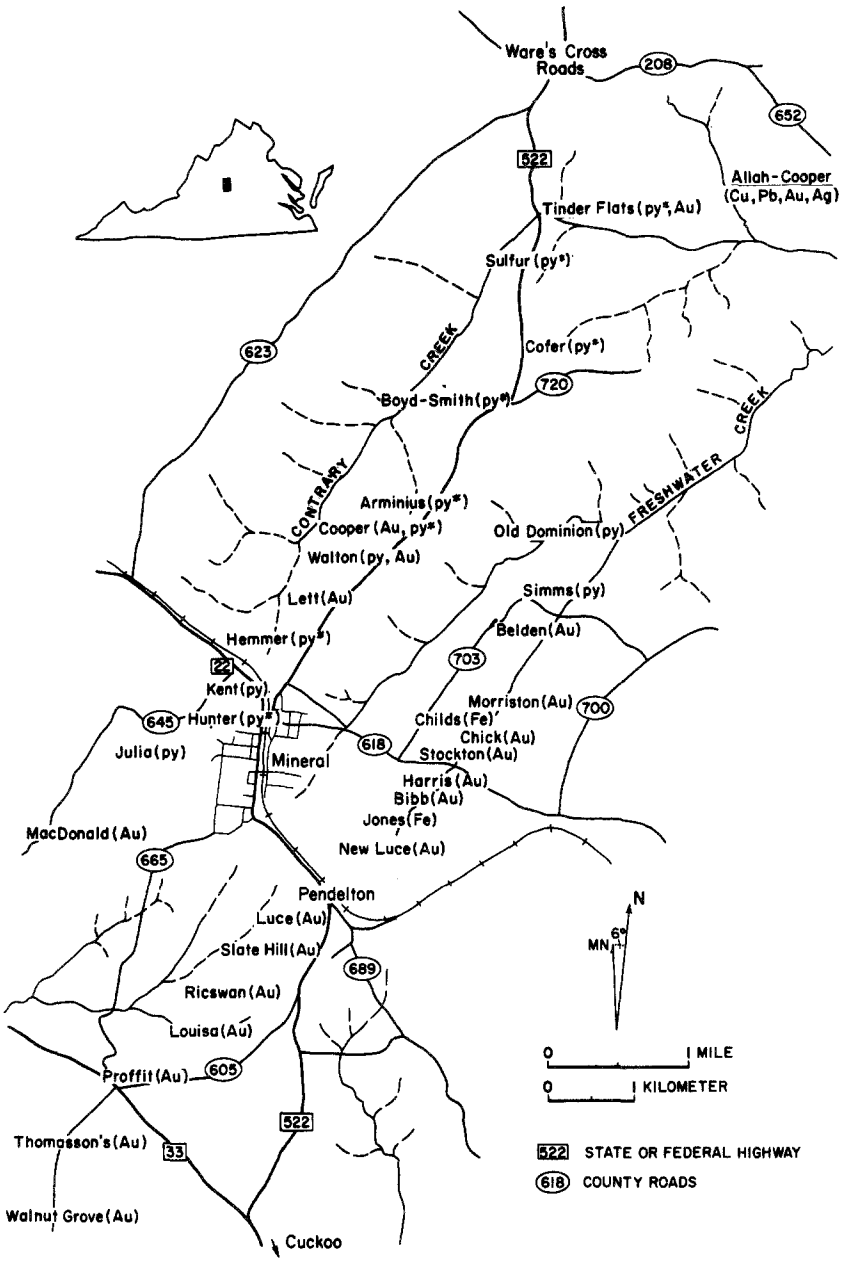

Fig. 1. General map of the Mineral District, Louisa County, Virginia, showing the locations of the Julia, Sulphur, Arminius, Cofer and other deposits (after *Craig* et al., 1978)

ments (*Southwick* et al., 1971) of probable Cambrian age (*Gair*, 1978). The base-metal sulfide mineralization, that occurs as a series of concordant lenses and plate-like bodies, coincides with a regional thickening of the Chopawamsic Formation. This thickening has been interpreted by *Hodder* et al. (1977) to represent an accumulation of submarine basaltic flows, tuffs, siliceous iron- and sulfide-rich sediments, and volcaniclastic debris in a series of roughly linear troughs.

The setting, mineralogy, and Cu-Zn-Pb ratios of the ores are very similar to those of many other volcanogenic deposits of comparable age in many parts of the world (*Franklin* et al., 1981). These deposits have been interpreted as submarine exhalites that formed through episodic discharge from vents in confined basins (*Craig*, 1980; *Gair* and *Slack*, 1980).

The Mineral District contains two principal subparallel northeasterly trending mineralized belts, a western consisting primarily of base-metal deposits, and an eastern consisting primarily of gold occurrences (Fig. 1). The base-metal deposits, though locally variable, are dominantly pyrite with significant to minor amounts of sphalerite, chalcopyrite, galena, and tetrahedrite, with traces of pyrrhotite, arsenopyrite, Pb-Sb-Bi sulfosalts, and electrum (*Miller*, 1978; *Cox*, 1979; *Craig*, 1980; *Miller* and *Craig*, 1983).

Amphibolite-grade, regional metamorphism at temperatures of approximately 470 °C and pressures of 3 kb has resulted in recrystallization of the ores and host rocks and the growth of typical metamorphic minerals such as garnet, biotite, and amphibole.

Distribution of Gahnite Within the Mineralized Zones

The four deposits in which gahnite has been found exhibit considerable variation in terms of geometry, size, and ore- and gangue-mineral assemblages. There appears, however, to be no pattern in the overall distribution of the gahnite, neither in spatial location nor in terms of the coexisting mineralogy. General observations on the nature of each deposit and the occurrence of gahnite in each are given below:

Julia Deposit

The Julia deposit, at the south end of the district, consists of interspersed massive and disseminated sulfide zones underlain by cross-cutting stringers that have been interpreted by *Sauer* (1980) as feeder zones. The dominant ore mineral in nearly all zones is pyrite; sphalerite, chalcopyrite, and galena are minor and relatively evenly distributed. Monoclinic pyrrhotite is locally abundant and traces of arsenopyrite, tetrahedrite, mackinawite, sulfosalts, and corroded magnetite are present.

The mineralized zones are usually hosted by biotite-sericite schists and quartzites, and the general gangue mineral assemblage is quartz + biotite + sericite + chlorite (prograde) + gahnite + Ca,Mg-carbonates + amphibole. Staurolite has been observed in only two samples and tourmaline in one. Gahnite

was found in 24 of the 68 samples examined from the ores of the Julia deposit in abundances of up to 20 modal percent. Gahnite is randomly distributed and is found both in sphalerite-rich ore and pyrite-rich ores containing little sphalerite. There is, however, a tendency for gahnite content to increase as the sphalerite content decreases (Fig. 2) and for gahnite to be more abundant in disseminated sulfide zones adjacent to massive sphalerite-rich ore than in the massive ores. Little gahnite has been found outside of the mineralized zones, but *Holland* (1980) does report traces in the hanging-wall biotite-sericite schist.

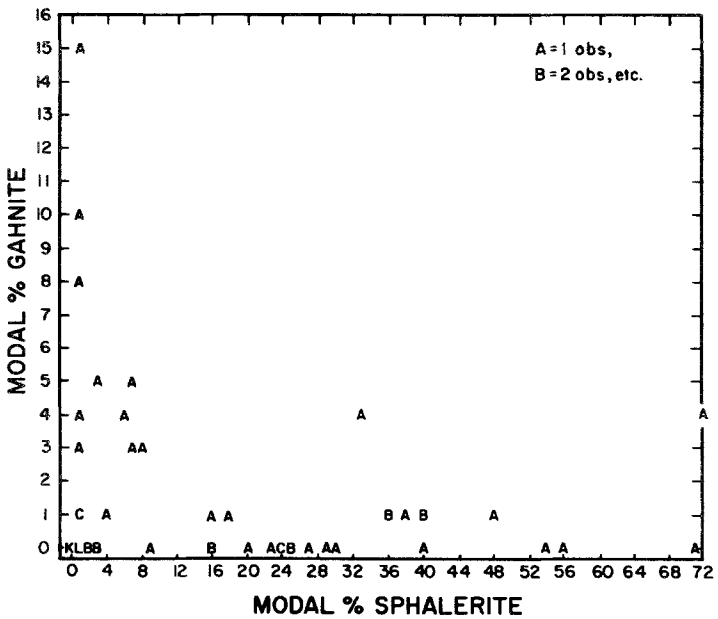

Fig. 2. Plot of modal gahnite versus modal sphalerite in samples of the Julia deposit

Sulphur Deposit

The Sulphur deposit, lying near the northern end of the district, consists of massive to disseminated pyrite and pyrrhotite-bearing lenses that lie at the contact of an overlying biotite-sericite schist and an underlying "accessory mineral" chlorite schist (*Sauer*, 1980). Microprobe analyses indicate that most of the green micas of this schist are actually biotite, not chlorite. The ore mineralogy of the Sulphur deposit consists of pyrite with significant amounts of pyrrhotite and local concentrations of sphalerite, chalcopyrite, and galena. Magnetite is common in small amounts and traces of tetrahedrite and marcasite have been observed.

The non-sulfide assemblage within the ore zone and the chlorite schist is biotite + chlorite + gahnite + staurolite + garnet + epidote + quartz + siderite.

Gahnite was observed in 22 of the 56 samples examined from the Sulphur deposit. The greatest concentrations of gahnite, up to 15 modal percent, occur

at the upper and lower contacts of the mineralized lens, but small amounts were found dispersed throughout the zone. Gahnite is generally observed in the absence of sphalerite, but many gahnite-bearing samples also contained small amounts of sphalerite.

Cofer Deposit

The Cofer deposit, that lies between the two major trends of the district, consists of four concordant mineralized lenses (*Miller*, 1978). The hanging wall consists of fragmental mica schist with clast of chert, rhyolite, and quartz-sericite schist in a fine-grained matrix of quartz and sericite; the foot-wall is a pyritic quartzite with minor amounts of biotite and sericite. The mineralized zones are pyrite-rich with significant amounts of sphalerite, chalcopyrite, galena, minor tetrahedrite, arsenopyrite, sulfosalts, and traces of pyrrhotite, mackinawite, bornite, molybdenite, and electrum (*Miller*, 1978). Gangue minerals include quartz, sericite, biotite, garnet, gahnite, Ca,Fe,Mg,Mn-carbonates, K-feldspar, plagioclase, kyanite, rutile, ilmenite, and magnetite.

Gahnite occurs in only about 10 percent of the more than 300 samples examined and is most common in the uppermost lens; it decreases in abundance downward and is absent from the lowermost lens. The gahnite occurs as disseminated grains and in thin (millimeter to centimeter) discontinuous layers and lenses interspersed in the mineralized zones.

Arminius Deposit

The Arminius deposit, largest in the district, consists of two massive en echelon lenses enclosed in mafic to felsic rocks including amphibolites, sericitic schists, and quartz-carbonate rocks. Pyrite is overwhelmingly the most abundant ore mineral, but minor sphalerite, chalcopyrite, arsenopyrite, and magnetite are also present (*Cox*, 1979). Gahnite generally occurs as scattered grains in about 10 percent of the samples, but may locally constitute as much as 35 modal percent of this rock. It is found with both amphibolitic and pelitic gangue assemblages, but is absent from quartz-calcite rocks.

Physical and Optical Properties

Gahnite, although exhibiting relatively distinctive physical and optical properties, has apparently often been overlooked or misidentified in many occurrences because of its small grain size, low modal abundance, and a color somewhat similar to that of many greenish silicates. Furthermore, when ores have been studied in polished sections, the low reflectance of gahnite has probably generally led to its being merely classed as a "gangue" mineral.

Megascopically, gahnite of the Mineral District appears as dark green, 1 to 4 mm equant subhedral to octahedral crystals. They may occur as isolated or disseminated crystals or in thin, nearly monomineralic bands up to 1 cm in thickness. Reflected light examination reveals that the gahnite has a reflectance of approximately 8% that is intermediate between that of sphalerite and

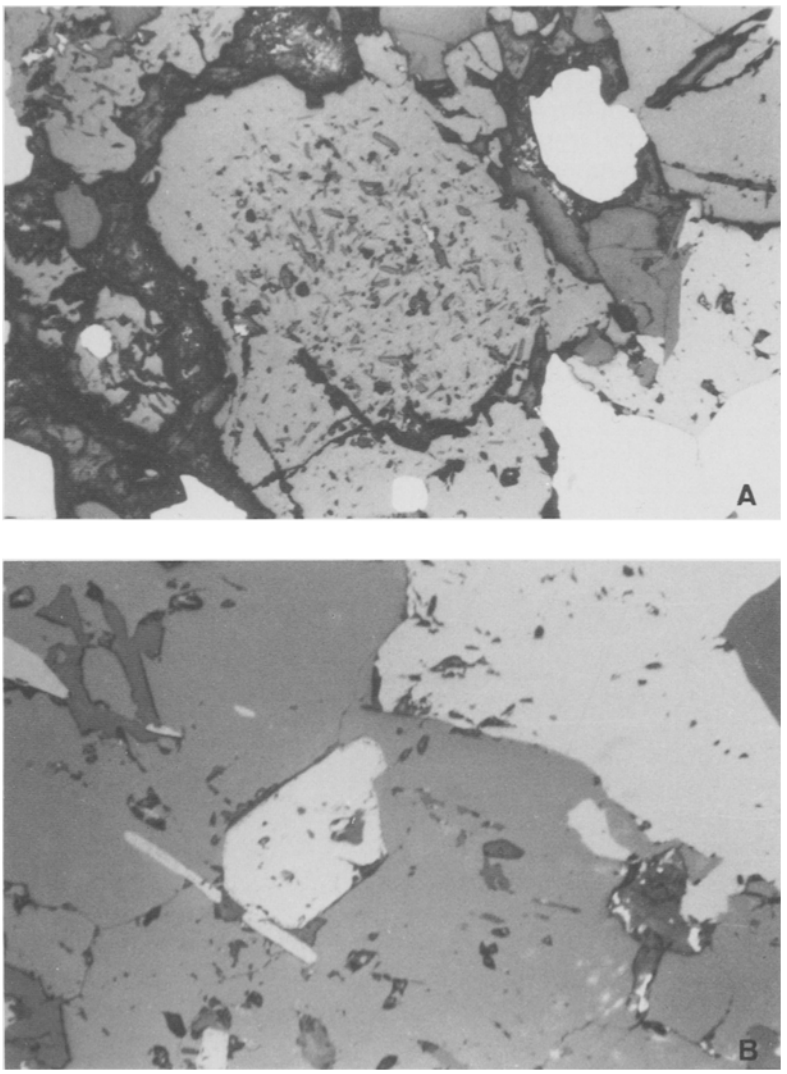

Fig. 3. Photomicrographs of poikilitic gahnite. A) Typical gahnite with poikioblastic texture. Inclusions are quartz, biotite, muscovite, pyrite and chalcopyrite. Sample 74-12 425, reflected light, field of view = 1.1 mm. B) Gahnite adjacent to sphalerite. Included within the gahnite are two euhedral ilmenite crystals. Sample C 112 HS 386.2, reflected light, field of view = 0.55 mm

magnetite (~ 17–19%) and the common gangue minerals (~ 5%). Once recognized, the reflectance provides a useful characteristic for identification. The gahnite commonly exhibits a high polishing relief (due to its hardness of 7.5–8 on the Moh's scale), subhedral to euhedral crystal outline, is commonly poikilitic with inclusions of quartz (Fig. 3), is isotropic, and exhibits blue-green to green internal reflections. In thin section, gahnite is characterized by a high optical

relief ($n \sim 1.80$), by being isotropic, by its poikilitic habit, and by its pale green color.

Gahnite has been seen in association with a variety of mineral assemblages throughout the deposits of the Mineral District (Table 1). Grains tend to be larger and to possess better crystal form in the mafic than in the felsic assemblages, and reach a maximum of 4 mm in size in the prograde chloritic schist of the Sulphur deposit. In the felsic and pelitic rocks, gahnite ranges downward from a maximum of approximately 1 mm.

Table 1. Gahnite-bearing assemblages in the sulfide deposits of the Mineral District. Chemical analyses of the gahnites are given under the corresponding sample number in Table 4. Analytical procedures and additional assemblages are given in Sandhaus (1981). x = present; - = absent.

Deposit	Arminius				Cofer				Julia				Sulphur			
Sample No.	1	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17
Mineral																
gahnite	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
quartz	x	x	-	-	x	x	x	x	x	x	x	x	x	x	x	x
biotite	x	x	x	-	x	x	x	x	x	x	x	x	x	x	x	x
chlorite	x	-	x	x	-	-	-	-	-	-	-	-	x	-	-	-
muscovite	x	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
garnet	x	-	x	x	-	-	-	-	-	-	-	-	-	-	-	-
staurolite	x	-	-	-	-	-	-	-	-	-	-	x	-	-	-	-
amphibole	x	-	x	x	-	-	-	-	-	-	-	-	-	-	-	-
plagioclase	-	-	-	x	-	-	-	-	-	-	-	-	-	-	-	-
epidote	-	-	-	-	-	-	-	-	-	-	-	-	-	x	-	-
kyanite	-	-	-	-	-	-	x	-	-	-	-	-	-	-	-	-
magnetite	x	-	-	x	-	-	-	-	x	-	-	-	x	x	x	-
pyrite	x	x	x	-	x	x	x	x	x	x	x	x	x	x	x	-
pyrrhotite	-	x	x	-	-	-	-	-	x	-	-	-	x	-	x	x
sphalerite	-	x	x	-	x	x	x	x	x	x	x	x	x	x	-	-
galena	x	-	x	x	x	-	x	-	x	x	x	x	-	-	x	x
chalcopyrite	x	x	x	-	x	x	x	x	x	-	x	x	x	x	x	x

Little information is available on the reflectance of gahnite. Accordingly, measurements (Table 2) were made using monochromatic light at 460, 546, and 589 nm in air; unfortunately, resolution at 650 nm proved to be insufficient to define variations. At 546 nm the average reflectance was found to be 7.8%, but there is a tendency for the reflectance to decrease with increasing gahnite component (Fig. 4).

The unit cell dimensions of gahnites of the Mineral District (Table 3) were determined by X-ray powder diffraction and were found to be near $a_0 = 8.100$ Å, intermediate between those of pure gahnite ($a_0 = 8.087$ Å) and pure hercynite ($a_0 = 8.135$ Å), their principal components.

The higher reflectance and larger unit cell dimensions of the sample from Sterling Hill, New Jersey, are probably due to significant substitution of iron for aluminum as the trivalent (B) cation and the presence of a larger than normal amount of galaxite component. *Carvalho* (1978) has shown that gahnites from Sterling Hill contain up to 15 mol.% franklinite component ($ZnFe_2O_4$). Analyses of Sterling Hill gahnites carried out in this study (one example is given in Table 3;

Table 2. Reflectances (R%) of spinels from the Mineral District, Virginia, and Sterling Hill, New Jersey measured in air.

Sample[1]	R% (546nm)	R% (460nm)	Mole % end member component Gahnite	Hercynite	Mg-spinel	Galaxite
1. SCV-80-88 1417	7.8	9.1	73.9	17.7	8.1	0.3
2. SCV-79-85 1448.5	7.8	8.9	75.1	17.7	7.0	0.3
3. A U44A 20	7.8	8.7	75.2	17.6	7.0	0.3
4. SCV-80-88 1405.5	7.8	8.3	75.5	17.3	7.0	0.2
5. A U9A 9.5	7.4	8.2	77.5	17.7	4.7	0.1
6. JRC 1390 Sterling Hill	8.3	9.5	84.5	12.7	1.3	1.5

[1] Samples listed in order of increasing gahnite component. Numbers correspond to those in Figure 4.

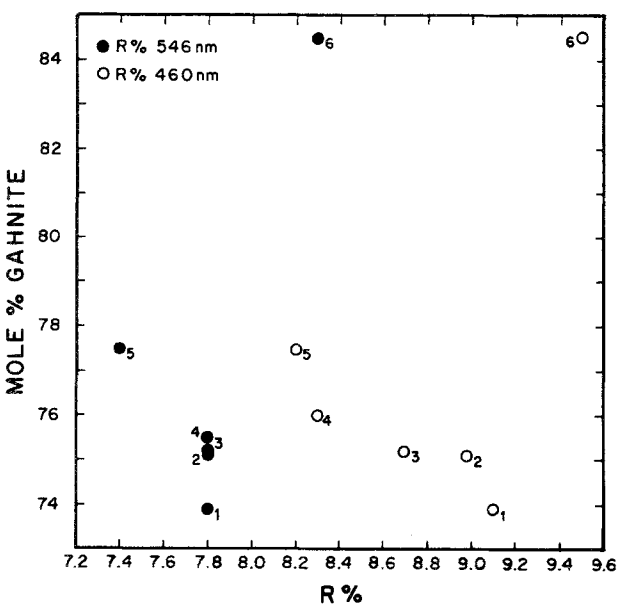

Fig. 4. Reflectance (R%) of gahnites (no. *1–5* in Table 1) from the Mineral District; note the increase in R% as a function of decreasing gahnite component. No. *6*, from the Sterling Hill, New Jersey, deposit, has 1.5 mol.% galaxite component

six are given in *Sandhaus*, 1981) typically calculate at about 85 mol.% gahnite, 13 mol.% hercynite, and 2 mol.% spinel – N on Fig. 5b. If recalculated on the basis of trivalent ions, these analyses are approximately 7 mol.% franklinite and 7 mol.% spinel.

Table 3. Unit cell dimensions of spinels from the Mineral District, Virginia and Sterling Hill, New Jersey.

Sample[1]	a_o Å ± σ	Number of Peaks	Mole % end member component			
			Gahnite	Hercynite	Mg-spinel	Galaxite
1. S 2-S 564.5	8.103+0.004	13	72.2	20.0	7.6	0.2
2. SCV-80-88 1417	8.103+0.002	10	73.9	17.7	8.1	0.3
3. C 74-12 425	8.096+0.002	11	77.2	11.4	10.9	0.6
4. JRC 1390	8.116+0.01	11	84.5	12.7	1.3	1.5
Sterling Hill						
Gahnite (ferroan)[2]	8.104		54.6	36.6	8.8	0.0
Gahnite[2]	8.0848		100.0			
Hercynite[2]	8.119		100.0			
Mg-spinel[2]	8.0800				100.0	
Galaxite[2]	8.258					100.0

[1] Samples listed in order of increasing gahnite component.

[2] From JCPD Powder Diffraction File (1970): cards 12-267 (ferroan gahnite), 5-669 (gahnite), 3-894 (hercynite), 5-672 (Mg-spinel), and 10-310 (galaxite).

Gahnite Compositional Data

Gahnite, ideally $ZnAl_2O_4$, is a member of the oxide spinel group that possess aluminium as the trivalent cation. These spinels are cubic (space group *Fd3m*) and have the general formula $A^{2+}B_2^{3+}O_4^{-2}$. The four naturally occurring members of this series, among which there is complete solid solution (*Winchell*, 1941), are spinel ($MgAl_2O_4$), hercynite ($FeAl_2O_4$), gahnite ($ZnAl_2O_4$), and galaxite ($MnAl_2O_4$).

In calculating the end member components, the hercynite component has been calculated from the total iron content, that is, all iron has been considered to be FeO as in hercynite; this follows the convention established by *Nemec* (1972) and used by *Kramm* (1977). The stoichiometric formulae as calculated for the gahnites by the program SUPER RECAL often show minor Fe^{3+} in the trivalent (B) cation site. These formulae were calculated so that Mn + Mg + Zn + Ca + K + Fe = 1.000 in the divalent (A) cation site and excess Fe assigned to the B site. The placement of this iron in the B site is a function of the calculation method and represents the theoretical if not the actual cation distributions.

The spinels of the Mineral District may be termed ferroan-gahnites in that they exhibit 8 to 24 mol.% hercynite. The ranges of all analyses are shown in Figs. 5a–b and representative examples are given in Table 4; all analyses are given in the Appendices of *Sandhaus* (1981). Although microprobe analyses revealed that most gahnite grains are homogeneous, a slight zonation was found in some of the larger, more euhedral grains in the Sulphur deposit. These grains show a maximum variation of a 3.7 mol.% decrease in gahnite component from the core to the rim with a corresponding increase of hercynite and spinel components; this is apparent in analyses 16 and 17 in Table 4. Gahnite compositions

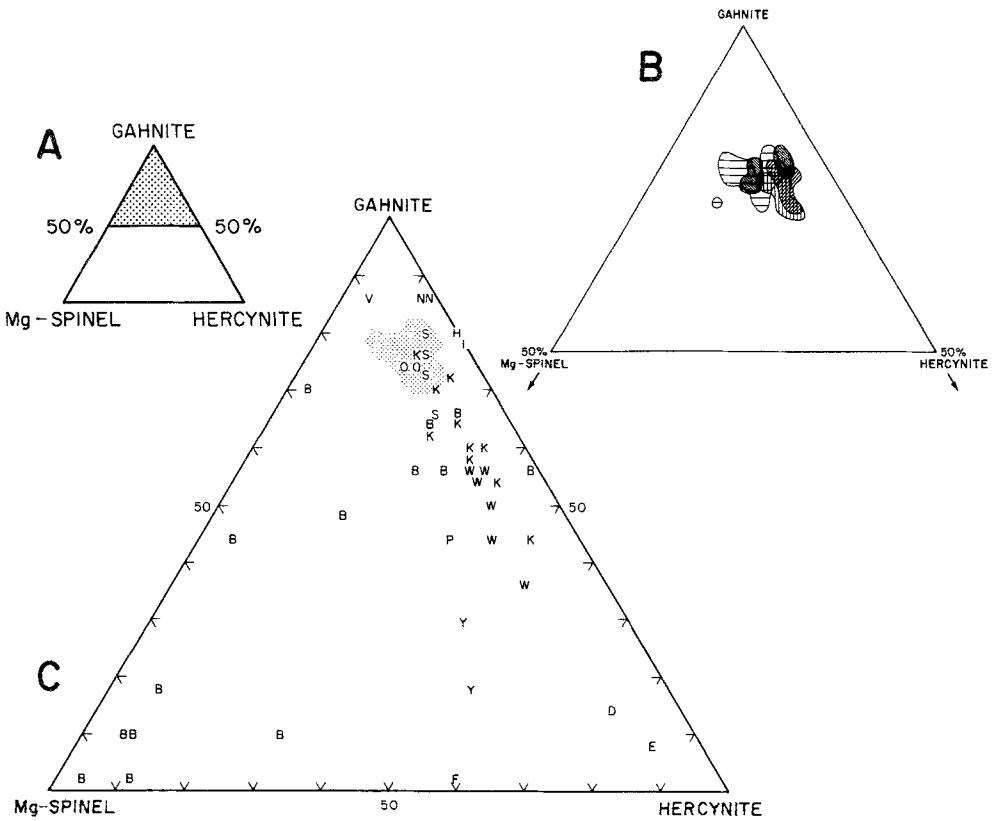

Fig. 5. A) Portion of gahnite, spinel, hercynite compositional diagram shown in (B). B) Plot showing the compositional range of gahnite from the Mineral District (stippled area) relative to those of gahnite from other localities. *B* Bohemian Massif (*Nemec*, 1972); *D* Donegal, Eire (*Atkin*, 1978); *E* southern Spain (*Loomis*, 1972); *F* Front Range, Colorado (*Gable* and *Sims*, 1969); *K* Kenio, SW Finland (*Dietvorst*, 1980); *H* Outer Hebrides (*Knorring* and *Dearnley*, 1960); *I* Mamandur, India (*Gandhi*, 1971); *N* Sterling Hill, New Jersey; *O* other Piedmont localities; *P* Pennsylvania (*Wagner* and *Crawford*, 1975); *S* Sweden (*Sunblad*, 1982); *V* Venn-Stavelot Massif (*Kramm*, 1977); *W* Wyoming (*Frost*, 1973); *Y* Adirondacks, NY (*Stoddard*, 1979). C) Compositions of gahnites from the Mineral District in terms of mol.% gahnite, hercynite, and Mg-spinel components: horizontal line = Cofer deposit; vertical lines = Arminius deposit, NW-SE lines = Julia deposit; NE-SW lines = Sulphur deposit

display minor variations from one grain to another within each deposit and from one deposit to another as is shown in Table 3 and Figs. 5a–b. These figures show that there is a slight tendency for gahnite from deposits with more mafic host rocks (more biotite, chlorite, and amphibole as in the Sulphur and Arminius deposits) to have lower gahnite and spinel contents and higher hercynite contents. In contrast, the gahnites from the deposits with more felsic host rocks (Cofer and Julia deposits) have slightly higher gahnite and Mg-spinel contents and lower hercynite contents.

Table 4. Compositional data of representative gahnites from the four volcanogenic sulfide deposits of the Mineral District. The end member components given below are calculated on the basis of mole percent components of gahnite, spinel, hercynite and on the basis of mole percent components gahnite, spinel, hercynite, galaxite.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
					weight percent				
ZnO	35.89	34.74	35.66	35.22	37.01	35.43	34.72	35.35	41.34
FeO	7.22	7.82	5.91	7.23	5.94	3.58	4.11	5.49	5.72
MgO	1.11	1.55	1.72	1.67	1.55	3.17	3.15	2.72	0.40
MnO	0.14	0.10	0.16	0.12	0.18	0.22	0.09	0.21	0.62
TiO2	0.04	0.02	0.04	0.04	0.03	0.12	0.02	0.03	0.10
Al2O3	55.28	56.00	55.77	55.18	54.90	57.83	55.78	54.57	51.35
SiO2	0.02	0.12	0.0	0.37	0.79	0.16	0.72	0.26	0.04
K2O	0.01	0.01	0.03	0.03	0.13	0.04	0.13	0.07	0.02
CaO	0.01	0.03	0.02	0.03	0.0	0.01	0.03	0.0	0.07
SUM	99.72	100.39	99.31	99.89	100.53	100.56	98.75	98.70	99.66
				moles (calculated on basis of 4 oxygens)					
Mn	0.004	0.003	0.004	0.003	0.005	0.005	0.002	0.005	0.016
Mg	0.050	0.069	0.077	0.075	0.069	0.138	0.140	0.123	0.019
Zn	0.802	0.766	0.794	0.782	0.819	0.765	0.765	0.791	0.957
Ca	0.0	0.001	0.001	0.001	0.0	0.0	0.001	0.0	0.002
K	0.0	0.0	0.001	0.001	0.005	0.001	0.005	0.003	0.001
Fe+2	0.144	0.161	0.123	0.138	0.103	0.088	0.087	0.078	0.004
Fe+3	0.039	0.034	0.026	0.044	0.046	0.0	0.016	0.061	0.146
Si	0.001	0.004	0.0	0.011	0.024	0.005	0.021	0.008	0.001
Al	1.971	1.971	1.981	1.955	1.938	1.992	1.961	1.948	1.898
Ti	0.001	0.0	0.001	0.001	0.001	0.003	0.0	0.001	0.002
O	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
					mole percent				
gahn	77.50	74.35	77.82	75.29	78.97	77.22	75.92	75.12	85.02
spin	4.84	6.70	7.58	7.21	6.68	13.95	13.90	11.67	1.66
herc	17.66	18.95	14.61	17.50	14.35	8.84	10.18	13.21	13.32
gahn	77.24	74.17	77.51	75.07	78.62	76.80	75.75	74.74	83.79
spin	4.82	6.68	7.55	7.18	6.65	13.87	13.87	11.61	1.64
herc	17.60	18.91	14.55	17.45	14.29	8.79	10.16	13.15	13.13
galx	0.35	0.24	0.40	0.29	0.44	0.55	0.23	0.51	1.44

Comparison with Gahnites From Other Localities

Zinc-bearing spinels are relatively minor phases that have been reported from several types of geologic settings, only some of which are similar to that of the Mineral District. Table 5 is a compilation of available data for some gahnite-bearing localities in other parts of the world. Chemical analyses of zinc spinels from the Mineral District and other localities are plotted in Fig. 5b. Specific types of zinc spinel occurrences include: (1) metamorphosed volcanogenic massive sulfides; (2) other types of metamorphosed zinc deposits (i.e., Franklin and Sterling Hill, New Jersey); (3) metapelitic or other metamorphic rocks not related to any known zinc accumulation; (4) marbles and skarns; (5) zinc-rich

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
					weight percent				
ZnO	34.46	34.82	35.76	34.62	35.18	33.58	35.65	34.10	35.68
FeO	5.61	5.21	4.61	4.99	7.37	8.80	7.18	7.86	7.20
MgO	2.34	2.46	2.13	2.91	1.51	1.82	1.62	2.30	1.74
MnO	0.24	0.21	0.22	0.23	0.11	0.14	0.09	0.13	0.15
TiO2	0.07	0.03	0.05	0.04	0.11	0.09	0.09	0.08	0.10
Al2O3	55.58	56.99	57.08	57.40	55.52	55.24	54.74	55.51	55.36
SiO2	0.08	0.0	0.13	0.0	0.0	0.0	0.01	0.02	0.0
K2O	0.03	0.04	0.03	0.04	0.01	0.01	0.02	0.02	0.0
CaO	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.02
SUM	98.43	99.77	100.02	100.25	99.82	99.69	99.41	100.04	100.26
				moles (calculated on basis of 4 oxygens)					
Mn	0.006	0.005	0.006	0.006	0.003	0.004	0.002	0.003	0.004
Mg	0.105	0.109	0.094	0.128	0.068	0.082	0.073	0.103	0.078
Zn	0.769	0.763	0.783	0.753	0.782	0.747	0.799	0.754	0.791
Ca	0.001	0.0	0.0	0.001	0.0	0.0	0.0	0.001	0.001
K	0.001	0.002	0.001	0.002	0.0	0.0	0.001	0.001	0.0
Fe+2	0.118	0.121	0.114	0.112	0.146	0.167	0.124	0.139	0.126
Fe+3	0.024	0.008	0.0	0.011	0.039	0.054	0.058	0.058	0.055
Si	0.002	0.0	0.004	0.0	0.0	0.0	0.0	0.001	0.0
Al	1.979	1.993	1.994	1.991	1.970	1.960	1.958	1.958	1.960
Ti	0.002	0.001	0.001	0.001	0.002	0.002	0.002	0.002	0.002
O	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000
					mole percent				
gahn	75.67	76.22	79.97	75.02	75.53	71.11	75.77	71.57	75.36
spin	10.37	10.87	9.50	12.73	6.54	7.78	6.95	9.74	7.42
herc	13.95	12.92	11.53	12.25	17.92	21.11	17.28	18.68	17.22
gahn	75.22	75.82	78.54	74.60	75.33	70.87	75.60	71.35	75.09
spin	10.31	10.81	9.44	12.66	6.53	7.75	6.93	9.71	7.39
herc	13.87	12.85	11.47	12.18	17.87	21.03	17.24	18.63	17.16
galx	0.60	0.52	0.55	0.57	0.27	0.34	0.22	0.31	0.36

1-4, Arminius
5-8, Cofer
9, Sterling Hill, NJ
10-13, Julia
14-18, Sulphur

pegmatites in metamorphic terrains; (6) pelitic rocks in contact metamorphic aureoles of plutons; and (7) stream sands derived from the above sources.

It is apparent that gahnite from the Mineral District is much more restricted (Figs. 5, 6) in composition than is gahnite from many other localities but is silimar to that from other massive sulfide deposits (e.g., *Bleikvassli*, *Vokes*, 1962; *Graskevardo* and *Ripudden*, *Sunblad*, 1982). In the course of the present study, the authors obtained and examined several gahnites from the Sterling Hill deposit in northern New Jersey even though that deposit is very different geologically from the Mineral District (see *Frondel* and *Baum*, 1979 for a discussion of the Sterling Hill Deposit). Examination of the Mn-rich gahnites allowed for determination of the effect of increased galaxite component on properties of

Table 5. *Comparative Listing of Gahnite-Bearing Localities*

Location	Type of occurrence	Metamorphic grade	Average ZnO wt.% in spinels	Ore mineralogy	Gangue mineralogy
1. Broken Hill, Australia	volcanogenic massive sulfides in meta-sediments	upper amphibolite (sillimanite) facies	NA	*sph, gn, Po, cpy, marc, aspy, loal, tet, as, Sn&W* minerals + many others	*q, ght,* w/minor K-spar *grt, mu, bt, ap, tour*
2. Rocky Mountains, Colorado	volcanogenic massive sulfides in amphi-bolites, feldspathic sillimanite and calc-silicate, gneisses and impure marbles	amphibolite facies	NA	*sph, cpy,* Ag-bearing *gn*	*am, mu, bt, grt, q, cord, ght*
3. Mamandur, India	base metal mineralization in quartzo-feldspathic gneiss	amphibolite facies	32.50	*sph, cpy, gn, cc, cv, po*	
4. Wind River Mts., Wyoming	small sulfide zone in meta-sediments	amphibolite facies	23.78	*mt, py, hem,* w/traces of *sph* and *cpy*	*q, bt, grt, ght*
5. Franklin and Sterling Hill, New Jersey	Zn deposit of uncertain origin in marble and calc-silicate	upper amphibolite (sillimanite) facies	42.06	*frk, znt, will, rhod, teph, ght, aph*	*cal,* Mn-augite, *bt*
6. Kemio, SW Finland	metapelites and volcanogenic amphibolites w/ no known ore deposits	upper amphibolite facies	28.06		*q, plag,* K-spar, *ght, bt, grt, cord, sill, chl, mu, tour,* Fe-sulfides
7. Adirondacks, New York	metasediments and metavolcanics w/ no known ore deposits	granulite facies	12.15		*q, plag,* K-spar, *grt, bt, sill, spl, ilm, rut, cord*

8. Old Woman Mts., California	metamorphic rock *w/* no known ore deposits	amphibolite facies	19.78		*cord, ged, am, plag, bt, ilm, q, rut, staur, apl*
9. Venn-Stavelot Massif, Belgium	metamorphosed Mn-rich slate	lower amphibolite facies	39.70		viridine, braunite, *mu, q, ght*
10. Bohemian Massif, eastern Europe	peralic pegmatite, Zn ores in quartzose schists, marbles and skarns, W deposit and stream sand	–	range 1.20 to 33.80	Zn ore – *sph* W ore – wolframite, scheelite	various assemblages in pegmatite, *bt* gneiss and marble
11. Southern Spain	contact metamorphosed pelitic rocks	amphibolite facies	3.45		*sphl, sill, bt, ilm, cord, q*
12. Donegal, Eire	contact metamorphosed pelitic rocks	amphibolite facies	7.02		*cord, grt,* feldspar, *sil*
13. Outer Hebrides	metamorphosed pegmatite	–	35.72		*q, plag,* K-spar, *mu, bt, mt, beryl, grt, ght,* columbite, monazite, zircon, *py, ap, tour, ap,* thorite + others
14. Scourie, NW Scotland	shear zone gneiss *w/* no known deposit	amphibolite facies	26.10		*ky, sill, staur,* corundum, *spl, bt, plag, q, grt, ep, ilm, hem, ap,* parovskite
15. Ceylon	gem gravels	–	18.22		
16. Graskerado, Ripudden, Sweden	volcanogenic massive sulfides	amphibolite facies	33–37.8	*po, py, gn, sph, cpy, mt, staur, bt, chl, cumm*	*q, plag, anthoph, grt,* zircon

zircon

1. *Andrews* (1922), *Stillwell* (1959), *Segnit* (1961), *Barnes* (1979), *Lawrence* (1968); 2. *Sheridan* and *Raymond* (1977), *Karlsson* et al. (1980); 3. *Gandhi* (1971); 4. *Frost* (1973); 5. *Frondel* and *Baum* (1974); 6. *Dietvorst* (1980); 7., 8. *Stoddard* (1979); 9. *Kramm* (1977); 10. *Nemec* (1973); 11. *Loomis* (1972); 12. *Atkin* (1978); 13. *Knorring* and *Dearnley* (1960); 14. *Beach* (1974); 15. *Anderson* and *Payne* (1937); 16. *Sunblad* (1982).

gahnites. The large galaxite component of those spinels results in a higher reflectance (Fig. 4) and a larger unit cell dimension (Table 3) as expected because the Mn-ion is larger than the Fe-ion.

Metamorphism and the Origin of the Gahnite

The mineralized zones of the Mineral District have been regionally metamorphosed to amphibolite grade. Minerals indicative of the metamorphic facies include almandine garnet, staurolite, kyanite and oligoclase-andesine at the

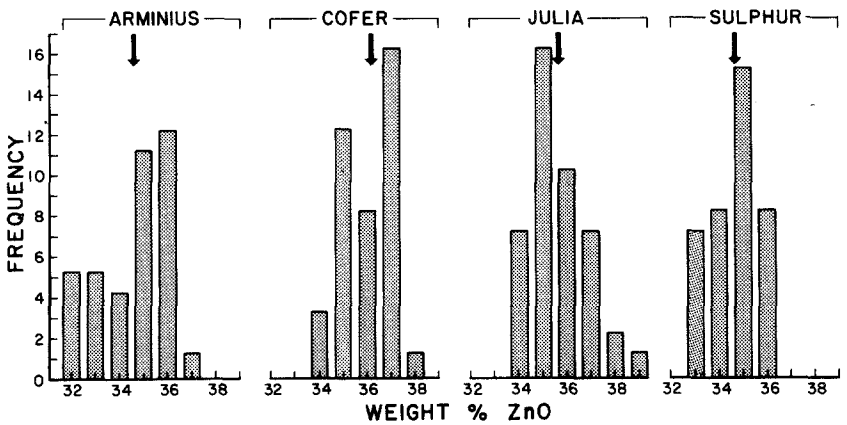

Fig. 6. Histograms of gahnite from the four deposits of the Mineral District in terms of wt.% zinc; the averages for each deposit are indicated by the arrows

Sulphur deposit (*Katz*, 1961); hornblende, almandine garnet and staurolite at the Arminius deposit (*Cox*, 1979); and garnet and kyanite at the Cofer deposit.

Electron microprobe analyses indicate a strong interdependence in the partitioning of the Fe and Mg between gahnite and biotite and the Zn and Fe between gahnite and sphalerite. Fe/Mg distribution coefficients between garnets and biotites (*Sandhaus*, 1981) are consistent among all of the deposits and indicate an equilibration temperature of approximately 470 °C on the basis of extrapolation of the curves of *Goldman* and *Albee* (1977) and *Ferry* and *Spear* (1978). This value is in close agreement with the value of 465 °C obtained from biotite/garnet pairs by *Cox* (1979). The reasonable linearity of the plot of Zn/Fe in gahnite versus Zn/Fe in biotite (especially in the Julia and Sulphur Mine samples) suggests that equilibrium between these phases is generally achieved, at least at 470 °C. It is not known if the distribution coefficient between these phases is temperature dependent.

The iron contents of sphalerites that appear to have equilibrated with pyrite and pyrrhotite during metamorphism range from 12.1 to 16.2 mol.% FeS suggestive of pressures in the range of 3 to 7.5 kb (*Scott*, 1973). No doubt

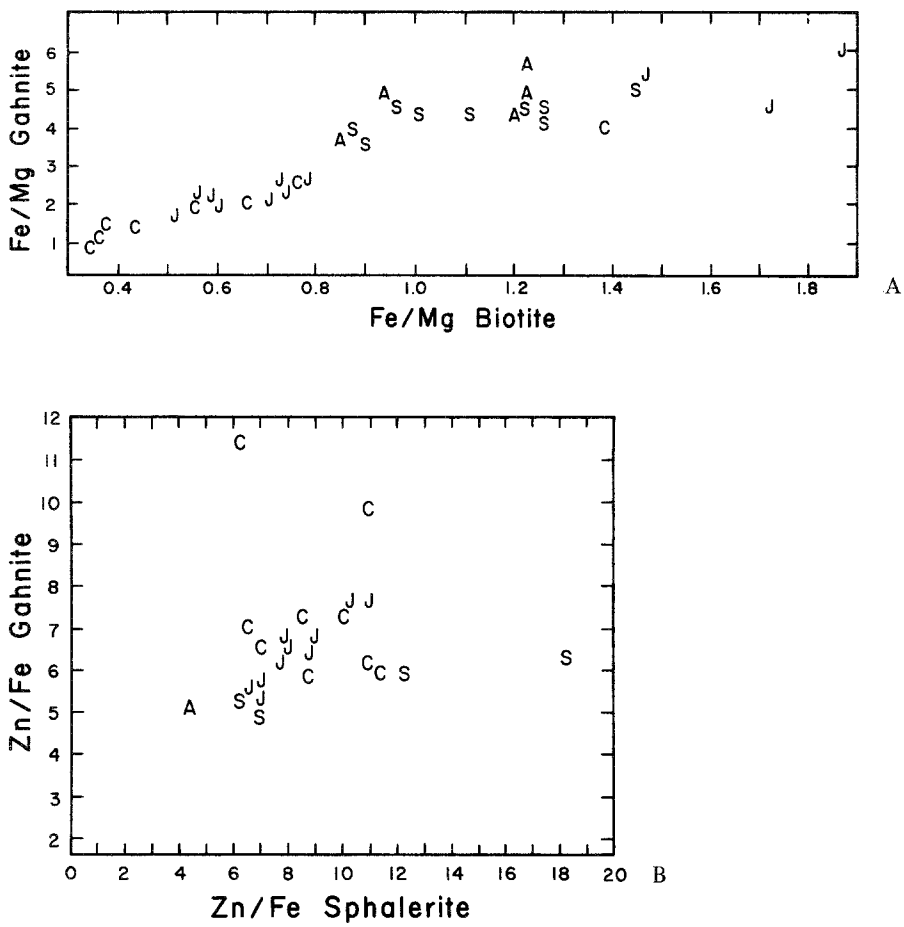

Fig. 7. Plot of distribution coefficients of: A) Fe and Mg between gahnite and biotite and B) the coefficients of Zn and Fe between gahnite and sphalerite in the deposits of the Mineral District. *A* Arminius deposit; *C* Cofer deposit; *J* Julia deposit; *S* Sulphur deposit

reequilibration has affected some of the sphalerite compositions. The presence of kyanite in some of the deposits suggests that the pressure was above about 3.5 kb at the thermal maximum.

Wall and *England* (1979) have noted that "gahnite-bearing assemblages" (at Broken Hill, Australia) cover a wide range of f_O and f_S with magnetite at higher f_O and Fe-silicates and pyrrhotite at lower f_O. The occurrence of gahnite in a very wide range of oxygen- and sulfur-controlling assemblages in the Mineral District is certainly consistent with their observation. Gahnite has been observed with pyrite, with pyrrhotite, or both and with or without magnetite. The generally widespread nature of all three of these minerals in the Mineral District does, however, suggest that at the thermal peak of metamorphism (470 °C) the f_O and

f_S would have been at or near the values dictated by the *py* + *po* + *mt* triple point (i.e., approximately 10^{-20} for f_O and 10^{-4} for f_S).

The origin of gahnite is, at best, poorly understood. Hypotheses proposed for its formation during metamorphism include:

(i) desulfidation and reaction of sphalerite with Al-bearing phases (*Frost*, 1973; *Wall* and *England*, 1979; *Sunblad*, 1982);

(ii) reaction of a preexisting zinc oxide phase, possibly adsorbed on clay minerals, with Al-bearing phases (*Segnit*, 1961; *Cox*, 1979; *Karlsson* et al., 1980);

(iii) breakdown of zincian biotite (*Dietvorst*, 1980), zincian staurolite (*Stoddard*, 1979; *Loomis*, 1972; *Atkin*, 1978), or some other zincian-silicate (*Kramm*, 1977).

The mode of occurrence of gahnite in the Mineral District is not unequivocal but appears to be consistent with either of the first two hypotheses. Specific observation relevant to this interpretation, but by no means conclusive, include the following:

(1) The Gahnite appears to occur primarily within the mineralized zones with only minor scattered grains in quartz veins.

(2) There is no systematic pattern in the distribution of gahnite vertically or laterally within the mineralized zones, but there is a tendency for the greatest concentrations of gahnite to occur at the periphery of the zones.

(3) Gahnite occurs in the presence and absence of sphalerite, but there is a general inverse relationship between the abundances of the two phases (Fig. 2). It does not, however, appear to be forming at the expense of the sphalerites.

(4) Gahnite is found in virtually all gangue mineral assemblages except for the uncommon calcite + quartz rocks.

(5) There is no discernible relationship between the presence of gahnite and biotite or the zincian staurolite (6 to 7 wt.% ZnO content), and the gahnite does not appear to be forming at the expense of sphalerite, biotite, staurolite or any other phase.

(6) Biotites are generally Zn poor, averaging approximately 0.30 wt.% ZnO (the maximum Zn-content found was 0.76 wt.%) and the Zn-staurolite is very rare (only found in four samples in the four deposits; it ranged from 6.04 to 6.90 wt.% ZnO).

(7) The inclusions within the gahnite are nearly all quartz and thus not indicative of any specific precursor. The quartz may represent material trapped during growth, or it may represent the product of a reaction of an original zinc or aluminum silicate or a clay that contained both the zinc and the aluminum.

In light of these observations, there is no compelling evidence that the gahnite owes its occurrence to sphalerite, biotite, staurolite or any other phase now present. It is probable, however, that the metamorphic recrystallization has reequilibrated grains and destroyed any textural evidence of the growth of gahnite at the expense of any other mineral. The irregular distribution with a tendency to be more abundant at the peripheries of the mineralized zones would be consistent with the zinc being present as an original zinc oxide phase or adsorbed onto clays as suggested by *Segnit* (1961). Either a phase could have

formed intermittently and locally where zinc was in excess of sulfur (as noted in portions of the Red Sea geothermal brine deposits by *Bischoff* (1969) and as suggested by *Plimer* (1978) in portions of the Broken Hill, Australia, deposit) or could have formed at the exposed edges or surfaces of sulfide zones where oxidation of sphalerite occasionally occurred between episodes of sulfide deposition. Such oxidation is seen occurring to considerable depth in modern sulfide deposits forming around sea floor vents. It is also possible that some local oxidation of sphalerite also occurred during metamorphism or that some of the sphalerite reacted directly to form gahnite during metamorphism; however, most of the sphalerite, and indeed, most of the sulfides in the ores of the Mineral District appear to have been recrystallized but not oxidized during metamorphism.

Sunblad (1982) has pointed out that gahnite occurrences in stratiform sulfide deposits in the Swedish Caledonides are confined to rocks of at least amphibolite grade. That observation is consistent with grades of metamorphism present in the gahnite-bearing zones in the Mineral District. The conclusions reached here are consistent with, though much less rigorously derived than, those reached by *Spry* and *Scott* (1984).

Potential of Gahnite as an Ore Mineral or as an Exploration Guide

Gahnite is widespread as an accessory mineral within the mineralized zones of the stratiform sulfide deposits of the Mineral District; in some of these deposits, gahnite is sufficiently abundant locally to contain a substantial amount of zinc. The highest concentration of gahnite in a single sample (35 modal percent) is equivalent to more than 12 wt.% Zn contained in the gahnite alone. Using modal and chemical data on gahnite and sphalerite from the Julia and Sulphur deposits, the relative amount of Zn contributed by each of these minerals can be estimated (Table 6). Gahnite contains 3.9% of the total Zn in the Julia deposit and 14.9% of the total zinc in the Sulphur deposit. The high proportion of gahnite-contained Zn in the sulphur deposit is, however, a reflection of a relatively low sphalerite content as well as a high gahnite content. In the Arminius and Cofer deposits, only about 1% of the total zinc is in gahnite.

The proximity of gahnite to massive sulfide ores was recognized at Broken Hill more than 60 years ago (*Andrews*, 1922), but its potential in the Mineral District and in other localities throughout the world has only recently being

Table 6. Estimated modal quantities of sphalerite and gahnite in the Julia and Sulphur deposits and the percentage of zinc of each deposit contained in each mineral.

	modal percent		wt percent Zn		percent of total Zn	
Deposit	sphalerite	gahnite	sphalerite	gahnite	sphalerite	gahnite
Julia	14	1.18	8.4	0.42	96.1	3.9
Sulphur	3.53	1.34	2.13	0.37	85.1	14.9

realized. Its discovery in many stratiform sulfide ore deposits indicates that gahnite is clearly much more common, albeit in small quantities, in these ores than previously realized. This, combined with the rarity of gahnite in any other mode of occurrence, has led *Sheridan* and *Raymond* (1977) and *Spry* and *Scott* (1982) to suggest the utility of gahnite as an exploration guide. Gahnite is hard and resistant to chemical weathering and is thus retained in gossan, saprolite float and the heavy mineral fraction of stream sediments. Gahnite is readily recognized megascopically and microscopically and thus should be used increasingly as an exploration tool.

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