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GEOCHEMISTRY OF THE EARLY CRETACEOUS KOEGEL FONTEIN ANOROGENIC IGNEOUS COMPLEX, SOUTH AFRICA

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ABSTRACT

The Koegel Fontein Igneous Complex in the Western Cape Province of South Africa is a high-level granite-syenite intrusive suite with minor plugs and dykes of felsic and mafic composition. Age dating and field relations show that the felsic rocks intruded as two sequential series, beginning with syenites and the Kerskloof suite of felsic dykes (andesite-trachyandesite, trachyte-rhyolite) at about 144 Ma, followed by the Rietpoort granite pluton and quartz-porphyry dykes at about 134 Ma. The intrusion of the mafic dykes and plugs took place between the two felsic series. The early Cretaceous age of the Koegel Fontein associates its

formation with Gondwana breakup and establishment of the volcanic rifted margin in SW Africa. This paper reports results from the geochemical study of the Koegel Fontein Complex.

Two groups of mafic units are distinguished based on mineralogy, field characteristics and chemical composition. The tholeiitic group comprises basalt and basaltic andesites, the alkaline group ranges from basanite-tephrite to phono-tephrite and basaltic trachy-andesite. Distinctions of incompatible element concentrations (K, P, Ti) and ratios (Y/Nb, Zr/Nb) indicate the presence of two separate magma series. Regional dolerite dykes (Gariep dykes and others) associated with contemporary magmatism along the continental margin occur in and near the complex. These regional dolerites are much more homogeneous compositionally than the mafic dykes of Koegel Fontein. Compositionally, they closely resemble the less-differentiated tholeiite dykes.

The felsic units at Koegel Fontein show geochemical and isotopic evidence for two magma series, which correspond to the two intrusive episodes suggested by geochronology and field relations. The first series comprises the volumetrically minor intrusions of syenites, Kerskloof dykes and the Rooivleijtjie granite, with high values ($\epsilon\text{Nd}(t) = -0.4$ to -1.8) indicating a strong mantle input. Similarities of trace element signatures suggest an affinity with the alkaline mafic units. The second series of felsic magmas makes up the bulk of the Koegel Fontein complex, with the large Rietpoort granite pluton and quartz-porphyry dykes ($\epsilon\text{Nd}(t) = -4.8$ to -6.9). These rocks may be related to the tholeiitic mafic series but their isotopic composition indicates a large crustal component. The granitic rocks at Koegel Fontein have geochemical characteristics regarded as typical for anorogenic (A-type) granites, including high contents of Y, Nb, U and Th. In this and in many other features, the Koegel Fontein complex resembles the contemporary intrusive complexes in the Damaraland of NW Namibia. Like the Damaraland granites, the Koegel Fontein magmas are of mixed origin, and their isotopic composition reflect the proportion of mantle vs. crustal source contributions.

Keywords: A-type granites, Sr, Nd, Pb isotopes, Rietpoort granite, syenite, large igneous province

Introduction

The breakup of Western Gondwana in the early Cretaceous was preceded by intense magmatic activity involving the formation of igneous complexes, dyke swarms and the Paraná-Etendeka flood basalt province (e.g., Peate, 1997). Silicic magmas form a significant part of the total magmatic activity, both as volcanic units in the Etendeka province (Ewart et al., 1998b; Marsh et al. 2001) and as large composite intrusive complexes. The latter are prominent in the Damaraland of NW-Namibia and have been extensively studied (e.g., Harris, 1995; Trumbull et al., 2004). The Koegel Fontein Complex ($30^{\circ}59'05''\text{S}$; $17^{\circ}59'11.24''\text{E}$) is the only felsic intrusive complex known to have formed during the early Cretaceous event south of Namibia, although dolerite dykes of that age (Fig. 1) occur along the coast as far south as Cape Town (Reid, 1990; Trumbull et al., 1997; Backeberg et al., 2011). Jansen (1960) produced a detailed map of the Koegel Fontein Complex (Fig. 2) and he distinguished Koegel Fontein intrusive units from the surrounding granite gneisses

of the Namaqua province because the rocks are undeformed. Joubert (1971) and Jack (1980) confirmed the lack of metamorphic fabric in granite from the northern part of the complex. Further evidence for a post-Namaqua age for the complex was the observation of metasomatism and contact metamorphism of Neoproterozoic (Pan-African) schists. Jansen (1960) grouped Koegel Fontein with the Mesoproterozoic Richtersveld Igneous Complex, which received support from conventional U-Pb zircon ages of 1075 ± 40 Ma for syenite and 910 ± 40 Ma for Rietpoort granite reported by Burger and Coertze (1973). On the other hand, McIver (1981) postulated a Jurassic-Cretaceous age for the complex based on analogy with other alkaline complexes in southern Africa and this was confirmed de Beer and Armstrong (1998), who determined in-situ U-Pb zircon SHRIMP ages of 144 ± 2 Ma for the syenite and 133.9 ± 1.3 Ma for the main granite pluton and associated quartz porphyry dykes.

Koegel Fontein is a subcircular complex about 35 km in diameter, consisting mostly of high-level granite and syenite intrusions with associated felsic dykes, and with minor mafic components that occur as dykes and small intrusive plugs. Unlike the contemporary granitic complexes in Namibia, that of Koegel Fontein is only partly un-roofed (Fig. 2); however the main unit, the Rietpoort granite, is thought to underly the Namaqua granites in the entire western portion of the map area (de Beer et al., 2002). Partly because its true age was only recently determined, the Koegel Fontein Complex has remained relatively unstudied. This paper presents the first geochemical study of the complex, which covers all of the main igneous units. Our emphasis is on the felsic units because these are by far the most abundant volumetrically. We present new Sr-, Nd- and Pb-isotope data in order to assess the origin of the felsic magmas and to draw comparisons with those that formed during the same event farther north along the rifted margin in Namibia.

Regional Geological Setting

Three main events have affected the study area since the mid Proterozoic, 1) the Namaqua-Natal metamorphic event, 2) the Pan-African tectono-thermal event and 3) the break-up of Western Gondwana during which the Koegel Fontein magmas were generated. The Mesoproterozoic (1600-1000Ma) Namaqua-Natal Metamorphic Province constitutes the regional country rocks of the complex. Briefly, this province underwent rifting between 1600 and 1300 Ma, followed by subduction and arc magmatism at 1300-1200 Ma. The main Namaqua orogenic event (1220-1150 Ma) occurred as a consequence of collision of crustal blocks during the formation of Rodinia. Finally, an oblique strike-slip system developed at 1080 Ma, along which large volumes of A-type granitoids were emplaced (Cornell et al., 2006).

The "Pan-African" event describes a regional development of Neoproterozoic tectonic and metamorphic belts that formed between older crustal blocks in and around much of the African continent. Parts of this Neoproterozoic province in the study area are remnants of the Gariep Belt along the coast north of Brandsebaai (Fig. 2). The Gariep Belt formed during breakup of Rodinia and formation of the Adamaster Ocean at 770 Ma (Gresse et al., 2006). The sediments deposited in the Gariep Basin document an evolution from initial rifting (immature terrigenous sediments) to continental drift (marine sediments and ophiolites) before subduction closed the Adamastor Ocean (Porada, 1989; Gresse et al., 2006). Deformation in the

Gariep Belt is characterised by thrusting to the south east of supracrustal cover sequences and basement gneisses (Porada, 1989; Gresse et al., 2006). The Pan-African event also caused tectono-metamorphic overprinting of Namaqua gneisses in the study area (de Beer et al., 2002).

The break-up of Western Gondwana is the most important event with respect to formation of the Koegel Fontein Complex. Watkeys (2006) divided the fragmentation of Gondwana into five stages, with the magmatism and the initial rifting of Western Gondwana falling in stages three (155-135Ma) and four (135-115Ma), respectively. During stage three, movement along the Gaste Fault System and the Agulhas-Falkland fracture zones at the southern tip of South Africa may have caused fractures to propagate northwards along pre-existing faults that formed during the Namaqua and Pan-African events. These structures seem to have been important for localising the intrusion of Koegel Fontein, and some of the regional dolerite dykes in the Cape Peninsula (Trumbull et al., 2007). Rifting and continental separation occurred during stage four when the orientation of the plates changed and the Tristan Plume intersected weakened, thinned crust (Watkeys, 2006). Breakup-related magmatism varies in volume from north to south along the South Atlantic rift. Due presumably to the extra heat and dynamic upwelling of the Tristan Plume, the highest magma flux is in the north, represented by the Walvis Ridge offshore and the Paraná-Etendeka large igneous province onshore (Peate, 1997). Both the intensity and diversity of breakup-related magmatism decrease south of the Paraná-Etendeka province. Apart from the Koegel Fontein complex, the only known igneous rocks of this age are dolerite dykes which occur all along the margin as far south as the Cape Peninsula. Well after continental separation in the late Cretaceous and Palaeogene, a second episode of magmatism affected the Cape Peninsula, forming scattered dykes and plugs of alkaline to ultrabasic composition (Janney et al., 2002; 2010). Associated with this late event are small olivine melilitite and nephelinite dykes and plugs in the northern part of the study area, which were described by McIver (1981). These intrusions, termed the Biesiesfontein Suite by De Beer et al. (2002), intruded the Reitpoort granite along a N-S striking shear zone (Fig. 2). Further north along the same structure, about 10 km north of Rietpoort town, is the Sandkopfsdrif Complex (Fig. 2) of alkaline dykes, carbonatite and deeply-weathered, brecciated bodies of glimmerite with olivine melilitite fragments.

Geology of the Koegel Fontein Complex

The Koegel Fontein complex was emplaced at the intersection of two shear zones, one trending north-south and the other northeast-southwest. The north-south lineament appears to be an ancient, large-scale zone of crustal weakness (de Beer et al., 2002). The host rocks of the Koegel Fontein complex are felsic gneisses of the Mesoproterozoic Namaqualand province. The Jakkelshoek Granite gneiss forms the roof rocks of the complex (de Beer et al., 2002) and it displays varying degrees of contact metamorphism and fenitisation, whereby the fenitisation is strongest along fractures in the centre of the complex (de Beer and Armstrong, 1998). Hand specimens and thin sections from the sparse outcrops of the Jakkelshoek Granite show varying degrees of carbonate, chlorite and epidote alteration. Some samples also contain secondary aegirine.

The Koegel Fontein complex consists of a variety of intrusive rock types (Fig. 2). These can be divided into a felsic and mafic association, each of which has plutonic and dyke components. Felsic plutonic bodies dominate the complex, mainly the very large Rietpoort Granite which has about 20 km exposed diameter (Fig. 2). Smaller plutonic intrusions include syenites, the Rooivleijtjie granite and the Zoet Rivier diorite plug. The hypabyssal dyke rocks comprise the Kerskloof suite (mainly microsyenite, bostonite, trachyte), the quartz porphyry dykes (rhyolitic quartz-feldspar porphyry, quartz porphyry), and two mafic suites: alkaline and tholeiitic. A third group of dykes relevant to the study are regional dolerite dykes, which occur in many locations along the Atlantic coast of southern Africa and farther inland (e.g., Trumbull et al., 2007) including the vicinity of Koegel Fontein. Differences in strike orientation and dyke width distinguish the regional dolerites (e.g., the Garies swarm NW of the complex, Fig. 1) from alkaline mafic dykes associated with the complex, whereas some of the tholeiitic dykes share the same strike direction as the regional dolerites (de Beer et al. 2002). Regional aeromagnetic data reveal a strong positive magnetic anomaly centred on the Koegel Fontein complex (inset, Fig. 2). Since granite makes up by far the majority of the complex at surface and should not contrast greatly in magnetic properties from felsic gneisses of the Namaqualand basement, this positive magnetic anomaly suggests the presence of mafic rocks beneath the complex, from which the dykes and dolerite plugs may be derived (see discussion).

Felsic units in the Koegel Fontein Complex were emplaced in two phases. The first involved the intrusion of the 144.4 ± 2 Ma syenites (de Beer et al., 2002). Field relationships indicate that the Rooivleijtjie granite and the Kerskloof felsic dykes also intruded in the first phase (de Beer et al., 2002). The initial magmatism at Koegel Fontein therefore appears slightly older than that found in the Paraná-Etendeka Large Igneous Province (128-138Ma; Ewart et al., 1998a; Trumbull et al., 2007). The second intrusive phase began with a swarm of quartz porphyry dykes, which are observed to cut the Kerskloof dykes and to be truncated by the Rietpoort granite pluton. The zircon ages of granite and quartz porphyry dykes are indistinguishable at 133.9 ± 1 Ma, but field relationships show that the quartz porphyry is older than the granite (de Beer, et al 2002). The mafic dykes and Zoet Rivier diorite plug have not been dated but field relations indicate that the mafic intrusions postdate the 144.4 ± 2 Ma rocks and predate the 133.9 ± 1.3 Ma quartz porphyries and granite.

Descriptions of the Koegel Fontein units

Rietpoort granite

The Rietpoort granite (De Toren Pluton of Jansen, 1960) makes up the bulk of the Koegel Fontein Complex. It is a homogeneous medium to coarse-grained ($> 5\text{mm}$) pluton with few enclaves or xenoliths. The granite is a relatively shallow intrusion as evidenced by miarolitic cavities, but these are few in number and together with the lack of aplite or pegmatite veins, indicate that the granite magma was relatively dry (de Beer et al., 2002). Mineralogically the granite consists of quartz (35-40 vol.%), and about 60 vol.% feldspar (orthoclase, microperthite and albite-oligoclase), with minor amounts of biotite, hornblende, opaque phases, zircon and

apatite. Granophyric intergrowths are common and the feldspar is commonly slightly turbid (Fig. 3a). Jansen (1960) reported rare feldspar phenocrysts with Rapakivi texture from the Rietpoort Granite.

Syenite

There are several small plugs and stocks of syenite in the northern, central and southern parts of the Koegel Fontein complex, the largest of which is the 10 km² Sandkop Syenite (Fig. 2) from which the samples studied here were obtained. The Sandkop Syenite is medium- to coarse-grained and consists of orthoclase, oligoclase, microperthite, hornblende, biotite, apatite and zircon (Fig. 3b). The smaller outcrops and plugs consist of biotite syenite, and some small plugs in the centre of the complex, 20m in diameter, consist of aegirine syenite and fenite (de Beer et al., 2002).

Rooivleijtjie Granite

The Rooivleijtjie Granite is a small plug about 2 km to the east of the Sandkop Syenite. The characteristically reddish, granophyric Rooivleijtjie Granite is coarse-grained and consists of about 70 vol. % feldspar (orthoclase and microperthite) and 20 vol. % quartz, with biotite and hornblende as mafic phases, and accessory zircon and opaque minerals (Fig. 3c). Turbid feldspar, chloritized biotite and hornblende and secondary epidote and calcite are evidence of hydrothermal alteration. The granite is thought to have intruded at the same time as the syenites as it is cut by one of the Kerskloof dykes.

Kerskloof suite

The Kerskloof suite is a series of dykes which were grouped together as microsyenite or bostonite by de Beer et al. (2002) owing to their felsic composition and distinctive trachytic texture with subparallel laths of feldspar aligned parallel to the dyke walls. Chemical analyses show that the suite includes a range of compositions from andesite through trachyandesite and trachyte to rhyolite. Distinctive of the Kerskloof dykes are a relatively narrow width, typically around 1m, rarely up to 5 m), trends of E-W to ENE-WSW and near-vertical dips (de Beer et al., 2002).. The dyke rocks are fine-grained and holocrystalline, generally equigranular. Granophyric texture is common in the more coarse-grained rocks and the groundmass in some of the fine-grained dykes has a quench texture. The groundmass is made up mostly of feldspar (60-70 %), with up to 20 % quartz in the more silica-rich samples. and minor biotite, zircon and opaque minerals. Some dykes contain primary and secondary aegirine-augite, the latter occurring in veins. More common secondary minerals are carbonate, chlorite and epidote, which are present to varying degrees in all samples.

Quartz porphyry dykes

The quartz porphyry dykes are light grey or reddish orange when weathered. Compared with the Kerskloof suite, the quartz porphyry dykes are thicker, mostly 3-10 m and up to 20 m wide (de Beer et al., 2002). Their strike directions (EW to NE-SW) and subvertical dips are similar to those of the Kerskloof suite. Field relations suggest there may be two generations of quartz porphyry intrusion. The younger and more

numerous of the two is light grey in colour. An older type is dark grey-brown and has been observed as xenoliths in the light grey quartz porphyry in the northwestern section of the complex. In both varieties, the phenocryst content reaches up to 20 vol. % and comprises mainly quartz (up to 55 vol. % of the phenocryst population) and feldspar (to 45 vol. %), with up to 5 vol. % biotite (Fig. 3d). Quartz locally shows the bipyramidal high quartz morphology. The groundmass ranges from phaneritic to aphanitic in texture. Primary groundmass phases are quartz (to 30 %), feldspar (to 60 %), chloritized biotite (to 15 %), minor zircon and opaque phases. Secondary minerals are carbonate (locally up to 10 %), chlorite, sericite and epidote.

Zout Rivier diorite

The Zout Rivier diorite forms a small stock or plug about 80m in diameter in the eastern part of the complex. Several tholeiitic mafic dykes are spatially associated with this plug and may be related to the same magmatic source (de Beer et al., 2002). The diorite is older than the Kerskloof felsic dykes and quartz porphyry dykes as it is cut by both rock types (de Beer et al., 2002). In the field, the Zout Rivier plug is distinguished by an area of reddish sand with a few poor outcrops in the centre. The rock is medium-grained (1-5mm) and notable for an abundance (40 vol.%) of phenocrysts. Tabular plagioclase up to 5 mm in length (60 vol.%), clinopyroxene (35 vol.%), and orthopyroxene (5 %) are the dominant phenocryst phases. The groundmass comprises about 50 vol.% plagioclase and 40 vol.% clino- and orthopyroxene with accessory opaque minerals. Alteration minerals affecting both phenocrysts and groundmass include calcite, chlorite, epidote and very fine-grained secondary iron minerals.

Mafic dykes

In addition to dolerite dykes grouped as regional (or Garies) dykes (here termed regional dolerites), two groups of mafic dykes are associated with the Koegel Fontein complex. These were distinguished by different strike direction, spatial distribution and mineralogy by de Beer et al. (2002). The first group, of tholeiitic dykes, strike N-S to NNW-SSE, are <2 metres wide, and occur mostly near the Zout Rivier plug, suggesting a possible genetic relationship (Fig. 2). These dykes contain up to 5 vol.% phenocrysts, which are mainly plagioclase (to 70 vol.% of the total phenocryst population), clinopyroxene (to 30 vol.%), and minor olivine (Fig. 3e). Many of the samples are altered, with chlorite, epidote and carbonate minerals. The second group comprises mafic alkaline mafic dykes, which were emplaced along NE-SW striking fractures, commonly the same ones that host the Kerskloof dykes (de Beer et al., 2002). Like the tholeiite group, alkaline dykes are fine-grained porphyritic rocks. They contain up to 10 vol.% phenocrysts comprising variable proportions of clinopyroxene and plagioclase (Fig. 3f), but are distinguished by the presence of deep brown hornblende and, in some cases, kaersutite phenocrysts. Where kaersutite is present the clinopyroxene shows pink colour in plane polarised light indicating Ti enrichment. Secondary minerals are sericite, chlorite, amphibole and calcite.

The regional dolerites described in this paper occur in the Garies region to the north of Koegel Fontein (Fig. 1), and along the coast to the west of the complex. Similar dykes continue south as far as the Cape Peninsula. The regional dolerites trend NW-SE or NNW-SSE, and are typically wider than the dykes within Koegel Fontein itself. Compositional comparisons are given below.

Methods

Concentrations of major elements and some trace elements (Rb, Sr, Ba, Zr, Cr, Nb, Y, Zn) were analysed by X-ray fluorescence on powdered whole-rock samples. Seventy samples were analysed at the German Research Centre for Geosciences (GFZ) in Potsdam and a further 47 samples were analysed at the University of Cape Town, (UCT). Total volatile components were determined as loss on ignition (LOI) for the samples analysed at UCT. In Potsdam, CO₂ and H₂O were determined separately by infrared spectroscopy. An additional suite of low-abundance trace elements including the rare-earth elements (REE) were determined on 55 samples by ICP-MS at the GFZ in Potsdam, employing a PerkinElmer/SCIEX DRC-e instrument (see Dulski, 2001). See Trumbull et al. (2007) for details of analytical procedures in Potsdam and Le Roex et al. (2001) for procedures at UCT. The appendix lists selected analyses of samples covering all units, the complete data set is available from the authors on request.

Radiogenic isotope ratios of Sr, Nd and Pb were determined on 20 unspiked, whole-rock samples at the GFZ in Potsdam. The isotope analysis was restricted to the felsic members of the Koegel Fontein complex. Samples were dissolved with concentrated HF for four days at 160 °C on the hot plate, then dried and redissolved in 6 N HCl. Sr and Nd were separated and purified using ion-exchange chromatography employing Bio Rad AG50 W-X8 resin for Sr and HDEHP-coated Teflon for Nd (see Romer et al. 2005 for details). Strontium was loaded on Ta-filaments and measured on a VG sector 54-30 mass spectrometer using dynamic multi-collection. Nd was loaded onto double Re-filaments and analysed on a Finnigan MAT262 mass spectrometer using dynamic multi-collection. The Sr data were normalized to $^{87}\text{Sr}/^{86}\text{Sr} = 0.1194$ and Nd data were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Multiple analysis of the Sr reference material NBS987 yielded $^{87}\text{Sr}/^{86}\text{Sr} = 0.710249 \pm 0.000004$ (2 s.d.). Total procedural blanks are < 50 pg Sr. Repeated measurements of the La Jolla Nd standard gave $^{143}\text{Nd}/^{144}\text{Nd} = 0.511850 \pm 0.000004$ (2 s.d.). Total blanks are < 30 pg Nd. Initial Sr and Nd isotope ratios were calculated based on U-Pb zircon ages for the units and element concentrations from ICP-MS analyses. Lead was separated using HCl-HBr ion exchange chromatography using Bio Rad AGI-8X resin. The Pb fraction was collected in a teflon container and purified by a second pass through the column then taken up in phosphoric acid and loaded with silica gel onto single Re-filaments for isotope determination with a Finnigan MAT262 mass spectrometer operated with static multi-collection. Isotope ratios were corrected for mass discrimination with 0.1 % per AMU based on repeated measurements of reference NBS981. The reproducibility of reported Pb isotope data is better than 0.1 % at the two sigma level and total procedural blanks were less than 15-30 pg Pb. Initial ratios for the Pb isotopes are not calculated because of the pervasive alteration of feldspar in the samples. Feldspar, in particular K-feldspar is an important mineral host for Pb of granitic rocks and alteration is likely to cause

some Pb loss and thus higher U/Pb and Th/Pb ratios. Age-correction of such altered rock can significantly overestimate the magmatic in-growth of radiogenic Pb, resulting in anomalously low $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios.

Results

Major and trace element variations

Major and trace element data for selected samples of all units in the Koegel Fontein complex and samples of regional dolerites are reported in the appendix. Secondary alteration (hydration, carbonatisation) is significant in the Koegel Fontein rocks. The degree of alteration, as expressed as the wt.% LOI (or $\text{H}_2\text{O} + \text{CO}_2$ if determined separately), increases sharply in samples with less than about 60 wt.% SiO_2 (Fig. 4a), and reaches values near 10 wt.%. The higher LOI values in mafic rocks partly reflects the greater abundance of mafic minerals sensitive to hydration or carbonation (olivine, pyroxenes, oxides), and it may also relate to the fact that almost all samples with <60 wt.% SiO_2 represent rather thin dykes that are structurally more prone to alteration than massive intrusions. The regional dolerites (asterisk symbols, Fig. 4a) are significantly less altered than dykes within the Koegel Fontein complex. Total volatile contents in the felsic samples rarely exceed 2 wt.%. Because of the variable alteration in the sample set, data presentation is based on compositions recalculated to total 100 wt.%, volatile-free, with total Fe expressed as Fe_2O_3^* . Uncorrected data are presented in the appendix. The total alkali-silica (TAS) diagram (Fig. 4b) gives an overview of the compositional variety present, selected major and trace element variations with SiO_2 and MgO are illustrated on Figures 5 and 6.

Composition of mafic units

The Koegel Fontein mafic units include the Zout Rivier diorite plug and dykes of tholeiitic to alkaline basaltic character. The tholeiitic dykes range from basalt to basaltic andesite on the TAS diagram (Fig. 4b). They have about 45-55 wt.% SiO_2 and 2 to 10 wt.% MgO. The Zout Rivier dolerite is represented by sample CCK-11 (black star). Poor outcrop and strong surface alteration prevented better coverage. The Zout Rivier sample is compositionally similar to the less-evolved tholeiite dykes in major and trace elements (Figs. 5 and 6), but it has higher incompatible element contents (K, Ti, P, Zr, Sr). An interesting feature of the tholeiite dyke samples is an apparent division into two groups in the TiO_2 vs. SiO_2 diagram (Fig. 5b). One group, has $\text{TiO}_2 < 2$ wt.% and these samples overlap on the plot with most but not all regional dolerites. The second group of samples, with 2 to 4 wt.% TiO_2 , overlaps with the alkaline basaltic dykes and follows the same variation trend defined by the less-silicic members of the Kerskloof dykes.

The alkaline basaltic dykes plot on the TAS diagram (Fig. 4b) across the fields of foidites, tephrite to phono-tephrite and trachyandesite. Note that the high total-alkali content of these dykes is controlled by high K_2O (maximum 5.5 wt.%, see Fig. 5d), whereas their sodium contents (not shown) overlap with those of the tholeiite dykes. The alkaline and tholeiitic dykes also show similar ranges in MgO, Fe_2O_3^* , SiO_2 and CaO

but the alkaline dykes tend to higher contents of K_2O and P_2O_5 . (Figs. 5a,d). The mafic dykes show the expected positive correlations of compatible trace elements Cr and Ni with MgO (6a,b). The maximum Cr and Ni contents in these rocks are about 350 and 300 ppm, respectively, at 10 wt.% MgO. Both groups of dykes show the same range of Ni and Cr contents, but that is not the case for Sr and the incompatible elements Rb and Zr (6c,d,e).

The regional dolerites (asterisk symbols) are more homogeneous and less differentiated (lower MgO, higher SiO_2) compared with the mafic dykes from the complex. Further comparisons of the mafic dykes and the regional dolerites are made on incompatible trace element plots of Zr, Nb and Y (Fig. 7a,b). The data clearly distinguish two series, with especially strong contrast in Y/Nb (Fig. 7a). The one series, with $Y/Nb = 3$, includes most tholeiitic dykes, all regional dolerites and the Zout Rivier plug. The other series has $Y/Nb = 0.1$ and it comprises most of the alkaline mafic dykes as well as some of the tholeiitic dyke samples. The same two groups are distinguished by Zr/Nb (Fig. 7b). Since the ratio of highly incompatible elements like Y and Nb is insensitive to fractional crystallisation, the contrasts in Nb-Zr-Y ratios indicate that there are two distinct magma types in the mafic units of Koegel Fontein, although they do not correspond exactly to the division of alkaline and tholeiitic dykes. Chondrite-normalised REE patterns of the tholeiitic and alkaline mafic dykes are not distinctly different (Fig. 8c) with the exception of one alkaline dyke (sample CDB329), which has a steeper pattern than the others. The REE patterns of regional dolerites are indistinguishable from those of the Koegel Fontein tholeiite dykes, but the latter are more variable and most samples have higher REE abundances.

After-the-fact examination of the compositional ranges shown by the alkaline and tholeiitic dykes (Figs. 5, 6, 7) suggests that the field designation of some samples should be revised. We elected not to do this because of the large scatter in both groups of samples and the real possibility of overlap. We retain the names given for these units on the published geological maps (De Beer et al., 2002).

Felsic units

Felsic magmas of a plutonic and dyke association make up the bulk of the Koegel Fontein complex (Fig. 2). The three plutonic units Rietpoort granite Rooivleijtjie granite and Sandkop syenite are each distinctly different compositionally and well-separated in the TAS diagram (Fig. 4b). Compared with these, the two groups of felsic dyke rocks: quartz-porphyry and Kerskloof dykes, are much more variable in composition, but they can be distinguished in terms of silica and total alkaline contents (Fig. 4b). Quartz porphyry dykes have high silica contents (72 to 80 wt.% SiO_2 , volatile-free) and they plot in the rhyolite field on the TAS diagram (one exception). The Kerskloof dykes have less than 72 wt.% SiO_2 , and with one exception, they are richer in alkali elements than the quartz porphyry, plotting in the trachy-andesite to trachyte fields on the TAS diagram. Plots of major element variations with silica (Fig. 5) illustrate the very low contents of P, Ti, Ca and Mg among the quartz porphyry dykes, Rietpoort granite and Roovleijtjie granite. These units show a negative correlation of $Fe_2O_3^*$ vs. silica (Fig. 5f) and considerable scatter in K_2O (and Na_2O , not shown), which may relate to the widespread feldspar alteration and presence of secondary mica. The Kerskloof dykes

show negative correlations of TiO_2 , CaO , MgO and Fe_2O_3^* with SiO_2 , consistent with a differentiation series. In terms of their alkali-alumina ratios the felsic units classify as metaluminous to weakly peraluminous but there is some ambiguity to this ratio based on the possible mobility of alkali elements by alteration.

The felsic units in general, and the dykes in particular, show wide ranges in trace element content and poor correlations with SiO_2 and other major element oxides (Fig. 6). Considering the petrographic evidence for alteration, it is possible that some of the compositional scatter is due to alteration. Hydrothermal alteration affects fluid-mobile elements hosted in feldspars and mica (e.g., Rb, Ba, Sr) more than elements of higher charge density hosted in less-soluble minor and accessory phases (e.g., Ti, Zr, Nb, Y, REE, Th). If alteration were a major factor, ratios of fluid-mobile vs. less-mobile elements (Rb/Y, Ba/Nb) should vary with volatile content, but we see no such dependence. Also, the scatter in many of the interelement plots (e.g. Fig. 6c) is not significantly reduced by limiting samples to low volatile content (< 2 wt.% LOI). We conclude that hydrothermal alteration may have contributed to element variations in the felsic units but was not a controlling factor.

The plutonic units are relatively homogeneous in trace elements and each has a distinctly different composition. The Rietpoort and Rooivleijtjie granites are similar in SiO_2 and many trace element abundances, but the Rooivleijtjie samples are distinguished by high Rb (Fig. 6c), high Nb and very low Y/Nb and Zr/Nb ratios (Fig. 7c,d). The Sandkop syenite has low SiO_2 contents (60 to 61 wt.%), high Sr (Fig. 6e) and correspondingly moderate to low Rb and Zr (Fig. 6c,d). The dyke rocks cover a wide compositional range and show much overlap, but still there are important differences between the two units. Concentrations of Rb (Fig. 6c) and the high field-strength incompatible elements (represented by Zr, Fig. 6d) increase systematically with SiO_2 in the Kerskloof suite, whereas the quartz porphyry dykes show more irregular variations. There is a weak negative correlation between Zr with silica in most of the quartz-porphyry dykes (< 1000 ppm Zr) and the Rietpoort granite, which is typical for high-silica magmas which become saturated in zircon. The continuous increase of Zr with SiO_2 shown by the Kerskloof dykes may relate to higher solubility of zircon in peralkaline magmas. The distinction of mafic units into two series based on the Y/Nb and Zr/Nb ratios (Fig. 7a,b) was noted above, and it appears that the felsic units also show this division (Fig. 7c,d). There is much more scatter to the data and as pointed out, these elements are not perfectly incompatible in high-silica granitic magma, nevertheless we note a clear tendency for low Y/Nb and Zr/Nb ratios in the Kerskloof dykes and high ratios of these elements in the quartz-porphyry dykes. Further evidence that the two groups of dykes represent separate magma series is given by their radiogenic isotope ratios (below).

The REE abundances and patterns of Koegel Fontein units are compared on chondrite-normalized diagrams (Sun and McDonough, 1989) in Figure 8. The Rietpoort granite and quartz porphyry dykes (Fig. 8a) have similar REE patterns, with strong Eu anomalies and moderate LREE/HREE enrichment. The variation in REE abundance within this group of samples is extreme. Most dyke samples have higher REE contents than the granite, and some attain extremely high values of up to 300 ppm La and 30 ppm Yb (see appendix). Two atypical samples (CDB588 and CDB594) have lower REE abundances and flatter patterns,

which resemble those of the Rooivleitsjies granite (Fig. 8b). The Kerskloof dykes and Sandkop syenite (Fig. 8b) are characterised by much weaker negative Eu anomalies than the Rietpoort and quartz porphyry dykes, but they have a similarly wide range of REE abundances reaching extremely high values. The syenites and three Kerskloof dyke samples are distinctive in their flat REE patterns and lack of Eu anomalies, which is consistent with their low degree of differentiation ($\text{SiO}_2 = 56$ to 62 wt.%). Finally, the Rooivleitsjies granite (Fig. 8b) is distinct in terms of its low overall REE abundances, convex-upward pattern with a strong negative Eu anomaly. The similar patterns shown by two of quartz porphyry dykes suggest that they may be related to the same or similar magma, but the contrast in isotope ratios rules this out (Table 1).

The Koegel Fontein felsic units have high concentrations of a group of trace elements, including Zr, Nb, Th, U and REE, which are typically enriched in anorogenic or within-plate granites worldwide. This characteristic is the basis for the "within-plate" designation on the tectonic discrimination diagrams of Pearce et al. (1984) and is one criterium for the "A-type" granites suggested by Whalen et al. (1987). The Rietpoort granite, Rooivleitsjies granite and quartz-porphyry dykes from Koegel Fontein classify as A-type granites (Figure 9a), and show a close correspondence to the anorogenic granites from the Damaraland complexes in Namibia (gray dots). Trumbull et al. (2004) pointed out the looseness of an A-type classification for the Damaraland granites because some have nearly pure crustal sources (e.g., Erongo) and others derived from basaltic material of mantle origin (Brandberg). Eby (1992) recognized the diversity of A-type granites and suggested a subdivision based on Nb, Y and Ce abundances (Fig. 9b). The A-1 subtype is typical for peralkaline granites in mature rift settings with mantle-derived, OIB-type basaltic rocks. The A-2 characteristics are typical for granites from continental, post-collisional or arc settings according to Eby (1992). The mixed genesis of Damaraland granites shows up as a data array straddling the A-1 and A-2 boundary (gray dots, Fig. 9b) and the same behavior is shown by the Koegel Fontein felsic units. The Rooivleitsjies granite has Nb-dominated, A-1 signatures whereas the Rietpoort granite plots in the A-2 field, as do many but not all of the quartz-porphyry dykes. The inference that A-1 subtypes have a stronger input from the mantle and A-2 from the crust is supported by the contrasts in radiogenic isotope ratios described below.

Radiogenic isotopes

The focus of isotopic analyses is on the felsic magmas that dominate the Koegel Fontein Complex. The results of Sr, Nd and Pb analyses, parent-daughter element concentrations and calculated initial ratios are presented in Table 1. Two samples of the Mesoproterozoic basement rocks (augen gneiss and granite gneiss) were also analysed to provide data from the local crust for assessing the magma source. The syenites and Rietpoort granite have uniform Sr and Nd isotopic compositions, which contrast strongly from each other (Fig. 10). The syenites have high ϵNd values (-0.5 to -1.8) compared to the Rietpoort (-6.1 to -6.4) and their initial Sr ratios are much lower (0.7046 to 0.7060 , vs. 0.7246 to 0.7272 , respectively). The Rooivleitsjies granite is represented by a single sample, which has similar Sr and Nd-isotope composition to the syenite (-1.2 , 0.7024). The Kerskloof suite and quartz-porphyry dykes show a range of initial Sr isotope ratios but

much more uniform ϵNd values. One of the two Kerskloof samples (CDB704) has an initial Sr-isotope ratio similar to the syenites and Rooivleijtjie granite (0.7080), whereas the other (CDB552) yielded the highest initial Sr-isotope ratio of all units, at 0.7367. The ϵNd values of both Kerskloof dykes are almost identical (-1 and -0.4), and because Nd is less susceptible than Sr to alteration, we believe the Sr ratio of CDB552 is disturbed (see discussion). The quartz porphyry dykes span a range of ϵNd (-4.8 to -6.9) which overlaps the Rietpoort granite composition. Their initial Sr ratios range overall from 0.7092 to 0.7319, with 7 of 9 samples between 0.7128 and 0.7227, slightly lower than the Rietpoort granite (Fig. 10). To summarize, the felsic units are clearly divided into two groups in terms of their Nd isotope ratios, one group including the alkaline-rich syenites, Rooivleijtjie granite and Kerskloof dykes ($\epsilon\text{Nd} = -0.4$ to -1.8); and the other including the Rietpoort granite and quartz-porphyry dykes ($\epsilon\text{Nd} = -4.9$ to -6.9). The Sr isotope data are consistent with this grouping, with the exception of Kerskloof sample CDB552 which we attribute to secondary enrichment in radiogenic Sr by fluid interaction.

The Pb isotope compositions of the felsic units (measured ratios shown, Fig. 11) tend not to follow the same grouping of samples as suggested by Sr-Nd isotope ratios, and correlations between Pb and Sr or Pb and Nd isotope ratios are poor. Fifteen of 18 samples overlap with one another in the range of $^{206}\text{Pb}/^{204}\text{Pb}$ from 17.87 to 18.55, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.61 to 15.66 and $^{208}\text{Pb}/^{204}\text{Pb}$ from 38.19 to 39.24. These compositions are on the radiogenic side of Stacey and Kramers (1975) terrestrial Pb growth curve, indicating a crustal affinity for the lead, and they overlap with the field of published data from felsic crust of the Namaqua Province. Note the good agreement of our two country rock samples (open stars) with the Namaqualand field. Three outlier samples deviate from the others and all have higher radiogenic isotope ratios. The outlier samples are Kerskloof dyke (CDB552), Rooivleijtjie granite (CCK-17) and Rietpoort granite (CCK-55). Sample CDB552 also stands out because of its higher Sr initial ratio as mentioned above, and it is likely that fluid interaction has affected both Sr and Pb in this rock. The other two samples show no special features in terms of Sr isotope ratio (Fig. 9). The tendency of all units to cluster in Pb isotope composition whereas Nd and Sr isotopes show distinct groupings is consistent with the suggestion (see discussion) that the proportion of crust vs. mantle-derived sources is the first-order control on isotopic composition in this complex. The ratio of Pb concentration in crustal vs. mantle rocks (50-100 times higher) is much larger than for Sr or Nd, making Pb isotope ratios much more sensitive to even minor crustal input.

Discussion

The aim of this study was to characterise the mafic and felsic intrusive units making up the Koegel Fontein complex within the regional context of breakup-related magmatism at the rifted continental margin of southern Africa. Detailed petrogenetic interpretations relating to magma genesis and evolution are beyond the scope of the present paper but we discuss the major implications of the geochemical and isotopic results for the origin of the Koegel Fontein complex and draw comparison with the contemporary and geologically similar anorogenic intrusive complexes in the Damaraland province of NW Namibia.

Relations of mafic and felsic units to genesis of the Koegel Fontein magmas

It was shown above that both the mafic and the felsic units from Koegel Fontein each comprise two compositionally distinct groupings. The best evidence for two genetically distinct magma series within the mafic units is the near-perfect discrimination of two groups based on incompatible trace element ratios Y/Nb and Zr/Nb (Fig. 7a,b). Rocks with distinctly low Y/Nb of 0.10 and Zr/Nb of 5 include most of the mafic alkaline dykes and a minority of tholeiitic dyke samples. The second group has Y/Nb of about 3 and Zr/Nb near 10. This group includes the Zout Rivier diorite plug and most of the tholeiite dyke samples. The regional dolerite dykes from the Garies swarm (Fig. 7a,b) and False Bay (not shown) correspond to the high Y/Nb group. The Garies dykes and other regional dolerites overlap compositionally with a subset of tholeiitic dyke samples from Koegel Fontein, namely those with relatively low incompatible element contents (i.e., $\text{TiO}_2 < 2.5$ wt.%, $\text{P}_2\text{O}_5 < 0.3$ wt.%, $\text{K}_2\text{O} < 1$ wt.%, Fig. 5). It is possible that both groups of dykes derive from the same or similar magma source, with the Koegel Fontein dykes having undergone more differentiation and perhaps mixing with other magma types in the complex. In any case, the low-Y/Nb magma type is not present among the regional dolerites.

The two distinctive magma types represented among the mafic units are also expressed in the composition of the felsic rocks, although much less cleanly. Figures 7c and 7d distinguish a low-Y/Nb series made up of syenites, Kerskloof dykes and Rooivleitsjies granite and a high-Y/Nb series with Rietpoort granite and quartz-porphyry dykes. The compositions of the felsic units are too variable and element correlations among the plotted variables are too weak to put much confidence in this distinction based on trace elements alone, but it is supported by field evidence, geochronology and isotopic compositions as described below.

Field relations and U-Pb SHRIMP ages indicate two intrusive events separated by as much as 10 Ma. The earlier units are syenites, Rooivleitsjies Granite and Kerskloof dykes, and the younger intrusions comprise quartz-porphyry dykes and the Rietpoort Granite. Verwoerd and de Beer (2006) postulated that the syenites, Kerskloof suite and Rooivleitsjies granite may be a comagmatic suite as distinct from the younger Rietpoort Granite and quartz-porphyry dykes. This is the same division suggested by trace element characteristics described above (e.g., Fig. 7c,d). More conclusive is the division in terms of Nd-isotope ratios (Fig. 10) into two groups, one with low ϵNd values (-6.9 to -4.8) and the other with high values (-1.8 to -0.4). The clean distinction indicated by Nd isotope ratios is not evident in the Sr and Pb isotope data. Initial Sr ratios for the syenites and Rooivleitsjies granite are similar to one another (0.703 - 0.707) and distinct from the high values of Rietpoort granite (0.726 - 0.727). The dyke rocks have much more variable composition, with up to 0.02 variation in Sr initial ratio. The wide range of Sr initial ratio at near-constant ϵNd values can be attributed to fluid interaction, which is consistent with the pervasive clouding of feldspars and chloritization of mafic minerals in the rocks. Fluid interaction is likely to have affected the magmatic Pb isotopes signature as well. For example, Kerskloof dyke sample CDB552 shows both elevated Sr-isotope and Pb-isotope ratios (Figs 11 and 12). With few exceptions, the samples form approximately linear arrays on the $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{207}\text{Pb}/^{204}\text{Pb}$ plot and $^{206}\text{Pb}/^{204}\text{Pb}$ - $^{208}\text{Pb}/^{204}\text{Pb}$ plot, and significantly, these arrays correspond reasonably well to the slope of Pb-growth curves for 135 Ma (gray lines). For the upper plot, growth curves are shown for two Th/U

ratios. The data more closely fit the curve for $\text{Th/U} = 4$, which is the observed ratio in most of these samples. The implication of this is that the spread in Pb isotope ratios of the main group of samples could result from a uniform starting composition of the magmas at 135 Ma, with subsequent, variable in-growth of radiogenic Pb in the different samples. Samples plotting above the reference lines may have experienced additional crustal assimilation or assimilation of older crustal materials having higher radiogenic Pb ratios.

The origin and evolution of the felsic magmas at Koegel Fontein was obviously complex, but the geologic setting and the Nd isotope data suggest that a fundamental aspect of it must be the relative contribution of mantle and crustal sources. This can be explored in a simple way using the Nd-isotope data if the problem is reduced to a two-component mix (DePaolo et al. 1992). There are few data available from which to define the mantle and crustal Nd-isotope composition for Koegel Fontein magmatism. The crustal value is taken as -9 for ϵNd (at 135 Ma), is based on analyses in this study of two felsic gneisses from the Mesoproterozoic country rocks at Koegel Fontein. For the mantle component we assume two possible values of ϵNd . The first is -1, based on the most primitive dolerite from the False Bay dyke swarm, which is related to the same magmatic episode as Koegel Fontein but located about 300 km to the south (Trumbull et al., 2007; Backeberg et al., 2011). The other value is +4 based on data from late Cretaceous alkaline basalt and melilitite dykes from the Western Cape by Janney et al. (2002). The mantle and crustal compositions so defined yield estimates for the proportions of crustal-derived Nd in the felsic units of between 68 - 80 % in the Rietpoort granite, assuming $\epsilon\text{Nd} = +4$ for the mantle, or 48 - 68 % for the alternative mantle ϵNd of -1. The crustal proportion in the other units ranges from 0 to 10% or 34 - 45% depending on the assumed end-member compositions. The exact numbers have limited value because they are sensitive to the choice of end-member composition, but it is worth emphasizing that the Kerskloof dykes, syenite and Rooivleitijs granite have the same Nd isotope composition as olivine-tholeiite dykes from the False Bay swarm with 7 wt.% MgO.

Comparisons with the Damaraland complexes in NW Namibia

The association of tholeiitic and alkaline mafic dykes and plugs with dominantly felsic intrusive units at Koegel Fontein is a feature shared by many of the contemporary Damaraland Complexes in NW Namibia (Erongo, Paresis, Brandberg). In Namibia there is a consistent observation is that the mafic alkaline intrusions are younger than the tholeiitic units. This is the case for Okenyanya (Martinez et al., 1996), Messum (Korn and Martin, 1954; Harris et al., 1999), Paresis (Siedner, 1965; Mingram et al., 2000), and Erongo (Pirajno, 1990; Wigand et al., 2004). The relative ages of the alkaline and tholeiitic dykes at Koegel Fontein are as yet unknown for lack of cross-cutting relationships and dating.

Petrogenetic studies of several Damaraland complexes have shown the highly proportion of mantle-derived magmas in the granitic units (Schmitt et al., 2000; Mingram et al., 2000; Frindt et al., 2004). Trumbull et al. (2004) showed that the Nd and oxygen isotopic compositions from these complexes can be explained at first order by a two-component mixing of crustal and mantle sources. Like Koegel Fontein, only very minor intrusions of dykes and plugs of mafic composition are exposed in the Damaraland granitic

complexes. However, many of the complexes are associated with strong positive magnetic anomalies with which probably relate to mafic intrusions at depth. Good examples of these include Brandberg, Cape Cross, Erongo and Paresis (Eberle and Hutchins, 1996; Corner et al., 2002, Bauer et al., 2003). The positive magnetic anomaly centred on the Koegel Fontein complex (Fig. 2 inset) has not been interpreted by petrophysical modeling but a possibly close analogue may be the Brandberg granite, which has the same Nd-isotope ratio as the Rooivleijie granite and syenite and is clearly derived from a mafic precursor (Schmitt et al., 2000). Vietor et al. (2001) interpreted the Brandberg magnetic anomaly as resulting from a gabbroic layer intrusion beneath the granite.

Conclusions

The early Cretaceous Koegel Fontein intrusive complex is in many ways similar to the well-known and contemporary anorogenic ring complexes in the southern Etendeka province, Damaraland, in NW Namibia. Koegel Fontein is mainly composed of high-level granite and syenite intrusions, accompanied by a large number of dykes and plugs of felsic and mafic composition. It is the only known complex of its kind to have formed south of Namibia during Gondwana continental breakup.

The felsic units from Koegel Fontein can be divided geologically into two intrusive events, and the results of this study suggest that the associated magmas were part of two compositional series. The earlier, less silicic and more alkaline series of syenite, Kerskloof dykes and the Rooivleijie Granite have similar and distinctly radiogenic Nd-isotopic composition. These rocks have a narrow range of $\epsilon\text{Nd}(t)$ values from -1.8 to -0.4, which overlaps with that of dolerite-dykes from the False Bay dyke swarm in the Cape Peninsula, and indicate a dominance of mantle-derived components in the magma source. The younger series of Rietpoort Granite and quartz-porphyry dykes are richer in SiO_2 and subalkaline, with lower values of $\epsilon\text{Nd}(t)$ from -6.9 to -4.8 suggesting stronger crustal input. The Sr isotope compositions of the plutonic units show the same distinction into two groups but the dyke rocks have much more variable and overlapping Sr-isotope ratios. Lead isotope ratios of all felsic units overlap, which we attribute to a dominance of the crustal Pb signature. All of the felsic units from Koegel Fontein have trace element characteristics of the A-type granites, with high Ga/Al ratios and high concentrations of Nb (to 700 ppm), Th (to 72 ppm), Zr (to 1990 ppm) and REE (total REE to 1480 ppm). The two felsic magma series recognized by Nd-isotope compositions are poorly discriminated by their geochemical composition, and scatter in most variation diagrams is significant. Part of this scatter may reflect rock alteration, which is pervasive.

The mafic units at Koegel Fontein also form two compositional groups but the age relation between them is unknown. The subalkaline, tholeiitic group comprising dykes and the Zout Rivier diorite plug covers a wide range of composition (MgO from 2 to 12 wt.%). Some of these rocks overlap compositionally with regional dolerite dykes including the nearby Garies swarm, but the Koegel Fontein mafic dykes range to higher contents of TiO_2 (to 4 wt.%) and incompatible trace elements Nb, Zr, Y, REE. Isotopic data from the mafic units are presently lacking, but distinctions in the trace element ratios Y/Nb and Zr/Nb suggest two separate magma types which correspond for the most part to the alkaline and tholeiitic dykes.

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References

- Backeberg, N., Reid, D.L., Trumbull, R.B., and Romer, R.L. 2011. Petrogenesis of the False Bay dyke swarm, Cape Peninsula: evidence for basement assimilation. *South African Journal of Geology*, (this volume).
- Bauer, K., Trumbull, R.B. and Vietor, T. 2003. Geophysical images and a crustal model of intrusive structures beneath the Messum ring complex, Namibia. *Earth and Planetary Science Letters*, 216, 65-80.
- Burger, A.J. and Coertze, F.J. 1973. Radiometric age measurements on rocks from South Africa to the end of 1971: *Bulletin of the Geological Survey of South Africa* 58, 46pp.
- Cornell, D.H., Thomas, R.J., Moen, H.F.G., Reid, D.L., Moore, J.M. and Gibson, R.L. 2006. The Namaqua-Natal Province in *The Geology of South Africa*, Johnson, M.R., Anhaeusser, C.R., Thomas, R. J. (Eds.), Council for Geoscience, Pretoria, South Africa, pp. 325-379.
- Corner, B., Cartwright, J. and Swart, R. 2002. Volcanic passive margin of Namibia; a potential fields perspective. In: Menzies, M.A., Klemperer, S.L., Ebinger, C.J., Baker, J. (Eds.), *Volcanic Rifted Margins*. Geological Society of America Special Paper 362, 203-220.
- de Beer, C.H. and Armstrong, R.A. 1998. Age and tectonic setting of Mesozoic anorogenic complex west of Bitterfontein, Namaqualand, South Africa. *IAVCEI International Volcanological Congress*, Cape Town, 11-16 July, 1998. Abstracts, p. 15.
- de Beer, C.H., Gresse, P.G., Theron, J.N. and Almond, J.E. 2002. *The Geology of the Calvinia Area*. Explanation of 1:250,000 scale Sheet 3118 Calvinia. The Council for Geoscience South Africa, Pretoria, 92pp.
- DePaolo, D.J., Perry, F.V and Baldrige, W.S. 1992. Crustal versus mantle sources of granitic magmas: a two-parameter model based on Nd isotopic studies. *Transactions of the Royal Society of Edinburgh, Earth Science*, 83, 439-446.
- Dulski, P. 2001. Reference materials for geochemical studies: New analytical data by ICP-MS and critical discussion of reference values. *Geostandards Newsletter*, 25, 87-125.
- Eberle, D. and Hutchins, D.G. 1996. Compilation of the Namibian airborne magnetic surveys. Procedures, problems and results. *Journal of African Earth Science*, 22, 191-205.
- Eby, G.N. 1990. The A-type granitoids: A review of their occurrence and chemical characteristics and speculations on their petrogenesis. *Lithos*, 26, 115-134.

- Eby, G.N. 1992. Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications, *Geology*, 20, 641-644.
- Ewart, A., Milner, S.C., Armstrong, R.A. and Duncan, A.R. 1998a. Etendeka volcanism of the Goboboseb Mountains and Messum Igneous Complex, Namibia. Part i: Geochemical evidence of early Cretaceous Tristan Plume melts and the role of crustal contamination in the Paran'a-Etendeka CFB. *Journal of Petrology*, 39, 191-225.
- Ewart, A., Milner, S.C., Armstrong, R.A. and Duncan, A.R. 1998b. Etendeka volcanism of the Goboboseb Mountains and Messum Igneous Complex, Namibia. Part ii: Voluminous quartz latite volcanism of the Awahab Magma System. *Journal of Petrology*, 39, 227-253.
- Frindt, S., Trumbull, R.B. and Romer, R.L. 2004. Petrogenesis of the Gross Spitzkoppe topaz granite, central western Namibia: a geochemical and Nd-Sr-Pb isotope study. *Chemical Geology*, 206, 43-71.
- Gresse, P. G., von Veh, M.W. and Frimmel, H.E. 2006. Namibian (Neoproterozoic) to Early Cambrian successions in The Geology of South Africa, Johnson, M. R., Anhaeusser, C. R., Thomas, R. J. (Eds.), Council for Geoscience, Pretoria, South Africa, pp. 395-20.
- Harris, C. 1995. Oxygen isotope geochemistry of the Mesozoic anorogenic complexes of Damaraland, northwest Namibia: evidence for crustal contamination and its effect on silica saturation. *Contributions to Mineralogy and Petrology*, 122, 308-321.
- Harris, C., Marsh, J.S. and Milner, S.C. 1999. Petrology of the alkaline core of the Messum igneous complex, Namibia: evidence for the progressively decreasing effect of crustal contamination. *Journal of Petrology*, 40, 1377-1397
- Jack, A.M. 1980. The geology of western Namaqualand. *Bulletin of the Precambrian Research Unit* 29, 173.
- Janney, P.E., le Roex, A.P., Carbon, R.W. and Viljoen, K.S. 2002. A chemical and multi-isotope study of the Western Cape olivine melilite province. South Africa: Implications for the sources of kimberlites and the origin of the HIMU signature in Africa. *Journal of Petrology*, 43, 2339-2370.
- Janney, P.E., Shirey, S.B., Carlson, R.W., Pearson, D.G., Bell, D.R., le Roex, A.P., Ishikama, A., Nixon, P.H. and Boyd, F.R. 2010. Age, Composition and Thermal Characteristics of South African Off-Craton Mantle Lithosphere: Evidence for a Multi-Stage History. *Journal of Petrology*, 51, 1849-1890.
- Jansen, H. 1960. The geology of the Bitterfontein area, Cape Province: Explanation of Sheet 253 (Bitterfontein). Geological Survey of South Africa, Pretoria, 97pp.
- Joubert, P. 1971. The regional tectonism of the gneisses of part of Namaqualand. *Bulletin of the Precambrian Research Unit*, 10, 220.
- Korn, H. and Martin, H. 1954. The Messum igneous complex in South West Africa. *Transactions of the Geological Society of South Africa*, 57, 83-124.
- LaBas, M.J., LaMaitre, R.W., Streckeisen, A. and Zanettin, B. 1986. A chemical classification of volcanic rocks based on the total alkali silica diagram. *Journal of Petrology*, 27, 745-750.

- Marsh, J.S., Ewan, A., Milner, S.C., Duncan, A.R. and Miller, R. McG. 2001. The Etendeka Igneous Province: magma types and their stratigraphic distribution with implications for the evolution of the Parana-Etendeka flood basalt province. *Bulletin of Volcanology* 62, 464-486.
- Martinez, I.A., Harris, C., LeRoex, A.P., and Milner, S.C. 1996. Oxygen isotope evidence for extensive crustal contamination in the Okenyenya complex, Namibia. *Geochimica et Cosmochimica Acta*, 60, 4497-4508.
- McIver, J.R. 1981. Aspects of ultrabasic and basic alkaline intrusive rocks from Bitterfontein, South Africa. *Contributions to Mineralogy and Petrology*, 78, 1-11.
- Mingram, B., Trumbull, R.B., Littmann, S. and Gerstenberger, H. 2000. A petrogenetic study of anorogenic felsic magmatism in the Cretaceous Paresis ring complex, Namibia: evidence for crust-mantle hybridization. *Lithos*, 54, 1-22.
- Pearce, J. A., Harris, N. B. W. and Tindle, A. G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology*, 25, 956-983.
- Peate, D.W. 1997. The Parana-Etendeka Province. *In* Mahoney, J.J. and Coffin, M.F. (editors) *Large Igneous Provinces: Continental, Oceanic and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monograph 100, 217-231.
- Pirajno, F. 1990. Geology, geochemistry and mineralization of the Erongo Volcanic Complex, Namibia. *South African Journal of Geology*, 93, 485-504.
- Porada, H. 1989. Pan-African rifting and orogenesis in southern to equatorial Africa and eastern Brazil. *Precambrian Research*, 44, 103-136.
- Reid, D.L. 1990. The Cape Peninsula dolerite dike swarm, South Africa. *In*: A.J. Parker, P.C. Rickwood and D.H. Turner (Editors), *Mafic Dikes and Emplacement Mechanisms*. A.A. Balkema, Rotterdam, 325-334.
- Reid, D.L., Erlank, A.J., Welke, H.J. and Moyes, A. 1987. The Orange River Group: a Major Proterozoic Calcalkaline Volcanic Belt in the Western Namaqua Province, Southern Africa. *Geological Society, London, Special Publication*, 33, 327-346.
- Reid, D.L., Welke, H.J., Smith, C.D. and Moore, J.M. 1997. Lead isotope patterns in the Proterozoic stratiform mineralization in the Bushmanland group, Namaqua Province, South Africa. *Economic Geology*, 92, 248-258.
- Romer, R.L. and Xiao, Y. 2005. Initial Pb-Sr-Nd-isotopic heterogeneity in a single allanite epidote crystal: implications of reaction history for the dating of minerals with low parent- to daughter- ratios. *Contributions to Mineralogy and Petrology*, 148, 662-674.
- Schmitt, A.K., Emmermann, R., Trumbull, R.B., Buhn, B. and Henjes-Kunst, E. 2000. Petrogenesis and ^{40}Ar - ^{39}Ar Geochronology of the Brandberg complex, Namibia: Evidence for a major mantle contribution in metaluminous and peralkaline granites. *Journal of Petrology*, 41, 1207-1239.
- Siedner, G. 1965. Geochemical features of a strongly fractionated alkali igneous suite. *Geochimica et Cosmochimica Acta*, 29, 133-137.

- Stacey, J.S. and Kramers, J.D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters*, 26, 207-221.
- Sun, S.S. and McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *Earth and Planetary Science Letters*, 42, 313-345.
- Trumbull, R.B., Buhn, B., Romer, R.L. and Volker, F. 2003. The petrology of basanite-tephrite intrusions in the Erongo complex and implications for a plume origin of Cretaceous alkaline complexes in Namibia. *Journal of Petrology*, 44, 93-111.
- Trumbull, R.B., Harris, C., Frindt, S. and Wigand, M. 2004. Source diversity on Cretaceous anorogenic granites from Namibia, O-Nd evidence for mixing of mantle derived magmas with isotopically homogenized orogenic crust and implications for A-type granite genesis. *Lithos*, 73, 21-40.
- Trumbull, R.B., Reid, D.L., de Beer, C., van Acken, D. and Romer, R.L. 2007. Magmatism and continental breakup at the west margin of Southern Africa: A geochemical comparison of dolerite dikes from northwestern Namibia and the Western Cape. *South African Journal of Geology*, 110, 477-502.
- Verwoerd, W.J. and de Beer, C.H. 2006. Cretaceous and Tertiary igneous events. *In*: Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds.) *The Geology of South Africa*, Council for Geoscience, Pretoria, South Africa, pp. 573-583.
- Vietor, T., Trumbull, R.B., Nowaczyk, N.R., Hutchins, D.G. and Emmermann, R. 2001. Insights on the deep roots of Mesozoic ring complexes in Namibia from aeromagnetic and gravity modelling of the Messum and Brandberg complexes. *Zeitschrift Deutsche Geologische Gesellschaft*, 152, 157-174.
- Watkeys, M. 2006. Gondwana Break-up: A South African perspective. *In*: Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds.) *The Geology of South Africa*, Council for Geoscience, Pretoria, South Africa, pp. 531-539.
- Whalen, J.B., Currie, K.L. and Chappell, B.W. 1987. A-type granites: geochemical characteristics and discrimination. *Contributions to Mineralogy and Petrology*, 95, 420-436.
- Wigand, M., Schmitt, A.K., Trumbull, R.B., Villa, I.M. and Emmermann, R. 2004. Short-lived magmatic activity in an anorogenic subvolcanic complex; ^{40}Ar - ^{39}Ar and ion microprobe U-Pb zircon dating of the Erongo. *DamaraLand Province, Namibia. Journal of Volcanology and Geothermal Research*, 130, 285-305.

Figure captions

Figure 1 - Regional map of southern Africa showing location of the Koegel Fontein complex and dolerite dyke swarms (from Trumbull et al., 2007).

Figure 2 Simplified geological map of the Koegel Fontein complex from Verwoerd and de Beer (2006). Inset shows the positive aeromagnetic anomaly coinciding with the complex (Council for Geoscience, South Africa).

Figure 3. Photomicrographs illustrating typical petrographic features of Koegel Fontein units. (A) Granophyric texture in Rietpoort granite (cross-polarised light - XPL); (B) Sandkop syenite with amphibole-biotite glomerocrysts (plane-polarised light, PPL); (C) Rooivleittjie granite with turbid feldspar, partly altered amphibole-biotite glomerocryst and interstitial biotite (PPL); (D) quartz porphyry dyke with rounded quartz phenocryst with coronae of fine-grained feldspar (XPL); (E) Tholeiitic dyke, showing subhedral plagioclase and interstitial clinopyroxene (XPL); (F) Mafic alkaline dyke with a skeletal olivine phenocryst and groundmass clinopyroxene and plagioclase (XPL).

Figure 4 (a) Total volatile content of Koegel Fontein rocks and regional dolerites, expressed as loss on ignition (LOI, or sum of CO₂ + H₂O where analysed separately), plotted against measured SiO₂ content (b) Normalised volatile-free whole-rock compositions of the Koegel Fontein complex plotted on the total alkali-silica diagram with classification fields from Le Bas et al. (1986).

Figure 5. Selected major-element variations against SiO₂ for Koegel Fontein rocks and regional dolerites.

Figure 6. Selected trace-element variations against SiO₂ and MgO for Koegel Fontein rocks and regional dolerites.

Figure 7. Variations in Y, Nb and Zr contents for Koegel Fontein rocks and regional dolerites, shown separately for mafic units (a,b) and felsic units (c,d). Note the near-perfect discrimination of mafic units into two series by Y/Nb ratio (Fig. 7a) and a similar, but less well-defined discrimination of the felsic units (see text).

Figure 8. Chondrite-normalized REE plots of felsic (a, b) and mafic (c) units from the Koegel Fontein complex and regional dolerites, with chondrite values from Sun and McDonough (1989).

Figure 9. Comparison of trace element characteristics of Koegel Fontein felsic rocks on A-type granite discrimination diagrams; (a) discrimination after Eby (1990), discrimination of A-subtypes after Eby (1992). Shown for comparison in gray dots are data from the Damaraland granitic complexes from NW Namibia (from Trumbull et al. (2004)).

Figure 10. Initial Sr isotope ratios and initial Nd epsilon values for the Koegel Fontein felsic units, age-corrected to 144 Ma for syenite, Rooivleittjie granite, Kerskloof dykes and country rocks; or 134 Ma for Rietpoort granite and quartz-porphyry dykes. Fields for Damara metasediments, intrusive complexes Brandberg, Gross Spitzkoppe, Cape Cross, Erongo, Paresis and Etendeka quartz latites are from Trumbull et al. (2003; 2004) and references therein. Composition of False Bay dolerite (gray circle) represents the least-

evolved sample from the dyke swarm south of Koegel Fontein (from Trumbull et al., 2007), taken to represent the mantle composition.

Figure 11. Lead isotope composition (measured ratios) of the felsic units from Koegel Fontein. The linear trend of data can result from an initially uniform source composition, followed by variable ingrowth of radiogenic Pb in the rocks since 135 Ma - see grey reference line and text discussion. The dot-dashed line in each plot represents the crustal Pb growth curve from Stacey and Kramers (1975). Data sources as in Figure 10, and Reid et al. (1987; 1997) for Namaqualand felsic basement.

Curtis Figure 1

Curtis Figure 2

Curtis Figure 3

Curtis Figure 4

Curtis Figure 5

Curtis Figure 6

Curtis Figure 7

Curtis Figure 8

Curtis Figure 9

Curtis Figure 10

Curtis Figure 11

Table 1. Radiogenic isotope compositions of felsic units from the Koegel Fontein complex and two country rock samples

Rock type	Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_i$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_i$	$\epsilon\text{Nd (t)}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
Kerskloof dyke	CDB552	0.743972 ± 3	0.73673	0.512492 ± 6	0.51241	-1.0	19.274	15.690	39.947
Kerskloof dyke	CDB704	0.718480 ± 7	0.70804	0.512518 ± 5	0.51244	-0.3	18.459	15.649	38.787
Quartz Porphyry	CDB336	0.725819 ± 9	0.72034	0.512247 ± 5	0.51214	-6.2	17.916	15.608	38.122
Quartz Porphyry	CDB388	0.951374 ± 17	0.73188	0.512335 ± 5	0.51218	-5.4	18.348	15.629	38.676
Quartz Porphyry	CDB580	0.757120 ± 9	0.71278	0.512300 ± 5	0.51220	-5.0	18.312	15.642	39.237
Quartz Porphyry	CDB588	0.754404 ± 4	0.71580	0.512294 ± 5	0.51219	-5.3	18.187	15.636	38.341
Quartz Porphyry	CDB594	0.844030 ± 15	0.71606	0.512329 ± 5	0.51219	-5.3	18.458	15.630	38.580
Quartz Porphyry	CDB650	0.744771 ± 6	0.72521	0.512205 ± 5	0.51211	-6.9	17.869	15.617	38.188
Quartz Porphyry	CN495	0.752718 ± 3	0.72266	0.512316 ± 5	0.51221	-4.8	18.341	15.646	38.817
Quartz Porphyry	CCK-10	0.744642 ± 7	0.71550	0.512261 ± 6	0.51217	-5.6	18.375	15.647	38.817
Quartz Porphyry	CCK-23	0.830019 ± 17	0.70918	0.512319 ± 4	0.51221	-4.9	18.298	15.626	38.499
Rietpoort Granite	CCK-52	0.767108 ± 15	0.72719	0.512232 ± 4	0.51214	-6.2	17.945	15.644	38.423
Rietpoort Granite	CCK-53	0.749619 ± 4	0.72570	0.512235 ± 4	0.51213	-6.3	17.959	15.635	38.422
Rietpoort Granite	CCK-55	0.772047 ± 6	0.72460	0.512247 ± 5	0.51215	-6.1	18.652	15.722	38.406
Roovleijie Granite	CCK-17	1.253980 ± 9	0.70235	0.512504 ± 6	0.51240	-1.2	20.288	15.742	39.522
Syenite	CDB703	0.707447 ± 6	0.70602	0.512526 ± 6	0.51243	-0.5	18.516	15.661	38.940
Syenite	CDB753	0.706034 ± 4	0.70451	0.512459 ± 7	0.51242	-0.8	18.545	15.635	38.640
Syenite	CCK-18	0.705924 ± 10	0.70478	0.512500 ± 5	0.51237	-1.8	18.422	15.626	38.462
Banded gneiss	CCK-2	0.744142 ± 5	0.72631	0.512046 ± 6	0.51195	-9.9	18.995	15.731	47.416
Augen gneiss	CCK-27	0.940702 ± 4	0.90987	0.512164 ± 5	0.51204	-8.1	18.689	16.693	37.736

Sr and Nd-isotope Initial ratios for Rietpoort granite and quartz porphyry are calculated to 134 Ma based on U-Pb zircon dates.

Sr and Nd-isotope Initial ratios for syenite, bostonite, Roovleijie granite (and country rock for reference) are calculated to 144 Ma based on U-Pb zircon dates.

Uncertainty in Pb isotope ratios are better than 0.1% at the 2 sigma level. Initial Pb ratios are not used because alteration of feldspar likely caused some Pb loss, resulting in increased rock U/Pb, Th/Pb ratios and thus over-correction for radiogenic Pb growth.