THE CO-OCCURRENCE OF GREEN AND BLUE GAHNITE IN THE NAMAQUALAND METAMORPHIC COMPLEX, SOUTH AFRICA

JUDY A. HICKS, JOHN M. MOORE AND ARCH M. REID

Department of Geology, University of Cape Town, Rondebosch 7700, South Africa

ABSTRACT

Two contrasting types of gahnite are closely associated in a variety of quartzitic and garnet–phlogopite rocks at the contact between metapelitic schists and quartzites at Oranjefontein, 50 km east of Springbok in the Namaqualand Metamorphic Complex, South Africa. Green gahnite ($Ghn_{50-63}Hc_{11-20}Spl_{20-33}$) formed during prograde metamorphism of an unknown Fe-, Mn-, Mg- and Zn-rich precursor assemblage to granulite grades. The presence of minor galena and chalcopyrite suggests that sphalerite was the premetamorphic Zn-bearing mineral. Blue gahnite ($Ghn_{88-97}Hc_{2-11}Spl_{0-1}$) occurs in or is closely associated with the green gahnite-bearing rocks and in part forms overgrowths on green gahnite cores. The blue gahnite formed at relatively low temperatures by retrograde metamorphism, involving the breakdown of green gahnite, phlogopite and garnet, yielding an assemblage of end-member zinc spinel, zinc-bearing chlorite, hematite and rutile.

Keywords: gahnite, zinc-bearing chlorite, Namaqualand, Aggeneys deposit, electron-microprobe analyses, metamorphic reaction.

SOMMAIRE

Deux types différents de gahnite se trouvent intimement associés, dans une série de roches quartzitiques et roches à grenat et phlogopite, au contact entre schistes métapelitiques et quartzites à Oranjefontein, 50 km à l'Est de Springbok, dans le complexe métamorphique de Namaqualand, en Afrique du Sud. La gahnite verte ($Ghn_{50-63}Hc_{11-20}Spl_{20-33}$) s'est formée par métamorphisme prograde (jusqu'au facies granulite) d'un assemblage originel inconnu, mais riche en Fe, Mn, Mg et Zn. La présence de galène et chalcopyrite comme minéraux accessoires fait penser que le minéral de Zn prémétamorphique était de la sphalérite. La gahnite bleue ($Ghn_{88-97}Hc_{2-11}Spl_{0-1}$) se présente dans les roches à gahnite verte ou leur est intimement associée, parfois même en surcroissance sur substrat de gahnite verte. La gahnite bleue s'est formée à température relativement basse par métamorphisme rétrograde, impliquant la décomposition de gahnite verte, phlogopite et grenat, pour produire un assemblage de spinelle de zinc (pôle de solution solide), chlorite à teneur de zinc, hématite et rutile.

(Traduit par la Rédaction)

Mots-clés: gahnite, chlorite zincifère, Namaqualand, gîte d'Aggeneys, analyse par microsonde électronique, réaction métamorphique.

INTRODUCTION

The zinc spinel *gahnite* is commonly reported as a minor component of metamorphosed zinc-sulfide-bearing ore deposits (Plimer 1977, Sundblad 1982, Craig 1983). Gahnite also occurs in widespread thin quartz–gahnite bands and lenses in the metasediments of the Willyama Complex, Australia (Barnes *et al.* 1983) and is present as a minor to trace constituent of certain metapelitic rocks, ranging from low metamorphic grades (Kramm 1977) to upper-amphibolite- and granulite-facies environments (Stoddard 1979, Dietvorst 1980).

In the western part of the Namaqualand Metamorphic Complex, gahnite was reported from metaquartzitic rocks at Oranjefontein by Joubert (1971) and Spry (1984). Gahnite is a relatively common minor constituent of the Aggeneys and Gamsberg sulfide deposits (Ryan *et al.* 1982) and has recently been recognized at several further localities, either in association with sillimanite-rich rocks (Moore 1983) or in quartzitic rocks together with galena (J. Hobbs, pers. comm. 1984).

The Oranjefontein occurrence is unusual amongst recorded gahnite localities in that it contains two distinct gahnite phases, one coarse-grained and dark green, the other finer-grained and bright blue. The aim of this study is to describe this occurrence and relate the formation of the two varieties of gahnite to the metamorphic history of the area.

GEOLOGICAL SETTING

Gahnite-bearing rocks are present at Vioolskraalberg, a prominent hill at the northeastern corner of the farm Oranjefontein, approximately 50 km east of Springbok, western Cape Province (Fig. 1). They occur within a narrow belt of paragneiss enclosed by biotite gneisses and augen gneisses belonging to the Little Namaqualand Intrusive Suite of the mid-Proterozoic Namaqualand Metamorphic Complex (SACS 1980). The paragneiss sequence is preserved within a flat-lying, late-stage synformal structure (F3, Joubert 1971), and consists predominantly of quartzitic and metapelitic rocks with minor leucogneisses, two-pyroxene granulites, calc-silicate rocks and hypersthene–cordierite gneisses. The stratigraphic
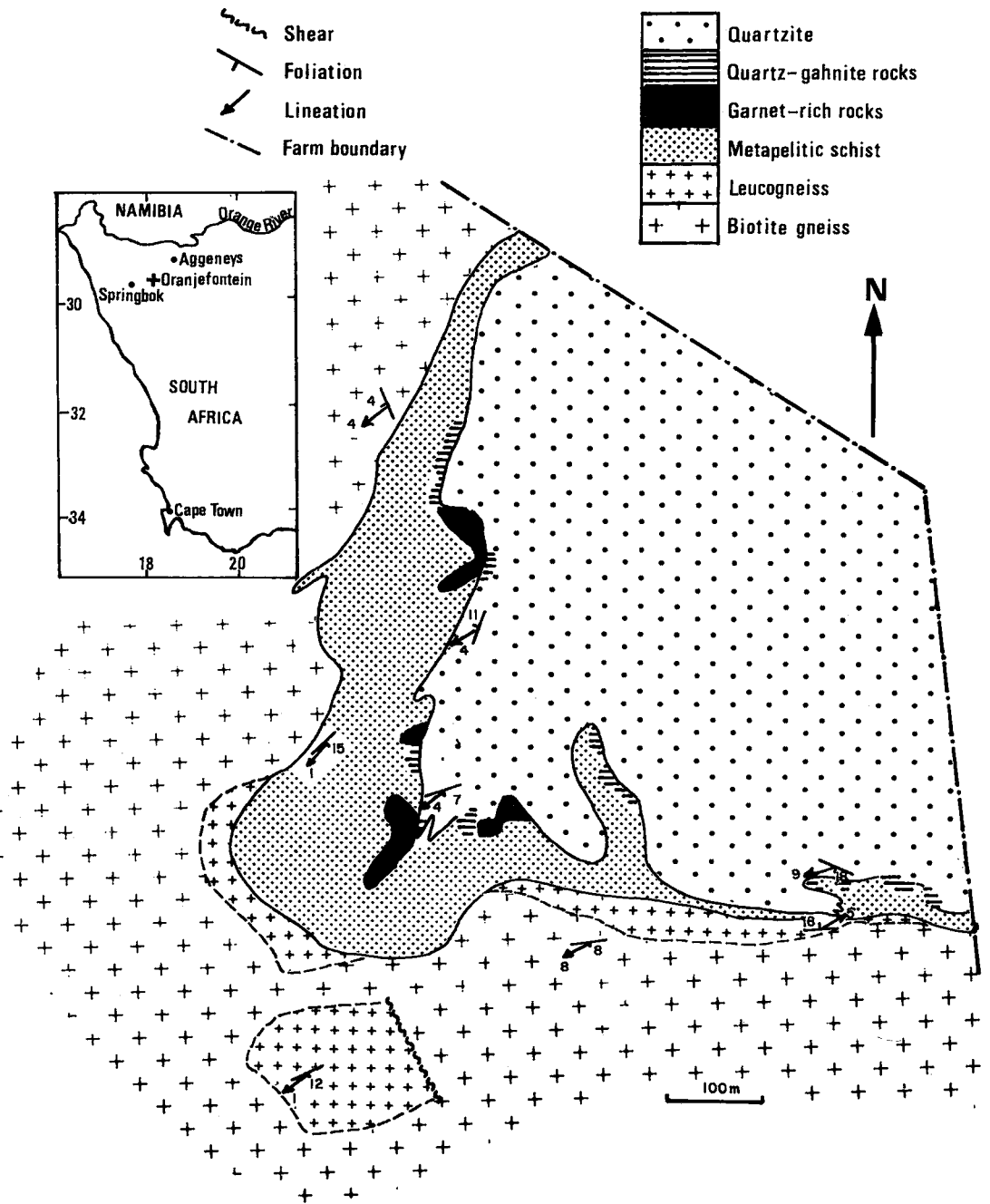
FIG. 1. Geological map of the Vioolskraalberg locality on the farm Oranjefontein. Gahnite- and garnet-bearing rocks occur at the interface between schist and quartzite. Inset: map of western South Africa showing the location of the farm Oranjefontein.

succession bears a strong resemblance to the metasediments of the lower portion of the Bushmanland Group (SACS 1980), which hosts the base-metal sulfide deposits of Aggeneys (Ryan *et al.* 1982) and

Gamsberg (Rozendaal 1980), situated approximately 70 km northeast of the study area.

Coarse-grained biotite gneiss crops out as the basal unit at Vioolskraalberg. Thin lenses of a leucocratic

quartzofeldspathic gneiss locally overlie the biotite gneiss and are succeeded by poorly exposed aluminous schists of variable thickness and composition. The metapelitic schists are capped by a thick succession of massive, coarsely crystalline, white quartzites that form the uppermost unit preserved within the paragneiss belt (Fig. 1).

Garnet- and gahnite-rich rocks occur as lenses and pods, rarely greater than 0.5 m thick and 5 m long, at the contact between the aluminous schist and the white quartzite. Massive garnet-rich rocks and garnet–phlogopite schists with minor concentrations of gahnite crop out in the uppermost portion of the schist horizon, and are overlain by gahnite-bearing quartzites that form the lowermost part of the white quartzite unit. The gahnite–quartz rocks show greater lateral extent compared to the garnet-rich rocks, which are restricted to a few lenses preserved within the major synformal fold closure (Fig. 1).

PETROGRAPHY

The Oranjefontein area is located within a major regional granulite-facies terrane (Joubert 1971), close to its northern transition to an upper-amphibolite-facies terrane. Across this boundary metapelitic rocks are transformed in dehydration and melt-forming reactions from quartz – biotite – muscovite – sillimanite schists (upper amphibolite facies) to quartz – K-feldspar – garnet – cordierite – sillimanite gneisses (granulite facies) (Albat 1984, Waters & Whales 1984). Mafic rocks are similarly transformed from hornblende – plagioclase amphibolites to orthopyroxene – clinopyroxene – plagioclase gneisses, and magnesian gneisses from cordierite – anthophyllite assemblages to cordierite – hypersthene – spinel rocks. P–T conditions in the range 700 – 900°C and 5 – 6 kilobars have been calculated for the granulite-facies terrane (Albat 1984), and estimates of 650 – 700°C in the region of 4.5 kilobars have been made for the amphibolite-facies terrane (Moore 1977).

Retrograde zones of intense chloritization and sericitization are localized along east–west-trending shear zones and fractures that cross-cut the major synformal structure at Oranjefontein. The mineral assemblages in these zones, which have a widespread distribution in the northern amphibolite-facies terrane, comprise chlorite, muscovite, epidote, hematite, calcite, albite and piemontite, indicative of greenschist-facies conditions and temperatures below 500°C (Moore 1977).

The gahnite-bearing rocks have been variously affected by both the above-mentioned metamorphic events. The garnet-rich and garnet–phlogopite-rich varieties are medium-grained, massive or poorly banded rocks in which subhedral to euhedral Mn-rich garnet $Alm_{42}Sps_{39}Prp_{13}Grs_6$ forms the main

constituent, surrounded by and in some cases penetrated by phlogopite laths. Quartz and large anhedral grains of green gahnite are present in varying amounts. Disseminated galena was found at one locality.

In retrograde examples of these rocks, garnet and phlogopite are partly or totally replaced by Mn-bearing epidote and chlorite. In the quartz-bearing varieties, phlogopite is replaced either by chlorite pseudomorphs or by blue gahnite, quartz, hematite and rutile. Phlogopite 'ghosts' can be recognized by concentrations of fine grains of hematite along original grain-boundaries and cleavages (Fig. 2), whereas blue gahnite and quartz cross-cut the former grain-boundaries (Fig. 3). Blue gahnite also fills fractures in garnet or forms polycrystalline aggregates that may show a core of green gahnite (Fig. 4).

In the gahnite-bearing quartzites, green gahnite occurs as bands or disseminations of coarse anhedral porphyroblasts. Minor constituents in these quartzites include phlogopite, garnet, galena, rare chalcopyrite and zircon. Garnet in the gahnite-bearing quartzites is considerably Mg-rich and Mn-poor $(Alm_{36}Sps_{25}Prp_{39})$ compared to that in the garnet-rich rocks. Subhedral to euhedral blue gahnite commonly forms a corona surrounding the porphyroblasts or occurs as aggregates and veinlets in the quartz matrix (Fig. 4). The aggregates of blue gahnite are associated with irregular masses of webbed hematite. Phlogopite is almost entirely replaced by quartz, blue gahnite, hematite and rutile. Locally, however, small laths of mica, totally enclosed in quartz or green gahnite, have survived the retrograde event.

Analyses of these phlogopite laths show that they have Mg/(Mg + Fe) values of approximately 0.75 and contain, on average, 0.36 wt.% ZnO. Prograde biotite from similar gahnite-bearing metamorphic rocks surrounding the Broken Hill orebody, Australia (Plimer 1977) and in the Wind River Mountains, Wyoming (Frost 1973) also contain significant amounts of zinc (up to 0.5 wt.% ZnO). Zinc-bearing biotite with up to 0.24 wt.% ZnO from Kemiö, Finland, is believed to be a precursor to gahnite formed during retrograde metamorphism (Dietvorst 1980).

Retrograde chlorite in the garnet- and gahnite-rich rocks, much of it as a pseudomorph after phlogopite, shows a range of compositions reflected by varying Mg/(Mg + Fe) values (0.21 to 0.57). The Oranjefontein chlorite also contains significant amounts of zinc (3.9 to 7.5 wt.% ZnO) and manganese (2.8 to 4.4 wt.% MnO). The zinc and manganese contents vary widely, even within single grains. Reports of zinc-bearing chlorite are rare (e.g., Frondel & Ito 1975), although chlorite is a common phase in many zinc-rich sulfide deposits.

Two distinct metamorphic parageneses are present in the garnet- and gahnite-rich rocks. An earlier paragenesis is represented by relict porphyroblasts of
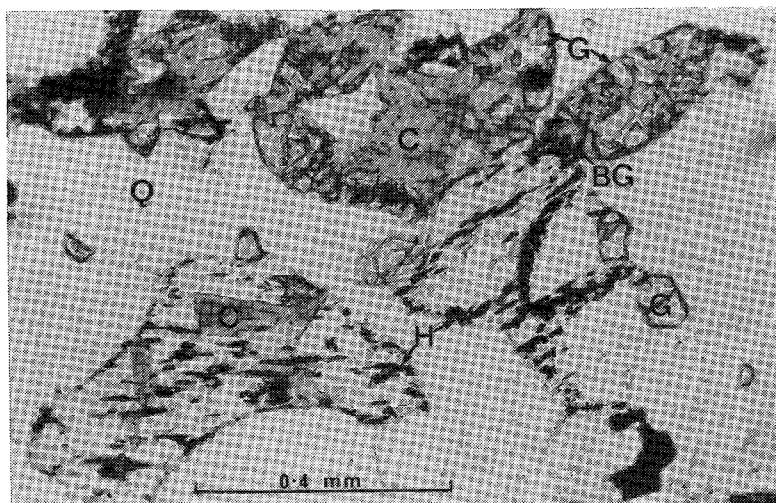
FIG. 2. Photomicrograph of garnet-bearing quartzite. Former grain-boundaries and cleavage planes of phlogopite are partly outlined by hematite (H) blebs. Quartz grains Q are optically continuous across the former grain-boundaries of phlogopite. Chlorite C partly replaces garnet G and also occurs within the 'ghost' phlogopite as does blue gahnite BG.
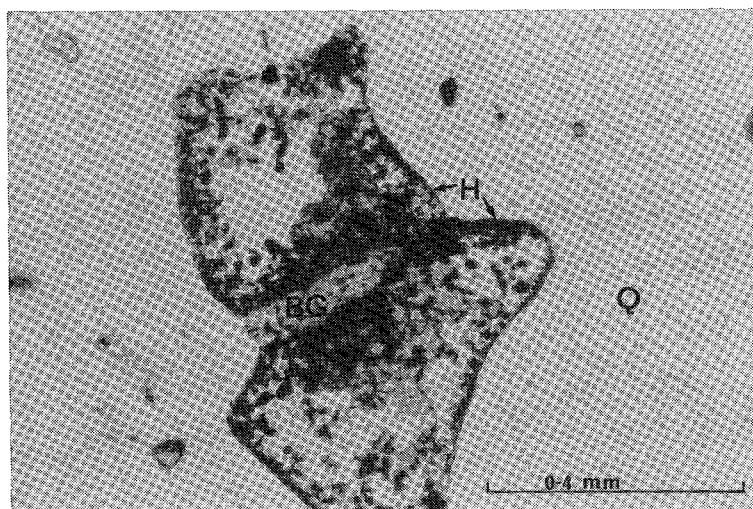

FIG. 3. Photomicrograph of gahnite-bearing quartzite. Hematite H blebs form haloes outlining two former phlogopite grains. Blue gahnite BG occurs preferentially in association with 'ghost' phlogopite, transgressing former grain-boundaries of phlogopite.

green gahnite associated with garnet, phlogopite and quartz. This mineral suite represents the regional prograde granulite-facies metamorphic event. A subsequent paragenesis is represented by a variety of lower-grade minerals, as pseudomorphs or partial replacements of the prograde assemblage. Garnet is replaced by chlorite and epidote, phlogopite by chlorite as well as blue gahnite, quartz, hematite and rutile, and green gahnite by blue gahnite. This more localized greenschist-facies mineral suite appears to be associated with retrograde metamorphism accompanying the late-stage episode of shearing.

MINERAL CHEMISTRY OF GAHNITE

Representative electron-microprobe data on green and blue gahnite, Zn-bearing chlorite, garnet and phlogopite are listed in Tables 1 and 2. Gahnite com-
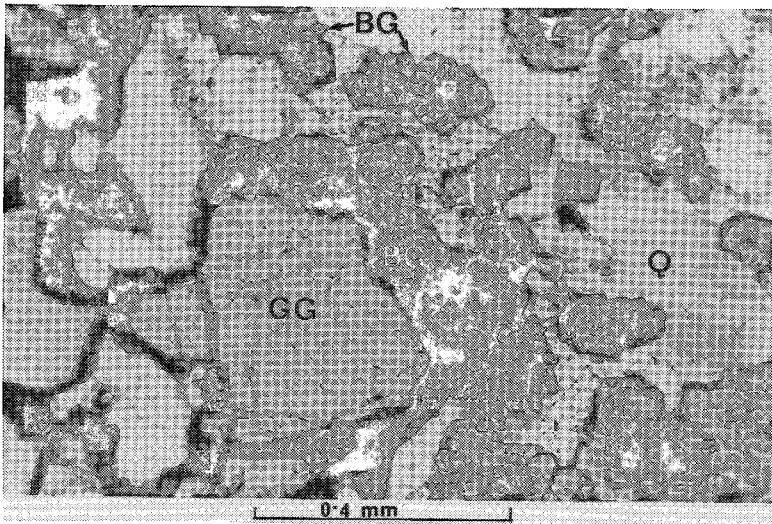
FIG. 4. Photomicrograph of a gahnite-bearing quartzite showing coarse green gahnite GG rimmed by blue gahnite BG in a quartz matrix Q. Many of the small aggregates of blue gahnite have a core of green gahnite.

TABLE 1. CHEMICAL COMPOSITION OF GAHNITE FROM NAMAQUALAND

	1. Green Gahnite		2. Blue Gahnite	3. Aggeneys Gahnite	
TiO_2	0.01	(.0.01)	0.12	(0.20, 0.1 - 0.4)	0.01	
Al_2O_3	60.08	(59.12, 57.7 - 60.8)	55.55	(55.53, 54.3 - 57.1)	57.04	(56.3 - 57.6)
FeO*	4.96	(6.98, 4.7 - 8.9)	2.10	(1.92, 0.8 - 2.8)	7.12	(6.1 - 7.8)
MnO	0.27	(.0.33, 0.1 - 0.6)	0.09	(0.06, 0 - 0.2)	0.51	(0.5 - 0.6)
MgO	7.89	(6.69, 4.8 - 7.9)	0.06	(0.10, 0 - 0.3)	1.15	(0.9 - 1.3)
ZnO	26.56	(26.82, 24.5 - 29.7)	42.05	(42.03, 40.8 - 43.3)	33.60	(32.9 - 34.9)
TOTAL:	99.77		99.97		99.43	
O	4		4		4	
Ti	0.000		0.003		0.000	
Al	1.993		1.994		2.014	
Fe	0.117		0.053		0.178	
Mn	0.007		0.002		0.013	
Mg	0.331		0.003		0.051	
Zn	0.552		0.945		0.743	
	3.000		2.999		3.000	

* Total iron as FeO. 1. Green gahnite from JE23 (gahnite quartzite). Numbers in brackets are the average and range for all 25 compositions of green gahnite. 2. Blue gahnite from JE18 (gahnite garnet quartzite). Numbers in brackets are the average and range for all 25 compositions. 3. Average composition and range (in brackets) for 11 analyses of gahnite from the Broken Hill ore body, Aggeneys, Namaqualand. Analyses by electron microprobe (Cameca, accelerating potential 15 kV, sample current 40 nA, against natural and synthetic mineral standards).

positions, normalized to molar proportions of end-member gahnite, hercynite and spinel, are plotted on a triangular diagram (Fig. 5) that also shows the composition of gahnite from the Aggeneys ore deposit. Figure 6 (adapted from Spry 1984) provides a comparison of the composition of the Oranjefon-tein gahnite with that of gahnite from other localities.

Green gahnite has a compositional range of $Ghn_{50-63}Hc_{11-20}Spl_{20-33}$, and blue gahnite has a more restricted range of $Ghn_{88-97}Hc_{2-11}Spl_{0-1}$. The Oran-jefontein green gahnite is relatively Mg-rich compared to gahnite from typical aluminous metasedi-ments or metamorphosed sulfide deposits. Blue gahnite is very close to the end-member composition, more so than most reported compositions from

metasediments and sulfide deposits (Fig. 6).

In the Oranjefontein samples in which green gahnite porphyroblasts are rimmed by blue gahnite, there is an abrupt increase in Zn content and a cor-respondingly abrupt decrease in Fe and Mg content between the green core and blue rim (Fig. 7). The two varieties of gahnite are each homogeneous. The blue gahnite commonly occurs as a polycrystalline overgrowth on single, large porphyroblasts of green gahnite (Fig. 4). The blue gahnite apparently formed subsequently to the green gahnite during a distinct later event, and not as the result of late-stage equilibration with falling temperature, as observed in zoned crystals at other localities (Spry 1984).

Green gahnite coexisting with quartz, muscovite,

TABLE 2. CHEMICAL COMPOSITION OF ASSOCIATED MINERALS

	1. Garnet	2. Phlogopite	3. Chlorite
SiO_2	38.76	37.09	27.84
TiO_2	0.04	4.90	0.03
Al_2O_3	22.16	15.57	19.23
FeO*	17.98	9.97	10.53
MnO	9.77	0.38	3.58
MgO	9.11	16.73	21.90
CaO	2.42		
ZnO		0.35	5.34
Na_2O		0.19	
K_2O		9.27	
	100.24	94.46	88.95
O	24	22	28
Si	5.953	5.973	5.604
Ti	0.004	0.594	0.004
Al	4.012	2.955	4.681
Fe	2.309	1.343	1.774
Mn	1.271	0.052	0.610
Mg	2.085	4.015	6.570
Ca	0.398		
Zn		0.041	0.794
Na		0.061	
K		1.905	

* Total iron as FeO. 1. Garnet from JE3 (gahnite quartzite). 2. Mica from JE2 (gahnite quartzite). 3. Chlorite from JE36 (garnet-phlogopite rock). These are selected compositions of phases that occur with a range of composition in the gahnite-bearing rocks. Analyses by electron microprobe (Cameca, accelerating potential 15 kV, sample current 40 nA, analyzed against natural and synthetic mineral standards).

biotite, sphalerite and other sulfides from the massive-sulfide zone of the Broken Hill upper orebody at Aggeneys has a zinc content intermediate between the prograde green gahnite and the retrograde blue gahnite from Oranjefontein (Fig. 5). The

Aggeneys gahnite is also relatively more Fe-rich and Mg-poor and plots in the field of gahnite from typical metamorphosed massive-sulfide deposits, as defined by Spry (1984) (Fig. 6).

DISCUSSION

There is no direct evidence in the Oranjefontein samples of the nature of the zinc-bearing precursor phase to the prograde green gahnite. The presence of minor galena and chalcopyrite associated with the gahnite is consistent with a hypothetical precursor-assemblage containing sphalerite. Lithological and stratigraphic similarities to the sulfide ores of Aggeneys and Gamsberg also suggest that sphalerite is the most probable candidate. It is therefore proposed that the green gahnite formed during prograde metamorphism, culminating at granulite grade, by reactions involving the desulfidation of sphalerite (Frost 1973, Williams 1983, Spry 1984).

The relatively high Mg content of the green gahnite and phlogopitic mica suggests that chlorite or Mg-rich clays, such as palygorskite or attapulgite, may have been involved as precursor components. A probable prograde reaction involves sphalerite together with magnesian clay minerals reacting to
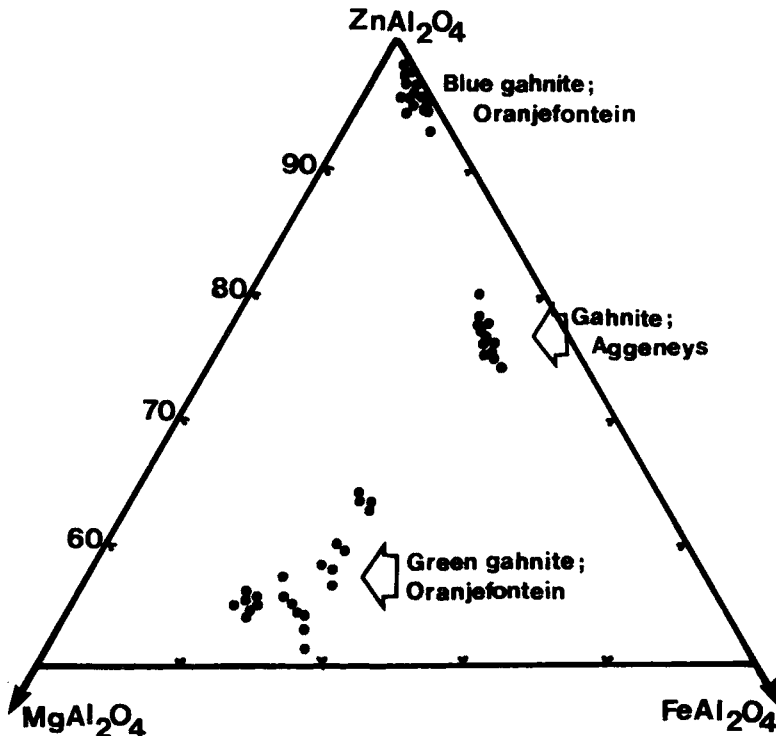

FIG. 5. Triangular plot showing the composition of blue and green gahnite from Oranjefontein and gahnite from the Broken Hill orebody, Aggeneys. Compositions have been normalized to end-member gahnite, spinel and hercynite (after removal of calculated galaxite, chromite and magnetite).

produce green gahnite + phlogopite + garnet + quartz + S_2 + H_2O. Minor, but significant, amounts of zinc were taken up by phlogopite during this reaction.

Mineralogical and textural evidence for the formation of near-end-member blue gahnite indicates that it formed during a period of retrograde metamorphism of greenschist grade subsequent to the formation of green gahnite. This evidence includes the appearance of blue gahnite in transgressive veins, its presence as coronas mantling green gahnite or as grains cutting across the original boundaries of phlogopite 'ghosts', and its euhedral crystal habit. Mobilization of K, Si, Zn and Mg within the system is required to explain the wide variety of phlogopite-replacement assemblages observed in the gahnite-bearing rocks. This ranges from pseudomorphism by chlorite to transgressive replacement by varying proportions of quartz, blue gahnite, hematite and rutile.

Dietvorst (1980) proposed the formation of gahnite during breakdown of zinc-bearing biotite to form chlorite. Overstepping of the zinc-saturation limit of biotite occurred due to an increase in the zinc content of the remaining biotite as chloritization proceeded. An implication of this breakdown reaction is that zinc does not enter the newly formed chlorite phase to any large degree. At Oranjefontein, chlorite contains more zinc than the phlogopite, and this process cannot have operated.

Using mineral compositions from Tables 1 and 2, it is possible to propose the following reaction for the retrograde formation of blue gahnite: green gahnite + phlogopite + garnet + quartz + $H_2O \rightarrow$ blue gahnite + chlorite + rutile + hematite + sericite. Observed retrograde assemblages have abundant quartz replacing phlogopite and very little sericite, suggesting that the blue-gahnite-forming reaction was accompanied by the local addition of SiO_2 and removal of potassium under open-system conditions.

The presence of gahnite–quartz assemblages in granulite-, amphibolite- and greenschist-facies parageneses indicates that this mineral association is stable over a wide range of P–T conditions and fluid compositions. Frost (1973) and Kramm (1977) observed that with decreasing metamorphic grade, increased incorporation of zinc into spinel stabilizes it in quartz-rich environments. Wall & England (1979) have commented on the potential for using the hercynite component of zincian spinel in the presence of quartz, almandine and sillimanite as a geothermometer in high-grade peraluminous metamorphic rocks. These findings are apparently supported by the data from the Namaqualand Metamorphic Complex, where the mole fraction of gahnite in spinel coexisting with quartz increases from granulite-facies gahnite at Oranjefontein (Ghn < 65%), through amphibolite-facies gahnite
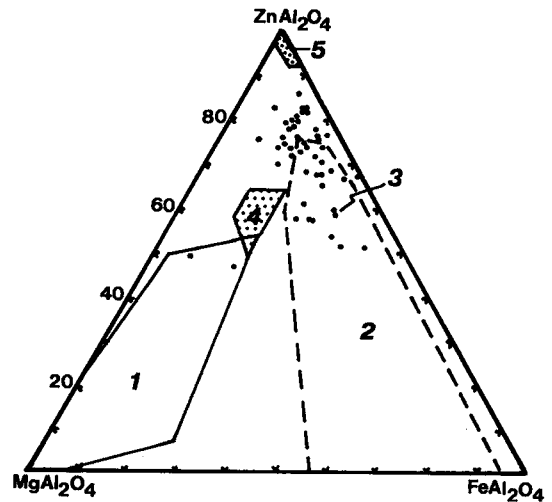

FIG. 6. Composition of zinc-bearing spinel (after Spry 1984). Compositional fields 1-5 represent zinc-bearing spinel from 1 marbles, 2 aluminous metasediments, 3 (dots) metamorphosed massive-sulfide deposits, 4 green gahnite from Oranjefontein, and 5 blue gahnite from Oranjefontein.
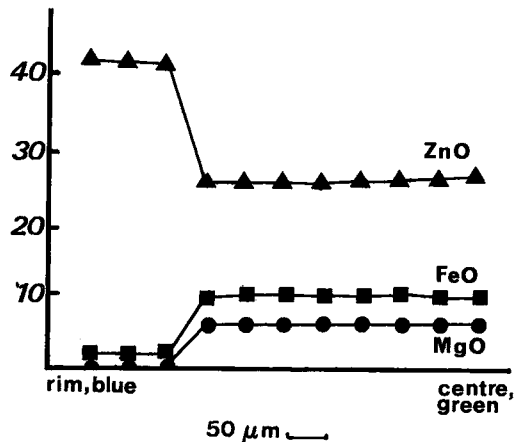

FIG. 7. Composition profile across a composite grain of green gahnite rimmed by blue gahnite. Plotted data (weight percent ZnO, FeO, MgO) are taken from complete electron-microprobe analyses made at 50-μm intervals across the grain from core to rim.

from Aggeneys (Ghn 74–80%) to the retrograde greenschist-facies gahnite at Oranjefontein (Ghn > 85%) (Fig. 5). The presence of additional zinc-bearing minerals (phlogopite, sphalerite, chlorite) in all of these assemblages indicates that zinc availability was not a limiting factor of spinel composition.

Gahnite–quartz rocks contain Fe sulfides at Aggeneys, Fe silicates in the prograde assemblage at Oranjefontein and hematite in the retrograde assem-

blage, indicating stability over a wide range of $f(O_2)$ conditions. The magnetite component of zincian spinel coexisting with almandine, sillimanite and quartz can be used as an indicator of metamorphic $f(O_2)$ (Wall & England 1979). Molar proportions of magnetite were calculated for Namaqualand spinel coexisting with garnet, biotite or phlogopite and quartz. Green gahnite from the sulfide-bearing gahnite quartzites at Oranjefontein and gahnite from the Aggeneys orebody have magnetite components of zero, whereas the green gahnite from the sulfide-free garnet-rich rocks at Oranjefontein has a magnetite component of approximately 2%. Variations in the mole fraction of magnetite in the spinel at constant P–T suggest that the gahnite–quartz association may also be an indicator of locally prevailing $f(O_2)$ during metamorphism in the Namaqualand Metamorphic Complex.

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