

**ECONOMIC GEOLOGY
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**EMPLACEMENT FEATURES OF CUPRIFEROUS
NORITOIDS IN THE OKIEP COPPER DISTRICT,
NAMAQUALAND, SOUTH AFRICA**

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by

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EMPLACEMENT FEATURES OF CUPRIFEROUS NORITOIDS IN THE OKIEP COPPER DISTRICT, NAMAQUALAND, SOUTH AFRICA

ABSTRACT

Intrusive features of cupriferous noritoids from the deeply eroded Proterozoic granite-gneiss terrane of the Okiep Copper District in South Africa illustrate the emplacement of basic magmas into a mid- to lower- crustal environment. The small, easterly trending intermediate-to-basic intrusions of the so-called Koperberg Suite display a wide variety of geometries, occurrence and emplacement modes, including dyke-, sill- and plug-like bodies. Coeval granulite-facies metamorphism, partial melting and ductile deformation during intrusion of the basic magmas led to emplacement- and dilation- processes of the intrusions which differ significantly from those described for dykes and sills at shallow crustal levels. Regional tectonic stresses are largely negligible due to very low differential stresses ($\sigma_1 - \sigma_3$) during deformation and intrusion, which permits emplacement at high angles to the principal compressive stress and which follows favourably inclined structural anisotropies. Dilation of the basic intrusions is largely determined by compositional differences of host rocks and occurs by thermal erosion, i.e. assimilation of wall-rock gneisses. Low length-to-width ratios of basic-to-ultrabasic dykes and predominantly diapir-like outlines of intermediate intrusions are indicative of low viscosity contrasts between the mafic magmas and high-grade metamorphic host-rock gneisses. Buoyancy controlled ascent of the basic-to-intermediate intrusions is expressed by a broad compositional zoning of basic bodies with respect to the granite-gneiss stratigraphy. Various intrusion modes within the stratigraphic column of the granite-gneiss sequence reflect a lithological and structural stratification of the seemingly homogeneous granite-gneiss terrane.

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INTRODUCTION

The Okiep Copper District, situated in the Northwest Cape region of South Africa (Fig. 1), represents the oldest mining district in southern Africa. First recorded investigations of the copper occurrences date back to 1685 (Smalberger, 1975) but the remoteness and harsh conditions of the area inhibited large-scale exploitation of the copper ores until the mid-nineteenth century. Since then, some 30 mines and numerous prospects have been in production at various times throughout the region.

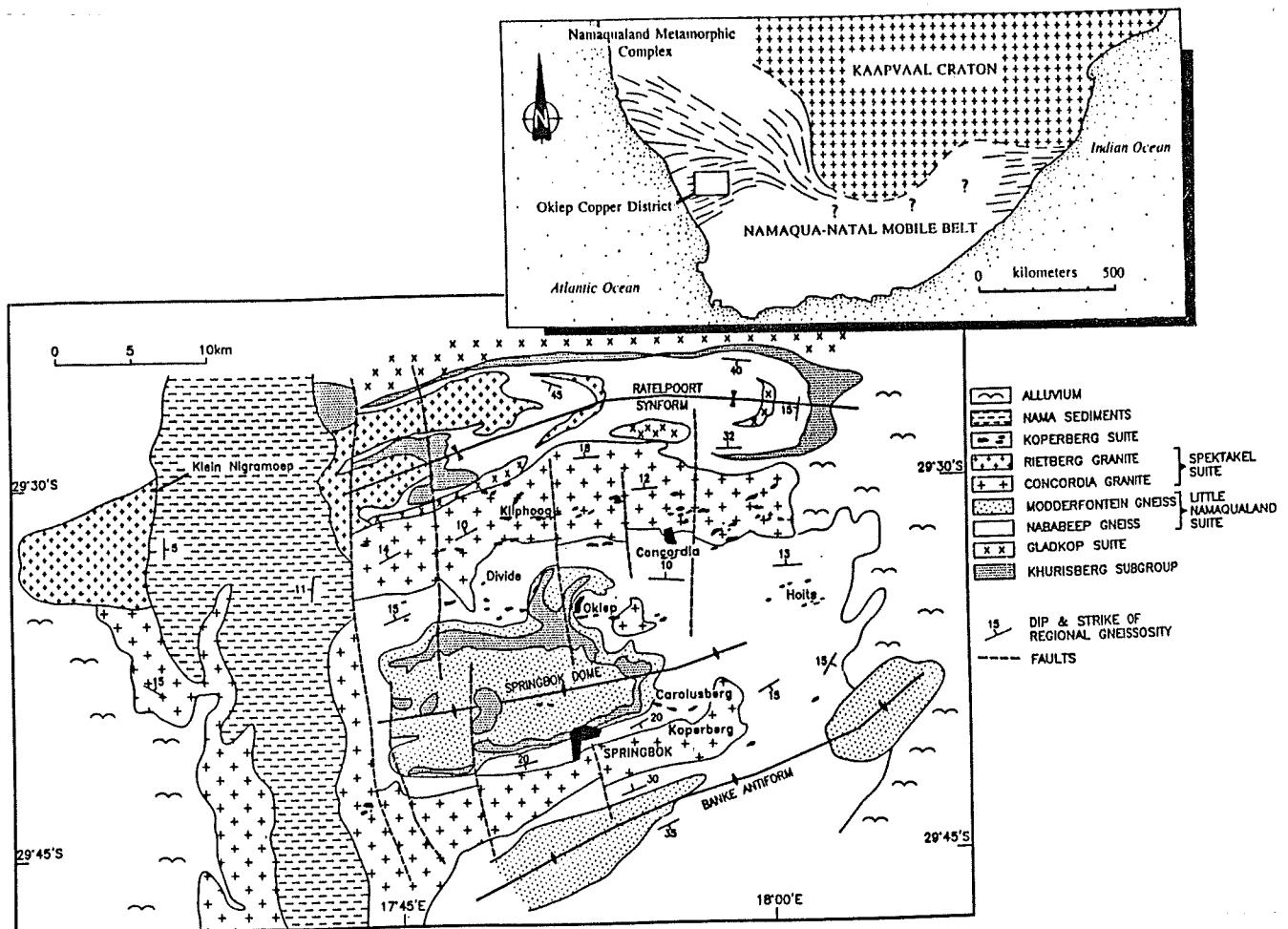


Figure 1: Location of the Okiep Copper District within the Proterozoic tectonic framework of southern Africa (modified after Tankard et al., 1982) and simplified geological map of the Okiep Copper District (modified after maps of the O'okiep Copper Company).

Copper mineralization is hosted within basic-to-intermediate rocks of the Koperberg Suite, locally referred to as "basic bodies" or "noritoids", emplaced into the granulite-grade gneisses and granites of the Okiep Copper District. The intrusions occur as easterly trending, discontinuous, irregular dykes which are frequently associated with narrow, subvertical, easterly trending structures, known locally as steep structures, or as shallowly dipping sills or steeply inclined plug- or diapir-like bodies.

Despite the long mining and exploration history and numerous studies on the Koperberg Suite, the origin and emplacement of the basic bodies remains somewhat enigmatic. The intrusive nature of the Koperberg Suite into the granitic gneisses of the Okiep Copper District was emphasized by earlier workers such as Wyley (1857), Strauss (1941), Latsky (1942), and Van Zyl (1967). Read (1952), however, suggested that the basic bodies represented "resisters" derived from copper-bearing volcanic flows and pyroclastics, which became dismembered from the original layer during "granitization" of the Okiep Copper District during high-grade metamorphism. Benedict et al. (1964) concluded that metasediments and metavolcanics of the Khurisberg Subgroup constituted a source-bed for the Koperberg Suite and that the basic bodies were derived and mobilized by partial melting of this copper-bearing source-bed. This view of a crustal-derived origin of the Koperberg Suite was supported by Clifford et al. (1975a,b), who also proposed that the localization of basic bodies occurred in large-scale boudin necks within granitic gneisses of the Okiep Copper District, which are supposedly represented by steep structures (see also Hälbig, 1978). McIver et al. (1983) opposed an intrusive origin for the basic bodies and interpreted the emplacement pattern of the Koperberg Suite to be the result of a dismemberment of larger intrusive bodies as a consequence of shear deformation during high-grade metamorphism.

This paper presents new evidence on the Koperberg Suite intrusions in the Okiep Copper District which illustrates the intrusive nature of the basic bodies and various modes of occurrence, emplacement and propagation of mafic magmas in a segment of mid- to-lower Proterozoic crust. It demonstrates that the geometry of the intrusions is the product of the interaction and interdependence between coeval high-grade metamorphism, ductile deformation and the intrusion of the basic magmas.

GEOLOGICAL SETTING

The Okiep Copper District is situated in the mid- to late- Proterozoic Namaqualand Metamorphic Complex (Joubert, 1986) (Fig. 1). The Namaqualand Metamorphic Complex forms the northwestern part of the extensive Namaqua-Natal mobile belt, which extends from southern Namibia and Namaqualand along the west coast of southern Africa to the Natal Province along the eastern seaboard (Fig. 1).

The granite-gneiss terrane of the Okiep Copper District is characterized by several phases of voluminous granitic intrusions (Clifford et al., 1975a; Lombaard and Schreuder, 1978; Holland and Marais, 1983; Lombaard et al., 1986) (Fig. 1). Emplacement of the granitic rocks is mainly sheet-like and occurs at various stages relative to the main structural and metamorphic events. The stratigraphic column of the Okiep Copper District granite-gneiss sequence can be subdivided into a lower, well-foliated gneissose unit, the Little

Namaqualand Suite, comprising the Nababeep and Modderfontein Gneisses, and an upper, largely unfoliated granitic unit, the Spektakel Suite (Fig. 1). The Spektakel Suite comprises quartz-microcline \pm biotite \pm garnet granites and includes the Concordia and Rietberg Granites, and the subordinate Kweekfontein Granite. The granitic gneisses and granites intrude and dismember an older metavolcano-sedimentary sequence, the Khurisberg Subgroup, and earlier gneisses, the Gladkop Suite, which now occur as large rafts within the Okiep Copper District sequence. The most prominent unit of the Khurisberg Subgroup is the Springbok Quartzite and Schist. Gneisses of the Gladkop Suite outcrop mainly to the north of the Okiep Copper District, where they are referred to as "grey and pink gneisses" (Van Aswegen, 1983).

Rb-Sr whole rock ages for the older metasedimentary sequence of parts of the Khurisberg Subgroup and the Gladkop Suite yield about 1800 Ma (Barton, 1983). Rb-Sr ages for the Nababeep Gneiss yield 1213 ± 22 Ma (Clifford et al., 1975a) while the stratigraphically higher granites yield ages of 1166 ± 26 Ma (Rb-Sr whole-rock age for Rietberg Granite, after Clifford et al., 1975a).

These ages of 1100-1200 Ma for the granitic gneisses of the Okiep Copper District sequence are believed to reflect the timing of the emplacement of the bulk of the granitic intrusions as well as the time of the syn-intrusive M₂-Namaqua metamorphism (Clifford et al., 1975a). Peak metamorphic conditions during this event reached granulite-facies grades (Clifford et al., 1975a,b; Waters and Whales, 1984). Temperatures of 850 to 900°C at pressures of 5.5 - 7 kb (Clifford et al., 1975a,b; Waters, 1986) led to partial melting and local migmatization of the country-rock gneisses (Waters, 1988; Kisters et al., 1992).

An early D₁-deformation, which is expressed by intrafolial folds in older metasediments and orthogneisses north of the Copper District (Joubert, 1971; Blignault et al., 1983), is only recorded in xenoliths and rafts of the Khurisberg Subgroup and Gladkop Suite within the later granitic gneisses and granites of the Copper District sequence (Clifford et al., 1975a; Lombaard et al., 1986).

The most pervasive deformation phase recorded in the Copper District is the D₂- or Namaqua-event (Joubert, 1971). The D₂ deformation imparted a pervasive regional subhorizontal gneissosity (S₂) onto the earlier syntectonic intrusions of the Little Namaqualand Suite. These typically augen gneisses comprise the widespread lithologies of the Nababeep and Modderfontein Gneisses which occur in the lower parts of the stratigraphic column of the Okiep Copper District (Fig. 1). The Namaqua deformation is, furthermore, characterized by large-to-small scale isoclinal folds which are particularly well developed in the Springbok Quartzite. The late- to post- D₂ intrusions of the Spektakel Suite show only a weakly developed gneissosity or no fabric development at all.

A subsequent N-S directed, compressional D₃ deformation event resulted in the formation of regional-scale, upright, easterly trending folds, which gently deform the subhorizontal lithologies and fabrics of the gneisses of the Copper District sequence. The most prominent of the regional-scale D₃ fold structures are the Springbok Dome and the Ratelpoort Synform (Fig.1) which determine the disposition of the lithologies in the central and northern parts of the Copper District, respectively. On a smaller scale, the D₃ fold

phase resulted in the formation of mega-kink folds in parts of the granitic gneisses (Kisters, 1993; Kisters et al., 1992). These complex kink-fold structures are locally referred to as "steep structures" (e.g. Benedict et al., 1964; Hälbich, 1978; Lombaard and Schreuder, 1978). The term "steep structure" was coined by geologists in the Okiep Copper District to describe narrow, easterly trending, antiformal and/or monoclinal zones, in which the regional subhorizontal gneissosity has been rotated to subvertical attitudes. Steep structures not only represent a unique structural feature but are, furthermore, of economic interest as they form the host structures to the majority of the copper-bearing noritoids in the Okiep Copper District. Amplitudes and wavelengths of these steep structures range from metres to several hundred of metres and strike lengths vary from tens of metres to several kilometres. Steep structures are well-developed in the lower, foliated, gneissose units of the Copper District sequence (i.e. the Little Namaqualand Suite and lower parts of the Spektakel Suite) but are poorly expressed or absent in the stratigraphically higher, unfoliated, granitic units of the upper Concordia Granite and Rietberg Granite (Kisters, 1993).

Late Proterozoic sediments of the Nama Group, comprising weakly deformed grits, sandstones, conglomerates, shales, and limestones unconformably overlie the granite-gneisses in the western parts of the Okiep Copper District (Fig. 1).

THE KOPERBERG SUITE AND ASSOCIATED COPPER MINERALIZATION

The basic to intermediate rocks of the Koperberg Suite are intrusive into the granitic gneisses and granites of the Copper District sequence. The occurrence of the Koperberg Suite is largely restricted to the granulite facies terrane of the Copper District, an area of approximately only 60 x 40km. Rock types of the Koperberg Suite comprise predominantly anorthosites and diorites (Benedict et al., 1964; Lombaard et al., 1986). Norites and hypersthenites are comparatively rare along with more exotic varieties such as glimmerites and orbicular diorites. An intrusive sequence of the frequently multiple intrusions from earlier, more leucocratic phases, such as anorthosites and diorites to later, more mafic members such as norites and hypersthenites, is evident throughout the District (Clifford et al., 1975a; Stumpf et al., 1976; Lombaard and Schreuder, 1978; Conradie and Schoch, 1986, 1988). The basic rocks of the Koperberg Suite yield Rb-Sr ages of 1042 ± 42 Ma (Nicolaysen and Burger, 1965) and 1072 ± 20 Ma (Clifford et al., 1975a) and, as such, largely post-date the youngest granitoids of the Copper District sequence by 50 to 100 Ma. However, metamorphic textures and tectonic fabrics described by McIver et al. (1983) and the metamorphic sulphide mineral assemblage of the ore-bearers (Cawthorn and Meyer, 1993) suggest a syn- to late- tectonic and metamorphic timing for emplacement of the bulk of the Koperberg Suite.

Copper mineralization is generally confined to the later, more basic varieties of the Koperberg Suite (i.e. norites and hypersthenites), while anorthosites and diorites show little economically viable copper mineralization. The sulphidic copper mineral assemblage consists mainly of bornite, chalcopyrite and chalcocite. Pyrrhotite, pentlandite and pyrite, together with numerous other sulphides, and occasional tellurides and arsenides, are rare (Strauss, 1941; Stumpf et al., 1976; Cawthorn and Meyer, 1993). Oxide minerals comprise mainly magnetite, hematite and ilmenite.

Currently, four mining centres are operating in which copper is mined from depths of up to 1600m below surface. These are the Carolusberg, Klein Nigramoep, Hoits and Divide mines (Fig. 1). The annual production is approximately 2 Mt of copper ore at a cut-off grade of 0.8% Cu. Tonnages of past and present mines vary from > 35 Mt at the Carolusberg Mine to less than 20000 t in the smallest mines and prospects. The total production of the Okiep Copper District approximates 90 Mt.

Emplacement features of the Koperberg Suite

More than 1500 surface outcrops of Koperberg Suite lithologies are scattered throughout the Copper District. They range in size from a few metres to several hundred metres in diameter and strike length respectively and may be highly irregular in shape. The vertical extent of the frequently steeply inclined bodies may locally exceed 1000 m (e.g. Fig. 2).

Three main geometries can be distinguished:

- 1) steeply inclined, easterly trending, irregular, dyke-like bodies which are commonly localized in the subvertical structural features of steep structures;
- 2) shallow-dipping, sill-like bodies which are emplaced subparallel to the regionally developed subhorizontal gneissosity (S_2) or along lithological contacts; and
- 3) large plug- or diapir-like bodies.

Each of these geometries can be shown to be preferentially developed at certain stratigraphic and structural levels within the granite gneiss terrane of the Okiep Copper District. Transitions between individual intrusion modes are, however, frequently observed.

Dykes

Rocks of the Koperberg Suite commonly occur as easterly trending, subvertical, discontinuous dyke-like intrusions. Dyke compositions cover a wide range from anorthosites and diorites to norites and hyperstheneites. These dyke-like bodies are commonly associated with, and structurally controlled by, the easterly trending, subvertical gneissosity in steep structures (Figs. 2 and 3). The basic bodies usually occur subparallel or concordant to the steeply inclined gneissosity in the central parts of the antiformal and/or monoclinal structures (Figs. 2 and 3), but locally cross-cut the host stratigraphy and fabrics (Fig. 2), testifying to their dyke-like nature.

Composite dyke lengths vary from several metres up to 2.5 km. Dykes range from dykelets (i.e. < 5 cm) to about 100 m in width (Figs. 2-5). Length-to-width ratios are generally low and range from 5:1 to 50:1 for overall dykes as well as individual dyke segments, resulting in rather lensoid shapes (Figs. 2-5). A segmentation of larger dykes into smaller dyke segments is common and generally accounts for the very irregular branching and coalescing outcrop pattern. In plan view, as well as in the vertical section, the dykes display an en-échelon emplacement pattern and pinch-and-swell structures are commonly

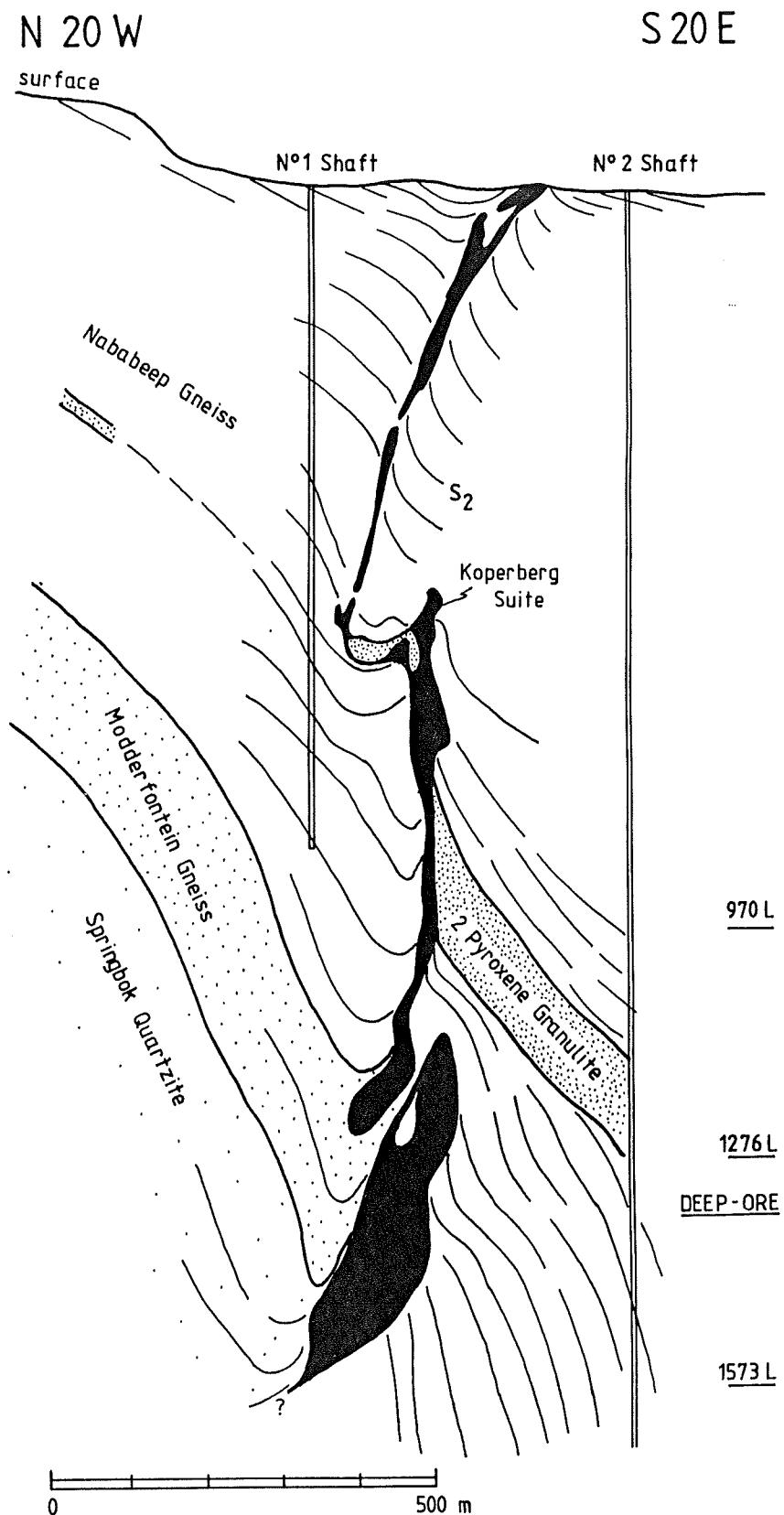


Figure 2: Schematic cross section through the central portions of the Carolusberg Mine (section CCH of the O'okiep Copper Company). Emplacement of the Koperberg Suite occurs in the central, subvertical part of the monoclinal steep structure but is cross-cutting the gneissosity. Note the en-échelon segmentation of the basic body and termination within the metasediments of the Springbok Quartzite.

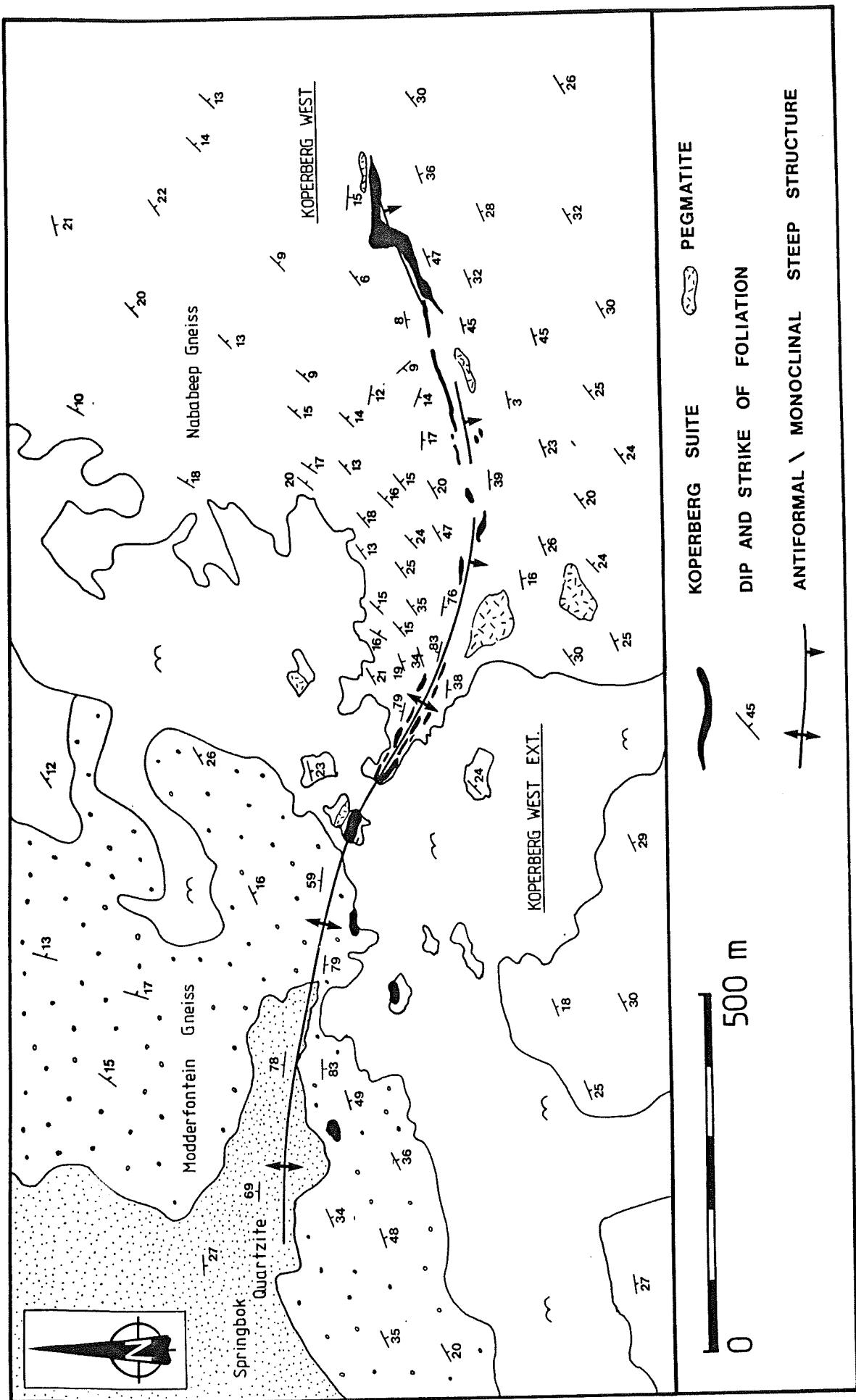


Figure 3: Steep structure development at Koperberg West and Koperberg West Extension and intrusion of basic bodies into the central, subvertical parts of the steep structure. Note the confinement of basic bodies to the steep structure and the strong segmentation and low length-to-width ratios of basic bodies.

developed (Figs. 2-5). In particular, the more mafic phases of hypersthenites and, to a lesser extent, norites have a very stringer-like appearance. Thin stringers of hypersthenite in the Carolusberg Mine can be traced for considerable vertical distances of up to several hundred metres, intruding and brecciating earlier intrusive phases of the Koperberg Suite.

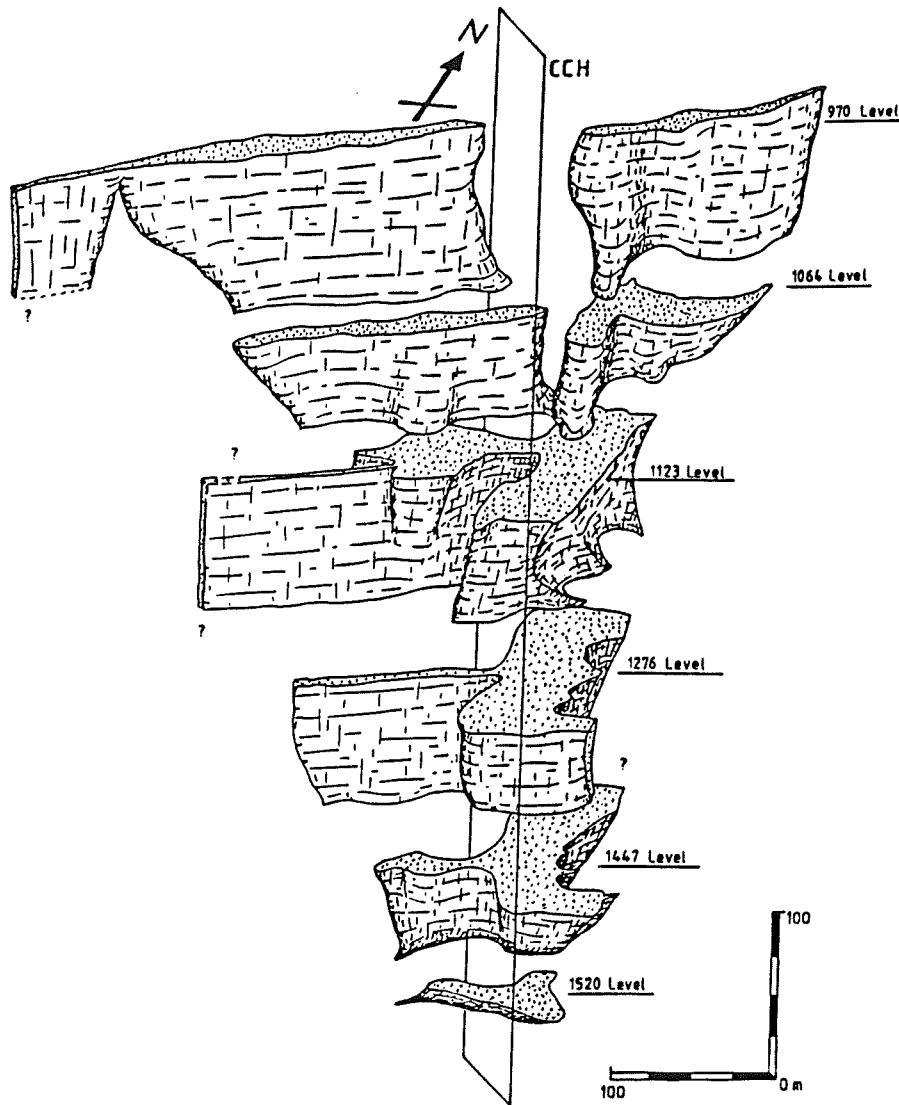


Figure 4: Schematic representation of the Deep Ore body of the Carolusberg Mine illustrating the irregular and varying geometries of a basic body in plan-view as well as in the vertical. Note the low length-to-width ratios of the bodies. Section CCH, see Figure 2 (compiled from level plans and cross-sections of the O'okiep Copper Company).

Contacts between the noritoids and host rocks are usually sharp with hardly any alteration features. This and the absence of chilled margins within the basic bodies are interpreted to reflect an emplacement of the Koperberg Suite into a deep crustal environment while host rocks were undergoing high-grade metamorphism (Lombaard et al., 1986; Schoch and Conradie, 1990). This is supported by locally developed cumulate layering within some of the small intrusions which suggests very slow cooling and crystallization of the basic

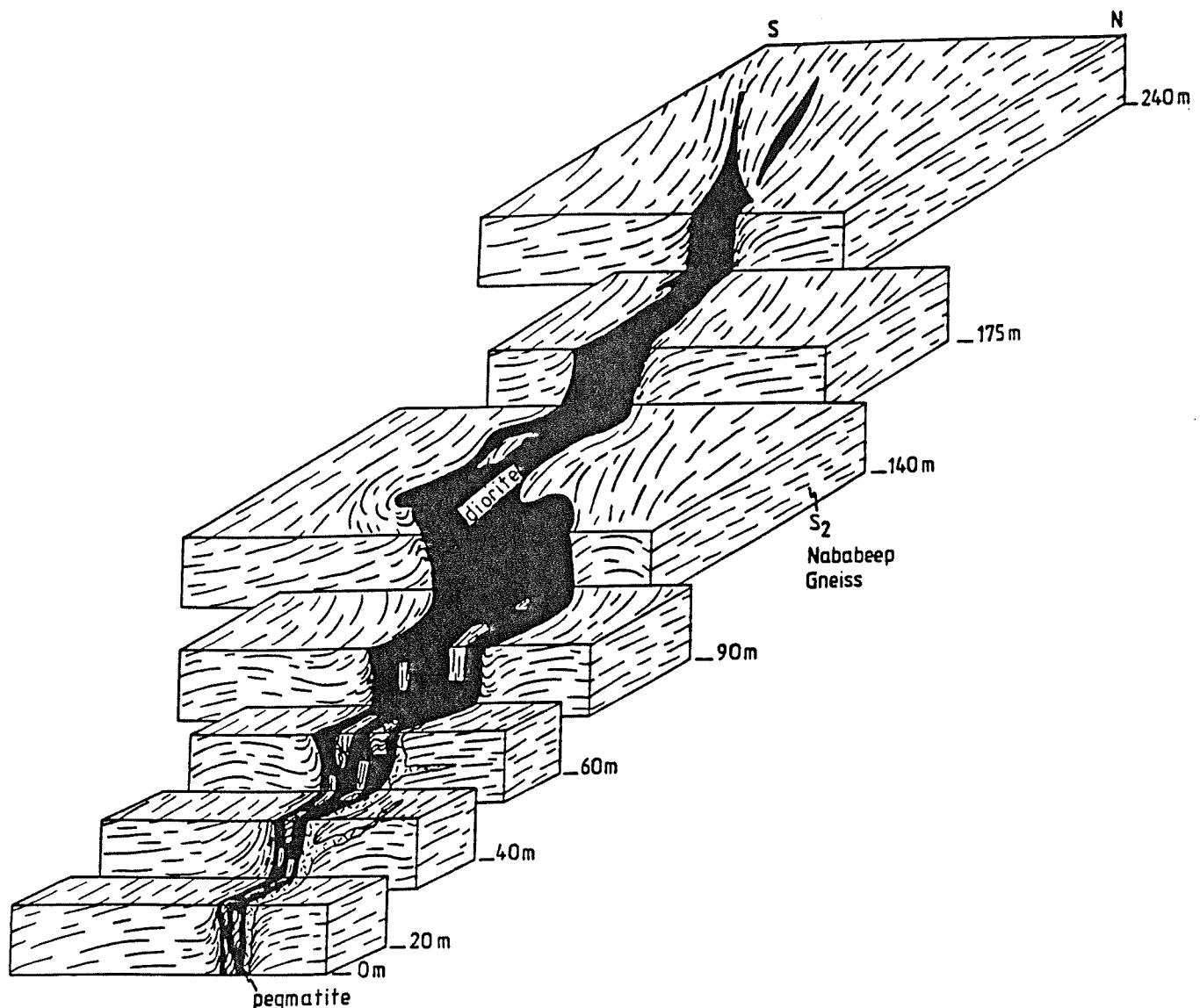


Figure 5: Diagrammatic sketch of a steeply inclined dioritic dyke at Koperberg West showing left-stepping echelon emplacement and numerous deformed xenoliths at the eastern termination.

bodies. Layering is manifested by alternating orthopyroxene-rich and plagioclase-rich bands on a mm- to cm-scale (Fig. 6a) (Kisters, 1993).

Many contacts between noritoids and wall-rock gneisses are characterized by "horn" or "bayonet" structures (after Nicholson and Pollard, 1985; Cadman et al., 1990) of noritic material (Fig. 7) which have a wedging-off effect of the country rocks leading to the development of bridge structures and, ultimately, the incorporation of wall-rock gneisses into the intrusions (Fig. 7).



(a)

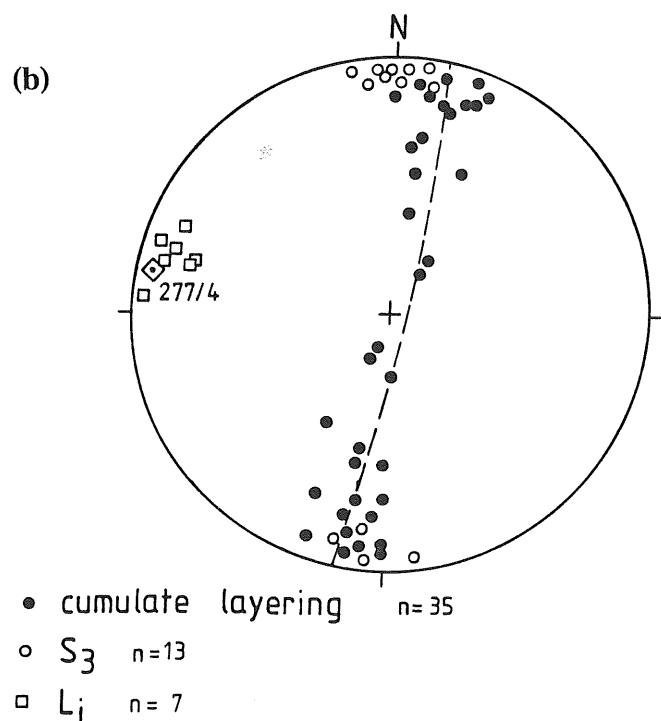


Figure 6a. Southerly dipping cumulate layering within a noritic basic body at Koperberg Central. 6b. Lower hemisphere equal area projection to poles of the cumulate layering, axial planar schistosity (S_3) and resulting intersection lineation (L_i) outlining an upright, shallow, westerly plunging fold.

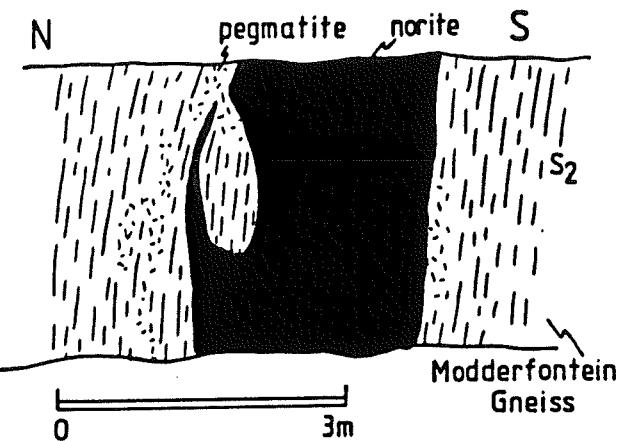


Figure 7: Schematic sketch of the contact relationship between a noritic basic body and country-rock gneisses showing a "horn" - or "bayonet" - structure wedging off and incorporating wall-rock gneiss (Carolusberg Deep Ore, 1123 Level).

Sills

Sill-like intrusions of the Koperberg Suite occur subparallel to the subhorizontal gneissosity and/or along contacts between various lithological units (Fig. 8). The intrusions are mainly of anorthositic or dioritic composition, with rarer hypersthene-diorites and norites. Sills commonly show flattened, ellipsoidal shapes as they pinch out towards their margins (Fig. 8). The lateral margins of sills tend to be highly irregular as a result of the interfingering of the sills with the host-rock gneissosity. Thicknesses of sills range from merely centimetres to several tens of metres. The lateral extent of the bodies is of the order of tens of metres to several hundreds of metres. Individual sills are, in places, compositionally heterogeneous, showing either evidence of multiple intrusion or compositional layering. In the case of copper mineralized intrusions, ore-grade mineralization is usually concentrated in the footwall parts of the basic bodies, possibly suggesting in-situ differentiation.

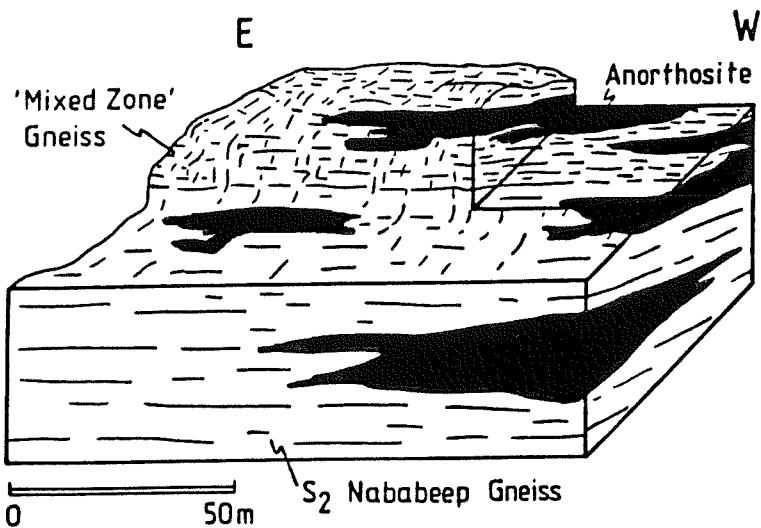


Figure 8: Sill-like bodies of anorthositic to dioritic composition within "Mixed-Zone" Gneiss at Koperberg East.

Plugs

Plug- or diapir-like bodies are large compared to sills or dykes of the Koperberg Suite and comprise some of the most voluminous basic bodies in the O'kiep Copper District (Fig. 9). Plug-like bodies of the Koperberg Suite are commonly tear-drop shaped and are of mainly quartz-anorthositic, anorthositic or dioritic composition. Noritic and hypersthenitic varieties are rare.

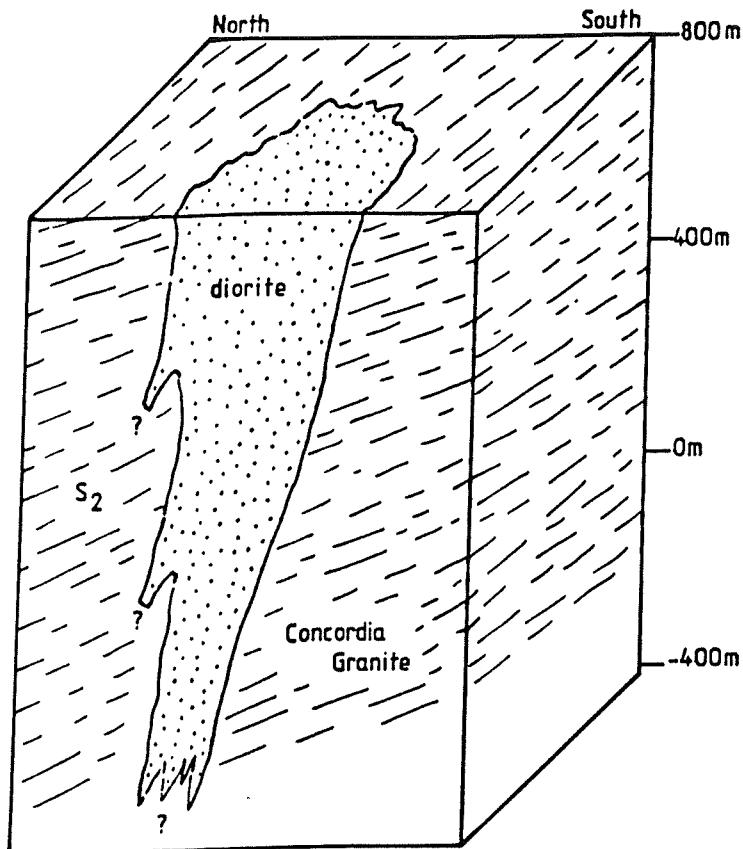


Figure 9: Dioritic-to-anorthositic plug- or diapir-like intrusion at Kliphoog within poorly foliated, northerly dipping Concordia Granite (modified after sections of the O'kiep Copper Company).

Little evidence is found of segmentation and en-échelon emplacement of plugs compared to dyke-like bodies occurring in steep structures, and some plug-like bodies can be shown to have a persistent vertical depth extent in excess of 1000m (Fig. 9). Surface expression of plugs within the Concordia Granite is somewhat more rounded to oval, showing markedly lower length-to-width ratios compared to the basic bodies in steep structures.

Contacts between plug-like bodies and country-rock gneisses are sharp, and, where cross-cutting, intrusions commonly truncate the regional gneissosity at high angles with little signs of deformation. Brecciation of country-rock gneisses is rarely observed. Multiphase intrusive relationships are evident, but are not as prominently developed as in the more basic dykes. In contrast, anorthositic and dioritic bodies intruding into the Concordia Granite are

commonly very homogeneous and show little compositional variation. Copper grades within these anorthosites are, in general, below ore-grade mineralization, but are usually fairly homogeneous, in contrast to the locally high-grade noritic dykes. However, compositional changes to more mafic and locally mineralized rock types in the otherwise largely anorthositic plugs are observed towards deeper levels.

Deformation and timing of the emplacement of the Koperberg Suite

While most workers believe that the basic bodies retain their pristine igneous nature (e.g. Clifford et al., 1975a; Schoch and Conradie, 1990; Conradie and Schoch, 1986, 1988; Lombaard et al., 1986), some workers have described tectonic fabrics and metamorphic textures in the silicate and sulphide mineral assemblages of the noritoids (McIver et al., 1983; Cawthorn and Meyer, 1993).

Field evidence collected in this study provides clear evidence of a syn- to late-tectonic emplacement of the Koperberg Suite and includes:

- 1) Cumulate layering within a noritic body at Koperberg Central showing variable dips throughout the intrusion (Fig. 6a,b). Orientation data of the layering, taken across the intrusion, indicate that the cumulate layering has been deformed into an upright, easterly trending, close fold (Fig. 6b). A weak, steeply inclined, easterly trending secondary cleavage, expressed by biotite and hypersthene, is axial planar to the fold (Fig. 6b);
- 2) A planar tectonic fabric, defined by aligned biotite and/or hypersthene, is commonly recorded in dyke-like bodies within steep structures. The fabric parallels dyke margins and the subvertical gneissosity in the host steep structure (Kisters, 1993);
- 3) A reverse drag of host-rock gneissosities is observed, in places, adjacent to basic bodies (Fig. 10) suggesting a shear deformation along the margins of the intrusions. A tectonic fabric within the dykes which is parallel to dyke-margins and the shear zone, respectively, suggests a syn- to late- deformational emplacement for the dykes.
- 4) Country-rock xenoliths within basic bodies locally display sigmoidally folded gneissosities indicating deformation of the xenoliths prior to or during intrusion of the basic bodies (Fig. 11).

Intrusion of dyke-like basic bodies into steep structures usually occurs into the subvertical, central parts, close to the axial surface of the steep structures (Kisters, 1993). This indicates that the intrusion of basic bodies into steep structures occurred at high angles to the principal compressive stress (σ_1), close to the principal plane of shortening. Intrusion of basic bodies normal to σ_1 during steep structure formation is manifested by the folding of occasionally observed cumulate layering and the associated development of a planar tectonic fabric parallel to dyke margins and steep structures respectively (Fig. 6a,b).

The reverse drag of wall-rock gneissosity adjacent to basic bodies as well as the sigmoidal folding of country-rock gneissosity suggest an emplacement of basic bodies along shear zones associated with steep structure development, i.e. an emplacement into

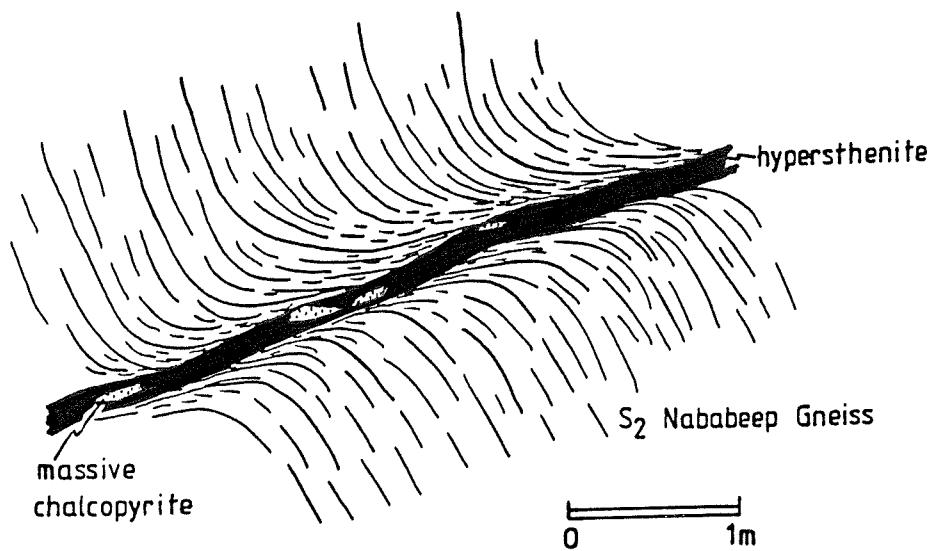


Figure 10: Intrusion of a hypersthenitic dyke into a shear zone. Shear deformation is indicated by reverse drag of wall-rock gneissosity adjacent to dyke walls and a planar tectonic fabric within the dyke parallel to the dyke walls and shear zone, respectively (1447 Level, Carolusberg Deep Ore).

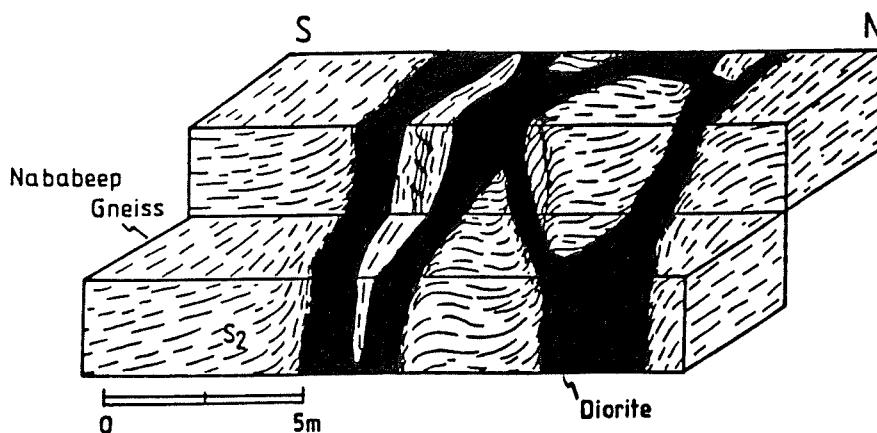


Figure 11: Schematic cross-section through a dioritic dyke at the eastern termination of Koperberg West (see Figure 5) illustrating the deformation of country-rock gneisses within the intrusion.

transpressional sites. Intrusion and progressive dilation of basic bodies along shear zones that produced the sigmoidal folding of country-rock gneissosities and which led to the incorporation of country rocks into the basic magmas are illustrated in Figure 11 for a dioritic basic body at Koperberg West.

Folding of igneous layering and fabric development in the basic bodies parallel to D₃-related steep structures indicates an emplacement of most of the Koperberg Suite during the D₃ deformation phase.

Similarly, many sill-like intrusions display a shallowly dipping, planar tectonic fabric, which is expressed by aligned biotite and feldspar developed parallel to the margins of sills. In some cases, fabric development resulted in a pervasively developed gneissosity, making it difficult to distinguish the sills from the surrounding granitic gneisses difficult. This intense fabric development, which parallels the regional gneissosity, indicates an early D₂ timing for emplacement of parts of the Koperberg Suite.

Brecciation and stress conditions during intrusion

Multiphase intrusive relationships in dyke-like basic bodies are ubiquitous (Latsky, 1942; Strauss, 1941; Lombaard et al., 1986). Brecciation of earlier, more leucocratic phases of the Koperberg Suite by later, progressively more mafic varieties is evident in many dykes resulting in the often heterogeneous compositions of dykes (Fig. 12).

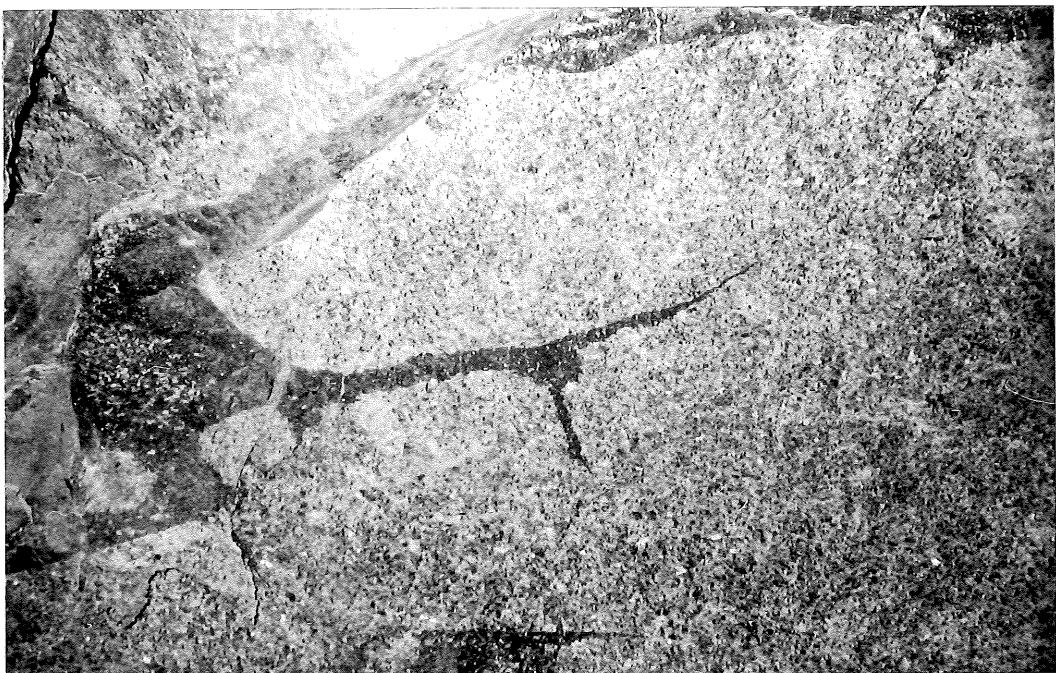


Figure 12: Brecciation of anorthosite (light grey) by hypersthene (black). Note fracture propagation at right angles illustrating the case of hydraulic fracturing (width of photograph is approximately 1.5m; located between 2435 and 2600 level, Carolusberg Mine, Upper Ore).

Brecciation of an earlier anorthosite by a later hypersthene (Fig. 12) illustrates that the fracture propagation of the infilling hypersthene occurred at orthogonal angles and, thus, appears to have been independent of the orientation of the regional tectonic stresses. Individual fragments of anorthosite mould into each other and can be pieced together to form the original anorthosite fragment, indicating in-situ brecciation with very little movement or rotation. It is inferred that brecciation was caused by hydraulic fracturing as the intruding magma was at elevated pressures and able to overcome the regional tectonic stresses under conditions of very low differential stresses ($\sigma_1 - \sigma_3$). Indeed, differential stresses for lower crustal levels undergoing partial melting and ductile deformation are assumed to be low (e.g.

Etheridge, 1983; Etheridge et al., 1983; Weber, 1986), so that dyke intrusion and fracture propagation do not necessarily occur normal to the least compressive stress (σ_3) (e.g. Delaney et al., 1986).

VARIATIONS OF KOPERBERG SUITE INTRUSIONS IN RELATION TO THEIR STRATIGRAPHIC POSITION

The mode of emplacement, abundance, geometry, and mineralogical composition of intrusives of the Koperberg Suite varies throughout the stratigraphic column of the Okiép Copper District (Fig. 13).

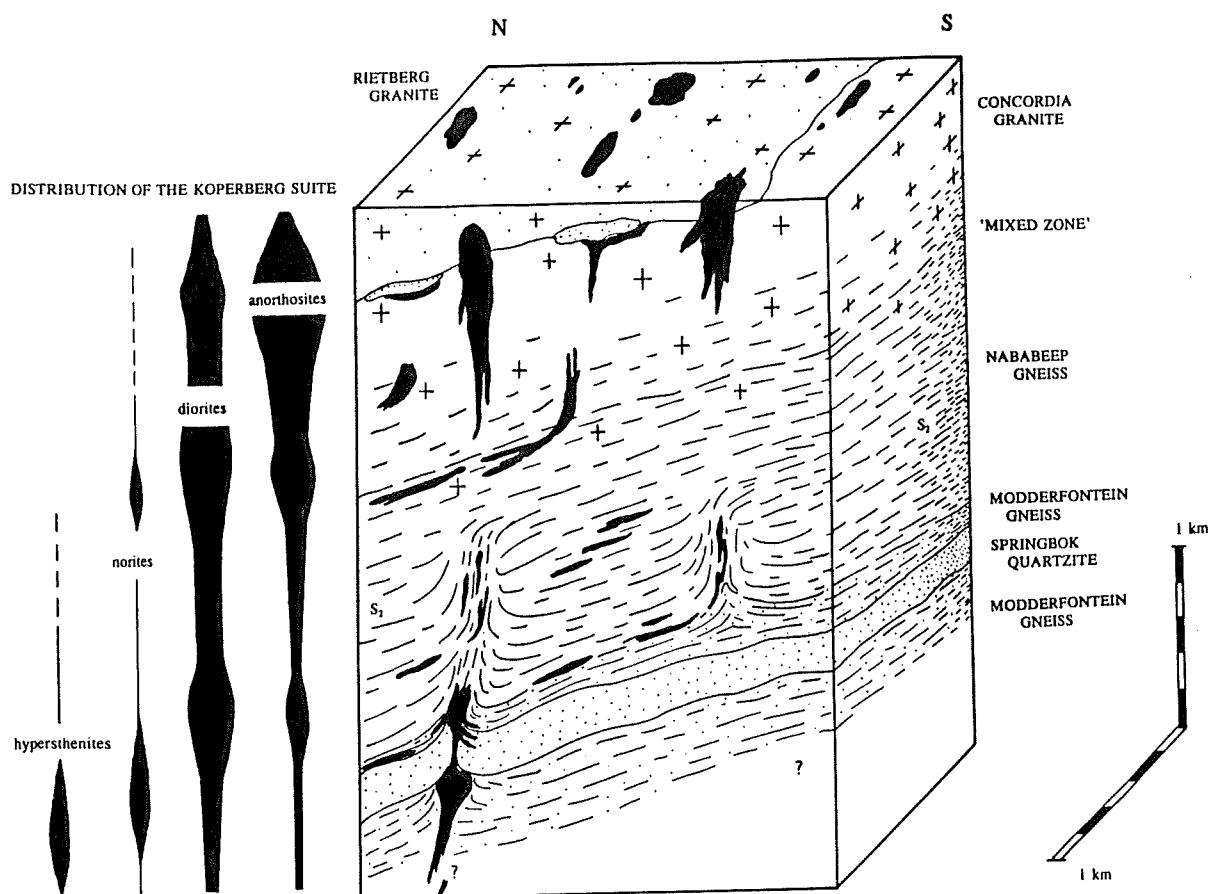


Figure 13: Schematic stratigraphic column through the Okiép Copper District, illustrating the relative abundance (left hand side) and mode of occurrence of the Koperberg Suite.

Dyke-like intrusions of the Koperberg Suite occur predominantly in the lower stratigraphic units of the Copper District granite-gneiss terrane (Fig. 13). This is a consequence of the fact that steep structures, which are the host structures to most of the basic dykes, are best developed in the well-foliated gneisses of the Copper District sequence

(i.e. the lower stratigraphic units of the Nababeep and Modderfontein Gneiss and the lower parts of the Concordia Granite).

Sill-like bodies tend to occur predominantly at three levels in the sequence (Fig. 13) as follows:

- 1) Mining and exploration on the northern limb of the Springbok Dome has outlined shallow-dipping sill-like bodies which intruded along the contacts between the metasediments of the Springbok Quartzite and the overlying Modderfontein Gneiss and between the Modderfontein Gneiss and the Nababeep Gneiss;
- 2) Sill-like bodies of the Koperberg Suite are also concentrated close to the base of the Concordia Granite within the so-called Mixed Zone Gneiss. The horizon of the Mixed Zone Gneiss represents a zone, up to 150m wide, in which the well-foliated Nababeep Gneiss has been intruded by Concordia Granite in a sheeted manner, yielding a pronounced lithological layering on a dm- to m- scale; and
- 3) Sills are, furthermore, concentrated between Concordia Granite and Rietberg Granite and outcrop predominantly parallel to xenoliths of the Khurisberg Subgroup and earlier gneisses of the Gladkop Suite which occur abundantly at this stratigraphic level.

Plug- or diapir-like bodies of Koperberg Suite lithologies occur predominantly in Concordia and Rietberg Granite (i.e. within stratigraphically higher, unfoliated granites of the Copper District sequence; Fig. 13).

Transitions between these emplacement modes are common (Figs. 13 and 14). Exploration has demonstrated that subvertical dykes contained in steep structure zones commonly assume shallower attitudes outside steep structures and occur as shallowly dipping sills subparallel to the regional gneissosity (Fig. 14). Similarly, sill-like bodies within Mixed Zone Gneiss underlie dykes in steep structures which are developed in the lower parts of the Concordia Granite or diapiric bodies of largely anorthositic composition in the higher parts of the Concordia Granite (Fig. 13). Sills between the Concordia Granite and the Rietberg Granite appear to be the result of the deflection of steeply inclined bodies in the underlying Concordia Granite. The steeply inclined plugs assume shallower attitudes at the base or within xenoliths of the Khurisberg Subgroup and the Gladkop Suite, both of which occur in abundance at this stratigraphic level.

Compositional variations and effects on the buoyancy and geometry of basic bodies

Variations in the mode of occurrence of the basic intrusions concur with a broad compositional zonation of basic bodies within the circa 4 km-thick stratigraphy of the Okiep Copper District.

Although the majority of basic bodies are of anorthositic to dioritic composition (e.g. Conradie and Schoch, 1986, 1988), the more mafic varieties such as norites and hyperstheneites are predominantly found in the lower parts of the stratigraphy. In contrast, anorthosites, which are invariably of andesinitic composition (e.g. Stumpf et al., 1976;

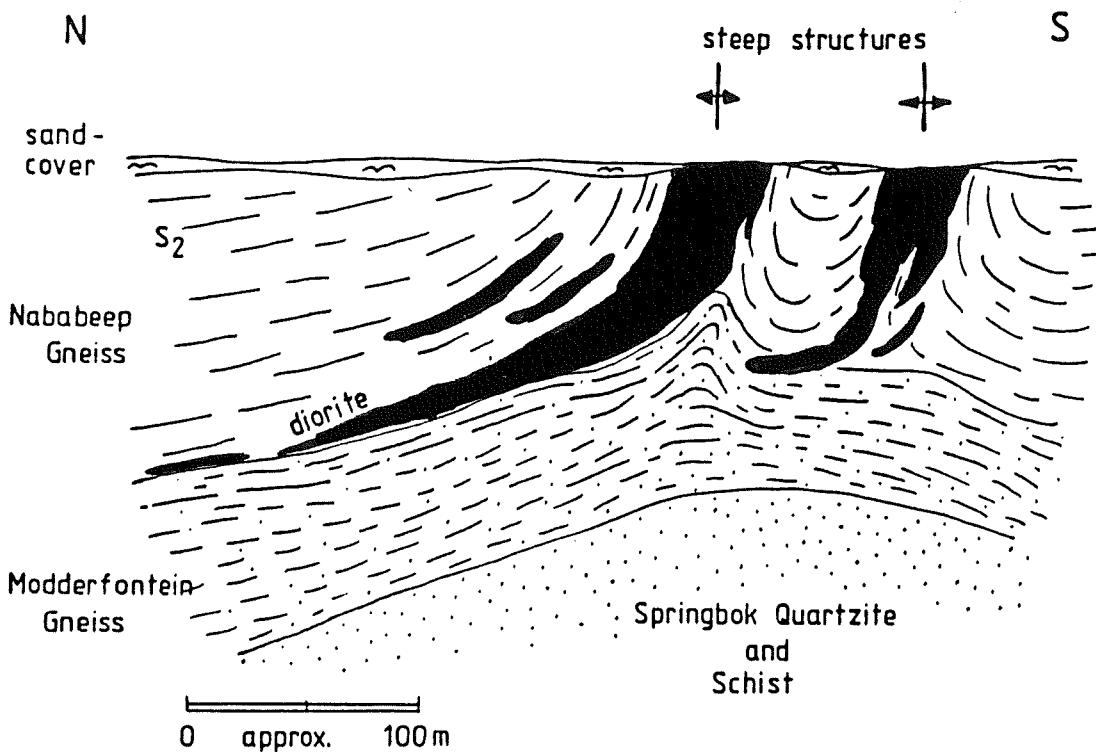


Figure 14: Schematic cross section through the Divide Mine illustrating the transition of a sill-like dioritic basic body subparallel to the regional gneissosity (S_2) and lithological contact, respectively, to steeply inclined attitudes within a steep structure (modified after sections of the O'okiep Copper Company).

McIver et al., 1983), occur mostly concentrated at the base of and within the stratigraphically higher Concordia Granite (Lombaard et al., 1986).

This zonation is interpreted as a reflection of differences in densities of the various mafic magmas which control the buoyancy-driven ascent of basic bodies. The effect of buoyancy on the emplacement of the Koperberg Suite is illustrated by the concentration of anorthosites at the level of the Concordia Granite (Lombaard et al., 1986). The clustering of predominantly anorthosites and diorites at this level indicates that the horizon of the Concordia Granite acted as a "level of neutral buoyancy" (after Lister and Kerr, 1990), where density contrasts between magma and host rocks were not sufficiently large to promote further ascent of basic bodies.

The geometry and shape of the intrusions are largely controlled by compositional variations of the magmas as the rheology of the different magmas is of great influence on the effective viscosity contrasts between basic bodies and wall rocks (e.g. Pitcher, 1979; Ramberg, 1970; Rubin, 1993). Viscosities of the diverse basic-to-intermediate magmas, ranging from the relatively low-viscosity basic-to-ultrabasic hyperstheneites to intermediate anorthosites of much higher viscosities, is clearly controlled by the mineralogical composition of the basic bodies. High viscosity contrasts and high strain rates during intrusion favour the development of dykes as host rocks tend to behave in an elastic manner (Rubin, 1993).

Lower viscosity contrasts between the more viscous anorthositic magmas and host rocks are likely to result rather in diapir-like shapes typical of the intermediate varieties of the Koperberg Suite.

However, even in the case of basic-to-ultrabasic hyperstheneites, viscosity contrasts between intruding magmas and host-rock gneisses appear to be low. Low-viscosity contrasts are evidenced by the low length-to-width ratios of dyke-like basic bodies in steep structures. Equations formulated by Pollard (1987) relate low length-to-width ratios of dykes to high ratios of driving magma pressures to host-rock stiffness. Moreover, Rubin (1993) and Emerman and Marrett (1990) demonstrated the tendency of intrusions to attain ellipsoidal and ultimately diapir- or stock-like shapes when viscosity contrasts between intrusions and host rocks are low. Typical length-to-width ratios for dykes of 1000:1 (Pollard, 1987) to 300:1 (Gudmundsson, 1983, 1986) are never attained by basic bodies in the Copper District (Figs. 2-5). The low viscosity contrasts between basic magmas and host rocks in the Okiep Copper District, as evidenced by the geometries of basic bodies, reflect the high-grade metamorphic conditions and lower crustal environment during emplacement of the mafic magmas. Country-rocks were undergoing ductile deformation and partial melting at the time and the mechanical behaviour of the gneisses in response to the intrusion of the Koperberg Suite is a viscous rather than elastic behaviour. This lowers the effective viscosity contrasts between the basic magmas and their wall rocks, leading to the observed intrusion geometries.

Thermal erosion of wall rocks as a dilation mechanism

The basic bodies of the Koperberg Suite typically pinch or terminate at and within the metasedimentary unit of the Springbok Quartzite and bulge in the granitic gneisses adjacent to the quartzitic metasediments (e.g. Lombaard et al., 1986). The Springbok Quartzite is a prominent metasedimentary unit of predominantly coarsely recrystallized, mature quartzite, on average 80 to 120 m thick. Most of the mines in the Copper District are located at this geological position (Lombaard et al., 1986). Fragments of Springbok Quartzite are by far the most abundant country-rock xenoliths found within, for example, the Carolusberg Mine (Fig. 2) - this despite more than 90% of the mine workings being located within granitic gneisses of the Klein Namaqualand Suite. Moreover, quartzitic xenoliths are mainly angular to subangular with little sign of assimilation while gneissic fragments show varying degrees of assimilation by the basic magma.

These features are interpreted to reflect the importance of thermal erosion and assimilation of wall rocks by basic bodies. The intrusion and subsequent dilation of dykes is, generally speaking, thought to be the result of the parting of host rocks along magma-generated fractures orientated perpendicular to the least compressive stress (e.g. Anderson, 1936, 1951; Spence and Turcotte, 1985). Wall rocks behave elastically and are pushed apart by the internal magma pressure acting against the dyke walls. Internal deformation of the wall rocks is small. Assimilation of wall rocks by basic dyke magmas, sills or small magmatic bodies has been theoretically modelled (Bruce and Huppert, 1989) but the mechanism of thermal erosion is believed to be operative only at deeper crustal levels (e.g. Cadman et al., 1990) and examples of considerable melt-back of wall rocks by dykes are rarely documented.

The pinching or termination of basic bodies within the Springbok Quartzite is an expression of different fusion temperatures of the quartzitic metasediments and granitic gneisses. Granitic gneisses were undergoing partial melting at temperatures of approximately 850°C during the intrusion of the Koperberg Suite (Waters, 1988), thus facilitating assimilation by the mafic magmas which were intruding at approximately 1200°C. The fusion temperature of the mature, monomineralic quartzites is, in contrast, likely to be in the order of 1600-1700°C. Consequently, mafic magmas of the Koperberg Suite had little melt-back effect on the quartzitic metasediments, which acted as a refractory horizon that was difficult to penetrate. Assimilation of the granitic country-rock gneisses, however, accounts for the preferential emplacement and dilation of basic bodies by melt-back in the granitic host rocks.

SUMMARY

Intrusion features of copper mineralized basic-to-intermediate intrusions of the Koperberg Suite reflect an emplacement into a mid- to lower-crustal environment. Propagation and emplacement of basic bodies occurred via a complex pattern of structural and lithological conduits. This pattern can be identified by the transitions of geometries of the basic bodies and changes of intrusion modes which occur concomitantly with compositional changes of the intrusions throughout the Copper District sequence. Internal structural and intrusive features of the basic magmas allow the establishment of certain constraints such as the regional tectonic stresses during intrusion, magma pressures, and relative rheologies of magmas as compared to their host rocks. Taking these factors into account, the following sequence of events and emplacement history can be deduced.

Initial intrusion and propagation of basic bodies is determined by regionally developed anisotropies (i.e. along lithological contacts between different gneissose units and/or subparallel to the subhorizontal gneissosity). Therefore, earliest intrusions of the Koperberg Suite occur invariably as sills, often containing the S₂ gneissosity.

The D₃ deformation during the prograde high-grade metamorphism led to the development of steep structures. The significance of steep structures for further propagation of basic bodies lies in the fact that the subvertical gneissosity in the steep structures provides channelways which facilitate the ascent of the basic intrusions. If steep structure formation coincides with and intersects the propagation path of subhorizontal sills, further magma ascent and propagation will be channeled by the steep structures. Transitions between sills contained in S₂ and steeply inclined basic bodies in steep structures has been recorded at numerous localities (Figs. 13 and 14). Frequently recorded "barren" steep structures (i.e. structures containing no or only minor basic bodies) represent structures that did not intersect the propagation path of a Koperberg Suite intrusion. Thus, tapping of basic magma did not occur.

Intrusion of the steeply inclined, easterly trending basic bodies occurred at high angles to the principal compressive stress (i.e. subparallel to the axial surfaces of steep structures). Emplacement occurred also along shear zones (i.e. into transpressional sites) associated with steep structures. Emplacement into transpressional sites or planes of subsequent shortening is indicated by an internal tectonic foliation within the basic bodies, folded cumulate layering,

and the opposite drag of the wall-rock gneissosity parallel to dyke margins. Intrusive hydraulic breccias indicate very low regional deviatoric stresses and high magma pressures during intrusion which allow a propagation of basic bodies along structural anisotropies independently from the orientation and magnitude of the differential stresses.

Dilation is partly determined by melt-back (i.e. assimilation of wall-rock gneisses). The refractory lithology of the Springbok Quartzite resulted in a marked pinching, deflection or termination of the basic bodies.

Length- to- width ratios of the predominantly dyke-like bodies within steep structures is low. The resulting rather ellipsoidal shapes of basic bodies reflect relatively low viscosity contrasts between the intruding basic magmas and the granitic wall rocks - this being due to the lower crustal environment during emplacement.

At higher stratigraphic levels ascent of the basic bodies is largely buoyancy-controlled, as manifested by the concentration of basic bodies of anorthositic composition at higher stratigraphic levels. Buoyancy-controlled ascent, as well as low viscosity contrasts between anorthositic magmas and granitic wall rocks, is indicated by the predominantly diapir- or plug-like shapes of basic bodies in the stratigraphically higher parts of Concordia and Rietberg Granite. Sill-like intrusions at the base of Concordia Granite, in the prominently layered Mixed Zone Gneiss and between Concordia and Rietberg Granite are, however, evidence of the structural control of lithological and structural anisotropies even in higher parts of the granite-gneiss sequence.

CONCLUSIONS

- 1) The small intrusions of the Koperberg Suite describe a broad differentiation trend with respect to the stratified, high-grade metamorphic granite-gneiss sequence of the Okiép Copper District. Although predominantly of intermediate composition, Koperberg Suite lithologies of more basic composition (i.e. norites and hypersthenites) occur most prominently in the lower stratigraphic units of the Copper District, while the bulk of the anorthositic-to-dioritic basic bodies are concentrated in the stratigraphically higher granitic units. In-situ differentiation of individual basic bodies is locally suggested, but detailed petrological work has still to be undertaken.
- 2) Intrusion and propagation of the basic magmas is largely independent of the orientation of regional differential stresses due to a combination of very low deviatoric stresses in the mid- to lower-crustal environment and elevated magma pressures. This allows propagation and intrusion of magmas into compressional and/or transpressional structural sites.
- 3) Low length-to-width ratios of mafic dykes and plug-or diapir-like shapes of intermediate anorthosites and diorites indicate relatively low viscosity contrasts between intruding magmas and ductilely deforming country rocks.

- 4) Transitions between various intrusion modes are located at the intersection, overlap, or change of pre-existing structural controls and/or lithologies.
- 5) Dilation of basic bodies occurs by melt-back (i.e. assimilation of country-rock gneisses). Hence, dilation is partly controlled by composition and fusion temperatures of wall rocks.

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