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Geochemistry and Metamorphism of the Prieska Zn-Cu Deposit, South Africa

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Abstract

The Prieska orebody is a 50-million-ton massive sulfide Zn-Cu deposit situated near the eastern border of the middle Proterozoic Namaqua province of southern Africa.

The strata-bound, stratiform deposit lies in a terrane which has been affected by high-grade metamorphism and intense deformation. Textures now seen in the ore and country rocks are not primary but reflect the complex tectono-metamorphic history. The deposit is contained in a peraluminous unit underlain by a metadacite and overlain by a composite sequence containing metapelites, metabasic rocks, and a variety of reworked volcanic rock types. Amphibolite layers that originated as intrusive basaltic dikes and sills are found in all of these rock types.

It is suggested that the massive sulfide ore formed above hydrothermally altered metadacite. The rock types thus derived include a gedrite-bearing assemblage, the metamorphic equivalent of a chloritic alteration pipe, and a quartz-perthite-sillimanite gneiss representing silicified and sericitized sediments at the floor of the discharge basin. Overlying these rocks is the massive sulfide unit. Calcite-anhydrite-barite rocks immediately above the ore may have formed a sulfate-carbonate capping during sulfide deposition.

The Prieska deposit and other smaller sulfide deposits in the same region have geochemical features (including metal composition and Pb and S isotope characteristics) that distinguish them from the important massive sulfide deposits of the central part of the Namaqua province. Whereas the Prieska deposits are related to hydrothermal action in a volcano-sedimentary sequence, no metamorphic equivalents of alteration pipes have been found at the sediment-hosted Aggeneys-Gamsberg deposits.

Introduction

DURING the last two decades several strata-bound, stratiform massive sulfide deposits were discovered in the middle Proterozoic, high-grade metamorphic Namaqua province. Their size and composition are given in Table 1 and their distribution is shown in Figure 1. The largest individual deposits are around Aggeneys in the central part of the province.

The Prieska Zn-Cu deposit and the smaller deposits at Areachap and Kielder are situated close to the eastern boundary of the Namaqua province (Fig. 1). This paper attempts to reconstruct the geologic environment at the time of origin of the Proterozoic Prieska Zn-Cu orebody.

Two conflicting models have been proposed for the origin of the Prieska Zn-Cu deposit. Middleton (1976) suggested a model based on explosive volcanism, whereas Wagener (1980) and Wagener and Van Schalkwyk (1986) favored one dominated by chemical sedimentation, not directly related to volcanism or exhalative action. Both authors based their conclusions largely on the recognition of what they considered to be primary textures in the highly metamorphosed ore and surrounding silicate rocks.

The validity of these models is examined in this work and some fundamental differences between the Prieska Zn-Cu deposit and the Aggeneys-Gamsberg deposits are shown.

Regional Stratigraphy and Age

The eastern part of the Namaqua province has been subdivided by Hartnady et al. (1985) into two tectonic regions; the Kakamas terrane, very similar to the central part of the Namaqua province, and the Upington terrane, considered to be transitional between the Namaqua and Kheis provinces (Fig. 1).

The exposed supracrustal rocks along the eastern margin of the Kakamas terrane belong to three different formations. The Copperton Formation (Cornell et al., 1986) in the south contains the Prieska Zn-Cu deposit and the Kielder deposits described by Gorton (1981); the Areachap deposit is contained within the Jannelsepan Formation (Vajner, 1978). The Hartebeest Pan Formation (Vajner, 1974) in the central portion of the eastern Kakamas terrane contains no significant strata-bound, stratiform Zn-Cu deposits. Collectively the three formations are included in the Areachap Group of the Korannaland Sequence (SACS, 1980).

Several attempts have been made to determine the age of the Korannaland Sequence, the results of which

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TABLE 1. Cu-Pb-Zn-Ag Contents of Some of the Stratiform Base Metal Sulfide Deposits in the Namaqua Province

Deposit	Million metric tons of ore	Cu (%)	Pb (%)	Zn (%)	Ag (g/ton)	Reference
Prieska Cu-Zn mine	47	1.7		3.8		1
Areachap mine	8.9	0.4		2.24		2
Black Mountain	81.6	0.75	2.67	0.59	29.83	3
Broken Hill	85	0.34	3.57	1.77	48.10	3
Big Syncline	101	0.04	1.01	2.45	12.90	3
Gamsberg	143		0.55	7.41		4

References: 1, Wagener (1980); 2, Voet and King (1986); 3, Ryan et al. (1982); 4, Rozendaal (1980)

are summarized in Table 2. The Rb-Sr isotope system in these rocks has been influenced by the regional metamorphism and does not reflect the age of formation. Theart (1985) concluded that lead contained in the ore has an anomalous (mixed) character and that its isotopic composition does not have age significance. Lead is thought to have invaded the wall rocks of the deposits during the long tectono-metamorphic history, rendering the Pb isotope composition in rocks near the ore deposits unsuitable for age determination. Samples collected from the Hartebeest Pan Formation were analyzed by Theart (1985) and R. Scheepers (pers. commun., 1986). These rocks, unrelated to massive sulfide mineralization, gave a Pb-Pb isochron age of 1,535 ± 98 m.y. (2 σ) (μ_2 = 9.86), which may also represent the age of the ore-bearing Copperton and Jannelsepan Formations. Sm-Nd age determinations gave a maximum of 1,514 ± 80 m.y. when laminated amphibolite samples were included in the regression, although a younger 1,350 ± 130-m.y. age was preferred by Cornell et al. (1986) in view of the lead and strontium isotope systematics

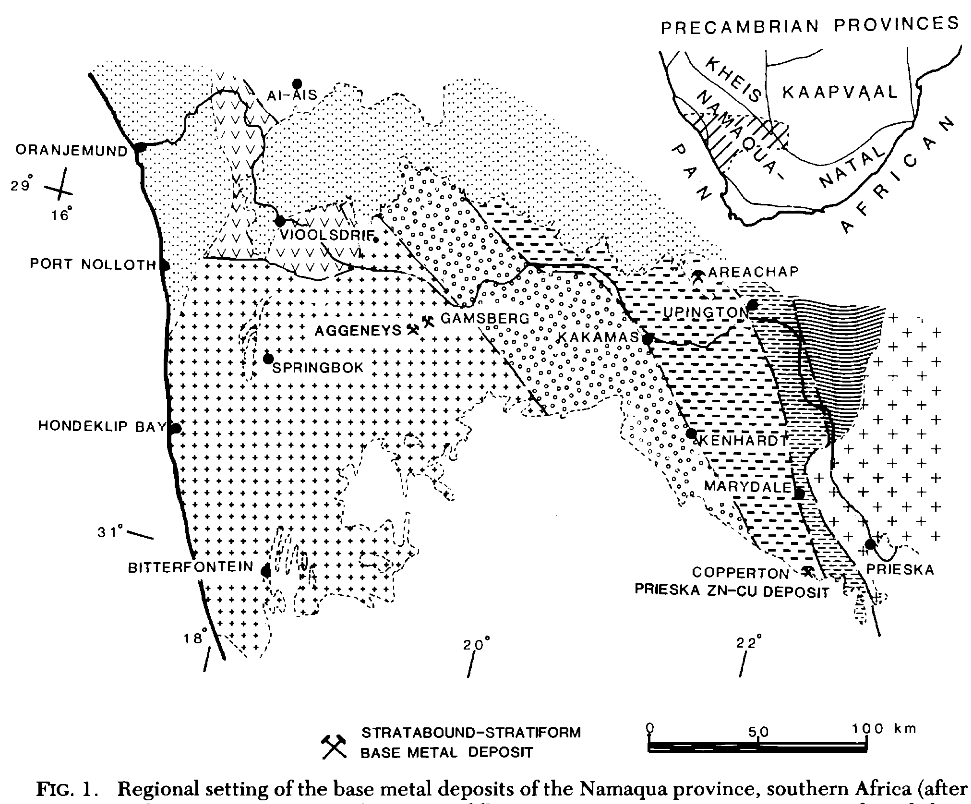


FIG. 1. Regional setting of the base metal deposits of the Namaqua province, southern Africa (after Hartnady et al., 1985). Terrains within the middle Proterozoic Namaqua province are from left to right: Bushmanland (small crosses), Aus (circles), Kakamas (thick dashes), and Upington (thin dashes). The Namaqua province is bounded to the north by the early Proterozoic Richtersveld province (V's) and by rocks of pan-African age (dots), to the south by Karoo sedimentary rocks, and to the east by the Kheis (waved lines) and Kaapvaal (large crosses) provinces.

TABLE 2. Geochronology of the Korannaland Sequence

Method	Age (m.y.)			Reference
	Copperton Formation	Jannelsepan Formation	Hartebeest Pan Formation	
Rb-Sr (whole-rock isochron)	1,312 ± 110			1
Pb-Pb (galena model age)	1,305 ± 100			2
Rb-Sr (whole-rock errorchron)		1,319 ± 710 (Olive Member)		3
Pb-Pb (whole-rock errorchron)		$1,208^{+264}_{-282}$ (Olive Member)		3
U-Pb (zircon mineralization age)		1,120 (Olive Member)		3
Rb-Sr (whole-rock errorchron)		1,268 ± 246 (Group II)		3
Rb-Sr (whole-rock isochron)	1,210 ± 38			4
Pb-Pb (whole-rock isochron)			1,535 ± 98	5
Sm-Nd (whole rock)	1,514 ± 80			4[1]
Sm-Nd (whole rock)	1,350 ± 130			4[2]

References: 1 = Cornell (1978), 2 = Köppel (1980), 3 = Barton and Burger (1983), 4 = Cornell et al. (1986), and 5 = Theart (1985)
[1] Maximum
[2] Preferred age

of rocks from the Copperton and Jannelsepan Formations.

Regional Structure of the Kakamas Terrane

At least three periods of folding, subsequent shearing, and faulting affected the supracrustal sequences along the eastern margin of the Kakamas terrane. The earliest period of deformation is represented by isoclinal slip folds with subhorizontal axial planes. This was followed by the formation of buckle folds with subhorizontal axial planes. Subsequent north-south-directed stress caused broad open folds to develop and their interference with the earlier folds is responsible for the regional basin and dome structures. During and after the third period of folding, the Upington terrane was activated as a transcurrent zone of shearing (Van Zyl, 1981).

The following structural features constrain models for the genesis of the orebodies:

1. Supracrustal rocks at different localities along the eastern margin of the Kakamas terrane all show the effects of the same tectono-metamorphic history.
2. The units containing the massive sulfide deposits show the imprint of all the phases of folding recorded in the country rocks.
3. Although the sulfide ores are deformed, they were not concentrated along fold axes nor mobilized into late shear zones. The apparent thickening of the ore is an exception since this presents the position where the thickest part of the orebody, forming a southerly plunging linear feature on the longitudinal section of the orebody, enters the hinge zone of the fold.
4. The effects of the deformation were so severe that no primary microscopic and mesoscopic textures in the sulfide ores and silicate wall rocks survived.
5. Although the banded nature of the sequence may reflect primary compositional differences, this cannot be regarded as proof of an initially concordant sequence, since crosscutting contact relationships are transposed into apparent parallelism during extensive tectonic flattening.

Metamorphic Evolution

The Copperton, Hartebeest Pan, and Jannelsepan Formations all show evidence of the same metamorphic history. It is not seen as a sequence of distinct metamorphic events separated by periods of lower metamorphic grade but rather as a continuous cycle of prograde and retrograde reactions.

The different phases of deformation are superimposed on the metamorphic evolution, each phase characterized by fabric elements made up of diagnostic mineral assemblages, which reflect the conditions at the time of their formation. The notation phase 1 to 4 is used to describe different phases in this metamorphic history in the sense explained above. Textural evidence of these phases is summarized in Table 3.

Phase 1

Metamorphic conditions during the early fabric-forming event (isoclinal slip folding) are confined to the stability field of sillimanite and to temperatures above the stability field of coexisting quartz and muscovite. For a restricted group of whole-rock compositions these metamorphic conditions are also within

TABLE 3. Petrographic Indicators of the Metamorphic History

Phase	Silicate assemblages	Sulfide assemblages
1	A. Foliation in peraluminous rocks defined by biotite and sillimanite B. Orthopyroxene-bearing parageneses C. Inferred staurolite-bearing parageneses	No textural features outlasted subsequent metamorphism
2	A. Cordierite coronas found around the breakdown products of staurolite and separating sillimanite from biotite and almandine B. Staurolite replaced by hercynite, sillimanite, and cordierite C. Corundum replaces sillimanite within grains rimmed by cordierite D. Extensive development of migmatitic gneisses in the Hartebeest Pan Formation	Development of granoblastic textures retained in monomineralic clasts formed during the subsequent deformation
3	A. Replacement of cordierite by one or more of the following minerals: sillimanite, phlogopite, and almandine B. Replacement of hypersthene by anthophyllite and gedrite C. Invasion of feldspar grains by myrmekitic intergrowths of quartz and albite D. Minor cataclasis indicated by fine-grained recrystallized quartz at grain boundaries	Textures reflecting the durchbewegung process seen as clasts of monomineralic pyrite and sphalerite aggregates together with clasts of the wall rocks all contained in a recrystallized sulfide matrix
4	A. Formation of assemblages containing one or more of the following minerals: chlorite, muscovite, epidote, calcite, and quartz	Annealing textures seen as recrystallization of sulfide and gangue minerals

the stability field of coexisting cordierite, magnesium-rich staurolite, orthopyroxene, and almandine. Evidence for the former existence of staurolite is shown in Figure 2. This inferred paragenesis would be stable at approximately 700° to 750°C and 5.5 to 6.5 kbars (Schreyer, 1976).

Phase 2

The absence of a directional fabric in stage 2 minerals shows that no significant deformation can be linked to this stage which represents the thermal peak of metamorphism.

The following two reactions characterize this stage: phlogopite + Al silicate + quartz = cordierite + K-feldspar + water (Schreyer and Seifert, 1969), and staurolite = cordierite + hercynite + Al silicate (Richardson, 1968). Anatexis occurred in some metapelitic gneisses.

These reactions indicate an increase in the temperature without much change in the pressure compared to stage 1 conditions. The temperature was somewhat higher than 730°C and the pressure remained between 5.5 and 6.5 kbars.

Phase 3

A group of grain boundary textures provides evidence for a metamorphic event following the formation of the cordierite-bearing assemblages. These textures, illustrated in Figure 3, formed during the second phase of folding (buckle folding), and the growth of biotite implies the influx of an aqueous fluid. This influx appears to have been short-lived as the textures are of an incipient nature. Phase 3 pressure-temperature conditions returned to those prevailing during phase 1.

Phase 4

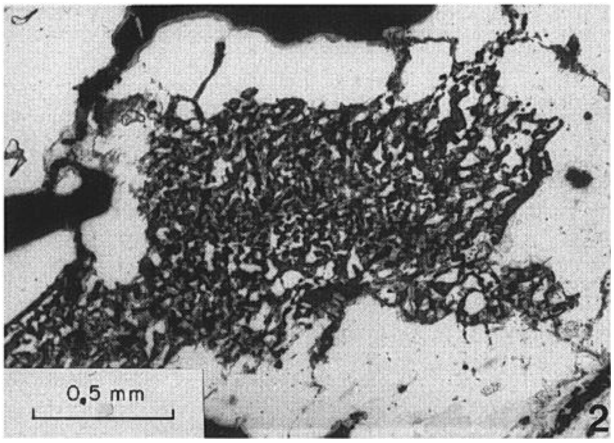
A marked decrease in temperature and pressure took place before the formation of hydrous retrograde assemblages which reflect low-grade metamorphic conditions. The fluid needed for the formation of these hydrous minerals may have been derived from crystallization of partial melts generated during phase 2 and also from crystallization of late tectonic granite plutons. Pegmatites derived from these magmas intruded the supracrustal sequences at various times after the beginning of phase 3.

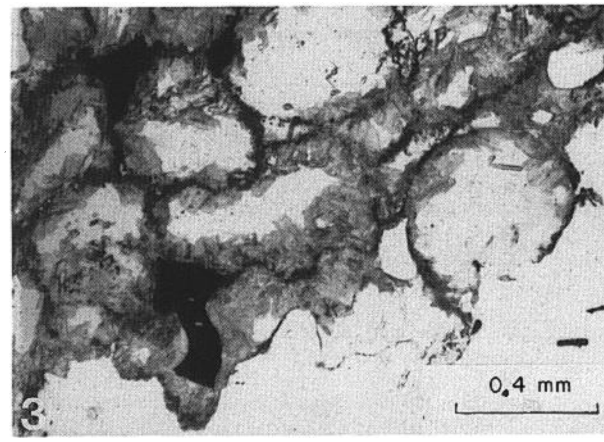
Metamorphism of the Ore

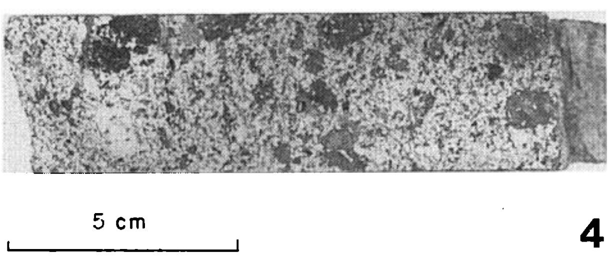
The most prominent mesoscopic feature of the Prieska ore is the presence of abundant rounded fragments of gangue material of various sizes contained in a matrix of sulfide minerals (illustrated in Fig. 4). These gangue aggregates consist of all the lithological types of the wall rocks on both sides of the ore and also of monomineralic pyrite aggregates. In appearance this is strikingly similar to the textures caused by the process called "durchbewegung" described by Vokes (1969); a process whereby fragments of the host rock become detached and rotated as relatively competent clasts within a matrix of sulfide minerals that behaved plastically during deformation.

The sequence of textural responses to deformation and metamorphism of the massive sulfide ore was determined by Theart (1985) and is summarized as follows:

1. Extensive deformation of the ore took place during the period of buckle folding giving rise to the formation of durchbewegung textures. Pressure and temperature conditions during this time correspond







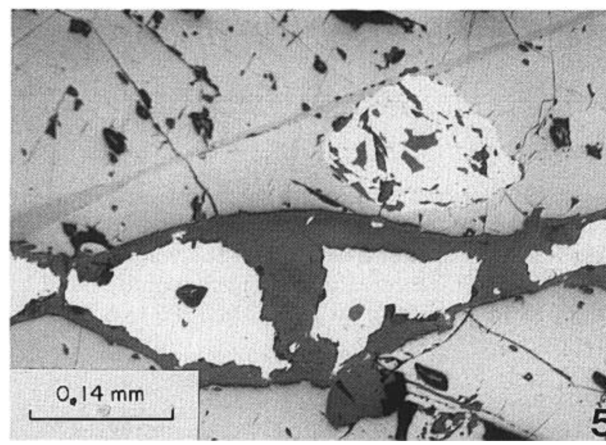


FIG. 2. A symplectic enclave of hercynite, sillimanite, cordierite, and magnetite surrounded by phase 2 cordierite providing evidence for the former existence of phase 1 staurolite (transmitted light).

FIG. 3. Unoriented grain boundary replacement of cordierite by sillimanite and phlogopite, providing evidence for a short period of high-temperature water influx during phase 3 (transmitted light).

FIG. 4. Spherical clasts of silicate gangue in recrystallized sulfide matrix, seen in polished, halved drill core, providing evidence for a durchbewegung process during phase 3.

FIG. 5. A crosscutting veinlet of white pyrrhotite and gray calcite in magnetite, containing an ilmenite exsolution lamella and a pyrite inclusion (reflected light).

to stage 3. The redistribution of all sulfide minerals took place and earlier textural relationships were severely disrupted.

2. Subsequent annealing gave rise to intergrowths between sulfide minerals and also between sulfide and gangue minerals such as the graphic intergrowths of pyrite, sphalerite, and celsian. Sulfide and sulfate minerals provide good examples of granoblastic textural annealing. Grain boundary angles at triple junctions of barite grains are approximately 120°. Theart (1985) showed that 219 angles measured within pyrite aggregates define a mean of 119.1°, with a standard deviation of 17.7°. This relative flattening compared to the equilibrium frequency distribution (Stanton, 1972) may reflect either late deformation of the ore or incomplete annealing after the last event of high-grade metamorphism. Large idioblasts of pyrite formed during the recrystallization of pyrite and pyrrhotite.

3. Sphalerite exsolved chalcopyrite. Chalcopyrite replaced sphalerite and pyrrhotite on a limited scale.

4. The formation of magnetite porphyroblasts in the wall rocks and in the ore was intimately associated with a new generation of fine-grained idioblastic pyrite in the ore. The magnetite and late pyrite frequently occur in the form of overgrowths on earlier sulfides.

5. Cataclastic deformation of pyrite was accompanied by mobilization of chalcopyrite, sphalerite, and pyrrhotite into fractures within the pyrite.

6. Unmixing of titanomagnetite resulted in ilmenite exsolution lamellae in magnetite porphyroblasts (Fig. 5).

7. Localized replacement of magnetite grains by sulfide minerals (illustrated in Fig. 5) and the crystallization of calcite, chlorite, and epidote in late foliation planes indicate infiltration of sulfur-bearing aqueous fluids.

8. The unmixing of pyrrhotite resulted in an intergrowth of two pyrrhotitelike phases that probably correspond to a monoclinic and hexagonal phase.

9. Oxidizing aqueous fluids reacted with the sulfide minerals and formed mainly goethite and other oxide and carbonate phases, along late fractures. This is similar to the phases of gossan development described by Andrew (1979). Examples include pyrrhotite inverted to marcasite with small islands of magnetite (J. H. F. Wagener, pers. commun., 1988); pyrrhotite oxidized to form colloform goethite; pyrite oxidized to goethite; chalcopyrite altered to digenite, which in turn was oxidized to covellite and finally replaced by goethite, calcite, malachite, and siderite-smithsonite; and sphalerite oxidized to form smithsonite-goethite assemblages.

All except the first textural adjustments listed above took place during and after the late phase (4) of retrograde metamorphism.

Wall Rocks and Their Composition

The distribution and mineral composition of the different rock types associated with the massive sulfide ores of the Prieska Zn-Cu mine are shown in Figures 6 and 7. Average chemical compositions are given in Table 4. Major and trace element concentrations were determined by X-ray fluorescence spectrometry except for U which was determined by isotope dilution analysis.

Smouspan Gneiss Member

The Smouspan Gneiss Member, considered to form the base of the Copperton Formation, is a homogeneous gneiss of intermedite composition consisting of the following minerals in order of decreasing abundance: plagioclase, quartz, hornblende, and biotite, with or without orthoclase, sphene, magnetite-ilmenite, apatite, and zircon. The gneiss contains from 60 to 65 percent silica which corresponds to between 16.5 and 24 percent normative quartz; it is also metaluminous in character.

Cornell (1975), Middleton (1976), and Uiterwyk and Frick (1985) interpreted the Smouspan Gneiss to be a metadacite whereas Wagener (1980) and Wagener and Van Schalkwyk (1986) argued that its precursor was a calcareous shale. The present protolith interpretation is based on the following observations:

1. The gneiss shows very little variation in mineral mode and chemical composition and is homogeneous over a considerable thickness and strike distance.

2. No primary textures could be identified which survived the deformation and metamorphism. Since no evidence was found for partial melting or metasomatism during metamorphism, isochemical metamorphism is assumed.

3. Most calcareous shales of Pettijohn (1975) have a peraluminous chemical character, whereas the metaluminous shales are three to five times richer in calcium than the Smouspan Gneiss and have lower alumina and alkali contents.

4. The major element composition of the Smouspan Gneiss is similar to that reported for dacites (e.g., Cole, 1982; Innocenti et al., 1982; Fitton et al., 1982).

5. Trace element comparisons are summarized as follows. Smouspan Gneiss is enriched in Ba relative to Puchelt's (1978) average dacite, but it lies within the range reported for dacite by Fitton et al. (1982). The Sc content of the Smouspan Gneiss is similar to that of the average dacite and much higher than that of sedimentary rocks (Frondel, 1978). Although most dacites have more Ni than Smouspan Gneiss (10 ppm Ni), some island-arc dacites also have low Ni levels (Ewart, 1979; Cole, 1982). The gneiss has an average K/Rb ratio of 282, similar to that of continental dacites (K/Rb = 270, Heier and Billings, 1978).

It is therefore concluded that the Smouspan Gneiss originated as a dacitic lava.

Prieska Copper Mines Member

A composite unit of peraluminous silicate rocks contains the massive sulfide ore of the Prieska Zn-Cu mine. It displays great compositional and mineralogical variation and includes some unusual rock types. Contacts between the different rock types within the Prieska Copper Mines Member and that between it and the Smouspan Gneiss are gradational. However, in some of the borehole intersections a massive amphibolite layer separates the Smouspan Gneiss from the Prieska Copper Mines Member. The massive amphibolite layers will be discussed separately. Two major rock types are distinguished by their mineralogy and silica content. The gedrite fels, consisting of gedrite, anthophyllite, cummingtonite-grunerite, phlogopite, and variable amounts of dravite, contains less than 50 percent SiO_2. The second rock type is quartz-perthite-sillimanite gneiss that contains between 70 and 80 percent SiO_2. Figure 8a demonstrates that it is unlikely that the gedrite fels had a common sedimentary rock type as precursor. The abnormally high magnesium content of both the gedrite fels and the quartz-perthite-sillimanite gneiss distinguishes them from typical pelite and semipelite in Figure 8b.

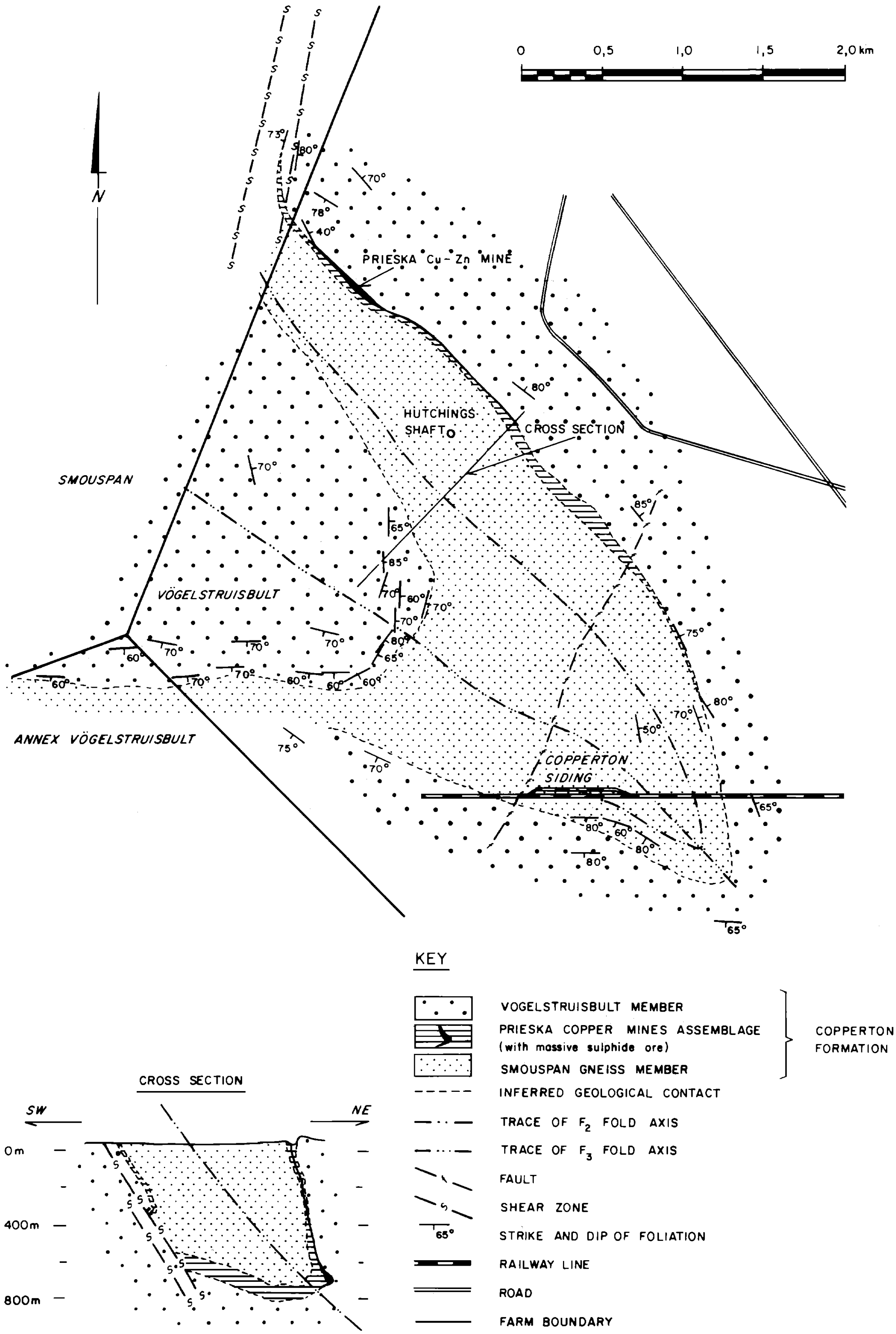


FIG. 6. Geologic map and section of the Prieska Zn-Cu deposit.

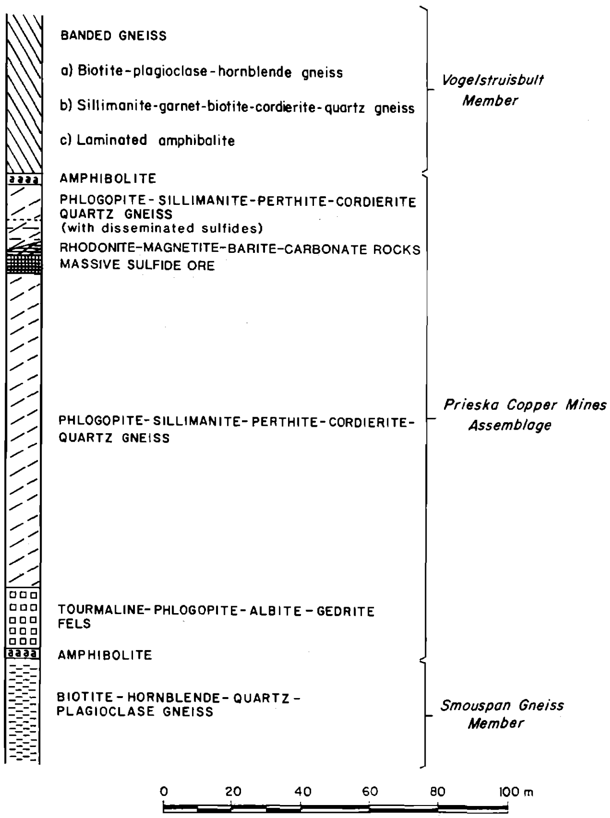


FIG. 7. Simplified stratigraphic setting of the ore at the Prieska Zn-Cu deposit.

The gedrite fels of the Prieska Copper Mines Member strongly resembles some of the rock types of the Outokumpu deposit in Finland (Treloar et al., 1981) as shown in Table 5. Eskola (1914) and contemporary authors considered that the Outokumpu rocks formed by synmetamorphic metasomatism, but more recently Vallance (1967) and Koistinen (1981) have argued that these and similar rocks at other localities formed by syngenetic alteration prior to metamorphism.

Treloar et al. (1981) suggested that the Outokumpu rocks formed in a stockwork alteration zone below the massive sulfide ores, and it is proposed that the gedrite-bearing felses of the Prieska Copper Mines Member formed in a similar way. The geochemical differences between the gedrite-bearing rocks from the two localities reflect differences in their precursors. At Outokumpu these rocks were probably derived from altered basalts, whereas at Prieska the dacitic precursor of the Smouspan Gneiss was hydrothermally altered to form the protolith of the gedrite-bearing fels.

In the process of hydrothermal alteration, the dacite was depleted in Si, Ca, Na, Sr, and Zr, released by the breakdown of feldspars, pyroxenes, and volcanic glass, all being prone to chemical attack. The altered rock was relatively enriched in elements such as Al, Mg, Fe, Mn, K, Ti, V, Sc, Ni, Ba, Cu, and Zn that were fixed in chlorite, clay minerals, and sulfides formed during the alteration. Elements such as the lanthanides, Y and Zr, generally regarded as immobile during weathering and metamorphism, were mobilized during this severe hydrothermal alteration, and heavy rare earth element enrichment is found in some samples (Theart, 1985).

The gradational contact between the Smouspan Gneiss and the gedrite fels is reflected by unevenly distributed patches of coarse-grained phlogopite and gedrite within the former, becoming more abundant until the rock is solely represented by a gedrite fels. Within the Smouspan Gneiss component of the transitional rock, hornblende becomes progressively paler colored until completely replaced by cummingtonite. This change is also reflected by the mineral chemistry (see later) and is explained as a result of a decrease in the degree of alteration away from the fluid conduit within the protolith.

A granitic precursor such as rhyolite for the quartz-perthite-sillimanite gneiss seems unlikely in view of its low alkali content. Its strong enrichment in Si, Ba, and Zr and strong depletion in Ca, Sc, V, and Ni relative to the Smouspan Gneiss and gedrite-bearing fels suggest that it could not have formed directly from the Smouspan Gneiss. It is proposed that the quartz-perthite-sillimanite gneiss formed by precipitation of silica, sericite, and trace minerals, such as phosphates, in basin-floor sediments close to the fumarolic vent, due to the decreasing temperature and pH of the hydrothermal fluid.

The massive sulfide ore of the Prieska Zn-Cu deposit consists mainly of the following minerals in decreasing order of abundance; pyrite, sphalerite, chalcopyrite, pyrrhotite, and minor amounts of galena. No consistent metal zonation could be established across the ore, but there exists lateral variation, with the highest copper concentrations found along an axis roughly in the center of the orebody, which plunges in a southerly direction. Higher zinc values follow the margins and slightly overlap the copper-rich ore (Wagener and Van Schalkwyk, 1986). The copper-rich zone appears where the ore is thickest. This distribution may be primary or may have developed during deformation.

A carbonate-sulfate zone is developed on the Vogelstruisbult Member's side of the ore, consisting mainly of calcite, dolomite, anhydrite, and barite. Associated with this zone are manganese-rich rhodonite-bearing assemblages dominated by magnetite. The carbonate-sulfate zone's distribution mirrors the copper-rich zone of the ore, indicating that the latter may be a primary feature.

TABLE 4. Composition of Silicate Wall Rocks of the Prieska Zn-Cu Deposit

Major elements (wt %)

	Smouspan Gneiss		Gedrite-bearing felses		Quartz-perthite-sillimanite gneiss		Massive amphibole		Laminated amphibole	
	Mean	n	Range	n	Mean	n	Range	n	Range	n
SiO_2	63.57 ± 1.38	19	49.90–47.56	3	76.56 ± 3.27	10	48.08–53.89	5	46.21–48.20	3
TiO_2	0.57 ± 0.05	19	0.58–0.72	3	0.12 ± 0.02	10	0.60–1.65	5	0.68–1.39	3
Al_2O_3	15.09 ± 0.56	19	15.03–17.05	3	11.41 ± 1.80	10	13.24–15.87	5	12.49–14.86	3
Fe_2O_3	6.73 ± 0.44	19	12.49–15.39	3	2.57 ± 0.79	10	13.97–16.78	5	10.69–13.88	3
MnO	0.14 ± 0.04	19	0.31–0.48	3	0.06 ± 0.05	10	0.17–0.33	5	0.21–0.30	3
MgO	2.18 ± 0.39	19	12.70–14.66	3	3.38 ± 1.03	10	4.69–8.30	5	5.80–8.39	3
CaO	4.93 ± 0.43	19	0.18–1.36	3	0.15 ± 0.21	10	5.78–9.56	5	9.90–16.21	3
Na_2O	3.53 ± 0.31	19	0.58–1.51	3	0.80 ± 0.64	10	2.10–2.94	5	1.78–2.65	3
K_2O	2.10 ± 0.34	19	2.76–3.43	3	2.23 ± 0.63	10	0.18–1.79	5	n.d.–0.49	3
P_2O_5	0.17 ± 0.08	19	0.12–0.16	3	n.d.	10	0.03–0.43	5	0.05–0.12	3
S	0.29	1			0.54 ± 0.63	6				

Trace elements (ppm)

	Smouspan Gneiss			Gedrite-bearing felses		Quartz-perthite-sillimanite gneiss			Massive amphibole		Laminated amphibole	
	Range	Mean	n	Range	n	Range	Mean	n	Range	n	Range	n
Rb	48–75	63	11	106–330	3	29–143	91	9	n.d.–60	5	4–15	3
Sr	236–310	280	11	7–106	3	n.d.–63		11	122–242	5	68–283	3
Ba	907–1,121		2	990–1,377	3	191–3,022	1,747	11	n.d.–227	5	n.d.	1
U	0.70–2.72	1.57	5[1]						0.16–0.26	3[1]	0.07–0.37	3[1]
Y	27–35	31	11	9–26	3	24–120	54	10	15–52	5	30–32	3
Zr	109–173	131	12	26–39	3	131–340	231	10	11–48	5	32–57	3
Nb	6–8	7	8	n.d.–4	3	n.d.–21		11	n.d.	5	n.d.–4	3
Sc	18–20		2	29–33	3	n.d.–14		11	38–43	5	40	1
V	108–139	123	5	351–450	3	n.d.–20		11	290–453	5	291	1
Ni	n.d.–20	10	11	12–52	3	n.d.–6		9	5–59	5	75–113	3
Cu	7–50	30	7	22–192	3	n.d.–5,250		9	25–55	5	45–489	3
Zn	68–100	80	7	116–245	3	43–290	102	9	94–249	5	76–85	2
Pb	14–32		4	3–74	3	3–37	15	9	3–35	5	1–4	3

Total Fe as Fe_2O_3, n.d. = not detected, n = number of samples
[1] Determined by isotope dilution technique

The presence of dravite-rich layers on the Smouspan Gneiss side of the Prieska Copper Mines Member, with barite, anhydrite, and calcite-rich layers on the Vogelstruisbult Member side provides some indication of facing direction. In less metamorphosed massive sulfide deposits, boron-rich rocks usually occur at the base and sulfates at the top of the ore zone (Campbell et al., 1984).

Vogelstruisbult Member

This member consists of a variety of rock types, including banded hornblende gneiss of intermediate composition, laminated amphibolite and metapelites.

The laminated amphibolite layer forms a conspicious unit within the Vogelstruisbult Member. It is distinguished from the massive amphibolite layers found throughout the Copperton Formation by its 5- to 10-mm-thick color banding. Darker plagioclase-hornblende layers alternate with paler lamina, commonly containing diopside, plagioclase, and sphene and less frequently grossular, calcite, and scapolite. The laminated amphibolite has a higher calcium content than massive amphibolite, but it is also tholeiitic in character.

Although trace element concentrations of laminated amphibolites (Table 4) could have been affected during diagenesis and subsequent metamorphism, their abundance is similar to that of low potassium tholeiites. This is confirmed by the flat lanthanide profiles of these rocks (Theart, 1985). Its precursor could have been a basaltic lava or subaqueous tuff, with interbedded calcium carbonate layers formed during weathering or diagenesis.

Layering within the banded hornblende-bearing gneisses range in thickness from 1 cm to as much as 25 m. Leucocratic layers consist mainly of quartz and oligoclase with minor amounts of biotite, hornblende, and magnetite. The dark layers comprise hornblende, andesine, quartz, biotite, and magnetite. Whereas the Smouspan Gneiss displays limited chemical variation, the banded gneisses vary considerably but are also of intermediate composition (Theart, 1985).

Pelitic gneisses of the Vogelstruisbult Member have a flaser fabric with composite augen consisting of cor-

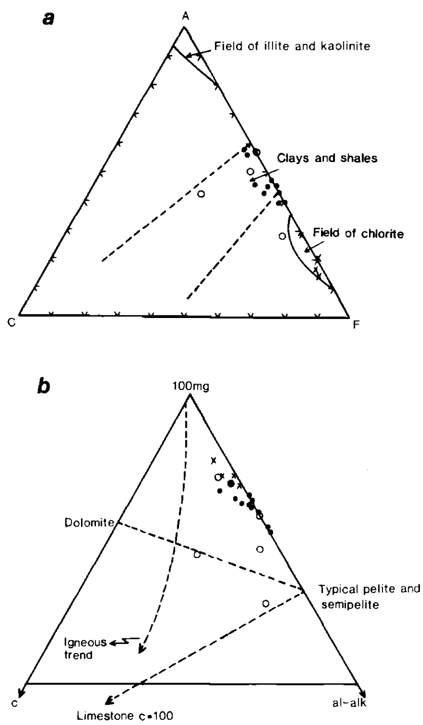


FIG. 8. Chemographic diagrams for peraluminous rocks from the Prieska deposit: (a) ACF diagram and (b) Niggli diagram parameters plotted according to Leake (1964), showing samples of gedrite fels (crosses), quartz-perthite-sillimanite gneiss (filled circles), and pelitic rocks of the Vogelstruisbult Member (open circles).

dierite, garnet, and biotite within a matrix of perthitic K-feldspar and quartz. Their major element compositions are intermediate between the quartz-perthite-sillimanite gneiss of the Prieska Copper Mines Member and that of common pelites as may be seen in Figure 8a and b.

The chemical and mineralogical compositions of the banded and metapelitic gneisses are thought to reflect their origin as immature sediments derived from basaltic to intermediate volcanic rocks (Theart, 1985). The Vogelstruisbult Member is considered to lie stratigraphically above the ore-bearing Prieska Copper Mines member. It is thought not to reflect the ore-forming hydrothermal alteration.

Massive amphibolites

Rocks described in this section consist primarily of hornblende and plagioclase. They contain less than 55 percent silica with relatively high concentrations of calcium, magnesium, and iron (Table 4). Massive amphibolite layers are not considered to be part of the original layered sequence and may occur at any level, as schematically shown in Figure 7. The major element composition of the massive amphibolite is similar to that of tholeiitic basalts.

Gorton (1981) studied similar rocks related to the Zn-Cu deposits at Kielder, 12 km northwest of the Prieska deposit, and concluded that they had tholeiitic lava precursors. The massive amphibolite layers within the Prieska assemblage probably intruded the sequence as dikes or sills after the ore formation (since they escaped the pervasive hydrothermal alteration that affected the Smouspan Gneiss) but prior to the regional deformation and metamorphism (Theart, 1985).

Mineral Chemistry

The anomalous chemical composition of the Prieska Copper Mines Member compared to the other parts of the Copperton Formation can be demonstrated using minerals such as the amphibole and mica groups which are found throughout the sequence. Hornblende represents the amphibole group in most of the gneisses and amphibolites, whereas in the Prieska assemblage the low Ca amphiboles cummingtonite and gedrite are found (Table 6).

The composition of brown micas shows large variation in Fe/Mg ratio (Fig. 9), decreasing from about 3 in biotite of typical Smouspan Gneiss to 0.2 in phlogopites of the Prieska Copper Mines Member. Apart from a small reversal in almandine-bearing rocks at the transition of gedrite fels to quartz-perthite-sillimanite gneiss, the overall trend from Smouspan Gneiss to the Prieska assemblage is a gradual transition from iron-rich biotite to magnesium-rich phlogopite. By contrast the biotite in banded plagioclase-hornblende-biotite gneiss near the base of the Vogelstruisbult Member has an abruptly higher iron content than phlogopite in the adjacent Prieska assemblage. This confirms the earlier statements on the gradational relationship between the Smouspan Gneiss and the Prieska assemblage and also of rock types within the assemblage.

TABLE 5. Average Composition (wt %) of Gedrite-bearing Felses from the Prieska Zn-Cu Mine and Outokumpu, Finland

Sample group	1	2
	$n = 3$	$n = 5$
SiO_2	46.62 ± 0.87	39.48 ± 3.02
TiO_2	0.64 ± 0.07	0.45 ± 0.24
Al_2O_3	15.91 ± 1.03	15.17 ± 3.23
Fe_2O_3	14.03 ± 1.47	17.27 ± 2.13
MnO	0.38 ± 0.09	0.16 ± 0.07
MgO	13.77 ± 0.99	16.16 ± 3.51
CaO	0.96 ± 0.68	0.57 ± 0.78
Na_2O	1.14 ± 0.49	0.64 ± 0.52
K_2O	3.11 ± 0.35	0.47 ± 0.32
P_2O_5	0.14 ± 0.02	0.02 ± 0.01

1 = gedrite-bearing fels, Prieska Copper Mines Member, 2 = gedrite-bearing fels, Treloar et al. (1981)

n.d. = not detected, n = number of samples, Fe_2O_3 = total iron

TABLE 6. Major Element Composition of Amphiboles

Sample group	1	2	3	4	5	6	7	8
SiO_2	53.82	53.81	46.31	45.34	50.34	45.36	41.94	41.44
TiO_2	0.01	0.01	0.22	0.34	0.11	0.77	1.35	1.26
Al_2O_3	3.13	2.56	13.81	14.83	5.22	11.17	10.86	9.67
FeO	16.31	18.69	18.55	19.42	18.68	13.79	21.42	22.75
MnO	0.64	1.27	0.09	0.67	0.68	0.25	0.84	0.84
MgO	21.90	19.89	16.74	15.53	18.99	13.26	8.04	7.72
CaO	0.22	0.14	0.41	0.31	0.55	11.15	11.32	10.78
Na_2O	n.d.	n.d.	1.27	1.20	n.d.	1.23	1.49	1.75
K_2O	n.d.	n.d.	n.d.	n.d.	n.d.	0.24	0.24	1.41
Total	96.03	96.36	97.40	97.61	95.08	97.24	97.50	97.84
			Number of ions (on basis of 23 O)					
Si	7.72	7.80	6.67	6.57	7.49	6.67	6.45	6.49
Ti	0.00	0.00	0.02	0.04	0.01	0.09	0.16	0.15
Al	0.53	0.44	2.35	2.53	0.91	1.94	1.97	1.77
Fe	1.69	2.27	2.24	2.35	2.30	1.70	2.76	2.96
Mn	0.08	0.06	0.01	0.08	0.08	0.03	0.11	0.11
Mg	4.68	2.30	3.60	3.35	4.17	2.91	1.84	1.79
Ca	0.03	0.02	0.06	0.05	0.09	1.76	1.87	1.80
Na	0.00	0.00	0.36	0.34	0.00	0.35	0.44	0.53
K	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.28
Total	15.01	14.98	15.31	15.30	15.05	15.47	15.65	15.88

Sample groups: 1 = amphibole, sample D303/368 (cummingtonite), Prieska Copper Mines Member; 2 = amphibole, sample D352/8 (cummingtonite), Prieska Copper Mines Member; 3 = amphibole, sample D352/9 (gedrite), Prieska Copper Mines Member; 5 = amphibole, sample D352/16 (gedrite), Prieska Copper Mines Member; 6 = amphibole, sample D352/17 (hornblende), amphibolite; 7 = amphibole, sample UP1-10 (hornblende), Smouspan Gneiss, Uiterwyk and Frick (1985); 8 = amphibole, sample UP1-135 (hornblende), hornblende-bearing gneiss, Vogelstruisbult Member, Uiterwyk and Frick (1985)

Comparison with Other Deposits of the Namaqua Province

The metal contents of deposits within the Namaqua province are given in Table 1 and plotted on a Cu-Pb-Zn ternary diagram (Fig. 10). Deposits of the Aggeneys area (Black Mountain, Broken Hill, and Big Syncline) and to a lesser extent the Gamsberg deposit are all enriched in lead relative to the Areachap and Prieska Zn-Cu deposits. Although a little galena was found in the Prieska ore, none was seen at Areachap.

Stratiform, strata-bound base metal deposits at Aggeneys and Gamsberg lie within essentially metasedimentary successions with subordinate metavolcanic amphibolites (Rozendaal, 1980; Ryan et al., 1982). Alteration pipes are not recognized near any of these deposits. In contrast, the Prieska Zn-Cu deposit is interpreted to lie above a metamorphosed alteration pipe, whereas the Areachap mine is regarded as a distal deposit (Voet and King, 1986) within a sequence containing the erosion products of an alteration pipe (Theart, 1985).

Sulfur isotope data for the different deposits are given in Table 7 and illustrated in Figure 11. The Prieska sulfides probably equilibrated with sulfate minerals during the durchbewegung process at upper amphibolite-grade conditions. Thus Prieska $\delta^{34}S$ values may be slightly higher than their original values, but they are nevertheless lower than those of Aggeneys and Gamsberg sulfides. The single Areachap pyrite sample is indistinguishable from the Prieska sulfides and the low $\delta^{34}S$ value implies a magmatic rather than sedimentary origin for the sulfur of both deposits.

Lead isotope data given in Table 8 further illustrate the genetic relationships between the different deposits. Köppel (1980) and Theart (1985) demonstrated the lead isotope similarity of Prieska and Areachap sulfides. The μ_2 ($^{238}U/^{204}Pb$) values calculated for the second stage of Stacey and Kramers' (1975) model range from 9.93 to 10.10 for Areachap and Prieska sulfides, compared to 10.22 to 10.66 for the Aggeneys and Gamsberg deposits. According to Doe and Zartman's (1979) Pb evolution model, the Aggeneys and Gamsberg μ_2 values suggest a crustal origin, whereas those of the Areachap and Prieska ores indicate both crustal and mantle contributions. Although these deposits all have approximately 1,300-m.y. model ages, it has been suggested that the lead

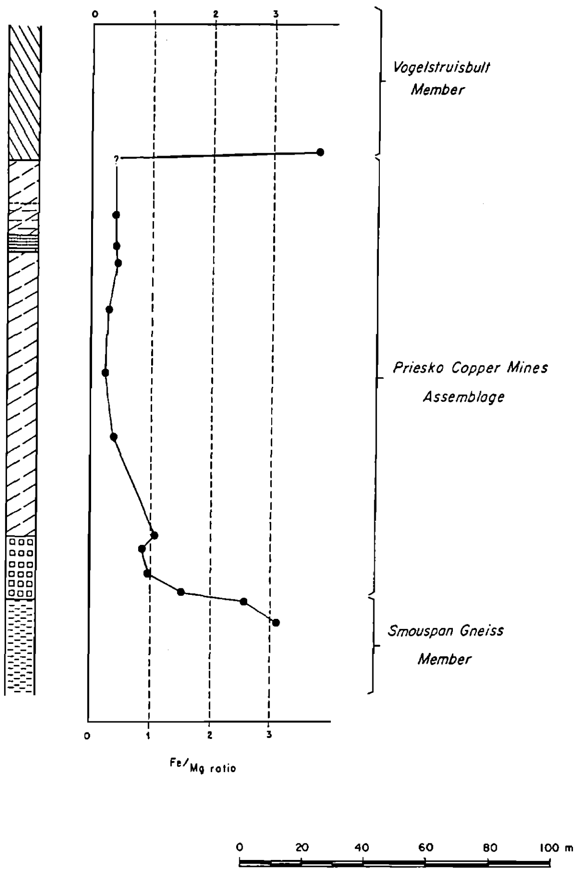


FIG. 9. Variations in the Fe-Mg ratio of brown micas across the stratigraphic sequence at Prieska Zn-Cu deposit.

of all these deposits is of an anomalous (J type) nature without model age significance (H. J. Welke and C. B. Smith, pers. commun., 1984; Theart, 1985).

Discussion and Conclusions

The massive sulfide deposits at Areachap and the Prieska Zn-Cu mine are found within successions containing intermediate to acid gneiss, amphibolite, and peraluminous rocks (given in decreasing order of abundance). It is concluded that most of these rocks had volcanic precursors, some representing volcanoclastic sediments reworked in a sedimentary cycle. The lack of evidence for significant premetamorphic units of sandstone, shale, and chemical sediments indicate that such a sedimentary cycle did not reach maturity. At the Prieska Zn-Cu mine the massive amphibolites within the Prieska Copper Mines assemblage intruded the sequence as tholeiitic basaltic dikes and sills after the mineralizing event but before metamorphism and deformation.

Two distinct rock types at the Prieska mine are regarded as the metamorphosed and deformed equivalents of rocks formed during hydrothermal alteration of the volcanic protoliths at the time of ore deposition. The gedrite-bearing fels which has a gradational relationship to the Smouspan Gneiss represents the magnesium and iron-rich chloritic core of the alteration pipe (shown as zone 4 in Fig. 12) similar to that described from the Millenbach deposit (Noranda, Canada) by Riverin and Hodgson (1980) and the Bruce mine of Arizona (Larson, 1984). The precursor of the quartz-perthite-sillimanite gneiss formed just below the site of discharge, probably by the silicification and sericitization of a sedimentary layer that itself may have been partly derived from the underlying dacite (zone 6 in Fig. 12).

During the early phases in the development of the hydrothermal system, silicification may have sealed off some of the fractures in the dacite, thereby increasing the fluid flow and temperature in the main conduit, resulting in less sulfide deposition below the vent and more intense alteration of the adjacent dacite. Silicification also continued during the waning phases of the hydrothermal system, after the deposition of the ore and caused the silicification of sediments deposited above the sulfides (the white area of zone 6 in Fig. 12).

Unlike most of the Zn-Cu deposits described by Franklin et al. (1981), the Prieska Zn-Cu mine contains a significant amount of barite, which together with calcite, is thought to have formed part of an anhydrite cap to the sulfide ores as described by Campbell et al. (1984). Some of this material became detached and included within the massive sulfide ores during the durchbewegung process. Sediments at the discharge site and the immediately underlying altered dacite became enriched in boron, now represented by a tourmaline-rich layer. The relative positions of the sulfate-carbonate unit on the Vogelstruisbult

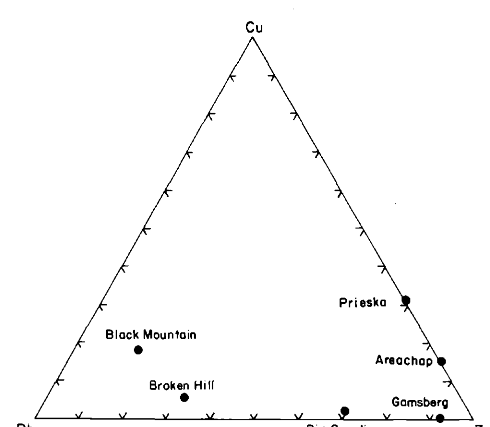


FIG. 10. Atomic Cu, Pb, and Zn proportions of average ore from massive sulfide deposits of the Namaqua province.

TABLE 7. Sulfur Isotope Composition of Some Base Metal Sulfide Deposits in the Namaqua Metamorphic Complex

Deposit	Average $\delta^{34}S$ value (‰) Sulfides	Barite	Reference
Black Mountain, Aggeneys	8.9 ± 3.7 (9 samples)	20.6 ± 4.3 (3 samples)	1
Broken Hill, Aggeneys	19.8 ± 3.1 (19 samples)		1
Big Syncline, Aggeneys	12.8 ± 0.7 (3 samples)	30.2 ± 0.1 (2 samples)	1
Gamsberg	29.2 ± 1.8 (24 samples)	35.4 ± 0.2 (2 samples)	1
Prieska Zn-Cu mine	5.5 ± 0.5 (8 samples)		2
Areachap	5.2 (1 sample)		2

References: 1, Von Gehlen et al. (1983); 2, Theart (1985)

Member side of the ore and the tourmaline-enriched rocks on the Smouspan Gneiss side are consistent with the interpretation of the Smouspan Gneiss as the base of the original sequence.

Intense tectonic flattening of the Copperton Formation, mainly during the early periods of isoclinal slip folding, destroyed the inferred original transgressive relationship of the altered zone (Fig. 12) with the Smouspan Gneiss precursor. All the rock types, including intrusive basaltic dikes, took on their present parallel dispositions during the deformation. This represents the final stage in the sequential deforma-

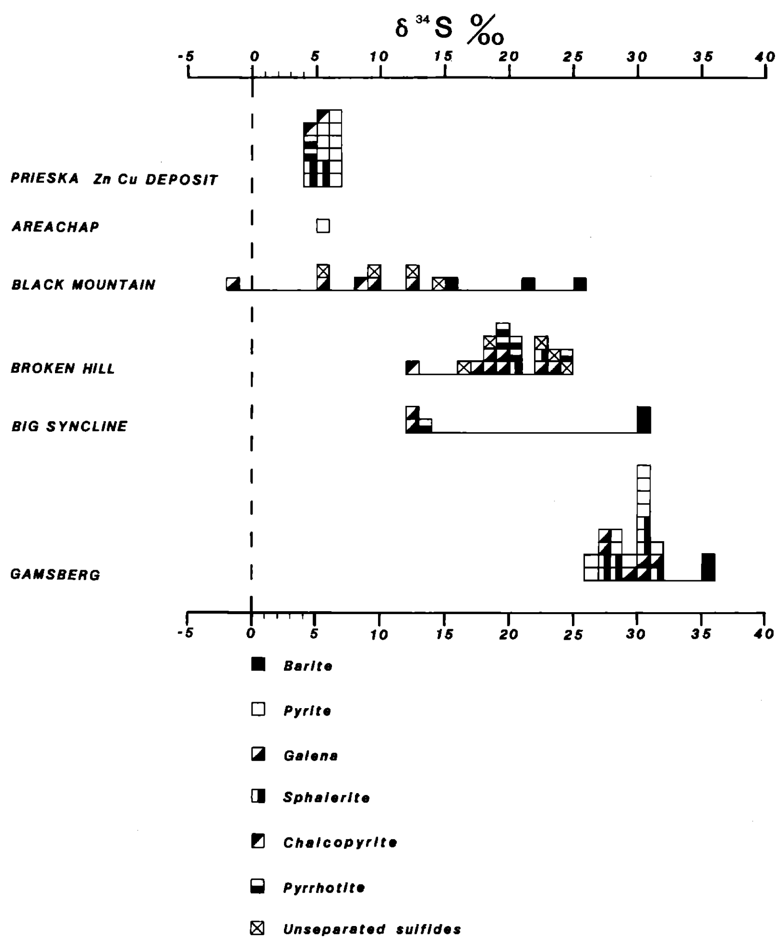


FIG. 11. Sulfur isotope data for sulfide and sulfate minerals from massive sulfide deposits of the Namaqua province. Data for the Bushmanland deposits is from Von Gehlen et al. (1983).

TABLE 8. Pb Isotope Composition of Sulfide Minerals from the Namaqua Province

Deposit	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	μ_2[1]	Sulfide mineral	Reference[3]
Prieska Zn-Cu mine	16.697–16.701	15.524–15.530	36.456–36.491	10.07–10.10	Galena (n = 4)[2]	1
	16.679–(±0.008)	15.508–(±0.009)	36.417–(±0.029)	9.98	Galena (n = 1)	2
Areachap	16.668–(±0.008)	15.498–(±0.009)	36.348–(±0.029)	9.93	Pyrite (n = 1)	2
Aggeneys						
Black Mountain	16.728–16.839	15.566–15.648	36.603–6.882	10.22–10.66	Galena (n = 5)	1
Broken Hill	16.736–16.789	15.565–15.622	36.630–36.878	10.26–10.66	Galena (n = 7)	1
Big Syncline	16.739–16.770	15.575–15.617	36.659–36.804	10.32–10.55	Galena (n = 3)	1
Gamsberg	16.7–16.809	15.554–15.598	36.580–36.746	10.17–10.39	Galena (n = 5)	1

[1] Values calculated for the second stage of the Stacey and Kramers (1975) model
[2] n =number of samples
[3] 1 = Köppel (1980), 2 = Theart (1985)

tion model of Sangster (1972) for Canadian deposits such as the Anderson Lake mine at Snow Lake, Manitoba (Franklin et al., 1981). The supracrustal rocks belonging to the Jannelsepan and Copperton Formations, and containing the massive sulfide deposits, probably formed approximately 1,500 m.y. ago in a region dominated by extensional tectonics which facilitated the extrusion of predominantly mantle-derived volcanic rocks.

The model proposed in this work is similar to that of Middleton (1976), although the textural evidence which he cited in favor of a volcanic origin is rejected. The sedimentary model of Wagener (1980) is also rejected because no textural evidence of sedimentary structures has been found and because the geochemical evidence supports a predominantly volcanogenic origin for the ore and host rocks.

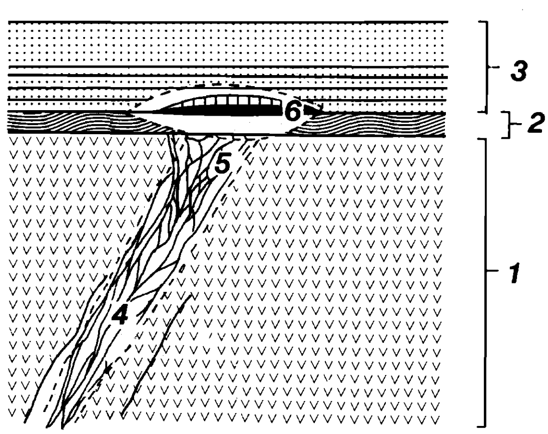


FIG. 12. Representation of the Prieska Zn-Cu deposit before deformation and metamorphism. 1. Dacitic lava (now Smouspan Gneiss). 2. Sediments on the floor of a discharge basin. 3. Sedimentary and volcaniclastic cover sequence (now Vogelstruisbult Member). 4. Chlorite alteration pipe and fracture system. 5. Zone of boron enrichment. 6. Silicification zone (white), massive sulfide zone (black), and sulfate-carbonate capping (hatched) (4, 5, and 6 now Prieska Copper Mines Member).

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