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U–Pb Zircon Calendar for Namaquan (Grenville) Crustal Events in the Granulite-facies Terrane of the O'okiep Copper District of South Africa

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The O'okiep Copper District is underlain by voluminous 1035–1210 Ma granite gneiss and granite with remnants of metamorphosed supracrustal rocks. This assemblage was intruded by the 1030 Ma copper-bearing Koperberg Suite that includes jotunite, anorthosite, biotite diorite and hypersthene-bearing rocks ranging from leuconorite to hypersthenite. New sensitive high-resolution ion microprobe age data demonstrate the presence of 1700–2000 Ma zircon as xenocrysts in all of the intrusive rocks, and as detrital zircon in the metasediments of the Khurisberg Subgroup. These data are consistent with published Sm–Nd model ages of c. *1700 Ma (*T_{CHUR}*) and* c. *2000 Ma (*T_{DM}*) of many of the intrusives that support a major crust-forming event in Eburnian (Hudsonian) times. In addition, U–Th–Pb analyses of zircons from all major rock units define two tectono-magmatic episodes of the Namaquan Orogeny: (1) the O'okiepian Episode (1180–1210 Ma), represented by regional granite plutonism, notably the Nababeep and Modderfontein Granite Gneisses and the Concordia and Kweekfontein Granites that accompanied and outlasted (e.g. Kweekfontein Granite) regional tectonism [*$F_2(D_2)$*] and granulite-facies metamorphism (*M_2*); (2) the Klondikean Episode (1020–1040 Ma), which includes the intrusion of the porphyritic Rietberg Granite and of the Koperberg Suite that are devoid of regional planar or linear fabrics. Klondikean tectonism (*D_3*) is reflected by major east–west-trending open folds [*$F_3(D_{3a})$*], and by localized east–west-trending near-vertical ductile folds ['steep structures';* $F_4(D_{3b})$*] whose formation was broadly coeval with the intrusion of the Koperberg Suite. A regional, largely thermal, amphibolite- to granulite-facies metamorphism (*M_3*) accompanied* D_3*. This study demonstrates,* inter alia, *that the complete spectrum of rock-types of the Koperberg Suite, together with the Rietberg Granite, was intruded in a short time-interval (<10 Myr) at* c. *1030 Ma, and that there were lengthy periods of about 150 Myr of tectonic quiescence within the Namaquan Orogeny: (1) between the O'okiepian and Klondikean Episodes; (2) from the end of the latter to the formal end of Namaquan Orogenesis 800–850 Ma ago.*

KEY WORDS: *U–Pb, zircon; O'okiep, Namaqualand; granite plutonism; granulite facies; Koperberg Suite; Namaquan (Grenville) Orogeny*

INTRODUCTION

The crystalline rocks of O'okiep Copper District of Namaqualand (Fig. 1) have been the subject of detailed field and laboratory investigations over the past 50 years (Lombaard *et al.*, 1986; Clifford *et al.*, 1995; Marais *et al.*, 2001). The work was motivated by the fact that the area contains 1700 small bodies of intrusive intermediate-to-mafic charnockitic rocks of the Koperberg Suite, of which 30 have been mined for copper since the middle of the

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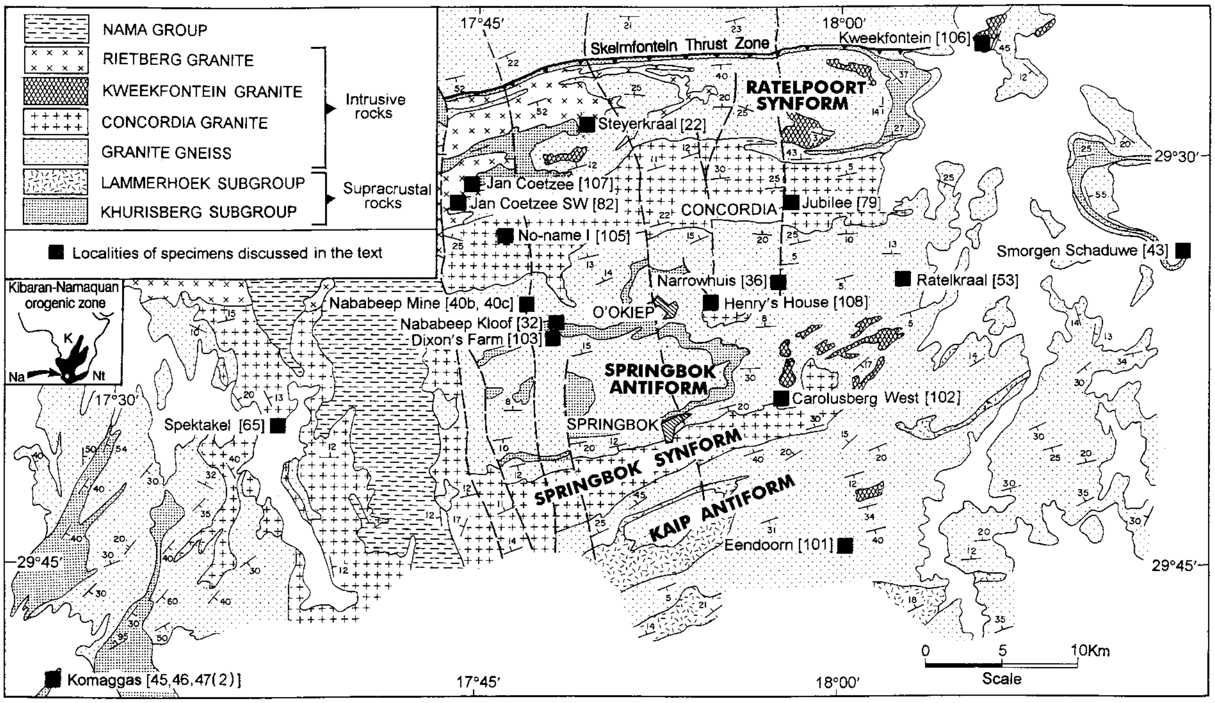


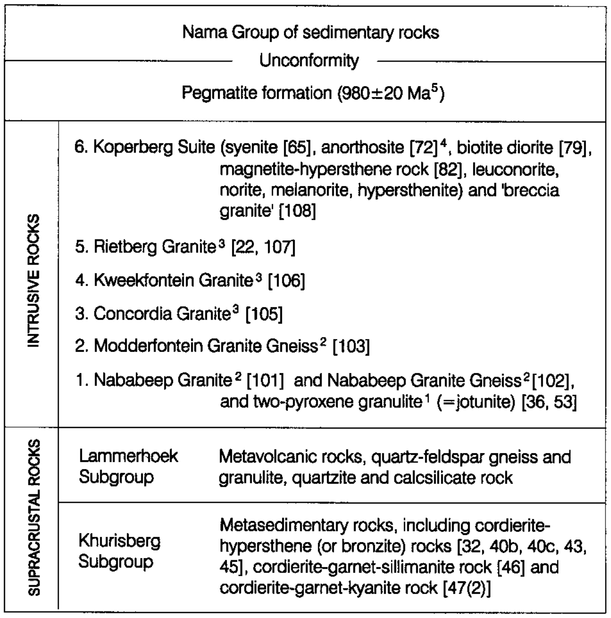
Fig. 1. Generalized geological map of the O'okiep District (after Lombaard *et al.*, 1986) showing localities of specimens discussed in the text; the 1700 known bodies of the Koperberg Suite are each far too small to be shown at this scale; their distribution is, however, clearly illustrated in Fig. 5 of Lombaard *et al.* (1986). The following features are particularly identified: (1) the Skelmfontein Thrust Zone that separates the granulite-facies terrane to the south from the amphibolite facies to the north (Blignault *et al.*, 1983; Raith & Harley, 1998); (2) the F_3 Ratelpoort and Springbok Synforms and the Springbok and Kaip Antiforms. Inset shows the Kibaran–Namaquan Orogenic Zone (K, Kibara Mountains; Na, Namaqualand; Nt, Natal). Historical comment: the name O'okiep is said to have two meanings in the local Nama language depending on pronunciation: 'the place of the big tree' or 'the little fountain' (Smalberger, 1975).

nineteenth century. These bodies are concentrated in an area of about 2500 km^2 (Fig. 1) that is underlain by granite gneiss and granite with remnants of granulite-facies metasedimentary and metavolcanic rocks (Benedict *et al.*, 1964; Clifford *et al.*, 1975*a*, 1981; Raith & Harley, 1998). These crystalline rocks are unconformably overlain by the sediments of the Late Neoproterozoic–Early Palaeozoic Nama Group (Fig. 1).

A number of divergent views on the timing and interpretation of the major rock-forming episodes in the O'okiep District have been proposed. In particular, Clifford *et al.* (1995) suggested that the principal tectonothermal activity, accompanied by high-grade metamorphic conditions, took place in the interval 1220 Ma (granite plutonism and alpine-type tectonism) to 1030 Ma (intrusion of the Koperberg Suite). In contrast, Gibson *et al.* (1996) and Robb *et al.* (1999) have de-emphasized the tectonothermal significance of events at 1200 Ma and argued that there was an intimate temporal relationship between the principal prograde granulite-facies metamorphism and the intrusion of (1) the Concordia and Rietberg Granites (at 1065–1060 Ma) (Figs 1 and 2), and (2) the Koperberg Suite over a 30 Myr period (at 1060–1030 Ma).

In this work we present new U–Th–Pb sensitive high-resolution ion microprobe (SHRIMP) age data for zircon populations from 20 rock-types covering the principal stratigraphic–petrographic units in the O'okiep Copper District (Fig. 2). These are: (1) cordierite-bearing parageneses of the Khurisberg Subgroup; (2) granitic intrusives including the syntectonic (D_2) Nababeep Granite Gneiss and Granite and the Modderfontein Granite Gneiss, the syn-to-late-D_2 Concordia Granite, the late-D_2 Kweekfontein Granite, and the Rietberg Granite; (3) a range of rock-types grouped with the Koperberg Suite. We also examine the timing of the intrusion of the Spektakel syenite, and of two pyroxene-bearing rocks (previously grouped with the Lammerhoek Subgroup). A list of the localities, and brief descriptions of the petrography for each of the rocks are presented in Electronic Appendix A, which can be viewed online at http://www.petrology.oupjournals.org.

The new results show: (1) no evidence for any major rock-forming event at 1065–1060 Ma; (2) that the principal regional granite plutonism (including the emplacement of the Concordia Granite) took place at 1200 Ma; (3) that the Rietberg Granite was intruded at 1035 Ma; (4) that the complete spectrum of rock-types of the



Nama Group of sedimentary rocks		
Unconformity		
Pegmatite formation (980±20 Ma[5])		
INTRUSIVE ROCKS	6. Koperberg Suite (syenite [65], anorthosite [72][4], biotite diorite [79], magnetite-hypersthene rock [82], leuconorite, norite, melanorite, hypersthenite) and 'breccia granite' [108]	
	5. Rietberg Granite[3] [22, 107]	
	4. Kweekfontein Granite[3] [106]	
	3. Concordia Granite[3] [105]	
	2. Modderfontein Granite Gneiss[2] [103]	
	1. Nababeep Granite[2] [101] and Nababeep Granite Gneiss[2] [102], and two-pyroxene granulite[1] (=jotunite) [36, 53]	
SUPRACRUSTAL ROCKS	Lammerhoek Subgroup	Metavolcanic rocks, quartz-feldspar gneiss and granulite, quartzite and calcsilicate rock
	Khurisberg Subgroup	Metasedimentary rocks, including cordierite-hypersthene (or bronzite) rocks [32, 40b, 40c, 43, 45], cordierite-garnet-sillimanite rock [46] and cordierite-garnet-kyanite rock [47(2)]

Fig. 2. A condensed lithostratigraphic sequence for the O'okiep District [largely after Lombaard *et al.* (1986)] listing the zircon populations analysed in this study (e.g. [65]; see Fig. 1). [1]These two-pyroxene rocks have also been regarded as part of the Lammerhoek Subgroup (Lombaard *et al.*, 1986) or as a part of the Koperberg Suite (Van Zyl, 1975). [2]The Nababeep and Modderfontein Granites/Gneisses are grouped as the Little Namaqualand Suite (Lombaard *et al.*, 1986). [3]The Concordia, Kweekfontein and Rietberg Granites have been grouped as the Spektakel Suite (Lombaard *et al.*, 1986). [4]U–Pb zircon age, 1029 ± 10 Ma (Clifford *et al.*, 1995). [5]U–Pb monazite age (Nicolaysen & Burger, 1965).

Koperberg Suite was intruded in a short time interval (<10 Myr) at *c.* 1030 Ma.

Country-rock geology

The geology of the O'okiep Copper District has been summarized by Lombaard *et al.* (1986) and Marais *et al.* (2001). The oldest elements are the Khurisberg Subgroup of metasediments and the Lammerhoek Subgroup of metavolcano-sedimentary rocks (Figs 1 and 2). Of these, the Khurisberg Subgroup includes quartzite, and cordierite parageneses bearing bronzite (or hypersthene) ± gedrite ± sapphirine or garnet–sillimanite–biotite ± kyanite ± microcline (Clifford *et al.*, 1975*b*, 1981). The Lammerhoek Subgroup includes quartz–feldspar–biotite granulite, mafic rocks, quartzite and calc-silicate rocks; horizons of two-pyroxene granulite have been included in this group by Lombaard *et al.* (1986).

These supracrustal sequences supposedly pre-dated the intrusion of *c.* 1820 Ma old granitic rocks of the Gladkop Suite (Barton, 1983; Robb *et al.*, 1999) that occur extensively to the north of, and locally within, the Ratelpoort Synform (Botha *et al.*, 1980; Lombaard *et al.*, 1986; Fig. 1). However, if those (as yet undated) granitic rocks in the eastern part of that synform are not part of the Gladkop Suite, then the Khurisberg Subgroup of metasediments may well be correlative with the *c.* 1650 Ma Bushmanland Group in the Aggeneys region (100 km ENE of O'okiep) (Reid *et al.*, 1987, 1997) as has been suggested by Clifford *et al.* (1981) and Joubert (1986).

Both the supracrustal sequences and the Gladkop intrusives were post-dated by large volumes of granite gneiss of the Little Namaqualand Suite that occur to the south of the Ratelpoort Synform (Fig. 1), and that include the Nababeep Granite Gneiss and Granite together with the intrusive Modderfontein Granite Gneiss. Younger granites include the sheet-like Concordia Granite (1500 m thick and lineated towards the base), the generally poorly foliated sill- and dyke-like bodies of the fine-grained Kweekfontein Granite, and the porphyritic Rietberg Granite, which is devoid of a regional tectonic fabric. Traditionally, the Concordia, Kweekfontein and Rietberg Granites have been grouped under the name 'Spektakel Suite' (Marais & Joubert, 1980; Lombaard *et al.*, 1986).

Koperberg Suite

The cupriferous Koperberg Suite, intrusive into the country rocks, is composed largely of andesine anorthosite and biotite diorite [plagioclase cumulates of Van Zyl (1975)], and hypersthene-bearing rocks [hypersthene cumulates of Van Zyl (1975)] that include leuconorite (hypersthene diorite), norite, melanorite, hypersthenite and magnetite–hypersthene rock (Strauss, 1941). Glimmerite (phlogopite–apatite rock) is a minor but important component of this suite, and it has been argued that it may be the only rock-type in the Koperberg Suite to represent a liquid composition (McIver *et al.*, 1983). Rare syenite and diopside- and hornblende-bearing rock have also been included in the suite (Lombaard *et al.*, 1986).

The Koperberg Suite occurs as dykes up to 100 m in width and generally less than 1 km in length, or as irregular pipes that rarely exceed 200 m in diameter, often associated with F_4 steep structures. In addition, these rocks occur as small intrusive bodies within breccia pipes, where they are accompanied by the local development of anatectic melt referred to as 'breccia granite' (Lombaard & Schreuder, 1978).

Structure

In the O'okiep District the principal regional tectonism, metamorphism and plutonism (including emplacement of the Koperberg Suite) took place at *c.* 1200–1000 Ma (Nicolaysen & Burger, 1965; Clifford *et al.*, 1975*a*; Barton, 1983; Joubert, 1986). This area represents the southern (Namaqualand) extension of the zone of Kibaran Orogeny of Central Africa [Fig. 1 (inset); see Holmes, 1951; Cahen

& Snelling, 1966; Clifford, 1970; Cahen *et al.*, 1984; Pohl, 1994; Thomas *et al.*, 1994]. In Namaqualand, the term Namaqua Orogeny has been used as a synonym for the Kibaran Orogeny (Blignault *et al.*, 1983). This is now invalidated by the fact that the timing of the Kibaran Orogeny *sensu stricto* in the Burundian segment of the type Kibaran Orogenic Zone of Central Africa has recently been constrained between 1370 Ma (extensive synorogenic magmatism) and 1205 Ma (limited post-orogenic magmatism) (Tack *et al.*, 1994, 2002). In terms of this redefinition there is as yet no evidence of the influence of the Kibaran Orogeny in the O'okiep District.

The dominant tectono-thermal events in the interval 1210–800 Ma that are recorded in the O'okiep District of Namaqualand are herewith referred to as the Namaquan Orogeny; this extends the definition of 'Namaquan' proposed by Thomas *et al.* (2004) for events in the age range 1250–950 Ma. The Namaquan Orogeny is also well documented in the Natal segment of the Namaquan–Kibaran Orogenic Zone [Fig. 1 (inset)], where it is represented by two tectonic events: D_1, at *c.* 1200–1140 Ma, characterized by recumbent folding and thrusting, and D_2, at *c.* 1080–1030 Ma, reflected by major shear zones (Eglington *et al.*, 1986, 2003; Thomas *et al.*, 1993*a*, 1996, 1999; Jacobs *et al.*, 1997). The minimum age for the deformation in Natal is provided by a U–Pb age of 1026 ± 3 Ma for zircon from a post-tectonic microgranite dyke (Thomas *et al.*, 1993*b*).

The structure of the O'okiep region has been described in terms of intrafolial folds (F_1), regional recumbent folding (F_2) (Vellet, 1958; Clifford *et al.*, 1975*a*), open folding (F_3), and localized, mainly antiformal steep structures (F_4) (Benedict *et al.*, 1964; Lombaard *et al.*, 1986; Kisters *et al.*, 1996). Of these, the area is dominated by the $F_2(D_2)$ recumbent folding of the Nababeep Nappe with an amplitude of >25 km (Clifford *et al.*, 1975*a*). This is reflected by an accompanying shallow-dipping regional S_2 foliation that is particularly characteristic of the granite gneisses, and by an east–west-trending L_2 lineation that is typical of the lower part of the Concordia Granite sheet.

The most obvious regional structures of the O'okiep Copper District are the east–west-trending F_3 open folds such as the Springbok and Kaip Antiforms and the Ratelpoort and Springbok Synforms (Fig. 1). Younger structural features (F_4) are narrow, east–west-trending, generally anticlinal, linear zones known as steep structures (Lombaard & Schreuder, 1978; Marais *et al.*, 2001, p. 30). These folds vary in length from 30 m to 7 km with widths ranging from 3 m to 500 m and have a marked discrepancy (up to 10:1) between fold amplitude and wavelength; locally, an axial planar fabric accompanies this folding (Kisters *et al.*, 1996). Pipes of megabreccia that occur along F_4 steep structures are collapse-structures containing exotic blocks of the country-rock sequence (Lombaard & Schreuder, 1978).

The Skelmfontein Thrust Zone (Fig. 1) forms the northern structural boundary of the O'okiep granulite-facies terrane. The thrusting is reflected by penetrative shear fabrics, most notably in the Concordia, Kweekfontein and Rietberg Granites, and it has been argued that this shearing took place at high temperatures (Martens, 1979; Blignault *et al.*, 1983; Raith & Harley, 1998).

Metamorphism

In the O'okiep District F_2 deformation was accompanied and outlasted by the M_2 regional metamorphism for which the peak P–T conditions were estimated as follows: $P = 6$–7 kbar and $T = 800$–$870°C$ determined for garnet–cordierite; and $P = 5{\cdot}9$–$6{\cdot}1$ kbar for $T = 800°C$ for a garnet–plagioclase paragenesis (Clifford *et al.*, 1981). Recently, $T = 750$–$820°C$ and $P = 5$–6 kbar have been determined for garnet–cordierite parageneses for that metamorphism that has been designated M_{2a} by Raith & Harley (1998). Rb–Sr whole-rock ages of 1179 ± 28 Ma (Barton, 1983) and 1223 ± 48 Ma (Clifford *et al.*, 1995) for the Nababeep Granite Gneiss are believed to reflect the age of the high-grade (M_2) metamorphism. In contrast, Waters (1989) speculated that the *c.* 1200 Ma granite ages reflect amphibolite-facies conditions, and that peak granulite-facies metamorphic conditions outlasted the emplacement of later granites such as the Concordia Granite. Raith & Harley (1998) suggested that the upper-amphibolite- to granulite-facies was also reached during M_3 metamorphism synchronous with the emplacement of the Koperberg Suite at 1029 ± 10 Ma (Clifford *et al.*, 1995).

SHRIMP METHODOLOGY

The SHRIMP II analyses were conducted at the J. C. Roddick Laboratory at the Geological Survey of Canada, Ottawa. They were carried out in three periods during 1996, 1998 and 2000, following the analytical techniques described in detail by Stern (1997), with recent modifications by Stern (2001) and Stern & Amelin (2003). Five mounts (IP26, IP27, IP85, IP86, IP141) were prepared; the first four containing fragments of the standard Kipawa zircon (993 Ma) and the fifth the 6266 zircon (559 Ma). The internal structure of the zircon grains was characterized using a scanning electron microscope to detect cathodoluminescence and backscattered electron contrast. Sputtering of the zircon targets was carried out using 15, 20 or 30 µm diameter primary spots of uniform beam intensity (1·5 nA O_2^-, 4–10 nA O^-). Calibration of $^{206}Pb/^{238}U$ ratios was accomplished using linear calibrations of $^{254}[UO]^+/^{238}U^+$ vs $^{206}Pb^+/^{238}U^+$ or $^{206}Pb^+/^{270}[UO_2]^+$ for the appropriate standard zircon. The standard deviation of the discrimination curves (1·0%) has been propagated along with counting

Table 1: Summary of new SHRIMP ages for zircon from cordierite-bearing metasediments of the Khurisberg Subgroup, O'okiep Copper District

Sample number	Mineral paragenesis	Inheritance T_0 (Ma)	M_2 T_I (Ma)	M_3 T_{II} (Ma)	Text figure	Electronic Appendix table	Electronic Appendix figure
45	cordierite–hypersthene		1173 ± 20	1034 ± 10	4	B1 (a)	B1
46	cordierite–garnet–sillimanite	2046 ± 170	1182	1022 ± 12		B1 (b)	B2
47(2)	cordierite–garnet–kyanite	1510		1057 ± 10 1028 ± 14		B1 (c)	B3
40b	cordierite–hypersthene–magnetite–sulphide	2043 ± 97		1018 ± 7		B2 (a)	B4
40c	cordierite–hypersthene–magnetite–sulphide–anthophyllite–talc			1003 ± 22		B2 (b)	B5
32	cordierite–bronzite–sapphirine	1887 ± 260		1021 ± 13		B3 (a)	B6
43	cordierite–bronzite–gedrite	2044 ± 64	1197 ± 96	1024 ± 14	5	B3 (b)	B7

errors in estimating the errors in the final $^{206}Pb/^{238}U$ ratios of the unknowns. The $^{207}Pb/^{206}Pb$ are reported without correction for mass fractionation, but these and the $^{206}Pb/^{238}U$ are corrected for common Pb at the Pb–Pb age using the measured ^{204}Pb content and the Cumming & Richards (1975) terrestrial Pb. Errors in the data tables are at 68% confidence level, with final weighted mean ages in the text at 95% confidence level. Decay constants used are $1{\cdot}55125 \times 10^{-10}$($^{238}U$) and $9{\cdot}8485 \times 10^{-10}$($^{235}U$). Statistical analysis and U–Pb concordia diagrams were generated using Isoplot (Version 2.49) (Ludwig, 2001). The SHRIMP analytical data and the complete set of concordia plots for the 20 analysed zircon populations are presented in Electronic Appendix B, which can be viewed online at http://www.petrology.oupjournals.org.

U–Pb ZIRCON GEOCHRONOLOGY

The results of some 500 new SHRIMP analyses of zircon from 20 representative O'okiep crystalline rocks are discussed below under two headings.

(1) Supracrustal rocks are represented by seven cordierite-bearing parageneses from the Khurisberg Subgroup (see Fig. 2). U–Pb isotope data for these zircons are listed in Electronic Appendix Tables B1–B3, and are illustrated in Electronic Appendix Figs B1–B7.

(2) Intrusive rocks are represented by samples from the regional granite gneisses and granites, and the Koperberg Suite (see Fig. 2). U–Pb isotope data are presented for zircons from these rocks as follows: granite gneiss and granite (and syenite), Electronic Appendix Tables B4–B6 and Figs B8–B15; jotunite, biotite diorite and magnetite–hypersthene rock of the Koperberg Suite (and the breccia granite), Electronic Appendix Tables B7 and B8 and Figs B16–B20.

Supracrustal rocks

The localities of cordierite-bearing parageneses of the Khurisberg Subgroup studied here are Komaggas [45, 46, 47(2)], Nababeep Mine [40b, 40c], Nababeep Kloof [32] and Smorgen Schaduwe [43]. The U–Pb ages obtained for zircons from these rocks are summarized in Table 1.

Komaggas

The cordierite–hypersthene [45], cordierite–garnet–sillimanite [46] and cordierite–garnet–kyanite [47(2)] rocks from this locality are part of a horizon 15 m thick and 650 m in strike length (Fig. 1). Of these, parageneses 45 and 46 reflect granulite facies whereas sample 47(2) is an amphibolite-facies metamorphic paragenesis showing the retrograde formation of kyanite from cordierite and sillimanite. The zircon populations from all of these samples are anhedral, translucent, almost colourless and devoid of inclusions.

The CL images for sample 45 show distinct cores that occasionally exhibit remnant euhedral shapes and zoning (Fig. 3a), but that are more generally completely spherical; well-developed radial fractures occur emanating from anhedral cores. The rims are largely homogeneous but indistinct banding is sometimes present, and the core–rim boundaries are diffuse. U–Pb zircon data for sample 45 record two age groups as follows: four core analyses give a weighted mean $^{207}Pb/^{206}Pb$ age of 1173 ± 20 Ma whereas analyses on five rims and six cores are within error and indicate a mean $^{207}Pb/^{206}Pb$ age of 1034 ± 10 Ma (Fig. 4).

The zircons from sample 46 are uniformly anhedral, and devoid of inclusions and radial fractures. All are very small (*c.* 90 μm) but show distinct, but complex, euhedral to anhedral cores that preserve remnant zoning, whereas

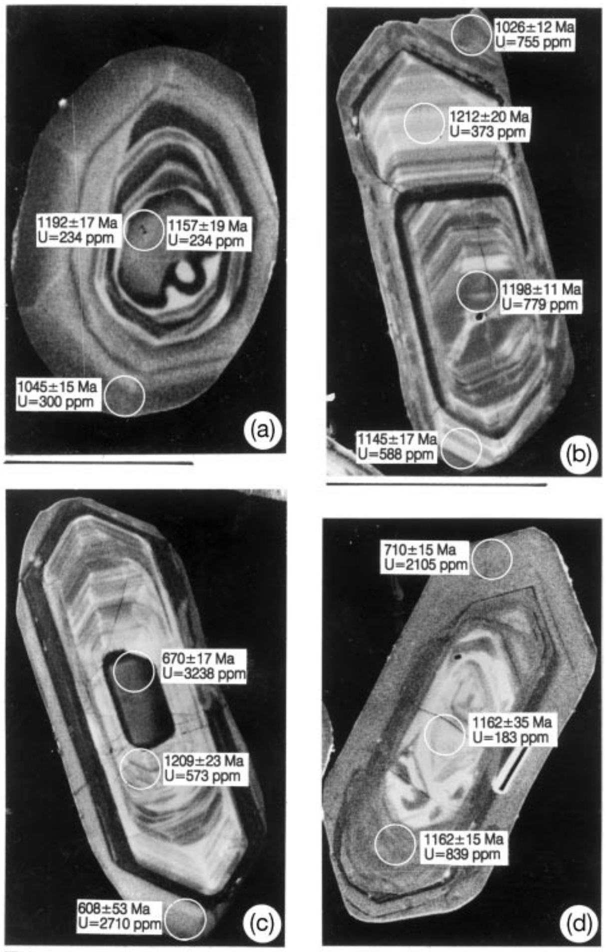


Fig. 3. CL images for zircons, illustrating SHRIMP $^{207}Pb/^{206}Pb$ ages and U concentrations for analysed data points, as follows: (a) grain 55, cordierite–hypersthene rock [45], Khurisberg Subgroup, Komaggas; (b) grain 25, Nababeep Granite Gneiss [102], Carolusberg West Mine; (c) grain 2B-12, Concordia Granite [105], No-name 1; (d) grain 1-20, Kweekfontein Granite [106], Farm Kweekfontein (Fig. 1). Analytical data are as follows: grain 55, Appendix Table B1(a); grain 25, Appendix Table B4(a); grain 2B-12, Appendix Table B5(a); grain 1-20, Appendix Table B5(b). Bar scales represent 100 μm; white circles indicate locations of the analysed 20–30 μm target areas.

the zircon rims are <40 μm in width and are homogeneous. Of these, eight U–Pb analyses of zircon cores reflect inheritance (Table 1), and the data are distributed along a linear array with an upper intercept age of 2046 ± 170 Ma and a lower intercept suggesting a Pb-loss event at 1200–1000 Ma. One core with an age of 1182 Ma is within error of the 1173 Ma group found in sample 45, whereas analyses on five zircon rims and one zircon core in sample 46 indicate a mean $^{207}Pb/^{206}Pb$ age of 1022 ± 12 Ma (Table 1), within error of the youngest population in sample 45.

The CL images for zircons from the kyanite-bearing rock [47(2)] show oscillatory-zoned cores and featureless rims. The core–rim contacts are sharp, with the latter truncating the former. Some domains within the cores, especially where they show oscillatory zoning, comprise highly altered zircon. One discordant analysis on a zircon core indicates a minimum $^{207}Pb/^{206}Pb$ age of 1510 Ma. The remaining 22 U–Pb zircon analyses fall into two groups (Table 1): 14 analyses on cores yield a weighted mean $^{207}Pb/^{206}Pb$ age of 1057 ± 10 Ma, whereas eight analyses on featureless rims yield a mean $^{207}Pb/^{206}Pb$ age of 1028 ± 14 Ma.

Nababeep Mine

About a dozen occurrences of cordierite–hypersthene–magnetite–sulphide rock ranging in thickness from 2·5 cm to 30 cm have been recognized on the '546-foot' level in the Nababeep Mine (Fig. 1; Benedict *et al.*, 1964; Clifford *et al.*, 1981). Of the two samples, 40b is largely unaltered whereas sample 40c is characterized by pervasive retrogression that resulted in the complete hydration of hypersthene to anthophyllite + talc.

Both samples (40b, 40c) contain about 4% of zircon with a gem-quality appearance. The grains (200–350 μm) are anhedral to rounded–subhedral, and are pale hyacinth in colour. In sample 40b the CL images show distinct core regions (<150 μm) that exhibit remnant euhedral shapes with diffuse zoning. The cores are mantled by featureless zircon rims. In contrast, the cathodoluminescence (CL) images for sample 40c show that the zircon grains are entirely featureless. Fifteen analyses on uniform zircon rims from 40b are concordant and indicate a well-constrained weighted mean age of 1018 ± 7 Ma (Table 1), whereas seven analyses of cores are distributed in a linear array consistent with a primary age of about 2000 Ma and episodic Pb loss at about 1000 Ma. The interior regions in sample 40c give a weighted mean $^{207}Pb/^{206}Pb$ age of 1003 ± 22 Ma (Table 1).

Nababeep Kloof and Smorgen Schaduwe

These two parageneses occur as concordant lenses within quartzite and schist successions. The petrology and petrogenesis of the cordierite–bronzite–sapphirine rock [32] from Nababeep Kloof and of the cordierite–bronzite–gedrite paragenesis [43] from Smorgen Schaduwe have been discussed by Clifford *et al.* (1975*b*, 1981).

Previous U–Pb studies of zircons from sample 32 showed apparent ages of up to 1700 Ma interpreted as inheritance, and zircon overgrowths with ages of *c.* 1200 Ma (Clifford *et al.*, 1981). The zircons are 100–150 μm in size, and are mainly anhedral, and pink to pale hyacinth in colour. The CL images show distinct cores (80–100 μm) that are euhedral with well-developed zoning. The surrounding rim regions are homogeneous

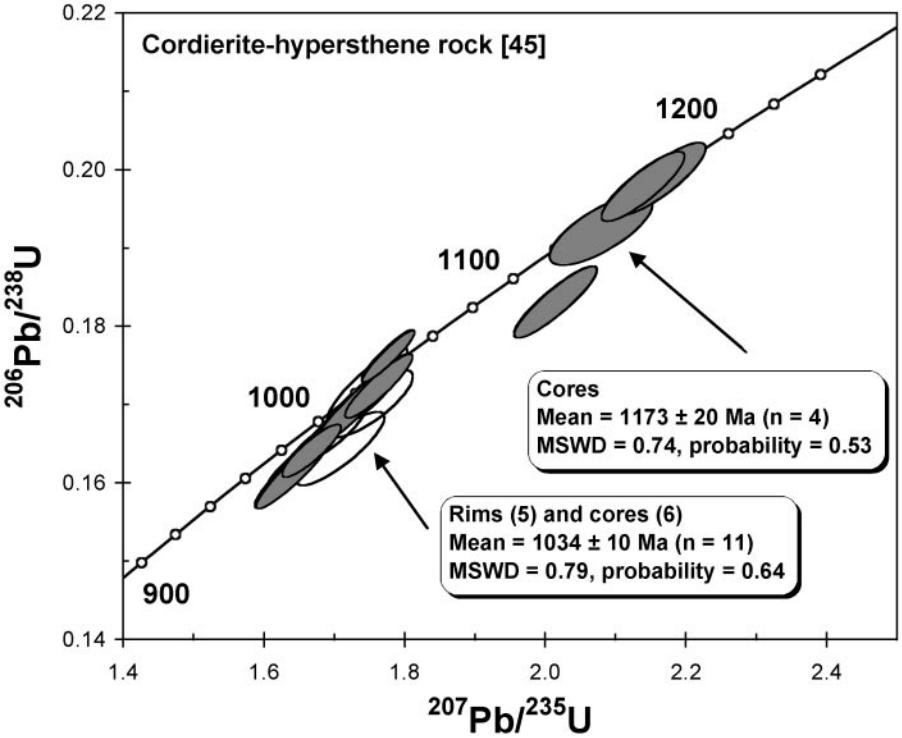


Fig. 4. U–Pb concordia diagram for zircons from cordierite–hypersthene rock [45] of the Khurisberg Subgroup, Komaggas (Fig. 1). [See Appendix Table B1(a) for analytical data.]

and rounded in outline. The zircons in sample 43 are also rounded, but all are small (<90 μm) and show narrow (20–50 μm) rims. As in sample 32, the CL images show distinct cores (<70 μm) that are variably euhedral or anhedral and are either homogeneous or show remnant zoning.

In sample 32 there are major chemical differences between the zircon cores (mean U 209 ppm; mean Th 127 ppm) and zircon rims (mean U 409 ppm; mean Th 11 ppm); the very low mean Th/U of 0·02 in the latter [Electronic Appendix Table B3(a)] clearly reflects a loss of Th during M_3 metamorphism (Table 1). These growth events are recorded in the zircon geochronology as follows: (1) five cores show variable degrees of discordance consistent with Pb loss from a primary 1887 ± 260 Ma zircon population; (2) 10 zircon rims yield a weighted mean ^{207}Pb/^{206}Pb age of 1021 ± 13 Ma (Table 1). U–Pb analyses of zircon from sample 43 indicate a similar history as follows (Fig. 5): seven core analyses are consistent with an episodic Pb-loss model with upper and lower intercept ages of 2044 ± 64 Ma and 1197 ± 96 Ma, respectively, whereas four rims have a weighted mean ^{207}Pb/^{206}Pb age of 1024 ± 14 Ma.

Discussion

Three distinct events at 2000 Ma, 1175 ± 23 Ma and 1020–1035 Ma are recognized in the zircon populations from the Khurisberg metapelites in the O'okiep District (Table 1). Of these, the 2000 Ma populations record the age of detritus from an Eburnian source (see Clifford *et al.*, 1995) preserved in all samples except 40c and 45.

It has been argued that the Khurisberg Subgroup either (1) pre-dated the Gladkop Suite of granitic intrusives (Lombaard *et al.*, 1986, p. 1424) that have yielded an emplacement age of 1820 Ma (Barton, 1983; Robb *et al.*, 1999) or (2) is correlative with the *c.* 1650 Ma Bushmanland Group (Joubert, 1986; Reid *et al.*, 1987). Whichever of these alternatives is selected it is clear that the event at 1175 ± 23 Ma that is documented from zircon cores in sample 45 (Fig. 4) records a subsequent metamorphic event that is consistent with M_2 granulite-facies metamorphism (Table 1) that accompanied *c.* 1200 Ma regional granite plutonism in the O'okiep District (Clifford *et al.*, 1981, 1995). The concordia lower intercept age of 1197 ± 96 Ma for zircon cores from sample 43 (Fig. 5) may also record this event.

Ages in the 1020–1035 Ma range are given by featureless zircon in all metapelite samples (Table 1), and record the age of M_3 upper-amphibolite- to granulite-facies metamorphism (see Raith & Harley, 1998). The 1057 ± 10 Ma age recorded by oscillatory-zoned cores of zircons in sample 47(2) (Electronic Appendix Fig. B3) is problematical, as there is no independent confirmation of an event of that age in this study. It is noteworthy, however,

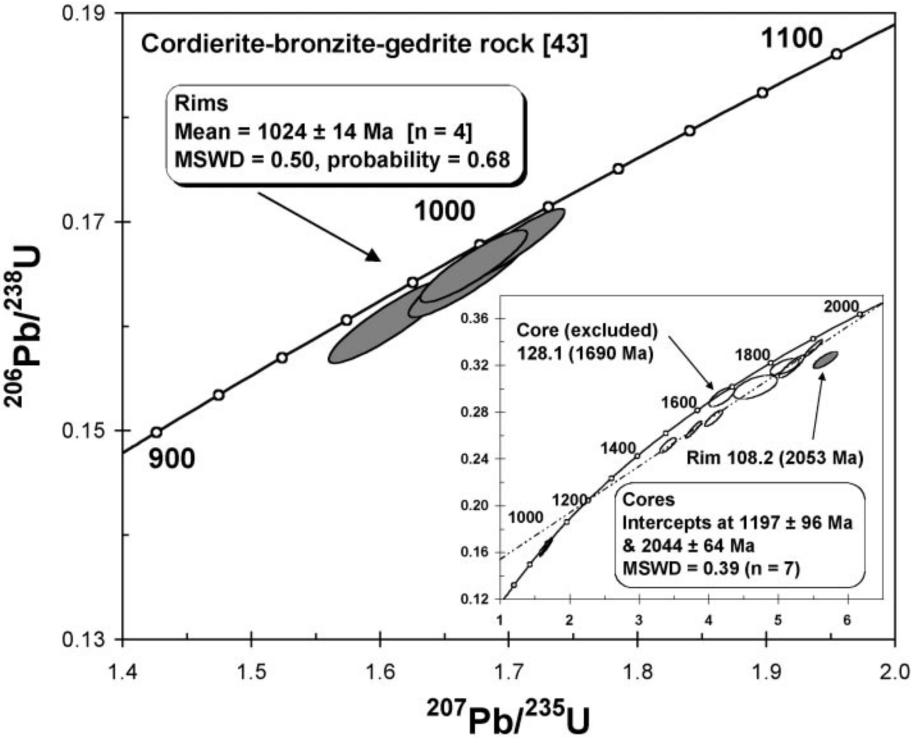


Fig. 5. U–Pb concordia diagram for zircons from cordierite–bronzite–gedrite rock [43] of the Khurisberg Subgroup, Smorgen Schaduwe (Fig. 1). [See Appendix Table B3(b) for analytical data.]

that zoned cores of zircons in two other metapelite samples [45, 46] from Komaggas record ages of *c.* 1200 Ma (Fig. 3a; Table 1). It is suggested, therefore, that the intermediate 1057 Ma age reflects incomplete Pb loss from 1200 Ma zircon at *c.* 1030 Ma.

Intrusive rocks

The geology of the O'okiep District is dominated by granitic plutonic rocks, notably the Nababeep Granite Gneiss and Granite, the Modderfontein Granite Gneiss, and the Concordia, Kweekfontein and Rietberg Granites (Figs 1 and 2). These rocks were post-dated by the intrusion of the Koperberg Suite (and the breccia granite) that includes, *inter alia*, jotunite, biotite diorite and magnetite–hypersthene rock. New U–Pb ages obtained for zircons from each of these rock-types and for syenite are summarized in Table 2.

Nababeep Granite Gneiss and Granite

Previously published age data for the Nababeep granitic rocks include Rb–Sr whole-rock isochron ages of 1179 ± 28 Ma (Barton, 1983) and 1223 ± 48 Ma (Clifford *et al.*, 1995), and a U–Pb SHRIMP zircon age of 1212 ± 11 Ma (Robb *et al.*, 1999). In this study, samples were collected from a typical example of well-foliated biotite-bearing Nababeep Granite Gneiss [102] from Carolusberg West, and from coarse-grained hypersthene-bearing Nababeep Granite [101] from Eendoorn (Fig. 1).

The zircons in the Nababeep Granite Gneiss [102] are large hyacinth-coloured crystals. The CL images show well-zoned subhedral to euhedral cores with magmatic crystallization features; these cores are overgrown by narrow carapace-like rims, which in many cases have been broken away (Fig. 3b). Thirteen out of 18 U–Pb analyses of the zircon cores yield a weighted mean ^{207}Pb/^{206}Pb age of 1192 ± 9 Ma (Fig. 6), interpreted to reflect the crystallization age of the magmatic precursor of the Nababeep Granite Gneiss. Three rim analyses (6.1, 23.2, 25.3) are within error of the core age. Six of seven rim analyses yield an average age of 1037 ± 12 Ma (Fig. 6) recording the time (M_3) of new metamorphic zircon growth or resetting as a result of Pb loss. Three younger core analyses (6.2, 7.1, 41.1) may be a reflection of the latter, whereas three intermediate ages (rim 5.2; cores 23.1, 39.1) are interpreted to reflect incomplete Pb loss during M_3 metamorphism.

The CL images of the zircons from the Nababeep Granite [101] illustrate cores that contain complex internal structures, overgrown by euhedral rims. Internal fracturing is common in many grains. Two xenocryst cores indicate inheritance with minimum ^{207}Pb/^{206}Pb ages of 2010 and 1719 Ma (Table 2). Excluding a highly

Table 2: Summary of new SHRIMP ages for zircon from intrusive rocks of the O'okiep Copper District

Sample number	Rock type	T_0 (Ma)	T_I (Ma)	T_{II} (Ma)	Text figure	Electronic Appendix table	Electronic Appendix figure
Koperberg Suite and breccia granite							
108	Breccia granite			**1018 ± 20**	14	B8 (c)	B20
82	Magnetite–hypersthene rock	1855	1183 ± 43	**1035 ± 33**		B8 (b)	B19
79	Biotite diorite	1800	1192 ± 12	**1030 ± 6**	13	B8 (a)	B18
53	Jotunite		1200 $\xrightarrow{\text{Pb loss}}$	1030		B7 (b)	B17
				1069 ± 44			
36	Jotunite	1804	1203 ± 10	**1035 ± 13**	12	B7 (a)	B16
Granitic rocks and syenite							
65	Syenite			**1035 ± 7**		B6 (c)	B15
22	Rietberg Granite	1779	1200 ± 45	**1032 ± 11**		B6 (b)	B14
		1722	1176 ± 15				
107	Rietberg Granite		1110–1160	**1035 ± 13**	9	B6 (a)	B13
106	Kweekfontein Granite[1]	1760	**1186 ± 15**		8	B5 (b)	B12
105	Concordia Granite[2]	1635 ± 110	**1206 ± 16**	1055 ± 23	7	B5 (a)	B11
103	Modderfontein Granite Gneiss	> 1592	**1187 ± 25**	1039 ± 11		B4 (c)	B10
101	Nababeep Granite	2010	**1197 ± 55**	1048 ± 20		B4 (b)	B9
		1719					
102	Nababeep Granite Gneiss		**1192 ± 9**	1037 ± 12	6	B4 (a)	B8

[1] Three inner cores and seven euhedral rims with U contents of 2068–7620 ppm yield discordant ages of 322–905 Ma [Table 3; Electronic Appendix Table B5(b)].
[2] Five inner cores and six rim regions with U contents of 1455–4650 ppm yield discordant ages of 360–970 Ma [Table 3; Fig. 7 (inset)].
Bold type-face denotes age of intrusion.

discordant analysis (A25.2), the remaining eight cores yield a weighted average ^{207}Pb/^{206}Pb age of 1197 ± 55 Ma (Table 2) that is interpreted to reflect the time of crystallization of the granite. Of 16 (mainly euhedral) rim analyses, seven yield a ^{207}Pb/^{206}Pb age of 1205 ± 26 Ma within error of the age obtained for the cores. Five rims yield a significantly younger weighted mean ^{207}Pb/^{206}Pb age of 1048 ± 20 Ma (Table 2) reflecting recrystallization of the zircon or Pb loss during M_3. Four rim analyses (A8.1, A16.1, B13.1, B35.1) have intermediate ages that are either discordant or reflect partial Pb loss during the M_3 event.

Modderfontein Granite Gneiss

Robb *et al.* (1999) interpreted a ^{207}Pb/^{206}Pb SHRIMP zircon age of 1199 ± 12 Ma to represent the age of emplacement of the magmatic protolith of the Modderfontein Granite Gneiss, and the age of 1032 ± 12 Ma on zircon rims to reflect metamorphism.

The Modderfontein Granite Gneiss [103] from Dixon's Farm (Fig. 1) is intrusive into the Brandberg Gneiss, a local correlative of the Nababeep Granite Gneiss. The zircons from sample 103 display mainly euhedral overgrowths on cores showing complex internal zoning suggesting two generations of growth. Eight core analyses yield a ^{207}Pb/^{206}Pb age of 1187 ± 25 Ma (Table 2) interpreted as the age of intrusion of the granite. Thirteen analyses on the rim regions indicate a weighted mean ^{207}Pb/^{206}Pb age of 1039 ± 11 Ma (Table 2) that records the time of new metamorphic (M_3) zircon growth, or alternatively complete resetting during M_3, as is illustrated by core analysis 19.1 with an age within error of that mean. The remaining three core and four rim analyses record a more complex Pb-loss history. Of these, two cores give minimum ^{207}Pb/^{206}Pb ages of 1592 Ma (13.1) and 1305 Ma (37.2A) (Electronic Appendix Fig. B10); their regression including a rim age of 1331 Ma (8.1) suggests a concordia upper intercept age of *c.* 1900 Ma for this xenocryst component.

Concordia Granite

Clifford *et al.* (1995) published a Rb–Sr whole-rock errorchron age of 1060 ± 69 Ma for the Concordia Granite. More recently, Robb *et al.* (1999) reported a U–Pb zircon

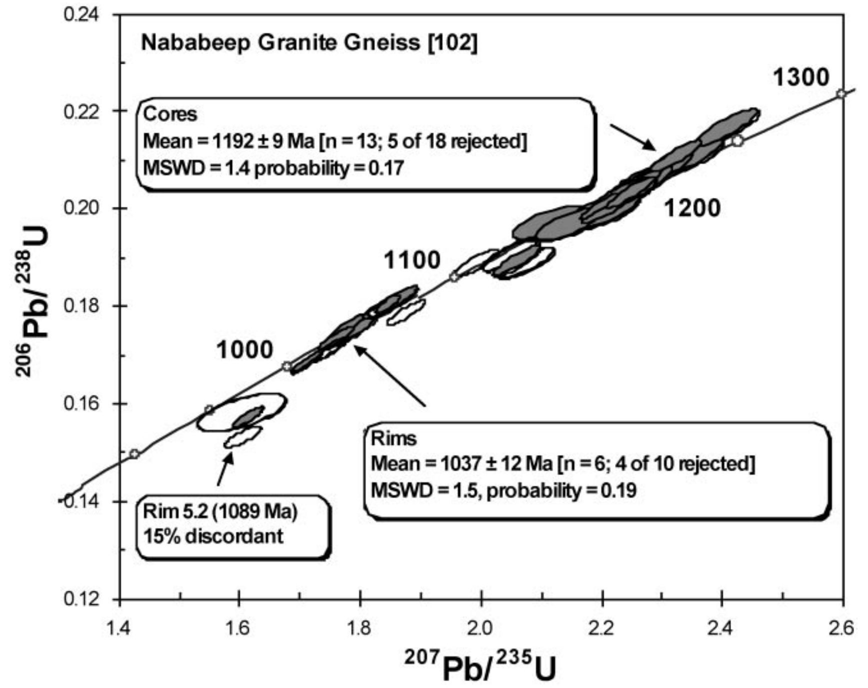


Fig. 6. U–Pb concordia diagram for zircons from the Nababeep Granite Gneiss [102], Carolusberg West Mine (Fig. 1). [See Appendix Table B4(a) for analytical data.]

age of 1161 ± 15 Ma on cores that they interpreted as inheritance, and ages of 1064 ± 31 Ma and 861 ± 45 Ma for zircon cores and rims interpreted as the time of granite emplacement and of initiation of a new orogenic episode, respectively. The age of 861 Ma is suspect because the majority of the analyses show varying degrees of discordance (53–89%), and the age of 1064 Ma is poorly constrained by only four isotope analyses.

The Concordia Granite sample [105] is a medium- to coarse-grained leucogranite that is petrographically identical to the Modderfontein Granite Gneiss [103]. The Concordia Granite, a U-rich intrusive, contains zircon that is largely metamict, but a careful selection of 41 hyacinth-coloured more translucent grains was made from sample 105. In general, the zircons are euhedral and show high-U and low-U cores mantled by high-U rims (Fig. 3c). Four xenocryst zircon cores (14.1, 21.1, 24.1, 2-22.2; Fig. 7) indicate a poorly constrained concordia upper intercept age of 1635 ± 110 Ma that may reflect a minimum age of the crustal precursor of the Concordia Granite. Nineteen euhedral to subhedral cores (Fig. 3c) with U contents <1225 ppm yield a weighted mean ^{207}Pb/^{206}Pb age of 1206 ± 16 Ma (Fig. 7; Table 2) interpreted to represent the crystallization age of the Concordia Granite. Six cores with similar U contents indicate a younger age of 1055 ± 23 Ma (Fig. 7) perhaps reflecting the influence of M_3 metamorphism. Finally, five core and six rim regions [Fig. 3c; Fig. 7 (inset)] with high U (≥1455 ppm) are metamict and yield discordant ^{207}Pb/^{206}Pb ages ranging from 360 to 970 Ma.

Kweekfontein Granite

The Kweekfontein Granite [106] is fine grained and generally devoid of any obvious tectonic fabric. In reflected light, the zircons are metamict in appearance but show clear core–rim relationships (Fig. 3d). The CL images illustrate three generations of zircon growth: homogeneous and euhedral high-U and low-U core regions mantled by a high-U zircon rims. Euhedral grains showing minimum 'metamictness' were selected for analysis. Twelve low-U (<1000 ppm) core regions characterized by euhedral morphology yield a weighted mean ^{207}Pb/^{206}Pb age of 1186 ± 15 Ma (Fig. 8; Table 2) interpreted to be the age of emplacement of the Kweekfontein Granite. In addition, the ^{207}Pb/^{206}Pb ages for seven low-U cores range from 1328 to 1762 Ma [Fig. 8 (inset)] and reflect minimum age estimates for inheritance; one core (1-24.3) with a minimum age of 1056 Ma is aberrant. Finally, three core regions and seven euhedral zircon rims with U contents >2000 ppm are discordant and indicate minimum ^{207}Pb/^{206}Pb ages of 322 to 904 Ma.

Rietberg Granite

The porphyritic Rietberg Granite is confined to the northern part of the O'okiep Copper District (Fig. 1).

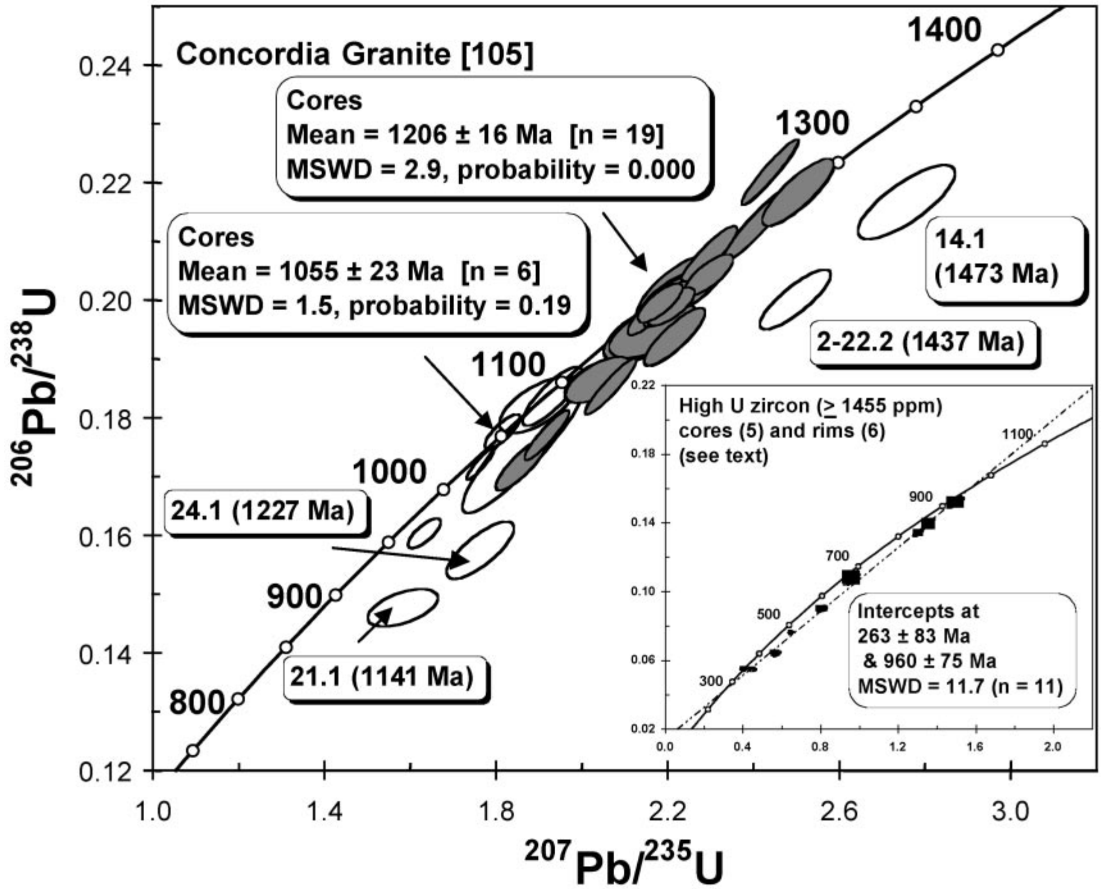


Fig. 7. U–Pb concordia diagram for zircons from the Concordia Granite [105], No-name 1 (Fig. 1). [See Appendix Table B5(a) for analytical data.]

Clifford *et al.* (1995) published a Rb–Sr whole-rock errorchron age of 1169 ± 69 Ma for this granite. Robb *et al.* (1999) reported a weighted mean $^{207}Pb/^{206}Pb$ zircon age of 1058 ± 30 Ma, which they interpreted as the emplacement age of the granite. The latter age is, however, based on largely discordant data with the majority (60%) of zircons analysed having U concentrations of >1500 ppm, a feature that is uncharacteristic of pristine Rietberg Granite zircons.

Zircon populations from typical examples of the Rietberg Granite at Jan Coetzee [107] and Steyerkraal [22] (Fig. 1) have been analysed. The zircons from the former are euhedral to subhedral, occasionally translucent, and appear to be a single population. Although some cores are present, most zircons show oscillatory magmatic zoning and, in the majority of cases, there is no discordance at the core–rim boundary. There is, moreover, no significant difference in age between cores and rims of zircons from the Rietberg Granite [107]. Seventeen analyses give a weighted mean $^{207}Pb/^{206}Pb$ age of 1035 ± 13 Ma (Fig. 9) that records the age of crystallization of the granite. Three zircons (A19.1, A24.2, B30.1) with ages of 1110–1160 Ma represent xenocrysts that were subjected to Pb loss at 1035 Ma, whereas one analysis (A16.1) is highly discordant (U 2075 ppm) with a minimum $^{207}Pb/^{206}Pb$ age of 812 Ma.

The zircons from Steyerkraal [22] are hyacinth to almost colourless clear grains that are euhedral to subhedral in shape, and the CL images show well-zoned crystals indicative of magmatic crystallization (Fig. 10a). Although no distinct boundaries can be discerned, older core regions have been recognized. Thirteen analyses of zircon rims from this sample give a weighted mean $^{207}Pb/^{206}Pb$ age of 1032 ± 11 Ma (Table 2) that dates the time of emplacement of the Rietberg Granite. In addition, two xenocryst populations are recognized: an older one represented by two cores with minimum $^{207}Pb/^{206}Pb$ ages of 1779 Ma and 1722 Ma (Table 2); and a younger one (4.2, 18.1, 23.2) with a $^{207}Pb/^{206}Pb$ age of 1200 ± 45 Ma. Two of the latter younger xenocrysts are rimmed by 1020–1035 Ma zircon (4.1 and 23.1). Finally, three zircon rims (13.2, 18.2, and 35.2) indicate a $^{207}Pb/^{206}Pb$ age of 1176 ± 15 Ma (Table 2) suggesting that these grains may belong to the younger xenocrystic population.

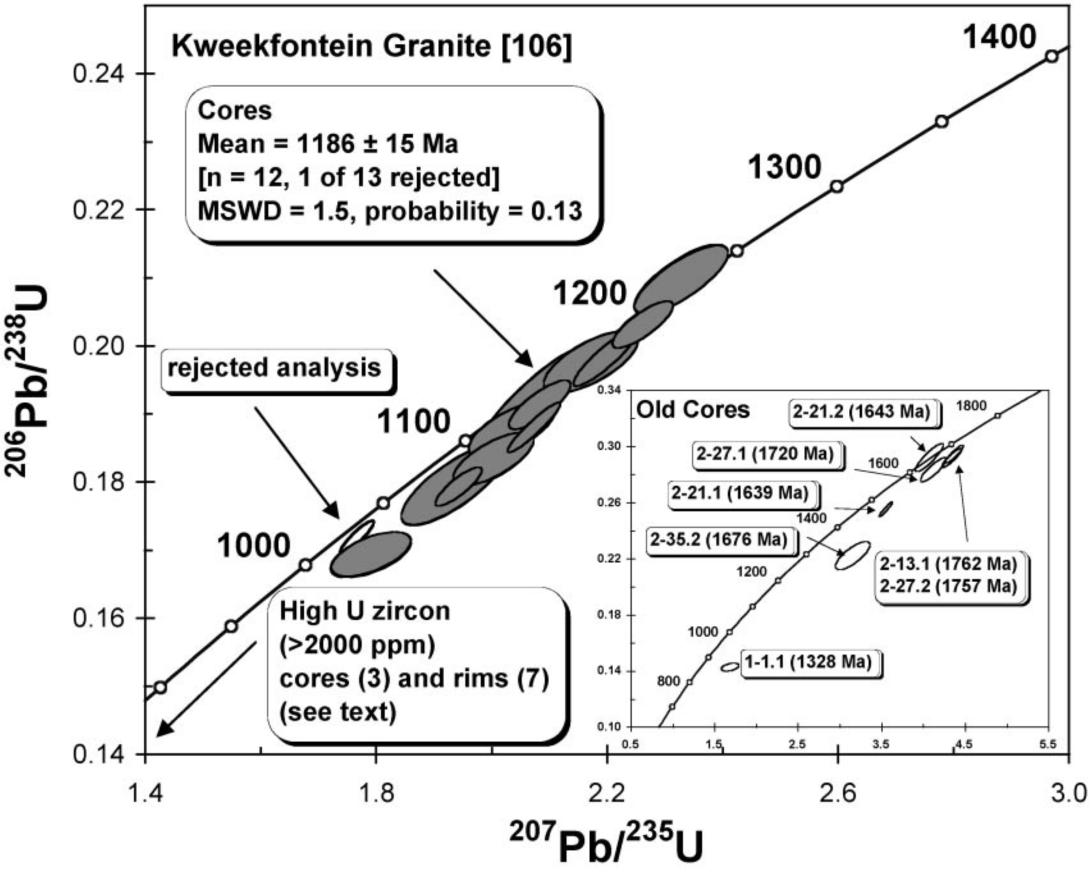


Fig. 8. U–Pb concordia diagram for zircons from the Kweekfontein Granite [106], Farm Kweekfontein (Fig. 1). [See Appendix Table B5(b) for analytical data.]

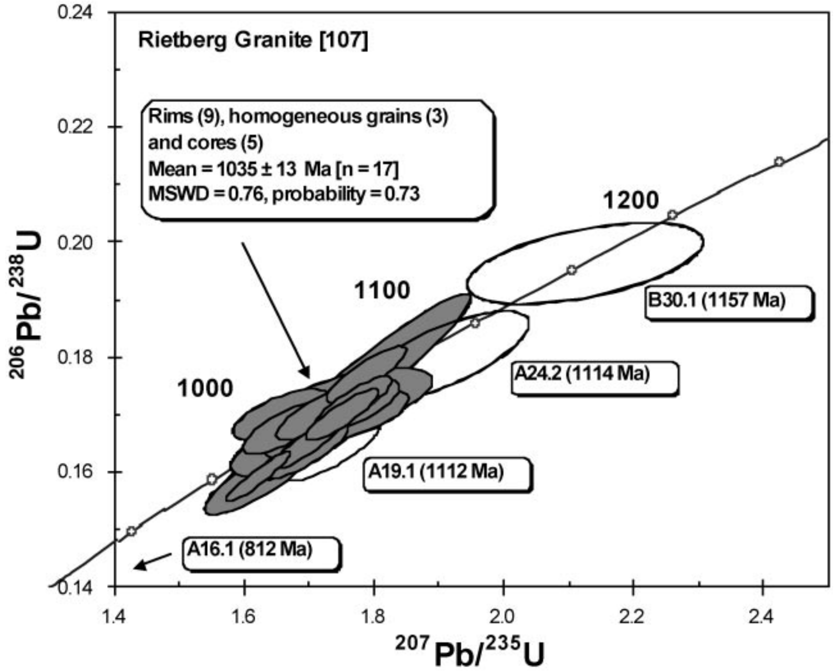


Fig. 9. U–Pb concordia diagram for zircons from the Rietberg Granite [107], Jan Coetzee (Fig. 1). [See Appendix Table B6(a) for analytical data.]

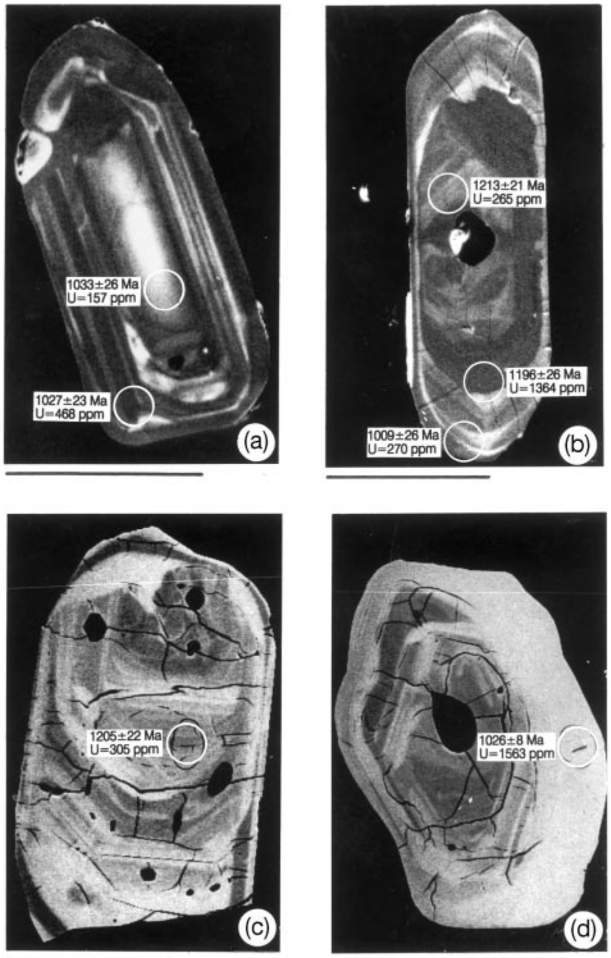


Fig. 10. CL images for zircons, illustrating SHRIMP ^{207}Pb/^{206}Pb ages and U concentrations for analysed data points, as follows: (a) grain 15, Rietberg Granite [22], Steyerkraal; (b) grain 51, jotunite (formerly two-pyroxene granulite) [36], Koperberg Suite, Narrowhuis; (c) and (d) grains 8.1 and 93.1, respectively, biotite diorite [79], Koperberg Suite, Jubilee (Fig. 1). Analytical data are as follows: grain 15, Appendix Table B6(b); grain 51, Appendix Table B7(a); grains 8.1 and 93.1, Appendix Table B8(a). Bar scales represent 100 μm; white circles show the locations of the analysed 20–30 μm target areas.

Syenite

The syenite [65] (locally referred to as shonkinite) at the Spektakel Mine is areally associated with a body of anorthosite–biotite diorite of the Koperberg Suite. However, Conradie & Schoch (1988) have argued that the absence of a Eu anomaly and the high light rare earth element to heavy rare earth element (LREE/HREE) ratio of the syenite mitigates against a genetic relationship with that suite.

The zircons from the syenite are colourless to pale pink, euhedral to subhedral prismatic crystals with rounded terminations. Cores are apparent, but incomplete rims resulted in irregularly shaped grains. The weighted mean ^{207}Pb/^{206}Pb ages for the 24 cores and the eight rims are indistinguishable at 1034 ± 9 Ma and 1040 ± 21 Ma, respectively. Combining all of the data yields an age of 1035 ± 7 Ma (Table 2). The prismatic morphology and the concordant (> 90%) highly constrained distribution of the data support the view that this is the age of syenite crystallization, which is within error of that obtained for the Rietberg Granite (Fig. 9).

3 INTRUSION OF HYPERSTHENE-BEARING ROCKS INCLUDING LEUCONORITE, NORITE, MELANORITE, HYPERSTHENITE AND MAGNETITE-HYPERSTHENE ROCK, AND GLIMMERITE II. *IN SITU* (ANATECTIC) FORMATION OF 'BRECCIA GRANITE'

2 INTRUSION OF PLAGIOCLASE-BIOTITE ROCKS INCLUDING: (1) ANDESINE (±QUARTZ) ANORTHOSITE; (2) GLIMMERITE I; AND (3) BIOTITE DIORITE.

1 INTRUSION OF TWO-PYROXENE ROCKS, VARIOUSLY NAMED GABBRO[1,2], HORNBLENDE GNEISS[3], FELSIC NORITE[4], TWO-PYROXENE GRANULITE[5] AND JOTUNITE[6].

Fig. 11. Summary of the stratigraphy of the Koperberg Suite. [1]Strauss (1941); [2]Van Zyl (1967); [3]Benedict *et al.* (1964); [4]Van Zyl (1975, 1978); [5]Clifford *et al.* (1981); [6]Duchesne (this work).

Koperberg Suite and breccia granite

U–Pb age data are presented for zircons from biotite diorite and magnetite–hypersthene rock of the Koperberg Suite, and from the breccia granite that is associated with the Koperberg Suite in a megabreccia pipe (Fig. 1). New age data are also presented for two-pyroxene rocks, now referred to as jotunites, that support the view that they are a part of the Koperberg Suite as suggested by Strauss (1941) and Van Zyl (1967, 1978). The revised stratigraphy for the Koperberg Suite is shown in Fig. 11.

Jotunite. The two samples of jotunite from Narrowhuis [36] and Ratelkraal [53] (Fig. 1) are petrographically identical and consist predominantly of andesine, diopside and ferrohypersthene (Clifford *et al.*, 1981). Previously published U–Pb zircon data for these rocks include an age of 1160 ± 50 Ma (composite sample, thermal ionization mass spectrometry analysis; Clifford *et al.*, 1981). More recently, zircon ages of 1168 ± 9 Ma and 1063 ± 16 Ma interpreted as the age of intrusion and metamorphism respectively were reported by Robb *et al.* (1999).

Zircons separated from sample [36] are mainly prismatic grains in which the zoned euhedral magmatic rims (20–50 μm) clearly truncate the remnant zonation in the irregular-shaped xenocryst cores (Fig. 10b). The CL images show complex cores with inner and outer regions that are luminescent, homogeneous grey or zoned. Thirteen analyses of oscillatory-zoned zircon rims give a weighted mean ^{207}Pb/^{206}Pb age of 1035 ± 13 Ma (Fig. 12) that is interpreted to be the age of jotunite intrusion. Provenance ages are defined by 13 xenocryst cores with a weighted mean ^{207}Pb/^{206}Pb age of 1203 ± 10 Ma [Fig. 12 (inset); Table 2], and a single core with a concordant ^{207}Pb/^{206}Pb age of 1804 Ma. Intermediate

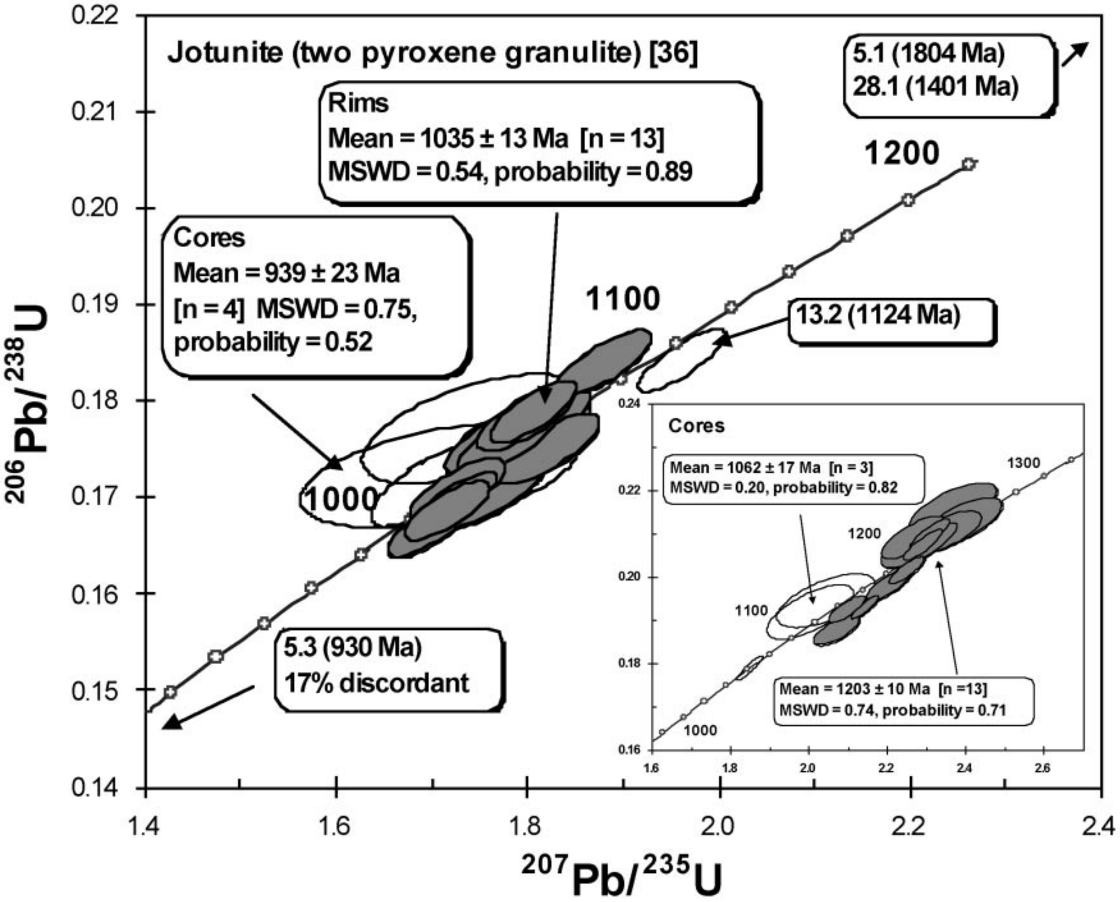


Fig. 12. U–Pb concordia diagram for zircons from jotunite [36] of the Koperberg Suite, Narrowhuis (Fig. 1). [See Appendix Table B7(a) for analytical data.]

[1062 ± 17 Ma; Fig. 12 (inset)] and younger ages on the remaining cores and rims are ascribed to Pb loss during the M_3 event.

The zircons from jotunite [53] are characterized by anhedral shapes. In transmitted light, core–rim(I) relationships are evident but on the CL images the internal structures are less obvious and the cores and rims(I) cannot generally be differentiated on the basis of U concentrations. The distribution of the U–Pb data for both cores and rims(I) is interpreted to reflect continuous Pb loss from 1200 Ma zircons (Electronic Appendix Fig. B17). A notable feature of the zircon in [53] is the universal development of rims(II), generally < 20 μm in width, with low U and Th contents. Three analyses on those rims, which were difficult to target, yield an imprecise weighted average ^{206}Pb/^{238}U age of 1069 ± 44 Ma (Table 2) that is within error of the 1035 ± 13 Ma age of magmatic zircon growth in jotunite [36].

Biotite diorite. The biotite diorite [79] from the Jubilee Mine is a medium-grained rock consisting predominantly of oligoclase (*c.* 70%) and biotite (*c.* 25%). CL images of the zircon from this sample show that most grains contain rounded cores of sector- and oscillatory-zoned zircon (Fig. 10c) with a mean U content of 360 ppm that are overgrown by new featureless zircon rims (Fig. 10d), up to 70 μm in width, with dramatically higher mean U contents of 1550 ppm. The core–rim contacts are sharp, with the latter clearly truncating the remnant zoning of the former (Fig. 10d).

Eleven high-U rims yield a weighted mean ^{207}Pb/^{206}Pb age of 1030 ± 6 Ma (Fig. 13) that is interpreted as the age of intrusion of the biotite diorite. These new data are in conflict with the ^{207}Pb/^{206}Pb age of 1057 ± 8 Ma obtained by Robb *et al.* (1999) for zircon from this rock-type at this locality. Provenance ages are reflected by eight out of 13 mostly oscillatory-zoned xenocryst zircon cores with a weighted mean ^{207}Pb/^{206}Pb age of 1192 ± 12 Ma, and a single concordant age of 1800 Ma (Fig. 13). Intermediate and younger ages of 1130 to 1028 Ma are ascribed to Pb loss during the M_3 event.

Magnetite–hypersthene rock. This rock-type [82] occurs as a thin (< 1 m wide) boudinaged dyke-like body intruding

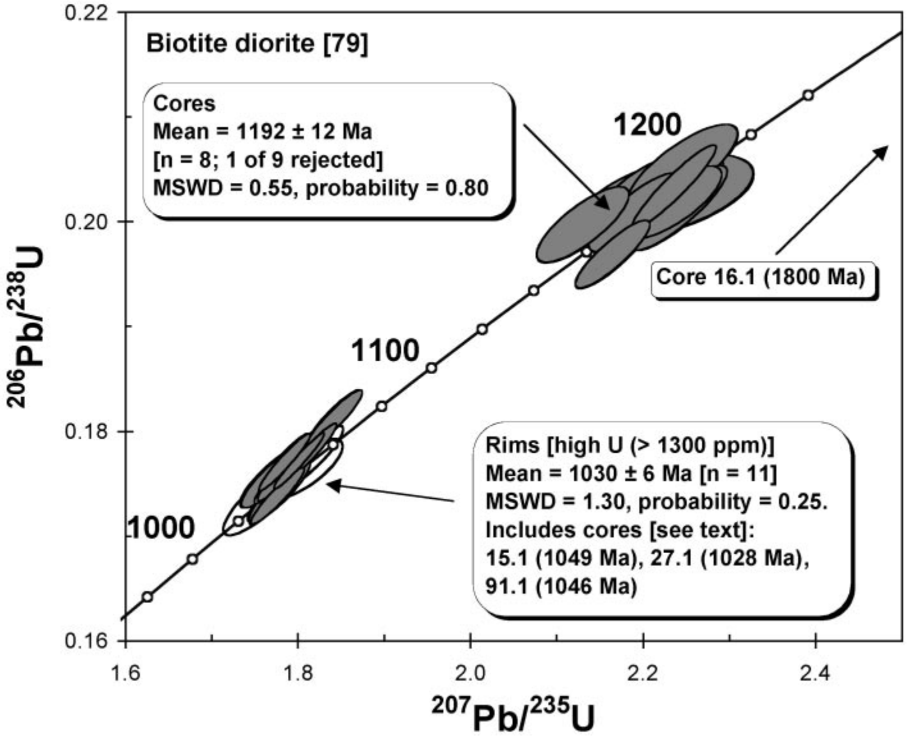


Fig. 13. U–Pb concordia diagram for zircons from biotite diorite [79] of the Koperberg Suite, Jubilee (Fig. 1). [See Appendix Table B8(a) for analytical data.]

biotite diorite at Jan Coetzee SW (Fig. 1). The zircons from this rock are largely broken grains that are uniform in appearance. Relics of cores are visible on the CL images, and analyses of three of them yield minimum $^{207}Pb/^{206}Pb$ ages of 1855, 1711 and 1511 Ma [Electronic Appendix Fig. B19 (inset)]. Three other cores are consistent with the presence of a younger xenocrystic component with an age of 1183 ± 43 Ma (Table 2). Fourteen analyses of zircon rims and homogeneous grains yield a weighted mean $^{207}Pb/^{206}Pb$ age of 1035 ± 33 Ma (Table 2) that records the time of emplacement of the magnetite–hypersthene intrusive.

Breccia granite. The breccia granite [108], a locally generated anatectic melt, occurs along with intrusive Koperberg Suite lithologies in the Henry's House megabreccia pipe. This granite provided a mixed zircon population of mainly metamict grains with fewer very translucent euhedral to subhedral almost colourless grains. Transmitted-light and CL images show that the majority of the euhedral grains contain both well-defined cores and relics of cores that are devoid of internal structure apart from growth zoning.

The majority of the U–Pb analyses targeted the clear euhedral rims and structureless cores in the zircon. Fourteen such analyses yield a weighted mean $^{207}Pb/^{206}Pb$ age of 1018 ± 20 Ma (Fig. 14) that records the date of *in situ* generation of the granite and of the formation of the megabreccia pipe. Analysis 29.1 (Fig. 14) with a minimum $^{207}Pb/^{206}Pb$ age of 769 Ma is highly discordant, and is excluded from the weighted average age. This analysis targeted a well-defined core with radial fractures emanating from it which is a characteristic feature of a high-U nucleus, in this case with > 3000 ppm U.

Discussion

Zircon age data. Xenocryst zircon from almost all of the intrusive rocks in the O'okiep District records the presence of crustal precursors that were probably as old as 2000 Ma (T_o) (Table 2). Subsequent igneous activity is reflected by U–Pb zircon ages of 1192 ± 9 Ma and 1197 ± 55 Ma for the Nababeep Granite Gneiss and Granite, respectively, and of 1187 ± 25 Ma for the Modderfontein Granite Gneiss (Table 2) that record the time (T_I) of syn-D_2 plutonism. Euhedral low-U zircon core regions for Concordia and Kweekfontein Granites have given $^{207}Pb/^{206}Pb$ ages of 1206 ± 16 Ma and 1186 ± 15 Ma, respectively, indicating that they are broadly contemporaneous with the Nababeep and Modderfontein granite plutonism. In contrast, two localities of the porphyritic Rietberg Granite (Fig. 1) yield well-constrained ages of 1032 ± 11 Ma and 1035 ± 13 Ma interpreted to reflect the age of intrusion (T_{II}). Syenite [65] with an

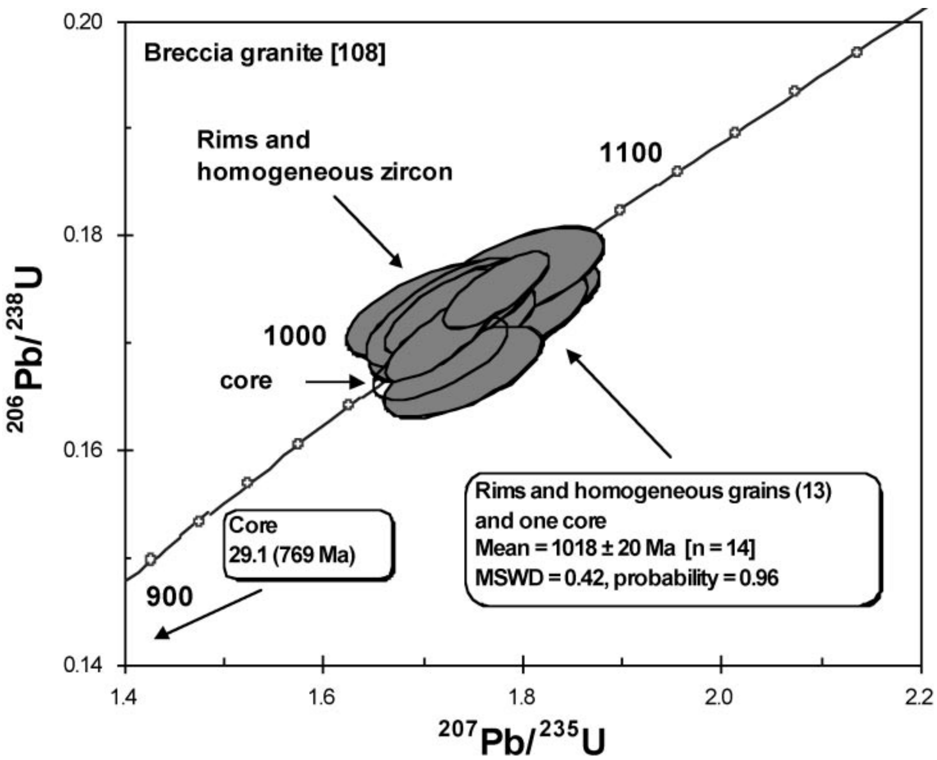


Fig. 14. U–Pb concordia diagram for zircons from the breccia granite [108], Henry's House (Fig. 1). [See Appendix Table B8(c) for analytical data.]

emplacement ^{207}Pb/^{206}Pb age of 1035 ± 7 Ma was contemporaneous with the intrusion of that granite. The Rietberg Granite has traditionally been grouped with the Concordia and Kweekfontein Granites as the 'Spektakel Suite' (Marais & Joubert, 1980), but the new data presented in this study demonstrate that it is 150 Myr younger than the Concordia and Kweekfontein Granites. The grouping of the three granites as the 'Spektakel Suite' is, therefore, redundant.

Although the Koperberg Suite post-dates the Rietberg Granite, new and published ^{207}Pb/^{206}Pb ages for zircons from a wide range of Koperberg lithologies are indistinguishable from that of the Rietberg Granite as follows: (1) 1029 ± 10 Ma for andesine anorthosite (Clifford *et al.*, 1995); (2) 1037 ± 86 Ma and 1037 ± 8 Ma for 'anorthosite' and 'hypersthenite', respectively (Robb *et al.*, 1999); (3) 1035 ± 13 Ma, 1030 ± 6 Ma, 1035 ± 33 Ma and 1018 ± 20 Ma for jotunite, biotite diorite, magnetite–hypersthene rock and breccia granite, respectively (see Table 2). Finally, except for syenite and breccia granite (Table 2), xenocryst 1200 Ma (T_{I}) zircon has been identified in all elements of the 1030 Ma (T_{II}) magmatic zircon, whereas narrow 1040 Ma zircon rims around 1200 Ma magmatic zircon in the Nababeep and Modderfontein granitic rocks (Table 2) record new zircon growth (or resetting) during M_3 metamorphism that was contemporaneous with T_{II} magmatism.

Th/U for zircon in granitic rocks. Heaman & Parrish (1991) have noted that zircons in felsic igneous rocks have average U contents of 50–300 ppm and an average Th/U ratio of 0·45. These results are in agreement with the range and average Th/U ratio of 0·15–1·20 and 0·47, respectively, reported by Ahrens *et al.* (1967) for granite zircons. In addition, Williams & Claesson (1987) distinguished zircon cores with igneous Th/U signatures of 0·1–1·6, from new zircon mantles with very low Th/U of < 0·1 that formed during granulite-facies metamorphism; Cornell & Hegardt (2003) have argued that such low Th/U ratios result from the depletion of Th in the metamorphic fluid by minerals such as monazite.

The oscillatory-zoned zircons from the 1200 Ma Nababeep and Modderfontein granitic rocks, and the 1035 Ma Rietberg Granite, all show mean Th/U signatures of 0·40–0·80 (see Electronic Appendix Tables B4–B6) that are typical for felsic igneous rocks. However, the unzoned rim zircons (Fig. 3b) in the Nababeep and Modderfontein granitic rocks generally also show 'igneous' Th/U signatures (mean, 0·12–0·25), notwithstanding the fact that these rims obviously reflect new zircon growth (or resetting) during M_3 metamorphism (see Table 2).

The zircons from the Concordia and Kweekfontein Granites are also anomalous. They contain core regions that either (1) are enriched in uranium (range

Table 3: U and Th contents, Th/U ratios and ^{207}Pb/^{206}Pb ages for zircon from the Concordia and Kweekfontein Granites

High-U cores	Low-U cores	High-U rims
Concordia Granite [105]		
[*n* = 5]	[*n* = 19]	[*n* = 6]
U = 1455–4175 ppm	mean U = 530 ppm	mean U = 2890 ppm
Th = 50–3500 ppm	mean Th = 270 ppm	mean Th = 215 ppm
mean Th/U = 0·43	mean Th/U = 0·56	mean Th/U = 0·06
ages 670–970 Ma	age = **1206** ± **16 Ma**	ages 360–800 Ma
Kweekfontein Granite[1] [106]		
[*n* = 3]	[*n* = 12]	[*n* = 7]
U = 2490–7620 ppm	mean U = 370 ppm	mean U = 2280 ppm
Th = 250–2305 ppm	mean Th = 170 ppm	mean Th = 135 ppm
mean Th/U = 0·10–0·53	mean Th/U = 0·56	mean Th/U = 0·06
ages 322–795 Ma	age = **1186** ± **15 Ma**	ages 510–905 Ma

[1] Six low-U xenocryst cores yielded ^{207}Pb/^{206}Pb ages of 1640–1760 Ma [see Fig. 8 (inset)].

1455–7620 ppm) with the resultant discordant ages, or (2) have low uranium (generally $<$ 700 ppm) and record crystallization ages of *c.* 1200 Ma (Table 3). The Th contents are proportional to the U contents, resulting in average Th/U ratios of about 0·5 for both types of cores (Table 3). In contrast, the high-U (2060–4650 ppm) rims of zircon from both granites have Th contents that range from only 80 to 380 ppm, yielding very low Th/U ratios of about 0·06 (Table 3) that are commonly regarded as a 'metamorphic' signature (see Williams & Claesson, 1987; Cornell & Hegardt, 2003). However, the rim zircon in the Concordia and Kweekfontein Granites clearly crystallized from a magma that was significantly enriched in U (Table 3); the very low Th/U ratio of the zircon was not, therefore, the result of decoupling migration of Th and U in a metamorphic fluid, but is rather a clear reflection of the chemistry of the magma during crystallization.

SYNTHESIS

Overview

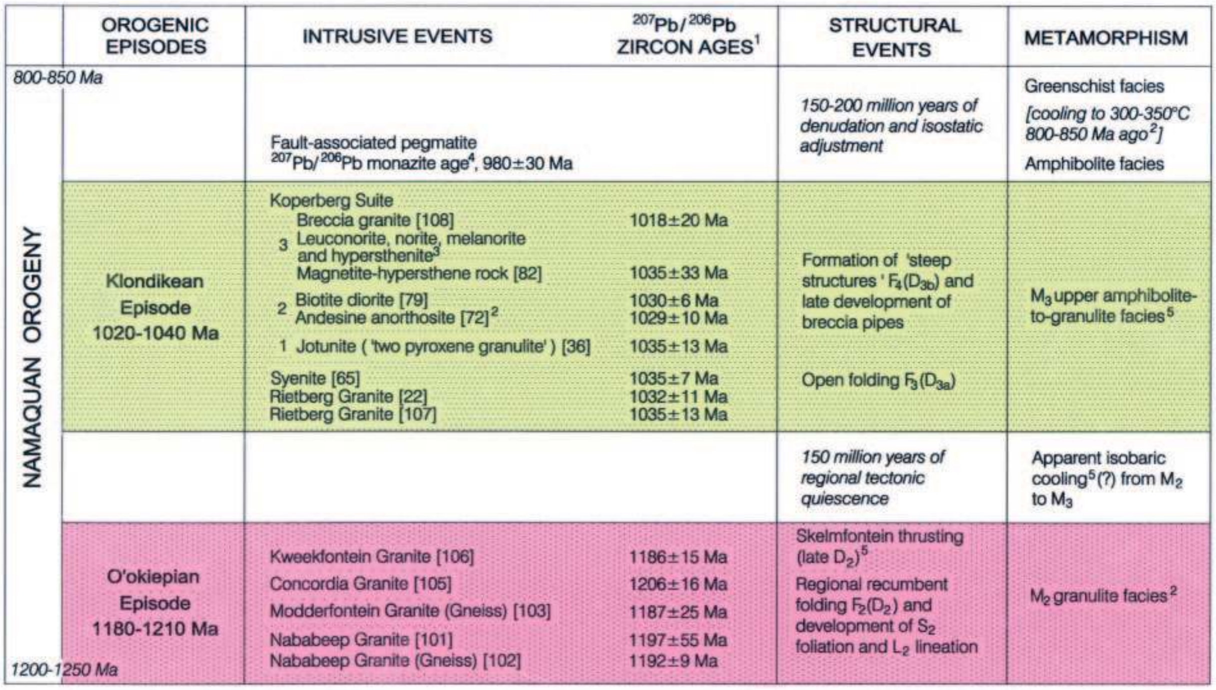
The O'okiep Copper District represents one of the most intensely studied areas of crystalline rocks in Africa, and the principal tectonothermal events in the area have been summarized by Lombaard *et al.* (1986), Clifford *et al.* (1995) and Marais *et al.* (2001). New U–Th–Pb SHRIMP data presented in this paper demonstrate the presence of 1700–2000 Ma xenocryst zircon in all major granites in the area and in the jotunite, biotite diorite and magnetite–hypersthene rock of the Koperberg Suite, and as detritus in the supracrustal metasediments of the Khurisberg Subgroup. These data are consistent with the published Sm–Nd model ages of *c.* 1700 Ma (T_{CHUR}) and *c.* 2000 Ma (T_{DM}) for a wide range of intrusives in the O'okiep District that support a major crust-forming event in Eburnian (Hudsonian) times in this part of Namaqualand (Clifford *et al.*, 1995; see Reid *et al.*, 1997).

Zircon data from all major rock units also confirm the duality of Mesoproterozoic tectono-thermal activity in the O'okiep District (see McIver *et al.*, 1983). The two principal Precambrian events grouped as the Namaquan Orogeny are here termed (Fig. 15): (1) the O'okiepian Episode (1180–1210 Ma) based on the regional dominance of syntectonic to late tectonic granite plutonism of that age throughout the O'okiep District; (2) the Klondikean Episode (1020–1040 Ma) because one of the most impressive structural manifestations of that episode is the development of steep structures (F_4) such as the one at Klondike (see Lombaard *et al.*, 1986, p. 1427).

The O'okiepian and Klondikean Episodes of the O'okiep District are broadly coeval with the Elzevirian (1290–1190 Ma) and Ottawan (1080–1020 Ma) 'Pulses', respectively, of the Grenvillian Orogenic Cycle (*c.* 1300–950 Ma) in the Grenville Province of eastern North America (Davidson, 1995; Rivers, 1997). However, in the O'okiep District of Namaqualand there is no evidence for the Shawinigan 'Pulse' (1190–1160 Ma; Rivers, 1997) of the Grenville Province, whereas the Rigolet 'Pulse' (1000–850 Ma) in the latter is represented by pegmatite formation and prolonged cooling in the O'okiep District (Fig. 15).

The principal characteristics of the O'okiepian (D_2) and Klondikean (D_3) Episodes of the Namaquan Orogeny are discussed in detail below; and they are illustrated in Fig. 15, which also shows that those episodes were short-lived events representing only a total of 10% of the duration of the orogeny. In contrast, there were lengthy periods of about 150 Myr of tectonic quiescence: (1) between the O'okiepian and Klondikean Episodes; (2) from the end of the latter to the time of cooling below the Ar–Ar and Rb–Sr closure temperatures (300–350°C) for biotite–phlogopite in the Koperberg Suite at 800–850 Ma (Onstott *et al.*, 1986; Clifford *et al.*, 1995), which is taken as the formal end of Namaquan orogenesis. We have found no evidence of zircon ages that have been used to speculate on 'the initiation of a new orogenic episode at ~850 Ma' (Robb *et al.*, 1999, p. 1760).

Finally, the cooling and denudation in the O'okiep District was completed by the time of deposition of the sediments of the Nama Group at *c.* 650 Ma (Kent, 1980; see Fig. 1). The Ar–Ar ages of 500–570 Ma given by the Koperberg Suite and hydrated country-rocks (Onstott *et al.*, 1986; Clifford *et al.*, 1995) record an event of



	OROGENIC EPISODES	INTRUSIVE EVENTS	^{207}Pb/^{206}Pb ZIRCON AGES[1]	STRUCTURAL EVENTS	METAMORPHISM
800-850 Ma		Fault-associated pegmatite ^{207}Pb/^{206}Pb monazite age[4], 980±30 Ma		*150-200 million years of denudation and isostatic adjustment*	Greenschist facies *[cooling to 300-350°C 800-850 Ma ago[2]]* Amphibolite facies
NAMAQUAN OROGENY	Klondikean Episode 1020-1040 Ma	Koperberg Suite		Formation of 'steep structures' $F_4(D_{3b})$ and late development of breccia pipes	M_3 upper amphibolite-to-granulite facies[5]
		Breccia granite [108]	1018±20 Ma		
		3 Leuconorite, norite, melanorite and hypersthenite[3]			
		Magnetite-hypersthene rock [82]	1035±33 Ma		
		2 Biotite diorite [79]	1030±6 Ma		
		Andesine anorthosite [72][2]	1029±10 Ma		
		1 Jotunite ('two pyroxene granulite') [36]	1035±13 Ma		
		Syenite [65]	1035±7 Ma	Open folding $F_3(D_{3a})$	
		Rietberg Granite [22]	1032±11 Ma		
		Rietberg Granite [107]	1035±13 Ma		
				150 million years of regional tectonic quiescence	Apparent isobaric cooling[5](?) from M_2 to M_3
	O'okiepian Episode 1180-1210 Ma	Kweekfontein Granite [106]	1186±15 Ma	Skelmfontein thrusting (late D_2)[5]	M_2 granulite facies[2]
		Concordia Granite [105]	1206±16 Ma	Regional recumbent folding $F_2(D_2)$ and development of S_2 foliation and L_2 lineation	
		Modderfontein Granite (Gneiss) [103]	1187±25 Ma		
		Nababeep Granite [101]	1197±55 Ma		
1200-1250 Ma		Nababeep Granite (Gneiss) [102]	1192±9 Ma		

Fig. 15. Detailed chronology for the Namaquan Orogeny in the O'okiep District. [1]This work—new ^{207}Pb/^{206}Pb SHRIMP age data; [2]Clifford *et al.* (1995); [3]'hypersthenite' gave a ^{207}Pb/^{206}Pb zircon age of 1037 ± 8 Ma (Robb *et al.*, 1999); [4]Nicolaysen & Burger (1965); [5]Raith & Harley (1998).

subsequent low-temperature reheating in Cambrian times during the Damaran Episode of the Pan-African Orogeny (Kennedy, 1965; Clifford, 1967).

Namaquan Orogeny

O'okiepian Episode

The O'okiepian Episode is the dominant new rock-forming event in the O'okiep District; granitic rocks cover >80% of the outcrop area of crystalline rocks, and predominant amongst these are the Nababeep and Modderfontein granitic rocks, and the Concordia and Kweekfontein Granites (Fig. 1). New zircon ages of *c.* 1200 Ma for Nababeep Granite Gneiss and Granite and the Modderfontein Granite Gneiss (Fig. 15) record the time of plutonism that was synchronous with F_2 recumbent folding that dominates the structure of the O'okiep region (Vellet, 1958; Clifford *et al.*, 1975*a*). The regional metamorphism that accompanied (and outlasted) F_2 tectonism has by definition been designated M_2 (Clifford *et al.*, 1975*a*), and thermodynamic calculations for garnet–cordierite and garnet–plagioclase indicate equilibration temperatures of *c.* 800°C and pressures of *c.* 6 kbar for that granulite-facies metamorphism (Clifford *et al.*, 1981; Raith & Harley, 1998). These data refute Waters' (1989, p. 357) speculation that 'F_2 was probably accompanied by amphibolite-facies conditions'. The weighted mean ^{207}Pb/^{206}Pb age of 1175 ± 23 Ma (Fig. 4) for zircons from a cordierite–hypersthene paragenesis is believed to reflect the time of M_2; the concordia lower intercept age of 1197 ± 96 Ma yielded by zircons from cordierite–bronzite–gedrite rock (Table 1) is within error of that age.

The Concordia and Kweekfontein Granites intruded at 1206 ± 16 Ma and 1186 ± 15 Ma, respectively (Fig. 15). These ages also record the timing of the late stages of $F_2(D_2)$ tectonism. In particular, the basal part of the 1500 m thick sheet of the Concordia Granite shows a conspicuous L_2 lineation and a less distinct S_2 foliation (Lombaard *et al.*, 1986; Raith, 1995), whereas the upper part of the sheet and the Kweekfontein Granite are generally devoid of a regional structural fabric. This suggests that the emplacement ages for these two granites reflect the timing of the waning stages of $F_2(D_2)$ deformation (Fig. 15).

Finally, the emplacement of the Kweekfontein Granite was syn-deformational with respect to the formation of the Skelmfontein Thrust Zone (Fig. 1; Martens, 1979; Blignault *et al.*, 1983). The 1186 ± 15 Ma age for that granite thus dates the late-D_2 phase of that thrusting that separates the M_2 granulite-facies metamorphic terrane in the O'okiep District from the amphibolite-facies domain to the north (Raith & Meisel, 2001). However, a later phase of that thrusting also affected the 1035 Ma Rietberg Granite (J. Raith, personal communication, 2002) implying that there was also an element of reactivation during D_3.

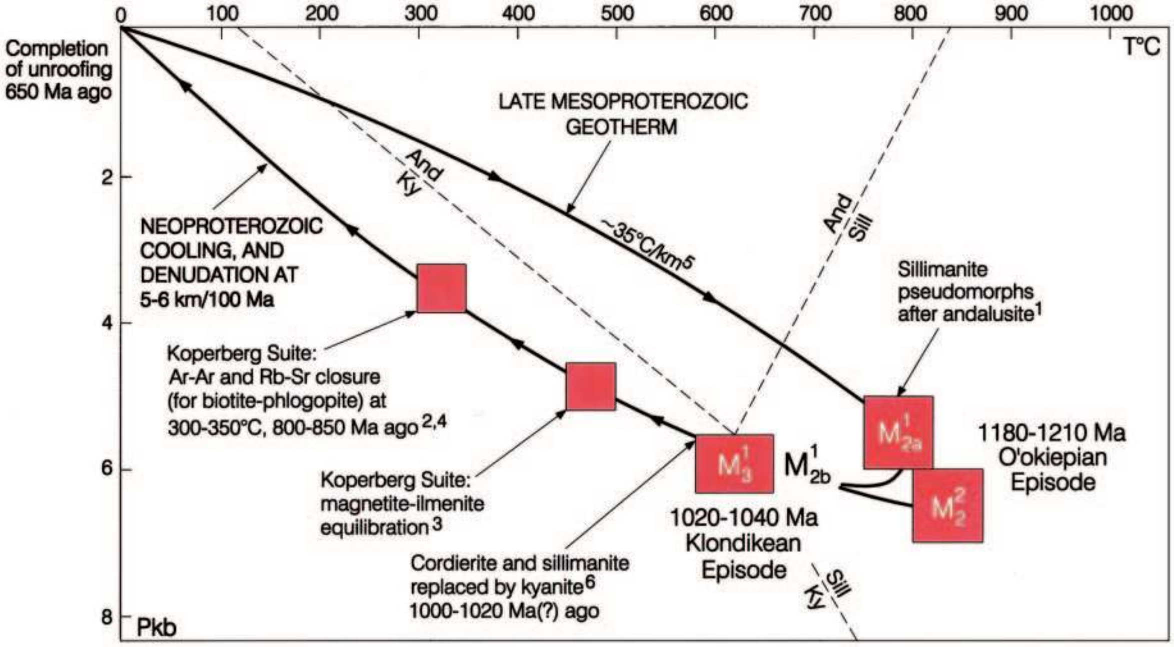


Fig. 16. Schematic P–T–t diagram for the O'okiep Copper District for the time-interval from *c.* 1210 Ma ago to 650 Ma ago. [1]Raith & Harley (1998); [2]Clifford *et al.* (1995, and this work); [3]Conradie & Schoch (1986); [4]Onstott *et al.* (1986); [5]Clifford *et al.* (1975*a*, p. 178); [6]this position reflects the calculated $T = 550$–$650°C$ for Ga–Co from retrograde kyanite-bearing paragenesis [47(2)] (Clifford *et al.*, 1981, p. 240)—the inferred P of 7–8 kbar appears now to be an overestimate. Comments: (1) the aluminosilicate data are from Richardson *et al.* (1969) (And, andalusite; Ky, kyanite; Sill, sillimanite); (2) the absence of muscovite at the modest temperatures proposed for M_3 (Raith & Harley, 1998, p. 301) implies a low $P(H_2O)$ [$<0{\cdot}5P$(total)] (Kerrick, 1972; Clifford *et al.*, 1981) at the time of M_3 metamorphism.

Klondikean Episode

The Klondikean Episode differs from the O'okiepian Episode in that it was not accompanied by regional penetrative planar or linear fabrics. Instead, Klondikean tectonism is reflected (1) by east–west-trending open folds [$F_3(D_{3a})$] such as the Ratelpoort Synform and the Springbok Antiform (Fig. 1), and (2) by localized tight east–west-trending, near-vertical, generally anticlinal, steep structures [$F_4(D_{3b})$; see Marais *et al.*, 2001, p. 30]. Moreover, in contrast to the regionally extensive granitic rocks that characterize the O'okiepian Episode, Klondikean granite plutonism is restricted to the Rietberg Granite in the northern part of the O'okiep District (Fig. 1), which has yielded well-constrained weighted mean $^{207}Pb/^{206}Pb$ ages of 1032 ± 11 Ma and 1035 ± 13 Ma (Fig. 15) that define the age of intrusion.

The Koperberg Suite post-dated the intrusion of the Rietberg Granite, but new zircon ages for a wide range of rock-types from the suite are indistinguishable from those given by that granite (Table 2: Fig. 15). It follows from these new data that the intrusion of the Rietberg Granite and Koperberg Suite was a very short-lived event (perhaps <10 Myr). It has, moreover, been suggested that the intrusion of the Koperberg Suite, the formation of steep structures and the development of breccia pipes represent a trinity of associated features in the O'okiep District (Lombaard & Schreuder, 1978). Additionally, Rogers (1912) argued that the absence of chilling at the margins of the bodies of the Koperberg Suite indicates that they were intruded while the country-rocks were hot, and McIver *et al.* (1983), Cawthorn & Meyer (1993) and Kisters *et al.* (1994) all considered that the Koperberg bodies were subjected to high-grade metamorphism. That essentially thermal metamorphism is logically designated M_3, and Raith & Harley (1998) have suggested that upper-amphibolite- to granulite-facies temperatures ($T = 580$–$660°C$) were reached during that event, and that they were accompanied by pressures of 5·8 ± 0·5 kbar that are consistent with apparent isobaric cooling between M_2 and M_3 (Fig. 16).

Zircon ages of 1020–1035 Ma are also represented in a wide range of cordierite-bearing metapelites (Table 1), and similar ages of 1035–1050 Ma have been recorded for narrow rims around 1200 Ma magmatic zircon in the Nababeep and Modderfontein granitic rocks (Fig. 6; Table 2). All record the influence of M_3 Klondikean metamorphism, and are consistent with U–Th–Pb ages of 1038 ± 12 Ma and 1047 ± 18 Ma obtained for monazites (closure $T \sim 725 \pm 25°C$; Parrish, 1990) from metapelites in the area (Raith *et al.*, 1999). In contrast, molybdenite (closure $T \sim 500°C$; Suzuki *et al.*, 1996) from stratabound W(Mo) mineralization in the O'okiep

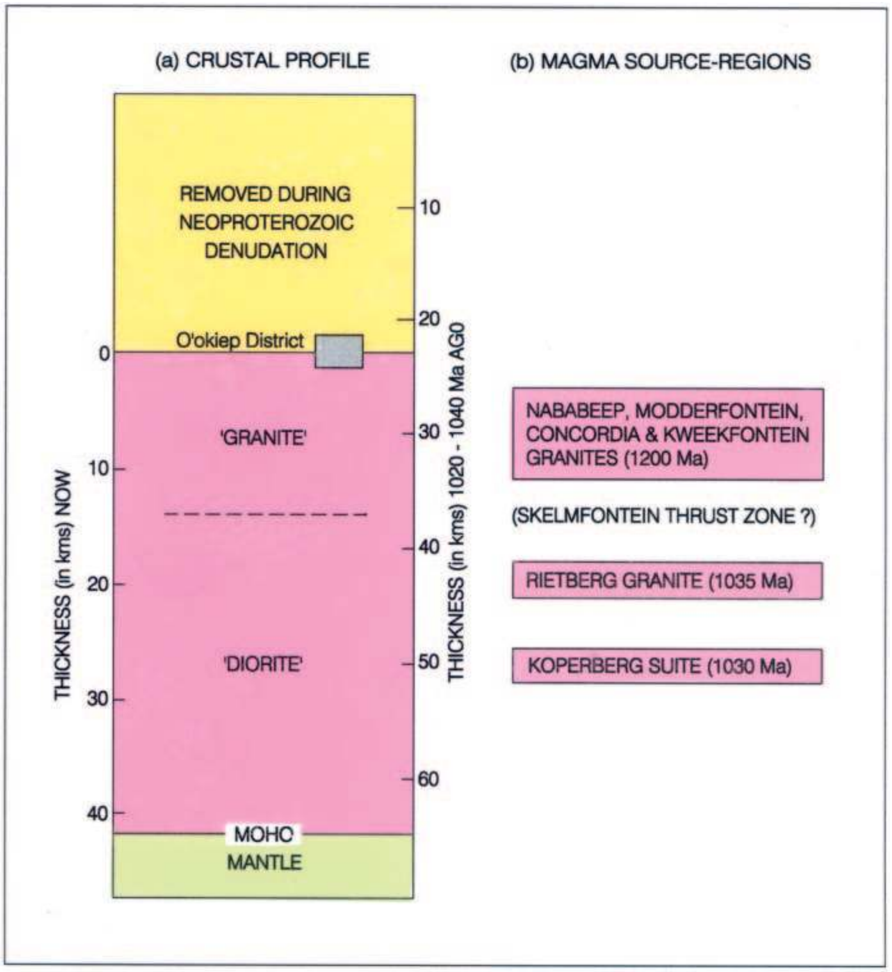


Fig. 17. (a) Reconconstruction of the crustal profile for the O'okiep region 1020–1040 Ma ago, incorporating the present-day seismic profile for this part of Namaqualand (after Green & Durrheim, 1990), and Neoproterozoic denudation (see Fig. 16); (b) hypothetical magma-source regions for the O'okiep igneous rocks (see text).

District yielded ^{187}Re/^{187}Os ages of 1019 ± 6 Ma, and it has been suggested that the mineralization was related to the retrograde stages of Namaquan metamorphism (Raith & Stein, 2000). Perhaps the anthophyllite–talc paragenesis [40c] records that retrogression.

CONCLUDING COMMENTARY AND SPECULATIONS

The Precambrian thermal history of the O'okiep District is summarized in Fig. 16. The *PT* conditions of O'okiepian metamorphism (M_2) indicate a geothermal gradient of about 35°C/km at 1200 Ma (see Clifford *et al.*, 1975*a*). The suggestion by Raith & Harley (1998) that subsequent cooling to M_3 (Klondikean) times was isobaric implies a minimum of denudation during the 150 Myr post-D_2(M_2) pre-D_3(M_3) interval (Fig. 16). A similar lengthy period, involving isobaric heating–cooling, is implied by the *P*–*T*–*t* data from the Prieska Copper Mine in the eastern marginal zone (Areachap Terrane) of the Namaqua Zone (Thomas *et al.*, 1994).

The sediments of the Nama Group (550–650 Ma) rest unconformably on the eroded roots of these crystalline rocks (Fig. 1), demonstrating that a thickness of *c.* 20–25 km of crust was removed in Neoproterozoic times (Fig. 16); this reflects denudation of 5–6 km/100 Myr that is a refinement of the previously published figure (Clifford *et al.*, 1995, p. 253). The average cooling rate in Neoproterozoic times was about 1·5°C/Myr and, during that slow cooling, magnetite–ilmenite equilibrated at 450–500°C in the Koperberg Suite, which then cooled through temperatures of 300–350°C at 800–850 Ma (Fig. 16).

Sm–Nd model ages of 1700–2000 Ma for the major granitic rock-units and for the Koperberg Suite in the O'okiep District support a major crust-forming event in early Mesoproterozoic times (Clifford *et al.*, 1995). Moreover, Clifford *et al.* suggested that the negative ε_{Nd} supports a crustal-melt source for the Concordia Granite, and that high $^{87}Sr/^{86}Sr$ initial ratios (1030 Ma) (0·7061–0·7272), low ε_{Nd} (1030 Ma) (–9) and high μ_2 (10·1) that characterize the Koperberg Suite also imply a crustal source. Oxygen-isotope and K/Rb ratios reported for the Koperberg Suite by Boer *et al.* (1994) are consistent with this conclusion. These views are also supported by trace- (including REE) and major-element data by Duchesne and his co-workers (1999), who have concluded that: (1) the Concordia Granite is the product of melting of a juvenile crust composed of high-K andesites; (2) the jotunite, and magmas parental to the anorthosite, of the Koperberg Suite were derived by partial melting of crustal rocks in dry conditions at high pressures (11–13 kbar).

The reconstructed crustal profile for late Mesoproterozoic times is consistent with these conclusions (Fig. 17a). The present crustal thickness in this part of Namaqualand is 42 km (Green & Durrheim, 1990; see De Beer & Meyer, 1983; Nguuri *et al.*, 2001). If it is reasonably assumed that movements during the Neoproterozoic denudation (Fig. 16) were entirely epeirogenic (and that no new crust was added during that time) it follows that the crust was about 60–65 km thick during Klondikean times at *c.* 1030 Ma (Fig. 17a). One possible model for such an overthickening is the underthrusting of the lower crust to depths of 50 km to produce the massive anorthosite parental magma by melting of gabbronoritic rocks, as in the Sveconorwegian Province of Scandinavia (Duchesne *et al.*, 1999). Alternatively, intracontinental (Ampferer-type) subduction has been proposed by Bird (1978) to explain the duplication of the crust in the Himalayas.

In speculation on the timing of underthrusting–subduction, attention is drawn to the Skelmfontein Thrust Zone (Fig. 1), which had a major phase of movement in late-D_2 times (Raith & Harley, 1998). If that was indeed the time of crust duplication, it follows that: (1) the crust had a normal *c.* 35–40 km thickness during the major O'okiepian deformation (D_2), granulite-facies metamorphism (M_2) and the generation of the Nababeep, Modderfontein, Concordia and Kweekfontein Granites (Fig. 17b); (2) the duplication of the crust at the end of D_2 resulted in an increase in its thickness to *c.* 60 km, which was maintained until Klondikean times (D_3) at 1020–1040 Ma, when the Rietberg Granite and the Koperberg Suite were generated from depths of 35–45 km and > 50 km, respectively (Fig. 17b).

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SUPPLEMENTARY DATA

Supplementary data for this paper are available on *Journal of Petrology* online.

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