The O'okiep Copper District, Namaqualand, South Africa: A review of the geology with emphasis on the petrogenesis of the cupriferous Koperberg Suite

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ARTICLE

The O'okiep Copper District, Namaqualand, South Africa: a review of the geology with emphasis on the petrogenesis of the cupriferous Koperberg Suite

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Abstract The O'okiep Copper District is the oldest formal mining area in South Africa. Between 1852 and 2002, the 2,500-km^2 area yielded two million tons of copper from 32 mines ranging in ore tonnages from 140,000 to 37 million tons. This paper summarizes the calendar of events from the formation of the first primitive crust 1,700–2,000 Ma ago to early Cambrian times ~500 Ma ago, with particular emphasis on the Namaquan (Grenville) Orogeny, notably: the O'okiepian Episode (1,180–1,210 Ma ago) of alpine-type folding, regional granite plutonism, and granulite facies metamorphism and the Klondikean Episode (1,020–1,040 Ma ago) of open and tight folding and the intrusion of the Rietberg Granite and the Koperberg Suite. Almost all of the copper in the O'okiep District occurs in the Koperberg Suite, of which there are 1,700 small bodies that constitute 0.7% of the outcrop area. The suite comprises jotunite, anorthosite, biotite diorite, and hypersthenic rocks ranging from leuconorite to hypersthenite, and it is one of only two world examples of economic copper mineralization in rocks of the anorthosite–charnockite kindred; the second example is Caraiba, Brazil. High I_{Sr} and low ε_{Nd} (for a 1,030-Ma intrusion age), and high μ_2 of 10.1, for Koperberg rock-types indicate a crustal progenitor for the suite, and the presence of jotunite suggests a (subducted) crustal source at ca. 40–50-km depth. The magmatic sulphide paragenesis in the Koperberg Suite is chalcopyrite+pyrrhotite (Narrap-type ore) that, in a number of ore-bodies, has been inverted under upper amphibolite facies conditions to bornite+Ti-free magnetite (Carolusberg-type ore). Meteoric fluids resulted in supergene Cu enrichment in Koperberg bodies to ~500 m below the pre-Nama peneplane, and lower greenschist facies metamorphism 500–570 Ma ago is reflected by *inter alia* Hoits-type ore bearing second-generation bornite+chalcopyrite(±covellite±chalcocite).

Keywords O'okiep · Namaqualand · Copper · Koperberg Suite · Anorthosite–charnockite · Namaquan Orogeny

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Introduction

O'okiep regional setting

The regional setting of the O'okiep Copper District is shown in Fig. 1. The Richtersveld Subprovince to the north has been interpreted as a 1,700–2000 Ma old island arc complex comprising predominantly andesitic lavas and granitic intrusives (Reid and Barton 1983; Hartnady et al. 1985). In the west, the Gariep Supergroup of supracrustal sedimentary and volcanic rocks crop out in the Gariep Belt of Late Neoproterozoic–Cambrian (Pan-African) orogenesis along the Atlantic Coast (Fig. 1; Frimmel and Frank 1998; Frimmel 2008). The belt is the southern extension of the Damara Orogen from its Namibian-type region (Miller 2008, p. 13-5), and it is characterized by east-verging recumbent folds and thrusts; metamorphism reached greenschist/lower amphibolite facies (~520°C) ca. 540 Ma ago (Gresse et al. 2006).

Namaquan metamorphic and igneous rocks occupy an area of 70,000 km^2 and comprise three principal structural terranes: the Aggeneys, O'okiep, and Garies Terranes

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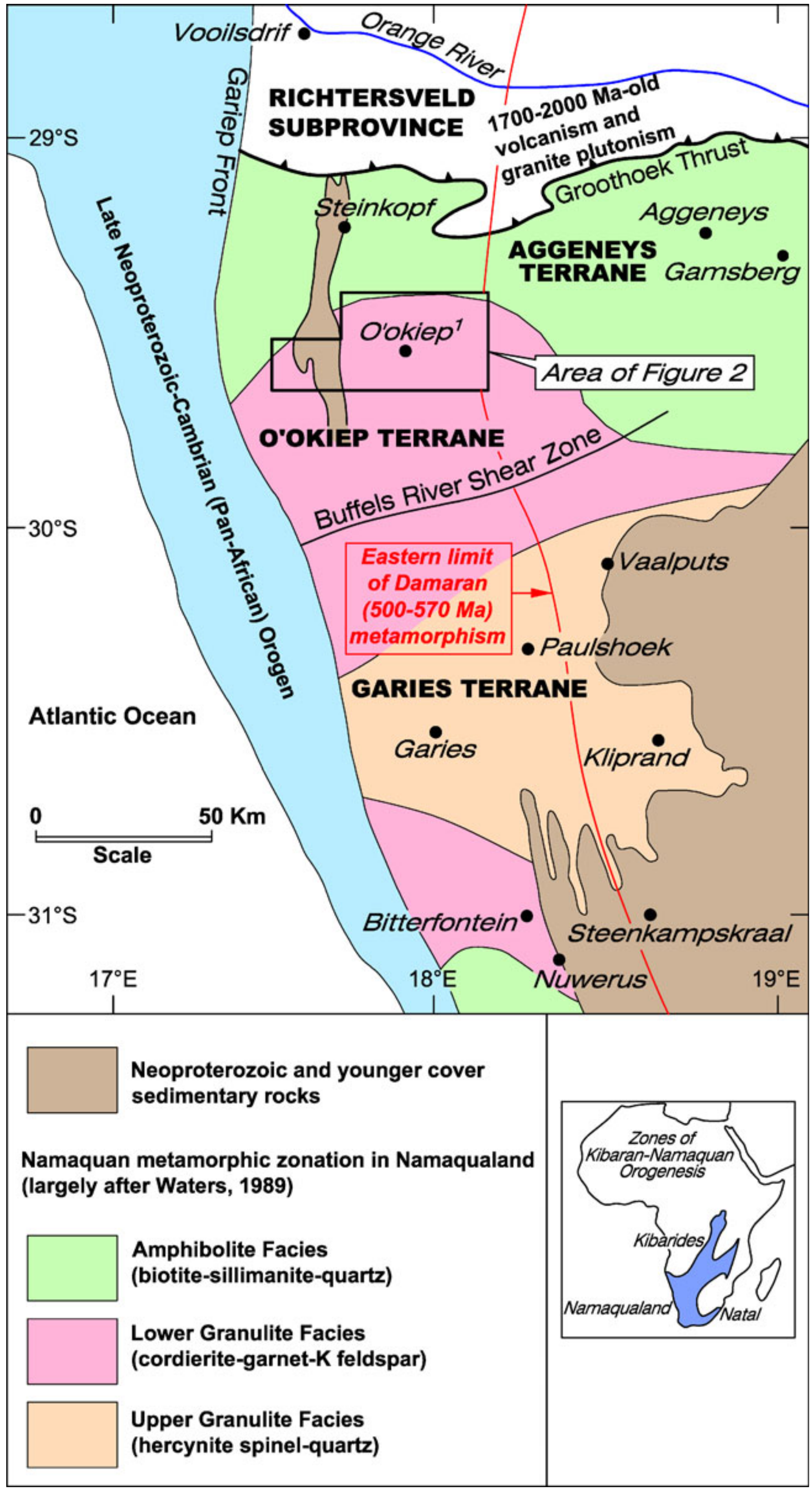


Fig. 1 The O'okiep Copper District (see Fig. 2) shown in relation to the Namaquan regional metamorphic zonation of Namaqualand, the Late Neoproterozoic-Cambrian Orogen (Frimmel and Frank 1998; Gresse et al. 2006), and the eastern limit of Damaran metamorphism (see text).

[1] The name *O'okiep* is said to have one of two meanings in the local indigenous Nama language depending on pronunciation: "the place of the big tree" or "the little fountain" (Smalberger 1975, p. 104); it is believed to have been derived from the Nama word "u-gieb", meaning a big brackish place (Smalberger 1975, p. 120). Although O'okiep takes historical precedence (cf. Wyley 1857; Van Zyl 1967; Burke 1995), as in the name *O'okiep Copper Company* (Lombaard et al. 1986), Okiep has also become common usage since the late 1970s

(Fig. 1). All were profoundly affected by orogenesis in the interval 1,200 to 800 Ma ago, but there are fundamental differences in crust evolution on either side of the Buffels River Shear Zone (Fig. 1). Notably, intrusive rocks in the Aggeneys and O'okiep Terranes show Nd model T_{CHUR} ages of 1,700–1,900 Ma and T_{DM} ages of 2,000–2,300 Ma (Clifford et al. 1995, 2004; Reid et al. 1997; Bailie et al. 2007a), with some Aggeneys crystalline rocks yielding T_{DM} ages of 2,740–2,840 Ma (Bailie et al. 2007b; Pettersson et al. 2009). In addition, O'okiep crust experienced 150 million years of tectonic quiescence between the O'okiepian and Klondikean Episodes (Clifford et al. 2004), while U–Pb ages of ~1,650 Ma for "magmatic" zircons from granite gneiss at Aggeneys suggest a shorter (ca. 135 million years) "quiet period" between the two episodes in the Aggeneys Terrane (Cornell et al. 2009, p. 401; see Fig. 1). In contrast, intrusive rocks in the Garies Terrane (Fig. 1) have younger T_{CHUR} and T_{DM} ages of ca. 1,040–1,200 Ma and ca. 1,570–1,650 Ma, respectively (Ashwal et al. 1997; Yuhara et al. 2001; Andreoli et al. 2006). The juvenile Garies crust is therefore 500 million years younger than the O'okiep and Aggeneys crust to the north. Moreover, in the Garies terrane, the intra-Okiepian/Klondikean interval was punctuated by 1,065–1,110 Ma old granite plutonism, including the Stoffelkop, Bloukop, and Stofkloof Granites (Thomas et al. 1996; Ashwal et al. 1997; Raith et al. 2003).

The differing histories north and south of the Buffels River Shear Zone are reflected in metallogeny. To the north, the Aggeneys and O'okiep Terranes (Fig. 1) are characterized by rich base metal deposits: (1) Aggeneys Terrane: Sedex-type ores, Aggeneys (Black Mountain, Broken Hill, and Big Syn deposits, 180 million tons), Pb (1.0–3.6%), Zn (0.6–2.5%), and Cu (0.1–0.8%), and Gamsberg (150 million tons), Zn (7.1%), and Pb (0.6%) (Rozendaal 1986; Ryan et al. 1986) and (2) O'okiep Terrane: Koperberg ores (>100 million tons), Cu (1.75–14%) (Lombaard et al. 1986). In contrast, ore-bodies in the Garies Terrane to the south of the Buffels River Shear Zone are small. For example, the Ni–Cu–(Co) sulphide deposits near Kliprand (Fig. 1) total two million tons with Ni(0.9%)–Cu(0.2%)–Co(400 ppm); the mineralization occurs in sheared gabbro–norite with anorthosite (Hamman et al. 1996; Marco Andreoli, personal communication). In addition, at Steenkampskraal (Fig. 1), monazite–apatite–chalcopyrite–magnetite mineralization associated with anorthosite–norite–charnockite has been mined for thorium (Andreoli et al. 1994).

O'okiep mining history

The history of exploration and mining of copper deposits in the O'okiep District (Fig. 2) has been reviewed by Smalberger (1975) and Cairncross (2004), both of whom emphasize that copper was worked and refined in Namaqualand by indigenous Namaqua peoples long before the explorer Pieter van Meerhof made the first contact with them in 1661. The precise location of the copper was, however, unknown until Isaq Shrijver's expedition in 1684. In the following year, Simon van der Stel identified copper at what he named Koperberg, in the area now known as the O'okiep Copper District. The deposits were too small and remote to be mined at the time, but their general location was shown on maps by Paterson in 1777–1779 and by LaValliant in 1791 (Cairncross 2004). Mining began at Springbok (Fig. 2; then Springbokfontein) in 1852, and the mine produced about 15,000 tons of ore averaging 10–27% Cu, with mining reaching a depth of 200–250 m. The Springbok Mine was the first formal mine in South Africa: it was opened 15 years before Daniel Jacob's children picked up the first alluvial diamond (a 21.75-carat stone) in the Orange River, 18 years before farmer De Klerk unearthed the first kimberlite diamond (a 50-carat stone) on Farm Jagersfontein and 34 years before the discovery of the great Witwatersrand goldfields by George Walker and George Harrison. By 1855, 32 "mining companies" had been formed in the O'okiep District. In 1856, this was reduced to two: the Cape Copper Company that managed the Nababeep, O'okiep and Spektakel Mines, and the Namaqua Copper Company that worked in the Concordia area (Fig. 2).

The earliest comment on the geology of the O'okiep Copper District was by Delesse (1855) who briefly mentioned the copper ores of the Tweefontein, Spektakel, Wheal Julia, Hester Maria (now Concordia), Skaaprivier, and Springbok Mines (Fig. 2; cf. Rubidge 1856; Zerrener 1860; Dunn 1872). In his historical report on the geology and mining at those mines and at O'okiep and Rietberg, Wyley (1857) referred to the ore-bearing rock, now the Koperberg Suite, as feldspar rock or feldspar–mica rock and noted its igneous and intrusive character. Between 1852 and 1862, the total ore raised from O'okiep, Springbok, and Spektakel Mines was 200,000 tons, averaging 29.5% Cu (Ronaldson 1905). In the earliest petrographic study of Koperberg diorite at O'okiep, Schenck (1902) noted that mineralization is both disseminated and massive; up to 1930, the mine yielded 900,000 tons of hand-sorted ore and concentrates at 20% Cu (Latsky 1942). Kuntz (1904) published "profiles" of the Tweefontein and O'okiep ore-bodies. The Cape and the Namaqua Copper Companies closed down in 1919 and 1931, respectively. The O'okiep Copper Company was formed by the Newmont Mining Company (USA) in 1937 acquiring all the assets of the two companies. Copper production recommenced in 1940 at the O'okiep, Nababeep, and Narrap Mines and thereafter a further 20 new mines were opened. All mining ceased in 2002 with the closure of the Nigramoep Mine (Fig. 2). The copper produced in the O'okiep district from 1852 to 2002 totaled two million tons.

Focus of this review

This paper deals with the cupriferous rocks of the O'okiep Copper District and their geological setting. Virtually, all of the copper occurs in the Koperberg Suite, formerly referred to as "noritoids" (Benedict et al. 1964) or "basic bodies" (Lombaard and Schreuder 1978). The suite belongs to the anorthosite–charnockite kindred (Jackson 1979) but, of the

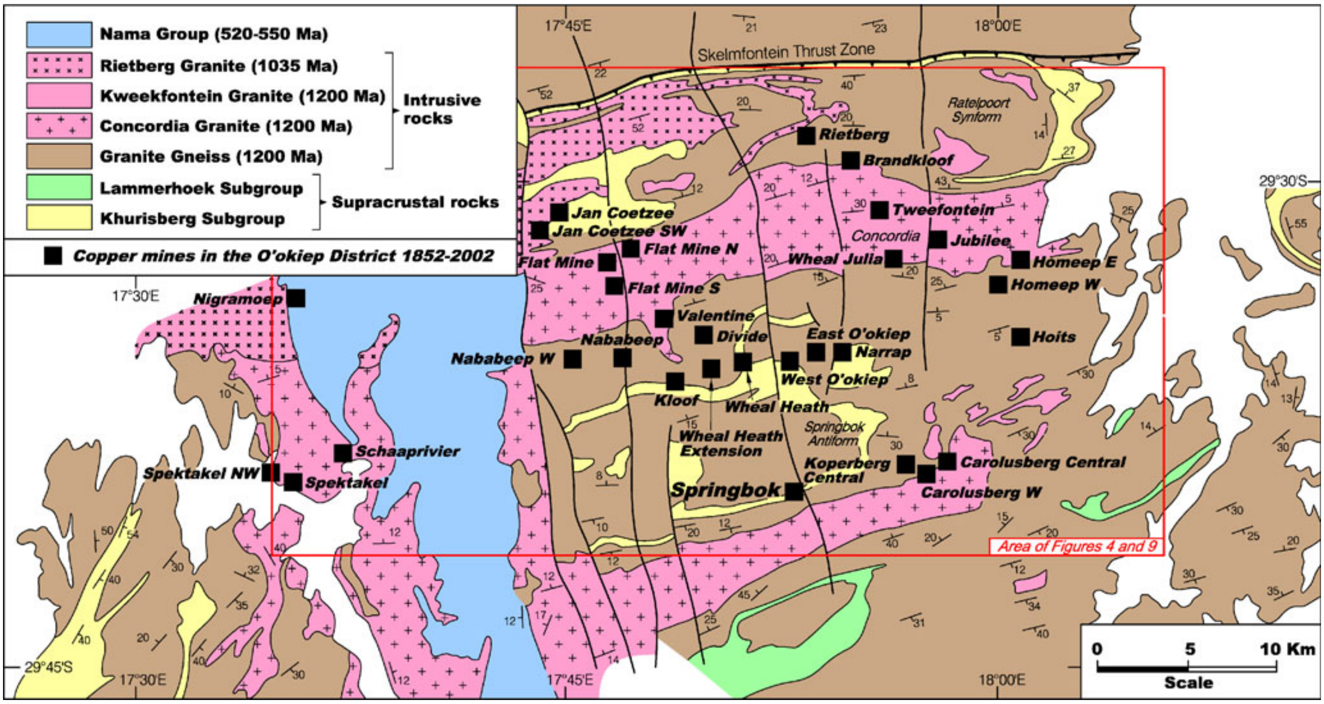
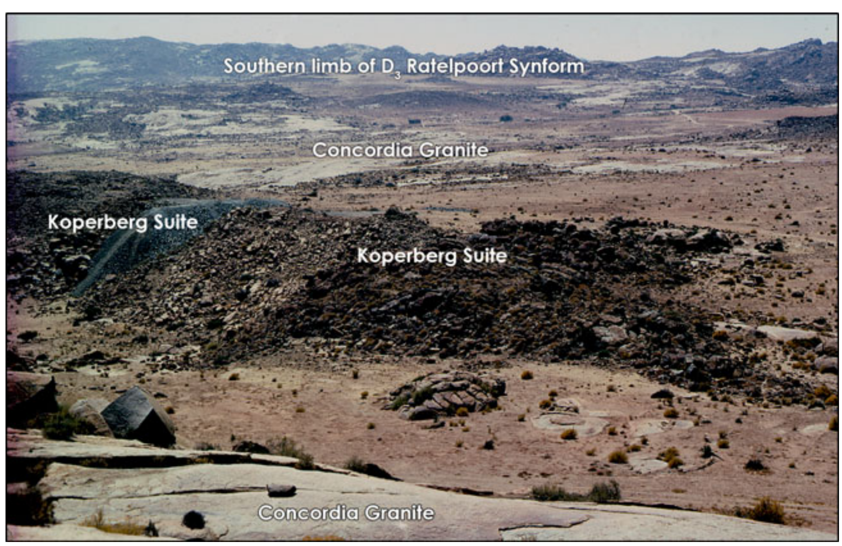


Fig. 2 Generalized geological map of the O'okiep Copper District (after Lombaard et al. 1986) showing the distribution of copper mines and, outlined in *red*, the area covered by Figs. 4 and 9

range of similar associations elsewhere in Africa (Clifford 1974), O'okiep is unique in its base metal wealth. The Koperberg Suite comprises 1,700 small pipes and dykes (Figs. 3 and 4), with the largest dyke 1 km in length. Thirty-two bodies have been mined for copper (Fig. 2), with tonnages ranging from 140,000 tons (Tweefontein) to 37 million tons (Koperberg–Carolusberg). However, low average ore grades of 1.75% Cu in 100 million tons of ore since 1940 stand in stark contrast to high grades averaging 14% Cu before 1940 (Lombaard et al. 1986). That distinction is self-evident from classic ore deposit volumes: (1) by Lindgren who commented (1933, p. 810) on the *rich* bornite deposits of Ookiep and (2) by Bateman who remarked (1959, p. 522) on the low-grade copper sulphide ores in the O'okiep mines. The geological reason for these two totally disparate ore grades is addressed in this review work. In addition, the geology of the O'okiep District is discussed in light of investigations by the O'okiep Copper Company since 1940 and the substantial volume of field and analytical data for the Koperberg Suite and crystalline country rocks published since 1966.

Fig. 3 Panoramic view (looking north) showing the New Prospect body of the Koperberg Suite and the country rock Concordia Granite; note the core-shed at the lower left



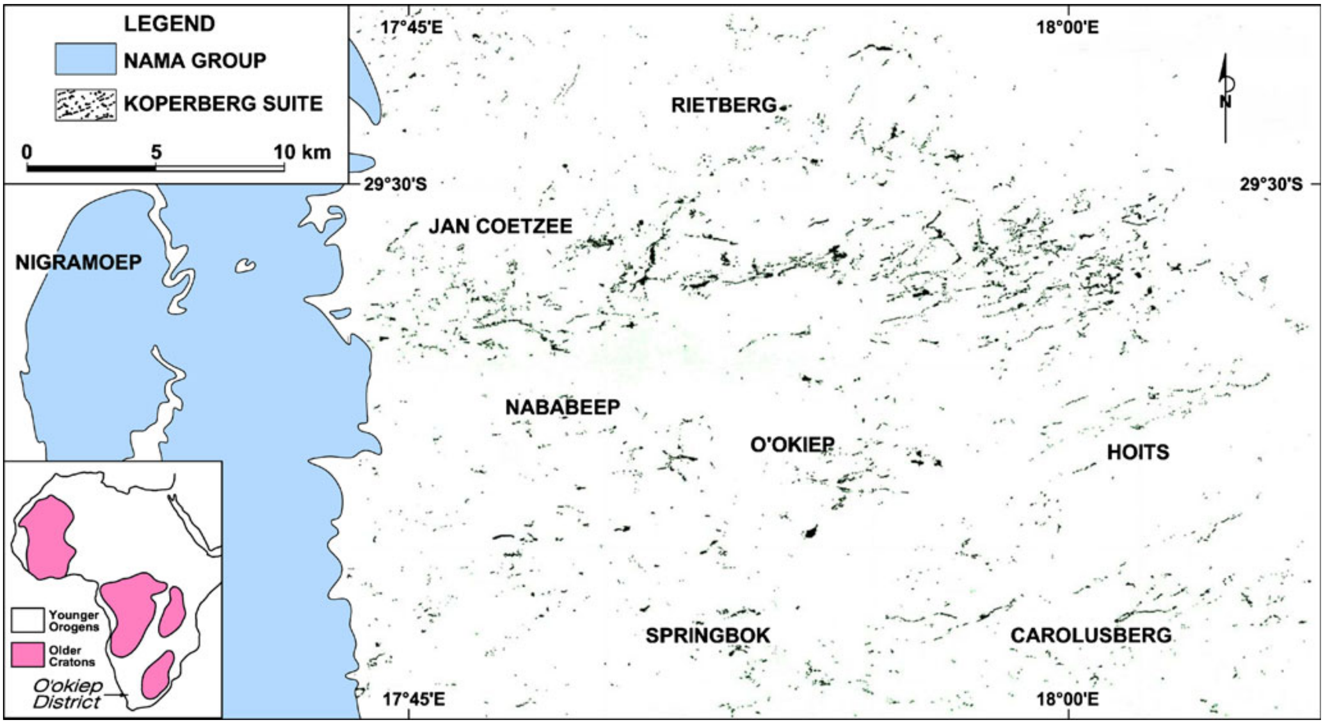


Fig. 4 Map showing almost 1,700 individual bodies of the Koperberg Suite in the O'okiep Copper District (after Lombaard et al. 1986). *Inset*, the fundamental tectono-metallogenic units of Africa (after Clifford 1966): (1) *younger orogens* characterized by major deposits of *inter alia* Cu, Pb, Zn, and Co and (2) *older cratons* characterized by important deposits of diamonds and gold

Geology of the O'okiep Copper District

Preamble

The geology of the O'okiep Copper District has been described by *inter alia* Strauss (1941), Pennebaker (1952), Vellet (1958), Benedict et al. (1964), Lombaard et al. (1986), and Gibson et al. (1996), and the regional setting has been discussed by Joubert (1971, 1986), Thomas et al. (1994), Cornell et al. (2006), and Eglington (2006). The principal sequence of events in the district is (see Fig. 5):

1. The first primitive crust in Eburnian (cf. Cahen 1970, p. 142 et seq.) times is reflected by Nd model ages of 1,700 Ma (T_{CHUR}) and 2,000 Ma (T_{DM}) for a range of intrusive rocks.
2. Deposition of a supracrustal succession, ca. 1,650 Ma ago, including (Fig. 2) metasedimentary rocks of the Khurisberg Subgroup and the metavolcanic–metasedimentary sequence of the Lammerhoek Subgroup.
3. Intrusion of large volumes of granite 1,180–1,210 Ma ago during the O'okiepian Episode of the Namaquan Orogeny (Fig. 5) including: (1) the Nababeep and Modderfontein Granites (now granite gneiss) that have been grouped as the Little Namaqualand Suite (Marais and Joubert 1980a), and (2) the 1,500 m thick sheet of Concordia Granite (Figs. 2 and 3) and small bodies of Kweekfontein Granite (Marais and Joubert 1980b), both of which are of younger age than the Little Namaqualand Suite.
4. Intrusion of the Rietberg Granite and the copper-bearing Koperberg Suite 1,020–1,040 Ma ago during the Klondikean Episode of the Namaquan Orogeny (Fig. 5).
5. From 1,030 to 550 Ma ago: erosion and denudation with the removal of 20 km thickness of crust and the exhumation of the present erosion level.
6. Deposition, 520–550 Ma ago, of 350–400 m of sedimentary rocks of the Nama Group (Fig. 2).
7. Damaran Orogeny, 480–580 Ma ago (Clifford et al. 1995, p. 249; cf. Hoffmann et al. 2004, p. 818; Clifford 2008, p. 117) with the circulation of low-temperature meteoric fluids.

Eburnian protocrust

Evidence for an Eburnian protocrust in the O'okiep Copper District is provided by Sm–Nd model ages of 1,700–2,000 Ma for a range of intrusive rocks together with 1,600–2,000 Ma ages for detrital zircons in Khurisberg metapelite and for zircon xenocrysts in all granitic rocks and in the Koperberg Suite (Clifford et al. 1995, 2004). In addition, Barton (1983) records a whole-rock Rb–Sr age of 1,824±70 Ma for granite gneiss from the amphibolite facies

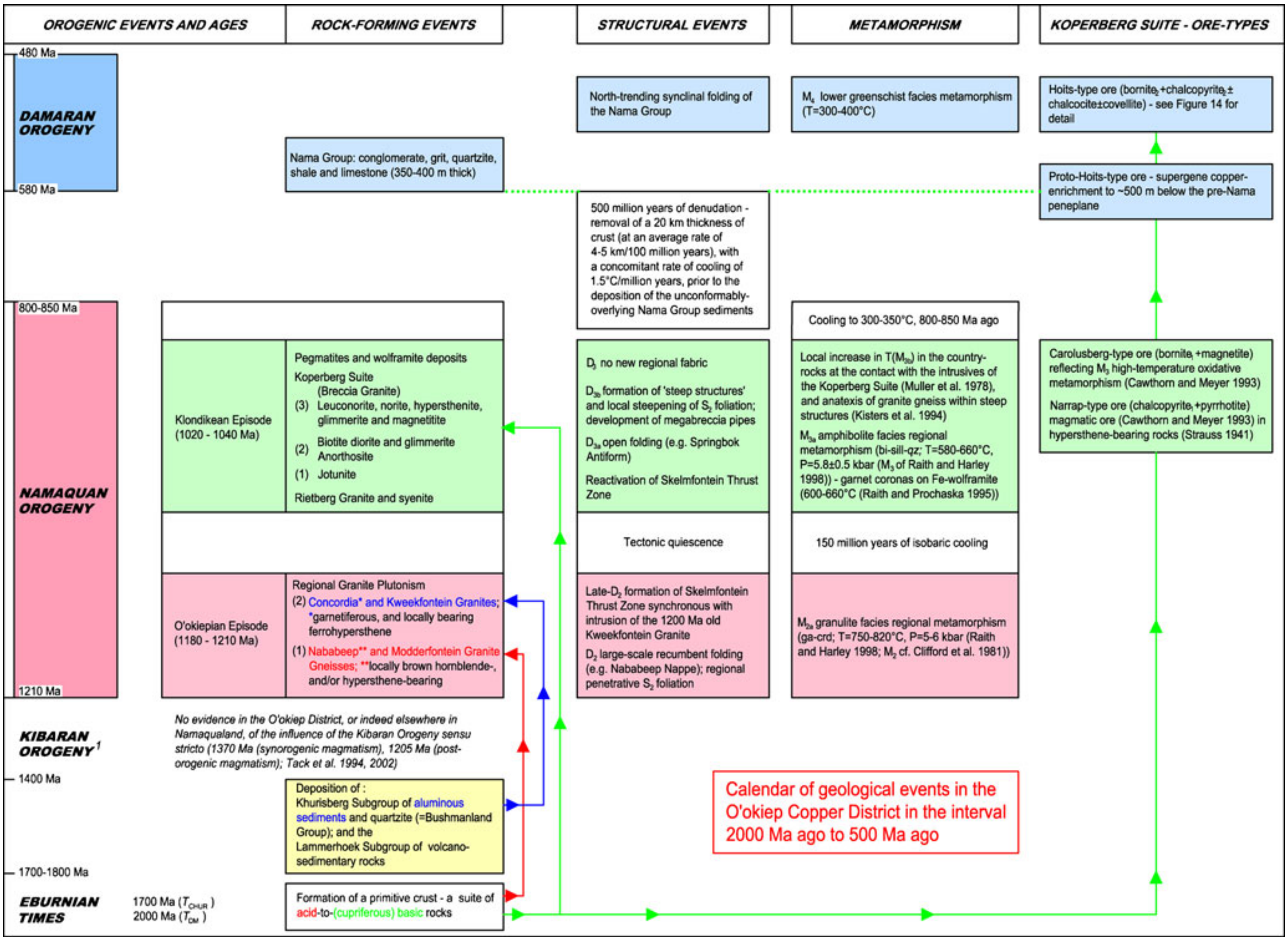


Fig. 5 Calendar of geological events in the evolution of the O'okiep Copper District in the interval 2,000 to 500 Ma ago. [1] "Kibaran Orogeny" was formerly incorrectly applied to regional tectono-thermal events with ages of 1,100±200 Ma (Clifford 1970), 1,100–1,200 Ma (Blignault et al. 1983) and 1,170–1,220 Ma (Robb et al. 1999)

terrane to the north of the Skelmfontein Thrust Zone (Fig. 2; Blignault et al. 1983), while Robb et al. (1999) obtained a $^{207}Pb/^{206}Pb$ zircon age of 1,822±36 Ma for granite gneiss.

Namaquan Orogeny

The calendar of Namaquan tectono-thermal events 1,200 to 800 Ma ago is discussed below under four headings: O'okiepian Episode, Klondikean Episode, Steep Structures and Megabreccias, and Late-Namaquan Cooling. These events span the Shawinigan, Ottawan, and Rigolet "Pulses" of the Grenvillian Orogenic Cycle of the Grenville Province of North America (Davidson 1995; Rivers 1997).

O'okiepian Episode

Granitic rocks underlie 80% of the O'okiep Copper District, and the most voluminous is granite gneiss (Fig. 2) that includes the locally hypersthene-bearing Nababeep Granite Gneiss and the Modderfontein Granite Gneiss, with $^{207}Pb/^{206}Pb$ zircon ages of 1,192±9 and 1,187±25 Ma, respectively (Clifford et al. 2004; cf. Robb et al. 1999). The pervasive regional S_2 foliation is axial–planar to the Nababeep Nappe (F_2), with an amplitude of 25 km (Clifford et al. 1975b, p. 177), whose lower and upper limbs are most clearly defined by the structural duplication of the Khurisberg Subgroup in the Springbok Antiform and the Ratelpoort Synform, respectively (see Fig. 2). The coeval regional metamorphism (M_{2a}; Fig. 6) is reflected by *inter alia* cordierite parageneses bearing sillimanite+garnet+K-feldspar, bronzite+sapphirine and bronzite+gedrite that are regarded as restites after extraction of 70–80% of anatectic granite from pelites (Clifford et al. 1975a, 1981). Raith and Harley (1998) determined peak M_{2a} conditions as: P= 5–6 kbar, T=750–820°C (Fig. 6). The garnetiferous, and locally ferrohypersthene-bearing, Concordia Granite (Fig. 2) was intruded during M_{2a} metamorphism or at a slightly lower grade of metamorphism (M_{2b}; ibid.). That granite

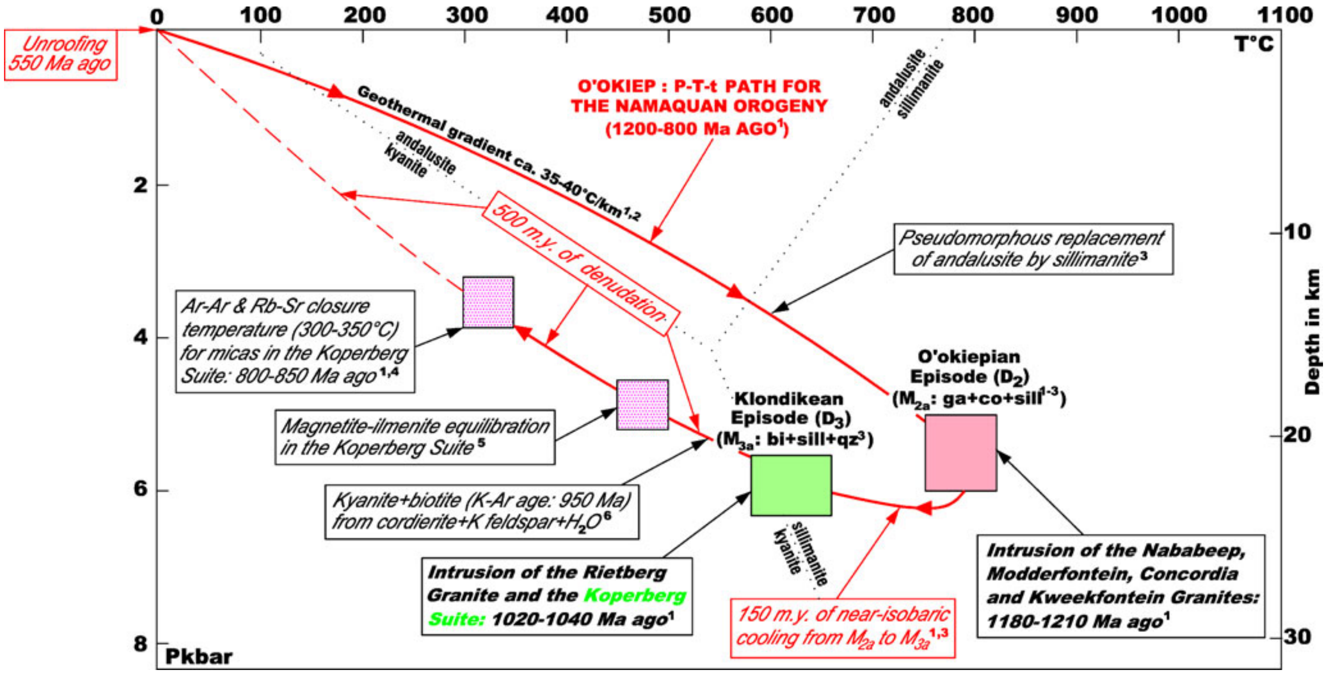


Fig. 6 P–T–t diagram for the Namaquan Orogeny in the O'okiep Copper District. Data sources: [1] Clifford et al. (2004), [2] Gibson and Walmach (1992), [3] Raith and Harley (1998), [4] Clifford et al. (1995), [5] Conradie and Schoch (1986b), [6] Clifford et al. (1981). *co* cordierite, *ga* garnet, *qz* quartz, *sill* sillimanite

has yielded a $^{207}Pb/^{206}Pb$ zircon age of 1,206±16 Ma (Fig. 7a) and is enriched in U (up to 66 ppm) and Th (up to 93 ppm) (Raith 1995; Duchesne et al. 2007) that are, in part, responsible for high heat production values of up to 12.3 μW m^{-3} (Jones 1987). The origins proposed for this granite are: mantle-derived potassic melts (Reid and Barton 1983), a peraluminous crustal source (Raith 1995), and melting of lower-crustal basic granulites (McCarthy 1976). However, the Rb, Sr, and Ba contents, a Rb/Ba ratio of >0.25, and the high K_2O of ca. 6% suggest a pelite-derived melt origin (Duchesne et al. 2007). The cogenetic Kweekfontein Granite was intruded at 1,186±16 Ma ago (Fig. 7b), and both granites were syn-deformational with respect to late-D_2 Skelmfontein Thrust Zone (Fig. 2; Blignault et al. 1983; cf. Martens 1979).

Klondikean Episode

The Klondikean Episode is reflected by regional east–west trending open folds such as the Springbok Antiform and the Ratelpoort Syform (F_{3a}; Fig. 2) and "steep structures" (F_{3b}; Fig. 8). This tectono-thermal event 1,020–1,040 Ma ago (Clifford et al. 2004) was accompanied by intrusion of the Rietberg Granite and the Koperberg Suite, and geochemical studies show: (1) that the Rietberg Granite belongs to the K-rich granitic kindred with A-type affinity that is explained by partial melting of andesitic crust and (2) that its REE distribution suggests consanguinity with some Koperberg melts (Duchesne et al. 2007). The Rietberg Granite predated the Koperberg Suite, but their $^{207}Pb/^{206}Pb$ zircon ages are, within error, the same: Rietberg Granite 1,035±13 Ma and syenite 1,035±7 Ma; and Koperberg Suite, 1,035±13 Ma (jotunite), 1,029±10 Ma (andesine anorthosite), 1,030±6 Ma (biotite diorite), 1,035±33 Ma (magnetite–hypersthene rock), and 1,018±20 Ma (breccia granite) (Clifford et al. 2004). These ages are supported by: (1) other Koperberg data, viz., a $^{207}Pb/^{206}Pb$ zircon age of 1,037±8 Ma for "hypersthenite" (Robb et al. 1999), a Rb–Sr age of ~1,040 Ma for glimmerite (Nicolaysen and Burger 1965), and a Sm–Nd whole-rock isochron age of 1,022±42 Ma (Clifford et al. 1995) and (2) ca. 1,020–1,040 Ma U–Pb zircon and monazite ages from country rocks (Nicolaysen and Burger 1965; Raith et al. 1999; Clifford et al. 2004) and a $^{187}Re/^{187}Os$ isochron age of 1,019±6 Ma for molybdenite from wolframite deposits (Raith and Stein 2000).

Raith and Harley (1998) recognized that the typomorphic pelite paragenesis for Klondikean regional metamorphism (M_{3a}) is biotite+sillimanite+quartz, reflecting PT conditions of P=5.8±0.5 kbar and T=580–660°C (Fig. 6). Importantly, Raith and Harley (1998, p. 302) comment on the "apparent isobaric cooling" between M_{2a} (P=5–6 kbar) and M_{3a} which, considered in conjunction with geochronological data (Figs. 5 and 6; cf. Clifford et al. 2004, p. 688), implies a period of 150 million years of near-isobaric cooling between the O'okiepian (D_2) and Klondikean (D_3) Episodes of the Namaquan Orogeny.

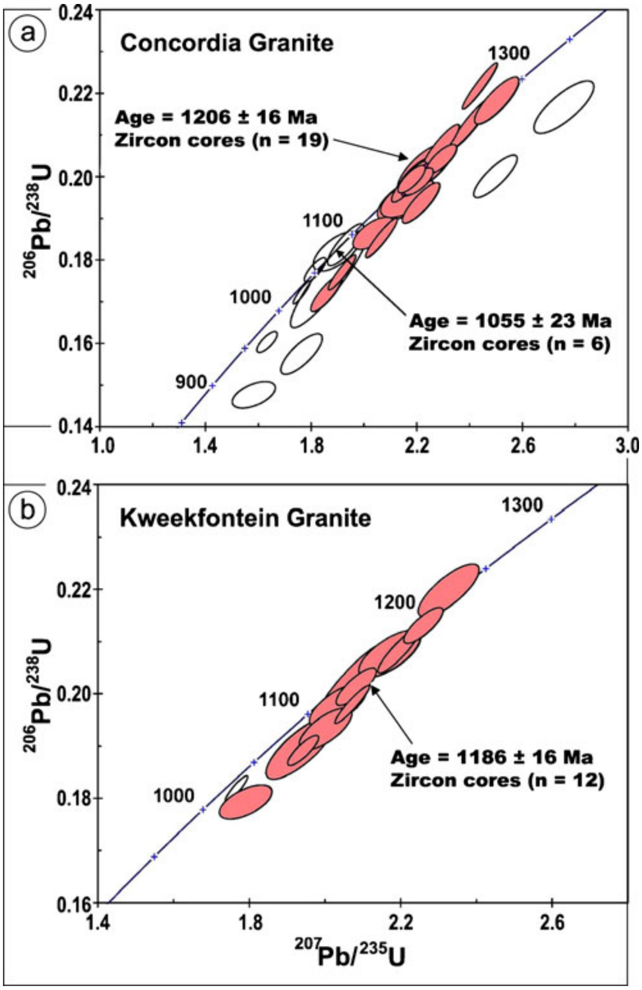


Fig. 7 U–Pb Concordia diagrams for zircons from: **a** Concordia Granite [1] and **b** Kweekfontein Granite (Clifford et al. 2004). [1] Robb et al. (1999) published a ^{207}Pb/^{206}Pb zircon "emplacement age" (*sic!*) of 1,064±30 Ma (n=5) for the Concordia Granite

Delineating the contact-thermal effects (M_{3b}) of the Koperberg Suite is prejudiced by the fact that it was intruded into hot ($T(M_{3a})$=580–660°C; Raith and Harley 1998; cf. Rogers 1912; Watkeys 1996, p. 180) largely granitic, country rocks. However, Muller et al. (1978) recognized that, at Koperberg Central (Fig. 2), country rock Nababeep Granite Gneiss is remagnetized (temperature>Curie T=560–610°C; ibid.) conformably with a 12 m thick body of Koperberg norite for a distance of 1.5 m from the norite contact. This implies that the recordable extent of the thermal imprint (M_{3b}) of Koperberg intrusion in neighouring country rocks is ca. D/10 where D is the thickness of the intrusive.

Steep structures and megabreccias

There is a close temporal relationship amongst a trinity of features: (1) formation of steep structures (F_{3b}), (2) formation of pipe-like bodies of megabreccia, and (3) intrusion of the Koperberg Suite (Lombaard and Schreuder 1978, p. 269). Of these, steep structures are narrow, generally ENE-trending, usually anticlinal, folds in which the regional flat-lying S_2 gneissosity has been rotated into a near-vertical attitude (Fig. 8). The folds are up to 7 km in length, but mostly 500–1000 m, with width of structural interference (steepened S_2 foliation) varying from 3 to 500 m (Fig. 9), and they are characterized by upward piercement into overlying strata by up to 1,500 m (Lombaard and Schreuder 1978). Strauss (1941) referred to rocks within steep structures as "fluxion gneiss." Benedict et al. (1964) regarded them as "diapiric" folds; Hälbich (1978) favoured a mega-boudin origin, the "necking" (steep structures) resulting from north–south extension, while Watkeys (1996) described the Klondike steep structure (Figs. 8 and 9) as a sinistral D_3 ductile shear. However, Kisters et al. (1996) interpreted steep structures as localized zones of high strain and proposed that they were formed by flattening of the regional S_2 foliation in response to north–south (D_3) shortening. The presence of hypersthene-bearing (charnockitic) anatectic melts demonstrates that rocks within steep structures were close to solidus temperatures (ca. 850°C; Gibson and Walmach 1992).

Fig. 8 Klondike steep structure (from Lombaard et al. 1986) in which the S_2 foliation in the Nababeep Granite Gneiss has been steepened over a distance of 150 m within this D_3 structure. Landrover at lower left for scale

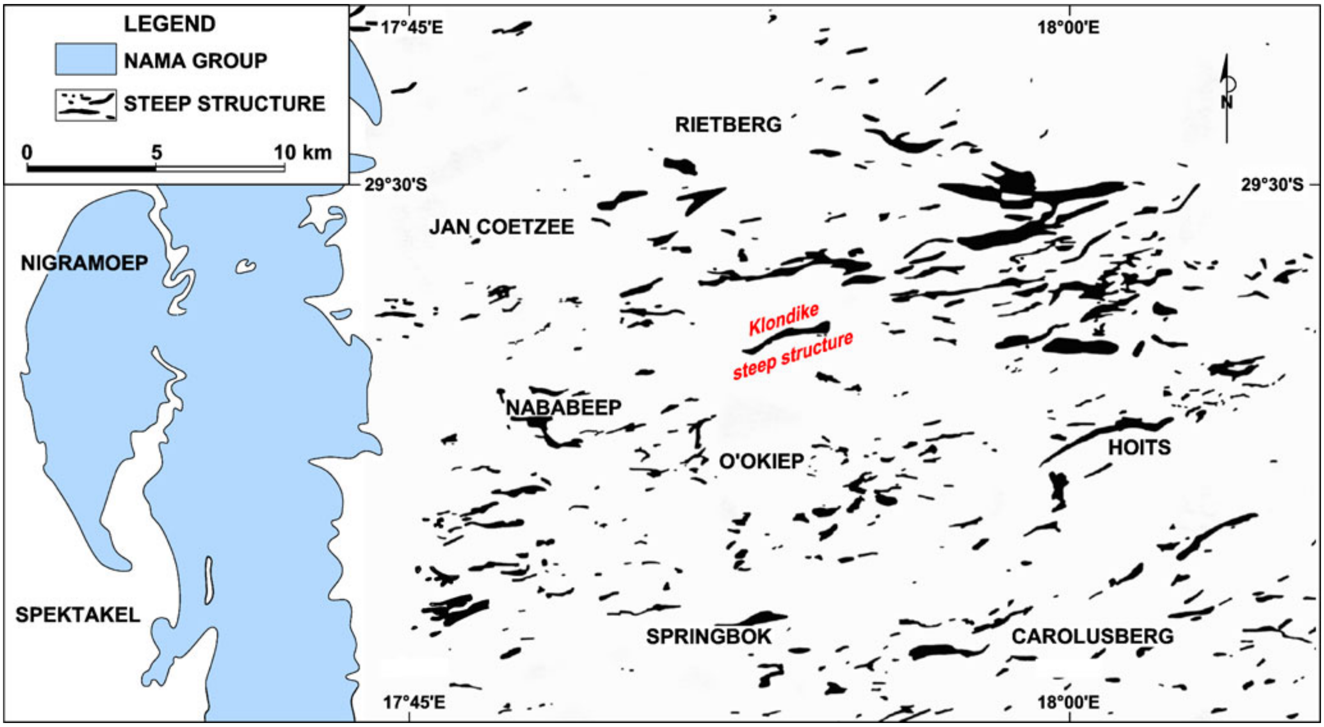


Fig. 9 Steep structure distribution in the O'okiep Copper District (after Lombaard et al. (1986))

Some 80 localities of megabreccia have been identified in the O'okiep Copper District. They are generally oval-shaped pipes ranging from 3 m in diameter to 400× 1,000 m, and they contain disoriented blocks of rock-types that can be matched with those up to 400 m higher up in country rock sequence (Lombaard and Schreuder 1978). Most of the pipes lie along steep structures and the "sharp termination of steep structures against megabreccia and the fact that individual blocks in the jumbled assortment within the megabreccia bear the characteristic imprint of deformation by steep structure indicate that brecciation succeeded the formation of steep structure" (Lombaard and Schreuder 1978, p. 283). The contact of the megabreccias is marked by shearing, and the blocks within the megabreccia are separated by shears and/or by in situ anatectic granitic melts locally termed "breccia granite." A $^{207}Pb/^{206}Pb$ zircon age of 1,018±20 Ma for breccia granite from the Henry's House pipe (Clifford et al. 2004; cf. Lombaard and Schreuder 1978, Fig. 17.10) dates the intimately related steep structure, breccia granite, and Koperberg intrusive events.

Late Namaquan cooling

Cooling following the Klondikean Episode resulted in retrograde kyanite in Khurisberg metapelite, reflected by a biotite K–Ar age of 950 Ma (Clifford et al. 1981) and in magnetite–ilmenite equilibration at 450–500°C in the Koperberg Suite (Conradie and Schoch 1986a; see Fig. 6). A Rb–Sr model age and an $^{40}Ar/^{39}Ar$ age for phlogopite from Koperberg glimmerite (Clifford et al. 1995), together with $^{40}Ar/^{39}Ar$ ages for biotite from Koperberg biotite diorite (Onstott et al. 1986) and for whole-rock Koperberg rock-types (Clifford et al. 1995), are all between 800 and 845 Ma and record the time of cooling through the biotite/phlogopite closure temperature (T_c=260–350°C; Spear 1993) that defines the end of the Namaquan Orogeny (Fig. 6). Perhaps related to that cooling is fluid entrapment: homogenization temperature (T_h) of 310–350°C for H_2O–CO_2 inclusions in quartz (Ougougdal et al. 1996) and T_h=375°C for H_2O and CO_2 in inclusions from regional samples (Schoch 1989).

Damaran Orogeny

Sedimentary rocks of the 520–550 Ma old Nama Group rest unconformably on the eroded roots of the crystalline rocks of the O'okiep Copper District, and the interface reflects 500 million years of Neoproterozoic denudation. In 1984, Clifford reported an $^{40}Ar/^{39}Ar$ plateau age of 560 Ma for mica-rich Koperberg diorite ("glimmerite") from Jan Coetzee (see Fig. 2; cf. Clifford et al. 1995, p. 248). Support for a thermal event at that time is particularly evident in minerals that reset easily as shown by $^{40}Ar/^{39}Ar$ ages of 570 Ma for plagioclase (T_c=225°C; Dodson and McClelland-Brown

1985) from Koperberg diorite (Onstott et al. 1986) and of 550 and 505 Ma for whole-rock Koperberg andesine anorthosites (Fig. 12 in Clifford et al. 1995). $^{40}Ar/^{39}Ar$ ages of 480 and 520 Ma have also been reported (ibid., Fig. 13) for whole-rock chloritized Koperberg jotunite from the Hoits Mine (cf. this work, Fig. 16a) and for hydrated Nababeep Gneiss, respectively, while sericite and muscovite separates from supracrustal metapelites gave K–Ar ages of 560 and 590 Ma (Raith and Prochaska 1995, p. 1952). Furthermore, oxygen isotope data for the Koperberg Suite are $\delta^{18}O_{plag}$=6.2 to 9.6‰ and $\delta^{18}O_{opx}$=6.2 to 7.4‰, and Boer et al. (1994) note a lack of temperature concordance in ^{18}O in mineral pairs, perhaps reflecting the influence of low temperature fluids ca. 500 Ma ago. Secondary fluids in gneiss (T_h=235–265°C; McStay 1988), dense brines in quartz in the Koperberg Suite (T_h=210°C; Schoch 1989), and aqueous fluid entrapped in quartz in Rietberg Granite (T_h=200-250°C; Ougougdal et al. 1996) may also reflect that low temperature event.

To the south, Raith et al. (2003, p. 358) reported a concordia lower intercept age of 505 Ma for zircon rims in the 1,110 Ma old Stoffelskop Granite at Bitterfontein (Fig. 1), while weakly metamorphosed Nama sedimentary rocks immediately to the east yielded whole-rock $^{40}Ar/^{39}Ar$ ages of 495–500 Ma that record the age of tectonism and a biotite $^{40}Ar/^{39}Ar$ cooling age (T_c=260–350°C; Spear 1993) of 476 Ma (Gresse et al. 1988). These ages, and the O'okiep data discussed above, reflect Damaran regional greenschist facies metamorphism (M_4 (Raith and Prochaska 1995); see Fig. 5) overprinted on the Namaquan metamorphic zonation and extending 55 km to the east of the Gariep Front (Fig. 1).

Koperberg Suite

Petrology

There are 1,700 known bodies of the Koperberg Suite (Fig. 4) but all are small, and together they occupy only 0.7% of the 2,500 km^2 O'okiep Copper District (Lombaard and Schreuder 1978; Marais 1980). They occur as irregular pipes or, more commonly, dykes; the former rarely exceed 200 m in diameter, while the latter are up to 100 m in width, are predominantly east–west trending, but are rarely more than 1 km in length (Lombaard et al. 1986). Although a part of the anorthosite–charnockite kindred (Jackson 1979; Conradie and Schoch 1986b), the Koperberg Suite exhibits a restricted compositional range of jotunite, andesine anorthosite, biotite diorite, and leuconorite–norite–hypersthenite. With the exception of biotite diorite, the terminology is consistent with IUGS recommendations on how charnockitic rocks should be named (Streckeisen 1974) and, as is typical of the anorthosite–charnockite kindred, the plagioclase in the Koperberg anorthosite and leuconorite–norite is *andesine* (Streckeisen 1976, p. 19). Strauss (1941) emphasized the association of primary copper sulphides with hypersthene-bearing rocks of the Koperberg Suite (Strauss 1941, p. 115): "no pyroxene–no syngenetic ore." Kisters et al. (1994) suggested that hypersthene-bearing parageneses are most prominent in the lower parts of the country rock sequence, while the bulk of anorthosite/diorite bodies occur in higher units, suggesting a buoyancy-controlled ascent.

Geological cross-sections of some mined bodies of the Koperberg Suite are shown in Fig. 10. The earliest members are two-pyroxene rocks that were formerly referred to as hornblende gneiss (Benedict et al. 1964) or two-pyroxene granulite (Clifford et al. 1981) and were grouped with the country rock sequence (ibid.). However, Strauss (1941) and Van Zyl (1975, 1978) respectively called them gabbro and felsic norite and considered them to be part of the Koperberg Suite, a correlation confirmed by the weighted mean $^{207}Pb/^{206}Pb$ age of 1,035±13 Ma for magmatic zircon rims (Clifford et al. 2004). This group includes: olivine-normative (monzonorite) types bearing modal clinopyroxene, hypersthene, labradorite and phlogopite, and quartz-normative (monzodiorite) types bearing modal clinopyroxene, ferroan-hypersthene, antiperthitic andesine, brown hornblende, and biotite (Clifford et al. 1981). Duchesne et al. (2007) identified the latter as jotunites (see Fig. 10a) and noted that they are Fe-, Ti-, and P-rich and typically contain abundant apatite occurring as thin elongate prisms dispersed in all minerals, a feature that, with the granular texture, is typical of "chilled" rocks in anorthosite provinces. The jotunites resulted from crystallization of melts (Duchesne et al. 2007).

Andesine anorthosite, biotite diorite, and hypersthene-bearing rocks each constitute about 30–35% of the Koperberg Suite, and Cornelissen (1959) suggested that the average composition of these rocks is hypersthene diorite (leuconorite). Van Zyl (1975) was the first to recognize their cumulate character with: (1) earlier plagioclase cumulates—andesine anorthosite and biotite diorite and (2) later hypersthene cumulates—leuconorite to hypersthenite (Fig. 11a, b). Minor rock types are glimmerite, magnetite–hypersthene rock, hornblendite, and clinopyroxenite (Strauss 1941). Of these, glimmerites are largely phlogopite (>75%) and show chemical similarities to lamprophyre (Boer et al. 1993). McIver et al. (1983) suggested that they represent liquid compositions, but Duchesne et al. (2007) has argued that, except for jotunite, none of the Koperberg rocks represent melts. Duchesne et al. (2007) also note that the biotite diorites are chemically heterogeneous, suggesting a derivation from melts with different trace element contents and laden with cumulus minerals. That lithology, and that of glimmerite, is common in orbicular structures that are developed at 50 Koperberg localities (Lombaard and Schreuder 1978); orbicules are also recorded in hypersthene cumulates (Rogers 1912).

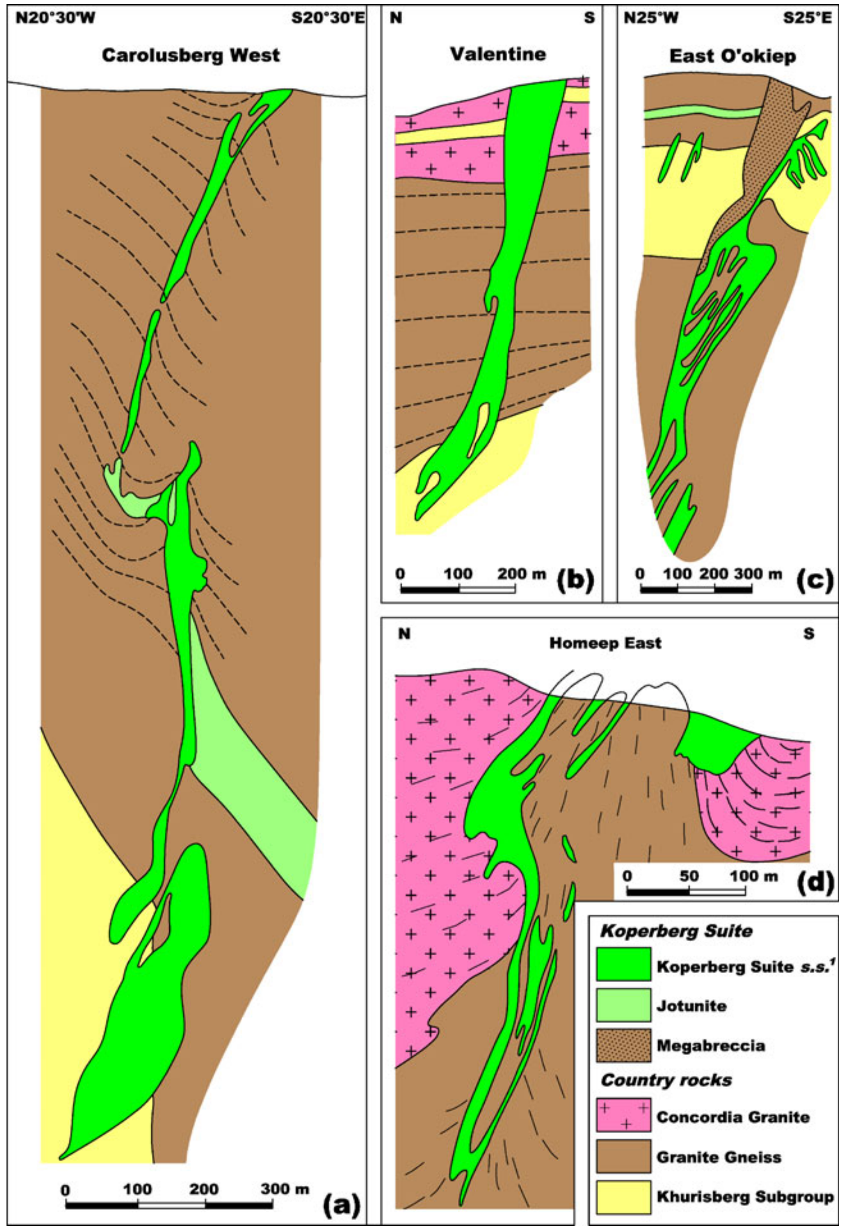


Fig. 10 Examples of mined ore-bodies of the Koperberg Suite in the O'okiep Copper District: **a**, **d** after Lombaard et al. (1986); **b**, **c** after Coetzee (1976).
[1] andesine anorthosite, biotite diorite, leuconorite, norite, melanorite, and hypersthenite

Petrogenetic models

Four models have been proposed for the Koperberg Suite (Fig. 12). Strauss (1941), Söhnge (1950), and Van Zyl (in Stumpfl et al. 1976) proposed that differentiated gabbroic magma at depth was tapped from the top down so that the order of intrusion was one of increasing basicity. In contrast, Wiid (1955) and Benedict et al. (1964) favoured a metasomatic origin; their model invoked local mobilization and concentration, often in steep structures, of Na, Ca, Mg, Fe, Al, and Cu collected by reacting fluids from metamorphic country rocks (Fig. 12). In the context of this debate, it is not surprising that Söhnge (1963) referred to the O'okiep Copper District as "this terrain of wild geology." In his study of the ore-bodies at O'okiep, Van Zyl (1967) reintroduced the name "magma" for the Koperberg liquid and suggested that the copper ores resulted from unmixing from a silicate melt.

The Koperberg Suite is now recognized as magmatic intrusives (Lombaard and Schreuder 1978), and debate has focused on the magma-source, be it mantle or crust or reflecting a mixture of both. Andreoli and Hart (1987) suggested that the high levels of K, REE, and P in the Koperberg Suite reflect melting of an enriched mantle source. In contrast, McIver et al. (1983), Schoch and Conradie (1990), Boer et al. (1994), Brandriss and Cawthorn (1996), and Van Zwieten et al. (1996) all consider that the rocks of the Koperberg Suite are mantle derivatives contaminated by crust (Fig. 12). More specifically, Geringer et al.

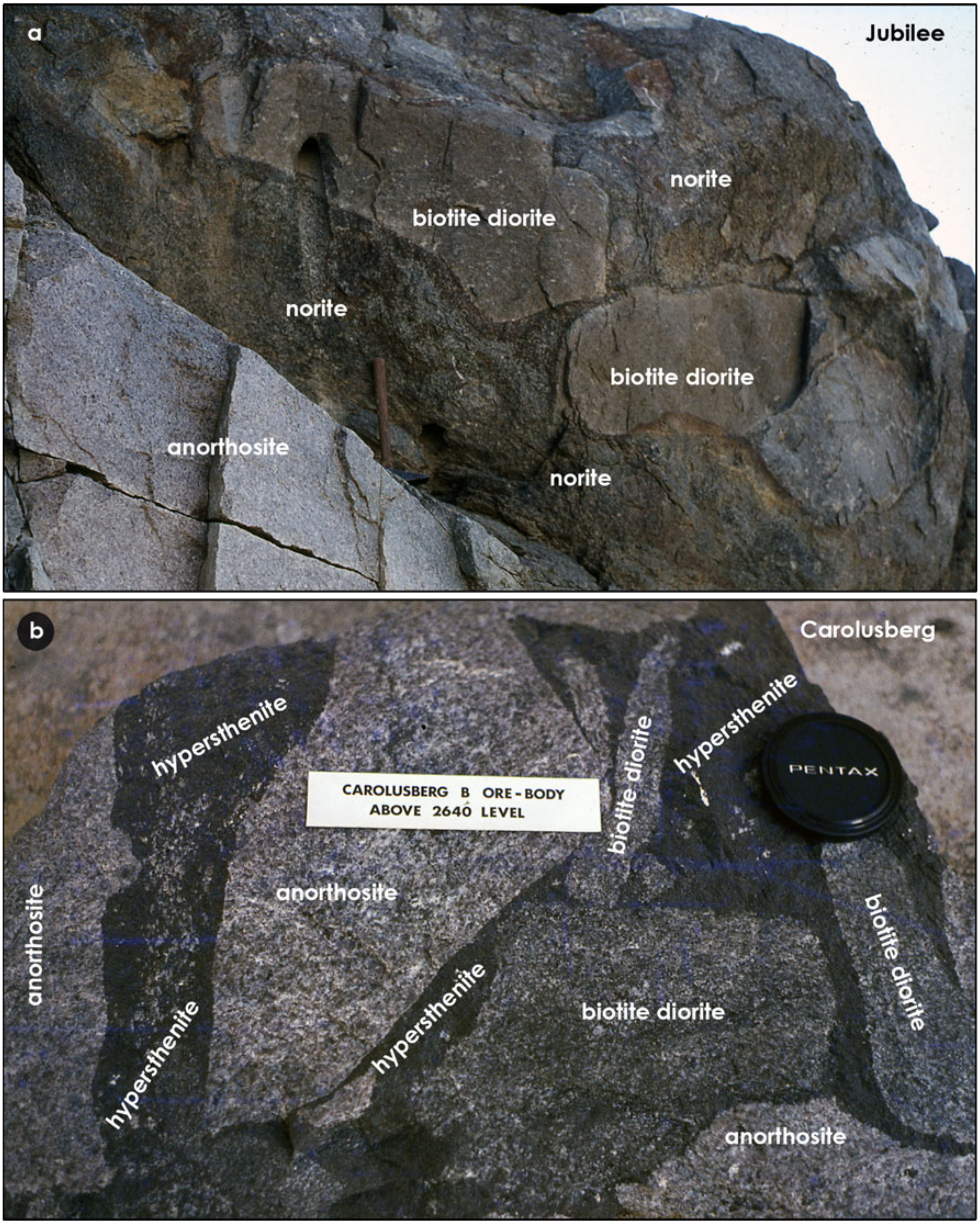


Fig. 11 Intrusion breccias in the Koperberg Suite. Cognate xenoliths of: **a** anorthosite and biotite diorite in norite, Jubilee Mine—hammer at center left is 37.5 cm in length; **b** anorthosite and biotite diorite in hypersthenite, 2,640-ft level, Carolusberg Mine—Pentax camera lens cap at upper right is 4.4 cm in diameter

(1998) argued that low ε_{Nd} and high I_{Sr} of the suite reflect mixing between an enriched mantle source and an extremely enriched crustal contaminant. However, Archaean or Proterozoic contaminants that are obligatory for that model are precluded because: (1) the crust of Archaean age is not recorded anywhere in the O'okiep or Garies Terranes of Namaqualand (Fig. 1) and (2) the crustal contaminant with ε_{Nd} of −2 and I_{Sr} of 0.760 invoked by Geringer et al. (1998) is unrealistic for Proterozoic material (Duchesne et al. 2007).

Fig. 12 Petrogenetic models for the Koperberg Suite

Differentiation	Differentiated gabbroic magma (iron-rich at top; magnesium-rich below) tapped from the top down so that the order of intrusion was one of increasing basicity	Van Zyl in Stumpfl et al. (1976); cf. Strauss (1941), Söhnge (1950), Pennebaker (1952), Lombaard et al. (1986)
Metasomatism	Fluids leached Na and Ca from the country-rocks and deposited them in 'steep structures' - in places later fluids brought in Mg, Fe, Cu and S	Wiid (1955), Cornelissen (1958), Benedict et al. (1964)
Contamination	Mantle-derived basaltic magma that underwent contamination by granite in the lower crust	Brandriss and Cawthorn (1996), Geringer et al. (1998); cf. McIver et al. (1983), Schoch and Conradie (1990), Boer et al. (1994)
Crustal Melting	Melting of lower crustal mafic granulite under dry conditions at P=11-13 kbar (depth 40-50 km) in an over-thickened crust	Duchesne et al. (2007); cf. Clifford et al. (1995, 2004)

K/Rb ratios for the Koperberg Suite are low (236; Boer et al. 1994) relative to mantle-derived mafic rocks (475–1830; Gast 1965) but are similar to crustal rocks (230; Heier and Adams 1964). Moreover, whole-rock isotope data and petrochemistry for a complete range of Koperberg rock-types, together with 1,020–1,040 Ma SHRIMP zircon ages for the main rock types (Clifford et al. 1995, 2004; Duchesne et al. 2007) demonstrate that: (1) Nd model ages for the whole spectrum of Koperberg rock-types are T_{CHUR}=1,731±93 Ma and T_{DM}=2,021±215 Ma (n=34) and record the age of separation, simplified to 1,900 Ma, of a primitive oceanic-crust protolith from the mantle in Eburnian times. Variation in $I_{Sr[1030\ Ma]}$ (0.707–746) may reflect hydrothermal alteration of the 1,900 Ma old protolith; (2) jotunite, the parent magma to, and earliest member of, the Koperberg Suite is the product of melting at ca. 1,200°C (Vander Auwera and Longhi 1994), 1,030 Ma ago, of lower crustal (gabbronoritic) mafic granulite under dry conditions at 11–13 kbar pressure (depth 40–50 km) (Longhi et al. 1999; Duchesne et al. 1999, 2007; see Fig. 12); and (3) the Koperberg Suite has negative (crustal) $\varepsilon_{Nd[1030\ Ma]}$ values of −5.1 to −6.2 for jotunite melt compositions and of −7.4 to −11.4 for andesine anorthosite and hypersthene cumulates and for biotite diorite quasi-cumulates (Fig. 13a). The $\varepsilon_{Nd[1030\ Ma]}$ values show that the progenitor had a REE-enriched distribution with Sm/Nd ratios between 0.15 and 0.25 (Fig. 13b), consistent with Mid-Ocean Ridge Basalts and Azores oceanic islands with Sm/Nd of 0.21±0.04 (White et al. 1979).

Ore parageneses

The ore minerals of the Koperberg Suite have been described by Rogers (1912, 1916), Tolman and Rogers (1916), Latsky (1942), Cornelissen (1958), Van Zyl (1967), and Stumpfl et al. (1976). The principal ore parageneses are: chalcopyrite+pyrrhotite/pentlandite (Narrap-type ore), bornite+Ti-free magnetite (Carolusberg-type ore), and bornite+chalcopyrite±chalcocite±covellite (Hoits-type ore) (Cawthorn and Meyer 1993; Clifford et al. 1995; see Figs. 5 and 14).

Narrap- and Carolusberg-type ores

Investigations over the past 90 years all concluded that the crystallization of magnetite and copper ore minerals post-dated that of primary silicates in the Koperberg Suite. In their pioneer work, Tolman and Rogers (1916) recognized that the ore paragenetic sequence in East O'okiep mica (biotite) diorite is: (1) magnetite, (2) pyrrhotite, and (3) chalcopyrite (Fig. 15a). However, in hypersthenite from the Nababeep Mine (Fig. 2) the ore is bornite+magnetite, while in Tweefontein norite it is bornite+chalcopyrite+magnetite (Fig. 15b). Latsky (1942) noted that pyrrhotite is confined to Narrap and East O'okiep (Fig. 1), that bornite and pyrrhotite are antipathetic (cf. Maier 2000, p. 423), and that the Koperberg Suite contains *inter alia* accessory amounts of native copper, molybdenite, linnaeite, and valleriite. Van Zyl (1967) described the East O'okiep ore-body and recognized that magnetite has been replaced by chalcopyrite and pyrrhotite/pentlandite, whilst Stumpfl et al. (1976) noted that the ore is 75% pyrrhotite/pentlandite+5% chalcopyrite, the veins of which penetrate country rock garnet gneiss.

Cawthorn and Meyer (1993) confirmed the strictly magmatic nature of the chalcopyrite+pyrrhotite/pentlandite (Narrap-type) ore (Fig. 15a), and Boer et al. (1994) obtained δ^{34}S values of −1.9‰ to −2.5‰ for both chalcopyrite and pyrrhotite from East O'okiep and Narrap that fall within the range (−3‰ to 2‰) considered to be typical for mantle-derived rocks (Ohmoto 1986). Cawthorn and Meyer (1993) also suggested that, during high-temperature oxidative metamorphism, Narrap-type ore was inverted to bornite+

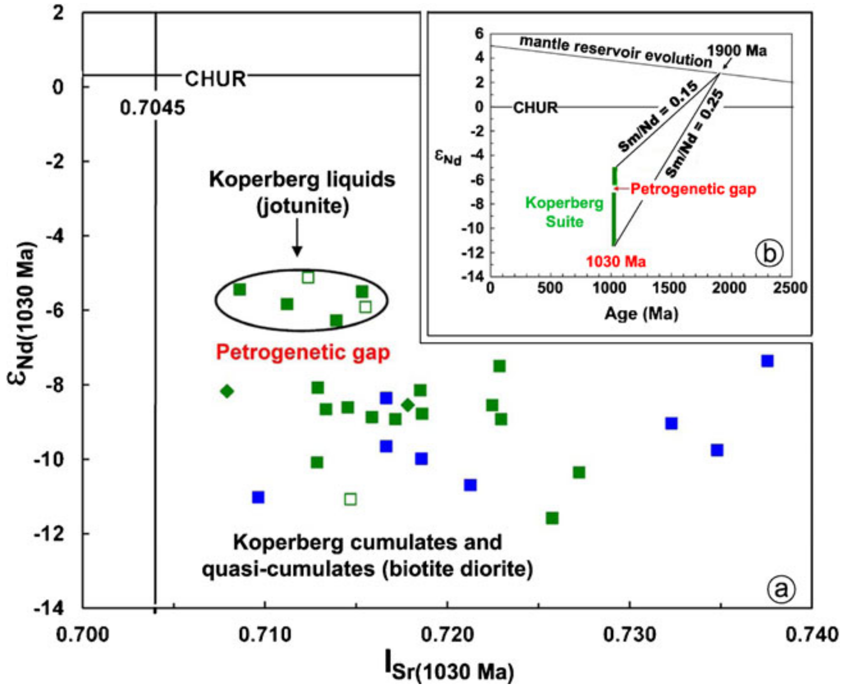


Fig. 13 **a** Conventional Sr–Nd evolution diagram for the Koperberg Suite showing initial Sr and Nd isotope compositions (at 1,030 Ma). Data sources: *solid green squares* and *diamonds* (Clifford et al. 1995); *solid blue squares* (Geringer et al. 1998); *open green squares* (Duchesne et al. 2007). The significance of the "petrogenetic gap" between jotunite melts and cumulates/quasi-cumulates is unknown. **b** ε_{Nd} vs age diagram for the Koperberg Suite (see text for discussion). The "mantle extraction age" of 1,900 Ma corresponds to an age intermediate between the T_{CHUR} (1,700 Ma) and T_{DM} (2,000 Ma) ages for the Koperberg Suite (cf. Duchesne et al. 2007).

Ti-free magnetite (Carolusberg-type ore; Fig. 15b) and that up to 90% of the original sulphur may have been lost in that oxidation. However, Maier (2000) argued that such desulphidization cannot account for Cu/Ni ratios up to 80; he considered that Carolusberg hypersthenites bearing bornite +chalcopyrite+magnetite are restites of a lower-crustal protolith intruded as pyroxene crystal mushes enriched in magnetite, apatite, and Cu-sulphides.

Hoits-type ore

Rogers (1916) was the first to recognize the association of sericite, epidote, and chlorite with low-temperature ore minerals such as chalcocite in the Koperberg Suite, while Latsky (1942) noted that those silicates, zoisite, and secondary hornblende occur where the sulphides are present as large masses. Moreover, in the West O'okiep ore-body, bornite

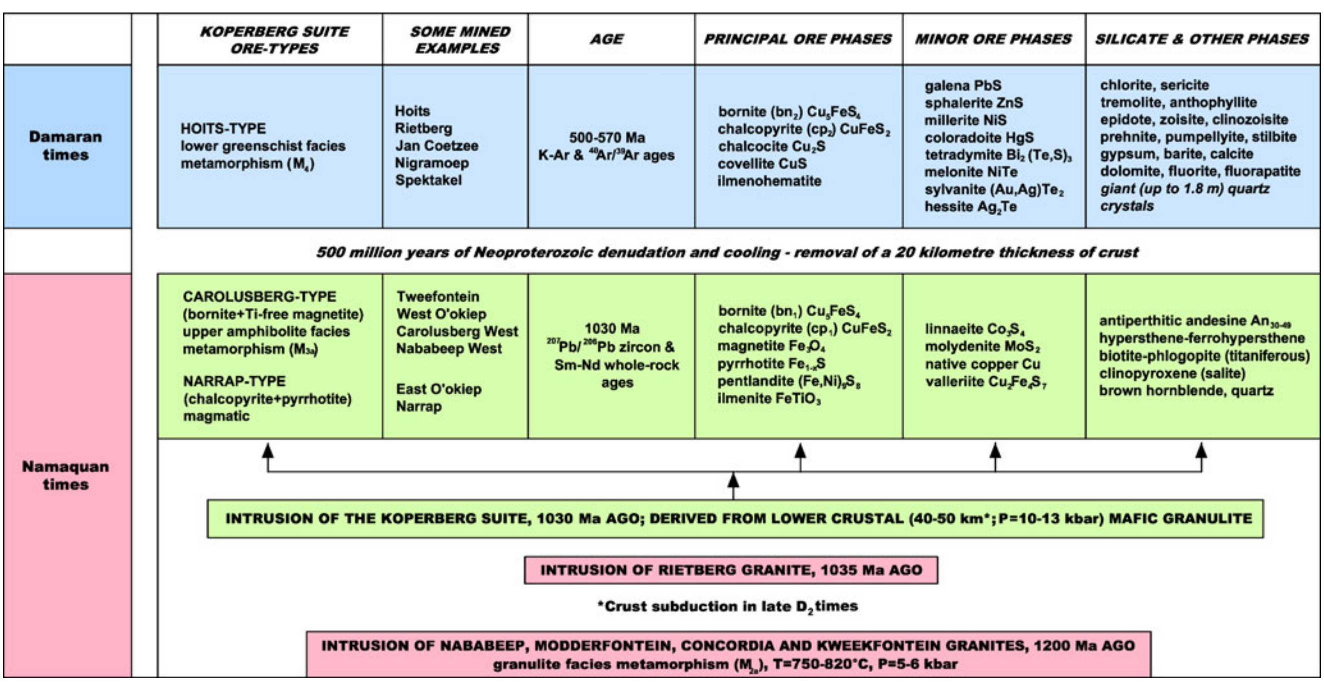


Fig. 14 Flow-chart for mineralization in the Koperberg Suite, O'okiep Copper District

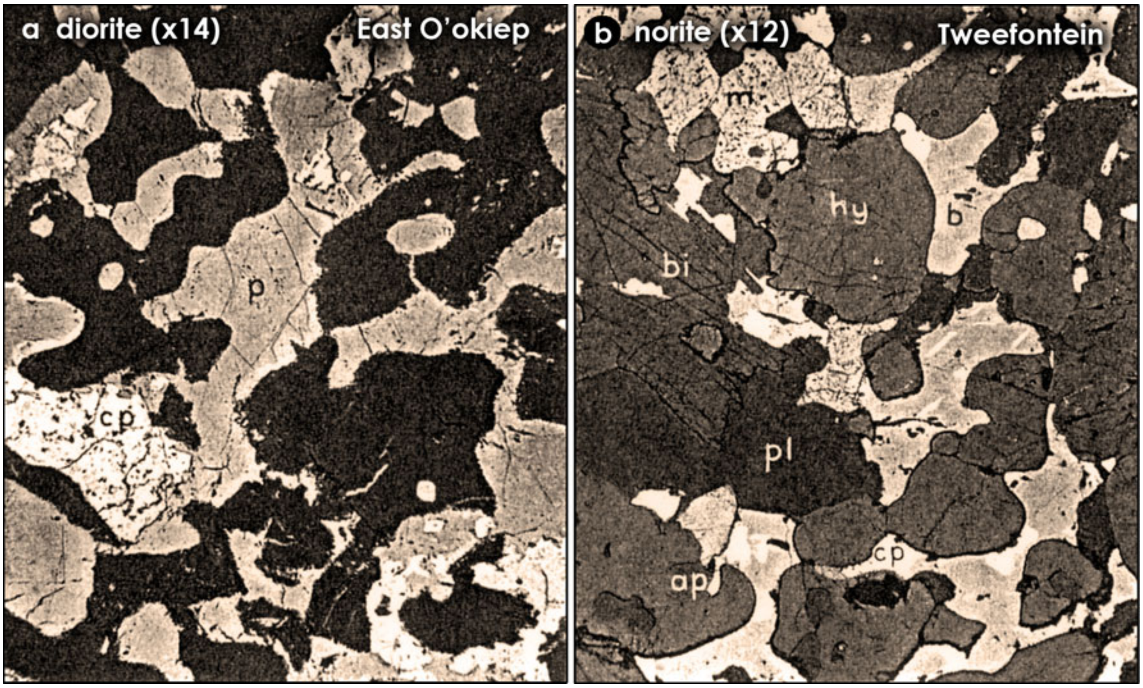


Fig. 15 Koperberg Suite. Photomicrographs (from Tolman and Rogers 1916) for: **a** Narrap-type ore, pyrrhotite (*p*), and chalcopyrite (*cp*) in mica (biotite) diorite, East O'okiep Mine; **b** Carolusberg-type ore, bornite (*b*), chalcopyrite (*cp*), and magnetite (*m*) with plagioclase (*pl*), hypersthene (*hy*), biotite (*bi*), and apatite (*ap*) in norite, Tweefontein Mine

and chalcopyrite have been replaced locally by chalcocite and covellite (Van Zyl 1967), while elsewhere bornite and chalcocite occupy alteration zones in hypersthene, and chalcopyrite has replaced altered pyroxene (Stumpfl et al. 1976). This phase of ore formation is referred to as Hoits-type ore (Clifford 1984; Fig. 14) and it constitutes virtually all copper-ore mined in the Hoits (Fig. 16a), Rietberg, Jan Coetzee, Nigramoep, and Spektakel Mines (Fig. 2), and was important in the shallower ores in the West O'okiep, Wheal Julia, Nababeep West, and Carolusberg Mines.

The most spectacular manifestation of the Hoits event is the presence of cavities, first described by Cornelissen (1958) in the Wheal Julia and Nababeep West Mines (Fig. 2), lined with quartz (Fig. 16b) or partly filled with gypsum with chalcocite, bornite, and chalcopyrite. Benedict et al. (1964) noted that hundreds of copper ore-bearing vugs and caves in the Nababeep West Mine occur on the "1,610-ft" level and above, *but not below* (Benedict et al. 1964, p. 285). One cavity measuring 2×8×5 m was coated by chlorite–epidote–quartz, chlorite–prehnite–quartz, and prehnite with quartz projecting into open cavities; coating on prehnite consisted of chalcocite coated with bornite itself coated with chalcopyrite (Benedict et al. 1964). In addition, Mostert (Benedict et al. 1964) described caves in which chalcopyrite and bornite were embebbed in gypsum, and chalcopyrite up to 10 cm in thickness coated the cave walls. More recently, Cairncross (2004) illustrated a gypsum crystal 80 cm in length, spectacular chalcocite (Fig. 16c), large barite coated with chlorite, ferroaxinite with fluorite, and acicular pumpellyite with epidote and chlorite from Nababeep West Mine, and he also records a 12×12×6-m chamber in Jan Coetzee Mine in which walls, floor, and roof were coated with 50,000 quartz crystals, the largest being 180 cm in length.

Stumpfl et al. (1976) related the Hoits hydration to the cooling phase of the Koperberg magma that "stewed in its own juices." In contrast, Cornelissen (1958) attributed the hydration and remobilization of copper to "circulation of groundwaters of meteoric origin." $^{40}Ar/^{39}Ar$ ages of 500–570 Ma support the latter interpretation and it is, then, unsurprising that secondary sulphides from vugs at Nababeep West and Carolusberg West Mines gave wayward $\delta^{34}S$ values of −3.5‰ to +14.2‰ (Von Gehlen 1990, p. 583). It is considered, therefore, that Hoits-type Cu redistribution/beneficiation was effected by meteoric fluids, ca. 600 Ma ago, in Koperberg bodies close to the pre-Nama peneplane (see Fig. 5); proto-Hoits ores were, thus, of supergene origin (cf. Park and MacDiarmid 1970, p. 478 et seq.). Later, Damaran lower greenschist facies metamorphism (cf. Raith and Prochaska 1995, pp. 1950–1951) is reflected by the ca. 500–570 Ma ages and by a wide range of low-temperature minerals in Hoits-type rock-types (Fig. 14). However, chlorite-prehnite-, chlorite–epidote- (Benedict et al. 1964), and pumpellyite- (Cairncross 2004) bearing parageneses in vugs/cavities at Nababeep West Mine suggest the local

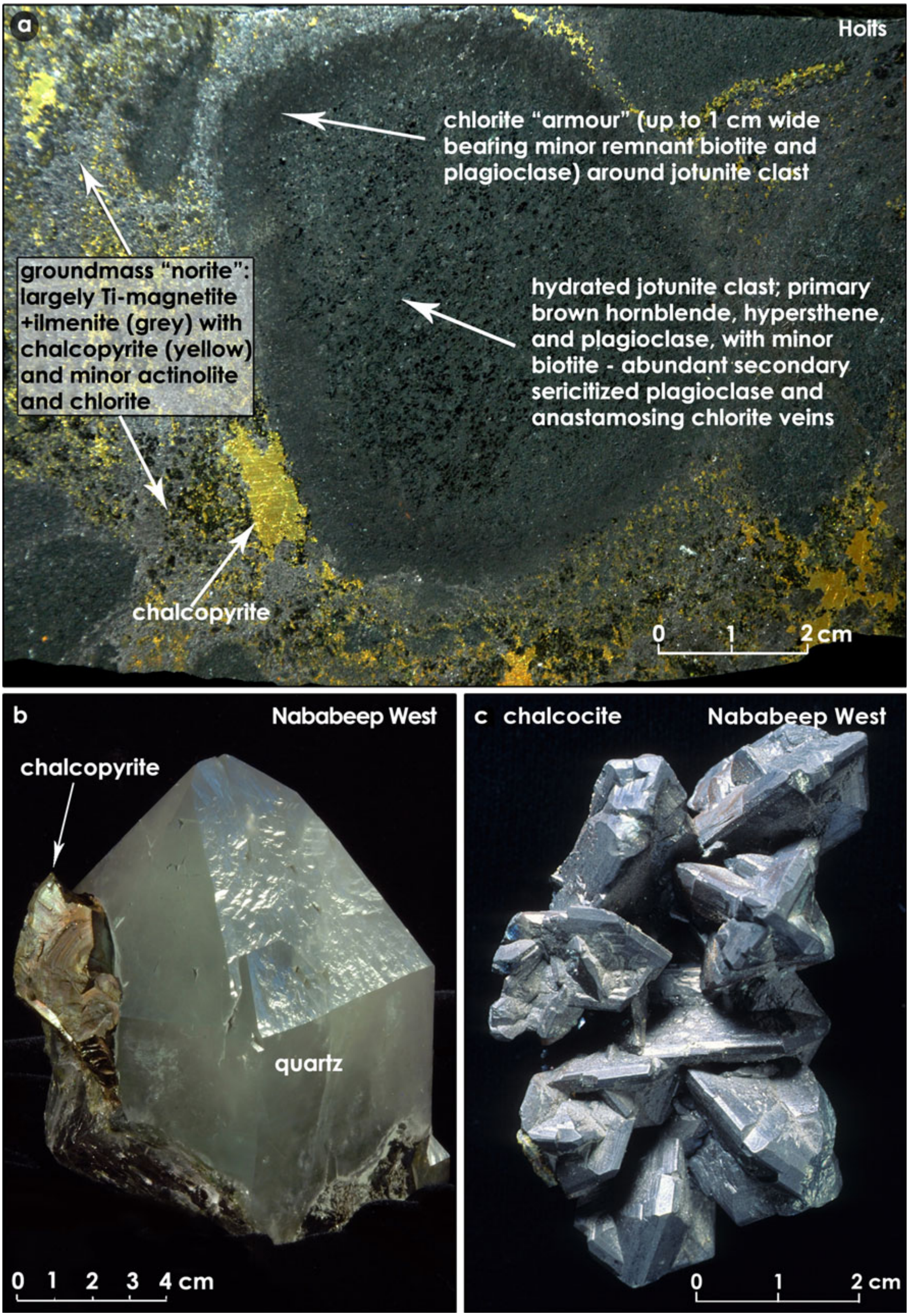


Fig. 16 Koperberg Suite. Hoits-type ore: **a** cognate xenolith of jotunite (rimmed by chlorite) in norite bearing chalcopyrite, ilmenite, and Ti-magnetite, 295 m level, Hoits Mine; **b** quartz with chalcopyrite, Nababeep West Mine; **c** twinned chalcocite crystals (photograph courtesy of Bruce Cairncross), Nababeep West Mine

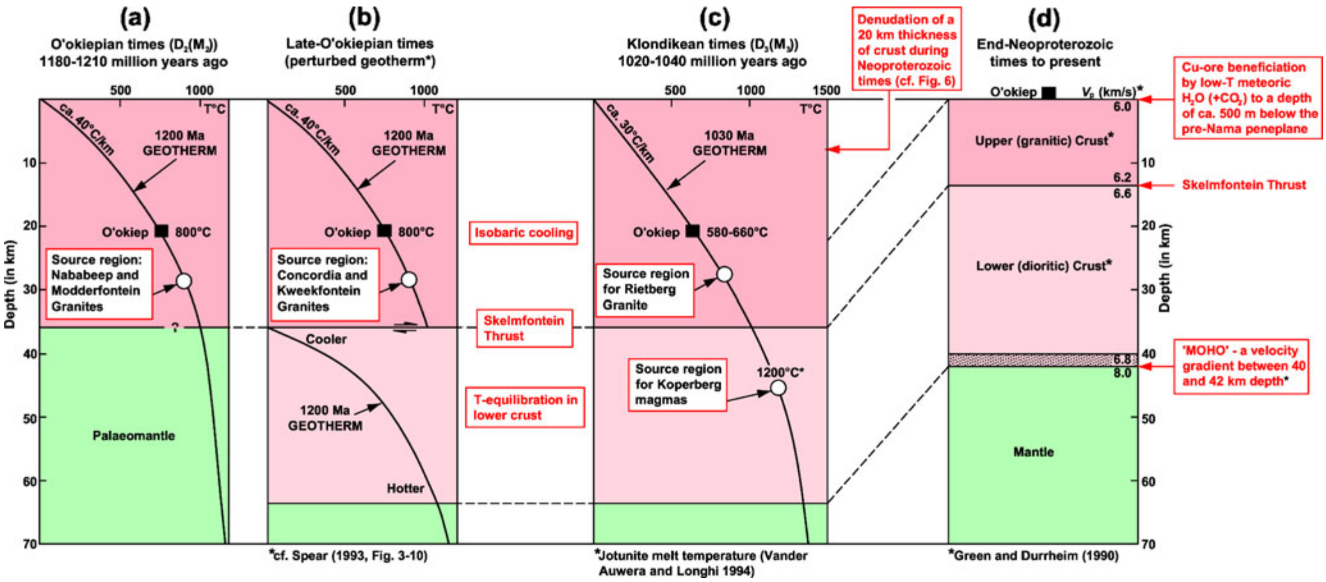


Fig. 17 Evolution of the O'okiep Crust from late Mesoproterozoic-through-Neoproterozoic times

influence of prehnite–pumpellyite facies metamorphic conditions.

Synthesis

Elements of 30% of Earth's history from 2,000 to 500 Ma ago are recorded in the geology of the O'okiep Copper District (Fig. 5). Within that interval, the dominant tectono-thermal event was the Namaquan Orogeny (Fig. 6) that comprised the O'okiepian (1,180–1,210 Ma ago) and Klondikean (1,020–1,040 Ma ago) Episodes that were separated, and followed, by lengthy periods of cooling. The O'okiepian Episode is characterized by alpine-type folding, regional granite plutonism, and granulite facies metamorphism (M_{2a}; Figs. 6 and 17a). By contrast, the Klondikean Episode is characterized by regional open folding and steep structures, the intrusion of the Rietberg Granite and the Koperberg Suite, and upper amphibolite facies metamorphism (M_{3a}; Fig. 6). Cooling from M_{2a} to M_{3a} was near-isobaric at ca. 6 kbar (Raith and Harley 1998) and implies denudation of a 20 km thickness of crust in Neoproterozoic times. The present-day crust at O'okiep is 42 km in thickness (Green and Durrheim 1990, p. 19930) and, on the reasonable assumption that movements during Neoproterozoic times were epeirogenic, it follows that the O'okiep crust was 60–65 km in thickness in O'okiepian–Klondikean times. Two seemingly similar models are suggested for the thickening: intracontinental subduction (Bird 1978) and underthrust "tongues" of mafic lower crust (Duchesne et al. 2007). On the basis of these models, Fig. 17b depicts duplication of the O'okiep crust by "decoupling" on the Skelmfontein Thrust (Fig. 2; Clifford et al. 2004, p. 688), the north-verging movement on which: (1) resulted in a perturbed

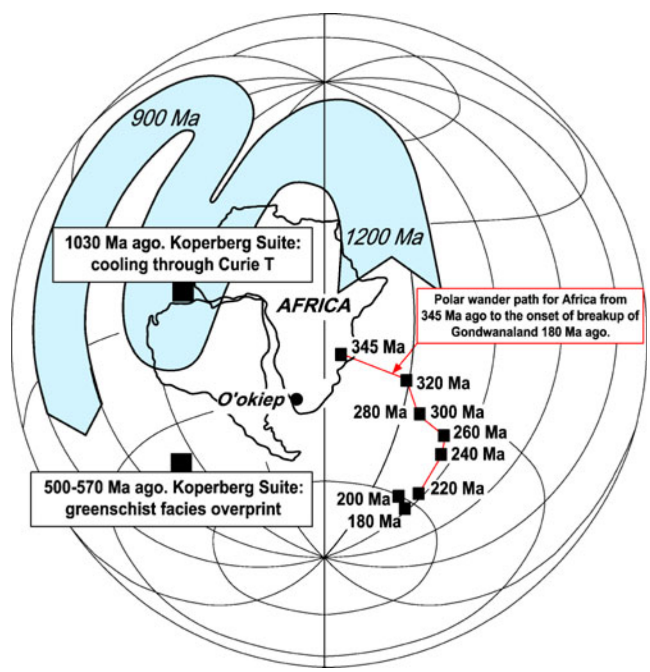


Fig. 18 Palaeomagnetic data for sample sites for the Koperberg Suite (Muller et al. 1978; Onstott et al. 1986) shown in relation to the polar wander path for the interval 1,200 to 900 Ma ago (ibid., p. 161). The polar wander path for African sites from 345 Ma ago (late Palaeozoic times) to initial break-up of Gondwanaland 180 Ma ago (Michiel de Kock, personal communication) is shown for comparison

"sharks tooth" geotherm (Fig. 17b), (2) carried the M_{2a} granulite facies O'okiep Terrane over the amphibolite facies terrane to the north (Fig. 2), and (3) was coeval with intrusion of the 1,200 Ma old Concordia and Kweekfontein Granites (Blignault et al. 1983). Figure 17c depicts the Klondikean thermal profile after cooling and temperature equilibration in the duplicated crust, and illustrates the source depths of the Rietberg Granite and Koperberg Suite at ca. 30 and 40–50 km respectively (see the following text).

The Koperberg Suite is a rare example of economic copper mineralization in rocks of the anorthosite–charnockite kindred; the only other presently exploited example is Caraiba, Brazil (Oliveira and Tarney 1995; Oliveira et al. 2004; Oliveira et al. 2010; see "Electronic supplementary material"). The Koperberg Suite is characterized by *inter alia* crustal isotope signatures (Fig. 13a), and it is concluded that the Koperberg magma was produced 1,030 Ma ago by melting of a cupriferous oceanic crustal protolith extracted from the mantle 1,900 Ma ago (Fig. 13b). More specifically, it is deduced: (1) that jotunites, the earliest members of the Koperberg Suite, are the product of melting of lower-crustal mafic granulite at a depth of 40–50 km (Fig. 17c) and (2) that almost all other members (anorthosite and hypersthene-bearing rocks) of the suite reflect crystallization in magma chambers at depth followed by forceful injection of cumulate crystal mushes. Intrusion of the suite into hot (ca. 650°C) country rocks resulted in the inversion of magmatic chalcopyrite+pyrrhotite (Narrap-type ore) to bornite+Ti-free magnetite (Carolusberg-type ore) (Fig. 14); cooling, 1,030 Ma ago, through the Curie temperature (560–610°C) is reflected by the palaeomagnetic pole for ten Koperberg sample sites (Fig. 18). There followed 500 million years of Neoproterozoic denudation, with concomitant isostatic uplift (Figs. 6 and 17c–d), prior to the deposition of the Nama sedimentary sequence (Fig. 5). Supergene copper enrichment by circulating meteoric $H_2O(CO_2)$, bearing trace amounts of *inter alia* antimony, barium, bismuth, fluorine, lead, nickel, mercury, silver, tellurium, and zinc (see Fig. 14), took place in Koperberg ore-bodies close to the sub-Nama peneplane (e.g., Jan Coetzee, Nigramoep; see Fig. 2). Post-Nama, Damaran greenschist facies metamorphism resulted in second-generation bornite+chalcopyrite(±chalcocite±covellite) (Figs. 5 and 14)—the palaeomagnetic pole for a Hoits site (500–570 Ma) of the Koperberg Suite (Fig. 18) likely reflects that low temperature event. Finally, attention is drawn to the two, very different ore grades in O'okiep mining history: averaging 14% Cu (Hoits-type ore) from 1852 to 1931, but <2% Cu (mainly Carolusberg-type ore) from 1940 to 2002; and it is fascinating to note that early mining was perforce in the former, close-to-surface ores with higher copper grades that reflect natural "high-grading" by circulating meteoric waters in end-Proterozoic times (Fig. 17d).

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