MAGMATIC Cu-Ni-PGE MINERALIZATION AT WATERFALL GORGE, INSIZWA, PONDOLAND, TRANSKEI*

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ABSTRACT

The existence of Ni–Cu–PGE mineralization in the basal portion of, and the sediments underlying, the Insizwa intrusion in the Transkei, southern Africa, has been known for a long time. Here we present a new interpretation, based on modern geochemical criteria, of the origin of the sulfides. It is suggested that the composition of the parental magma of the Insizwa intrusion is a high-MgO tholeiite, and that the possible cause of sulfide liquid segregation is the contamination of this magma by siliceous shales. The sulfur-isotope data are consistent with a magmatic origin.

Keywords: Insizwa intrusion, magmatic sulfides, nickel, copper, platinum-group elements, Transkei.

SOMMAIRE

On connaît depuis longtemps l'existence d'une zone minéralisée en Ni, Cu et éléments du groupe du platine dans la partie inférieure du complexe Insizwa (Transkeï, Afrique du Sud) et dans les unités sédimentaires sousjacentes. Nous proposons une interprétation nouvelle de l'origine des sulfures fondée sur des critères géochimiques modernes. La composition du magma initial à Insizwa serait tholéiitique à haute teneur en MgO; la ségrégation d'un liquide sulfuré résulterait de la contamination d'un tel magma par des shales siliceux. Les données isotopiques sur le soufre sont compatibles avec une origine magmatique.

(Traduit par la Rédaction)

Mots-clés: complexe intrusif Insizwa, sulfures magmatiques, nickel, cuivre, éléments du groupe du platine, Transkeï.

INTRODUCTION

A number of subhorizontal doleritic and gabbroic sheets exists in Pondoland, northern Transkei, southern Africa, as erosional remnants of a possibly continuous intrusion of Karroo dolerites between Upper Permian Ecca sediments (grey sandstones and mudstones) and Lower Triassic Beaufort sediments (red sandstones and mudstones). One of the more extensive of these is the Insizwa–Ingeli–Tonti–Tabankulu intrusion, which occurs near the border of the Transkei with South Africa, 175 km southwest of Durban (Fig. 1). It has been argued (Maske 1966) that the present Pondoland area formed the deepest part of the former Karroo basin, and that the Jurassic Karroo dolerites, which occur over an area of some 64,000 km² in southern Africa (Bruynzeel 1957), were emplaced under plutonic conditions. This resulted
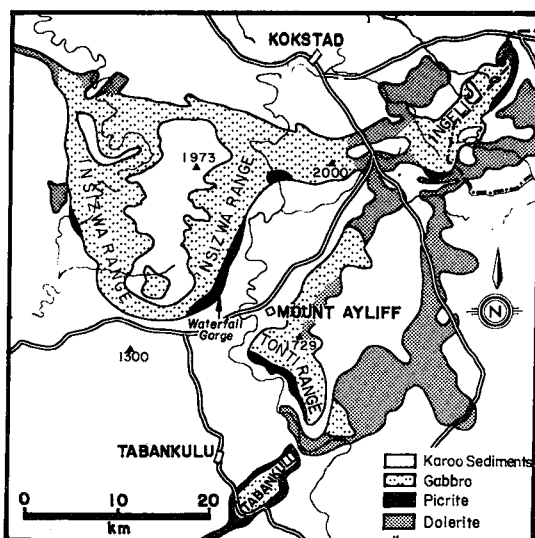
FIG. 1. Generalized map of the Insizwa-Ingeli-Tonti–Tabankulu intrusions, showing the lower picritic portions. Based on mapping of Scholtz (1937), Maske (1966) and Dowsett & Reid (1967).

in gravitational differentiation producing basal, central and upper zones. Picrite and troctolite dominate the basal zone, hypersthene gabbro the central zone, and quartz diorite and quartz monzonite the upper zone. Sections and mineral compositions are shown in Figure 2.

The basal zone at Waterfall Gorge (Fig. 3) has been described in detail by Scholtz (1937); it is characterized by disseminations of chalcopyrite, pentlandite and pyrrhotite grains as well as cross-cutting veins and sheets of massive sulfide in association with acid phases.

GEOLOGY OF THE WATERFALL GORGE AREA

The sulfide mineralization is spatially confined to the lower contact of the intrusive gabbroic sill; it is generally accepted that the two are genetically related (Scholtz 1937).

The sill is dissected by the Umzintlava and Umzimbubu river valleys. The Insizwa, Ingeli, Tonti and Tabankulu massifs probably were part of the same intrusion; if so, it has an areal extent of at least 1200 km² and a vertical thickness of up to 900 m. Although lateral variations in the intrusion have been recorded (Fig. 2), it was probably emplaced in not more than three very closely spaced intrusive events, and hence represents a very major injection of magma.

The base and top of the intrusion are not planar but undulate slightly, resulting in thickening in the troughs and thinning over arches. On a regional scale, the intrusive body is concordant. However, Maske (1966) indicated the presence of several transgressive relationships; in many places the dip of the contact attains 40° (Dowsett & Reid 1967), indicating local discordances with the essentially flat-lying sediments.

Most workers have subdivided the intrusion into a basal zone from about 100 to 130 m thick, a central zone from 300 to 500 m thick and a thin upper zone. The upper zone is composed of quartz diorite and quartz monzonite and, locally, micropegmatite, which show an anastomosing relationship to the hornfels in the roof. These rapidly grade downward into hypersthene gabbros of the central zone. At Waterfall Gorge there are three olivine hypersthene gabbro bands overlain by quartz hypersthene gabbro, whereas in the Ingeli section there are two bands of each rock type. The basal zone has been studied in more detail because of its sulfide mineralization; althoug it is largely picritic it has been subdivided into four units: troctolite, basal picrite, basal olivine hypersthene gabbro and a chill zone.

The troctolite is not developed in the Waterfall Gorge section, but is 50 m thick at Ingeli. The top of the basal zone is taken at the level where plagioclase increases markedly in abundance to about 70%. This is associated with a marked decrease in the abundance of olivine. However, a small proportion of olivine is present above this level for about 20 m, forming the lower olivine hypersthene gabbro unit of the central zone. The picrite, composed of over 60% olivine and about 100 m thick, is the dominant rock type of the basal zone. The chill zone and basal olivine hypersthene gabbro together are only 20 m thick. However, it is this lowest 20 m that contains the disseminated sulfide mineralization.

The textures of these rocks have been described by Scholtz (1937), Bruynzeel (1957) and Maske (1966) and, except for the finer grained chilled margin, are fairly typical of orthocumulate rocks. Layering is not well developed in the sequence, with the exception of the troctolite unit, but textures and mineral and whole-rock compositions are broadly consistent with an origin by crystal settling and fractional crystallization. However, the reappearance of olivine in the central zone in the Ingeli section led Maske (1966) to suggest that there was an addition of undifferentiated magma. Two sections through the intrusion are shown in Figure
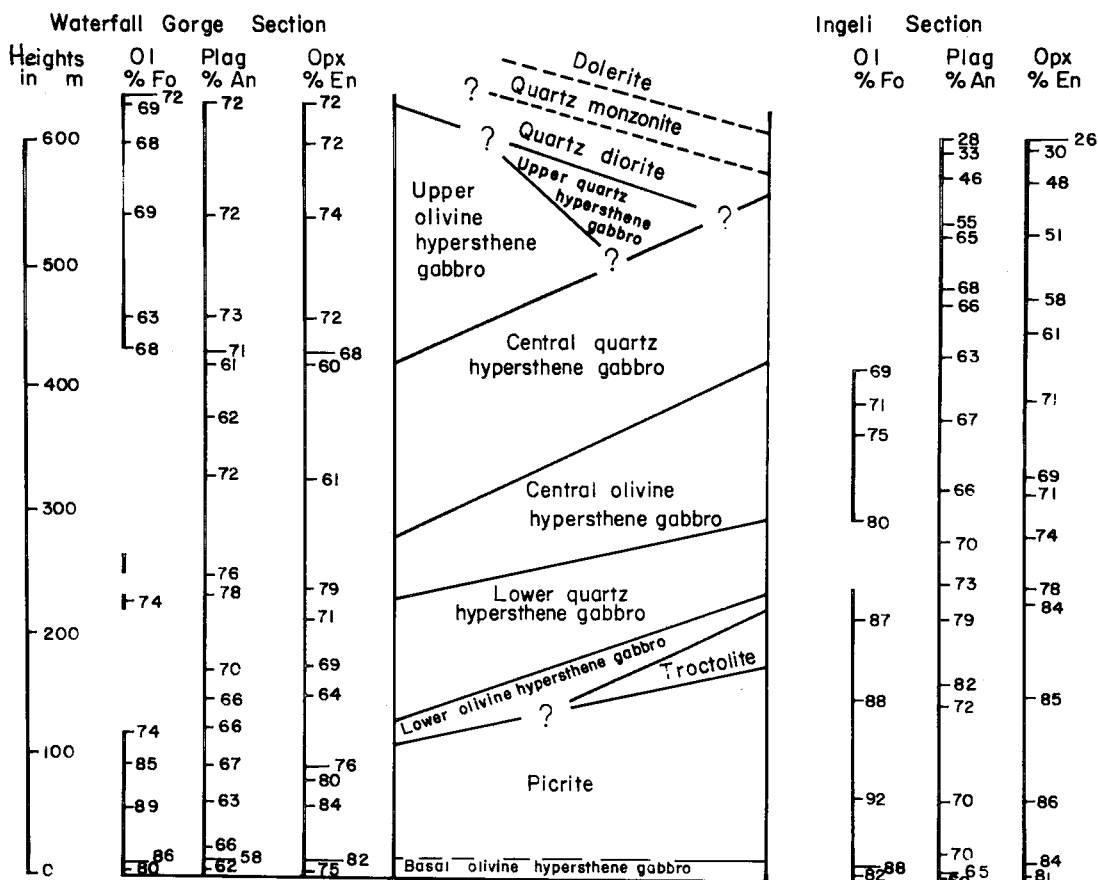
FIG. 2. Generalized profiles and mineral compositions through the Waterfall Gorge section (Scholtz 1937) and through the Ingeli section (Maske 1966).

2. The mineral compositions are not entirely definitive in this regard, nor do they show the range expected of a differentiating magma body. The compositions of the plagioclase crystals do not show a significant gross trend of differentiation, although zoning of individual crystals is well developed (Maske 1966). For example, in the Waterfall Gorge section, the feldspar becomes more anorthite-rich upward, from An_{60} to An_{78} through the basal zone and the lower half of the central zone. It shows a typical trend decreasing in An content upward to An_{60}, and then abruptly increases to An_{71} at the base of the thick upper olivine hypersthene gabbro. Above this levels its composition remains nearly constant. In the Ingeli section, the trend is similar except that the reversal at the olivine hypersthene gabbro horizon is insignificant.

The trend is analogous for orthopyroxene. It becomes more magnesian upward in the basal zone at Waterfall Gorge, showing an iron-enrichment trend thereafter, with a small reversal at the central thin olivine-bearing horizon and then another reversal at the upper olivine hypersthene gabbro. Above this level its composition remains constant. In the Ingeli section the mineral shows a gradual trend from En_{84} to En_{26} from bottom to top, with a reversal at the olivine-bearing horizon apparent in one profile but not in other profiles studied by Maske (1966).

In none of the sections analyzed is there a convincing reversal in the olivine composition where it reappears in the middle of the central zone. Again, in the Waterfall Gorge section, the olivine becomes more magnesian upward from Fo_{80} to Fo_{89} over an interval of 60 m, before it starts to follow a normal differentiation trend. Thus, although fractionation un-
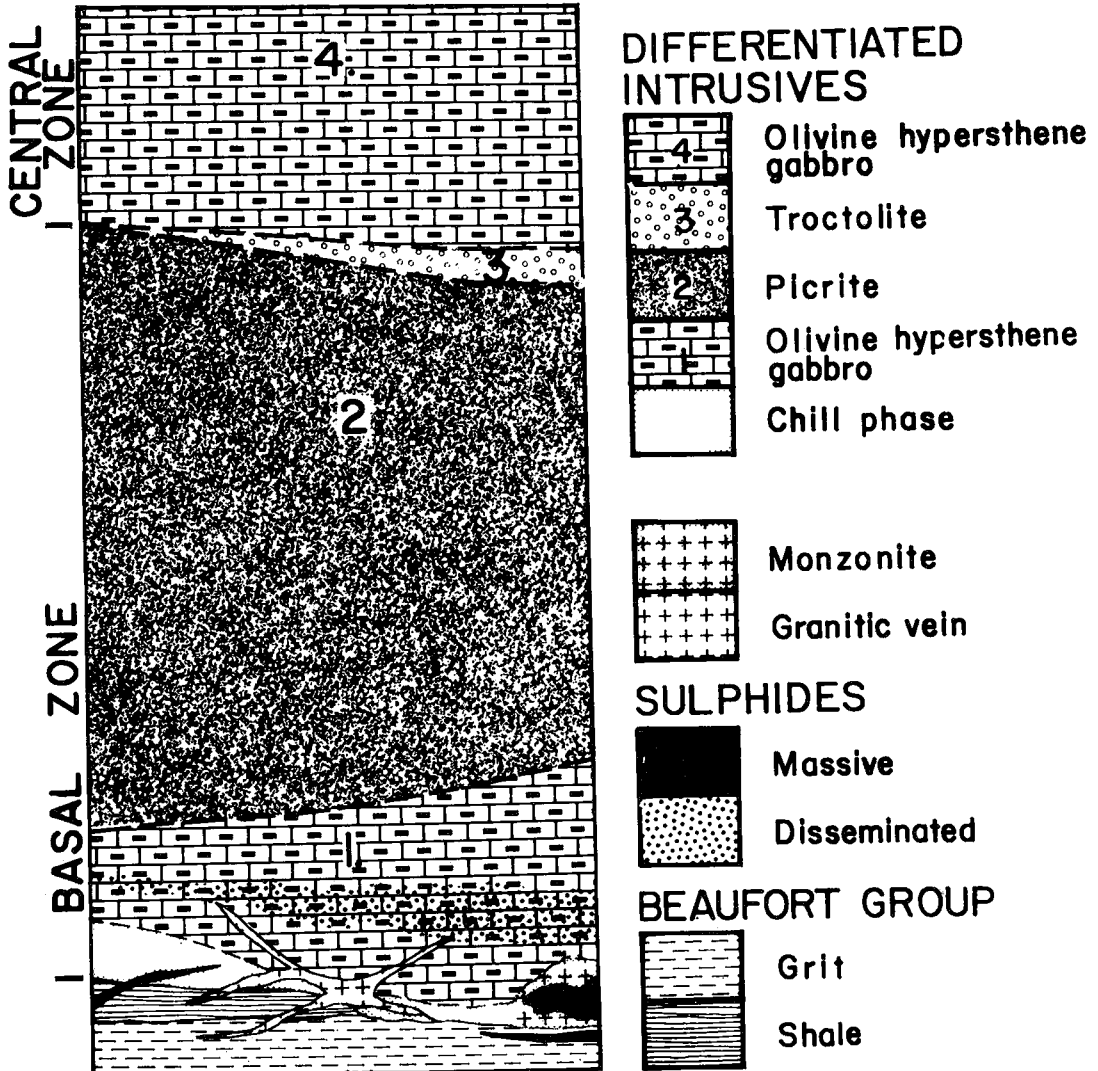
FIG. 3. Section through the basal zone at Waterfall Gorge, Insizwa, showing the sulfide distribution (after Scholtz 1937).

doubtedly has taken place, there are features of the mineral compositions that are enigmatic.

The floor sediments, which are host to some of the fracture-filled veins of sulfide, are siliceous shales. In immediate proximity to the floor of the intrusion they are hornfelsed, but growth of metamorphic minerals is very restricted. The shales are composed of fine grained quartz and feldspar (partly kaolinized) in a matrix of chlorite and sericite with some detrital biotite. There are also a few larger flakes of biotite that Scholtz (1937) viewed as formed by metamorphism. Very close to the contact, hypersthene is present as irregular poikiloblasts, and a few grains of cordierite have been reported (Scholtz 1937, p. 125). There are some calcareous nodules within the hornfels, and these contain a small proportion of wollastonite, grossular and diopside.

ORE MINERALOGY

Nickel sulfides were found at Waterfall Gorge as early as 1865 by Rudlin (Kenyon

1973). Since 1930, various companies have intermittently carried out exploratory work; however, few quantitative data have been published.

There are two principal ore types: (1) disseminations of chalcopyrite, pentlandite and pyrrhotite, mainly in basal hypersthene gabbro and, to a lesser extent, in the chill and picrite dykes in the surrounding areas; ((2) massive ore in sheets and veins, both in the basal hypersthene gabbro and adjacent hornfelsed sediments, always in close spatial association with acid phases. The possible interrelations between various types of ore and host rock are illustrated in Figure 3 (after Scholtz 1937). Assay values of the principal ore types were given by Scholtz and are shown in Table 1.

A detailed account of the mode of occurrence and textural features of the base metal sulfides in these ores is given by Scholtz (1937), who reported that in both the massive and disseminated types of sulfide ore, the principal sulfide minerals are pyrrhotite, pentlandite and chalcopyrite. Pyrrhotite is, however, by far the most dominant sulfide; it commonly displays a two-phase lamellar exsolution intergrowth of troilite and hexagonal pyrrhotite. Scholtz (1937) also identified minor amounts of pyrite, bravoite, valleriite and cubanite, together with rare sphalerite, niccoline, millerite, bornite, chalcocite and covellite. At least sixteen other distinct minerals were found to occur generally as such small grains as to render their identification uncertain. However, on the basis of microchemical tests on samples of minerals extracted from the polished sections, Scholtz suggested that this list include a sulfarsenide of nickel and iron, tetrahedrite/freibergite, a nickel antimonide, a lead telluride, a tellurium-rich mineral, native bismuth, gold–silver–copper alloys, galena, and a nickel sulfide and a platinum telluride that he named parkerite and niggliite, respectively.

An electron-microprobe investigation of the platinum-group minerals (PGM) in the Insizwa ores from Waterfall Gorge has been initiated by one of us (G.A.K.). Analyses were performed on a four-channel Cambridge Instrument Microscan III. Pure elements and pyrite were used as standards at an operating voltage of 20 kV and a specimen current of 100 mA. Our work, particularly on the disseminated sulfide ore, has so far revealed the additional occurrence of froodite $PdBi_2$ associated with parkerite $Ni_3Bi_2S_2$ and irarsite $IrAsS$ with sperrylite $PtAs_2$. Bismuthinite has also been confirmed for the first time (Fig. 4d), together with a lead telluride (Fig. 4a) that has a composition of Pb 66.4 and Te 33.0 wt. %, corresponding to the formula Pb_5Te_4. The difference between the lead telluride and altaite $PbTe$ (Pb 61.9, Te 38.1 wt. %) may be real or due to errors inherent in analyzing such small grains (4 x 14 μm). However, the euhedral prismatic habit suggests a nonisometric structure, although no anisotropy could be seen under crossed polars. Two analyses of parkerite, which was usually found intergrown with froodite (Fig. 4c), gave compositions of Ni 25.0, 26.6%, Fe 2.1, 3.3%, Bi 60.8, 61.6%, Te 1.9, 2.4% and S 9.7, 9.3%, respectively, approximating closely $(NiFe)_3(BiTe)_2S_2$.

The platinum-group minerals

Sperrylite $PtAs_2$ was previously reported by Scholtz (1937) as a relatively common PGM in the massive ore, where it invariably occurs as idiomorphic crystals of up to 0.2 mm in length in contact with pyrrhotite, cubanite and parkerite. His identification was based on optical properties, with qualitative microchemical tests for Pt and As. In the present preliminary polished-section study of the disseminated ore, one euhedral rectangular grain of sperrylite 25 x 32 μm in size was found; it is overgrown by chalcopyrite at the silicate–sulfide contact of an interstitial pyrrhotite–pentlandite–chalcopyrite aggregate (Fig. 4b). An electron-microprobe analysis gave the composition as Pt 56.5, As 42.3, Sb 1.4 and S 0.2%, corresponding to the formula $Pt(As_{0.97}Sb_{0.02}S_{0.01})_{2.03}$. The occurrence of "hard" PGM, such as sperrylite, braggite, cooperite and laurite, growing inward from the silicate wall of the sulfide aggregates is also a characteristic feature of the Merensky Reef (Kingston 1977, Vermaak & Hendriks 1976); this feature, together with the common euhedral nature towards all the principal base metal sulfides, could be interpreted as indicating a very early stage of crystallization.

TABLE 1. ANALYSES OF ORES FROM INSIZWA*

	1	2	3	4
Ni	0.83	4.48	5.95	5.08
Cu	0.60	2.69	15.35	3.45
Co	-	0.21	0.37	-
Ag	-	-	0-110	16
Au	-	-	0.5-9.0	0.4
PGE	1.8	6.5	20-143	0.75-3.75
S	-	31.6	26.8	-
No.+	6	7	4	2

* Data from Scholtz (1937). 1. Disseminated sulfide in olivine hypersthene gabbro: 2. Pyrrhotite-rich massive ore (PGE, Co and S are average of 2 samples only); 3. Chalcopyrite-rich ore; 4. Mixed massive ores; total weight assayed 10 tons, analyzed by Johnson, Matthey and Co., London. No+ = number of analyses averaged. Ni, Cu, Co and S quoted in wt %; Au, Ag and PGE in ppm.
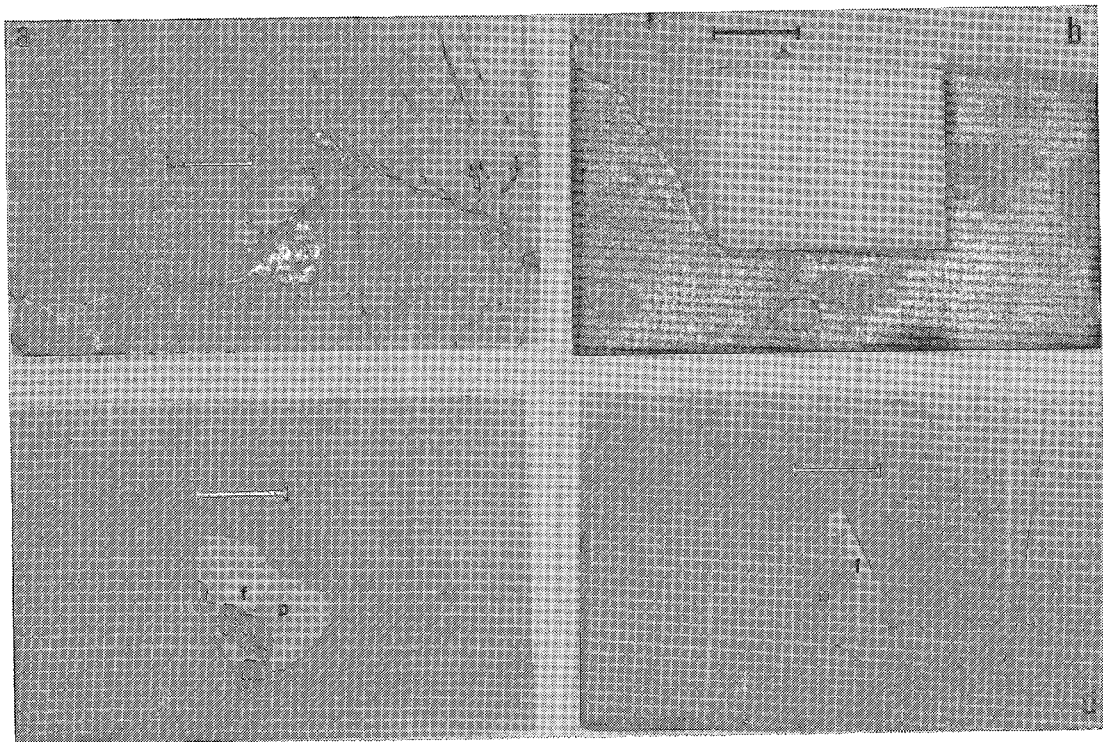
FIG. 4a. Photomicrograph of a prismatic crystal of a lead telluride in chalcopyrite that contains flame-like inclusions of mackinawite. Scale is 10 μm. 4b. Photomicrograph showing a euhedral crystal of sperrylite at a silicate–chalcopyrite boundary. Irarsite occurs as a small darker, euhedral corner overgrowth of sperrylite. Scale is 10 μm. 4c. Photomicrograph showing medium grey bireflecting parkerite (p) enclosing a euhedral grain of white froodite (f) in a matrix of chalcopyrite. A speck of gold is white (Au). A mottled dark grey area is a residue of carbon after analysis (c). Scale bar is 10 μm. 4d. Photomicrograph showing an anhedral composite grain of froodite (f) and bireflecting bismuthinite (b) in a matrix of pyrrhotite that displays a lamellar structure. Scale bar is 10 μm.

Froodite is considered to have an ideal end-member formula of $PdBi_2$ and a general composition of $(Pd,Pt)(Bi,Te)_2$ (Cabri & Laflamme 1976). In the disseminated sulfide ore of In-sizwa, the mineral considered to be froodite is normally intergrown with parkerite and, less commonly, with bismuthinite and native bismuth, forming small anhedral composite grains less than 25 μm in size dominantly in pyrrhotite and, in one case, in chalcopyrite (Fig. 4c, d). The mineral is bright, creamy white, with no detectable bireflectance (in contrast to the darker parkerite, which displays a distinct bireflectance, creamy white to greyish white with a bluish tint). The mineral is only weakly anistropic under crossed nicols, whereas parkerite displays a strong anisotropy. Froodite is softer than parkerite and has a higher reflectance. It is most probable that these minute composite grains in pyrrhotite resulted from exsolution.

Electron-microprobe analysis of three froodite grains approximately 5–10 μm in size gave compositions of Pd 17.0, 12.8, 14.8%; Fe 2.0, 2.4, 1.7%; Ni 0.2, n.d., 0.3%; Bi 74.4, 78.9, 72.6% and S 0.2, n.d., 0.2%, respectively, corresponding to total cation:anion ratios of 1:1.83, 1:2.3 and 1:2.05, respectively, with an average of 1:2.08. These rather unsatisfactory results may be due in part to analytical error caused by the small size of the froodite grains. Several attempts to improve on these analyses failed, and it seems likely that there is insufficient adjustment by the correction program for this particular combination of elements. However, the above results, although not conclusive, do strongly suggest that the mineral is a ferroan variety of froodite.

An *Ir–As–S phase* considered to be irarsite was found as an overgrowth on the corner of a sperrylite crystal in the disseminated sulfide ore (Fig. 4b). Its properties correspond to

those of irarsite (Uytenbogaardt & Burke 1971): greyish white with a distinct bluish tint (compared with white for sperrylite), reflectance lower than that of sperrylite and isotropic under crossed nicols. A qualitative electron-microprobe analysis confirmed major Ir, As and S.

Niggliite PtSn has been described in the massive pyrrhotite ore from Waterfall Gorge by Cabri & Harris (1972), who showed that the mineral named by Scholtz (1937) as niggliite is not a platinum telluride but Pt(Sn, Sb,Bi). The mineral occurs as inclusions up to 25 x 75 μm in size within insizwaite, parkerite and pentlandite. Niggliite has not yet been found in the disseminated-type ore.

Insizwaite $PtBi_2$ was described for the first time by Cabri & Harris (1972) in a sample from the Waterfall Gorge section, donated by Professor Scholtz. They found insizwaite as small rounded grains up to 70 x 120 μm in size enclosed in pentlandite, chalcopyrite and parkerite and enclosing niggliite. The average formula from five electron-microprobe analyses was given as $Pt_{1.0}Bi_{1.35}Sb_{0.57}$. This phase has not yet been found in the disseminated-type ore.

Gold–silver–copper alloys that could contain minor amounts of the platinum-group elements, particularly palladium, were reported by Scholtz (1937) in polished sections and nonmagnetic concentrates prepared from the massive ore at Waterfall Gorge. He recognized coppery red, pale yellow and silver-white alloy types; he considered these to correspond to copper-, gold- and silver-rich Au–Ag–Cu alloys, respectively. Small specks of such alloys have been located in the disseminated ore (Fig. 4c) but require further investigation.

It is clear from the evidence of the many unidentified phases described by Scholtz (1937), and the many distinctly different unidentified grains still to be analyzed in the present study, that the platinum-group mineralogy is most probably as complex and extensive as that found in the Merensky Reef. The authors' preliminary investigation indicates that a difference probably exists between the PGM assemblage of the massive and disseminated types of ore, and that this can be related to a difference in genesis. A detailed study of the mode of occurrence and types of PGM in the various ore types is essential to any future exploitation of these deposits.

GENESIS

A knowledge of the composition of the parental magma seems to be of crucial importance in understanding the genesis of the mineralization. It has long been known that there exists an excellent positive correlation between Ni and MgO contents of basic magmas. Eales & Marsh (1979) argued that dolerites from the central Karroo province with greater than 10% MgO were unlikely to represent true liquids, but were enriched in MgO by disproportionately high olivine content, owing to differentiation processes. However, it was argued by Cawthorn (1980) that such changes did not occur in the case of the Insizwa intrusion. As evidence of this, he cited the data of Scholtz (1937), who described the chill margin as containing only 0.9% olivine crystals even though the analysis he gave showed 13.4% MgO. Thus, the petrographic evidence clearly demonstrates that this composition is not enriched in olivine. Comparative analytical data on the chill-zone rocks from the Insizwa intrusion and from other Karroo dolerites are given in Table 2.

The second feature that appears to be anomalous relates to the composition of the olivine and, to a lesser extent, of the other silicate minerals. Bruynzeel (1957) presented results of several analyses of olivine from the chilled margin and the lower olivine-rich (picrite) zone. The compositions increased in their forsterite content from about Fo_{80} at the base to Fo_{90} in the middle of the zone, and then began to decrease with further increase in height. These values show a larger range than the values of Fo_{83-86} reported by Eales (1980) for the picrites from Insizwa. However, he did not indicate the stratigraphic range covered by his samples. Scholtz (1937) and Bruynzeel (1957) also analyzed orthopyroxene, clinopyroxene and plagioclase compositions and found that these displayed a reversed differentiation trend from

TABLE 2. COMPOSITION OF CHILLS FROM INSIZWA AND OTHER KARROO SILLS

SiO_2	52.00	54.05	49.18	51.71	54.73	51.96	0.57
TiO_2	0.60	0.71	0.64	0.98	1.18	0.90	0.06
Al_2O_3	12.81	15.07	13.23	15.31	15.64	15.64	0.31
Fe_2O_3	1.84	2.13	11.07*	11.20*	0.87	0.92	0.43
FeO	6.92	5.94			8.63	9.23	
MnO	0.28	0.33	0.21	0.18	0.16	0.17	
MgO	13.24	7.31	12.88	6.83	6.18	7.55	0.51
CaO	7.65	9.00	9.76	10.84	9.20	10.84	0.36
Na_2O	2.60	3.06	1.56	2.28	2.30	2.08	0.18
K_2O	0.76	0.89	0.41	0.51	0.87	0.56	0.19
L.O.I.	1.35	1.59	0.64	n.d.	n.d.	n.d.	

1 - Chill in Insizwa intrusion (Scholtz 1937); 2 - Analysis 1 less 15% olivine; 3 - High-MgO chilled dolerite at Munnik Pass, Graaff-Reinet (Eales & Marsh 1979); 4 - Average sill composition from the Eastern Cape (Eales & Marsh 1979); 5 - Chill to Hangnest sill (Le Roux & Reid 1978); 6 - Chill to Blaukrans sill (Le Roux & Reid 1978); 7 - Standard deviation in average analysis 4 (Eales & Marsh 1979). *Total iron as Fe_2O_3.

the base upward. Such reversed trends suggest that supercooling and crystallization of anomalous, lower-temperature mineral compositions may have occurred in the basal portion of the intrusion.

The reverse trend in olivine compositions near the base may also relate to the presence of sulfides. Campbell (1978) studied the Jimberlana intrusion, where disseminated sulfides occur at the base. He found that where sulfides are present, the olivines are more magnesian than elsewhere, by up to 5 mol. % forsterite. Although the effect described by Campbell (1978) may be important, it cannot be the entire reason for the discrepancy in mineral composition. Maske (1966) presented analyses of olivine from the adjacent (and probably originally contiguous) intrusion to Insizwa, the Ingeli massif. He reported values of Fo_{90} and a reversed differentiation trend from an essentially unmineralized section (Fig. 2). Thus, the more magnesian olivines do not always occur in association with sulfides.

The reversal in composition of the plagioclase, mentioned above, remains a problem even if the formation of a sulfide phase were capable of removing iron from the silicate liquid and producing more magnesian mafic minerals. As plagioclase contains no iron or magnesium, its composition should not be influenced by sulfide separation. The progressively more calcic nature of the plagioclase upward in the basal zone (Fig. 2) is contrary to what is expected for fractional crystallization conditions. Both Bruynzeel (1957) and Maske (1966) suggested that this reversal may be due to more rapid cooling of the magma near the base of the intrusion.

Thirdly, the chemical composition of the chilled margin of the Insizwa intrusion appears to be atypical in comparison with average compositions of Karroo dolerite. The composition determined by Scholtz (1937) is given in Table 2, where it is compared with other typical sill compositions from the Karroo. It is apparent that as well as being unusually high in MgO, the Insizwa composition is enriched in SiO_2, Na_2O and K_2O. It has been argued (e.g., by McBirney 1975) that, as a result of contamination, fine grained sample from the margins of intrusions may not represent original magma compositions. Although this may be true for large intrusions such as Skaergaard, it is unlikely that such a process would have changed the MgO content of the chill zone at Insizwa; furthermore, any contamination from adjacent shales would have decreased the MgO content. Thus, we believe that the high MgO content in

the analysis of Scholtz (1937) is a true indication of magma composition. It is possible to calculate theoretical compositions with MgO contents comparable to typical Karroo dolerite by removing varying proportions of olivine from the chilled margin composition to see if olivine accumulation has taken place. According to Eales & Marsh (1979), a typical dolerite composition would contain about 7% MgO. As shown in Table 2, 15% of olivine of composition Fo_{90} has been removed from the chilled margin composition of the Insizwa intrusion, so that the residual composition contains about 7% MgO and hence would allegedly be comparable to a typical Karroo dolerite. The SiO_2, Na_2O and K_2O contents of this calculated composition are now even more distinctly different from typical Karroo dolerite; SiO_2, Na_2O and K_2O are higher than average dolerite by more than 4, 3 and 2 times, respectively, the calculated standard deviations. Thus, the composition of the Insizwa intrusion given by Scholtz (1937) cannot be the result of olivine accumulation in a typical Karroo tholeiite composition, but points to the existence of a true liquid with greater than 10% MgO.

FORMATION OF AN IMMISCIBLE SULFIDE LIQUID

Silicate magmas contain low concentrations of Ni, Cu and S. However, if an immiscible sulfide liquid that scavenges Ni and Cu from the silicate magma forms, a high-grade ore deposit may be produced (MacLean & Shimazaki 1976). There are at least three possible processes by which the separation of an immiscible sulfide may be induced: (1) Separation may be the result of fractional crystallization. The silicate minerals crystallizing from a magma contain no sulfur; thus the concentration of sulfur in the residual liquid will increase. As the solubility of sulfur in a silicate liquid decreases with decreasing temperature (Haughton et al. 1974), ultimately a sulfide phase will separate. (2) The magma may react with sedimentary country rocks that are rich in sulfur. Selective addition of sulfur may occur, causing the saturation limit to be exceeded and inducing sulfide separation. (3) Siliceous country rock may be assimilated into the basic magma. The sulfur solubility is lower in a siliceous magma than in a basic liquid (Irvine 1975). If a basic magma is contaminated by a siliceous melt from the country rocks, sulfide saturation may result.

It is possible to test for these different mechanisms by geochemical techniques. There is a well-known correlation between Ni/Cu ratios

and element abundances and degree of differentiation; if extensive differentiation has taken place prior to sulfide separation, the Ni/Cu ratio of the sulfide will be low. Juvenile magmatic sulfur has a restricted isotopic ratio, whereas sedimentary sulfur generally has highly variable isotope ratios; hence such data may indicate the source of the sulfur.

Major- and trace-element compositions of Karroo dolerites are very different from those of their sedimentary hosts, which are mainly sandstones and shales. Consequently, any addition of these sediments to the basic magma would produce a noticeable change in amounts of SiO_2, Na_2O, K_2O, Rb, Ba and Zr. Such an atypical silicate composition may indicate the possibility of sulfide segregation resulting from the operation of process 3, and a possible example exists. Walker & Poldervaart (1941) described numerous sedimentary inclusions in the Hangnest sill in the Calvinia district of Cape Province and presented major-element analyses of rocks showing the effects of contamination. More recently, Le Roux & Reid (1978) presented trace-element data on the same sill and on an adjacent sill. They reported some differences in composition between the Hangnest and Blaukrans sills and noted that 1) Rb, Ba and Sr are significantly enriched in the Hangnest sill, and 2) SiO_2 is also slightly higher. They rejected the mechanism of contamination as the sole process for producing these differences because of the massive depletion in Ni in the Hangnest sill relative to the other sill. The Hangnest sill contains 3–5 ppm Ni at 7% MgO, whereas the Blaukrans sill has a normal Ni abundance of 100–120 ppm at 8% MgO. They concluded that, in the absence of any other process, almost 100% contamination would be needed to produce this difference. However, if contamination caused the separation of an immiscible sulfide phase, the Ni content might be drastically reduced by incorporation in the sulfide phase, so that its depletion in the remainder of the sill would be expected.

In conclusion, it is possible that the differences in chemical composition between the Hangnest and Blaukrans sills may be the result of contamination-induced sulfide separation, possibly associated with some degree of fractional crystallization.

Application to the Insizwa intrusion

The Ni/Cu ratio of the ores from Insizwa averages over unity, according to Scholtz (1937). This is slightly higher than typical values for ores associated with tholeiitic mag-

mas (Naldrett & Cabri 1976); thus it is unlikely that much fractionation occurred before the sulfide separated. The role of process 1 is therefore not thought to be important in the formation of these ores.

The ratio of sulfur isotopes of sulfides from the Insizwa intrusion has been determined by Jensen (1967). There is an extremely small scatter in the ratios, and they average exactly the value expected for magmatic sulfur. Unfortunately, no sulfur from the adjacent sediments was analyzed for comparison, but these data suggest that the sulfur is more likely to be magmatic. Even if the adjacent sediments had a sulfur isotope ratio different from magmatic sulfur, such a difference would not completely disprove an origin by contamination. As shown below, the possibility exists that sulfide separation, and hence possible contamination, commenced at depth, not at the present level of intrusion.

There are several facts that tend to support the third process. Scholtz (1937) frequently referred to the association of sulfide with biotite and granitic fractions within the lower, picritic portion of the sill. This led him to suggest that the sulfide had actually segregated from the end product of differentiation (the silica-rich residual liquid) of the basic magma. However, as discussed above, such a differentiated liquid should contain little Ni and would be incapable of producing the Ni-rich sulfide. Alternatively, this association of sulfide, biotite and granite could be interpreted as supporting the hypothesis that the addition of siliceous material changed the liquid composition such that it produced a separate, immiscible sulfide phase. In support of this and as shown earlier, the composition of the chilled margin is enriched in silica and alkalis.

It is also of interest to note the analytical data and conclusions of Eales (1980). He analyzed several picrites from the basal zone at Waterfall Gorge and found that one sample was anomalously enriched in incompatible elements, compared with other cumulate rocks in the section. He suggested that this was the result of a back injection of highly differentiated liquid into the crystal mush. This seems similar to the model envisaged by Scholtz (1937) for the granitic components and biotite distributed sporadically throughout the picrite. It could also be interpreted as the result of olivine accumulation into a heterogeneously contaminated portion of magma, which was enriched in incompatible elements owing to the assimilation of country-rock shale (see Fig. 5).

Small sulfide aggregates are present in the

FIG. 5. Photomicrograph of the top of the chill zone showing olivine pheno-crysts surrounded by bronzite, with interstitial plagioclase. Note the extremely resorbed nature of the olivine crystals A and B. The three small crystals of olivine marked C (and above) are in optical continuity and were probably originally one grain. Such high degrees of corrosion suggest a more extensive reaction than is usual in an olivine tholeiite; these crystals may be caught in the process of sinking into a siliceous, contaminated magma. An analysis of this rock gave 15 ppm Rb and 148 ppm Sr, and hence a rather high Rb and Rb/Sr ratio for a basic rock, consistent with the hypothesis of contamination. Photograph covers a width of 5 mm.

chilled margin (Scholtz 1937). These could not have formed *after* emplacement of the sill, as cooling would have been too rapid at the margins to allow the sulfide liquid to separate and sink in that zone. The presence of sulfide in the chill zone suggests that sulfide segregation commenced prior to emplacement of the sill. If this is correct, the basic liquid was saturated with respect to sulfide prior to emplacement, and so the contamination, indicated by the high silica and alkalis, may have commenced at depth. However, the heterogeneity observed by Scholtz (1937) in the marginal zone indicates that contamination and mixing of the two silicate liquids were still continuing after emplacement.

The Ni content of olivine may be informative in geochemical models relating to sulfide formation. If a sulfide liquid segregates, it will cause a decrease in the Ni content of the remaining silicate liquid. Subsequent crystallization will produce olivine that is depleted in Ni compared with typical olivine of similar composition in terms of Mg and Fe (Duke & Nal-drett 1978). In this regard, it is of interest that the olivine that accumulated in the Elephant's Head intrusion contains about 3000 ppm Ni (Eales 1980). The olivine in the picrites near the base of the Insizwa intrusion contains from 1000 to 2500 ppm Ni (Mitchell 1980). The reason for the variability of the Ni content of the olivines reported by Mitchell (1980) may be analogous to that proposed by Campbell (1978) and discussed above. If the sulfide liquid forms only near the base of the intrusion, it may not chemically process the entire magma column but only deplete the lowermost layer in Ni and Cu. Olivine crystallizing slightly higher up in the intrusion may form from a liquid that has a more normal Ni content. However, the important conclusion is that the olivine from near the base of the intrusion is variably and significantly depleted in Ni compared with olivine from the Elephant's Head sill, as would be expected if a sulfide phase had segregated at an early stage before the olivine crystallized, not at a late stage as proposed by Scholtz (1937).

SUMMARY

It is possible to reassess the abundant data on the Insizwa intrusion in the light of modern geochemical parameters. Unlike most Karroo dolerite sills, the chilled margin of the Insizwa intrusion is a high-MgO tholeiite, whose high magnesium content is not the result of olivine accumulation. The high Ni/Cu ratio of the sulfides found near the base of the intrusion also reflects the existence of a more magnesian liquid. However, the higher-than-average SiO_2, Na_2O and K_2O contents of the chilled margin suggest that contamination may have taken place, a feature consistent with petrographic evidence. It is thought that the sulfide phase was formed because this contamination lowered the solubility of sulfur in the basic magma. Contamination would account for the presence of sulfides in the chill zone. Massive ore in association with acid phases is attributed to further contamination *in situ*. Segregation of a separate sulfide phase from the high-MgO tholeiitic magma prior to emplacement may have significant implications for the economic viability of the Insizwa.

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