THE PETROGENESIS OF THE KOPERBERG SUITE IN THE JUBILEE MINE, NAMAQUALAND

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I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Master of Science in the University of the Witwaterstand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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ABSTRACT

The Koperberg Suite intrusion at Jubilee, Namaqualand varies in composition from anorthosite, through mica diorite to pyroxene leacodiorite and pyroxene diorite. Detailed mapping and petrological studies of these rocks indicate that they were sequentially emplaced into the Concordia Granite country rocks, and that each of the rock types represent discrete magmatic events. The sequence of intrusion is from more acidic to more basic.

Whole-rock geochemical analyses indicate that these rocks represent cumulates involving variable proportions of plagioclase, orthopyroxene, mica, quartz, oxides and immiscible sulphides. These cumulate phases intruded into the Concordia Granite at the time of peak of metamorphism and deformation in the Okiep Copper District, i.e. about 1030Ma ago. At the time of intrusion, the country rocks were undergoing partial melting under high grade (granulite facies) inetamorphic conditions, and granitic anatects were present in the crust. Hybridisation of basic magma and granitic melts occurred within the shear zones along which the basic magmas ascended. The En content of orthopyroxene in the Koperberg Suite exceeds the An content of plagioclase. This is atypical of basic intrusions and is a consequence of this mixing. Mixing calculations based on the initial 87 Sr/ 86 Sr ratio (R₀) of the Jubilee samples at 1030Ma, imply high levels of assimilation (as much as 80% assimilation in the case of anorthositic rocks) between a granitic component, similar in composition to the Nababeep 9 Gneiss, and a mantle-derived basic magma.

Sulphide mineralisation was initiated by the assimilation process, which caused the separation of immiscible sulphides from the hybridised magma. Subsequent oxidation of the original sulphide assemblage produced bornite, chalcopyrite and Ti-poor magnetite.

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CHAPTER 1

INTRODUCTION

1.1 Introductory statement

The Okiep Copper District is one of South Africa's major copper producing areas and has been mined almost continuously for over 140 years. The approximately 3000 km² Okiep Copper District is situated in the arid north-western Northern Cape Province (Fig. 1.1) and includes the towns of Springbok, Nababeep, Okiep and Concordia. The area has been the subject of geological investigations for more than 300 years, the first geological reports about the area appearing in the 1680's

Copper mineralisation is confined to basic intrusive rocks of the Koperberg Suite. Although over 1500 occurrences of Koperberg Suite have been identified, only a few have been mined profitably. The Jubilee ore body, which is the subject of this study, is situated about 2 km north-east of the town of Concordia (Fig. 1.2). This ore body was mined in the 1950's and 1960's, yielding 0.5 million tons of copper at an average grade of *ca*. 3%. Although mined out now, the Jubilee open pit mine provides good three-dimensional exposure of a fairly typical mineralised intrusion, and accordingly was chosen for this detailed field and petrogenetic study.

1.2 Historical

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The ornamentation worn by the Namaqua people and the samples of cupriferous ore brought by these people on visits to the Cape Colony, prompted expeditions in search of the copper ore deposits. These expeditions failed in their objectives until Commander Simon van der Stel's expedition in 1685 (Smalberger, 1975).

In the 1840's, several expeditions set out to reassess the possibility of profitably mining the Namaqualand ores, but commercial mining was not undertaken until 1852, when Messrs. Phillips and King began commercially exploiting the ores found on the farm Springbokfontein. Mining and exploration continued, almost uninterrupted, well into the 20th century when the post-war slump of 1918 saw the demise of even the largest mining companies in the area and a period of mining inactivity followed.

The O'okiep Copper Company, with the Newmont Mining Corporation as the major shareholder, was incorporated in 1937 and began production in 1941. In the early 1980's Gold Fields of South Africa acquired the majority shares in the O'okiep Copper Company and is presently managing the Company.

1.3 Regional geology - The Namaqualand Metamorphic Complex

The Okiep Copper District is situated in the gneissic terrane of the Namaqualand Metamorphic Complex, which is exposed in the north-western Northern Cape Province and in southern Namibia (Fig. 1.1). The Namaqualand Metamorphic Complex forms the Central Zone of the Namaqua Province, which is the western extension of the Namaqua-Natal mobile belt, developed along the southern and western margin of the Kaapvaal Craton (Tankard *et al.*, 1982).

The Proterozoic Namaqualand Metamorphic Complex consists of metasediments and metavolcanics intruded by a variety of granitic gneisses. These rocks have undergone polyphase deformation and metamorphism ranging from greenschist- to granulite facies.

Regional geochronological studies by Nicolaysen & Burger (1965) showed that widespread granitic emplacement and metamorphism took place between 1000Ma and 1100Ma ago, thereby confirming that the Namaqualand Metamorphic Complex forms part of the Kibaran orogenic zone (1100 ± 200 Ma). Several subsequent studies have confirmed the age of the main deformational and metamorphic event (the Namaqua event) to be *ca*. 1200Ma (e.g. Clifford *et al.*, 1975a; Barton, 1983).



Fig. 1.1 Locality map of the Okiep Copper District (after Schoch & Conradie, 1990).

1.4 Local geological setting - The Okiep Copper District

The Okiep Copper District is probably the most thoroughly mapped area in southern Africa, due mainly to its long history of exploration and mining and its excellent exposure. Detailed mapping by the O'okiep Copper Company (OCC) and the contributions of several authors notably Benedict *et al.* (1964), Clifford *et al.* (1975a), Lombaard & Schreuder (1978) and Lombaard *et al.* (1986), have added to our knowledge and understanding of the stratigraphy, structure, metamorphism, mineralisation and geochronology of the Okiep Copper District. Important regional studies have been done by Joubert (1971, 1986), Vanjer (1974), Holland & Marais (1983), and Bligmault *et al.* (1983), and together with the more localised studies have resulted in a detailed knowledge of the geology of the Okiep Copper District.

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1.4.1 Lithostratigraphy

The discussion of the lithostratigraphic subdivisions that follows is based on the work of the above-mentioned authors. The stratigraphy is divided into two broad subdivisions; a metavolcano-sedimentary group (the Okiep Group) and several granitoid intrusive suiter (Table 1.1). The basement to the Okiep Group is unknown.



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Fig. 1.2 Simplified geological map of the Okiep Copper District, indicating the loculity of the study area (Simplified from the maps of the O'okiep Copper Company and Gold Fields of South Africa).

		Nama Group	
		Koperberg Suite	
	INTRUSIVE SUITES Klein Suite Glad	() <u>.</u>	Kweekfontein Granite
		Spektakel Suite	Rietberg Granite
			Concordia Granite Mixed Zore Greiss
		Klein Namaqualand	Modderfentein Gneics
		Suite	Nababee: Griess
			Noenoemasberg Gaeiss
		Glackop Suite	Brandewynsbank Greiss
	META- OI	Okiep Group	Lammerboek Subgroup
	SEDIMENTARY ROCKS		Khurisberg Subgroup

Table 1.1 Lithostratigraphy of the Okiep Copper District (after Lombaard et al., 1986).

Okiep Group

The Okiep Group, which consists of metavolcanics and metasediments, may be regarded as remnants of a volcano-sedimentary succession which was incruded and fragmented by granitic intrusions. The Khurisberg Subgroup is the lower subdivision of the Okiep Group. It consists mainly of metasediments, namely the Springbok Quartzite and the Lura Schist. The Springbok Quartzite is typically coarse-grained and very mature, but may be locally feldspathic or conglomeratic, especially in the north in the Ratelpoort Synform area (Fig. 1.2). The Lura Schist is a quartz-biotite-garnet-sillimanite rock with a prominent schistose fabric which is closely associated with the Springbok Quartzite. Where rafts of the Lura Schist occur at the base of the Concordia Granite, they are referred to as the Wolfram Schist.

Overlying the Khurisberg Subgroup, is the Lammerhoek Subgroup. Occurrences of rocks classified into this subgroup are confined to the northern and southern portions of the Okiep Copper District (Fig. 1.2). This subgroup consists of quartz-feldspar-biotite schists which

may contain thin bands of amphibolite, quartzite, or conglomerate, suggesting a possible volcano-sedimentary origin (Lombaard *et al.*, 1986).

The so-called "two-pyroxene granulite" of Clifford *et al.* (1975a), which is a hypersthenediopside-horublende-plagioclase rock, occurs within the intrusive Nababeep Gneiss as rafts or thick sheets. Several workers (Clifford *et al.*, 1975a; Stumpfl *et al.*, 1976) believe that this lithology also forms part of the volcano-sedimentary succession and represents the source bed of the cupriferous Koperberg Suite.

Granitic Intrusions

Several phases of granitic intrusions occur in the Okiep Copper District as extensive, subhorizontal sheets whose thicknesses are not accurately known. These sheets intruded into the metavolcano-sedimentary pile of the Okiep Group. Radiometric age determinations, intrusive relationships and mineralogical characteristics have led to the establishment of a lithostratigraphic and chronostratigraphic subdivision of the different phases, listed in Table 1.1. The Gladkop Suite has been determined to be the oldest of the intrusive phases. This is followed by the Klein Namaqualand Suite, the latter being intruded by the youngest phase, the Spektakel Suite.

Gladkop Suite

The rocks in this suite are grey-red gramtic gneisses, consisting primarily of mediumgrained quartz, biotite and feldspar. Two subdivisons have been recognised within the Gladkop Suite: an older Brandewynsbank Granitic Gneiss and a younger Noenoemasberg Granitic Gneiss. The occurrence of these rocks is restricted to the northern parts of the area (Fig. 1.2), where the Noenoemasberg Granitic Gneiss can be seen to intrude into the Brandewynsbank Granitic Gneiss.

Klein Namaqualand Suite

This s ite consists of the Nababeep and Modderfontein Granitic Gneisses, the latter intruding the former. The Nababeep Granitic Gneiss is widespread and is exposed particularly in the central portion of the Okiep Copper District (Fig. 1.2). It is a well foliated rock, but often occurs as an augen gneiss. This heterogeneous fabric development (i.e. the transition from foliation to augen porphyroblasts) may occur on a large (regional) or small (outcrop) scale. The mineralogy consists mainly of quartz, microcline and biotite, with variable amounts of minor plagioclase, garnet, magnetite and hypersthene. The thickness of this unit varies from 200m in the east, to more than 1000m at Carolusberg.

The Modderfontein Granitic Gneiss occurs principally, although not exclusively, in the central mation of the Okiep Copper District, especially in the core of the Springbok Dome (Fig. 1.2). Although similar in chemical composition to the Nababeep Granitic Gneiss, the Modderfontein Granitic Gneiss is characterised by a much less distinctive fabric.

Spektakel Suite

The Spektakel Suite represents the last phase of granitic intrusions. The suite is further subdivided into three distinct intrusive phases, namely the Concordia, Rietberg and Kweekfontein Granites.

The Concordia Granite is a sheet-like intrusive occurring mainly near the type locality, the town of Concordia, but is also exposed around the Springbok Dome. It is a microcline anite with variable amounts of minor plagioclase, garnet and biotite (usually less than 3%).

towards the top. The lower contact of the Concordia Granite (with the Nababeep Granitic Gneiss) often displays lit-par-lit features, with Concordia Granite being intruded into the Nababeep Granitic Gneiss. Where this occurs, the resulting rock type is referred to as the "Mixed Zone Gneiss".

The Rietberg Granite occurs mainly in the north of the Okiep Copper District (Fig. 1.2). It is a plagioclase feldspar granite with uor biotite and conspicuous phenocrysts of Kfeldspar. The rock has a distinct porphyritic texture with little or no tectonic fabric (a weak quartz-feldspar mineral lineation may occur). Xenoliths of the Okiep Group, Gladkop and Klein Namaqualand Suites are common within the Rietberg Granite.

The Kweekfontein Granite is a rare lithology in the Okiep Copper District, but scattered outcreps may be found to the east of the Springbok Dome or within the Ratelpoort Synform. It is a fine-grained, poorly foliated microcline granite. The Kweekfontein Granite represents the youngest phase of the Spektakel Suite of granitic intrusions.

Koperberg Suite

This suite of rocks is often referred to (in the literature as well as in mining terms) as "basic bodies" or "noritoids" (e.g. Lombaard & Schreuder, 1978). This suite represents a phase of intrusion that postdates the granitic intrusions described above. The suite comprises a variety of different rock types, ranging from anorthosite and diorite to norite, glimmerite and pyroxenite. The most common rock type of this sure is of intermediate (dioritic) rather than basic (noritic) composition; it is thus surprising that the terms "noritoid" and "basic bodies" have been entrenched so deeply in the literature. Several attempts have been made to classify the rocks of the Koperberg Suite in a formal classification scheme (van Zyl, 1978).

Despite the small volumes of Koperberg Suite rocks that occur in the Okiep Copper District, they are of particular importance, since they are the host to the copper mineralisation that is at the centre of all interest in the Okiep district. A more detailed account of the rocks of the Koperberg Suite is given in Section 1.5.

Nama Group

The granite-gneiss terrane of the Okiep Copper District is unconformably overlain in the west by late Proterozoic sediments. These are the Nama Group sediments consisting of grits, sandstones, conglomerate, shale and limestone. In contrast to the intense deformation and metamorphism that the rocks of the Okiep Copper District have undergone, the Nama Group sediments have undergone very little deformation.

1.4.2 Structure

The regional survey of Joubert (1971) laid the foundation of the current knowledge and understanding of the structure and tectonics of Namaqualand. This survey has remained largely undisputed for over two decades; later authors either confirmed or slightly modified Joubert's conclusions. In the case of the Okiep Copper District, Clifford *et al.* (1975a) and Hälbich (1978) have modified Joubert's model to fit their observations in this district.

Joubert (1971, 1976) identified a polyphase deformational history in Namaqualand, and five deformation events were proposed (Table 1.2). The D_1 deformation phase produced tight isoclinal intrafolial folding caused by tectonism under intermediate- to high-grade conditions (Joubert, 1971; Albat, 1979). This deformation event is best preserved in the areas to the north and to the east of the Okiep Copper District. Evidence for this event in the Okiep Copper District is found as a fabric in gneissic xenoliths of the Khurisberg and Lammerhoek Subgroups in the Klein Namaqualand and Spektakel Suites.

The D_2 deformation phase (the "Namaqua event", of Blignault *et al.*, 1983) is the most pervasive phase of deformation orded in the Okiep Copper District. The characteristic sub-horizontal planar fabric (S₂), displayed as augen textures or gneissose banding, is the most prominent expression of this deformation phase. The gneissose banding is best developed in the Klein Namaqualand and Spektakel Suites which may also display an associated east-west trending mineral lineation (L₂).

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The D_2 deformation event is also expressed by the formation of regional large- to small-scale folds (F₂; Joubert, 1971). These tight- to isoclinal folds, which are often recumbent, are best developed in the Springbok Quartzite of the Khurisberg Subgroup. The presence of these flatlying folds constitutes the principle evidence for tectonic duplication in the fold-nappe theory of Clifford *et al.* (1975a). Kisters (1993) noted that the fold hinges of these F₂ folds have been dismembered and isolated, which makes the evaluation of the fold-nappe theory difficult.

Table 1.2 Correlation of deformational, metamorphic and intrusive events (after Joubert, 1971, 1986; Clifford et al., 1975a, 1981, 1990; Waters, 1988, 1990; Gibson & Walimach, 1992).

Radiometric Age (Ma)	Deformational Events	Metamorphic Events	Intrusive Events
	D5 N-S breccia faults		÷
	D4 NW-SE and NE-SW shear zones		
1072 ± 20	D3 F3 open E-W folding and steep structures	M 2	Koperberg Suite
1166 ± 26 1213 ± 22	D2 S2 gneissosity L2 lineation F2 isoclinal folds	Namaqua event	Spektakel Suite Klein Namaqualand Suite
1700 - 1900	Di F1 intrafoliai folds	M1 Orange River event	Gladkop Suite
			•

The S₂ regional fabric associated with the D₂ event decreases in intensity from the lower Klein Namaqualand Suite to the upper Spektakel Suite, implying syn- to late-D₂ intrusion of the former and late- to post-D₂ intrusion of the latter (Clinford *et al.*, 1975a).

The D₃ deformation phase is characterised by the formation of large, open upright folds (F_{3}) which trend east-north-east. The F₃ folds are prominently recorded as the Springbok Dome and Ratelpoort Synform structures (Fig. 1.2), where F₂ folds are often refolded.

In places, the normally flat-lying foliation in the country rock gneisses has been rotated to very steep attitudes. These narrow, linear zones are locally referred to "steep structures" and are unique to the Okiep Copper District. Since their orientations, i.e. trending east-northeast, are similar to those of the D₃ structures, eg. the Springbok Dome, most authors associate these steep structures with the D₃ event (Clifford *et al.*, 1975a; Lombaard & Schreuder, 1978; Lombaard *et al.*, 1986; Kisters, 1993), while Hälbich (1978) classes these structures into a separate deformation phase (F₄).

The D_4 event (Joubert, 1971, 1986) which produced conjugate sets of north-west and northeast trending mylonitic shear zones, is regarded by Hälbich (1978) as the fifth distinct deformation event (D_5). These narrow (up to 25m wide), subvertical shear zones represent the last phase of ductile deformation in the Okiep Copper District.

Brittle deformation is recorded as breccia faults which trend north to north-east and range in width from a few millimetres to several tens of metres. This phase of deformation is the youngest in the Okiep Copper District (D₅ after Joubert, 1986), even displacing the Nama Group sediments (*ca.*500 Ma, Clifford *et al.*, 1975a).

1.4.3 Metamorphism

Several regional studies of the Namaqualand Metamorphic Complex, and local studies in the Okiep Copper District, have concluded that the area is of a high-grade metamorphic nature. It has furthermore been established that this metamorphism is symmetrically zor.e.,

increasing from greenschist facies grade along the Atlantic Ocean coast, through kyanite- and sillimanite- amphibelite facies, to granulite facies in the castern and southern portions of the Namaousland Metamorphic Complex (Joubert, 1973).

Two main metamorphic events have been recognised in the Namaqualand Metamorphic Complex. The earlier, M_1 event (the "Orange River event" of Blignault *et al.*, 1983) is the dominant event recorded in the areas north of the Okiep Copper District. This event undoubtedly also affected the rocks of the Okiep Copper District, but the evidence for this event has been overprinted by the later, M_2 event (the Jamaqua event" of Blignault *et al.*, 1983).

The tinning of the metamorphic events, some dispute. Clifford *et al.* (1975a, 1975t, M_2 event, has been a topic of to be syn- to post-D₂ (i.e. 1187±22Ma). Just ert (2010, indeed that the metamorphism in the Namaqualand Metamorphic Complex predates the Virolschrif granites, i.e. older than 1850Ma. Other authors, e.g. Waters (1986, 1983, 1989, 1990) and Gibson & Wallmach (1992), dated the peak metamorphism as post-D₃ (i.e. younger than 1070Ma, Clifford *et al.*, 1975a).

Based on mineral chemistry and isotopic data, Clifford *et al.* (1975a, 1981) proposed peak M_2 conditions of *ca.* 850°C and P>6kb. These conditions are generally accepted by various authors. Based on garnet-cordierite and garnet-orthopyroxene thermobarometry, Waters & Whales (1984) and Waters (1989) favour a slightly lower pressure at the time of peak metamorphism (P=5kb), but agree that T>800°C. Gibson & Wallmach (1992) proposed a slightly higher temperature (*ca.* 900°C) and similar pressure (P=6-7kb). These peak metamorphic conditions for the M_2 event indicate a high temperature, low pressure granulite facies grade metamorphism, characterised by an elevated geothermal gradient (35-40°C/km) (Gibson & Wallmach, 1992).

Waters (1986, 1988, 1989, 1990) and Gibson & Wallmach (1992) have proposed an anticlockwise P-T-t path. The prograde metamorphism path shows increasing pressure with increasing temperature. Clifford *et al.* (1981) and Waters (1986, 1989) suggested isobaric

cooling for the retrograde path, while Gibson & Walimach (1992) proposed decreasing pressure with decreasing temperature (with a slight increase in pressure with decreasing temperature at peak metamorphic conditions, Fig. 1.3).

Joubert (1971, 1973, 1986) suggested that the metamorphism in the Namagualand Metamorphic Complex was caused by a thermal dome of regional extent underlying the area. Clifford *et al.* (1975b) supported this theory and concluded that the Okiep Copper District lies on the western flank of this dome. Zelt (1980) suggested deep level basement reworking under amphibolite facies conditions during the Pan-African event.



T (°C)

Fig. 1.3 Summary of inferred P-T-t paths and peak metamorphic conditions (after Gibson & Wallmach, 1992). Data from: (a) Waters (1986, 1989) (b) Clifford et al. (1975a,b) (c) & (d) Clifford et al. (1981) (e) Gibson & Wallmach (1992)

Waters (1986, 1988, 1989, 1990) stated that the anticlockwise P-T-t path (Fig. 1.3) developed in a compressional tectonic setting involving possible crustal underplating by basic material. Heating was produced by intrusion of granitic magma at, or above, the present $\frac{1}{12}$ erosional level. Gibson & Wallmach (1992) suggested that the metamorphism is a product of a transient thermal pulse, with heating produced by intrusive magmas (cf. Waters, 1989), or by some major lower crustal thermal event. Humphreys & van Bever Donker (1990) proposed that this lower crust thermal event may be crust-mantle delamination.

1.4.4 Geochronology

Several age determinations on the rock units of the Namaqualand Metamorphic Complex have been undertaken to describe more accurately the geochronological history of the region. This geochronological history spans some 2000Ma. The greatest age recorded is that of the Kheis orogeny (2500-2900Ma; Nicolaysen & Burger, 1965). Younger events such as the Damaran orogeny (*ca*, 500Ma; Clifford *et al.*, 1981) are also recorded.

The majority of ages from various radiometric age determination studies fall in the 2000-1000Ma range. From this range, two dominant age groupings record the two main igneous and metamorphic events in the Namaqualand Metamorphic Complex and in the Okiep Copper District. The age group of 1900-1700Ma reflects the earlier of these two events, the M_i (or Orange River) metamorphic and igneous events (Reid, 1975; Barton, 1983; Blignault *et al.*, 1983) which predominates in the northern parts of the Namaqualand Metamorphic Complex (Kröner & Blignault, 1976). Table 1.2 summarises these events.

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Radiometric age determinations in the Okiep Copper District have yielded ages ranging from 1200Ma to 1000Ma. These ages reflect the age of the M_2 (or Namaqua) metamorphic event, as well as the ages of late- to post- M_2 orthogneiss intrusions (e.g. Nicolaysen & Burger, 1965; Clifford *et al.*, 1975a, 1981, 1990; Stumpfl *et al.* 1976; Barton, 1983).

Barton (1983) reported the ages of pre- M_2 lithostratigraphic units. A Rb-Sr isochron age of 1800Ma is reported for the Lammerhoek Subgroup Gneisses (Okiep Group, Table 1.1). A Rb-Sr errorchron age of 1824 ± 70 Ma and a U-Pb isochron age of $1770\pm184/-190$ Ma are also given for the Brandewynsbank Gneisses (Gladkop Suite, Table 1.1).

Several ages have been obtained for the Nababeep and Modderfontein gneisses (Klein Namaqualand Suite, Table 1.1), but are *ca.* 1200Ma (e.g. Clifford *et al.*, 1975a, 1981, 1990; Barton, 1983). The Rb-Sr whole rock isochron age of 1187 \pm 22Ma for the Nababeep Gneiss is thought to reflect the age of the granulite facies M₂ metamorphic event (Clifford *et al.*, 1975a, 1981). Rb-Sr whole rock isochron ages of 1147 \pm 33Ma (*ibid.*) and 1141 \pm 22Ma (Clifford *et al.*, 1975a) reflect the time of intrusion of the Spektakel Suite.

Several emplacement ages of the economically important Koperberg Suite have been obtained. Rb-Sr whole rock analyses by Nicolaysen & Burger (1965) produced an age of 1042 ± 42 Ma. U-Pb zircon analyses yield Koperberg Suite emplacement ages of 1072 ± 20 Ma (Clifford *et al.*; 1975a), *ca.* 1100Ma (Stumpfl *et al.*, 1976) and 1075 + 48/-50Ma, and a Sm-Nd errorchron age of 1047 ± 59 Ma (Clifford *et al.*, 1990).

1.5 Kopecberg Suite

The Koperberg suite has been the subject of numerous investigations, data first being published in the 1850's by pioneer geologists including Bain (1854), Rubidge (1856), Atherstone (1857) and Wyley (1857). A general overview of the Koperberg Suite in terms of distribution and form of occurrence, wall rock relationships, composition and texture, and mineralisation is given by Lombaard *et al.* (1986). The Koperberg Suite represents the last intrusive phase in the District, and is particularly common within the Concordia Granite (Fig. 1.2).

About 1500 occurrences of the Koperberg Suite intrusive bodies have been documented in the 3000km² area of the Okiep Copper District. These bodies most commonly have an eastwest trending dyke-like form, while plugs and sills are less common. The width of these dykes is generally 60-100m and continuous strike length is in the range of several metres to about 1km. fatrusive bodies which lie outside these dimensions are rare (Lombaard *et al.*, 1986). The irregular, discontinuous outcrop pattern is also reflected in the vertical section; bodies exhibit pinching and swelling, branching and coalescing, and tapering out at depth. Koperberg Suite bodies are generally subvertical or very steeply north dipping. In most cases, they extend only for several hundred metres in depth before tapering out, commonly terminating close to certain refractory lithological horizons, e.g. the Springbok Quartzite. It has been shown, however, that in some cases, the bodies may continue well below these terminations, often to depths of greater than 1.5km (van Zyl, 1967; Lombaard *et al.*, 1986; Kisters, 1993).

The association of Koperberg Suite occurrences with steep structures (Section 1.4.2.) is well documented (Lombaard *et al.*, 1986). Kisters (1993) discussed this association in detail and concluded that the intrusion of the magmatic rocks in the central, subvertical zones of these structures is due to the steep structures providing subvertically inclined zones of anisotropy which the Koperberg Suite could occupy. Not all Koperberg Suite occurrences are associated with the central zones of steep structures. Intrusions commonly occur on the northern flanks of these structures, or less commonly on the southern flanks. In the rare cases of Koperberg intrusions that are not associated with steep structures at all, these intrusions are in the form of sill-like bodies lying subparallel to the regional foliation (Kisters, 1993).

Koperberg Suite intrusive bodies may consist of only a single lithology, but commonly several lithologies are present. The Jubilee ore body, on which the present study focuses, is an example of such a composite intrusion. From the contact relations within a composite intrusive body, relative age relationships may be determined for the various intrusive phases. Brecciation of the older phases by the younger phases indicates that the more felsic varieties (anorthosite and diorite) intruded before the more mafic varieties (norite and pyroxenite) (van Zyl, 1978; McIver *et al.*, 1983).

Contacts between the intrusive rocks of the Koperberg Suite and the surrounding country rocks are generally sharp with limited or no wall rock alteration (Prins, 1970; Venter, 1970; Prins & Venter, 1978). The notable lack of chilled margins associated with these intrusions, is considered to be the result of the Koperberg Suite being emplaced into a hot crust undergoing high-grade metamorphism (Clifford *et al.*, 1975a; Lombaard *et al.*, 1986; Gibson & Wallmach, 1992). The intrusive bodies are generally massive, but may exhibit some

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tectonic fabric parallel to their contacts (McIver et al., 1983).

The rock types documented for the Koperberg Suite include: syenite, shonkinite, quartzanorthosite, anorthosite, biotite-diorite, glimmerite, pyroxene-diorite, norite and pyroxenite (Lombaard *et al.*, 1986; Conradie, 1983). Various authors propose different subdivisions of these rocks based on their mineralogy, notably van Zyl (1978) and Conradie (1983). Van Zyl (1978) proposed a classification system, based on silicate and sulphide content of the rocks, to assist in the evaluation of potential ore bodies. This classification system lists the following rock types as making up the Koperberg Suite: andesinite, diorite type I, diorite type II, felsic norite and hypersthenite. Conradie (1983) classified the rocks of the Koperberg Suite on the basis of their petrographical relationships. The following rock types are considered by Conradie (1983) to make up the Koperberg Suite: anorthosite, leucodiorite, mice-a...te, glimmerite, hypersthene-diorite, hypersthenite, ferro-diorite and hornblendite.

Petrographic studies on the copper-bearing Koperberg Suite rocks have been undertaken since the early part of the twentieth century. Rogers (1916) produced an excellent account of the copper deposits in the Okiep Copper District, recognising at least ten different rock types. Petrographic and mineralogical studies were also undertaken by Strauss (1941) and Latsky (1942). The studies on petrographic relations by van Zyl (1967, 1978) produced descriptions of the more recently developed ore bodies. Since the early 1980's several important petrographic studies have been published. These include papers by Conradie (1983), McIver *et al.* (1983), Conradie & Schoch (1986a, 1986b), Boer (1989) and Schoch & Conradie (1990). Mineral chemical studies were largely neglected prior to the study by Stumpfl *et al.* (1976). Since then, several such studies have been published by Clifford *et al.* (1981),

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Contadie (1983), Contadie & Schoch (1986a, 1986b), Boer (1989) and Schoch & Contadie (1990).

Based on the work of the above-mentioned authors, the petrographic relations of the rocks of the Koperberg Suite are fairly well established. The main mineral constituents of the rocks of this suite are: plagioclase, which lies in the compositional range of An_{38} to An_{58} (andesine to labradorite), orthopyroxene, which lies in the compositional range of En_{58} to En_{68} (hypersthene), and brown mica (biotite and phlogopite). Apatite, zircon, sphene, quartz and magnetite represent the principal accessory minerals. Clinopyroxene and hornblende are generally scarce. Rock type classification by most authors is based on the relative abundance of these minerals; the most common rock types in the Koperberg suite are anorthositic (andesitic) to dioritic (plagioclase \pm orthopyroxene \pm brown mica).

The petrography and chemistry of the sulphides have been described in detail by many authors, notably Rogers (1916), Strauss (1941), Latsky (1942), van Zyl (1967, 1978), Stumpfl *et al.* (1976), Clifford *et al.* (1990) and Cawthorn & Meyer (1992). Ore mineralogy, as defined by the contributions of these authors, suggests that bornite and chalcopyrite constitute the principal ore minerals. Pyrite, pyrrhotite and pentlandite may occur as accessories in some ore bodies, while chalcocite occurs only as a replacement mineral of bornite. These sulphides may occur either as fine disseminations or as coarse granular, to locally massive concentrations. The relationships between silicates and sulphides have been summarised by Lombaard *et al.* (1986). The sulphides are interstitial to the silicates, or form aggregates with the silicates, or occur along the cleavage planes of the silicates, especially of pyroxene and mica. Cornelissen (1958) noted the occurrence of botryoidal and stalactitic

encrustations of chalcopyrite, bornite and chalcocite in fault-related vugs and cavities. Sulphur isotope studies by Jensen & Dechow (1964, 1965) and von Gehlen *et al.* (1990), indicate a very narrow spread of δ^{34} S values around δ^{34} S=0 permil, which is close to the mantle average of δ^{34} S=+0.5 permil.

Stumpfl *et al.* (1976) proposed that the sulphides represent a late stage phase in the intrusive bodies, being remobilised and precipitated by magmatically derived hydrothermal fluids. This theory is in direct contripst to those theories proposed by even the earliest workers in the Okiep Copper District which suggest that the sulphides are of magmatic, syngenetic origin, e.g. Wyley (1857) and Rogers (1916). Clifford *et al.* (1990) refined the model of Stumpfl *et al.* (1976), proposing two types of ores that represent end-members. These two ore types are: a magnatic ore, e.g. Carolusberg Mine, and a hydrothermal ore, e.g. Hoits Mine. Van Zyl (1967, 1978), McIver *et al.* (1983) and Cawthorn & Meyer (1992) agree that the sulphides crystallised after the crystallisation of the silicates and the oxides. Cawthorn & Meyer (1992) interpreted the presence of non-magmatic bornite in the ore bodies (first noted by Rogers in 1916) as being due to the oxidation of primary pyrthotite and chalcopyrite to bornite and Ti-free magnetite. This oxidation may have been related to the post-emplacement high-grade metamorphism (McIver *et al.*, 1983).

The timing of emplacement of the Koperberg Suite with respect to the regional deformation and metamorphism is controversial. An intrusive age of *ca*. 1100Ma for the Koperberg Suite is well documented (Nicolaysen & Burger, 1965; Clifford *et al.*, 1975a, 1990; Stumpfl *et al.*, 1976; Koeppel, 1978), while the M₂ metamorphic event has been dated at 1187 \pm 22Ma (Clifford *et al.*, 1975a, 1981). This implies that the Koperberg Suite was emplaced post-M₂.

Based on the relationships between the intrusives and the steep structures in which they are situated, most authors have proposed a post- D_3 emplacement age for the Koperberg Suite. Several author. (McIver *et al.*, 1983; Waters, 1989; Gibson & Wallmach, 1992) contended that, based on metamorphic textures and tectonic fabrics in the Koperberg Suite rocks, peak metamorphic and deformation conditions post-date the Koperberg Suite emplacement, i.e. the Koperberg Suite was emplaced syn- to late- D_3 and M_2 .

Despite over 140 years of research, there is still no consensus as to the origin of the Koperberg Suite. Early workers such as Wyley (1857), Ronaldson (1905) and Rogers (1916) noted the intrusive nature of the Suite and were convinced of a magmatic origin for the rocks and their included sulphides. Latsky (1942) similarly proposed an intrusive origin for the Koperberg Suite, based on petrographical textures and the presence of xenoliths within the Suite.

The years between 1950 and 1965 produced vastly contrasting ideas about the origin of the Koperberg Suite. Read (1952), in line with the granitisation model for the origin of the granites and gneisses of Namaqualand, believed that the Koperberg Suite bodies were derived from original copper-bearing flows, sills and pyroclastics. Their presence in steep structures was explained by regarding these bodies as being tougher "resistors" in the slightly plastic gneisses. Bereadict *et al.* (1964), who supported Read's (1952) granitisation theory, proposed that the granitisation fluids travelled along the bedding planes of the metasediments from which they were derived, mobilising elements such as Na, Ca, Mg, Fe, Cu and S, and depositing these into the steep structures. These theories were based mainly on the observation that many of the ore bodies appear to pinch out into the Khurisberg Subgroup.

Van Zyl (1967, 1978), however, showed that some ore bodies (at least) transect the proposed source beds for the metamorphic differentiation theory of earlier workers. He therefore reintroduced the idea of the Koperberg Suite being intrusive in nature, based on further evidence of country rock xenoliths in the Koperberg Suite, sharp contact and the absence of preserved country rock textures in the intrusive bodies. This author further proposed a deepseated magina chambes in which pre-intrusion differentiation took place and that these magmas were contaminated by country rock during their ascent through the crust to their intrusion levels.

Clifford *et al.* (1975a, 1975b, 1981, 1990) proposed a source-bed theory based on initial ⁸⁷Sr/⁸⁶Sr isotopic ratio and whole rock geochemistry. This theor, involves the anatectic derivation of the Koperberg Suite from gneisses and granulites of intermediate to basic composition. Based on similar isotopic ratios and identical mineralogy, a two-pyroxene granulite present in the Lammerhoek Subgroup (Section 1.4.1.) was proposed as the source bed. Stumpfl *et al.* (1976) supported this source-bed theory, based on mineral chemical data.

McIver *et al.* (1983) agreed with the magmatic theory of van Zyl (1978), but emphasised the fact that these rocks have undergone high-grade metamorphism and recrystallisation. Based on their geochemistry, these authors suggested an alkaline mantle-derived magma, contaminated by granitic anatects in the lower crust. Andreoli & Hart (1987) also proposed a basaltic precursor for the Koperberg Suite, enriched in K, REE, P, U, Th and Zr. This "KREEP" magma was possibly derived from the melting of an enriched mantle source. Kisters (1993) discussed the emplacement mechanism of the Koperberg Suite and confirmed the assertion of other authors that the Koperberg suite rocks are contaminated by assimilating

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country rock granites and gneisses.

Numerous confidential and unpublished reports by the mine and field geologists of the O'okiep Copper Company (OCC), have added greatly to the current understanding and knowledge of the Koperberg Suite in particular, and the geology of the Okiep Copper District in general.

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Possible comparisons between the occurrence of the Koperberg Suite with other areas include Caraiba, Brazil (Townend *et al.*, 1980; McIver *et al*, 1983), the Grenville Province, Canada (Wynne-Edwards, 1972; Clifford *et al.*, 1981), and massif-type anorthosite complexes (Isachsen, 1969; Conradie & Schoch, 1986a).

1.6 Present study

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Previous research on the rocks of the Koperberg Suite in the Okiep Copper District has largely been on a regional scale, with authors attempting to explain the formation and petrogenesis of the suite as a whole. Furthermore, these studies were based on selective sampling of the suite over a wide region. Although this method of investigation has resulted in several of the characteristics of the Koperberg Suite being well established, several aspects of the suite remain uncertain and controversial.

The present study was initiated by the Geology Department and the Economic Geology

Research Unit of the University of the Witwatersrand in conjunction with Gold Fields of South Africa. The aim is to document and describe the geology of a single Koperberg Suite occurrence, namely the Jubilee body. With particular emphasis on geochemical characteristics, a better understanding of the origin and petrogenesis of the Jubilee body and the processes of formation is to be attained. Furthermore, the effects, if any, of external processes such as crustal contamination, on the rocks of the Koperberg Suite present in the Jubilee body, are also investigated.

Mapping and sampling of the Jubilee body was undertaken during March 1993 and August 1993. The northern and western faces of the Jubilee open pit were mapped on a scale of 1:200. Mapping emphasis was on the distribution of the different rock types and their relationships with one another, as well as with the country rock. Samples of the rocks present in the study area were collected for petrographic investigation, and whole rock and mineral geochemical analyses. Although sampling was concentrated on the rocks of the Koperberg Suite, samples were also collected from the Concordia Granite country rock, as well as granitic xenoliths. Samples were collected to establish a representative data set of all the rock types present, as well as to illustrate any geochemical or petrographical differences within the various rock types, especially at contacts between adjacent rock types.

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CHAPTER 2

NOMENCLATURE OF THE KOPERBERG SUITE

2.1 Introduction

Given the extensive body of literature pertaining to the geology of the Okiep Copper District, it is not at all surprising that there exists an impressive array of names for the rocks, especially the Koperberg Suite. This brief chapter outlines the nomenclature of the rock types belonging to the Koperberg Suite at the Jubilee mine, with a view of bringing the terminology into line with modern, international names.

2.2 Koperberg Suite

The term Koperberg Suite is a fairly recent term, being adopted in 1980 by the South African Committee for Stratigraphy (SACS, 1980). Prior to the this, the most commonly used name for this suite was the Noritoid S rite. Lombaard *et al.* (1986) listed the rock types present in this suite as: shonkinite, quartz-anorthosite, anorthosite, quartz-diorite, biotite-diorite, glimmerite, hypersthene-diorite, norite and hypersthenite. Several other authors added to this list such names as leucodiorite, ferro-diorite, hornblendite, andesinite, leuconorite, melanorite etc. (van Zyl, 1978; Conradie, 1983; Clifford *et al.*, 1995). These names have been derived from a variety of classification schemes ranging from field-based, colour index and mineralogical schemes to petrographic and geochemical schemes.

2.3 Koperberg Suite at Jubilee

At the risk of increasing the already extensive list of rock names, this chapter proposes to list the rock types of the Koperberg Suite that occur in the Jubilee mine. Where applicable, names that have been used previously to describe these rocks are listed and discussed.

Field classification of the different Koperberg Suite phases present at Jubiler was done on the basis of overall colour index and the relative amount of the major constituent silicate minerals (plagioclase, pyroxene and brown mica). Using this classification, three main rock types were identified as belonging to the Koperberg Suite.

The first rock type is anorthosite. This rock consists almost entirely of plagioclase, with variable amounts of quartz. In cases where samples contain large amounts of quartz, the term **quartz-anorthosite** is used. The term **andesinite** (van Zyl, 1978) is not used here since, although all samples of this rock type analysed in this study have plagioclase of composition An_{30-50} (Chapter 5), plagioclase grains from Carolusberg West have compositions of An_{52} (Stumpfl *et al.*, 1976), hence the term **anorthosite** is considered to be adequate.

The second rock type is mica diorite which consists of plagioclase $+ \text{mica} \pm \text{pyroxene}$. As will be discussed in Chapter 5, the An content of the plagioclase grains in this rock type is less than 50%, hence the root name diorite (Streckeisen, 1967). Mica is the dominant mafic mineral (mica:pyroxene > 1), hence the qualifier mica is used. This rock is often referred to as the choppy diorite by the mining community, but this is clearly not acceptable as the meaning of the adjective choppy is unclear. Furthermore, the term biotite diorite (Strauss, 1941; van Zyl, 1978; Lombaard *et al.*, 1986) is not strictly correct since the composition of the mica in this rock is not always that of biotite *senso stricto*, but is often that of phlogopite (Chapter 5).

The third rock type is pyroxene diorite which has pyroxene, plagioclase and brown mica as its principal silicate components. Again, the An content of the plagioclase present in this rock is less than 50% (Chapter 5), hence the root name diorite. This is in contrast with the term norite which is commonly used for this rock type (Strauss, 1941; van Zyl, 1978; Clifford *et al.*, 1995). Of the two major mafic silicate minerals present, pyroxene is the more common hence the qualifying term pyroxen which is added to the root name. In principle, a rock with approximately equal proportions of mica and pyroxene would require the term pyroxene-mica-diorite, but no such rocks have been identified ai Jubilee.

In the field it was noted that several pyroxene diorite localities were distinctly lighter in colour and these were subsequently termed pyroxene leucodiorite. These rocks also consist of plagioclase, pyroxene and brown mica, but the plagioclase content is higher than in the pyroxene diorite; otherwise these two rock types are very similar. Pyroxene leucodiorite (as defined here) has previously been referred to as leuconorite by OCC geologists as well as in the literature (Clifford *et al.*, 1995).

2.4 Summary

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The field classification of the Koperberg Suite at Jubilee into anorthosite, mica diorite, pyroxene diorite and pyroxene leucodiorite was initially based on colour index and mineralogy. Later chapters of the present study will show that this classification is valid and that classification schemes based on other characteristics (eg. geochemistry) would result in a similar distinction of rock types, albeit with some overlap of the various rock types.

CHAPTER 3

GEOLOGICAL RELATIONSHIPS

3.1 Introduction

The Jubilee open pit mine is located about 2km north of the town of Concordia. This composite ore body of Koperberg Suite rocks intruded into the Concordia Granite of the Spektakel Suite (Fig. 1.2).

The dimensions of the ore body have been determined by exploration diamond drilling by the O'okiep Copper Company (OCC). The Jubilee ore body is an east-west trending dykelike structure on the northern flank of a steep structure. The width of the dyke is about 90m and its proven strike length is about 170m. The dyke pinches towards the east but may be connected to the Jubilee East intrusion, some 500m to the north-north-east. The proven depth of the Jubilee ore body is about 200m and the dip varies from 75°N to vertical.

The present study focuses only on those rocks of the Koperberg Suite which are exposed on the northern and western faces of the Jubilee open pit mine (Fig 3.1), and their relationship to the country rocks in the immediate vicinity. Geological sections of the northern and western faces of the Jubilee pit are shown in Figure 3.2 and will be discussed below.

3.2 Koperberg Suite

3.2.1 General

The rocks of the Koperberg Suite present at Jubilee are readily distinguished from the granitic country rocks in the field. The more mafic rocks (pyroxene leucodiorite and pyroxene diorite) are easily recognisable as belonging to the Koperberg Suite, owing to the dark green or black fresh surfaces and rusty brown weathered surfaces. The more leucocratic members of the Koperberg Suite (anorthosite and mica diorite) are identified by their lack of alkali feldspar and their overall more massive appearance (in contrast to the predominantly

foliated surrounding granitic country rock). Furthermore, anorthosite is generally lacking in any matic minerals, while mica diorite consists mainly of plagioclase feldspar, brown mica and minor pyroxene, which is quite distinct from the alkali feldspar-plagioclase-quartzhornblende assemblage of the granite.



KOPERBERG SUITE CONCORDIA GRANITE

APPROXIMATE UNIT OF THE KOPERBERG SUITE

APPROXIMATE LIMIT OF THE JUBILEE PIT

WASTE DUMP

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NORTHERN FACE SECTION

Fig. 3.1 Plan view of the Jubilee pit and surface geology.

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The distinction between mica diorite and pyroxene diorite is made on the basis of the pyroxene to mica ratio. Furthermore, pyroxene diorite generally has a larger proportion of mafic minerals (pyroxene, brown mica and opaque minerals) than mica diorite, and the latter is also generally finer grained than the pyroxene-rich rocks. Distinguishing between these rock types is usually possible in the field.

The contact relationships between the different rock types of the Koperberg Suite were used to establish a sequence of intrusion among these phases. These relationships indicate that the intrusion of the more felsic phases (anorthosite and mica diorite) predates the intrusion of the more mafic membors (pyroxene diorite).

The different rock types occur in discrete zones or xenoliths. There is, however, a zone where anorthosite and mica diofite occur together as a transition from one rock type to the other. This zone is called the Transition Zone and is described in more detail below (Section 3.2.2).

3.2.2 Rock types

Anorthosite

Anorthosite is a common and conspicuous rock type in the Jubilee pit. Exposures, which are restricted to the northern face of the pit, vary in size from small xenolians (10-20cm across) to large sheets (30-40m across) which have an overall steeply north-dipping orientation (Fig. 3.2). Xenoliths of this rock type occur within all other Koperberg Suite rock types present at Jubilee, indicating that anorthosite was the first phase to be emplaced. Besides the gradational contact between anorthosite and the Transition Zone rocks, t^{+} contacts between anorthosite and other rock types are sharp. It is interesting to note that nownere is anorthosite in contact with the Concordia Granite country rock, but is separated on all sides by younger members of the Koperberg Suite (pyroxene diorite).

The anorthosite at Juilee is a coarse-grained rock consisting of plagioclase and variable amounts of quartz. A decrease in grain-size and an associated increase in quartz content in the anorthosite occurs towards the west. As the anorthosite grades into a mica diorite in the Transition Zone, quartz content increases and grain-size decreases. Due to the nature of this Transition Zone (described below), these grain-size and mineralogical changes do not occur smoothly.



Fig. 3.3 Foliated quartz-rich anorthosite from the Transition Zone. The foliation is defined by elongated quartz grains orientated 083/32°N. View is to the north-east.

Elongate quartz crystals and lensoid aggregates of quartz in the anorthosite often define a discernable fabric within this rock type (Fig. 3.3). This foliation varies slightly between the different anorthosite xenoliths, suggesting that the foliation predates the intrusion of the mafic rocks in which these xenoliths are entrained.

Mica diorite

Mica diorite is a medium-grained plagioclase- and mica-rich rock which occurs at Jubilee as both xenoliths and as a large sheet which grades into anorthosite in the Transition Zone. This rock is fairly homogenous in appearance throughout the exposure (which is restricted to the northern face), although a fc¹iation, which is defined by alignment of mica flakes, is more pronounced in some areas than others. In one locality, orbicular structures are present within the mica diorite (Fig. 3.2).

The presence of xenoliths of this rock type in pyroxene diorite (Fig. 3.4) and an anorthosite xenolith within mica diorite, provide further evidence for the relative timing of the various intrusive phases. Although the contacts between mica diorite and the adjacent rock types are clear and well-defined, there is a gradational contact into the Transition Zone. Mica diorite does not occur adjacent to the granitic country rock, but is separated from it by the younger pyroxene diorite.



Fig. 3.4 Mica diorite (MD) xenoliths in pyroxene diorite (PD). View is to the north.

Transition Zone

Although this is not strictly speaking a separate lithology, it will be described here as a lithological unit which is distinct from other units in various ways. This zone occupies the area between the dominant masses of anorthosite and mica diorite and as such consists of both these rock types.

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Fig. 3.5 A plan view of the layering of anorthosite (lighter material) and mica diorite (darker material) in the Transition Zone, orientated 079°/43°N. East is to the right.

The Transition Zone represents a transition from true mica diorite to true anorthosite with the transition occurring as a weakly defined interlayering of the two rock types (Fig. 3.5).

From the mica diorite mass, there are increasingly persistent and more frequent layers and patches of anorthosite, until only a few thin slivers of mica diorite remain, with the rock ultimately becoming true anorthosite towards the east. This layering of anorthosite and mica diorite is clearly defined in places, but in other places, these layers are very diffuse, especially towards the edges of this zone. The layers are not persistent along their length, seldom reaching more than 70cm in length and 10cm in width. The orientation of the layering appears to be fairly consistent, striking approximately east-west and dipping between 30° and 50° to the north. In general, neither the anorthosite layers nor the mica diorite layers within the Transition Zone have a fabric, but where a fabric occurs, it is parallel to the layering. Orbicular structures may occur in the mica diorite layers.

Also of note are the presence of two large (ca. 10m) granitic xenoliths, as well as two smaller ones, in the Transition Zone. These granitic xenoliths will be described below. Within the Transition Zone, there are zones (generally about 2m across) in which there is a distinct, but gradational change in mineralogy. These zones are rich in quartz, alkali feldspar and plagioclase and are generally very coarse-grained. On the basis of mineralogy and texture, these zones are similar to the the granitic xenoliths which occur in the vicinity.

Pyroxene diorite

This is the dominant Koperberg Suite rock type at Jubilee. It has been subdivided into pyroxene leucodiorite and pyroxene diorite. The difference between these two is very slight in the field, both being dark, coarse-grained rocks consisting of plagioclase, pyroxene, brown mica and opaque minerals. Pyroxene diorite is darker and contains a higher proportion of ferromagnesian minerals ($\pm 50\%$). Differences in terms of petrography and chemistry between the two will be discussed in later sections.

Pyroxene leucodiorite occupies almost the entire western face exposure at Jubilee. It also occurs as xenoliths in pyroxene diorite exposed along the northern face (Fig. 3.2). The western exposure is a very homogenous mass with only minor mineralogical changes towards the contact with the Concordia Granite as described in Section 3.2.3 below. Exposures along the northern face are more varied in terms of their mineralogy.

The pyroxene diorite exposures are heterogenous, there being zones which are more felsic than the pyroxene diorites, and zones which are pyroxene- or mica-rich relative to the pyroxene diorite. These heterogeneities are in general small-scale features, measuring less than 2m in the longest dimension. Although there are clear and well-defined contacts between the pyroxene diorite and the heterogeneities, there are zones where the change in mineralogy is gradational. Orbicular structures are common in this rock type (Fig. 3.2).

Another feature of pyroxene diorite is the presence of sulphides. These have a very limited distribution and occur most commonly in the lower eastern corner of the northern face. Here chalcopyrite and bornite are abundant and clearly visible as coarse granular aggregates, while elsewhere sulphides occur as fine disseminations of chalcopyrite and are scarce. Since no accurate maps of the orebody prior to mining exist, it may be assumed that this well-mineralised zone extended into what is now the mined-out area of the Jubilee open pit.

Pyroxene diorite often occurs as narrow (<0.5m) veinlets. These veinlets surround large xenoliths of older intrusive phases, especially where the older xenoliths occur close to the Concordia Granite country rocks. Within these narrow zones, the rock is clearly layered, the layering being defined by alternating pyroxene-rich and plagioclase-rich bands (Fig. 3.6). This layering is strictly parallel to the margins of these zones and is in no way consistent throughout the intrusive body (Fig. 3.2).

Pyroxene leucodiorite is in contact with the granitic country rocks along the entire western face of the Jubilee open pit. Along the northern face, pyroxene diorite is in contact with the country rocks. Anorthosite and mica diorite never form the contact with the Concordia Granite.

3.2.3 Contact relationships within the intrusion

Contacts between the rocks of the Koperberg Suite at Jubilee may be both sharp and welldefined, or gradational. This applies to contacts between xenoliths and host rocks, as well as between major bodies of different lithologies. Xenoliths in pyroxene diorite are common and where sharp contacts exist between these xenoliths and their host rock, the xenolith

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Fig. 3.6 A plan view of a pyroxene diorite veinlet (PD) developed between the Concordia Granite country rock (CG) and a Concordia Granite xenolith (CGX). The layering defined by alternating plagioclase- and pyroxene-rich layers is orientated 083°/70°N. East is to the right.

material can clearly be identified as one of the earlier Koperberg Suite phases. There are also heterogeneities within the pyroxene diorite which are considered to be xenoliths of either the country rock or of earlier phases of the Koperberg Suite. The contacts between xenoliths of this type and the pyroxene diorite host rock are diffuse and the xenolith material does not resemble any of the other Koperberg Suite lithologies.

In the Transition Zone where layers of anorthosite and mica diorite occur, the contacts between these bands of different rock types are well-defined, without being sharp and intrusive. These contacts are gradational over a few millimetres or centimetres and are slightly uneven. This would argue against a lit-par-lit contact zone between the two

lithologies. Instead, it suggests mixing of the two lithologies while in a semi-crystallised state.

It was further noted that no chilled margins exist between the various intrusive phases, indicating that each magmatic pulse intruded while the previous intrusive phases were still hot. A temperature gradient may have existed between two successive phases of intrusion, as is suggested by the presence of small (ca. 2.5cm) xenoliths of pyroxene leucodiorite within the pyroxene diorite in one locality. These xenoliths are remarkable in that they exhibit a hornfels texture (Chapter 5), indicating that the xenoliths of pyroxene leucodiorite were too small to accommodate the difference in temperature without a physical alteration in texture.

3.3 Wall rock contact relationships

The rocks of the Koperberg Suite are in sharp contact with the well-foliated Concordia Granite country rocks. A steepening of the sub-horizontal foliation in the Concordia granites at the contact with the Koperberg Suite rocks is observed at one locality. In this instance, the foliation in the Concordia Granite steepens from sub-horizontal to sub-vertical over a distance of 20-30cm. Generally, however, the foliation in the Concordia Granite disappears in a 30-50cm zone along the contact with the intrusive Koperberg Suite (Fig. 3.7). This zone is lighter in colour and more competent in nature and commonly lacks foliation.

These zones may represent granitic melts resulting from the melting of country rocks by the hot intruding magma. This may also explain the absence of chill margins along the contacts between the Koperberg Suite and the C_{C} ordia Granite. Prins (1970) and Prins & Venter (1978) who described similar alteration zones in country rocks around Koperberg Suite intrusions, regarded the existence of chemical alteration and thermal aureoles as evidence of the magmatic nature of the Koperberg Suite bodies.



Fig. 3.7 Pyroxene diorite - Concordia Granite contact; note the foliation in the Concordia Granite, but the absence of this foliation towards the contact. View is to the north-west.

In some localities, the rocks of the Koperberg Suite, especially the pyroxene diorite, show a distinct change in the: mineralogy towards the contact with the granitic country rock. The rocks become more mafic towards the contact, in some places being pyroxenitic, consisting of almost pure pyroxene and oxides (Fig. 3.8). Moreover, in places, the Koperberg Suite rocks become distinctly foliated towards the contact with the country rocks. This foliation is defined by the alignment of mineral aggregates and is in general parallel to the contact with the Concordia Granite country rock.



Fig. 3.8 Close-up of the contact shown in Figure 3.7; note that the pyroxene diorite becomes more mafic towards the contact. View is to the north-west.

3.4 Granitic xenoliths

Two large (about 10m in diameter) and two smaller (about 2m in length) xenoliths of granitic material occur on the northern face of the Jubilee Pit (fig. 3.2). These xenoliths are distinct from the Concordia Granite country rocks. They are coarser-grained and lack the distinctive foliation and mineralogy of the Concordia Granite. Although similar in texture, the two larger granitic xenoliths are not identical in terms of mineralogy, one being richer in alkali feldspar. Both, however, are rich in quartz, plagioclase and amphibole.

The Transition Zone material in contact with these xenoliths is often very quartz- and plagioclase-rich. This material grades into the anorthositic and mica dioritic material more representative of the Transition Zone. The contacts between this quartz- and plagioclase-rich Transition Zone material and the granitic xenoliths are poorly defined. These features are suggestive of assimilation of the granitic material by the anorthosite/mica diorite. Similar changes in mineralogy have been noted in the Transition Zone (Section 3.2.2). but these are not associated with visible xenoliths. The quartz- and plagioclase-rich zones in the Transition Zone probably indicate the presence of partially digested xenoliths similar to the granitic xenoliths described here. The presence of granitic xenoliths in the Transition Zone suggests that this granitic material crystallised prior to the intrusion of the earliest recognised phase of the Koperberg Suite. This granitic material may represent a very early intrusive phase of the Koperberg Suite, or it may represent country rock from a different crustal level.

3.5 Pegmatites

Pegmatites (maximum width 30cm) cut across the rocks of the Koperberg Suite at Jubilee mine at several localities. In all cases these pegmatite dykes clearly show cross-cutting relationships to the Koperberg Suite rocks, and hence are not part of the magmatic suite. As such, these rocks were not studied in any detail. Suffice it to say that these pegmatite dykes, which consist primarily of plagioclase, quartz and brown mica, trend in a northerly direction and are subvertical. In places, the pegmatite dykes may change direction to follow a lithological contact or some other plane of weakness. These pegmatite dykes can not, however, be traced into the country rock.

3.6 Structure

The Concordia Granite country mck in the vicinity of the Jubilee Mine has a well-developed gneissosity. This foliation, as defined by mineral layering and preferential alignment, varies in orientation from north to south through the Jubilee area. To the north of the mine, the

foliation dips shallowly $(10^{\circ} \cdot 20^{\circ})$ to the south, while at the southern end of the mine, this foliation dips somewhat steeper (about 30°) to the north (Fig. 3.1). This change in orientation of the country rock foliation indicates the possible existence of a steep structure somewhere to the south of the mine. Limited exposure, however, prevented confirmation of this.

The prominent regional foliation observed in the Concordia Granite is not present in the lithologies of the Koperberg Suite. Layering and foliation in the Koperberg Suite rocks are, however, occasionally observed. Foliations and layering observed in several different localities tend to be developed parallel to nearby contacts, rather than having an orientation consistent with that observed in the country rocks (Figs. 3.3 & 3.6). Although foliations in some of the Koperberg Suite rocks, especially in pyroxene diorite, appear to be the result of magma flow, mineral alignment in quartz-rich anorthosite may be related to regional tectonic forces. The latter foliations are not parallel to regional foliations, suggesting that the xenoliths of anorthosite containing this foliation have been rotated with respect to their original orientation.

Joints are common at Jubilee and are seen to affect, but not off-set, both Concordia Granite and Koperberg Suite lithologies. These joints are more commonly developed in the Koperberg Suite which is more competent than the Concordia Granite. The latter may have accommodated the stress associated with joint formation along previously-formed foliations. These joints, which are clearly post-Koperberg, are developed in two dominant sets: one striking north-south and dipping steeply to the east, the other striking east-west and dipping steeply to the north. Pegmatite dykes are developed parallel to the north-south trending joints, suggesting that these pegmatites may have utilised the joints as zones of weakness.

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Chapter 4

PETROGRAPHY

4.1 Introduction

A study of about 150 thin sections was made to determine the mineralogy, as well as textural, deformation and alteration features of each of the rock types of the Koperberg Suite at Jubilee. Several samples of granitic material, which occur as xenoliths within the Koperberg Suite, were also investigated.

4.2 Koperberg Suite

The rocks of the Koperberg Suite present at Jubilee have been classified as anorthosite, mica diorite and pyroxene diorite (Chapter 2). These rocks consist primarily of plagioclase, orthopyroxene and brown mica. Quartz is present in most rocks, but only in quartz anorthosite does this mineral attain a major mineral status. Alkali feldspar is a rare mineral, existing mainly as microperthitic exsolution lamellae within plagioclase, or in rare cases, as fine grains interstitial to plagioclase. Apatite and zircon are the main accessory minerals. Other silicate minerals, which include chlorite, white mica (s. icite) and epidote are the alteration products of the major silicate minerals. Opaque minerals (oxides and sulphides) are major constituents in the more mafic rocks of the Koperberg Suite, while in the more felsic rocks, these are present in minor concentrations. As the main ore body at Jubilee has been totally mined out, the sulphide-rich, and presumably more mafic rock types, are not available for investigation.

4.2.1 Anorthosite

Anorthosite is the earliest intrusive phase recognised in the Koperberg Suite at Jubilee and it is also the most felsic (Chapter 3). Plagioclase is the dominant mineral, constituting more than 80% by volume of this rock. In quartz anorthosite, plagioclase may make up only 50%

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of the rock, the rest being quartz. Otherwise, quartz makes up less than 20% of the rock. Chloritised mica occurs in some samples as a minor mineral, while apatite and zircon are common accessory minerals.

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Plagioclase occurs mainly as subhedral megacrysts up to 8mm in diameter, or as aggregates of small (1-2mm) crystals. Contacts between plagioclase megacrysts may be straight or slightly interlocking, but more commonly, these megacrysts are rimmed by aggregates of smaller, polygonal grains of plagioclase. In the latter case, the margins of the plagioclase megacrysts are very uneven or serrated. Alkali feldspar exsolution blebs or lamellae are common, but not extensively developed. In some cases, very fine grains of alkali feldspar may occur between plagioclase megacrysts. These megacrysts generally exhibit deformation features such as bent twin lamellae, deformation or glide lamellae, subgrain formation, fracturing and undulose extinction (Fig. 4.1). The fine-grained plagioclase crystals, which occur in aggregates among the megacrysts or as rims around the megacrysts, are rarely deformed and none of the above-mentioned features are present. The texture of the finegrained plagioclase is generally granoblastic-polygonal and triple junctions between equant grains are common. Alteration (mainly saussuritisation) of the plagioclase is restricted to grain boundaries and fractures within the megacrysts. Less commonly alteration may also occur at subgrain boundaries and around interstitial sulphide grains. This alteration produces chlorite, epidote and sericite.

Quartz occurs either as ill, anhedral grains associated with fine-grained plagioclase aggregates, ... more commonly as large (up to 18mm in quartz anorthosite), anhedral and elongated grains which overgrow the plagioclase. These large amoeboid quartz grains often exhibit undulose extinction, but granoblastic textures are absent. Based on the observations that quartz overgrows highly deformed plagioclase, and that the quartz is less deformed than plagioclase, it is concluded that the quartz grains recrystallised after the deformation of the plagioclase.

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Fig. 4.1 Kinking of plagloclase twin lamellae at a subgrain boundary in anorthosite. (Sample 180; crossed polars).

Brown mica is an uncommon mineral in anorthosite and occurs as 1mm to 2mm long flakes, generally in association with fine-grained plagioclase aggregates. Single flakes may occur at plagioclase megacryst boundaries or within fractures in these megacrysts. The mica is extensively chloritised. Kinking and splaying of these flakes is ubiquitous. The general paucity of mica in anorthosite does not allow for determining whether these mica flakes are preferentially aligned or not.

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Opaque minerals occur in small amounts (maximum 3%) in a few anorthosite samples. Where they occur, opaques exist as small disseminated specks associated with fine-grained plagioclase and mica flakes, or more rarely, between or within plagioclase megacrysts. Where opaques occur in association with mica, the former may be developed along cleavage planes of the mica. Magnetite is the dominant opaque mineral, while ilmenite is less common, the latter occurring as an exsolution phase in magnetite. Sulphides are rarely present in anorthosite but where they occur, chalcopyrite prodominates over bornite. The sulphides occur as tiny disseminated specks at silicate grain boundaries. In some cases, sulphides occur together with magnetite in association with mica, but generally these sulphides occur as individual, polygonal grains associated with fine-grained plagioclase grains. The occurrence of chalcopyrite and bornite together is rarely observed.

4.2.2 Mica diorite

The term mica diorite is used to describe a medium- to fine-grained rock consisting essentially of plagioclase and brown mica (Chapter 2). Plagioclase constitutes 70% to 85% of the rock by volume, while brown mica is present in modal proportions of 5% to 20%. The rest of the rock is made up of quartz, orthopyroxene, opaque minerals and accessory silicate minerals. Comparing the proportion of plagioclase in mica diorite to the plagioclase proportion in quartz-rich anorthosite (Section 4.2.1), it is noted that mica diorite often contains a higher proportion of plagioclase than quartz anorthosite.



Fig.4.2

Deformation of twin and glide lamellae in plagioclase from mica diorite. (Sample 21).

Plagioclase occurs mainly as large (2-5mm) subledral megacrysts. Small, equant grains of plagioclase which range in size from 0.5mm to 1mm, commonly occur in aggregates among the megacrysts. As a rule, these smaller grains are polygonal and commonly meet in triple point junctions. In contrast to the smaller plagioclase grains, the megacrysts often have highly irregular or serrate grain boundaries, and commonly exhibit deformation features similar to those described for plagioclase in anorthosite (Fig. 4.2). Alteration of plagioclase megacrysts is common, but restricted to grain boundaries and fractures. Exsolution of alkali feldspars is not common, but a few exsolution blebs do occur in plagioclase megacrysts.

The proportion of brown mica (5%-20%) is a characteristic feature of this rock type. Mica occurs as single flakes at the contacts of plagioclase megacrysts, but more commonly as disseminated clusters of several flakes among the fine-grained plagioclase grains. Where mica occurs in association with plagioclase megacrysts, single flakes may project into the plagioclase crystals. Alteration of mica to chlorite is common but not extensive, the alteration occurring mainly along cleavage planes and at grain margins. Bending of the mica flakes or splaying along cleavage planes are commor deformation features exhibited by this mineral. These features are similar to those described for pyroxene diorite (Fig. 4.3).

Orthopyroxene is very uncommon in mica diorite. A few subhedral grains occur associated with mica and fine-grained plagioclase, forming small, irregular bands or patches between plagioclase megacrysts. Due to extensive alteration of the pyroxene grains to chlorite and oxides, only small unaltered relics of the original material are preserved near the core of the grains.

Quartz is present as a minor mineral in only a few of the mich diorite samples examined. In these samples, quartz occurs as small (0.5-1mm) anhedral grains associated with mica and fine-grained plagioclase. Zureon and apatite are very common accessory minerals in mica diorite, but are particularly abundant in samples from the mica diorite xenoliths that occur on the eastern side of the northern face of the Jubilee pit (Fig. 3.2). These accessicies occur as small, rounded grains, usually associated with fine-grained plagioclase and mica, but may occur between or within plagioclase megacrysts.



Fig. 4.3 Deformation of a mica grain in pyroxene diorite (Sample 172). Note the sharp contact between mica (M) and plagioclase (FL).

Opaque minerals make up between 3% and 10% of the mica diorite at Jubilee. In general, these occur as disseminated specks evenly distributed throughout the rock, most commonly in association with mica and fine-grained plagioclase concentrations. The opaque minerals are dominated by magnetite and ilmenite which may occur as co-existing phases or as independent grains. Magnetite often exhibits ilmenite exsolution, while independent ilmenite grains sometimes have exsolved bodies of rutile. Sulphides are rare in mica diorite, constituting only a small percentage of the total opaque fraction. These sulphides usually occur at silicate grain boundaries or along cleavage planes of mica. Although commonly associated with oxide mixerals, sulphides also occur in the absence of oxides, being

interstitial to the silicates. Chalcopyrite is the dominant sulphide mineral, but bornite may occur either as independent grains or in association with chalcopyrite. Where sulphides occur in contact with plagioclase, the latter is often altered to epidote.

4.2.3 Pyroxene diorite

As discussed in Chapter 2, pyroxene diorite may be subdivided into pyroxene leucodiorite and pyroxene diorite. Although the modal proportions of the constituent minerals (and hence the whole rock chemistry) are different between these two rock types, the petrographic relationships and features are similar enough to warrant them being described together here. These rocks consist predominantly of plagioclase (from 20% in the pyroxene diorite to as much as 80% in the pyroxene leucodiorite) and pyroxene (from 15% in the pyroxene leucodiorite to as much as 70% in the pyroxene diorite). Brown mica is a fairly common mineral, making up as much as 12% by volume in samples taken from close to contacts with Concordia Granite. Quartz and apatite are uncommon accessory minerals, while the opaque fraction of the rocks constitutes between 2% and 13% by volume.

Comparing the mafic mineral proportions in mica diorite (Section 4.2.2) and pyroxene diorite, it is noted that the latter has a higher proportion of mafic minerals. Some pyroxene leucodiorite samples have a lower proportion of mafic minerals than the mica diorite. These pyroxene leucodiorite samples correspond to those xenoliths which may represent partially digested granitic or Koperberg Suite material (Chapter 3).

Plagioclase occurs mainly as subhedral to anhedral grains in monomineralic bands or patches

where the grain-size is between 2mm and 5mm. Plagioclase may also occur as smaller (<1mm) polygonal grains between the larger plagioclase grains or in association with pyroxene concentrations, but this is not common. The larger grains generally have straight or slightly undulating margins, but may be very irregular in plars. In the latter case, fine-grained plagioclase grains are often developed. These smaller grains are more equant and polygonal than the larger ones and may meet in equal angle triple junctions. Deformation features, such as bending or kinking of twin lamellae, subgrain formation, deformation lamellae and fracturing of grains, are present, but not very common, in the larger plagioclase grains. In the fine-grained plagioclase crystals, these features are absent altogether. Alteration of plagioclase is limited, with saussuritisation sometimes occurring between larger plagioclase grains.

Subhedral pyroxesie grains, ranging in size from 1mm to 4hm in diameter, are clustered in mafic bands or patches between the plagioclase aggregates. These mafic bands also contain the majority of the brown mica, opaque minerals and fine-grained plagioclase present in the rock. Deformation of pyroxene crystals is restricted to fracturing of individual grains and rare instances of subgrain formation (Fig. 4.4). Alteration of the pyroxene grains is not extensive, occurring only along grain boundaries and fractures. This alteration produces a fine intergrowth between chlorite and iron oxide.

Brown mica is a ubiquitous mineral in pyroxene diorite. It occurs as single flakes or small clusters of flakes with no preferred orientation, disseminated throughout the pyroxene-rich mafic bands. Mica flakes of up to 2mm in length occur among pyroxene grain but also occur sporadically between plagioclase grains. Deformation of the mica flakes (bending and

kinking of flakes, or splaying along cleavage planes) is fairly common (Fig. 4.3) These mica flakes are generally unaltered, except in samples from close to contacts with the country rocks where the mica is extensively altered to chlorite.

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Fig. 4.4

Subgrain development in a pyroxene grain in pyroxene diorite (Sample 172). Note the change in orientation of the cleavage at these boundaries and the offset of the cleavage at fractures.

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Quartz is a rare mineral in μ roxene diorite, except in samples which occur close to the country rocks. In the latter case, quartz exists as small (<1mm) grains associated with pyroxene and mica, and makes up as much as 5% of the rock by volume. Apatite is similarly an uncommon accessory mineral, occurring mainly in association with pyroxene, often poikilitically enclosed in the latter.

Of the opaque minerals, oxides (magnetite and ilmenite) dominate over sulphides (bornite, chalcopyrite and chalcocite), especially in the pyroxene leucodiorite. In the pyroxene diorite, oxides and sulphides may be present in roughly equal proportions. These opaque minerals are generally associated with the pyroxene-mica concentrations, but may occur interstitially to plagioclase grains. Furthermore, sulphides often occur within silicate gra. specially along cleavage planes of pyroxene and mica, but also within plagioclase. Where these opaques occur in association with pyroxene, they exist as large, irregular interstitial masses, often partially enclosing the silicate crystals (Fig. 4.5). Where the opaque minerals occur within silicate crystals, they are small polygonal grains, often developed along cleavage planes or fractures.

Magnetite and ilmenite form either independent grains, or occur as co-existing phases. Bornite and chalcopyrite commonly occur together, usually with bornite dominating. Independent chalcopyrite is uncommon, but bornite is commonly developed in the absence of chalcopyrite. In the latter case, bornite is often associated with magnetite. Chalcocite replaces bornite in several grains, especially at the margins of pure cornite grains, but also in bornite-chalcopyrite intergrowths. The contacts between sulphides and plagioclase are characterised by an alteration halo in which the plagioclase is altered to epidote (Fig. 4.6).

Contacts between oxides and all silicate phases are sharp and no reaction rims occur (Fig. 4.5). Similarly, sulphides show no reaction with silicates other than plagioclase.



Fig. 4.5

Relationship between orthopyroxene (OPX), sulphides (S) and oxides (OX) in pyroxene diorite (Sample 121). Note the interstitual and poikilitic nature of sulphide with respect to orthopyroxene.



Fig. 4.6 Sulphide grain in contact with silicates in pyroxene diorite (Sample 25). Note the alteration of the plagioclase (PL) to epidote (EP) in contact with the sulphide (S).

In one sample of pyroxene diorite, xenoliths of hornfels were observed. These fine-grained xenoliths, which are between 10mm and 20mm in diameter, are of the same mineralogy as pyroxene leucodiorite, although the small (<0.5mm) grains are equant and polygonal, and brown mica may be porphyroblastic. The contacts between these hornfels xenoliths and the host rock are sharp and well-defined (Fig. 4.7).



Fig. 4.7 Sharp contact of hornfels to medium- to coarse- grained pyroxene diorite (Sample 114). There is no mineralogical or textural change in either the hornfels xenolith or host pyroxene diorite towards this contact.

4.3 Granitic xenoliths

Several granitic xenoliths occur within the rocks of the Koperberg Suite at Jubilee (Section 2.3). Two of these xenoliths were sampled and show that although they are similar in grain size and texture, the mineralogies are not identical. Both xenoliths contain plagioclase

feldspar and quartz as major constituents; one xenolith (the western xenolith in the lower Transition Zone, Fig. 3.2) contains alkali feldspar as a major phase and amphibole as a minor phase. The other (eastern xenolith in the lower Transition Zone, Fig. 3.2) xeno(ith contains brown mica and amphibole as a minor phases.

Plagioclase makes up between 30% and 50% by volume of the granitic xenoliths, while alkali feldspar is present in modal proportions of between 15% and 30% in the alkali feldspar-rich xenolith. In the latter xenolith, quartz is present in modal proportions less than 20%; in the alkali feldspar-free xenolith, quartz makes up about 45% — the rock by volume. Amphibole and brown mica constitute the remainder of the major silicate fraction of the granite xenoliths. Pyroxene is present as an accessory mineral in the xenolith containing alkali feldspar. Zircon and apatite an uncommon accessory minerals, except in one sample (sample 20) where these minerals are common accessories. Opaque mineral grains, which make up not more than 1% in all samples, are represented exclusively by magnetite.

Plagioclase occurs in the granites as large (3-5mm) anhedral crystals with irregular grain margins, or as smaller grains interstitial to the larger crystals. Subhedral alkali feldspar grains are small (about 1mm in diameter) and mainly occur interstitially to large plagioclase grains. Irregular grains of quartz, often greater than 6mm in length, overgrow both feldspar phases.

Brown mica and amphibole occur in proportions that are less than 5% by volume of the respective rocks. These minerals exist as small flakes (0.5-1.5mm in length) which are interstitial to the feldspars. Amphibole (hornblende) flakes may form rims around alkali

feldspar in some cases (Fig. 4.8). Pyroxene was observed in one sample only and in this case, occurred as a small subhedral grain associated with amphibole.



Fig. 4.8 Amphibole (hornblende, HBL) flakes surrounding a microcline (KSP) grain in a graniti? xenolith (Sample 152). Note the tangential arrangement of amphibot flakes.

Deformation of the feldspar grains (and quartz to a lesser extent) is common. Fractures, bending or kinking of twin launellae and undulose extinction are common deformation features. Alteration (sericitisation) of the feldspars is also common particularly along grain boundaries and fractures, with entire grains sometimes being affected.

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-4 Summary

The sequence of intrusion of the Koperberg Suite at Jubilee has already been established (Chapter 3) to be anorthosite, mica diorite, pyroxene leucodiorite, and pyroxene diorite in terms of mineralogy, this sequence represents a general decrease in the proportion of quartz and plagioclase, and an increase in the proportions of pyroxene and opaque minerals in the rocks. Important from an economic viewpoint is the increase in the copper sulphide content of the rocks with time.

Attention is also drawn to the presence of the granitic xenoliths present in the rocks of the Koperberg Suite. In terms of petrography, these granites are distinct from the immediate country rocks as well as the stratigraphically lower Nababeep Gneiss. Later chapters will show that these granitic xenoliths are also chemically distinct from the country rocks.

Features such as deformation, recrystallisation and alteration of the rocks are not immediately obvious from field relationships. The presence or abundance of these features has been determined by petrographic investigation. Deformation features, especially in the plagioclase and mica crystals, are more common in the earlier intrusive phases. Although these features are also developed in the later phases, i.e. the pyroxene diorite, they are not as well developed.

The presence of recrystallised plagioclase as small, equant and polygonal grains developed between large plagioclase megacrysts has been noted. This feature is present in all rock types of the Koperberg Suite at Jubilee, but is more common in the anorthosite and mica diorite (i.e. the older rocks) than in the pyroxene diorite.

Althougi, the Jubilee orebody does not represent an extensively altered, as for example the Hoits ore body (Cawthorn & Meyer, 1992), some alteration is nevertheless present. Saussuritisation of the plagioclase-rich rocks is common, while chloritisation of brown mica is especially common in the older rocks. Although these alteration features are present in the younger phases too, they are less common or less well developed. Alteration of orthopyroxene to chlorite and iron oxide is fairly common in all pyroxene-bearing rocks, but is more common in the earlier intrusive phases.

Deformation, recrystallisation and alteration features of the rocks of the Koperberg Suite appear to be more common in the older rocks. Anorthosite and mica diorite are generally more deformed and altered than the later pyroxene diorite. The significance of this phenomenon will be discussed in a later chapter.

CHAPTER 5

MINERAL CHEMISTRY

5.1 Introduction

Quantitative chemic 1 analyses of the major constituent silicate and oxide phases of the Koperberg Suite rocks were carried out using a CAMECA-SX50 electron microprobe. Silicate mineral compositions were determined in twenty-two samples, while oxide compositions were determined in eight samples. Representative samples from each rock type in the Koperberg Suite at Jubilee were subjected to mineralogical analysis to determine compositional variations of the constituent minerals. These variations may shed light on the petrogenesis of the Koperberg Suite. All analyses are presented in Appendix A.

5.2 Silicates

In each sample, several grains of plagioclase, pyroxene and brown mice were analysed. Rims as well as cores were probed, but no consistent evidence for zoning could be found in any of the minerals. Due to the compositional homogeneity of the different silicate phases in each sample, analyses were averaged per sample for the purposes of illustration and discussion. From these results general trends can be discussed. Abbreviated tables of silicate analyses are presented in Tables 5.1 to 5.3.

5.2.1 Plagioclase

Plagioclase from twenty-one samples, representing all the Koperberg Suite rock types present at Jubilee (Chapter 3) were analysed. The results, averaged per sample, are presented in Table 5.1. Fig. 5.1 shows that for the Koperberg Suite, the An content of plagioclase varies between An_{31} and An_{48} . Anorthosite samples contain plagioclase grains with the lowest An content and the greatest variation, ranging from An_{31-41} . Plagioclase in mica diotite has a restricted compositional range (An_{39-43}), while plagioclase in pyroxene leucodiorite and pyroxene diorite has an intermediate spread in An values (An_{41-48}).

Plagioclase in the anorthosite and mica diorite may have a high potassium content compared to plagioclase in pyroxene leucodiorite and pyroxene diorite. This is illustrated by the variation in the Or content of anorthosite and mica diorite in Fig. 5.1. Two alkali feldspar exsolution lamellae, which are common in anorthosite and mica diorite, were analysed from a sample of anorthosite. These alkali feldspar lamellae have an orthoclase content of greater than 60; in one case it is as high as 90% (Fig. 5.1).

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Anythodie					M	n diorite	Pyraxea from set	Pyranene diordie from mer contacts			
Sample	134	150	16\$	21.5	145	167	125	186	198	23	222
sio,	57.67	58.84	60.01	58.06	57.47	57.07	57.08	56 ,77	56.68	56.29	57.06
A1,0,	26.29	25.33	24.61	25.7 3	26.53	26.61	26 .47	26.66	27.03	27.27	26.38
FeO'	0.08	0.09	0.10	0.08	0.96	0.07	0.06	0.06	0.06	0.14	0.09
CaÖ	8.31	7.31	6.48	7.53	8.50	8.49	8.16	8.77	8,92	9.35	8.47
BaO	0.01	0.01	0.01	0.07	0.03	0.02	0,0¢	0.03	0.03	0.03	0.02
Na ₂ O	6.57	7.05	7.59	6.29	6.37	6.28	6.35	6.25	6,24	5.94	6.38
K,O	0.32	0.46	0.41	1.25	0.43	0.38	0.75	. 0.31	v.30	0.26	0.36
Total	99.29	99.11	99.23	99,98	99.44	98.95	98,9 3	98.86	99.30	99.31	98.80
				-							
¢	40.4	35.5	31.3	36.8	41.A	41.8	39.7	42.9	43.3	45.8	41.4
Ab	\$7.7	61.9	66.3	55 7	56.1	55.9	55.9	55.3	54.9	52.7	\$6 .5
Or	1.9	2.7	2.3	2.5	2.5	.2	4.3	1.8	1.8	1.5	2.1
	Pyroxene leacodiorite							-			
Sample	42	50	 	64	192	56	102	111	113	122	_
SiO ₂	55.52	55.78	55.14	54.27	56.00	56.32	56.56	56,88	53.48	55.88	
ALO.	77 41	27.66	27 27	26.28	27 19	27 33	77 75	26.04	70 14	57 AS	Î

 Table 5.1 Summary of microprobe analyses of Koperberg Suite plagioclase at Jubilee.

	Pyroxene leacodiorite					Pyrozene diorite				
Sample	42	50	动	64	192	56	102	111	113	122
510 ₁	55.52	55.78	55.14	54.27	56.00	56.32	56.56	56,88	53,48	55.88
АĻО,	27.41	27.66	27.37	26.28	27.18	27.33	27.25	26.94	29,14	27.68
FeO'	0.14	0.12	0.21	0.11	0.12	0.11	9.12	0.13	0.10	0.14
C#0	9.34	9,64	9.47	8.34	9,39	8,96	9.18	8.97	11.29	9,75
BaO	0,03	0.92	0.03	0.01	0.03	0.04	0.02	0.01	0.02	0.03
Na _i O	5.80	5.83	5,02	6.36	5.85	6.21	6.15	6.10	5.01	5,69
K20	0,41	0.28	0.46	0.52	0.36	0.31	0.21	0.42	0.23	6.31
Totai	98.77	99,35	98.52	98,84	98 .96	99.30	99. 52	99.4 7	91.30	99,52
	1	11 0				1		<i></i>		
An	45.6	47.0	46.1	40.7	46,0	43.6	44,5	43.7	45.5	47.7
Ab	52.0	51.4	51.2	56.2	51.9	54.7	54.1	53.8	52.7	50.5
Or	2.4	1.6	2.7	2.1	2.1	1.7	1.3	2.5	1.8	1.8

FcO' = Total Fe as PoO

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Fig. 5.1 Composition of plagioclase and alkali feldspar from the Koperberg Suite at Jubilee, plotted in the feldspar ternary diagram.

The BaO content of plagioclase is very low throughout the Koperberg Suite (typically <0.05% by weight). The FeO⁽²⁾ (total Fe as FeO) content of plagicclase is generally weakly dependent on the An content and ranges from 0.02% to 0.2% by weight (Fig. 5.2).

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Fig. 5.2 Plot of total Fe as FeO (wt%) vs. %An in plagioclase.

5.2.2 Pyroxene

Orthopyroxene was analysed in 14 samples, representing all pyroxene-bearing rock types of the Koperberg Suite at Jubilee. These analyses, averaged per sample are presented in Table 5.2, and the composition of the pyroxene is illustrated in Fig. 5.3.

The enstatite content of pyroxene crystals in rocks of the Jubilee pit varies from $En_{57.7}$ to $En_{55.5}$. This small range in pyroxene composition indicates that pyroxene is remarkably homogenous throughout the samples from Jubilee. Despite the apparent homogeneity of the pyroxene and despite the small sample population size, there appears to be a correlation between the En content of pyroxene and the rock type.

Figure 5.3 shows that the pyroxene in pyroxene diorite is consistently higher in enstatite (about En_{65}) and varies only slightly. Two pyroxene diorite samples, which were taken from close to the contacts with Concordia Granite country rock, contain pyroxene of composition En_{59} . As will be shown in Chapter 6, the latter rocks are also distinct from the rest of the pyroxene diorite samples in having significantly different whole rock compositions.

- Mica diorite
- Pyroxene ieucodiorite

+ Pyroxene diorite



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Pyroxene leucodiorite samples also have a high En content $(En_{61.64})$, but lower than for pyroxene diorite, and the former also shows more scatter in Fig. 5.3. Fig. 5.3 shows that pyroxene grains from two mica diorite samples have a large range in composition $(En_{63}-En_{57})$. From the above discussion and from Fig. 5.3, it can be concluded that there is a correlation between the proportion of ferromagnesian minerals and the pyroxene composition.

The Cr_2O_3 content in pyroxene varies slightly according to rock type at Jubilee. Pyroxene from pyroxene diorite samples have a Cr_2O_3 content between 0.05% and 0.2%, which is distinctly higher than the Cr_2O_3 content of pyroxene from pyroxene levodiorite and mica diorite ($\leq 0.05\%$). There is a positive correlation between the Cr content in pyroxene and the En content in pyroxene (Fig. 5.4a). This relationship, however, does not hold for the pyroxene diorite samples taken from close to the contact with the Concordia Granite country rock. In these latter samples, the En values are lower than in other pyroxene diorite samples (as noted above), but the Cr content remains unaffected regardless of the proximity to the contact with country rocks.

The NiO content of pyroxene grains analysed is independent of the rock type (Fig. 5.4b) and NiO contents in pyroxene are all $\leq 0.1\%$. Ni content is also independent of the En content. Ti content in pyroxene is similarly independent of both rock type and En content in pyroxene (Fig. 5.4c). TiO₂ content in pyroxene ranges between $\geq 0.05\%$ and $\leq 0.15\%$.

Table 5.2 Summary of microprobe analyses of Koperborg Suite pyroxene at Jubilee. (* denotes those pyroxene diorite simple taken from close to the contacts with Concordia Granitc). (FeO* = Total Fe as FeO).

	Mica dio)rite]	Pyroxene k	eucodiorite			
	145	185	42	50	53	64	192	
SiOz	51.28	49.78	51.12	° 51.72	51.25	51.13	51.40	
TiO ₂	0.10	0.11	0.09	0.09	0.09	0.09	0.09	
AhO3	2.18	2.65	1.92	1.60	1.74	1.93	1.92	
Cr ₂ O ₃	0.01	0.00	0.02	0.02	0.02	0.01	0.02	
FeO*	22.82	23.81	22.22	23.18	22.35	23.40	23.22	
MaO	1.19	1.23	0.55	0.50	0.51	0.84	0.63	
MgO	21.56	20.59	22.64	21.63	22.62	21.18	21.42	
NIO	0.02	0.01	0.06	0.06	0.06	0.00	0.05	
CaO	0.37	0.30	0.47	0.59	0.54	0.42	0.39	
Na ₂ O	0.02	0.01	0.02	0.01	0.01	0.01	0.00	
TOTAL	99.55	98.49	99.11	99.40	99.19	99.06	99.14	
En	62.3	57.8	63.6	61.7	63.5	61.2	61.7	
Fs	37.0	37.5	35.0	37.1	35.2	37.9	37.5	
Wo	0.7	9.7	0.9	1.2	1.1	0.9	0.8	
			Pyroxen	e diorize				
	234	56	102	111	113	122	222*	
SiO ₂	50.85	51.65	51.96	51.90	51.25	51.97	50,84	
TiO ₂	0.07	0.08	0.08	0.08	0.10	80.0	0.08	
AL ₂ O ₃	2.07	1.54	1.89	2.00	1.78	1.63	1.96	
Cr ₂ O ₃	0.08	0.11	0.11	0.11	0.14	0.15	0.09	
FeO*	24.20	21.36	21,38	21.76	21.61	21.20	24.07	
MnO	1.01	0.55	0.53	0.57	0.56	0.57	0.78	
MgO	20.34	23.32	22.97	22.65	22.96	23.04	20.64	
NiO	0.04	0.05	0.05	0.06	0.07	0.07	0.06	
CaO	0.47	0.43	0.51	0.43	0.53	0.50	0.48	
Na ₂ O	0.02	0.01	0.01	0.02	0.01	0.00	0.02	
TOTAL	99.05	99.10	99.49	99.58	99.01	99.21	99.02	
En	59.4	65.5	65.0	64.4	64.8	65.3	59.9	
Fs	36.6	33.7	34.0	37.7	34,2	33.7	39.1	
Wo	1.0	0.8	1.0	0.9	1.0	1.0	1.0	

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Fig. 5.4

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Fig. 5.4 (contd.) c) Plot of wt. % TiO₂ vs. %En in pyroxene,

5.2.3 Brown mica

Brown mica was analysed in eleven Koperberg Suite samples (Table 5.3). Mica occurs in anorthosite, but due to extensive chloritisation, no analyses were carried out on these grains.

Fig. 5.5 illustrates that the brown mica grains analysed from pyroxene leucodiorite and pyroxene diorite have Mg:Fe atomic ratios which are higher than 2:1 and plot in the phlogopite field. Analyses from mica diorite generally have lower Mg:Fe atomic ratios and

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plot in the biotite field of Fig. 5.5, although one sample plots in the phlogopite field. Another trend that emerges from Fig. 5.5 is that there is a correlation between the Al content of the mica and the rock type. The Al:(Mg+Fe) atomic ratio increases from pyroxene diorite to pyroxene leucodiorite and is highest in mica diorite.

The TiO₂ content in the brown mica is higher in mica diorite samples (>5.5%) than in pyroxene-rich samples (2-4.5%). Fig. 5.6a illustrates that there exists a negative relationship between the Ti content and the Mg content in the brown mica.

The Ba content in brown mica varies according to the rock type. In pyroxene diorite, the Ba content ranges from 0.1% to 0.3%, with samples taken from close to the country rocks occupying the lower end of the range. The BaO content in mica increases from pyroxene diorite to mica diorite, the latter rock type containing between 0.3% and 0.7% BaO. There is a negative correlation between Ba and Mg (Fig. 5.6b).

 Cr_2O_3 content in mica ranges from <0.05% to 0.45% (Fig. 5.6c). There is a distinct difference in the Cr content of mica from the different rock types. NiO contents in mica increase from mica diorite to pyroxene diorite. Figs. 5.6c and 5.6d show that there is a gradual increase in Cr and Ni content with increasing MgO content, although the increase in Cr content in the pyroxene diorite appears to be exponential. The pyroxene diorite samples further away from the Concordia Granite have the highest Cr_2O_3 and NiO contents.

The increasing BaO and TiO₂ contents and the decreasing NiO and Cr_2O_3 contents with increasing MgO content are all consistent with the predicted behaviour of these elements in terms of their known behaviour during fractional crystallisation.



Fig. 5.5 Composition of brown mica from Jubilee, plotted in the biotite-phlogopite reciprocal

binary diagram.

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 Table 5.3 Summary of microprobe analyses of Koperberg Suite brown mica at Jubilee.

 (denotes those pyroxene diorite sample taken from close to the contacts with Concordia Granite).

		»Sce diotite		· · · · · · · · · · · · · · · · · · ·	Pyraxene	leacodiarite	
1. j.	145	167	126	198	59	192	
SiO ,	37.28	36.71	36.87	37.21	37.57	37.27	
тю,	4.83	4.74	5.17	4.90	5.00	3.98	
ALO,	14.10	13.89	14.18	14.15	13.64	13.50	
Cr ₂ O ₁	0.02	0.91	0.00	0.00	0.09	0.06	
FeO'	12.77	14.57	14.05	13.77	13,10	14.43	
MaO .	0.16	0.07	0.20	0 14	0.04	0.20	
MeO	15.30	14.07	14.29	14.75	15.77	15.01	
NIO	0.02	0.00	0.02	0.03	0.17	0.12	
BeO .	<i>©.</i> 74	0.61	0.39	0.38	0.30	0.51	
K _t O	9.76	9.58	9.64	9,81	9.54	9.65	
NazO	C 05	9,13	0.12	9.11	3,08	0.03	
Total	94.75	94.38	94.84	95.25	95.32	\$4.66	
AJ/Mg+Fe	0.50	0.49	0,51%	0.45	0.47	0.47	
Mg/Mg+Fe	0.66	0.63	0.65	0.66	0.58	0.65	
	·; ·			· .	1	· .	
		· ~ ."	Pyrozene dio	rtie	ا ب		
	23*	182	- 116	122	222*	·	
iO,	38.55	38.14	38.08	38.67	38.35	فاطلعل وسعرصان بالاستجم بالصادك المستهجيني	
10,	2.72	4.22	3.79	3.74	3.43	1. juli - 1. jul	
J,O,	13.38	13.63	13.75	13.58	13.24		
Cr ₁ O,	0.14	0.37	0.41	0:38	0.24	7) 	
60	10.92	10.07	10.60	9.58	11.30		
(InO	0.10	0.05	0.04	0.05	0.09		
/gO	18.54	18.15	17.95	18.97	18.04		
40	0.07	0.21	0.15	0.19	0.12		
le Ö	0.15	0.18	9.27	0,27	0.12		
çó	9.53	9.34	9.75	9,55	9.70		
la ₂ O	0.06	0.14	0,08	0.07	0.09		
iutal	24.17	\$4.52	94,52	95.05	94.72		
\1/Mg +Fe	0.43	0.46	0.46	0.44	0 43		
	0.74	0.76	0.74	0.74	0.76		



Fig. 5.6 a) Plot of wt. % TiO_2 vs. Mg/Mg + Fe in mica. b) Plot of wt. % BaO vs. Mg/Mg + Fe in mica.



c)

d)

Fig. 5.6 (contd.) c) Plot of wt. % Cr_2O_3 vs. Mg/Mg + Fe in mica. d) Plot of wt. % NiO vs. Mg/Mg + Fe in mica.

As described in Chapter 4, magnetite and ilmenite make up variable proportions of the Koperberg Suite at Jubilee. It was further noted that magnetite may occur with or without ilmenite exsolution. Microprobe data can not illustrate the presence or absence of these ilmenite exsolution lamellae in magnetite, since the microprobe beam (2μ) can analyse only either the exsolution or the host. By using the microprobe, however, ilmenite exsolution in magnetite was identified on a scale that was not possible using optical techniques.

5.3.1 Magnetite

Magnetite grains were analysed in eight samples (Table 5.4a). As can be seen from a plot of Fe₂O₃ vs. FeO in magnetite (Fig 5.7), magnetite from different rock types has disonctly different compositions. Fig. 5.7 either illustrates that magnetite compositions from mica diorite and pyroxene leucodiorite are fairly uniform in composition within a particular rock type.

The magnetite analysed from mica diorite most closely resembles the theoretical magnetite end-member (Fig 5.7). Compared to the theoretical composition of magnetite (FeO=31.03%, $Fe_2O_3=68.97\%$, total Fe=100%), magnetite grains from mica diorite have slightly higher FeO contents and slightly lower Fe₂O₃ contents. Magnetite grains from pyroxene leucodiorite have similar compositions to

	Mica diorite		Pyroxene	Pyroxene leucodiorite Pyro sans			tene diorite (sversge per le)		
	185	186	42	53	207	56	113	122	
no,	0.13	0.02	0.15	0.15	0.06	0.62	0.54	0.71	
Al ₂ O ₃	0.16	0.04	0.30	0.31	0.32	1.19	1.53	2.24	
Cr ₂ O ₃	0.03	.D.CJ	1.41	1.42	1.43	6.12	8.10	8.84	
FeO*	93.SA	93,25	90.96	91.31	91,04	85.17	82.92	81.21	
MnO	0.03	0.04	0.05	C.04	0.06	0.18	0.32	0.36	
MgO	0.00	0.00	0.01	C 00	0.00	0.02	0.02	0.04	
V ₂ O _f	0.66	0.48	0.97	1.97	1.01	0.70	0.98	0.91	
Total	94.02	93.86	93.84	ં પ્રક્ર	ý 93,92	94.01	94,41	94.31	
Recalcul	Recalculated analyses								
Fe ₂ O ₃	68.44	68.90	66.25		39	59.44	57.00	54.96	
FeO	31.43	31.26	31.35	31.52		31.69	31.63	31.76	
Total	100.88	100.77	100.48	100.96	297.58	99.97	100.12	99.8 1	

 Table 5.4a) Summary of microprobe analyses of Koperberg Suite magnetites from Jubilee.

FeO' = Total Fe as FeO

 Table 5.4b) Examples of individual microprobe analyses of magnetite from pyroxene diorite to illustrate different magnetite compositions.

	TIO,- and FeO-poor magnetite				TiO ₂ - and Fe 3-rich magnetite			
	56MA	113M1	122MB	1 22M 7	56MB2	113M2	122MA	122MC2
TiO ₂	0.23	0.34	0.25	0.26	1.62	2.08	0.91	1.42
Al ₂ O ₃	0,95	1.76	1.90	2.05	136 -	1.61	2.13	2.89
Cr ₂ O ₃	6,62	8.07	8,73	9.22	5,35	8.37	8.75	8.65
FeO*	85.18	82.42	61.43	81.71	85.12	80,78	81.82	79.89
MnO	0.15	0.37	0.33	0.37	0.24	0.49	0.38	0.36
MgO	C.03	0.00	0.02	0.04	0.01	0.05	0.03	0.06
V ₂ O ₅	0.72	1.10	0.93	0.85	0.72	0.94	0.88	0.98
Total	93.88	94.06	93.58	94.50	94,41	94,32	94.90	94.24
							. •	
Recaiculat	ied analyse	s .						
Fe ₂ O ₃	59.89	56.75	55.89	55.91	58.26	53,41	55.25	52.77
FeO	31.30	31.36	31.13	31.40	32.70	32.72	32.11	32.40
Total	99.88	99.75	99.18	100.10	100.25	99.67	100.44	99.53

FeO = Total Fe as FeO

the magnetite grains from mica diorite, although magnetite from pyroxene leucodiorite have slightly lower Fe_2O_3 contents. Magnetite grains from pyroxene diorite have a much more varied composition (Table 5.4b). These deviations from the end-member compositions are the result of the inclusion of elements such as Cr, V, Mn, and Al in the composition of the mineral.

Magnetite grains from pyroxene diorite fall into two distinct populations, based on their FeO content. In the one population, the magnetite has a FeO content that varies from 31% to 31.5%, while in the other population, the magnetic has FeO contents well above 32%.



Fig. 5.7 Plot of Fe₂O₃ vs. FeO in magnetite calculated assuming perfect stoichiometry.

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Fig. 5.8 a) Plot of wt. % Cr₂O₃' vs. wt. % FeO in magnetite. b) Plot of wt. % Al₂O₃' vs. wt. % FeO in magnetite.

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b)

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Fig. 5.8 (contd.) c) Plot of wt. % V₂O₅ vs. wt. % FeO in magnetite. d) Plot of wt. % MnO vs. wt. % FeO in magnetite.

Fig. 5.) illustrates that these two distinct populations of magnetite may also be identified from the TiO₂ content. There two distinctly different magnetite; one has a low (<0.5%) TiO₂ content, while the other has a higher than average TiO₂ content (1%-2%). Those Ti-rich analy es correspond to those analyses with high FeO contents. It is of importance to note that several samples of pyroxene diorite contain magnetite from **both** populations. Note that only pyrokene diorite contains these TiO₂-rich magnetite grains.



Fig. 5.9 Plot of wt. % TiO₂ vs. wt. %Fe0 in magnetite.

 Cr_2O_3 contents in magnetite grains from pyroxene diorite can be as high as 9.5% (Fig. 5.8a). This high Cr content in magnetite is the principal cause for the low Fe₂O₃ contents in those grains. There are other factors which also contribute to the low Fe₂O₃ content, namely the high Al₂O₃, V₂O₅ and MnO contents (Figs. 5.8b, 5.8c & 5.8d).

The magnetite grains from pyroxene leucodiorite also contain a significant proportion of

 Cr_2O_3 ($\pm 1.5\%$) although this is much lower than the Cr content in magnetite from pyroxene diorite. Magnetite from mica diorite contains no Cr, and Al_2O_3 contents in magnetite from pyroxene leucodiorite and mica diorite are low (<0.5%).

5.3.2 Ilmenite

Six ilmenite exsolution lamellae were analysed from five samples (Table 5.5). Fig. 5.10 illustrates that the ilmenite compositions vary, but due to the small database, these variations can not confidently be attributed to different rock types. Consequently, only broad trends can be described which may prove to be inaccurate if the database is increased.

The theoretical end-member composition of ilmenite is FeO=47.3%, $TiO_2=52.7\%$, $FeO \rightarrow TiO_2=100\%$. As can be seen from Fig. 5.10, three ilmenite samples (two from pyroxene diorite and one from pyroxene leucodiorite) tend towards that composition. The substitution of Mn and Fe³⁺ for Fe²⁺ is mainly responsible for the deviations from end-member ilmenite (Fig. 5.11).

Mica diorite		Pyroxene	leucodior de		Pyroxene	diorite
•	185M1A	42M1B	207M1A	207M3A	56MB1	122MC1
TiO ₁	51.41	49.24	48.70	59,59	51.39	51.59
Al ₂ O ₅	0.03	0.04	0.01	0.03	0.00	0.02
Cr ₂ O ₃	0.01	0.15	0.10	0.14	0.25	0.45
FeO*	41.37	47.48	47.05	44.01	46.50	44.02
MnO	7.31	2.69	2.89	4.14	1.96	4.14
MgO	0.00	0.13	0.17	0.06	0.21	0.02
V205	0.00	0.11	0.45	0.00	0.00	0.00
Total	100.14	99.82	99.37	100.95	109.31	100.25
Recalcul	ated analyse	5	:			
Fe ₂ O ₃	2.83	6.82	7.20	1.13	2.94	2.08
FeO	38.82	41.35	40.57	42.99	43.85	42.16
Total	100.42 100.50 100.09 101.07 100.60		100.46			

 Table 5.5 Summary of microprobe analyses of Koperberg Suite ilmenite at Jubilee.

FeO' = Total I'e as FeO

The same substitutions are responsible for the compositions of the remaining ilmenite grains. U The illuenite exsolution analysed in mica diorite contairs 7.3% MrO (Table 5.5), while the two illuenite analyses from pyroxene leucodiorite which have lower FeO contents, contain $\pm 7\%$ Fe₂O₃ (Table 5.5). Ilmenite grains were also analysed for other substituting elements (Table 5.5), but these are insignificant.



Fig. 5.10 Plot of wt. % TiO₂ vs. FeO in ilmenite.

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Fig. 5.11a) Plot of wt. %MnO vs. wt. %FeO in ilmenite. b) Plot of wt. %Fe₂O₃ vs. wt. %FeO in ilmenite.

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5.4 Summary

From the above observations, it is clear that the silicate and oxide mineral compositions vary according to the mineralogy of the rock. This trend is especially apparent in the variation in composition of pyroxene and brown mica. In these cases, the rocks which have a higher ferromagnesian proportions, consist of minerals which are higher in magnesium content and, in the case of micas, are lower in aluminium. The compositional variation in plagioclase does not illustrate this trend clearly, although there is a general increase in calcium content in plagioclase with increasing ferromagnesian mineral content. Similarly, the rocks which have a higher in Fe₂O₃, but substantially richer in Cr_2O_3 .

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It is further evident from the data presented in this chapter that the intrusive suite of rocks interacted chemically with the country rocks, at least on a limited scale at Koperberg Suite - Concordia contacts. Mineral analyses indicate that samples from the same intrusive phase vary according to their proximity to the country rocks.

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CHAPTER 6

WHOLE-ROCK GEOCHEMISTRY

6.1 Introduction

Quantitative whole-rock chemical analyses were undertaken on samples from the Koperberg Suite at Jubilee to determine the petrochemical characteristics of these rocks. Samples of each of the rock types of the Koverberg Suite, as distinguished in Chapter 2, were analysed.

Over 150 samples were analysed by XRF (X-Ray Fluorescence) for major and selected trace elements. A summary of the average compositions for each of the different rock types of the Koperberg Suite is given in Table 6.1. Average compositions of the granitic rock types are given in Table 6.3. In addition, 26 samples were analysed by titration for ferrous iron content, permitting the calculation of ferric iron contents. A summary of the Fe₂O₃ and FeO contents is presented in Table 6.2. Complete analyses are presented in the Appendix.

Rb-Sr isotopic analyses were carried out by mass spectrometry on 15 samples of the Koperberg Suite. Table 6.4 presents mese data as well as initial ⁸⁷Sr/⁸⁶Sr ratios calculated for a model age of 1030Ma.

6.2 Koperberg Suite

6.2.1 Major elements

Major element abundances are displayed graphically in the form of Harker diagrams in Figs. 6.1 and 6.2. Ferrous and ferric iron contents are displayed in Fig. 6.3 and are discussed in a later section. From the data presented, general trends and compositional variation between the rock types can be discerned.



Fig. 6.1 Selected major element binary plots for the Jubilee samples.



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Fig. 6.2 Plc⁺ of Al₂O₃ vs. SiO₂ for the whole rock analyses of the Koperberg Suite. Major constituent mineral chemistry is also indicated. The populations An, Mdi, LDi-A, LDi-B, PDi-A and PDi-B are discussed in the text.

Each of the Harker diagrams in Fig. 6.1 can be explained by considering the rock types as being co-accumulations of the minerals orthopyroxene, plagioclase, mica, quartz, oxides and sulphides. The plot of Al_2O_3 vs. SiO₂ (Fig. 6.2) shows this principle clearly. In this diagram, the compositions of the constituent minerals, as determined by microprobe analyses (Chapter 5), are plotted together with the whole rock analyses.

Anorthosite

As discussed in Chapter 4, anorthosite at Jubilee consists of plagioclase and quartz and a small proportion of chloritised mica. Fig. 6.2 illustrates clearly that the anorthosite population (An) falls close to the plagioclase-quartz mixing line. The slight off-set from this mixing line is due to the presence of mica and accessory minerals.

Mica diorite

The mica diorite population in Fig. 6.2 (Mdi) falls close to the mixing line between plagioclase and mica. The presence of orthopyroxene, oxides, sulphides and accessory minerals causes the mica diorite population to plot as a scattered group rather than on the plagioclase-mica mixing line.

Pyroxene leucodiorite

Two distinct pyroxene leucodiorite populations can be identified in the Harker diagrams (Fig. 6.1). These populations are especially well illustrated in the plot of MgO vs. Si O_2 , as well as in the plot of Al₂O₃ vs. SiO₂ (Fig. 6.2). In Fig. 6.2, these populations have been labelled LDi-A and Ldi-B. Population Ldi-A represents pyroxene leucodiorite samples from the homogenous mass on the western face of the Jubilee pit (Fig. 3.1). These samples are remarkable in their whole-rock geochemical consistency, forming a well-defined and restricted population in the Harker plots of Fig. 6.1 (especially the plots of MgO vs. SiO₂ and Al₂O₃ vs. SiO₂). The chemistry of this population indicates a fairly consistent proportion of mixing between plagioclase, mica and pyroxene.

Population LDi-B (Fig. 6.2) represents the various pyroxene leucociorite xenoliths which occur in the northern face of the Jubilee pit (Fig. 3.2). The chemistry of this population is more variable, reflecting the variable proportions of the constituent minerals. Fig. 6.2 further illustrates that the whole-rock major element chemistry of the LDi-B population is a product mainly of plagioclase-mica mixing, with a lower proportion of pyroxene than the LDi-A population. This in contrast to the population of pyroxene leucodiorite from the western face (population LDi-A in Fig. 6.2) in which the chemistry is a product of mainly plagioclase-pyroxene mixing, with a minor mica influence.

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		Anorthosite	.4		a	0
Sample	19	136	150	168	170	Average
SłO ₂	62.11	56.77	74.48	59.09	59.28	64.01
TIO,	0.08	0.27	0.19	0.04	0.04	0.13
Al ₂ O ₃	22.56	20.03	13.98	24.49	24.56	20.78
Fe ₂ O ₃	1.39	5.25	1.82	0.36	0.41	1.85
MnO	0.03	0.05	0.01	0.01	0.02	0.02
MgO	0.40	0.88	0.00	0.00	0.00	0.20
CaO [°]	6.59	6.64	3.51.	5.69	5.06	5.84
Na ₂ O	4.99	5.01	3.50	7.74	7.81	5.06
К,0	0.93	0.93	1.00	1.36	1.37	0,98
P ₁ O _f	0.03	0.12	0.00	0.02	0.03	0.02
Cu	0.01	0.18	0.00	0.00	0.03	0.02
\$	0.00	0.89	0.00	0.00	0.00	0.04
LOI	0.63	2.24	0.68	0.67	1.17	0.66
TOTAL	99.76	99.24	99,16	99.46	99.77	99.62
Co	5	16	6	6	5	7
Ni	3	35	Û	2	2	5
Zn	24	78	24	15	16	31
Rb	9	44	28	32	39	22
Sr	607	772	454	376	415	565
¥	3	62	3	20	18	10
Zr	80	97	92	17	183	81
Nb	1	3	5	3	3	3
V .	26	69	47	6	4	36
Cr	18	3	14 👘	3	6	18
Ba	230	294	272	190	251	262

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Table 6.1 Representative whole-rock analyses for the Koperberg Suite samples.

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1		Mica Dio	rite				
Sample	28	145	167	186	195	Average	
SEO2	50.28	51.15	50.56	47.90	48.07	51.07	
TiO,	1.01	1.01	0.84	1.19	1.19	1.02	
Al ₂ O,	22.28	22.69	23.32	22.17	21.77	22.07	
Fe ₂ O ₂	9.29	9.00	7.14	10.61	10.46	9 ,08	
MnO	0.06	0.07	0.04	0.07	0.05	0.07	
MgO	2.67	2.13	1.83	2.99	2.96	2.40	
CaO	5.57	6.83	7.24	5,82	5,53	6.20	•
Na ₂ O	4.20	4.41	6.85	4,34	5.62	5.01	
K,0	1.88	1.56	1.83	2.59	1.66	1.86	
P ₂ O ₃	0.47	0.02	0.40	0.02	0.03	0.10	
Cu	0.05	0.00	0.10	0.01	0.06	0.04	
S .	0.01	0.01	0.04	0.00	0.00	0.02	
1.01	1.26	0.43	0.72	1.45	1.48	0.76	
TOTAL	99.02	99.31	100.89	99.16	98,88	99. 74	
Co	15	19	18	27	28	22	
Ni	16	26	14	38	44	30	
Zn	115	118	125	147	121	123	
Rb	119	97	102	180	117	122	
Sr	698	594	1166	787	706	707	
Y	58	10	16	13	12	21	
Zr	1061	64	829	88	82	223	
Nb	13	14	9	24	21	18	
v	176	218	217	333	318	250	
Cr	31	9	5	3	1	3	
Ba	725	827	1314	1192	754	861	

· /} -	Pyroxese Lescodiorite					
Sem	42	53	64	206	207	Average
SiO ₂	48.72	49,37	50.88	52.27	51.72	49.99
TiO ₂	0.41	0.40	0.52	0.63	0.32	0.40
AL ₂ O ₃	15.91	17.56	21.28	22.29	19.86	18.61
Fe ₂ O ₃	14.64	12.78	11.59	6.56	9.60	11.79
MaO	0,19	0.16	0.14	0.05	0.13	0.16
MgO	8.35	7.14	2.66	1.72	5,10	5.78
CaO	5.42	6.11	6.85	7.65	6.91	6.15
Na ₂ O	3.05	3.22	5.10	4.69	3.68	3.96
K ₂ O	0.60	0.59	0.81	1.49	0.73	0.71
P ₂ O ₅	0.09	0.09	0.04	0.29	0.05	0.08
Cu	1.66	1.28	0.06	0.24	0.66	0.95
S	0.57	0.46	0.11	0.10	0,24	0.31
LOI	0.03	0.20	0,07	0.65	0.15	0.66
TOTAL	99.63	99.37	100.10	98.61	99.14	99,56
Co	61	51	27	23	30	42
Ni	267	215	58	41	134	174
Za	239	1 92	137	96	143	177
Rb	18	16	10	92	22	27
Sr	688	765	673	884	827	730
¥	12	10	11	32	14	14
Zr	16	13	9	136	16	30
Nb	3	3	4	11	4	4
v	325	294	275	220	189	253
Cr	591	488	21	55	306	367
Ba	241	264	199	542	285	256
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			Pyroxene	Diorite			
Sample	23	99	102	111	218	Average	
SiO ₂	51.72	49.20	49.11	48.78	51.26	48.93	
тю,	0.56	0.36	0.28	0.28	0.29	0.31	
Al ₂ O ₃	12.46	14,54	11.20	10.84	15.66	12.49	
Fe ₂ O ₂	14.08	14.79	16.82	16.60	12.45	15.17	
MaO	0.27	0.24	0.30	0.32	0.20	0.29	
MgO	8.92	9.47	13.25	13.50	8.57	11.56	
CaO	3.12	4.58	3.79	3,44	4.72	4.05	
Na ₂ O	2.53	1.81	1.79	1.89	2.58	2.42	
K,0	1,78	0.65	0.48	0.47	0.85	0.62	
P ₂ O ₅	0.18	0.07	0.14	0.19	0.04	0.12	
Cu	0,53	2.87	2.26	1.16	2.07	2.03	
8	0.32	0.94	0.81	0.43	0.76	0.71	
LOI	2.92	0.96	0.12	0.999	0.24	0.57	
TOTAL	99.38	100.47	100.37	98.88	99.69	99.28	
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Co	50	63	75	80	46	71	
Ni	233	410	457	419	325	412	
Za	272	244	264	321	188	262	
Rb	203	46	46	42	74	54	
Sr	349	604	476	399	566	479	
¥	70	22	42	62	37	37	
Zr	21	21	22	19	37	41	
Nb	31	6	7	9	10	8	
V	157	208	185	212	155	178	
Cr	909	1755	1568	1363	1109	1357	
Ba	367	216	177	191	233	208	

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Petrographic studies of these samples (Chapter 4) do not reveal a significant difference in the proportions of mica and pyroxene in these two populations. However, since many of the pyroxene leucodiorite samples are very rich in plagioclase, the proportions of mica and pyroxene are very small in these samples. Hence, the relative proportions of these minerals are very sensitive to error and the petrographic analyses without point-counting may not be able to detect these proportions accurately enough.

Pyroxene diorite

Pyroxene diorite samples have a varied chemistry which reflects the local heterogeneities in mineralogy described in Chapter 3. Nevertheless, the whole-rock geochemistry of pyroxene diorite is distinctive from the rest of the Koperberg Suite, due to its comparatively low Al_2O_3 , CaO, K_2O_3 , Sr and TiO₂ contents, and high MgO and Fe₂O₃⁽¹⁾ contents.

Fig. 6.2 illustrates this variation in whole-rock chemistry clearly. Furthermore, this figure suggests a mineralogical explanation for this variation. The chemistry of most of the pyroxene diorite samples is the result of mainly plagiocluse-pyroxene mixing, with little mica influence. Several pyroxene diorite samples (population PDi-B in Fig. 6.2), however, appear to contain a much larger proportion of mica, and are the product mainly of pyroxene-mica mixing, with little plagioclase influence. These mica-rich samples were collected from zones in the pyroxene diorite in which several xenoliths of earlier intrusive phases occur. Several samples from the PDi-A population (Fig. 6.2) were also collected from these xenolith-rich zones, although most of the samples from this population were collected from more homogenous pyroxene diorite zones. During sampling, care was taken to avoid the xenoliths, but it is possible that these mica-rich samples represent xenoliths which are indistinct from the pyroxene diorite host.

Fig. 6.2 indicates that several samples fall close to the mica-orthopyroxene mixing line. This is due to the high proportion of oxides and sulphides in these samples and does not mean implies that these samples consist only of these two minerals and that plagioclase is absent.

The chemistry of oxides (Chapter 5) and sulphides are not plotted on Fig. 6.2, but the proportions of these minerals are larger in pyroxene diorite than in other rock types (Chapter

4). Therefore, they play a greater role in the whole-rock geochemistry of pyroxene diorite than in other rock types. This can be i^{μ} strated by regarding the pyroxene diorite samples that fall on or close to the mica-pyroxene mixing line in Fig. 6.2. Petrographic studies (Chapter 4) indicate that no samples taken from Jubilee consist only of mica and pyroxene, and that plagioclase is always present. The fact that these samples fall on the micaorthopyroxene mixing line is due to the effect of the high proportion of oxides and sulphides in these sample. The presence of the oxides and sulphides decreases the SiO₂ and Al₂O₅ in the rock and hence, the samples that contain more oxides and sulphides plot further from the plagioclase composition in Fig. 6.2 and, hence, appear to contain little or no plagioclase.

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6.2.2 FeO:Fe₂O₃ Ratio

The presence of Fe-Ti oxides, Cu-Fe sulphides, orthopyroxene and brown mica determine the $Fe_2O_3^{(T)}$ (total Fe as Fe_2O_3) content (Table 6.1). The FeO: Fe_2O_3 ra⁺ⁱo (Table 6.2, Fig. 6.3) is a reflection of the relative proportions of these minerals.

The FeO:Fe₂O₃ ratio for magnetite and ilmenite have been determined in this study (Figs. 5.7 & 5.11b). The FeO:Fe₂O₃ ratio for orthopyroxene is extremely high (Deer, Howie & Zussmann, 1978), while that for mica is highly variable (*ibid.*), but commonly well below unity. The presence of Fe sulphides increases the FeO:Fe₂O₃ ratio, while magnetite decreases this ratio. The composition of the magnetite varies according to rock type (Fig. 5.7), so the effect of the presence of magnetite is variable. The ratio in ilmenite is extremely high, but since ilmenite is present in small proportions, the effect of this mineral is minimal.

It can be clearly seen from Fig. 6.3 that the samples that contain mica as the dominant mafic silicate mineral lie below the FeO:Fe₂O₃=1 line, while those samples dominated by orthopyroxene, lie above this line. Hence, all mica diorite and most anorthosite samples lie below the FeO:Fe₂O₃=1 line and all pyroxene diorite samples lie above this line. There are two distinct populations of pyroxene leucodiorite in Fig. 6.3. One population appears to contain pyroxene as the dominant mafic silicate mineral (since this population lies above the FeO:Fe₂O₃=1 line), while the other population appears to be dominated by brown mica. These two populations correspond with the two populations identified and discussed in Section 6.2.1, i.e. a population from the western face of the Jubilee pit which contains



Fig. 6.3 Plot of the Fe_2O_3 vs. FeO contents in the Koperberg Suite and granitic samples from Jubilee.

Table 6.2	Average	ferrous	and	ferric	iron	contents.
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	No. of samples	TOTAL Fe as Fe ₂ O ₃	FeÖ	Fe ₂ O ₃	FeO/ Fe ₂ O ₃
Anorthosite	(3)	3.60	1.29	2.18	0.82
Mica diorite	(6)	7.8 1	2.65	4.89	0.60
Pyroxene leucodiorite	(11)	12.10	6.46	5.00	1.63
Pyroxene diorite	(7)	15.61	10.53	4.03	3.38
Granitic xenoliths	(1)	2.03	0.41	1.59	0.30

orthopyroxene as the dominant mafic silicate mineral, and the other population from the northern face which is dominated by mica.

6.2.3 Trace elements

Selected trace element abundances are presented in Table 6.1 and displayed in Fig. 6.4 in the form of Harker diagrams. Since the major minerals which occur in the Koperberg Suite samples were not analysed for trace elements (except for BaO in mica and plagioclase, and

 V_2O_5 and Cr_2O_3 in oxides), only general trends in trace element geochemistry can be described with reference to theoretical minerals. It is possible, however, to explain the whole-rock trace element geochemistry of the Koperberg Suite as being due to the mineral chemistry and the proportions of the constituent minerals.

The concentrations of Rb and Ba are fairly uniform, irrespective of rock type, except in mica diorite. The concentration of both of these elements is dramatically increased in this latter rock type due to the higher proportion of mica in mica diorite (Chapters 3 & 4). Fig. 6.4 illustrates that Rb in mica diorite ranges from 40ppm-190ppm, while the Rb concentration in the rest of the Koperberg Suite is less than 50ppm. There are several pyroxene diorite samples that also show anomalously high Rb contents. These samples were taken from close to contacts with the Concordia Granite.

The Ba concentration in mica diorite is between 400ppm and 1300ppm, compared to the less than 400ppm in the rest of the Koperberg Suite rock types (Fig. 6.4). The high concentrations of Ro and Ba in mica diorite is directly attributable to the high partition coefficients of the elements into mica. The significance of the high Rb concentration in some pyroxene diorite samples will be discussed later.

Fig. 6.4 illustrates that Sr is highly variable in the rocks of the Koperberg Suite. This is due to the proportion of plagioclase in the samples, since Sr is preferentially partitioned into plagioclase. There is a population of samples, however, that is enriched in both Sr and P_2O_5 relative to the rest of the samples (Fig. 6.5a). These mica diorite samples were all taken from two xenoliths on the northern face of the Jubilee pit (Fig. 3.2). These samples have



Fig 6.4 Selected trace element binary plots for the Jubilee samples.



Fig. 6.5 The wt. % An in plagioclase (averaged per sample) vs. a) P_2O_3 and b) CaO.

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previously been identified as being geochemically distinct from the samples taken from the larger mica diorite mass. The high concentration of P_2O_5 illustrates the greater proportion of apatite in these samples. The enrichment of both P and Sr in these mica diorite samples (Fig. 6.5a) indicates that Sr is strongly partitioned into apatite. The replacement of Ca by Sr in apatite has been well documented. For example, Larsen *et al.* (in Deer, Howie & Zussmann, 1978) report 11.6% SrO in a sample of strontian fluor-apatite. In Fig. 6.5b, the samples with the highest Sr (and also P_2O_3), do not follow the general positive correlation trend, but have lower CaO values, supportive of this replacement of Ca by Sr in apatite. Note that several pyroxene diorite samples are slightly enriched in P_2O_5 (Fig. 6.5a), but are not enriched in Sr. This suggests that Ca in apatite has not been replaced by Sr in this intrusive phase.

The concentrations of elements such as Cr, Zr, Ni, Co and V in the rocks of the Koperberg Suite (Fig. 6.4) reflect the relationship between these elements and the abundance of mafic silicate minerals, oxides and sulphides present in the rock. Therefore, in terms of trace elements, the whole-rock geochemistry is also a reflection of the mineralogy of the rocks.

6.2.4 Copper

As noted in Chapter 4, copper-bearing sulphides are present in the rocks of the Koperberg Suite in varying proportions. It was further noted that this proportion varies from zero in anorthosite to major mineral status in the more mafic rock types present at Jubilee. It is a well-documented fact that sulphides most commonly occur in the more mafic assemblages of the Koperberg Suite. Whole-rock geochemical analysis data from the present study strengthen this assertion: there exist positive correlations between Cu and elements that are commonly associated with orthopyroxene and magnetite (Fig. 6.6).

As expected, there is a strong, positive correlation between Cu and S (Fig. 6.6a). Furthermore, since the dominant Cu-bearing sulphide in these samples is bornite (Chapter 4), the high Cu:S ratio is also not unexpected. This ratio is between 2.6 and 2.9, which corresponds closely to that of bornite.

There also exist strong, positive correlations between Cu and Cr, Cu and MgO, and Cu and Ni (Figs. 6.6b, c, and d) in the pyroxene leucodiorite and pyroxene diorite samples. These rock types, however, define different trends. These trends converge at about 5% Cu and

1.6% S (Fig. 6.6a), suggesting that this is a cumulate phase common to both rock types. Furthermore, at 5% Cu, the component contains about 2500ppm Cr (Fig. 6.6b), 17% MgO (Fig. 6.6c), and about 43% SiO₂ (Fig. 6.1).

6.3 Concordia Granite

Whole-rock geochemical analyses were carried out on seven Concordia Granite country rock samples. These samples were collected from both the northern and southern side of the Jubilee pit (Fig. 3.1). The results of the analyses are presented in Table 6.3. Since the sample population for the Concordia Granite is small, only general trends in the geochemistry of this suite can be discussed (Figs. 6.1 & 6.4).

The concentrations of SiO₂ (73.1%-78.5%) and Al₂O₃ (11.4%-14.2%) in the Concordia Granite are higher than the concentration of these species in most of the Koperberg Suite samples, thereby making the samples of the two rock suite easily distinguishable on all Harker diagrams (Figs. 6.1 & 6.4). K₂) concentrations in Concordia Granite vary between 2.1% and 6.8%, reflecting the proportion of alkali feldspar present in the sample. The low CaO concentrations (0.83%-1.83%) reflect the fact that the feldspar is albitic. However, since the Concordia Granite samples contain very little plagioclase feldspar (Chapter 4), the CaO content of a sample is probably determined by the amount and composition of plagioclase in the sample. Where there is apatite present, Ca is also partitioned into that mineral. The low Na₂O contents (2.53%-3.48%) of Concordia Granite samples, also indicates the relatively low proportion of plagioclase in this suite.

The generally low proportion of mafic mineral in the Concordia Granite is reflected in the low Fe₂O₃⁽¹⁾ (0.62%-2.63%) and MgO (<0.2%) contents (Fig. 6.1). The concentrations of other elements usually associated with these two species, such as Ti, Cr, Zn, Ni, Co and V are consequently low (Figs. 6.1 & 6.4). P₂O₅ and Zr concentrations are dependant on the proportion of apatite and zircon present, respectively. The proportion of these minerals is low, which is reflected in the low abundances of P₂O₅ (0.01%-0.04%) and Zr (31ppm-187ppm). One sample does have a P₂O₅ content (0.15%; Fig. 6.1) which is slightly, but significantly, above the general trend for Concordia Granite samples. However, it still does not represent an apatite-rich granite.



Fig. 6.6 Plots illustrating the relationships between Cu and: a) S, b) Cr, c) MgO, and d) Ni.

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Sr contents of the Concordia Granite (32ppm-89ppm; Fig. 6.4) are very low compared to Koperberg Suite samples, indicating that the source of the granite suite was low in Sr. Rb abundances (97ppm-408ppm; Fig. 6.4) in the Concordia Granite samples are significantly higher than in the Koperberg Suite samples. This high Rb content reflects high Rb content of the granite, while the variation in Rb content reflects the proportion of K-feldspar present in the Concordia Granite.

6.4 Granitic xenoliths

Two granitic xenoliths which occur in the Transition Zone on northern face of the Jubilee pit (Fig. 3.2) were sampled. As noted in Chapter 4, these xenoliths are not identical in terms of their mineralogy, and hence are not identical in terms of their geochemistry. Whole-rock geochemical analyses (Figs. 6.1 & 6.7) reveal that there are variations in the compositions of these xenoliths; these variations represent the varying mineralogy (Chapters 3 & 4).

The relative proportions of plagioclase, alkali feldspar and quartz are largely responsible for the geochemical characteristics of the granitic xenoliths. These proportions vary (Chapter 4) in the individual xenoliths, and have a distinct effect on the whole-rock geochemistry (Figs. 6.1, 6.4 & 6.7). The granitic xenolith samples can therefore be separated into three populations (populations I, II and III in Fig. 6.7). This distinction between the populations of granitic xenolith samples is especially apparent in the difference in SiO₂, Al₂O₃, Na₂O and CaO contents and, to a lesser degree, in K₂O, TiO₂, Rb and Sr concentrations. The separation of two xenoliths into three populations most probably represents the presence of a third xenolith, whose presence was not noticeable in the field, nor apparent from petrographic studies. This implies that the western xenolith (Fig. 3.2) represents two separate xenoliths: an upper and a lower xenolith.

Although the xenoliths are geochemically similar in many aspects, the eastern xenolith (referred to as the alkali feldspar-poor xenolith in Chapter 4, and as population III here) is easily distinguished from the western xenolith by comparing the K_2O and Rb contents (Figs. 6.4 and 6.7d). The samples from the alkali feldspar-poor xenolith (population III) have very low K_2O (about 0.4 wt.%) and Rb (<50ppm) contents, reflecting the paucity of alkali feldspar in this xenolith, while the western xenolith (populations I and II) contains between 3.4 and 6.2 wt.% K_2O and 100 - 200ppm Rb.

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SAMPLE	10	94	95	%	163	217	223	AVE
SłO _z	76,83	76.46	73.29	72,78	78.79	74 51	l.	75.15
TiO ₂	0.07	0.02	0.21	0.25	0.04	0.09	0.20	e.13
AL ₂ O ₃	12.28	12.28	15.25	13.92	11.37	13.23	14.19	13.22
*F42O3	× 1.69	0.62	2,25	1.96	1.07	0.82	2.36	1.54
MaQ	0.11	0.15	0.07	0.02	0.23	0.03	0.05	0.09
MeO	0.20	0,00	0,00	0.00	0.00	0.00	0,07	0.04
CeO	1.68	1.10	0.89	:	1.83	0.83	1,15	1.22
NarO	2.56	3.48	2.99	2.59	3.30	2.53	2.75	2.89
K,O	3.31	4.07	6,75	6.03	2.05	5.87	6.03	4.87
P.O.	0,03	0.01	0.03	0,15 🖇	0.03	0.02	0.04	0.05
Cu	0,01	0.00	0.00	0.ú0	0.00	0.00	0.00	0.00
roi	0.25	0.38	0.70	0.58	0,16	0.29	0.37	Q.39
TOTAL	99.01	96.58	142.43	99.34	98.89	98.51	100.2\$	99.58
Co	4.	5	6	6	6	6	7	6
NI	7	Ū	8	14	4	2	8	6
Zz	["] 24	27	47	41	24	23	43	33
Rb	140	207	408	383	97	298	377	273
Sr	69	32	55	59	53	89	66 .	60
¥ .	51	34	86	134	69	15	102	70
Zr	31	49	187	167	88	64	177	109
Nb	ः सं 4	16	20	21	17	5	17	14
v	11	6	11	7	7	12	12	9
Cr	- 23	15	6	11	² 13	8	5	12
Ba	113	63	331	299	50	225	327	201

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 Table 6.3 Whole-rock analyses of the granitic xenoliths and the Concordia Granite samples at Jubilee.

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				GRANITIC	XENO	ITHS	·····		
SAMPLE	29	151	153	154	155	156	157	158	AYE
5102	81.19	77, 9 9	80.11	81.11	80.90	84.14	74.58	73.87	78.10
T102	0.49	0.24	0.27	0.37	0.28	0.35	0.16	0.16	0.29
A1203	7.05	19.36	9.21	8.92	5.19	7.19	13.36	13.35	10.40
fre203	3.94	1.47	1.59	2.03	2.12	2.44	1,48	1.49	2.38
MuO	0.06	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
MgO	0.97	0.00	0.00	0.21	0.13	0.32	0.00	0.00	Q.18
C#O	1.86 j	0.38	0.65	0,69	2.16	1.78	1.26	1.05	1.60
N#20	2.29	2.49	2.53	1.69	1.6]	1.60	3.74	3.86	2.78
K20	0,40	6.15	4.51	3.36	0.46	0.44	5.71	6.19	3.12
P205	0.10	0.03	0.03	0.06	0.01	0.05	0.01	0.03	0.04
Cu	0.01	0.00	0,00	0.00	0.00	0.00	0.00	0.00	0.00
LOI	0.74	0.42	0.41	0.54	0.56	0.60	0.37	0,53	0.51
TOTAL	99.09	99.54	99.34	98.97	96-42	98.93	180,48	199.53	99.4 2
Co .	11	7	7	7	8	10	110	6	8
NI	ġ	t	2	6	0	2	1	3	3
Zn	- 64	22	28	29	37	38	26	23	34
Rb	9	160	192	90	17	19	155	160	83
Sr	113	130	115	175	229	226	340	241	237
Y	37	19	24	68	12	21	14	17	24
Zr	312	‡11	145	164	130	166	127	168	150
Nb	5	5	5	7	4	5	2	3	4
v	108	13	ų	20	62	41	23	9	43
Cr	3	11	8	\$	10	4	8	9	9
Ba	184	524	297	466	216	185	1664	472	478

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 SiO_2 contents of the granitic samples range from 74% to 84%. The SiO_2 content of Population II (Fig. 6.7) is lower than the rest of the granitic xenolith samples and is comparable to the SiO_2 content in the Concordia Granite samples. The SiO_2 contents in Populations I and III are higher than in any other granitic country rocks in the Okiep Copper District. (Clifford *et al.* 1995)

CaO values vary between 0.4% and 2.2% (Table 6.4, Fig. 6.7c), depending on the relative proportions of quartz and plagioclase present. Although plagioclase is present in modal proportions of between 30% and 50% (Chapter 4), the CaO contents in the granitic xenolith samples are well below the most plagioclase-poor anorthosite sample in the Koperberg Suite. This suggests that the plagioclase in the granitic xenoliths is very Ca-poor. Since mica and amphibole are present in these xenoliths, and alkali feldspar is present in one of them, the whole-rock Ca:Na ratio can not be used to estimate the composition of the plagioclase. The low whole-rock Na₂O concentrations in the granitic xenoliths reflects the relatively low modal proportion of plagioclase and the high modal proportion of quartz.

The low proportion of mafic silicate minerals, oxides and sulphides affects the concentrations of elements which are usually associated with these minerals, viz. Ti, Fe, Mg, Cu, Cr, Zn, Ni, Co and V (Table 6.4, Figs. 6.1 & 6.4). TiO₂ contents range from about 0.16% to 0.49%. This is present mainly in the brown mica and amphibole flakes. The Ba content most probably also reflects the presence of mica and alkali feldspar, since the distribution coefficient of Ba into mica and K-feldspar is high. Fe₂O₃^(T) content varies from just below 2% to around 4%, most of which is in magnetite and mica or amphibole. MgO generally occurs in concentrations of less than 1%, while the concentrations of other trace elements associated with mafic minerals, are comparable to concentrations in anorthosite of the Koperberg Suite (Section 6.2.3) and in Concordia Granite (Section 6.3). Apatite and zircon are not common accessory minerals in the granitic xenoliths and this is reflected in the relatively low P₂O₅ (<0.1%) and Zr (<200ppm) concentrations.

Sr concentrations in the granitic xenoliths are low (<400ppm) compared to the Sr concentrations in the Koperberg Suite, but consistently higher than in the Concordia Granite samples (Table 6.4). Rb is present in concentrations which range from 9ppm to 160ppm. 1...2 concentration of Rb in the xenolith which contains the higher proportion of alkali feldspar and mica, is higher than in the plagioclase- and quartz dominated xenolith. The higher Rb concentrations are comparable to the Rb content of mica diorite in the Koperberg Suite. The Rb content of the granitic xenoliths is generally low compared to the Rb content of the Concordia Granite samples. This reflects the relative proportion of brown mica and alkali feldspar present in the granitic xenoliths.

The mineralogy of the granitic xenoliths at Jubilee dictates that the whole-rock geochemistry should be superficially similar to other granitic suites in the Okiep Copper District (Table 6.4). A comparison between the geochemistry of the granitic xenoliths found at Jubilee and the geochemistry of other granitic country rocks is difficult since the granitic xenoliths wary greatly in terms of their whole-rock geochemistry. However, the granitic xenoliths may be compared to other granitic suites if the former is subdivided into the three populations (I, II and III) discussed earlier. Due to the population sizes, this subdivision can not be proven statistically, but the populations are consistent in terms of sample localities and in terms of most major and some trace elements. These populations, are shown in Fig. 6.7. Population I samples were taken from the top part of the western xenolith (Fig. 3.2), population II represent the lower portion of this xenolith, and population III represents the eastern xenolith (Fig. 3.2). The consistent geochemical differences between populations I and II suggests that the western xenolith may in fact be two separate xenoliths, although this was not observed in the field,

6.5 Isotope geochemistry

Rb-Sr data for 14 samples, which represent all of the rock types of the Koperberg Suite as discussed in Chapter 2, are presented in Table 6.4. Initial 87 Sr/ 86 Sr (R₀) ratios, calculated for a model age of 1030Ma are also presented. These data are summarised in Fig. 6.8. All analyses were carried out in the Hugh Allsopp laboratory (B.P.I., University of the Witwatersrand) following the analytical procedures described by Smith (1983).

The different rock types of the Koperberg Suite have distinctive Rb-Sr isotopic compositions (Fig. 6.8). Anorthosite has 87 Rb/ 86 Sr ratios that vary between 0.1260 and 0.1588, 87 Sr/ 86 Sr ratios that range between 0.7224 and 0.7231, and initial ratios (R₀) that are very high (0.7205-0.7249). In mica diorite, 87 Rb/ 86 Sr values range from 0.4385 to 0.6292, and 87 Sr/ 86 Sr values range from 0.7226 to 0.7312. R₀ values for these three mica diorite samples analysed vary greatly: one sample has a very high initial ratio of 0.7248, while the other two samples have lower (but still high) ratios of 0.7155 and 0.7159.

Pyroxene diorite and pyroxene leucodiorite have a very restricted range in Rb-Sr isotopic compositions, exceptions being the pyroxene diorite samples (samples 23 and 222) taken

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Figure 6.8 Plots the ⁸⁷Sr/⁸⁶Sr ratio vs the ⁸⁷Rb/⁸⁶Sr ratio of the Koperberg Suite samples.

from close to contacts with Concordia Granite country rocks. Pyroxene leucodiorite and pyroxene diorite have average ^{\$7}Rb/^{\$6}Sr ratios of 0.0620 and 0.1390, respectively and average ^{\$7}Sr/⁸⁶Sr ratios of 0.7135 and 0.7153, respectively. Initial ratios calculated for a model age of 1030Ma are very similar for pyroxene leucoulorite and pyroxene diorite (Table 6.4). Pyroxene diorite samples taken from close to country rock contacts have high ^{\$7}Rb/^{\$6}Sr (1.6935 and 1.2595) and ^{\$7}Sr/^{\$6}Sr (0.7404 and 0.7328) ratios. Initial ratios for these samples (0.7154 and 0.7142) are very similar to other pyroxene diorite samples, however.

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SAMP	Total Rb	Total Sr	*7Sr/**Sr	*7Rb/**Sr	R,
N0. *	(ppm)	(ppm)	(present)		(1030Ma)
136	37.39	802	0.722447(24)	0.134999	0.720458(16)
150	26.17	473	0.723120(44)	0.158820	0.720780(16)
213	21.91	504	0.726751(24)	0.126010	0.724894(16)
145	88.14	583	0.731219(44)	0.438537	0.724758(25)
159	114.20	691	9.722613(96)	0.4 9075	0.715555(27)
186	168.24	775	0.725190(44)	0.629214	0.715919(33)
42	12.57	631	0.713352(84)	0.057630	0.712503(15)
50	19.13	759	0.713418(40)	0.072995	0.712343(15)
53	12.83	723	0.713282(40)	0.051365	0.712525(14)
64	11.34	643	0.720932(56)	0.051092	0.720179(15)
1 92	20.70	905	0.713947(44)	0.066165	0.712972(15)
23	187.92	322	0.740415(56)	1.693489	0.715464(80)
113	25.23	542	0.715552(52)	0.134649	0.713565(16)
122	21.60	435	0.715124(36)	0.143871	0.713004(16)
222	139.79	322	0.732778(56)	1.259513	0.714221(60)

Table 6.4 Rb-Sr isotope compositions of the Koperberg Suite samples.

* 136-213, Anorthosite; 145-186, Mica Diorix; 42-192, Pyroxene Leucodiorite; 23-222, Pyroxene Diorite

Number in parentheses is the precision in the fifth and sixth decimal places attained in mass spectrometer analyses at 2 standard errors of the mean.

Rb and Sr concentrations determined by isotope dilution.

⁸⁷Rb/⁸⁶Sr reproducibility is 1.5%.

*7Sr/*6Sr ratios were normalised to **Sr/*6Sr ratio of 8.375.

The accuracy of the ¹⁷Sr/¹⁶Sr ratios were monitored by the following standards:

NBS SRM987: 0.710219±32 (1 std. dev. on 57 replicates)

Eimer & Amend: 0.708023±59 (1 std. dev. on 10 replicates)

A decay constant of 1.42E-11 was used.

A Rb-Sr errorchron age of 1147 ± 70 Ma (MSWD=52.81) has been calculated by regression using only eight samples (pyroxene diorite and pyroxene leucodiorite) using the computer program GEODATE (Eglington & Harmer, 1991). An R₀ of 0.7127 ± 0.0002 Ma was obtained for these eight samples using the errochron age calculated (Fig. 6.8). As can be seen from Fig. 6.8, anorthosite and mica diorite samples fall well off this errorchron and have a much higher R₀ than the pyroxene-dominated samples. These isotopic data for the Koperberg Suite at Jubilee, especially the initial 87 Sr/ 86 Sr ratios, recalculated tor an age of 1030Ma, are comparable to analyses on similar rocks throughout the Okiep Copper District (Clifford *et al.*, 1995).

6.6 Summary

Trends in the major element Harker diagrams (Fig. 6.1) represent mixtures of the various constituent minerals. It is clear, therefore, that the mineralogy of the rocks of the Koperberg Suite exert a strong influence on the whole-rock geochemistry. These geochemical trends suggest that the rocks of the Koperberg Suite at Jubilee represent a suite of variable proportions of co-accumulation of plagioclase, pyroxene, brown mica, Fe-Ti oxides and Cu-Fe sulphides, rather than representing a suite of liquid compositions.

Positive correlations exist between Cu and S, as well as between Cu and several elements usually associated with pyroxene and magnetite. Cu:S trends for the pyroxene-dominated rock types converge at a point which represents a component common to both rock types. The Cu:S ratios also reflect the mineralogy of the sulphide assemblage.

Initial 87 Sr/ 86 Sr ratio (R₀) data (Table 6.4) indicate that the intrusive magmas possessed a very high 87 Sr/ 86 Sr ratio at the time of intrusion. Each magma pulse (rock type) has its own distinctive isotopic characteristics, some rock types having greater valiability in the isotopic ratios than others.

The whole-rock geochemistry of the granitic xenoliths that were sampled indicate that the chemistry of these rocks is also controlled by mineralogy. Although only two xenoliths were

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observed and sampled in the field, whole-rock geochemical trends indicate three. These three xenoliths are geochemically distinct, although there are enough similarities between them to distinguish them from Concordia Granite and the Koperberg Suite.

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CHAPTER 7

DISCUSSION

7.1 Introduction

The question of the petrogenesis of the Koperberg Suite and the nature and the origin of the parental magma from which the Koperberg Suite was derived, has been addressed by several authors over the last 140 years. A brief outline of the more important theories arising from this question is given in Section 1.5. In light of the data from the present study, focused on the Koperberg Suite occurrence at Jubilee, certain points concerning the petrogenesis of the Koperberg Suite can now be reassessed.

1.2 Cumulates

It is clear from the discussion of the Harker diagrams (Figs. 6.1 and 6.2) in Chapter 6 that the rocks of the Koperberg Suite represent co-accumulations of the major silicate, oxide and sulphide minerals. This mineralogical control on the geochemistry of the Koperberg Suite rocks characterises them as cumulates.

7.3 An intrusive body

An intrusive emplacement of the Koperberg Suite has been postulated by many authors, notably Latsky (1942), van Zyl (1967, 1978), Clifford *et al.* (1975a, 1981, 1990, 1995) and McIver *et al.* (1983). At Jubilee, the Koperberg Suite cuts across the regional foliation in the Concordia Granite (Fig. 3.1) and this foliation is not present in the Koperberg Suite. A common phenomenon is that do regional foliation has been obliterated in a 30-50cm zone around the Koperberg Suite, while at one locality, the foliation steepens through almost 90° against the Koperberg Suite over a distance of 20-30cm. Foliations and layering in the Koperberg Suite are parallel to lithological contacts and are generally not parallel to the regional foliation. These observations suggest an intrusive emplacement of the Koperberg Suite and render a metasomatic origin (Read, 1952; Benedict *et al.*, 1964; Halbich, 1978) untenable.

7.4 Timing of intrusion

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The relative and absolute ages of emplacement of the Koperberg Suite in the Okiep Copper District have been discussed by many authors. A summary of these discussions appears in Section 1.5. Data and observations presented in this study regarding the intrusive ages of the various phases of the Koperberg Suite will be discussed below.

Field relationships (Chapter 3) make it clear that the Koperberg Suite intrudes and therefore, post-dates the Concordia Granite. The sub-horizontal foliation (S_2) in the Concordia Granite country rocks, is a manifestation of the D_2 deformation event. This foliation is disturbed by the intrusive Koperberg Suite at Jubilee and is not present in the latter suite of rocks. It is clear then, that the emplacement of the Koperberg Suite post-dates the D_2 deformation event.

From field relationships, the sequence of intrusion of the various phases of the Koperberg Suite, has been determined (Chapter 3). Anorthosite has been determined as being the oldest Koperberg Suite rock type at Jubilee, followed by mica diorite. The pyroxene leucodiorite and pyroxene diorite phases of intrusion followed. The mica diorite intrusive phase occurred before the anorthosite had crystallised completely, resulting in a zone of mixing of the two rock types - the Transition zone. However, between the mica diorite and the pyroxene leucodiorite intrusive phases, enough time must have elapsed for the mica diorite to have crystallised to such a degree that it could be fractured and still s¹ as xenoliths. Since the country rocks were at elevated temperatures and pressures at the time of the Koperberg Suite intrusive event (Gibson & Wallmach, 1992), the rate of heat loss from the intrusive rocks to the country rocks would have been relatively slow. However, since the Jubilee intrusion is only in the order of 100m wide, the time span required for an intrusive phase to solidify would be small. Therefore, it is difficult to put numerical constraints on the time difference between the intrusion of mica diorite and the intrusion of pyroxene leucodiorite.

Petrographic studies (Chapter 4) reveal that the earlier phases of the Koperberg Suite (anorthosite and mica diorite) exhibit certain deformation features which are not present in the later phases. Features such as highly strained plagioclase megacrysts and mica flakes, and recrystallisation of plagioclase around the megacrysts, are very common in anorthosite and mica diorite. Deformation features and recrystallisation are uncommon in pyroxene

leucodiorite and pyroxene diorite. The deformation features may be interpreted as indicating that the earlier phases crystallised in a lower stress environment and underwent deformation and recrystallisation to adjust to an increasing regional stress field. The decrease in the amount of deformation in the later phases, suggests that these rocks crystallised close to the peak of the deformation event. This deformation event could have been the D_3 event. Alternatively, the earlier intrusive phases may have crystallised in a higher stress environment than the later phases, implying that the later phases crystallised after the peak of metamorphism. The second model seems more likely in light of other evidence presented in this study.

As noted in Chapter 4, the dominant sulphide present in the Koperberg Suite at Jullee is bornite. However, bornite is not representative of the original magmatic sulphide phase. Bornite is present as the result of oxidation of the original sulphides to bornite and magnetite. The magnetite thus produced would be a pure phase, with little or no impurities, such as TiO_2 , Cr_2O_3 , Al_2O_3 and V_2O_5 . Magnetite grains which approach end-member composition abound in mica diorite and pyroxene leucodiorite (Fig. 5.7). In pyroxene diorite, there are several instances of impure magnetite grains, but the presence of two discrete populations of magnetite suggests that there are two discrete phases of magnetite crystallisation. The population which contains a low proportion of impurities such as TiO₂, Cr₂O₃, Al₂O₃ and V_2O_5 may have been formed by the oxidation of sulphides as proposed by Cawthorn & Meyer (1992), while the population which contains these impurities may represent the original, magmatic magnetite. Since all phases of intrusion have experienced oxidation of sulphides, it is concluded that the oxidation event occurred after the intrusion of the final Koperberg Suite phase. The oxidation of sulphides in the Koperberg Suite may have been the result of a high temperature metamorphic event (Cawthorn & Meyer, 1992). The high temperatures attained during the M₂ metamorphic event (Chapter 1), makes this the likely cause for the oxidation of the sulphides to produce the pure magnetite observed in the Koperberg Suite. This suggests that the rocks of the Koperberg Suite intruded prior to the onset of peak metamorphic conditions of the M2 event. Furthermore, features such as the recrystallisation of plagioclase suggest post-crystallisation metamorphism.

From the discussion above, it is clear that the Koperberg Suite at Jubilee intruded into the

country rocks at some time during the D_3 and M_2 events. An extended period of time for the intrusive event is implied by the varying stress conditions experienced by the various phases, and by lithological contacts between the Koperberg Suite phases.

7.5 Temperature and pressure conditions at time of intrusion

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Metamorphic conditions in the Okiep Copper District during the D_3 event reached upper amphibolite- to granulite facies (Gibson & Wallmach, 1992). At these high grade metamorphic conditions, the granitic suites in the Okiep Copper District would have experienced nartial melting. It has been shown above that the Koperberg Suite at Jubilee intruded into the country rocks close to, or after, the peak of the D_3 deformation event. Therefore, at the time of intrusion of the Koperberg Suite, the country rocks were undergoing anatexis and partial melts of granitic material would have been present in the crust. These anatects would migrate down any existing pressure gradient and would accumulate in zones of lower pressure. Kisters (1993) has proposed that the sub-horizontal S_2 foliation in the granitic country rocks, and the sub-vertical shear zones associated with D_3 steep structure formation, represent zones of lower pressure where granitic anatect may accumulate. It therefore seems likely that, under the regional metamorphic conditions at the time of Koperberg Suite intrusion, there existed a certain volume of locally-derived anatects in zones of low pressure. A mafic magma ascending along these zones would very likely be hybridised by these granitic anatects.

7.6 Evidence for crustal contamination

Given the favourable conditions of elevated temperatures and pressures which produced locally-derived anatects in the granitic crust, it is highly likely that a mafic magma rising through this crust would become contaminated. Several lines of evidence from the present study suggest crustal contamination of a mafic or intermediate magma.

7.6.1 Mineral chemistry evidence

In Fig. 7.1 the %En in pyroxene versus the %An in plagioclase in samples from Jubilee is plotted, as well as En-An data from other igneous complexes. The ratio between the An content of plagioclase and the En content of pyroxene in samples from the Skaergaard, Bushveld and Stillwater igneous complexes is approximately 1:1. Koperberg Suite samples

from Jubilee deviate from this relationship. Data from Jubilee indicate that the plagioclase





is too sodic for the En content of the pyroxene relative to other igneous complexes. En in

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pyroxene exceeds An in plagioclase by up to 20 mole per cent. The addition of a granitic melt (which is rich in Na and K, but poor in Ca, Fe and Mg) to a mafic magma will affect the Ca:Na ratio (An content) in plagioclase, but the Mg:Fe ratio (En content) in pyroxene will remain virtually unchanged. The data from Jubilee suggest that the primary magma was increased in Na (and possibly K), thereby changing the An content in plagioclase, without changing the En content of pyroxene. An obvious candidate for the contaminant is a granitic anatect which was present in the crust at the time of intrusion.

The degree of contamination of a mafic magma by a granitic melt can not be calculated from the En-An data, since the chemistry of the neither the mafic magma, nor the granitic melt, is known. However, if all the magmatic phases were derived from the same (or similar) parental magma, and if they were all hybridised by the same (or similar) granitic melt, then intuitively, the more felsic rock types would have been hybridised to a degree than the more mafic rock types of the Koperberg Suite.

7.6.2 Rb-Sr isotopic evidence

The ⁸⁷Sr/⁸⁶Sr ratios for the Koperberg Suite vary greatly (Fig. 6.8). Although the pyroxene diorite samples fall on an errorchron, all anorthosite and mica diorite samples are enriched in ⁸⁷Sr/⁸⁶Sr with respect to this errorchron. One explanation for this high initial ⁸⁷Sr/⁸⁶Sr ratio is that the anorthosite and mica diorite were derived from a different source to the pyroxene diorite. However, Fig. 6.8 shows considerable scatter for the anorthosite and mica diorite samples and a second isochron can not be fitted to these points. So, a different source seems unlikely. It is possible that mica diorite samples do not fit the isochron defined by the pyroxene-dominated samples because this reflects the open system behaviour of mica which, during deformation and metamorphism, lost Rb.

The pyroxene diorite samples from near the contacts with Control dia Granite are richer in mica than the rest of the pyroxene diorite sample (Chapter 4). However, the proportion of mica in these samples is not as high as the proportion of mica in the mica diorite (Chapter 4). Nevertheless, pyroxene diorite samples from the contact zones (samples 23, 160, 161, 162, 166, 221 and 222) contain as much Rb (190 - 200ppm) as the mica diorite samples,

suggesting that when the pyroxene diorite magma was crystallising, mica in the magma behaved as an open system, gaining Rb from the country rock which is enriched in this element (Chapter 6).

It is possible that the increased ⁸⁷Sr/⁸⁶Sr values in the anorthosite and mica diorite samples is the result of contamination of the parental magma by a granitic anatect. A mafic magma would have a lower ⁸⁷Sr/⁸⁵Sr ratio than the granitic anatects present in the crust at the time of Koperberg Suite intrusion. If these two melts came into contact with one another and were allowed to mix, the resultant mixed magma would have a higher ⁸⁷Sr/⁸⁶Sr ratio than the parental magma. The degree of mixing or homogenisation of the two magmas with respect to the ⁸⁷Sr/⁸⁶Sr ratio, would determine how far off the pyroxene diorite isochron jhese samples would lie. In general, anorthosite samples lie further off this isochron than the mica diorite samples (Fig. 6.8), suggesting that the magma which gave rise to the anorthosite experienced a greater degree of contamination in term of this isotopic ratio. However, one mica diorite sample is also highly enriched in this ratio. This sample is taken from the Transition zone, which suggests that the material in this zone experienced a greater degree of contamination than the mica diorite from elsewhere in the Jubilee pit.

Since bulk mixing represent complete homogenisation between two end members, it can be used to illustrate the extreme case in which all the chemical species homogenise. In particular, it would illustrate the case in which Sr isotopes of two end members homogenise completely.

Quantitative modelling of the mixing process is difficult, since the compositions of neither end-member is known. Concordia Granite has an R_0 of 0.709 at 1030Ma, which is too low to produce initial ratios of up to 0.725 in rocks which are derived from mixing of a granitic anatect and a mafic magma. Therefore, although limited assimilation of Concordia Granite may have occurred *in situ* at the intrusive contacts, the assimilation of granitic material would most probably have occurred at depth. Material suitable as granitic contaminants exist deeper in the crust, such as the Nababeep Gneisses (Table 1.1). Similarly, the composition of the mantle-derived liquid is not known, since the rocks of the Koperberg Suite are cumulates and hence yield no information about the parental liquid from which they crystallised. A bulk mixing curve was constructed for the parameters R_0 and Sr between two hypothetical end members : a granitic component and a mafic component (Fig. 7.2). The mixing equation

$$(R_0/Sr)_M = f(R_0/Sr)_A + (1-f)(R_0/Sr)_B$$

is used, where the subscripts M, A and B denote the mixed magma, the granitic component and the magmatic component, respectively. The term f in the above equation represents the fraction of granitic component in the mixed magma.

 Table 7.1 Calculation of Sr content of the liquid from which the rocks of the Koperberg Suite

 were derived.

Rack type	Sample No.	R,	Wkole- rock Sr (ppm)	Norma tive plag	Sr in ping (ppm)	Au content of plag	D _{yie}	Sr in meit (ppm)
	136	0.720458	802	75	1069	36.0	3.40	315
Avorth-	150	0.720780	477	50	954	35.5	3.45	277
osile	213	0.724894	564	60	840	36.8	3.32	253
	145	0.724758	583	72	810	41,4	2.86	283
Mica	159	0.715555	691	65	1063	:42.0	2.80	380
dioríte	186	0.715919	775	57	1360	42.9	2.71	502
Pyrozene	42	0.712503	632	54	1170	46.0	2.40	488
lenco-	50	0.712343	759	68	1116	47.0	2,30	485
diorite	53	0.712525	723	59	1225	46.1	2.39	513
	192	0.712972	905	67	1351	46.0	2.40	563
	23	0.715464	322	37	870	46.0	2.40	363
Pyroxene	113	0.713565	542	45	1204	46.0	2:40	502
diorite	122	0.713004	435	42	1036	47.7	2.23	464
	222	0.714221	322	35	920	41.4	2.86	322

<u>Note</u>: The compositions of plagioclase in samples 136 and 177 were not analysed and are assumed to be An_{36} .



Fig. 7.2 Plot of R_0 vs. composition of the liquid from which the various rocks of the Koperberg Suite were derived (see text for discussion of calculation method).

These rocks are cumulates and therefore, whole-rock Sr values quoted in Table 6.4 do not represent the Sr content of the maginas from which these samples crystallised. Sr values in the melts can be determined from the Sr content of the plagioclase. However, since Sr was not determined for plagioclase separates in this study, Sr in plagioclase can be approximated using whole-rock Sr contents. It was assured that all the whole-rock Sr occurs in plagioclase. This assumption is not realistic, since Sr also occurs in apatite (Section 6.2.3), but this is a minor phase. The modal abundance of plagioclase is approximated from the normative An and Ab contents. From the normative content of plagioclase and the whole-

rock Sr content, the Sr of plagioclase can be calculated (Table 7.1).

From the Sr content of plagioclase and the partition coefficient between melt and plagioclase, the Sr content of the melts from which each individual rock type crystallised can be calculated (Table 7.1). The composition of plagioclase affects the partition coefficient for Sr between plagioclase and melt (Drake & Weill, 1975). Therefore, the partition coefficient of Sr between the melt and plagioclase (D_{pleg}) is taken to vary linearly from 2 for plagioclase of composition An₅₀ to 4 for plagioclase of composition An₃₀. The melt values thus calculated (Table 7.1) are plotted against R₀ in Fig. 7.2. Note that the whole rock Sr contents used in these calculations were determined by mass spectrometry, not by XRF.

Two mixing curves were calculated, using as the mafic magma end-member, a composition of Sr = 600ppm and $R_0 = 0.712$, and the granitic end-member, being the Brandberg Gneiss or the Augen Gneiss. These two gneisses represent end-member compositions of the Nababeep Gneiss (McCarthy, 1976). The gneisses contain 80ppm and 200ppm Sr, respectively. The R_0 for 1030Ma was calculated assuming an R_0 of 0.715 at 1220Ma (Clifford *et al.*, 1995) and a Rb/Ar ratio of 2.5 (McCarthy, 1976). The R_0 at 1030Ma thus calculated is 0.737. The parental magma end-member represents a hypothetical magma from which the Koperberg Suite *could* have been derived. This magma is highly enriched in Sr and R_0 relative to a normal mantle-derived magma, and the composition of this parental magma is significant in determining its source.

These two mixing curves are plotted on Fig. 7.2 and show that the Koperberg Suite samples from this study fall between these two mixing curves. Hybridisation with Concordia Granite (also plotted on Fig. 7.2) would produce a horizontal mixin curve on Fig. 7.2. This may account for the variation in Sr content at near constant R_0 for pyroxene diorite samples. It was observed in Chapter 3 that only pyroxene diorite occurs in contact with Concordia Granite at Jubilee, and a limited degree of *in situ* assimilation of Concordia by pyroxene diorite may have occurred. The high Rb contents of these pyroxene diorite from near contacts is further evidence for limited *in situ* assimilation of Concordia Granite by pyroxene diorite.

From Fig. 7.2 and the qualitative discussion on assimilation from mineral chemistry data,

it is clear that the degree of contamination decreases from anorthosite, through mica diorite to pyroxene leucodiorite and pyroxene diorite. Note that the pyroxene diorite samples from the contact zones exhibit a much higher apparent degree of contamination than other pyroxene diorite samples (Fig. 7.2). This is due to *in situ* contamination by Concordia Granite country rock material. The high degree of assimilation implied by Fig. 7.2 suggests that the granitic component must have been in τ molten state. Kisters (1994) argues that there was a significant amount of granitic anatect in the crust at the time of Koperberg Syste intrusion.

7.7 Sulphide formation

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There is a strong positive correlation between Cu and S in the Koperberg Suite samples (Fig. 6.6a). It was noted (Section 6.2.4) that the Cu:S ratio is between 2.6 and 2.9. This ratio reflects the bornite-dominated sulphide mineralogy. This sulphide assemblage was considered by Cawthorn & Meyer (1992) to be the result of later oxidation of earlier magmatic sulphides. This oxidation reprint of pyrthotite-chalcopyrite being oxidised to magnetitechalcopyrite-bornite can be illustrated by the Jubilee data. According to the interpretation of Cawthorn & Meyer (1992), the resulting magnetite will be Ti-poor. The analyses of magnetite in this study (Section 5.3.1) reveal that there exist two distinct populations of magnetite, especially in pyroxene diorite. This suggests that there were two phases of magnetite formation. One population deviates considerably from end-member composition due to the higher TiO₂ and FeO contents, relative to other magnetite grains. These Ti-rich magnetite grains represent the magmatic oxides while the Ti-poor grains represent the magnetite formed by the oxidation of the original sulphide assemblage. It is also significant that magnetite graphs from pyroxene diorite differ considerably from magnetite from pyroxene leucodiorite and mica diorite. The magnetite from the latter rock types approach end-member compositions, while magnetite from pyroxene diorite deviates from end-member composition due to the inclusion of Cr_2O_3 , Al_2O_3 , V_2O_5 and MnO. The magnetite grains which most resemble end-member compositions represent magnetite liberated during the oxidation of the original sulphide assemblage (Cawthorn & Meyer, 1992). Therefore, there appear to be no magmatic magnetite in pyroxene leucodiorite and mica diorite. This suggests that, in the magmas producing pyroxene leucodiorite and mica diorite all excess Fe, Ti, Cr, Al, V and Mn that had not been taken up by silicates were incorporated into sulphides, while

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in the magma that produced pyroxene diorite, magmatic magnetite (in addition to sulphides) was formed which incorporated these elements.

It was noted in Section 6.2.4 that the trends of pyroxene leucodiorite and pyroxene diorite in the plot of Cu vs. S (Fig. 6.6a) converge at a composition of 5% Cu, 1.6% S (F_{1}° , 5.6a), about 2500ppm Cr (Fig.6.6b), 17% MgO (Fig. 6.6c), and about 43% SiO₂ (Fig. c.1). This represents the composition of the magmatic phase from which sulphides crystallised in both pyroxene-rich magmas.

The positive correlation between Cu and Cr is significant, since Cr is a lithophile. At Jubi'ec, Cr_2O_3 is taken up by pyroxene (Table 5.2) and Cr-rich magnetity (Table 5.4a). The correlation between Cu and Cr therefore indicates that the Cu-bearin between Cu and Cr therefore indicates that the Cu-bearin between Cu and Cr therefore and magnetite.

7.8 Sequence of intrusion

The sequence of intrusion of the Koperberg Suite at Jubilee has been established as being from less mafic to more mafic (Chapter 3). This sequence is easily understood if one considers a series of magmatic pulses ascending along the same conduit which originally contained a certain volume of locally-derived granitic anatects.

The earlier pulses of magma ascending along the shear zone or conduit would have assimilated a major proportion of the granitic anatects that ponded in the shear zones. Furthermore, these early magmas would also have begun assimilating country rocks by undergoing rapid chemical and isotopic exchange. By leaching out all the rapidly diffusing species, the rising magma partially armoured the country rocks against further chi. ...ical exchange with subsequent transient magmas. These later phases of magma ascending along the same conduit would therefore be able to assimilate less country rock, since they would not be able to undergo chemical exchange for long enough to assimilate a larg- proportion of the country rock material. Also, there would be less crustal anatects present in the shear zones for the later magma pulses to assimilate.

The processes of contamination of a mafic magma by a crustal or ______ artic component (as

described above), result in the early intrusive phases of the Koperberg Suite containing a high proportion of crustal n aterial, while later intrusive phases are less contaminated. The extent of mixing between a mafic magma and crustal material determines the composition of the resulting rock types. Since the whole-rock geochemical composition is determined by the proportions of the constituent minerals present (Chapter 6), the mineralogy of the rock types are also a qualitative measure of the degree of contamination. The proportions of contaminant and parental magma, and the way in which these components mixed, have been described in Section 7.6.

The rock types of the Koperberg Suite at Jubilee can therefore be described in terms of their relative proportions of mafic and crustal components. Pyroxene diorite, which represents the last phase of intrusion, contains the lowest proportion of granitic material of all the Koperberg Suite rock types present. A small degree of contamination must have occurred to explain the absence of clinopyroxene (McIver *et al.*, 1983), the high initial ⁶⁷Sr/⁶⁶Sr ratio (relative to normal mantle values), the lack of correlation between En and An, and the absence of olivine (Gray, 1987). Pyroxene leucodiorite is very similar to pyroxene diorite, but represents a magma with a slightly higher proportion of crustal contaminant.

Mica diorite is an intermediate phase of the Koperberg Suite. Since it only contains a very small proportion of orthopyroxene, oxides and sulphides (Chapter 4), this rock type represents a highly contaminated magma. An indication of the amount of contamination that a mafic magma must have undergone to produce this rock type is illustrated in Figs. 7.2 and 7.7. Anorthosite is the earliest phase of intrusion recognised as belonging to the Koperberg Suite (Chapter 3). Only a small proportion of alkali feldspar is present in this rock type (Chapter 4), which indicates that anorthosite can not represent a pristine crustal melt. Hence, a certain proportion of the magma which produced this rock type must have been derived from a mafic magma. The bulk of the magma, however, must have been of a granitic material.

Granitic material, which occurs as xenoliths within the anorthosite and mica diorite rock types of the Koperberg Suite at Jubilee, may represent an intrusive phase which predates the intrusion of anorthosite. The granitic nature of these xenoliths suggests that very little or no,

rocks represent and intrusive phase to which no mafic magma was added, the granitic xenoliths may represent fragments or restites of granitic crust.

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CHAPTER 8

CONCLUSIONS

8.1 Summary model

Based on the data and discussions presented in the preceding chapters, the following model summarises the petrogenesis of the Koperberg Suite at Jubilee. The model attempts to reconcile the complex geochemical, petrographic and field characteristics of this suite into a single, coherent petrogenesis.

i) Partial melting of an enriched alkaline mantle produced a magma rich in incompatible, lithophile elements. The cause for melting of the mantle is not considered here.

ii) Large volumes of this mantle-derived partial melt ponded at the base of the crust in one or several large magma chambers. This injection of heat into the lower crust is a probable cause for the high geothermal gradient and the high grade of metamorphism recorded throughout the Okiep Copper District.

iii) Differentiation of the magma occurred in these deep-seated chambers. Repeated tapping of the residual liquids produced several phases of magma intrusions into lower- to mid-crustal levels.

iv) Regional metamorphism of at least upper amphibolite facies caused partial melting of the country rock granite gneisses. Sub-vertical shear zones and fractures, related to the D_4

deformation event, acted as traps for the locally-derived peraluminous anatects and as conduits for the ascending magma. One such shear zone or fracture must have occurred below the current Jubilee open pit mine.

Basic magma which ascended along these conduits experienced variable degrees of contamination due to bulk assimilation of locally-derived anatects, isotopic exchange and diffusive mixing with the country rocks. The earliest pulse of magma encountered larger volumes of granitic anatects, and underwent diffusive mixing with the country rocks to a larger extent than the later pulses. Later phases of intrusion brecciated and entrained xenoliths of earlier phases, as well as of the country rocks. The entire intrusive event spanned at least 10Ma during the later stages of the D_3 deformation event and possibly somewhat after this event, but predates the peak metamorphic conditions of the M_3 metamorphic event.

The ratio of mafic magma to contain ant thus increases from the earlier phases (anorthosite and mica diorite) to the later phase (pyroxene leucodiorite and pyroxene diorite). This ratio determined the mineralogical and geochemical character of the rock type resulting from each magma pulse, as well as the sulphur saturation point of the magma-contaminant mixture.

The later phases of intrusion containing less contaminant, were probably at a higher temperature and therefore less viscous. This enabled the later phases to brecciate rocks crystallising from earlier intrusions, and to entrain xenoliths of these rocks to their final sites of emplacement.

vi) A limited degree of *in situ* contamination occurred, mostly by assimilation of Concordia Granite country rocks, but also by continued homogenisation between the magma and included xenoliths.

vii) Peak metamorphic conditions, which occurred after the last phase of intrusion, caused oxidation of sulphides and textural changes in the rocks.



Fig. 8.1 Schematic representation of the petrogenetic model of the Koperberg Suite intrusion at Jubilee. See text for details.

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As can be appreciated from the petrogenetic model proposed above, the Koperberg Suite at Jubilee is the result of a complex and unique sequence of events. The scope of the present study is not sufficient to present a complete model, since many sources of evidence have not been explored. Several studies may still be undertaken at Jubilee to verify, modify and complete the petrogenetic model. Continued studies at Jubilee are considered vital since the Jubilee open pit mine offers a unique opportunity to study a single, composite and mineralised intrusion, as well as the surrounding country rocks. Besides easy and three-dimensional access to a large portion of the intrusion, much of the large scale mapping, sampling and whole rock geochemical analyses have already been done.

The following further studies are recommended:

- More accurate dating (eg. single zircon Pb/U) on each of the different phases of Koperberg Suite intrusion, to establish the age and duration of intrusive activity

- Further stable (eg. O and S) and radiogenic (eg. Sm/Nd and U-Th-Pb) isotopic studies on the rocks of the Koperberg Suite at Jubilee may shed more light on the contribution of the mantle to the parental mafic magma.

- Detailed geochemical and isotopic studies on the granitic xenoliths to determine whether they represent a genetically related early Koperberg Suite phase, or whether they represent the granitic anatect with which the mafic magma was contaminated.

- A detailed study on the significance of orbicular structures in some Koperberg Suite rock types.

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APPENDIX

GEOCHEMICAL TABLES

Table A1: Mineral chemistry analysesTable A2: whole-rock geochemical analysesTable A3: Whole-rock ferrous and ferric iron contents

A.

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	1 Pragaze		ani su y	THE YEARS	A second la				وبالمراد المراجع				in section of	
i Probe	1150.020	150 627	150.n3r	152.010	188.ptm	1260 128.07e	168.n9r	157.032	243.ote	213.0204	213.02	212.030	213 p. 100	213 040
540-	58.75	54.68	54.86	59.54	60.28	59.86	AD 05	80.02	59.37	58.44	57.97	57.44	55.45	57 70
AL-O	25.18	25.35	25.45	24.50	24.54	24.97	24.78	24.20	25.60	25.20	26.09	25.91	25.65	26.62
Fio	0.06	0.07	0.10	0.11	0.08	0.00	0.11	0.10	0.05	0.09	0.09	0.06	0.09	0.06
CLO	7.25	7.34	7.33	6.45	5.44	6.49	6.58	6.47	7.34	5.99	7.97	8.02	7.68	8.10
ReC	0.00	0.00	0.02	0.03	0.00	0.01	0.01	0.01	0.20	0.17	0.00	0.04	0.02	0.01
NagO	7.05	7.00	7,10	7.49	1.75	7.43	7.67	7.01	6.44	5.01	8.90	6.46	5.42	0.53
К,О	0.44	0.45	0.50	^{//} 0.49	0.26	0.53	0.27	0.48	1.34	4:05	0.33	0.78	0.67	0,43
TOTAL	98.80	89,09	59,39	96,95	\$9,38	99.35	99.45	98,89	99.25	99.94	99.34	96.72	99.60	96,39
An	3535	35 72	35.27	31.36	31.00	31.47	31.65	31 10	35.65	30 15	38.25	38 89	36.23	39.65
Ab	62,10	61.70	61.85	65.83	67.49	65.44	66.79	68.14	56.60	45.60	59.88	56.53	57.76	57.70
Or	2.54	2.58	2.68	2.62	1.51	3.09	1.56	2.76	7,75	24,25	1.87	4.48	3.99	2.48
	بينين والديني بالمراجع		وور ورسوند بد					يبتحد بتوكنا فاد		يول بي المربية		يبيد أحصف كرفين		
	_			M	iica diori	te			<i></i> *1					
Probe	134.010	134.p17	134.p2c	134.p3r	134.550	134.p5r	145.ptr	145.p3c	<u>1487 jr</u>	145.p4c	145.p4r	167.p2c	167.p3;	167.p3ta
8102	57.15	57.75	56.13	56.35	57.70	56 94	57.43	57 43	57.38	57.35	57.90	55.90	57.25	57.14
M-01	20.33		0.08	20.55	49.40	0.08	20 30 M	20.00	20.01 /107	20.04	10.34 0.00	0.07	20.00	20.84
CAO	8.57	8.30	7.89	7.83	8.37	6.66	8.51	8 51	8 53	8.48	8.46	5.42	8.52	8.55
BeQ	0.02	0.01	0.03	0.00	0.00	0.00	0.05	0.02	0.04	0.02	0.00	0.00	0.00	0.03 🕅
Na ₇ O ()	6.32	6.64	6.76	6.92	8.59	6.19	6.40	8.40	6.32	6.32	6.39	6.43	6.48	6.24
К,О	0.35	0.35	0.59	0.27	0.27	0.31	0.40	0.47	0.45	0.49	0.35	0.41	0.37	0.30
TOTAL	96,82	77,83	88.TU	99.31	59,42	8¥.22	39.47	99,14	\$9,39	\$9.29	39,41	88.37	99,35	99,20
Ал	41.99	40.03	38,35	37.86	4C 64	43.42	41.38	41.23	41.59	41.35	41.38	40.99	41 22	× 12.17
Ab	55.96	57.85	59.40	80.57	57.83	54 77	56.32	56.00	55.78	55.78	58.57	56.66	56.58	55.70
Or	2.03	2.02	2.25	1.57	1.53	1 81	2.28	2.66	2.62	2.86	2.05	2.35	2.15	2.10
] '				0						-				
Buster	المعد وحدة	487 -X-L	مريا الحد الطلال		100	407 -4		4 5 4	400-00-		100			
SICL	87 37	56.70	78.83	67 33	100.016 58.74	100.0112	44.00	100.µ.cr	196.p3C	46.67	144.p. 58.00	190.per	•	
ALO,	26.69	26.49	26.43	26.51	26.54	20 48	26 71	26.90	27.04	20.86	27.00	27 22		
5eO	0.06	0.08	0.07	0.08	0.07	0.08	0.04	0.05	0.08	0.03	G.05	0.10		6
CaO	8.42	8,55	6.08	8.25	8.82	8.66	8.71	8.90	8.70	8.88	8.82	9.26		1
BaO.	0.04	0.03	0.00	0.00	0.03	0.00	0.03	0.05	0.06	0.00	0.02	0.02		3:
Ne ₂ O	0.94	6,33	(5.19 1.01	631	6.21 0.17	6.33	5.18 0.32	5.28 5.34	6.37	6.21	6.30	- 15,11 - 1144		ù.
TOTAL	58.91	99.50	98.67	69.14	98.76	98.51	98.97	99.13	99.57	98.97	99.39	99.20	,	5
							·····							1
An	42.91	a 41.77	39,39	40.03	43.03	42.28	42.1	43.31	42.32	43.34	42.89	44,77		Ú,
Ab	C4.77	55.91	54.75	57, 15	54.95	55 92	55.16	55.23	58.04	\$4,78	55.39	53.45		
Or	2.32	2.31	5.85	2.82	2.12	1.00	1.87	1.36	1 64	1.88	1.72	1,77		
	-										ا محمد الشرق معم النمار ا			(⁴

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			Pyroxer	le leuco	dlorite 🧠						
Frobe	42.p2	42.p3	50.p2c	50.p2r	50.p4¢	50.p4ra	50 spôc	50.p5r			
tiO ₂	55.38	55 37	50.15	56.10	55.41	56.18	55.71	55.09	-		
Al ₂ O ₂	27.59	27.23	27.82	27.54	27.45	. 32	27 52	28.28			
FeO	0.13	0 18	0.14	0.05	0.18	9. 10	0.08	0.19			
CeO	9.47	9.21	9.51	9.44	9.78	9.26	9.75	10.07			
340	0.01	0.06	0.00	0.03	0.02	0.02	0.00	0.02			
Na _z O	5.83	5.93	5.5	5,96	5.66	5.90	5.85	5.65			
K,O	0.42	0.39	0.28	0.30	0.32	6.29	0.29	0.23			
TOTAL.	98.82	96.64	98.79	99.44	98,85	\$9.08	98,23	99,53			
								4			
An	45.15	45.13	46.62	45.81	47.95	45.84	47.03	48.96			
Ab	51.42	52.59	51.96	52.45	50.21	52.67	51.26	49.74			
Or	2.44	2.28	1.62	1.73	1.84	1.69	1.69	1.31			
1											
Probe	53.pta	53.µ3	\$4.p5c	64.p7c	64.p7r	192.p2c	192.p2r#	192.p5c	192.p5r	192.p8c	192.p6
\$10,	55.04	55.25	57.37	57.19	57.25	55.42	56.16	55.89	55.29	55.96	56.28
Altos	27.43	27.31	26.19	26.18	26.47	27.64	26.77	27.13	27 09	27.24	27.20
FeQ	0.21	6.21	0.09	0 12	0.12	0.10	0.12	0.14	0.11	0.13	0 12
CIIO	9,45	9 49	8.20	8.37	8 44	9.81	9.21	9.54	9.30	9.52	8,96
6¢O	0.04	0.03	0.03	0.00	0.00	0.04	0.03	0.05	0.02	0.00	0.05
NE ₂ O	5.78	9.86	8.34	5.43	0.31	5.50	5.00	5.71	3.85	5.79	5.17
K ₂ O	0.31	0.41	0.58	0.50	<u>6.48</u>	0.30	0.29	0.08	0.40	0.36	(1,40
TOTAL	98.45	\$8.54	98.80	98,79	99,07	SH.90	\$8.57	98.84	99.05	99.04	98,17
	48.08	44.00	40.00	40.08	64 07	40.04	48 44	48.02	47 BC	10 EF	13.40
All	40.06	44.80	-90.20	40.60	41.33	46.36	43.12	40.93	45 65	40.02	43.49
AD	51.00	53.55	56.36	56.47	≈ 55.8Q	49.51	53.21	50.51	52 02	51,25	54.18
Or	2.94	1.65	5.38	2.65	278	1.73	1.67	2.26	2.33	2.20	2.33
L											

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	AT (CONIC	s.) Plank	CIABA	hemieth	analys	**		Burovar	a diorite			- Formation			
Probe	23.ptc	23.p2c	23.p2r	58.p1e	56,p3	102.p4c	102.p4r	102.p5c	102.p5r	102.p 6 c	102.p6r	111.pic	² 111.p1r	111.p2c	111.p
5HC2	57.63	55.77	55.46	56.78	55 87	56.42	58.60	56.08	57.28	56.36	55.08	56.97	55,96	57.10	57.0
Al ₂ O ₂	25 41	27.93	27.48	27.14	27 52	27.40	27.30	27.51	27.05	27.10	27.12	26.68	27.53	26.91	27.0
Fe0	0.11	0.05	0.26	0.14	0.08	0.27	0.08	0.12	0.07	74.0	0.13	0.14	0.13	0.16	0.11
GeO	8.25	9,79	9.99	8.69	9 22	9.38	9 tt	9,60	8.64	8.94	9.44	8.80	. 9.6t	8.77	9,03
BeO	0.06	0.02	0.00	0.04	0.05	0.00	0 02	0.02	0.04	0.00	0.03	0.00	0.00	0.00	0.00
Nato	5.50	5.76	5.56	6.32	6.09	6.00	8 15	5.88	6.45	6.32	6 12	6. 16	5.73	6.23	6.01
K ₂ O	0.29	0.26	0.72	0.34	0 28	0.21	0.20	0 24	0.23	0.20	0.20	0.41	0.35	0.45	0.44
OTAL	\$9.25	\$9.59	98.95	99.42	99,11	99.69	99.45	99.43	99,75	99.59	99.11	99 ,13	99.32	99.82	89.65
An I	Sec	47 72	40 18	42.39	44.00	45 7 8	4.4 KD	A# 74	A1 0A	43.35	45 40	43.08	47 10	42 87	44 30
	47 7K	R(1 97	40.54	45.7£	R1 44	40.00 83.00	RJ 73	-40.FJ	46.70	55.48	43.77	54 88	50 87	44 80	53.25
a	1 77	1.50	1 28	1.95	184	1 22	1 17	1.40	1.35	1 17	1 14	2.34	208	258	2.55
				·						1	4.74	2.00	2.00		
			- Ka							• ».					
robe	111.p4c	111.p4r	113.01	113.p3	122.020	122.p2r	122.p24	122.p3c	122.p3r	122.010	122.p7r	222.p4c	222.00Ca	222.951	
810 <u>3</u>	0/.10 26.63	37.00 26.95	20.78	-7.40	27 42	47.83	22.94	33.17	22.27	33./3 37 30	20.20	97.U3 26 28	D/ 20	16.6C	
FeO	0.13	0.12	0.10	0.00	0.09	0.26	0.14	0.14	2.15	0.12	0.11	0.08	0.07	0.10	
CHO	8.71	8.90	13.18	-a.12	9.22 1	9.69	9.67	9 82	10.25	9.80	9.58	8.50	8.38	8.54	
BAD	0.00	0.03	0.0	×	à.09	0.05	0.04	0.05	0 03	0.02	0.04	0.03	0.01	0.00	
Na ₇ O	0.20	8.30	4)		*v.	5.73	5.58	5.63	5.52	5,73	5.74	8.41	6.38	6.34	
K,0	0.46	0.44	0	• ·		~ 0.28	0.42	0.33	0.30	0.27	0.24	0.37	0.38	0.34	
OTAL	93.28	99,70	9 9,				39,35	89,45	89.65	89.07	89.55	¥8,82	95.54	96.81	
	43 45	47 7R	- e4 no	1.40		<u>, C</u>	49.70	48.14	40 AG	47 83	47 34	41 17	41.05	41 80	
Ah	56 78	54 73	24 18				40.73	40.02	AA AB	50 50	51.24	58.49	RA 77	58.90	
a	2.67	2 A1	0.82		S			1 01	173	1 58	141	245	2 2 23	1 54	
			10.000			1.00				1.00	1.41	A. 19	2.67	1.90	

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Table A1 (contd.) Pyroxene chemistry analyses

	MI	ca dior	ite					
Probe	145.X1	146.X2	145.X6	185.X1A	185.X19			
S'O2	51.41	51.18	51.26	49.82	49.73			
TiO ₂	80.0	0.08	0.12	0.12	0.09			
A1,0,	2.08	2.13	2.32	2.66	2.63			
Cr ₂ O ₂	0.01	0.00	0.01	0.00	0.01			
FeO	22.84	22,94	22.69	23.68	23.93			
Mn/2	1,22	1.19	1.15	1.28	1.18			
MgO	21.55	21.42	21.72	20.65	20.52			· · •
NIO	0.02	0.01	0.02	0,01	0.02			
CaO	0.35	0.38	0.38	0.32	0.27			į
Na ₂ O	0.01	0.01	0.03	0.01	0.01			
TOTAL	99,56	99,33	\$9.71	98,55	98.40			
En	62,26	61.98	62,55	57.98	57.59			
Fs	37.02	37.23	36.66	37.34	37.74			
Wo	0.72	0.79	0.79	0.63	0.53			
					4 J			
	. F	byroxei	ne leuc	odiorite				_
Probe	42.X2	42.X3	50.X1	60.X3	50.X5	50.X6	53,X1	53.X3
SiOz	50,90	51.33	52.09	51.86	51.59	51.35	51.22	51,28
TlO₂	0.09	0.10	0.12	0.10	0.08	0.07	0.10	0.09
Al ₂ O ₃	1. 96	1,88	1,70	1.57	1,68	1.44	1.72	1.75
Cr ₂ O ₃	0.04	0.01	0.03	0.01	0.01	0.02	0.03	0.02
FeO	22.22	22.21	22.91	22.87	23.26	23.67	22.28	22.42
MnO	0.55	0.55	0.50	0,46	0.50	0.55	0.51	0.50
MgO	22.54	22.75	22.04	21.82	21.50	21.11	22.71	22.52
NiO	0.05	0.08	0.05	0.05	0.06	0,06	0.08	0.03
CaO	0.48	0.47	0.55	0.71	0.62	0.50	0.54	0.54
Na ₂ O	0.02	0.01	0.01	0.02	0.00	0.00	0.02	0.00
TOTAL.	98.83	99,59	99,99	99.45	99.35	98.77	99,20	99,15
Ел	63.27	63.86	62.46	62.07	61,51	60.75	63.75	63,21
Fs	35.04	35,03	36.42	36.48	37.23	38.22	35.12	35.36
Wo	0.93	0.92	1.12	1,44	1.20	1,05	1,05	1.00
Braha	04 YOA	84 Y3	RA YA	492 X1A	197.XA	192.XR		
SIC	51.32	50.81	51.40	51.32	51.23	51.64		
	0.08	0.10	0.09	0.09	0.09	0.09		
Al ₂ O ₃	2.09	1.79	1.92	2,03	1.85	1.87		
Cr2O1	0.00	0.02	0.01	0.02	0.01	0.04		
FeO	23.50	23.42	23.29	23.20	23.27	23.19		
MnO	0.80	0.85	0.86	0.62	0.68	0.60		
MgO	21.49	20.99	21.06	21.46	21.26	21,56		
NIO	0.00	0.00	0.00	0.05	0,04	0.05		
	0.37	0.44	0.44	0.49	0.19	0.00		
TOTAL	0.00	0.01	69.05	99.92	48.82	99.54		
I UINL	99,00	9 0,4 0	99,04	99,£0	66.V£			
Επ	61.51	60.94	61.16	61.62	61.72	61.74		
Fs	37.72	38.14	37.93	37.37	37 90	37.24		
Wo	0.77	0.92	0.91	1.01	0.40	1 02		1

0	Pyroxene diorite													
	Probe	23,X3	23.X4	48.X1	56.X3A	102.X1	102.X2	102.X5	111.X1	111.X3	111.33	115.X1	113.X3R	122.X2
	SiOz	51.05	50.64	51.49	51.81	52.02	51.90	51.98	51.74 🥹	52.08	51.87	51.17	51,33	51.97
	TIO2	0.06	0.08	0.07	0.08	0.08	0.09	0.08	0.08	0.07	0.08	0.11	0.10	0.05
	ALO,	2.00	2.15	1.60	1.48	2.01	1.92	1.74	1.99	1.92	2.08	1.81	1.75	1.63
	Cr ₂ O ₃	().08	0:08	0.11	0,11	0.13	Ç.11	0.09	0.12	0.11	0.11	0.12	0.17	0.14
	FeO	23.71	24.69	21.69	21,04	21.19	21.57	21.37	21.81	21.66	21.82	21.61	21,60	20.89
	MnO	1.05	0.95	0.53	0.58	0.52	0 55	0.5t	0.56	0.57	0.59	0,54	0.58	0.56
	MgO	20.66	20.02	23.01	23.52	22.95)	22.95	23,01	22.68	22.56	22.70	22.77	23.15	23.05
	NIO	0.03	0.05	0.06	0.04	0.03	0.03	0.07	0.04	0.07	0.06	0.08	0.06	0,09
	CaO	0.45	0.49	0,41	0.44	0.54	0.49	0.50	9.46	0.43	0.39	0.57	0,49	0.53
	Na ₂ O	0.03	0.01	0.00	0.02	0.00	0.02	0.01	0,03	0.01	0.03	0.02	0.00	0.00
	TOTAL	99.12	99,15	88.98	89.22	99.49	99.61	99.36	99.51	99.4 7	\$9.72	98.80	99.24	38.98
		80.05	69.40	RA EO	86 20	65 17	64 97	65.00	(x.) 35	AA 43	84.48	B) 61	84 09	85 50
	Fe	38.79	30.48 40.47	34 10	33 17	33.74	34 19	33.90	34.72	34 69	34 75	34.39	34.05	33.32
	Wo	0.95	1.04	0.79	0.86	1.09	0.98	1.02	0.93	0.86	0.79	1.13	0.96	1.09
			с. 2						1					
									þ					
	Probe	122.X3	122.X7	222.X1	222.X3	222.X4	222.X6	222.X7						
	SiO ₂	52.02	51.93	50.95	50.89	50.71	50.48	51.20						
	TIO	0,06	0.06	0.08	0.09	0.08	0.10	0.05				27		
	Al ₂ O ₃	1.75	1.51	2.13	1,91	2.10	1.94	1.71				:		
	Cr ₂ O ₃	0.17	0.13	0.11	0.09	0.08	0.09	0.10						
8	FeO	21.17	21,54	23.66	23.87	23.85	24.20	24.79		5.				
	MnO	0.54	0.61	0.75	0.77	0.78	0.77	0.84		¢.				
ſ	MgO	23.00	23.06	20.62	20.70	20.58	20.65	20.64						ļ
	NIO	0.08	0.04	0.09	0.05	0.08	0.05	0.05						
	CaO	0.50	0.46	0.51	0,48	0.47	P.43	0.41						
l	Na ₂ O	0,01	0.00	0.03	0.02	0.02	0.[13	0.00	١	. 0			•	1
	TOTAL	89,33	99.35	98.93	98.86	24.75	98.83	99.80						
		AN 27	AF 04	#4 + 0		ob 00	E0 00	50.00						
		03,2/ 33 70	70,07 74,05	10U.19 10 A	QU,12 38 99	20.00	- 39.59 ∉30.21	30,28 30,88						
	Wa	1.03	0.94	37	1.00	0,99	1.10	0.84						
ł		1.000	187 + 947		1.44	2199								

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					Mica did	rite	
Proba	148.B4A	167.B2	167.83A	187.8\$	188.B1	186.B2	198
\$iO ₂	37.28	35.64	36.82	36,86	37.09	38 85	37.12
Tio,	4,83	4,90	4.84	4.67	5.04	5,30	4,95
Al ₂ O ₃	14,10	14.41	13.78	13.48	14.20	14.15	13.99
Cr₂O₃	0.02	0,00	0.01	0.01	0.00	0.01	0.00
FeO	12.77	15.01	13.98	14.73	13.78	14.33	13.66
MnO	0.18	0,09	0.06	0.08	0.16	0.24	0.12
MgO	15.30	13.43	14.67	14.11	14.68	13.72	14.90
NIC	0.02	0.01	0.00	0.00	0.01	0.03	0.03
BaO	0.44	0.64	0.59	0.60	0.37	0.41	0.33
K ₂ O	9.76	9.62	9.54	9.58	9.52	9,76	9.78
Na₂O	0.05	0.15	0.09	0.14	0.11	0.12	0.09
TOTAL	94.74	94,89	94.17	94,08	94.95	94.71	\$4.97
							1
Al/Mg+Fe	0.50	0.52	0.48	0.48	0.50	0.51	0.49 j
Mg/Mg+≨e	0.68	0.62	0.65	0.63	0.66	0.63	0.66

Pyroxene leucodiorite

Probe	192.B1	192.B2	50.B6A
SiO ₂	37.67	37.50	37.57
TiO,	4.36	3.48	5.00
Al ₂ O ₃	13.50	13.87	13.66
Cr ₂ O ₃	0.06	0.07	0.09
FeO	12.12	14,66	13,10
MnO	0.08	0,22	0.04
MgO	16.64	14.78	15.77
Nio	0.12	0.13	0.17
BaO	0.33	0.20	0.30
K ₂ C/	9.60	9.62	9.54
Na _z O	0.03	0.03	0.08
TOTAL	94.89	94.56	96.31
			•••
Al/Mg+Fe	0.46	0.48	0.47
Mg/Mg+Fe	0.71	0.64	0.68

Table A1 (contd.) Mica chemistry analyses

			Pyroxen	e diorité	}					
Probe	102.B1A	111.81	111.83	122,87	222.B1A	222,B3	222.B6A	222.87A	23.81	23.83
8iO ₂	37.94	37.95	38.22	38.67	38.38	38,29	\$2,46	38.25	38,56	38.55
TIO2	4,16	3.84	3.74	3.74	3.71	3.21	3,44	3.36	2.35	3.09
Al ₂ O ₃	13.76	13.70	13.80	13.58	12.82	13.38	13.47	13.47	13,46	13.32
Cr ₂ O ₃	0.37	0.42	0.39	0.38	0.25	0.26	0.22	0.24	0.11	0,17
FeO	10.01	10.69	10.50	9.58	11.74	11.21	11.25	11.01	10.95	10.89
MnO	0.05	0.05	0.02	0.05	0.20	0.04	0.06	0.04	0.12	0.08
MgO	18.06	17.72	18.18	18.97	17.42	18.04	18.30	18.40	18.56	18.51
NIO	0.23	0.15	0.16	0.19	0.11	0.13	0.12	0.13	0.68	0,06
BaO	0.16	0.29	0.24	0.27	0.13	0.14	0.11	0.11	0,15	0.14
K₂O	9.40	9.79	9,70	9.55	9.42	9.85	9.75	9,79	9.42	9, 65
Na ₂ O	0.16	0,10	0.07	0.07	0.09	0.07	0.12	0.09	0.09	0.08
TOTAL	84.29	94.73	95,03	95.06	\$4.07	\$4.61	\$6.31	94,88	93.82	\$4.5 2
j			•							
AVMg+Fe	0.48	0.46	0,46	0.44	0.42	0.44	0,43	0.43	0,43	0.43
Mg/Mg+Fe	0.76	0,75	0,76	0.78	0.73	0,74	0.74	0,75	0,75	0.75

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Table A1 (contd.) Magnetite chemistry analyses

				Mica dic	prite			<u> </u>			
Probe	185.M1B	185.M2A	185,M28	185.M3A	188.M3C	185.MA	188.M#	185.MC	188.MD		
110 ₂	0.05	0.20	0,06	0.13	0.10	0.22	0.04	0.01	0.01	•	
Al ₂ O ₃	0.09	0,18	0.19	0.27	0.14	0.07	0.03	0.05	0,04		
Cr ₂ O ₃	0.03	0.02	0.05	0.04	0.04	0.02	0.02	0.03	0.04		
FeO	93.02	92,68	92.65	82.94	93,18	93.59	92.98	93.31	93.47		
MinO	0.05	0,03	0.04	0.01	0.03	0.03	0.02	0.03	0.08	ť,	
MgO	0.00	0.00	0.00	0.00	~0.00	0.00	0.00	0.00	0.00		
V ₂ O ₅	0.63	0,64	0.74	Q/48	0.75	0.53	0.54	0.42	0.46	_	
TOTAL	\$3,88	83.77	93.73	\$4.05	94.25	94.40	\$3.63	93.86	\$4.10	•	
Recalculat	ed analyse	\$									
FayOn	68.60	68.09	68.23	68.30	66.57	68.84	68.63	88.96	69.10		
FeO	31.29	31.41	31.27	31.48	31.48	31.65	31.22	31.25	31.29		
TOTAL.	100,75	100,58	100,57	100,90	101.12	101.37	100.50	100.76	101.02	,	
								14 A.			
L	· ·										
			Pyroxe	ne leuco	diorite						
Probe	207.M1B	207.M1C	207.M2	207.M3B	42.M1A	42.MA	42.MB	63.M2	53.M4A	53.M48	63.MA
TIO ₂	0.06	0.05	0.07	0.05	0.22	0.11	0.10	0.11	0.09	0.30	0.06
Al ₇ O ₅	0.35	0,29	0.31	0.34	0.29	0.39	0.23	0.32	0,29	0.29	0.35
Cr ₂ O ₂	1.61	1.46	1.36	1.31	1.51	1.39	1.34	1.45	1.25	1.50	1.46
FeO	91.07	80,36	90,99	91.74	90.55	91.11	91.22	91.56	91.19	91, 3 3	91.18
MnO	0,08	0.07	0.04	0.05	0.05	0.02	0.07	0.05	0.07	, 0.02	0.02
MgO	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.00
V ₁ O ₁	1.02	1.05	0.99	1.00	0,91	0.99	1.01	1.06	1.01	1.12	1.10
TOTAL	84,19	\$3.28	93.76	94.47	93.64	94.00	93,92	94.56	\$3.92	94.56	84.19
Recalculat	ed analyses	F						1.5			
Fe ₂ O ₃	66.35	8 5,90	86,35	66.96	65.84	68.34	66.56	66.67	66.55	65.20	65.37
FeO	31.37	31.08	31.27	31.49	31.31	31.41	31.33	31.57	31.31	31.76	31.45
TOTAL	100.84	99,88	100.40	101,18	100.14	100.65	100.86	101.24	100,58	101.19	106.83

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Table A1 (contd.) Magnetite chemistry analyses

MgO

TOTAL

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									ستر أفسي معيد ال	
	*****			<u></u>	Pyroxen	e diorite				
Probe	86.M1	56.M2A	68.MA	56.MB2	113.M1	113.M2	113.M3A	113.M3B	113.MA	113.MBR
TiOz	0.20	0.42	0.23	1.62	0.34	2.08	0,25	0.24	0.11	0.24
Al ₂ O ₂	1.53	0.94	0.95	1.36	1.76	1.61	1.82	1,72	0.79	1.46
Cr ₂ O ₃	6.24	6.28	6,62	5,35	8.07	8.37	8.66	8.09	8.01	7.40
FeÒ	85.24	85.15	85.18	85.12	82.42	80.78	82.03	83.62	84.48	84.16
MnO	0.17	0.18	0.15	0.24	0.37	0.49	0.24	0.28	0.29	0.27
MgO	0.04	0,02	0.03	0.01	0.00	0.05	0.05	0.04	0.00	0.00
V ₂ O ₈	0.72	0.66	0.72	0.72	1.10	0,94	0.96	1.04	0.88	0.95
TOTAL	\$4.13	93.64	\$3.87	94.41	94.06	84.32	94.01	95.03	94.55	84.47
Recaiculat	led analyse	4								
FazOz	59.83	59,77	59.89	58.26	56.75	53.41	56.36	57.79	59.13	58.55
FeO	31.40	31.37	31.30	32.70	31.36	32.72	31.32	31.62	31.27	31.47
TOTAL	100.12	\$9.63	99.88	100.25	99.76	89.67	99.65	100.82	100.48	100.33
	-	ir.								
Ì								r -		
								2		
Probe	122.M7	122,MA	122.MB	122.MC2						· •
TiO ₂	0.26	0.91	0.25	1.42					· ·	
Ai₂O₃	2.05	2.13	1.90	2.89				4		
Çr ₂ O ₃	9.22	8,75	8,73	8.65				i de la compañía de la		
FaO	81.71	81.82	81.43	79.89				:		
MnO	0.37	0.38	0.33	0,36			į.	:		

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table Al (collar) milenic chemisty analyses

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Drobe	42 M4R	64 M21	172 MC4	185 M4A	207 644 6	207 1434
11000	*A., (1) 1.5.5	10.00	125.111.01	INCOMIN	Lui atti i A	EUT MINI
TiO ₂	49.24	51.3 9	51.59	51.41	48.70	52.59
Al ₂ O ₃	0.04	0.00	0.02	0.03	0.01	Ü.03
Cr ₂ O ₃	0.15	0.25	0.45	0.01	0.10	0.14
FeO	47.48	46.50	44.03	41.37	47.05	44.01
MnO	2.69	1.96	4.14	7.31	2.89	4.14
MgO	0.11	0.21	0.02	0.00	0.17	0.08
V ₂ O ₅	0.11	0.00	0.00	0.00	0.45	0.00
TOTAL	99.82	100.31	100.25	100.14	99.37	100.95
	۵.			-	·	
Recalculat	ed analyse	8				
Fe ₂ O ₃	6.82	2.94	2.08	2.83	7.20	1.13
FeO	41.35	43,85	42.16	38.82	40.57	42.99
TOTAL	147.84	146,85	144.04	141.77	147.03	144.94

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Table A2 Whole-rock analyses of Koperberg Suite anorthosite

	-		1				<u> </u>									0	
Sample	14	19	22	24	63	85	107	<u>, 136</u>	137	141	143	144	147	148	150	151	
SiO2	61.97	62.11	6 0.04	57.79	57.42	56.29	55.47	56.77	67.14	/2.85	59.38	76.08	77.60	66.02	74,48	65.96	
TIO ₂	0.02	9.08	Q.19	0.01	0.03	0.02	0.24	0.27	0.16	0.14	0.12	0.10	0.13	0.16	0.18	0.31	r G
Al ₂ O,	23.22	22.55	23.49	24.45	25.83	25.72	24.05	20.03	17.94	15.08	25.85	13.85	12,52	20.09	13.98	18,20	
Fe ₂ O ₃	0,37	1,39	2.82	0.57	0,59	0.85	4,75	5,25	2.23	2,19	1.59	1.12	0.7	1,98	1.82	4,82	
MnO	0.03	0.03	0.07	0.03	0.05	0.02	0.06	0.05	0.64	0.01	0.04	0.03	0.00	0,00	0.01	0.01	
MgO	0.14	0.40	0.74	0.59	0.38	0.29	0.93	0.65	0.05	0.00	3.00	0.00	0.00	0.00	0.00	0.01	
GIO	0.21	0.39	9.6Z	6.66	8.11	8.17	0.01	6.04	3.29	4,44	(.))3 # = 0	3,80	3.12	6,22 4 74	3,51 3,50	4,00	
	0.60	4.29	0.0U ≮ 30	3.34	3,40	3,30 1.1.4	0.27	0.01	4,/4	2,30	9,90 4 4 5	3.21 0 KG	2.33	4./4 h-04	1.00	0.45	
P.O.	1.21	50.0 20.0	1.32	0.03	0.03	0.04	0.05	0.50	0.32	0.76	1.12 0.01	0.00	0.01	0,01 // 01	0.00	0.07	
Cu	0.00	0.01	0.03	0.01	0.00	0.04	0.04	0.18	0.02	0.07	0.00	0.00	0.01	0.00	0.00	0.02	0
1.01	0.68	0.63	1 31	1 09	0.44	0.55	1 02	2.74	0.57	0.24	0.00	0.42	0.40	0.29	0.65	0.43	
TOTAL	99.93	99.78	101.30	\$8.19	89.22	98.67	100.64	98.36	99.14	98.52	102.97	99.21	\$7.9B	100.32	99.16	101.47	•
																1	
Co	2	5	8	4	4	4	11	16	11	8	7	8	8	6	6	10	
Ni	1	3	19	3	2	8	24	35	4	0	0 9	0	1	4	ĉ	5	
Zn	15	24	46	17	19	21	69	78	38	25	26	21	19	28	24	40	
Rb	14	9	48	31	11	18	27	44	24	19	24	15	13	13	25	23	
Śr	300	607	500	752	983	1219	549	772	568	473	753	358	328	613	454	494	
Y	14	3	39	8	4	8	7	62	10	2	6	2	7	4	3	6	· ·
Zr	182	80	47	9	13	49	18	97	146	50	126	56	54	119	92	90	
Nb	2	1	8	2	1	1	4	3	3	3	2	4	4	4	5	з	
v	5	26	24	6	4	9	113	69	42	. 45	40	23	12	60	47	100	
Cr	3	18	50	11	2	48	34	3	10	14	39	18	14	24	14	16	
Ba	160	230	252	277	247	254	258	294	337	233	378	177	208	313	272	296	
																N.	
																ς.	
Sample	168	170	176	177	178	180	183	184	209	210	212	213	220				ý
SiO ₂	59,09	59,28	58 50	55.93	67.29	69.64	75.51	65.64	67.25	87.52	73,82	65.07	58.09				ĺ.
TiO ₂	0.04	0.04	0.15	0.11	0.10	0.11	0.17	0.27	0.14	0.18	0.15	9.32	0.05				ł
Al ₂ O ₃	24.49	24.56	27.06	25.89	20.17	17.93	13,61	17.34	18.55	13.55	13.85	18.08	25.73				1
FerO1	0.36	0.41	2.24	1.94	1.29	1.65	0.82	3.94	1,86	2.13	2.04	3.60	1.13				ų
MnO	0.01	0.02	C.C2	0.01	0.01	0.00	0,00	0.02	0.00	9.00	0.01	0.04	0.03				1
MgO	0.00	00,00	0.00	0,26	0.00	0.00	0.06	0.23	0.00	0,00	0.00	0.08	0.28				ij
5x0	5.69	5,06	8,31	6,90	5.55	5.12	3.46	4.55	5.40	5.38	3.91	5,31	8.09				
Na ₂ O	7.74	7.81	4.77	4.33	4,69	4.44	3.46	5.32	4,55	7.21	5.41	3.78	4.33		į.	,	
K20	1.36	1,37	0,96	1,38	1.00	0.60	0.86	85.2	0.86	0.76	0.63	0.90	0,97		(
P205	0.02	0,03	0,01	U,04	0.01	0.01	0.00*~	0.00	0.01	0.00	0.01	0,00	0.02				
Cu A	0.00	0,03	0.03	0,06	0.01	0.00	0.00	0.01	0.04	0.00	0.01	0.01	0.00				
	0.07	7.17	0.30	1.00	0.50	0.37	0.61	0.75	0.35	0.28	0.29	0.31	0.87				
TAL	\$8,46	4¥.77	192,43	a1.70	100.83	100.07	a9'21	¥3.34	A\$,80	102.05	100.12	87.50	97.37				
	a	=	7	R	*	a	đ	10	P	7	10	p	7				
Ni		3	, A	u K		1	3	7	ιμ Λ	۰ ۳	4	4	, F				а,
7-	-16	- 10	30	ગુન	~* 54	1 27	. 1	(87	74 74	37	- 97	د.	: 27€				
- Bh	39	30	15	40	10	15	55 77	20	10 12	44	41 1	- 1/ 1/2	2° 40 74				
ST.	378	415	739	784	10	428	307	461	. ∦ 07	354	376	20 489	41 034		<u></u>		
	20	18	1.44 . A	a.	5	5	2	-14-14 16	-101 K	¢	4		0.44 0				
z,	17	183	73	<u>42</u>	107	11Ř	10	53	177	V 149	75	-04 -04	- 9n				
Nh			4	3	3	3	, 9 K		(14) (13)	0	3	41 4	2				
V I	8	Ă	61	52	20	32	- 15 - 15	AR	<u>4</u>	31	47	9.4	17				
Cr I	3	8	25	74		1.	10	11	22	17		17	41 29				
	190	251	267	367	219	288	253	335	235	205	59 8	350	55 275				
					_						-						فبعداد

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Table A2 (conid.) Whole-rock analyses of Koperberg Suite mica diorite

1			وري والم											نمبندها ()ی هم :	فنسنان كتسنية	ويتبار والمتراف	
Sample	13	21	26	28	112	138	139	145	149	159	184	187	178	181	195	188	187
510,	52.10	49.44	51.60	50.25	53.21	50.06	49.37	51.15	52.41	51.88	49.96	50.56	50.72	51.14	49,50	47.90	49.87
TiO:	0.80	1.30	1.04	1.01	0.79	1.21	1.19	1.01	0.94	0.75	0.80	0.84	1.19	0.94	1.15	1.19	
AlzOa	23.31	22.35	22.72	22.28	24.16	22.21	22.18	22.89	22.30	23.13	23.34	23.32	22.16	20.94	21.87	22.17	22.61
Fe ₂ O ₁	6.66	10.39	5.32	9.29	6.60	10.11	10.14	9.00	8.37	8.03	8.80	7.14	10.21	8,32	10.07	10.61	9,81
MnO	0.64	0.08	0.05)0. 06	0.07	0.09	0.07	0.07	0,05	0.04	0.03	0.04	0.13	0.08	0.07	0.07	0.09
MgO	1:02	2.76	2.74	2.67	1.87	2.70	2.93	2.13	1.72	1.54	1.76	1.83	2.59	1 84	2.53	2.98	2.85
CaO	6.95	8.04	5.72	5.57	6,78	6.40	8.25	6.83	6,72	7.05	7.19	7.24	6.26	6.11	6.27	5,82	6.22
Na ₂ O	5.49	4.72	5.63	4.20	4.93	5.02	4.25	4.41	4.73	7.05	5.94	6.55	3.06	4,85	5.95	4.34	4.84
K₂O	1.88	2.06	2.04	1.88	1,94	1.86	1.85	1.58	1.40	1.68	1.73	1.83	1.71	1.47	2.03	2.59	1.96
P ₂ O ₅	0.37	0.03	0.37	0.47	0.48	0.02	0.03	0.02	0.02	0.29	0.38	0.40	0.01	0.02	0.01	0.02	0.01
j Cu	0.11	0.00	0.25	0.05	0.11	0.01	0.01	0.00	0.00	0.06	0.11	0.10	0.01	0.01	0.00	0.01	0.01
LOI	0.74	0.44	1.55	1.20	0.95	0.50	0.85	0.43	0.64	0.97	1.51	0.72	0.27	0.32	0.70	1,45	0.44
TOTAL	100.47	99.69	99.05	\$9.01	102.08	89.99	99.11	29.29	99.30	100.71	99,66	100,85	98,51	96,83	100.45	99,15	99,85
	1	19	4.0	16	10	-	24	10	15	44	90	40	10	47	70	-17	-10
	10	24	10	10	10	32	-31 -35	10	12	12	40	14	20	11	20	20	20
. Da 7#	111	194	4# 73	4145	124	124	140	4.0 112	445	OR	192	125	122	41	133	147	178
Dh	104	137	170	110	124	167	179	67	73	117	144	107	101	80	192	180	134
57 1	1561	636	876	698	1105	661	871	504	627	710	1002	1166	516	50.7	816	787	683
	10	200	010	58	70	10	11	10	8	50	16	16	11	11	13	13	12
i Zr	920	36	249	1061	826	73	79	54	65	385	848	829	40	121	94	85	83
Nb	R	17	26	13	22	16	17	14	13	19	3	9	15	12	20	74	20
v	204	214	132	176	220	307	324	217	724	128	208	217	199	175	311	333	301
Cr	s .	0	14	D	11	1	6	9	3	3	7	5	2	3	7	3	2
Bx	1133	812	596	725	831	974	920	827	637	573	1077	1314	812	784	977	1192	1007
			0														
Sample	198	139	190	193	194	197	198	211	214	215							
SiC,	47.78	48.23	46.97	50.03	46.59	47.94	48.07	52.07	48.27	52.03							
TIO	1.15	1.13	1.18	1.09	1.25	1.19	1,19	1.00	1.18	0.58							
Al ₂ O ₂	22.22	22,47	22.63	22.19	21.71	22.30	21.77	21.60	22.64	22.03							
F#2O3	10.65	10,41	10.48	9.86	13.16	10.30	10.45	10.00	10.72	8 98							
MnO	0.07	0.07	0.05	0.08	0.05	0.07	0.05	0.20	0.07	0.08							
MgO	2.80	2.77	2.92	2.32	2.79	2.69	2.96	2.78	3.21	2.10							
CeO	8.35	6.30	6.40	6,38	5.84	6 02	5.53	6.37	5 90	6.63							
Na ₂ O	5.55	4.79	4.45	3.47	3.90	4,16	5.62	4.99	7.11	7.30							
K20	2.10	2,26	2.14	1.82	2.34	2.57	1.66	1.05	2.31	1.02							
P ₂ O ₅	0.02	0.02	0.03	0.00	0.00	3.04	0.03	0.01	0.00	0.02							
Cu	0.02	0.04	0.03	0.02	0.02	0.05	0.06	0.01	0.04	0.01							
	0.67	0.00	400.02	0.36	0.00	1.03	1.46	400 55	409.99	0.41							1
	58/01	34,2 7	100.02	a1.04	#0.%£	40.41	20.00	100.00	144.49	101%1							
Cn 1	33	29	32	26	34	30	28	19	30	21							
Ni	22	36	38	34	40	43	44	25	58	15							
Žr,	148	151	149	128	53	158	121	131	144	111							
Rb	160	185	158	101	177	181	117	52	187	40							
Sr	770	752	783	618	736	706	706	482	687	670							
Y I	13	14	16	7	13	13	12	16	14	22							
Zr	72	77	62	48	128	114	12	89	82	167							
Nh	22	25	24	17	24	29	21	9	28	7							
	1 -																<
1 V I	313	323	319	290	424	307	318	176	344	1.95							
Cr	313 5	323 0	319 2	290 4	424 7	307 7	318	1/6	344 1	195 3							

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Table A2 (contd.) Whole-rock analyses of Koperberg Suite pyroxene leucodiorite

	¥																
Sample	12	35	36	37	40	41	42		44	46	47	48	49	60	51	62	53
SIO	54,90	50.02	49.75	49.58	50.71	49.52	48,72	49.40	48.88	49.51	49.51	49.15	48.80	49.45	50.06	52.15	49,37
THO2	0,18	0.35	0.33	0.36	0.39	0.41	0.41	0.35	0,40	0.39	0.38	0,37	0.30	0.32	1.01	Q.22	0.40
Al ₂ O ₂	29.32	17.74	1.02	17.00	17.11	17.04	15,91	17.44	17.06	15.61	17,13	17.30	17.40	10.5	10.13	20,51	17.56
14203	4.06	12.30	12.27	14.00	13,04	13.35	14.04	12.32	13.01	13.42	13,00	13.50	13.03	10.44	10.42	0.00	12.70
Millo	0.04	Ų.139 27.211	U.IQ	7 18	7.43	707	0.10 2 2 2	8.17	7.44	7.61	7.63	9.17 9.44	7.80	8 70	0.13 8 54	5 17	7.10
CaO .	7.51	6.01 # 02	5 64	4.88	5 79	5.55	5.47	8.20	5.04	7.0 · 5 78	5.64	5.95	3.84	4.20 # 51	8.57 8.58	7 00	R.11
Na-O	497	3.54	3.95	3.73	2.98	3 72	3.05	3.28	2.87	2.95	3:65	3.94	1.98	4.78	2.65	3.89	3.22
K-O	0.90	0.62	0.60	0.81	0.65	0.64	0.60	0.80	0.62	0.64	0.64	0.58	0.91	0.71	0.70	0.65	0.59
P ₂ O	0.14	0.10	0.09	0.12	0.08	0.07	0.09	0.00	0.09	0.10		0.08	0.08	0.06	0.13	0.13	0.09
Cu	0,15	1.21	1.26	1.49	1.30	1.38	1.68	1.17	1.19	1.33	1	1.34	0.88	0.96	0,84	0.57	1.28
LOF	0.50	0.1 5	0.10	0.31	0.03	0.01	0.03	1.41	1.27	0.08	0.12	0.08	4.09	1.83	1.51	0.21	0.20
TOTAL	98.48	29.20	99.32	99.91	100.29	100.34	99.06	99,34	98,65	98.80	99.38	100.05	99.24	100.08	99.01	99.69	86.92
1																	i
Co	10	50	51	50	54	51	61	50	53	53	. C.)	60	53	÷1	45	34	51
Ni -	14	220	210	233	234	238	267	225	234	243	231	236	209	195	181	134	215
Źn	49	196	187	185	212	219	239	203	210	216	213	213	265	174	174	130	19Z
Rb	8	13	15	21	20	18	18	12	- 17	-22	16	20	71	21	18	12	16
Sr	919	716	721	7Z	717	704	665	716	708	702	723	720	447	767	786	883	765
Y	33	12	12	14	10	13	12	9	10	11	14	14	20	11	- 14	12	10
Zr	351	5	6	16	13	20	16	14	14	7	15	12	13	17	8	14	13
ND		1	2	. 3	3	3	3	3	3	3	· 2	4	4	3	2	3	3
	82	270	251	291	312	309	325	283	198	311	301	378	225	217	306	180	284
Gr	250	208	46/	500	73/ 778	344	241	497 (010	204	450	24.3	402	350	402	323	400
	200	£33	220	~40	2/9	231	441	224	240	201	243	24.7	185	440	290	200	2004
1.																	
Sample	54	55	67	5 0	61	62	64	65	73	74	75	77	78	81	82	85	36
SIO2	49.54	49.61	49.82	48.96	50.61	50.74	50.88	51.14	49.04	49,77	49.57	48.98	49.01	49.76	49.00	50.46	49.86
TiO _z	0.39	0.40	0.55	0.58	0.47	0.67	0.52	0,43	0.38	0.35	0.36	0,35	0.34	0.37	0.38	0.35	0.29
Al ₂ O ₂	17.12	18.95	21.68	20.75	20.66	20.32	21,28	21.45	16,72	17,49	17.41	16.60	17.13	17.45	16.55	18.19	18.51
FryD;	13.22	13.63	12,35	13,56	11.81	13,77	11.59	10.71	13,34	12.53	12.08	12 87	.11.58	12.08	13.36	11.81	10.12
MnO	0.19	0.20	0.13	0,15	0.13	0.14	0.14	0.12	0.18	0.18	0.18	0.18	0.17	0.16	0.16	0.17	0.14
MgÖ	7.48	8.11	2.48	3.26	2.89	3.18	2.66	2.54	7.76	7.07	6,95	7.37	3.21	5.96	7.77	6.85	5.91
CaO	5.82	5.87	6,70	8.65	6,50	5.94	6.85	6.59	5.82	6.21	579	5.43	5.33	6.16	5.84	6.13	5.37
Na ₂ O	3.43	3.10	6,30	4.17	4.58	4,43	5.10	4,54	3.75	4.27	4.66	5.43	4 59	5.78	6.40	5.35	3.67
K.0	0.59	0.55	0.78	0.65	0.72	0.99	0.81	0.72	0.62	0.60	0.71	0.76	0.51	0,63	0.60	0.71	0.83
	0.09	0.13	0.06	0.03	0.06	0.05	0.04	0.05	0.07	0.10	0.10	0.08	0.08	0.10	0.09	0.09	0.09
	1.34	1.33	0.17	0.20	0.09	0.10	0.00	0.04	1.41	1,20	1,07	1.41	0.85	1.09	7.34	1.07	0.77
TOTAL	99 47	68.60	101 64	99.95	0.00	100 78	00.07	10.01	0.14	400.02	0.78	100 22	05 24	100 89	101	464	4.04
	40.41	30.84	10 5104	34.40	80.91	10040	#8.43	39.IJ	an,an	100.00	49,99	199.22	44.428	100.80	101.03	101,00	88.19
co	56	55	29	37	29	32	27	24	54	50	50	53	50	47	51	48	38
NI	234	225	82	75	72	81	58	68	225	228	217	241	217	204	238	206	184
Zn	203	197	148	155	147	179	137	128	194	189	177	212	192	181	188.2	187	171
Rb	17	15	10	12	18	51	10	10	16	22	37	46	45	16	19	25	45
5r	751	737	731	714	722	627	673	645	735	746	736	667	664	770	714	769	688
Y	11	16	17	18	19	21	41	11	11	11	12	14	14	10	12	13	16
7.5	7	7	4	3	24	55,	9	8	10	10	14	13	12	10	10	10	11
Nb	3	2	5	4	6	9	4	3	2	3	2	2	2	3	2	2	3
v	335	304	318	310	259	337	275	271	311	306	270	269	235	286	328	266	223
Cr	553	527	26	20	18	25	21	16	522	508	484	509	430	496	557	472	384
<u></u>	263	251	143	135	133	255	199	197	249	223	227	207	150	270	252	259	227

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Table A2 (contd.) Whole-rock analyses of Koperberg Suite pyroxene leucodiorite

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Sample	87	88	89	90	100	116	191	192	195	126	199	200	201	202	203	204	205
SiO	51.43	51,24	49.1 t	49,65	51,77	51,62	51.63	52.81	48.37	49,45	46.41	49.84	48.61	48,88	49,19	50,18	50.09
TIO	0,30	0.27	0.36	0.35	0.49	0.42	0.15	0,21	0.36	0.35	0.58	0.35	0.44	0.42	0.79	0,36	0.36
Al ₁ O	19.37	20.00	18.89	17.48	21.91	23.54	22,40	21.59	16.95	18.32	13.60	18.11	15.93	16,26	21,53	18,01	15.28
FerO3	9.64	8,97	12,46	12.59	11.06	7.83	5.21	6.87	12.92	11.66	19,25	12.31	15.15	14,59	13.47	12.12	11.48
M51O	0.13	0,11	0.15	0.16	0.10	0.08	0.07	0.11	0.19	0.14	0.26	0.20	0.24	0.22	0.15	0.16	0.17
MgO	5.49	5.08	7,23	7.23	2.18	0.76	2.95	3.84	8.98	5,98	9.56	6.44	8.07	7.86	1.73	6.57	5.97
C=O	6.18	5.71	5.99	5,73	6.74	7.61	7.58	7.37	5.59	5,93	4.40	5.90	5.25	5,48	8,19	5,28	8.50
Ne ₂ O	4,65	5,85	4.13	3.54	3.61	7.03	4.30	3.48	2.95	3.21	2.99	4.79	3.73	2.91	4.87	3,22	3.59
Kro	0.93	0,80	0.71	0.64	0.81	0.82	0.75	0.77	0.70	0.78	0.42	0.60	0.50	0.57	0.92	0.63	0.65
P2Os	0.07	0.06	0.07	0.19	0.03	0.11	0.01	0.05	0.08	0.08	0.09	0.04	0.06	0.07	0.02	0.04	0.07
Cu	0.62	0,67	1.11	1.13	0.05	0.04	0.17	0.40	1.10	0.96	2.11	1.35	1.63	1.84	.0.05	1.21	1.00
LOI	1.39	2.55	1.57	0.59	0.25	0.42	0.95	0.61	0.98	114	0.61	0.38	0.42	0.20	<u>0</u> 50	0.43	0.60
TOTAL	100.20	101.38	39.81	99. 21	99.01	100.28	96,19	97.93	97.17	98,00	100.25	100.29	100.25	\$\$,29	8F 48	\$8,81	99.05
1	36	47		40		4.9	10	24	49	45	· • •		**	**	A.		
	30	32	20	44	76	1.0	10	24	90	40 404	71	44	30	30	1.40	44	31
	100	192	221	210	70	404	11	30	.207	104	313	213	2//	249	(4 ¥	200	106
	197	104	197	190	140	101	40	112	210	100	583	139	230	210	197	1/8	163
	20	44	20	23	21 244	12	19	20	72. 72.	3(20	-22	23	24	25	- <u>2</u> E	21 7770
ar	(33	683	120	129	501	09(202	082	590	1	200	100	000	695	040	/41	/52
	10		13	12		495	Q ng	10	12	100	10	12	15	10	9 20	10	10
		10	14	4	1.24	404	4.J	1-7	1.9	# =	19	10	14	10	20	14	4
100	108	202	478	9 796	9 754	i Tiradk	ت. هغ	44.4	3 778	ע ע. רלר	4	204	ാ	9	-343	3	- 244
	180	202	473	400 475	50	200	1.42	114	450	401	423	462	200	300	243 73	234	232
	097	392	413	470	46 105	386	19.2	560	900	401	105	マイプ	270	1995 2992	23	200	210
	204	220	204	220	140	200	200	200	241	201	190	241	143	230	310	200	200
					,												
Sample	206	207															
SIO2	52.27	51.72															
TiOz	0.63	0.32															
Al ₂ O ₂	22.29	19.55															
Fe ₂ O ₂	6.56	9.60										ы N					
MuC	0.05	0.13		ie!													
MgO	1.72	5.10															
G*O	7.85	8.91											•				
Na,0	4.69	3.68											•				
, κ _z o	1.49	0.73							· .·								
P:O:	0.29	0.05											1		:.		
Çu	0.24	0.66	•												· ·		1
	0.65	0.15	1														1
TOTAL	98.61	98.90															
	Ì																
Go	23	30								:							
NI	41	134								3	:						
Zn	96	143								4							
Rb	92	22															
Sr i	854	827															
I Y I	32	-14	•														ļ
Zr	136	18															
Nb	11	4															
	220	189															
Cr	55	308															
<u>Ba</u>	542	285															

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Table A2 (contd.) Whole-rock analyses of Koperberg Suite pyroxene diorite

	1 44	-	**	27	80	8 0	76	44	73	00	154	102	102	4164	108	108	108
	48.00	£3 £4 72	44.49	40.61	87 04	45.82	24.86	49.07	40.51	49.20	18.05	40 14	48.02	49.01	A4 42	47 71	48.44
	10.26	01.72	0.93	10.01 D 201	74-41	40.40	40.00	13.07	12,31	0.40	0.95	n 28	0.20	0.21	0 37	0.52	0.25
ALO.	10.00	12.45	9.26	14.01	1749	10.91	11.78	10.01	11.46	14 54	12.97	11 20	10.43	12.48	18.76	19.37	13.31
Fe.O.	19.05	14.08	18.94	19 73	10.34	15.66	18.50	17 30	16.23	1478	13.86	18.82	18.19	15.66	9.97	13.07	14.70
MnC	0.39	0.27	0.34	0.24	0.19	0.31	0.30	0.34	0.31	0.24	0.25	0.30	0.33	0.30	0.14	0.13	0.26
MaQ	13.40	8.92	12.24	10.43	8.20	12.47	12.35	14.50	13.42	8,47	11.61	13.25	13.84	12.27	5.17	3,93	11.09
CEO	3.30	3.12	2.92	4.38	5.12	3.83	4.05	3.13	3.68	4.58	4.48	3,79	3,39	4.04	5.33	6.16	4.43
Na-C	2.20	2.53	1.45	2.33	3.53	2.19	2.27	1.63	2.14	1.81	2.13	1.79	1.89	2.30	3.17	3,95	2.62
K-0	0.54	1.78	0.28	0.76	0.79	0.49	0.40	0.51	0.48	0.65	0.57	0.48	0.47	0.47	0.69	0,70	0.45
P ₂ O ₄	0.20	0.18	0.19	0.06	0.13	0.12	0.14	0.13	0,12	0.07	0.11	0.14	0.09	0.06	0,18	0.04	0.14
Cu	1.78	0.53	2.14	2.01	0.69	4.32	2.33	2.32	1.61	2.87	2.32	2.28	2.14	1.85	0.57	1.86	1.72
LOI	0.00	2.92	3.92	0.93	1.66	0.17	0.23	0.35	0.33	0.40	0.00	0.12	0.02	0.33	11.80	0,05	0.37
TOTAL	100.02	59,06	97.50	98.76	98.66	\$7.50	99.41	99.73	99.51	98,97	97.13	99.56	97.91	98,69	98.66	\$7.47	97.71
										·							· [
Co j	92	50	114	73	33	93	3 77	98	79	63	60	75	74	74	34	47	58
NI NI	425	233	574	445 ·	° 1 84	588	441	541	427	410	408	457	475	401	202	261	375
Zn	315	272	407	227	212	267	249	297	273	244	226	284	275	253	151	153	244
R5	57	203	22	60	57	39	20	45	35	46	50	46	42	32	45	36	-3 2 -
Sr	364	349	360	600	644	471	481	422	475	804	544	478	503	554	770	909	528
Y	65	70	31	30	32	34	33	43	41	22	34	42	39	34	43	16	31
Źr	[17	21	10	9	29	18	10	11	13	21	20	22	17	19	377	17	19
Nb	11	31	2	8	.7	5	2	7	8	8	7	7	6	5	9	8	្ទា
	270	157	183	175	104	145	216	165	171	208	161	185	145	177	240	355	136
Cr	1680	909	1815	1542	870	1836	1525	⊎ 1830	1460	1755	1348	1568	1578	1321	459	199	1284
84	170	367	128	227	174	147	135	181	152	216	212	177	195	152	218	245	180
	400	444	442	142	112	417	440	110	120	173	199	199	124	195	478	197	170
Catality in	47.00	40 75	51 95	49.44	18 91	47.07	47.15	48.58	50 63	40.50	43.45	42.40	40 00	42.83	50.21	49 82	47 87
	47.00	0.76	01.00	10.44	-0.22	6 42	0.74	0.78	0.10	43.00 11 23	0.29	12,48 A 24	1000 11112	1.78	0.21	10.02	0.35
4.0	10.48	10.84	14 73	10.88	11 38	9.75	11 08	11.65	14.28	17.25	16.01	10.24	14 51	9.00	11 87	10 48	10.38
Fa-O.	16.55	18 60	12.80	18.05	15.05	17.95	15.04	15.72	12.73	15.21	14.55	14.71	18.23	15.28	15.62	16.73	17.23
MnO	0.32	0.32	0.27	0.31	0.30	0.32	0.29	0.32	0.26	0.28	0.30	0.30	0.30	0.32	0.29	0.33	0.31
NoO	14.07	13.50	10.69	13.60	12.29	14.26	12.91	13.24	11.22	12.81	12.05	12.38	13.08	13.44	12.94	14.09	13.80
CaO	3.64	3.44	4.79	3.87	3.77	3.21	3,80	3.75	4.77	4.07	4.05	3.68	3.90	3.23	4.21	3.60	3.53
Naju	1.89	1,89	2.52	2.03	2.15	1,59	2.04	12.22	4.45	2.97	2.12	2.42	1.87	2.00	2.15	1.79	2.20
ко	0.47	0.47	0.56	0.44	0.49	0.29	0.36	0.36	0.46	0.37	0.40	0.36	0.38	0,38	0.49	0.45	0.51
P2Os	0.13	0.10	0.14	0.11	0.13	0.10	0,10	0.12	0.09	0,10	0.09	0.10	0.14	0.11	0.20	0.12	0.11
Cu	1.66	1.18	1.02	2.92	2.13	4,85	2.73	3.05	1.62	2.30	3.26	3.70	2.94	3.02	0.96	2,36	3.12
LOI	0.00	0.99	0.58	0.10	0.03	0. 07	0.14	0.17	0.22	0.94	0.06	0.07	0.05	0.19	0.09	0.03	0.03
TOTAL	97.79	98.46	99.45	100,87	963	99.76	96.87	\$9.44	100.82	100.44	91.47	90.70	89.72	89,85	99.23	98.81	29.13
												I					
Co	75	80	53	F B	71	102	80	81	59	78	78	à 84	82	82	70	86	90
NI	435	419	334	574	454	656	511	530	362	447	508	534	504	53 0	344	493	542
Zn	290	321	228	293	269	306	256	276	232	284	275	279	276	273	283	294	286
୧୪	40	42	37	41	47	27	23	29	24	22	29	28	26	40	27	37	45
Şr 🕹	443	399	574	382	404	354	458	422	568	490	462	443	445	403	437	392	388
Y	42	82	34	38	51	17	15	18	17	22	29	25	23	24	54	43	32
Zr	20	18	17	30	27	24	13	14	18 -	18	18	20	27	31	20	24	21
Nb	8	9	8	6	6	5	4	4	4	4	4	4	4	5	5	7	7
I V I	180	212	126	197	162	211	153	165	121	157	144	155	156	178	184	178	194
Cr	1411	1363	1041	1826	1559	2422	1646	1821	1267	1853	1872	1765	1688	1807	1109	1667	1879
8.	165	191	198	165	110	144	163	163	207	175	138	145	148	226	137	127	205

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Table	A2 (contd.)	Whole-rock	analyses	of Koperbern	Suite p	vroxene diorit
1 44 10 1 10	Less families	41114IN 14011				LAVATIZE ALALIE

Sample	129	130	132	133	160	161	1\$2	165	166	169	171	172	173	174	175	208	216
SiO ₂	47.96	50,48	47.98	47.79	52.21	50.47	52.84	51.57	51 56	49.83	48.80	49.00	50.78	52.07	50.49	50.08	46.71
TiOz	0.24	0.59	0.26	0,28	0.39	0.52	0.34	0.31	0.51	0,33	0.26	0.28	0.23	0.21	0.22	0.28	0.45
Al ₂ O ₃	10,19	23.47	10.26	10.17	13.03	9.61	12.56	18.22	11.38	10.61	10,75	10.47	12.09	12.27	12.51	12.75	15.55
Fe ₁ O ₁	16.78	9,56	17.32	17.24	15.07	17.65	11.83	10.25	16.09	16.29	17.47	17.55	15.33	14.26	14.52	14,78	14.25
MnO	0.32	0.06	0.33	0,33	0,30	0.36	0.35	Q.19	0,39	0.30	0,32	0.32	0.31	0.27	0.30	0.27	0.24
∯ MgÖ	13.52	0.70	14.00	13.88	11.50	12.93	11,62	6.66	11.10	12.73	13,37	14.12	13.42	12.78	12.46	12.05	7.61
CaO	3.49	7.56	3,33	3.44	3.98	2.74	3,79	5.95	3.27	3.51	3,27	3.46	4.17	4.13	4.10	4.32	4.98
Na ₂ O	2.04	6.36	2.82	1,85	2.05	1.46	2.77	3.43	1.89	2.87	1,69	1.70	1,85	2.28	2.19	1.98	4.03
K O	0.43	0.97	0.32	0.36	1.03	1.35	1.09	0.73	1.27	0.60	0,40	0.48	0.47	0.49	0.43	0.59	0.77
P2O5	0.11	0.02	0.09	0.15	0.12	0.13	0.15	0.09	0.14	0.12	0,17	0.10	0.09	0.10	0.14	0.12	0.09
Gu	3.14	0.15	2.79	3,43	0.90	1.30	0,76	0.50	0.98	2.55	2.30	2.94	2.46	1.33	2.22	2.01	1.71
LOI	1.0.03	0.17	0.22	0.08	0.17	0.13	0.03	0.76	0.21	0.58	0,45	0.04	0.29	0.29	0.08	0.27	0.28
TOTAL	98.24	100.08	99.71	98,9 <u>9</u>	100.75	\$8.64	101.12	98.69	96.89	100.13	99.24	1(0.47	101.27	100.48	99.65	99.50	\$6.67
												ił.					
Co	.91	16	90	88	59	69	62	39	61	81	87	111		61	70	71	55
Ni "	542	26	533	574	311	388	306	173	310	472	478	538	469	388	421	389	251
Zn	281	101	268	293	279	-331	285	166	317	288	293	289	249	245	242	237	232
FLD	37	37	27	28	105	173	125	44	163	61	38	45	38	38	27	49	53
5r	384	786	399	388	434	276	405	634	344	388	349	372	426	437	495	446	601
Y	41	8.	26	23	51	59	53	26	60	43	52	45	37	38	28	42	32
Zr	16	17	21	15	13	21	22	15	32	17	24	22	19	35	16	17	17
Nb	5	7	3	5	17	28	21	8	27	8	7	6	5	6	5	8	8
	183	257	171	170	167	187	145	133	183	192	210	207	147	127	146	206	286
Gr	1801	28	1749	1887	1005	1188	100	519	1021	1654	1680	1833	1642	1236	1539	1384	487
Ba	135	366	160	147	280	348	264	239	329	175	112	148	138	148	154	152	262
																	-
Sample	218	219	221	777	1024												
80	61.28	47.85	61 20	54 10	10 65												
710	01.20	41.00	0 43	01.10	49.00												
Δ1.C).	15 63	11 08	11 74	12 17	11.60												
F.O.	12 45	15 15	15.75	15 17	18.11												
MnO	0.20	0.29	0.32	0.23	0.32												1
Math	8.57	13 13	11 37	11 43	13.38												1
CaO	4 72	3.68	3.67	3 59	3 74												8
Na.O	2 6R	1.86	1.86	2.04	2 33											25	1
к.о	0.85	0.43	1.15	1.29	0.51												
P.O.	0.04	0.06	0.12	0.14	0.13												-
Čn	2.07	1.98	1.15	1.03	2.03												
LOL	0.24	0.16	0.04	0.06	0.05												
TOTAL	98.93	55.82	98.51	98.81	100.01												
Co	46	77	61	52	69												l
NI	325	436	318	331	438												
Zn	188	254	304	312	259												į
Rb	74	35	136	160	44												
Sr	568	419	357	347	508												
Y	37	43	56	57	4D												
Zr	37	30	14	32	19												
Nb	10	5	22	25	5												
v	155	139	139	131	188												
cr	1109	1346	1017	1083	1444												
Ba	233	138	283	296	210												

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Table A2 (contd.) Whole-rock analyses of Concordia Granite

Sample	10	94	96	96	163	217	223	
SIO2	76,83	76.48	73.29	72.78	78.7 0	74.81	73.08	
7102	0.07	0.02	0.21	0.25	0.04	0.09	0.20	
NI2O1	12,28	12.28	15,25	13.22	11.37	13.23	14.19	
e,0,	1.59	0.62	2.25	1.98	1.07	0.82	2.36	
VinO	0.11	0.15	0.07	0.02	0.23	0.03	0.05	
da0	0.20	0.00	0.00	0.00	0.00	0.00	0.07	
GaO	1.68	1.10	0.69	1.08	1.83	0,83	1.15	
Nest	2.58	3,48	2.99	2.59	3.30	2.53	2.75	
K-0	3.31	4.07	6.75	6.03	2.05	5.87	6.03	
P.O.	0.03	0.01	0.03	0.15	0.03	0.02	0.64	
Ċu	0.01	0.00	0.00	0.00	0.00	0.00	0.00	
LOL I	0.25	0.38	0.70	0.58	0.16	0.29	0.37	
TAL.	99.02	88.58	102.43	99.36	98.89	98.61	100.28	•
					+			
co I	4	5	6	6	6	6	7	
Ní	7	Ō	8	14	4	2	8	
Zn	24	27	48	41	24	23	43	
Rb	140	207	408	383	<u>\$</u> 7	298	377	
Sr 1	84	32	55	59 1	53	89	66	
v I	51	34	84	134	69	15	102	
7.	31	49	167	167	88	54	177	
44 NH	4	16	20	21	12	5	17	
41A	41	4	- 4 4	7	7	12	12	
~.	22	14		11	44	16	5	
1	112	63	331	200	50	225	327	
		~~~	401	***		66.9	v2.	
	Table	A2 (cc	ontd.) V	Vhole-	rock a	naiyse	s of G	ranitic
ampia	4	20	153	154	165	166	157	158
5iO2	77.99	81,19	80.11	81.11	60.90	84.14	74,58	73.87
FIO2	0.24	0.49	0.27	0.37	0.28	0.35	0.16	0.16
120 I	10.36	7 05	9.21	8.92	8.19	7:19	13.16	49.96
	· · · · · · ·							13.33
e:O: 1	1.47	3.94	1,59	2.03	2.12	2,44	1.48	1.49
e ₁ O ₂ MnO	1.47	3.94 0.06	1.59 0.01	2.03	2.12	2.44 0.01	1.48	13.35 1.49 0.01
e:0: InO IaO	1.47 0.01 0.00	3.94 0.06 0.97	1.59 0.01 0.00	2.03 0.00 0.21	2.12 0.01 0.13	2.44 0.01 0.32	1.48 0.00 0.00	1.49 0.01 0.00
e ₁ O ₂ MnQ MgQ CaQ	1.47 0.01 0.00 0.35	3.94 0.06 0.97 1.86	1.59 0.01 0.00 0.68	2.03 0.00 0.21 0.69	2.12 0.01 0.13 2.16	2.44 0.01 0.32 1.78	1.48 0.00 0.00 1.26	1.49 0.01 0.00 1.05
e ₁ O ₃ MnO MgO CaO	1.47 0.01 0.00 0.35 2.49	3.94 0.06 0.97 1.86 2.29	1.59 0.01 0.00 0.66 2.53	2.03 0.00 0.21 0.69 1.69	2.12 0.01 0.13 2.16 1.61	2.44 0.01 0.32 1.78 1.60	1.48 0.00 0.00 1.26 3.74	13.35 1.49 0.01 0.00 1.05 3.86
e ₁ O3 MnO MgO CaO Va3O KaO	1.47 0.01 0.00 0.35 2.49 6.15	7.05 3.94 0.06 0.97 1.86 2.29 0.40	1.59 0.01 0.00 0.66 2.53 4.51	2.03 0.00 0.21 0.69 1.69 3.36	2.12 0.01 0.13 2.16 1.61 0.46	2.44 0.01 0.32 1.78 1.60 0.44	1.48 0.00 0.00 1.26 3.74 5.71	13.35 1.49 0.01 0.00 1.05 3.86 6.19
4103 MnO MgO CaO Va20 Va20 K20	1.47 0.01 0.35 2.49 6.15 0.03	7.05 3.94 0.06 0.97 1.86 2.29 0.40 0.10	1.59 0.01 0.00 0.66 2.53 4.51 0.03	2.03 0.00 0.21 0.69 1.69 3.36 0.06	2.12 0.01 0.13 2.16 1.61 0.46 0.01	2.44 0.01 0.32 1.78 1.60 0.44 0.05	1.48 0.00 0.00 1.26 3.74 5.71 0.01	13.35 1.49 0.01 0.00 1.05 3.86 6.19 0.03
e ₁ O ₃ MnQ MgQ CaO Na ₃ O K ₂ O F ₂ O ₅	1.47 0.01 0.00 0.35 2.49 6.15 0.03	7.05 3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.10	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00	13.33 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00
FetOy MnO MgO CaO NayO KyO FyOy Cu	1.47 0.01 0.35 2.49 6.15 0.03 0.00 0.42	7.05 3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.10 0.01 0.74	1.59 0.01 0.00 0.68 2.53 4.51 0.03 0.00 0.41	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60	1.48 0.00 1.26 3.74 5.71 0.01 0.00 0.37	1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53
Fe ₁ O ₃ MnO MgO CaO Na ₃ O K ₂ O K ₂ O Cu LOi	1.47 0.01 0.35 2.49 6.15 0.03 0.00 0.42	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.74 59.09	1.59 0.01 0.00 0.68 2.53 4.51 0.03 0.00 0.41 99.34	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98.97	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93	1.48 0.00 1.26 3.74 5.71 0.01 0.00 0.37	1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53
Fe ₁ O ₃ MnO MgO CaO Na ₃ O K ₂ O P ₃ O ₅ Cu LOi OTAL	1.47 0.01 0.35 2.49 6.15 0.03 0.00 0.42 99.54	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.74 99.09	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 29.34	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93	1.48 0.90 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48	1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53
e103 MnO MgO CaO Na30 K30 P203 Cu LO1 OTAL	1.47 0.01 0.00 0.35 2.49 6.15 0.03 0.00 0.42 99.54	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.74 99.09	1.59 0.01 0.00 0.68 2.53 4.51 0.03 0.00 0.41 99.34 7	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8	2,44 0,01 0,32 1,78 1,60 0,44 0,05 0,00 0,60 98,93	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48	1.33 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 6
e 10; MnO MgO CaO Ja; O La; O Lo; D TAL Co Ni	1.47 0.01 0.35 2.49 6.15 0.03 0.00 0.42 99.54	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.74 99.09	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 29.34 7 2	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97 7 6	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0	2,44 0,01 0,32 1,78 1,60 0,44 0,05 0,00 0,60 98,93 10 2	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10	1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 6 3
e 103 MnO MgO CaO JagO KgO 203 Cu LOI DTAL Co Ni 75	1.47 0.01 0.35 2.49 6.15 0.03 0.00 0.42 99.54 7 1 22	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.01 0.74 99.09	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 29.34 7 2 28	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97 7 6 29	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 38	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26	1.35 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 6 3 23
e 103 Ano Ago 2a0 (a)20 Cu LO DTAL Co Ni Zri Bb	1.47 0.01 0.35 2.49 6.15 0.03 0.00 0.42 <b>39.54</b> 7 1 22	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.01 0.74 99.09 11 6 64	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 <b>99.34</b> 7 2 28	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97 7 6 29 90	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37 17	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 36 19	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26	1.35 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 6 3 23 150
e 103 MnO MgO CaO JagO CaO JagO Cu LOI DTAL Co Ni Zri Rb	1.47 0.01 0.35 2.49 6.15 0.03 0.00 0.42 <b>39.54</b> 7 1 22 160	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.01 0.74 99.09 11 6 64 9	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 <b>99.34</b> 7 2 28 132	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97 7 6 29 90 175	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37 17 229	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 38 19 225	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26 155 340	1.35 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.54 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 10
e 103 MnO MgO CaO JapO Cu LOI DTAL Co Ni Zri Rb Sr	1.47 0.01 0.35 2.49 6.15 0.03 0.00 0.42 <b>99.54</b> 7 1 22 160 130	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.01 0.74 99.09 11 5 64 9 183	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 <b>29.34</b> 7 2 28 132 115	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97 7 6 29 90 175	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37 17 229	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 38 19 226	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26 155 340	1.35 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 100.53 100.53 100.53 150 241 17
e ₁ O ₃ MnO GaO GaO GaO K ₂ O SO Cu LOI DTAL Co Ni Zrk RSr Υ	1.47 0.01 0.36 2.49 6.15 0.03 0.00 0.42 <b>99.54</b> 7 1 22 160 130 19	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.74 99.09 11 6 44 9 183 37 27	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 <b>29.34</b> 7 2 28 132 115 24	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97 7 6 29 90 175 68	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37 17 229 12	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 38 19 226 21	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26 155 340 14	1.33 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 100.53 6 3 23 160 241 17 105
e:0; MnO MgO CaO Va;0 K;0 Cu LOI Co Ni Zrb Sr Y Zr	1.47 0.01 0.36 2.49 6.15 0.03 0.00 0.42 <b>99.54</b> 7 1 22 160 130 19 111	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.01 0.74 99.09 11 6 44 9 183 37 312	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 <b>29.34</b> 7 2 28 132 115 24 145	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97 7 6 29 90 175 68 184	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37 17 229 12 130	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 38 19 226 21 19 226 21 16	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26 155 340 14 127	1.35 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 10
etO MnO CaO CaO CaO Co Kt2O Co LO Co Si Co Si Co Si Co Si Co Si Co Si Co Si Co Si Co Si Co Si Co Co Co Co Co Co Co Co Co Co Co Co Co	1.47 0.01 0.05 2.49 6.15 0.03 0.00 0.42 <b>99.54</b> 7 1 22 160 130 19 111 5	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.01 0.74 99.09 11 6 44 9 183 37 312 5	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 <b>29</b> .34 7 2 8 132 115 24 145 5	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 98,97 7 6 29 90 175 68 184 7	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37 17 229 12 130 5	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 38 19 226 21 166 5	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26 155 340 14 127 2	1.35 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 10
eaOo MnO CaO CaO Co NaΩ Co Na Co Na CO NA CO N CO N	1.47 0.01 0.05 2.49 6.15 0.03 0.00 0.42 <b>99.54</b> 7 1 22 160 130 19 111 5 13	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.74 99.09 11 6 64 9 183 37 312 5 108	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 <b>29.34</b> 7 2 8 <b>39.34</b> 7 2 28 132 115 24 145 5 11	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.00 0.54 99,97 7 6 29 90 175 68 184 7 20	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37 17 229 12 130 5 8 22	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 38 19 226 21 166 5 41	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26 155 340 14 127 2 23	1.33 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.53 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 100.55 10
etOs MngO GaO GaO Kt2Os LOI LOI DTAL Co NI™RSY Zrb V Cr	1.47 0.01 0.05 2.49 6.15 0.03 0.00 0.42 <b>99.54</b> 7 1 22 160 130 19 111 5 13 11	3.94 0.06 0.97 1.86 2.29 0.40 0.10 0.74 99.09 11 6 64 9 183 37 312 5 108 3	1.59 0.01 0.00 0.66 2.53 4.51 0.03 0.00 0.41 <b>29.34</b> 7 2 8 <b>39.34</b> 7 2 28 132 115 24 145 5 11 8	2.03 0.00 0.21 0.69 1.69 3.36 0.06 0.54 99,97 7 6 29 90 175 68 184 7 20 8	2.12 0.01 0.13 2.16 1.61 0.46 0.01 0.00 0.56 96.42 8 0 37 17 229 12 130 5 62 10	2.44 0.01 0.32 1.78 1.60 0.44 0.05 0.00 0.60 98.93 10 2 38 19 226 21 166 5 41 4 4	1.48 0.00 0.00 1.26 3.74 5.71 0.01 0.00 0.37 100.48 10 1 26 155 340 14 127 2 23 8	1.33 1.49 0.01 0.00 1.05 3.86 6.19 0.03 0.00 0.53 100.53 100.53 6 3 23 160 241 17 108 3 9 8

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Rock	Sample	Total Fe	FeO	Fa ₂ O ₃	FeO/Fe ₂ O ₃
type		as Fe ₂ O ₃	-		
	136	5.25	1.74	3.33	0.52
Anorthosite	177	1.94	0.40	1.50	0.27
	213	3.60	1.72	1.71	1.00
	Average	3.60	1.29	2.18	0.60
			,, ,, ,, ,, ,, ,, ,, ,, ,, ,, ,, ,, ,, ,, ,, ,,		
	28	9.29	3.54	5.39	0.66
Mica	139	10.14	3,17	6,66	0.48
diorite	150	1.82	0.55	1.22	0.45
	159	6.03	2.32	3.48	0.67
	186	10.61	3.81	6.42	0.59
	215	8.98	2.54	6.18	0.41
	Average	7.81	2.65	4.89	0.54
	42	14.64	9.51	4.18	2.28
	49	13.03	8.11	4.11	1.97
	53	12.78	8.15	3.82	2.13
	64	11.59	4,85	6.26	0.78
Pyroxene	78	11.56	4.69	6.40	0,73
laucodiorite	89	12.46	8.34	3.29	2.53
	116	7.83	2.65	4.91	0.54
	192	6,87	4,21	2.24	1.88
	199	19.25	10.48	7.72	1.36
	203	13.47	4.71	8.29	0.57
	207	9.60	5,39	3.67	1.47
	Average	12.10	6.46	4.99	1.48
	23	14.08	7.24	5.11	1.18
_	56	19.94	12.60	6.09	2.07
Pyroxene	102	16.82	11.76	3.89	3,02
diorité	113	12.60	8.68	3.05	2.84
	122	14.55	10.83	2.63	4.11
	166	16.09	10.94	4.06	2.69
	222	15.17	11.67	2.34	5.00
	Average	15.61	10.53	4.03	2.99
Oceand in the	000	1 20	4 40	0.70	
Granita	223	2.30	1,49	0.72	2.07
Grannie		<u></u>	·····		
Granitic	154	2.03	0.41	1.58	0.26
xenolith			₩+-1° B		24
			······		

Table A3 Ferrous and ferric iron determination analyses

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#### Author:Van Zwieten AJM Name of thesis:The petrogenesis of the Koperberg Suite in the jubilee mine, Namaqualand

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