Mineral. Deposita 22, 81–89 (1987)

MINERALIUM DEPOSITA

Strata-bound copper-iron sulfide mineralization in a Proterozoic front arc setting at Boksputs, Northwest Cape, South Africa – a possible Besshi-type deposit

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Abstract. A low-grade, copper-iron sulfide deposit is present at Boksputs in the Northwest Cape, South Africa. It occurs in the Proterozoic amphibolite belt, the Areachap Group, along the eastern margin of the Namaqua mobile belt.

The mineralization, which is dominated by pyrite, chalcocopyrite, sphalerite, and magnetite, occurs as disseminated ore and thin layers of massive-type ore in the lower massive amphibiolite and associated amphibole gneisses of the Kraalkop antiform and synform.

Chemically, the host-rock amphibolite resembles low-K arc tholeiite and calc-alkaline volcanics, whereas the upper amphibolite is calc-alkaline.

The sulfide mineralization and the host-rock composition is explained in terms of modern plate tectonic principles. It is concluded that the Boksputs mineralization is a syngenetic, strata-bound, copper-iron deposit which to some extend resembles Besshi-type deposits. It is associated with low-K arc tholeiite which is tectonically related to a front arc environment or a rifted arc system along the eastern margin of the Namaqua mobile belt.

A low-grade, strata-bound, copper-iron sulfide deposit occurs within the amphibolites and associated gneisses of the Boksputs sequence, which forms part of the Areachap Group along the eastern margin of the Namaqua mobile belt in the Northwest Cape, South Africa (Fig. 1).

The metavolcanic belt, dated at 1200–1300 Ma (Barton and Burger 1983) separates the Archean Kaapvaal craton in the east from the Korannaland high-grade metamorphic gneiss terrain in the west. The amphibolite belt along the eastern margin, well known for its sulfide mineralization, was explored in the past by various mining companies who undertook extensive exploration and drilling programs in this region. These activities resulted in the discovery of one economic base-metal sulfide deposit, namely the Prieska Cu-Zn pyrite massive sulfide orebody (Copperton orebody) within the Copperton sequence as well as several other promising occurrences such as the pyrite deposit at Van Wykspan, the Ni-Cu deposit at Jacomynspan, and the Cu-Zn pyrite deposit at Areachap, which also was once mined.

Aim of study and previous findings

Although the potential for sulfide mineralization of the amphibolites and associated gneisses has been recognized, the origin of the host rocks as well as their tectonic relationships are hitherto unsolved.

Following the discovery of the Prieska orebody Middleton (1976) described the Cu-Zn pyrite massive sulfide deposit in great detail. He recognized the volcanogenic nature and origin of the ore and correlated it with the Kuroko-type deposits of Japan, associated with island-arc volcanism. Cornell (1975) investigated the amphibolites and related rocks of the Copperton Formation and also recognized their metavolcanic character, while Vajner (1974a) described the amphibolitic gneisses of the Hartebeest Pan Formation (Van Wykspan sequence) and stated that the amphibolites represent metamorphosed lavas, probably of a volcanic arc environment. Vajner (1978) described the amphibolitic sequence south of Upington as the metavolcanic olive member of the Jannelsepan Formation.

A geochemical investigation of the amphibolites of the eastern Namaqua mobile belt by Geringer (1979) and Geringer et al. (1986) revealed a calc-alkaline character for the amphibolites of the Areachap Group.

Stowe (1983) postulated a Cordilleran-type margin along the eastern margin of the Namaqua mobile belt.

Based on these findings the present investigation was conducted to unravel the character of the host rocks and mineralization and to reconstruct a possible tectonic model for the area.

Stratigraphy

In general, the lithostratigraphic succession at Boksputs is highly complicated by intensive structural deformation and late-stage shearing (Humphreys 1986) as well as the intrusion of granite and diorite bodies. Copper-iron mineralization occurs as thin, disseminated, strata-bound layers within a metavolcanic succession, called the Jannelsepan Formation, between a basal sequence of metapsammitic rocks and a sequence of metapelites at the top. The stratigraphic sequence at Boksputs is given in Table I.

The metapsammitic Sprigg Formation forms the base of the succession and overlies the older Dagbreek Formation unconformably with a conglomerate at its base. This is followed by finer-grained quartzofeldspathic muscovite schist

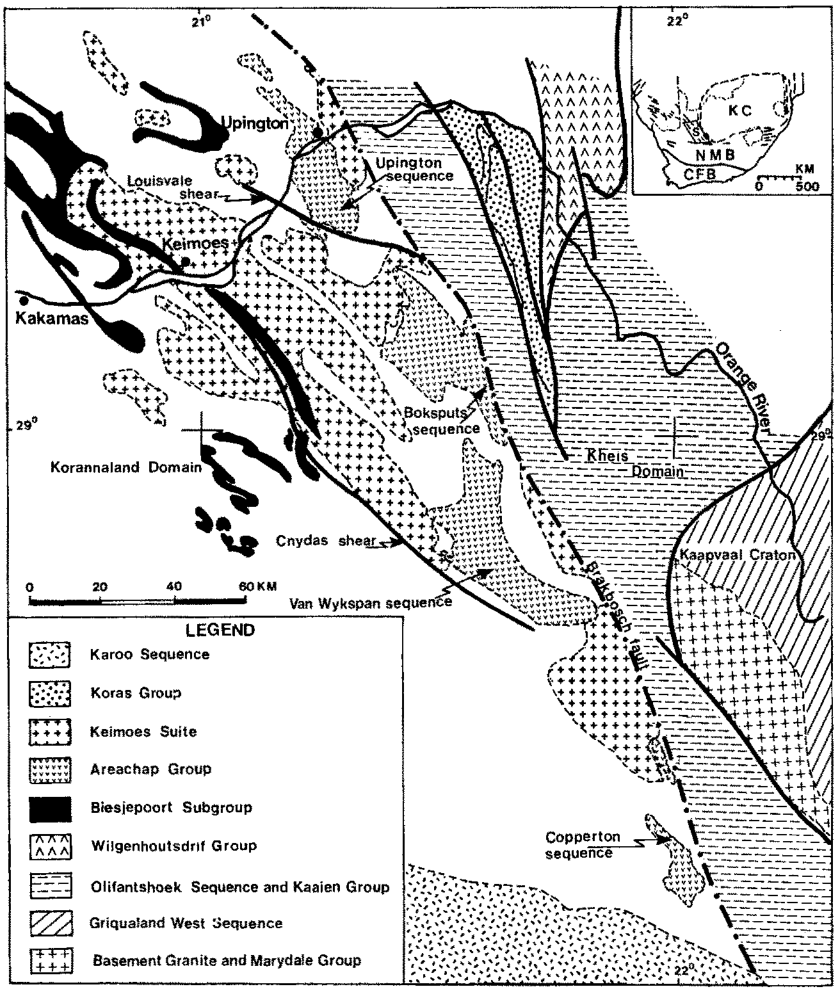

Fig. 1. Geologic map showing the regional distribution and tectonic position of the Areachap Group along the eastern margin of the Namaqua mobile belt

Table 1. Lithostratigraphy of the Areachap Group in the Boksputs area

Boksputs sequence	Formation	Chronology	General lithology
Areachap Group	Kantienpan	2	Garnet-cordierite-biotite gneiss
		1	Amphibolite, quartz-feldspar-amphibole gneiss, mottled amphibole gneiss, garnet-amphibole gneiss
	Jannelsepan	6	Calc-silicates with ferruginous chert (BIF)
		5	Pyroxene amphibolite with intercalated calc-silicates
		4	Mineralized horizon with ferruginous chert (quartzite) in places
		3	Feldspathic amphibole gneiss and chloritized feldspathic gneiss
		2	Massive amphibolite (> 50% hornblende), intercalated quartz-feldspar gneiss
		1	Quartz-feldspar gneiss
	Sprigg	4	Quartz-feldspar-muscovite gneiss
		3	Quartzite and quartz-muscovite schist and gneiss
		2	Amphibolite
		1	Metaconglomerate
Kaaien Group	Sultana-oord		Massive white quartzite
	Dagbreek		Quartzite, quartz-muscovite gneiss, and schist with quartz-feldspar gneiss and subordinate amphibolite

and gneiss to the west. The metavolcanic Jannelsepan Formation consists of three lithologically different units, i.e., a quartz-feldspar gneiss unit at the base, which can be seen in the core of the Kraalkop antiform (Fig. 2), a sequence of massive amphibolite with intercalated quartzofeldspathic gneiss with chert and muscovite-schist, and pyroxene amphibolite with intercalated calcsilicates and ferruginous chert (magnetite quartzite) at the top.

The lower massive amphibolite unit consists of thick layers of homogenous amphibolite which frequently reveal relict amygdaloidal textures. Thin layers of quartz-feldspar gneiss and chloritic muscovite schist occur near the base of this unit. The rather massive appearance of the homogenous amphibolite gave rise to the name "massive amphibolite".

The upper amphibolite unit is a rather heterogeneous succession of thick layers of amphibolite with intercalated calc-silicates and magnetite quartzites. The amphibolite shows rough, uneven weathered surfaces due to differential weathering of pyroxene concentrations along microscopically thin layers and aggregates. The presence of diopside in these rocks leads to the name pyroxene amphibolite.

The calc-silicate rocks, associated with the amphibolites, often occur as thin intercalations within the amphibolites or as layers a few meters thick. Mineralogically, the calc-silicates consists of diopside, plagioclase, hornblende, and epidote with titanite and calcite as accessory minerals.

Most of the amphibolites of the massive amphibolite unit and the upper pyroxene amphibolite unit are recognized as metalavas (see section on geochemistry), whereas some of the amphibolites intercalated with the calc-silicates may represent reworked volcanic material or marl associated with the carbonaceous sediments of the calc-silicate sequences.

The Jannelsepan Formation is overlain by a sequence of amphibole gneiss, garnet-amphibole gneiss, flecky amphibole gneiss, and garnet-cordierite-biotite gneiss of the Kantienpan Formation. It crops out to the west of the Kraalkop antiform and is not shown in Fig. 2.

Mineralization

The copper-iron sulfide mineralization at Boksputs occurs along the limbs of the Kraalkop antiform and in the Kraalkop synform. Detailed stratigraphic sections (Fig. 3a, b, c, d) show that the mineralization in the Kraalkop antiform is not confined to a single lithologic unit. Along the western limb of the antiform the mineralization is associated with a highly ferruginous chert and muscovite schist near the top of the massive amphibolite. Ferruginous gossan with boxwork textures is present. Along the eastern limb of the structure the mineralization occurs in an amphibole schist inside the feldspathic amphibole gneiss on top of the massive amphibolite. Malachite staining marks the presence of the sulfide mineralization on surface outcrop.

In the Kraalkop synform (Fig. 2) sulfides were detected by means of geophysical survey and diamond drilling by Shell (South Africa) during an extensive exploration program (Theron 1979). The mineralization occurs as intercalated lenses within a sequence of amphibolite, biotite-quartz-feldspar gneiss, and mica schist. The relationship of the ore with the host rocks was established from drillcore data and is illustrated in Fig. 4. The mineralized zone is highly chloritized and marked by intensive calcite and quartz vein fillings over an interval of approximately 40 m.

Pyrite, chalcopyrite, sphalerite, and small quantitites of pyrrhotite are the sulfides; magnetite, hematite and ilmenite are the oxides present in the ore. The sulfide minerals are predominantly present as disseminated grains and thin layers of massive sulfides parallel to the foliation in the host rocks. The effects of high-grade, upper-amphibolite-facies metamorphism, as displayed by the host-rock mineralogy, are also revealed by the sulfide minerals. Some of the more obvious features are the presence of fractured and disrupted pyrite, often seen as pyrite trains spreading from a single grain along the foliation, vein filling in pyrite by chalcopyrite, inclusions of pyrrhotite and chalcopyrite in pyrite, reaction rims of sphalerite between chalcopyrite and silicates of the host rock, and exsolution of ilmenite from magnetite. The metamorphic imprint on the sulfides and the host rocks is discussed in great detail by Humphreys (1986).

Host rock characteristics

The host rocks housing the sulfide mineralization within the Jannelsepan Formation varies from one locality to another. The main rock types involved are massive amphibolite and pyroxene amphibolite (western limb of Kraalkop antiform), feldspathic amphibole gneiss and amphibole schist (eastern limb of Kraalkop antiform), and biotite-quartz-feldspar gneiss with mica schist and amphibolite (in the Kraalkop synform).

Chemical composition

Since the nature of syngenetic sulfide mineralization depends to a large extend on the origin and general character of the host rocks, they were investigated chemically to unravel their proto-lithology and origin. The major elements were analyzed by the Geochemical Division of the Geology Department of the University of the Orange Free State, and the trace elements were determined by the laboratories of the Geological Survey of South Africa. Major elements were determined by wavelength dispersive XRF; iron is reported as Fe_2O_3, and accuracy for all major elements in excess of 10% is estimated to be within 2%. Trace elements are given in ppm. (Chemical analyses are available on request from the authors.)

Chemical alteration

The applicability of chemical data in the reconstruction of chemical and tectonic models depends to a large extent on the amount of chemical alteration that took place. Smith (1968) as well as Smith and Smith (1976) pointed out the effect of metamorphism on major element concentrations and the latter shows that the trace elements Ti, Zr, Y, and Nb remain fairly constant and can be used with a reasonable amount of confidence in the classification of magma types. Gunn (1976) stated that the major element chemistry of lavas is only slightly affected by metamorphic processes and that Archean volcanic assemblages differ only slightly from their younger counterparts.

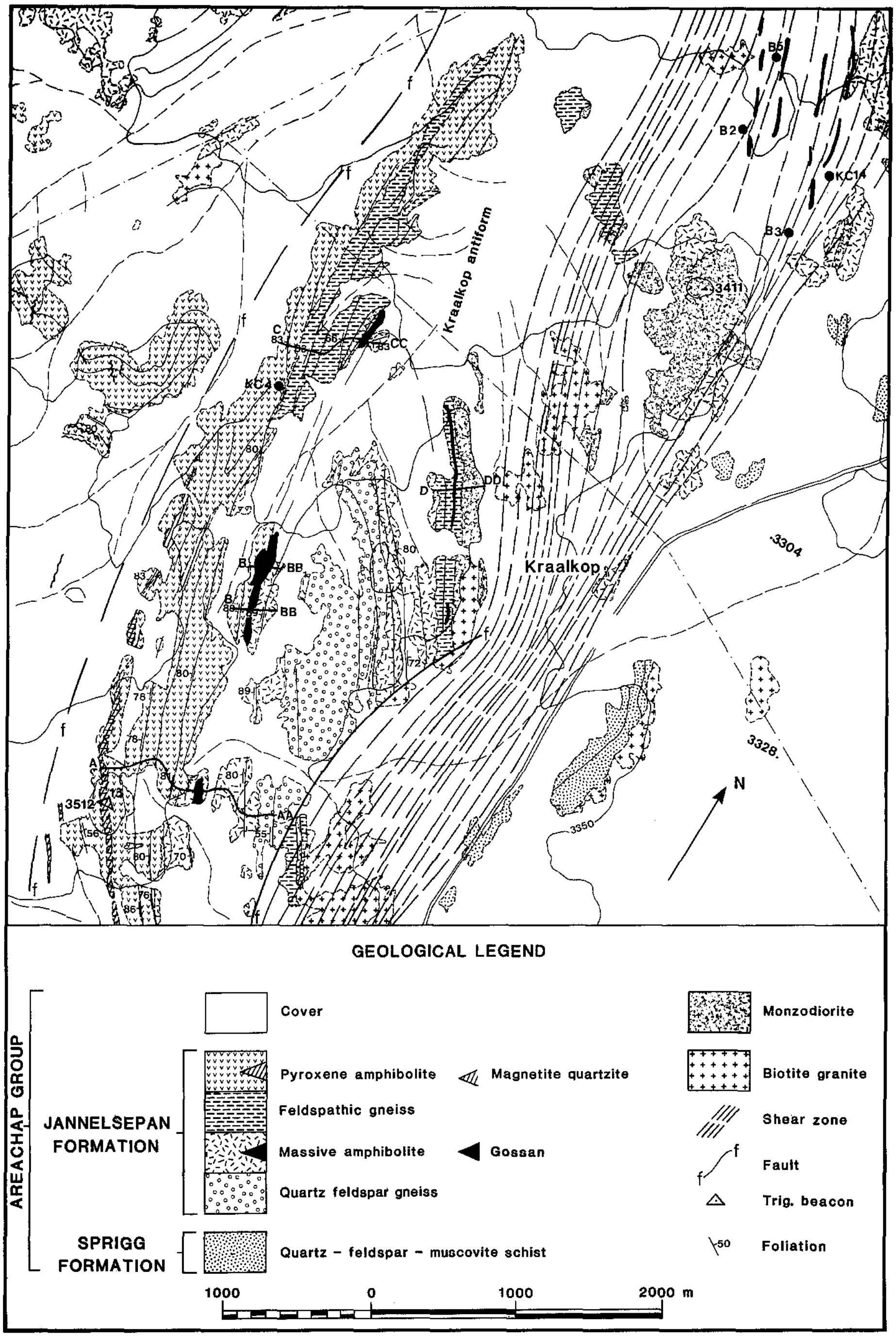

Fig. 2. Geologic map of part of the Boksputs sequence on the Kraalkop farm showing the various zones of sulfide mineralization and its relationship to the amphibolites of the Jannelsepan Formation

Beswick and Soucie (1978) described a procedure by which the analytical data of a metavolcanic suite can be tested for alteration. This method was also applied to the amphibolites of the Boksputs suite.

From Fig. 5 it is evident that the amphibolites plot in a very narrow field, but slightly below the trend of Beswick and Soucie (1978). This tendency could indicate that the amphibolites were chemically altered during metamorphism. Since the points show a minimum scatter, the possibility that the established trends do not represent island-arc tholeiites were tested by plotting average chemical values for island-arc settings from the literature (after Jakes and White 1972 and Barker 1968) onto the same diagrams.

As can be seen, the average chemical composition of the various volcanic assemblages from island-arc environments plot well inside the fields for the amphibolites of the Boksputs region. The amphibolites are seemingly not highly altered by metamorphism, and the chemical data can therefore be used with confidence in reconstructing a volcanogenic model for the sulfide mineralization.

Major element chemistry

A comparison between average MORB-normalized major element concentrations of the amphibolites and values

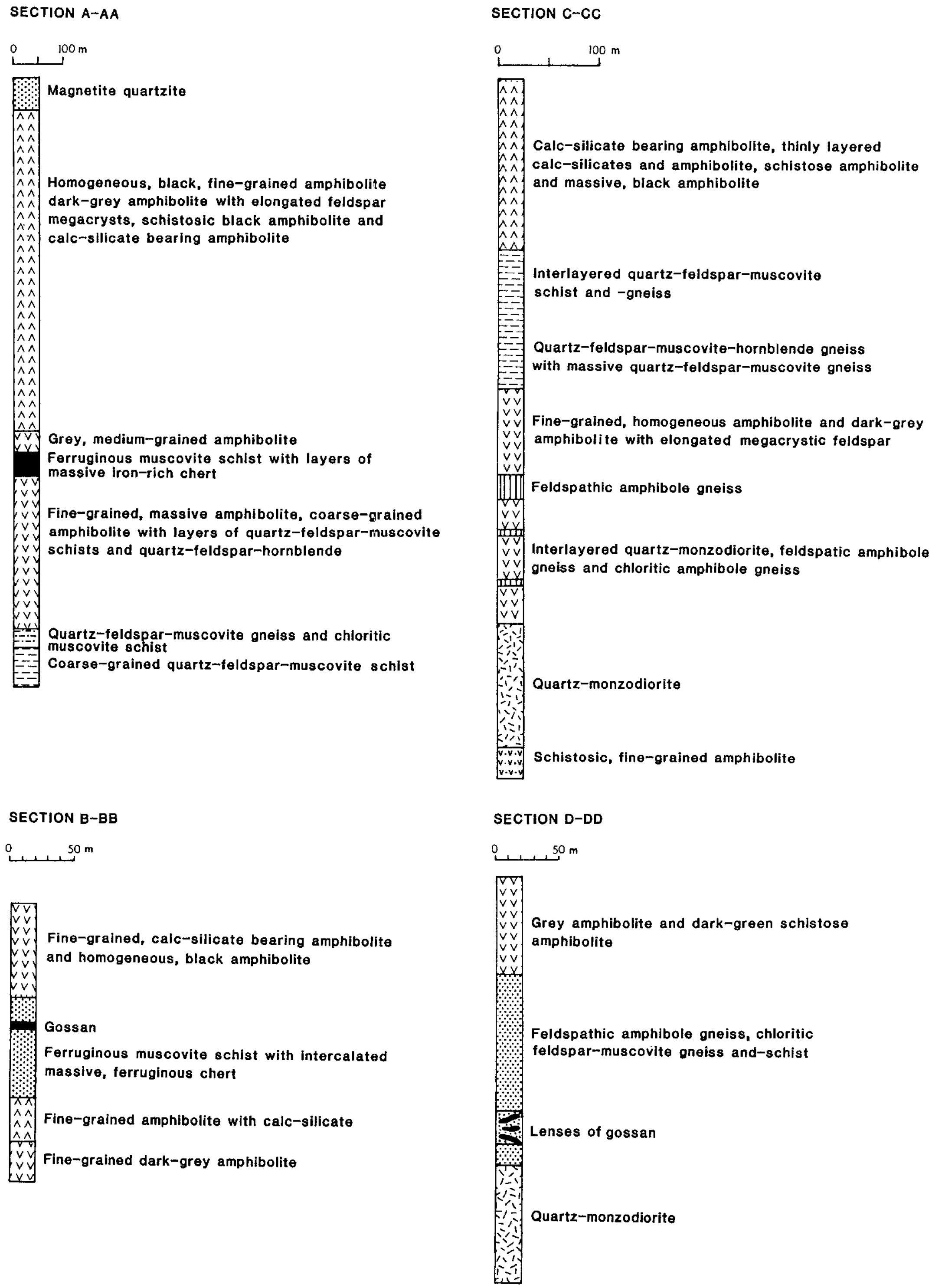

Fig. 3. Stratigraphic sections across the ore-bearing horizons of the Jannelsepan Formation along the flanks of the Kraalkop antiform (as illustrated in Fig. 2) showing the variation in stratigraphic position of the sulfide mineralization

from volcanic arc basalt as well as basic volcanics form the Sanbagawa belt (Tatsua Tatsumi 1970) shows that the Boksputs amphibolite corresponds with island-arc tholeiite (Fig. 6).

A FeO_{tot}-MgO-Al_2O_3 plot (Fig. 7) shows a strong calc-alkaline composition for the pyroxene amphibolites whereas the massive amphibolite plots in the tholeiitic field. This is in agreement with the chemical composition revealed by Fig. 6.

The composition of the precursors of the amphibolites is further enhanced by a K_2O vs SiO_2 diagram (Fig. 8). This diagram shows that the composition of the massive amphibolite varies from basalt, through low-K basalt and low-K basaltic andesite to low-K andesite. The pyroxene

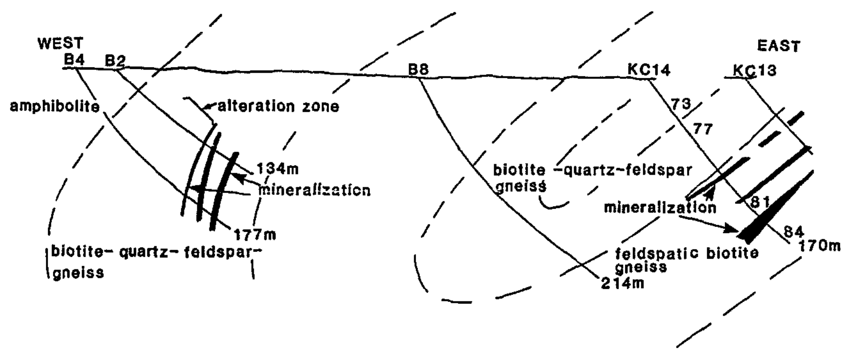

Fig. 4. Stratigraphic section constructed from borehole profiles showing the position of the ore horizons in the Kraalkop synform

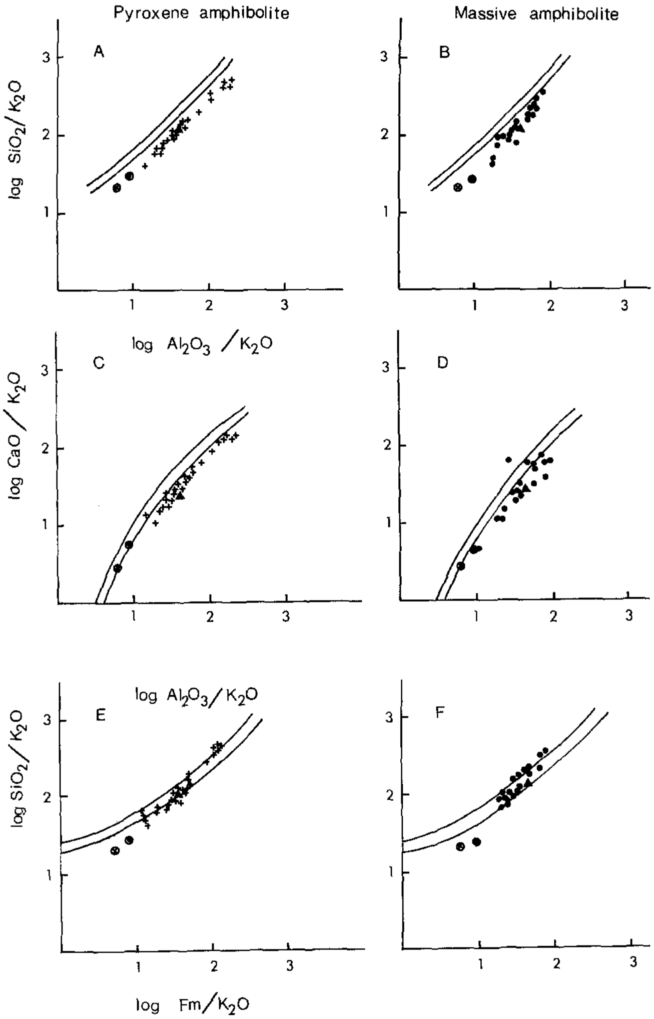

Fig. 5. Logarithmic oxide molecular proportion ratio plots illustrating only minor chemical alteration of the amphibolites during metamorphism. //, fields for modern volcanic suites (after Beswick and Soucie 1978); ⊗, average shoshonite (after Jakes and White 1972); ▲, average arc basalt (Barker 1968); ⊙, average calc-alkaline basalt (after Jakes and White 1972)

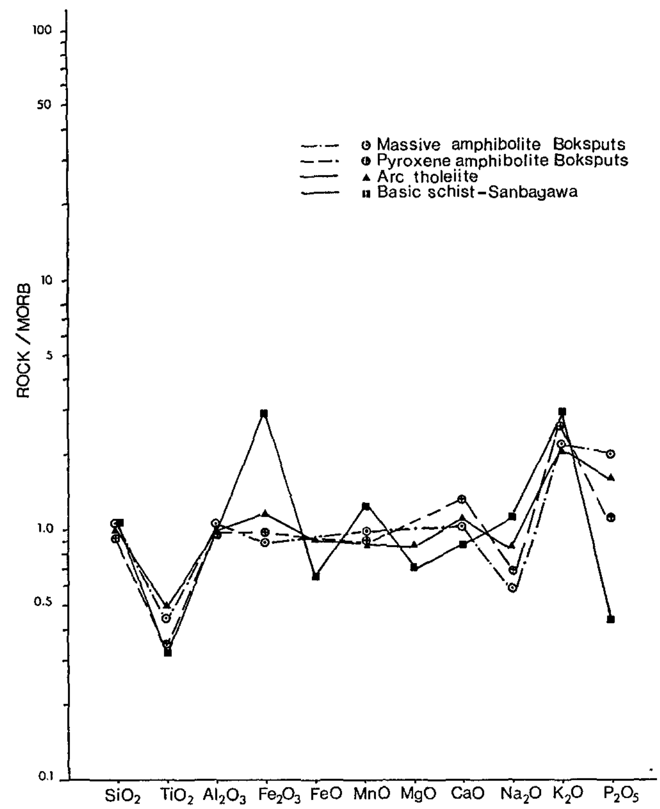

Fig. 6. A normalized major element rock/MORB plot of the amphibolites of the Jannelsepan Formation compared to that of average arc tholeiite and basalt of Besshi-type deposits of the Sanbagawa belt of Japan

amphibolite plots in the low-K tholeiite and calc-alkaline basalt fields.

Trace element chemistry

MORB-normalized trace element distribution patterns for the amphibolites (Fig. 9) also correspond with island-arc volcanics. The distribution pattern are distinctly different from that of oceanic tholeiite or within-plate continental tholeiites (Pearce and Gale 1977). A plot of Nb against SiO_2 (Fig. 10) also shows that the amphibolites are comparable with arc volcanics, whereas a plot of Ti (ppm) against Cr (Fig. 11) shows that the amphibolites compare favorable with island-arc basalts rather than ocean floor assemblages.

Rare-earth patterns

The rare-earth-element distribution curves (Fig. 12, after Schade et al., in press) show that the host-rock amphibolites are characterized by moderately enriched, light REE patterns with positive Eu anomalies and lower than normal MORB, heavy REE concentrations. These features

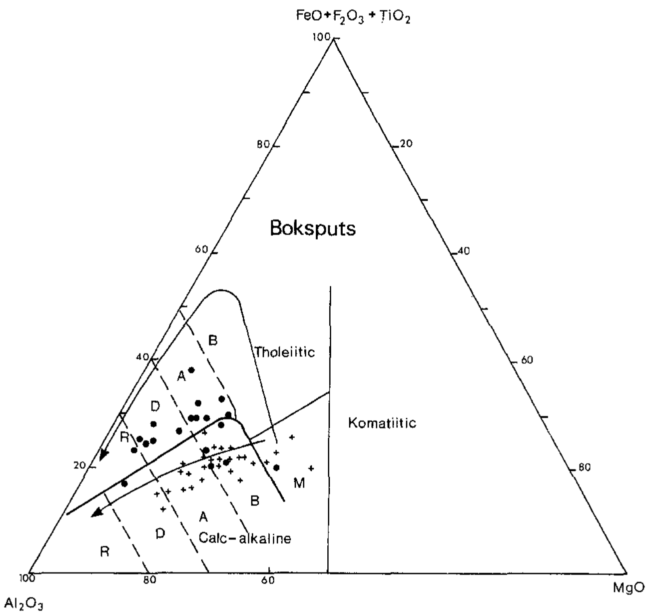

Fig. 7. A $FeO+Fe_2O_3+TiO_2$–Al_2O_3–MgO plot showing a calc-alkaline trend for the pyroxene amphibolites (+) and a tholeiitic trend for the massive amphibolites (●) (after Jensen 1976)

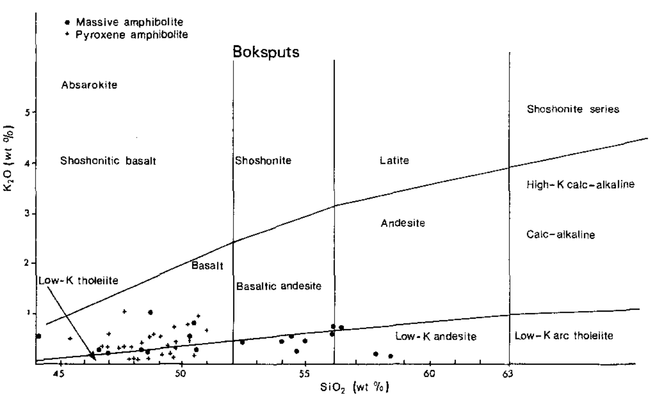

Fig. 8. A K_2O vs. SiO_2 plot revealing the low-K basalt, basalt-andesite and andesite character of the massive amphibolite and the more calc-alkaline composition for the pyroxene amphibolite

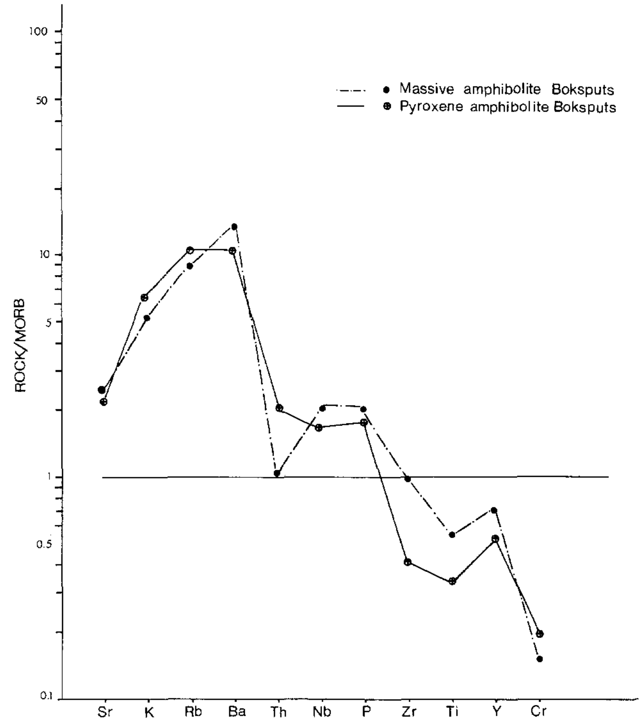

Fig. 9. A trace element rock/MORB normalized plot of the massive amphibolite and the pyroxene amphibolite of the Jannelsepan Formation

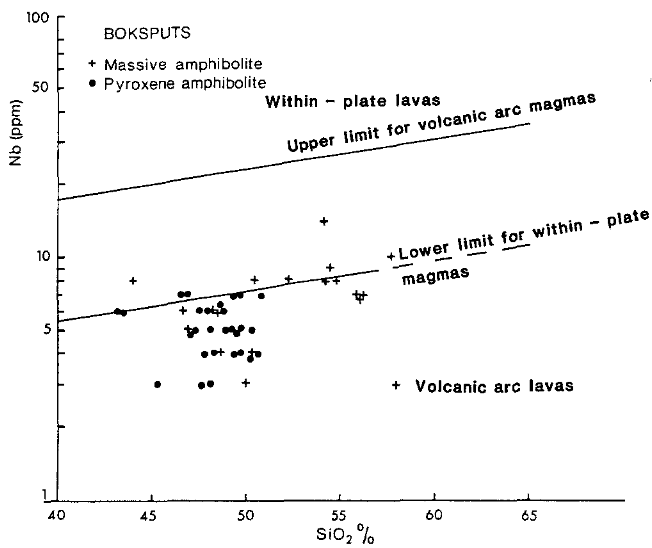

Fig. 10. A plot of Nb(ppm) vs. SiO_2(wt%) showing a strong resemblance with volcanic arc lavas

correspond with the general trends of calc-alkaline lavas of island-arc affinity, which agrees with the character of the rocks displayed by the major and trace element concentrations.

Tectonic setting

Since it is possible to distinguish between various tectonic domains by using the chemical composition of the host rocks as suggested by Pearce and Gale (1977), an attempt was also made to identify the tectonic environment in which the Boksputs sulfides were deposited. The conclusions regarding the tectonic setting of the sulfide mineralization and the host rocks are based on the assumption that modern plate tectonic processes were in operation during Proterozoic times. Based on this assumption the sulfide mineralization and the low-K tholeiite host-rock composition of the Boksputs region can be successfully fit into modern plate tectonic models for volcanogenic sulfide mineralization.

A comparison between the Boksputs mineralization and other volcanogenic strata-bound deposits shows a marked resemblance to the Besshi-type deposits of Japan. Features such as the association of the predominantly pyrite and chalcopyrite ores with basaltic host rocks of low-K tholeiitic composition, the absence of galena in the ore and the REE distribution curves all indicate a possible correlation with a Besshi-type deposit.

The tectonic setting of Besshi-type deposits is, however, disputable, and various tectonic models exist today. Kane-

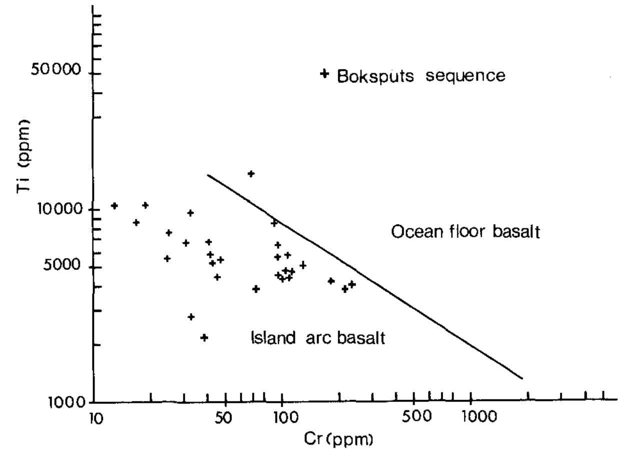

Fig. 11. A Ti(ppm) vs Cr (ppm) plot revealing the island-arc basalt characteristics of the amphibolites of the Boksputs sequence

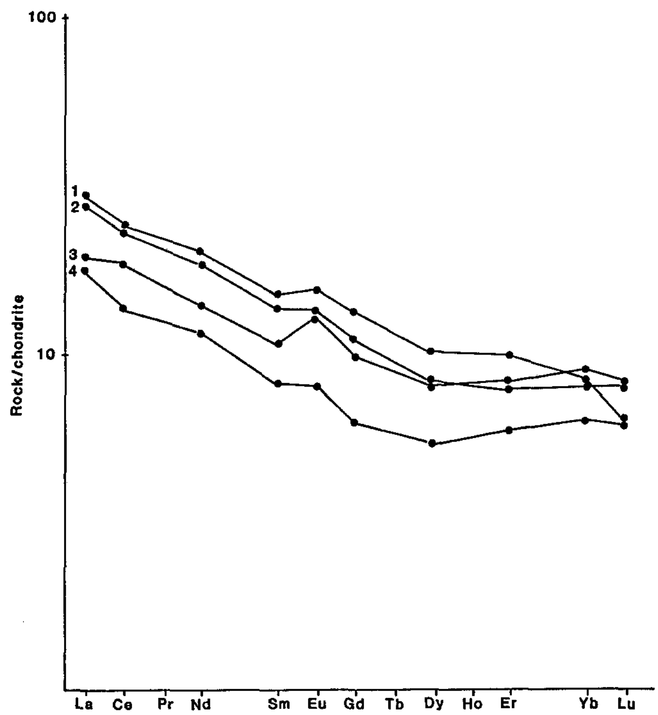

Fig. 12. REE distribution curves of the host-rock amphibolites showing strong affinities with island-arc-related volcanics

hira and Tatsumi (1970) as well as Mitchell and Bell (1973) and Garson and Mitchell (1976) related Besshi-type deposits to early island-arc volcanism in a distal setting. Klau and Large (1980) also stated that the Besshi deposits and Kuroko deposits are genetically related and simply represent different stages of arc development. Hutchinson (1980) is of the opinion that Besshi-type deposits are confined to forearc troughs. Fox (1984), however, strongly opposed the previous models and suggested that the Besshi-type deposits are genetically unrelated to the Kuroko deposits, and that Besshi-type deposits form in epicontinental or possibly back-arc extensional environments usually predating the subduction event with which the Kuroko deposits are related.

Low-K tholeiites are characteristic of both oceanic environments and also associated with island arcs. Jakes and White (1972) pointed out that the composition of the lavas change from low-K tholeiitic on the oceanic side of the arc to calc-alkaline to alkaline or shoshonitic on the back-arc side. According to Fox (1984) tholeiitic basalt occurs near the center of the fracture zone, whereas the lavas tend to become more alkaline toward the trench margins.

Due to the high degree of deformation in the Boksputs area it is not possible to unequivocally decide what the case was during the deposition of the sulfide mineralization. The low-K tholeiites which form the host rocks, however, pointed toward an arc-related environment rather than an oceanic environment, but could have formed in a rifted arc environment and therefore differ slightly from oceanic lavas.

According to the model by Hutchinson (1980) it is concluded that the Boksputs deposits in many respects resemble Besshi-type deposits and formed in a front-arc environment (Fig. 13) associated with low-K arc tholeiite along the eastern margin of the Namaqua mobile belt.

Conclusions

It is concluded that the low-grade, Cu-Fe sulfide mineralization at Boksputs, Northwest Cape Province, South Africa, is a volcanogenic strata-bound deposit hosted by amphibolites and associated gneisses which in many respects resemble Besshi-type deposits of Japan. The mineralization is not restricted to any particular lithologic unit but rather occurs as disseminated grains and thin layers in various lithologies.

The amphibolitic host rocks are interpreted as metavolcanic low-K tholeiites and calc-alkaline basalts, basalt-andesite, and andesite. Although similar rock types may be

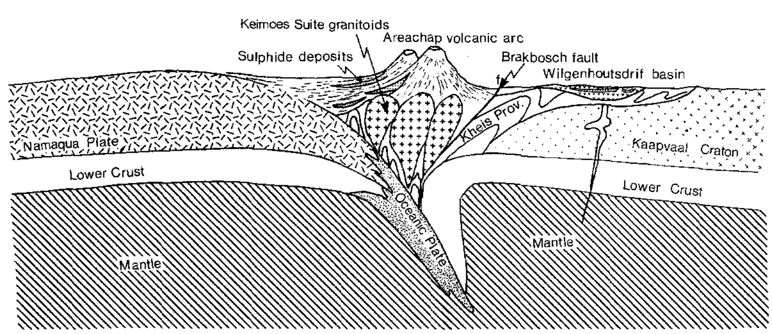

Fig. 13. Schematic plate tectonic model showing the structural relationships of the low-K tholeiites and the sulfide mineralization at Boksputs

related to other tectonic environments, such as oceanic or epicontinental rift zones, the chemical data, however, favors an arc-related source. It is concluded that the sulfide mineralization formed in a low-K tholeiitic volcanic assemblage intimately related to arc development along the eastern margin of the Namaqua mobile belt.

Acknowledgements. The authors would like to thank the CSIR for financing the project, Dr. W.A. van der Westhuizen and the Geological Survey for major and trace element analyses, the University of Stellenbosch for REE values. The figures were prepared by Mr. A. Felix, and Mrs. C. Greef typed the manuscript.

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Received: December 28, 1985
Accepted: September 30, 1986