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ORIGIN AND EVOLUTION OF LATE MAFIC DYKES IN AN ARCHAEAN GNEISSIC ASSEMBLAGE, KAAPVAAL CRATON, SOUTH AFRICA

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INFORMATION CIRCULAR No. 380

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ORIGIN AND EVOLUTION OF LATE MAFIC DYKES IN AN ARCHAEAN GNEISSIC ASSEMBLAGE, KAAPVAAL CRATON, SOUTH AFRICA

by

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June 2004

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ABSTRACT

A suite of mafic dykes occurs as a late component in a well-characterised trondhjemite-tonalite-diorite-granodiorite assemblage in the Johannesburg Dome of the central Kaapvaal Craton, Southern Africa. The dykes can be subdivided into two sets, based on their orientation, major and trace element geochemistry. Set 1 dykes are characterised by elevated SiO_2, Al_2O_3 and TiO_2, and particularly by enriched LILE and HSFE (e.g., Zr > 200 ppm, Nb > 20 ppm, Ba > 300 ppm), higher than in any of the accompanying felsic rocks. REE and trace element values for Set 1 dykes are very similar to those for calc-alkaline lamprophyres. The Set 2 dykes have similar trace element distributions, but are significantly less enriched in general, and are broadly tholeiitic in composition, with enriched MgO (> 11 wt. %) indicative of an olivine-phyric tholeiitic basaltic protolith. Field relationships and available U-Pb zircon geochronology indicate that the dykes are contemporaneous with components of the trondhjemitic host rocks, and late granodiorites. The geochemical, geochronological and field petrological setting indicates partial melting of basaltic and eclogitic lithosphere at ca. 3120 Ma in the basal Kaapvaal Craton, and subsequent emplacement into pre-existing ca. 3430 Ma tonalitic to dioritic crust.

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Published by the Economic Geology Research Institute
(incorporating the Hugh Allsopp Laboratory)
School of Geosciences
University of the Witwatersrand
1 Jan Smuts Avenue
Johannesburg
South Africa

http://www.wits.ac.za/geosciences/egri.htm

ISBN 1-86838-346-6

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INTRODUCTION

Precambrian gneiss terranes are notoriously challenging rocks with which to work, because of their complexity derived from multiple episodes of heating and deformation over < 3.0 Ga of evolution, which can render whole greenstone belts into discontinuous, migmatitic, dyke-like units, combined with their potential for revealing new and crucial information about the early evolution of the earth. The advent of precise geochronology and the refinement of geological and geochemical signatures of orogenic settings has allowed what were once characterized only as ‘seas of grey gneisses’ to be delineated into terranes or domains that can be unravelled in a modern plate tectonic context. This has been demonstrated particularly effectively in the Mesoproterozoic Grenville Province of the southern Canadian Shield (e.g., Rivers, 1997; Rivers *et al*., 1989), for an admittedly younger, but high-grade metamorphosed example. Thorough geochronological and isotopic studies in West Greenland are beginning to decipher the evolution of some of the oldest rocks on earth (e.g., Friend *et al*., 1996). The ability to apply precise geochronological information to complex terranes is dependent on combining information from field relationships, which are often obscured or rendered ambiguous by multiple intrusion and melting events, with geochemical tracing and correlation, also susceptible to secondary remobilization.

The Kaapvaal Craton of South Africa represents one of the largest and best preserved and exposed cratonic cores on earth, and includes some of the oldest and best preserved mafic volcanic suites yet discovered, in the *c.* 3.7-3.34 Ga Barberton greenstone belt (e.g., Kamo and Davis, 1994; Jaeckel *et al*., 1996). While most of the early work on the Archaean Kaapvaal Craton originated from its eastern parts such as the mineralized Barberton rocks, there has now been detailed study of the Murchison greenstone belt to the north (e.g., Poujol *et al*., 1996), the Amalia and Kraaipan greenstone belts in the west (e.g., Poujol *et al*., 2002), the Limpopo Province (e.g., Kröner *et al*., 1997) which bounds the craton to the north, and insights from the Vredefort Dome (e.g., Moser, 1997) in the central Kaapvaal.

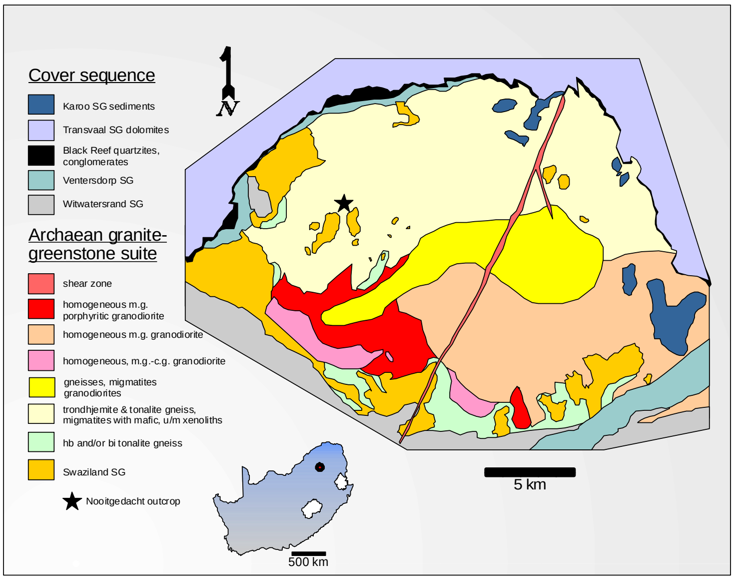

Figure 1a: *Geology of the Johannesburg Dome, simplified after Poujol and Anhaeusser (2001).*

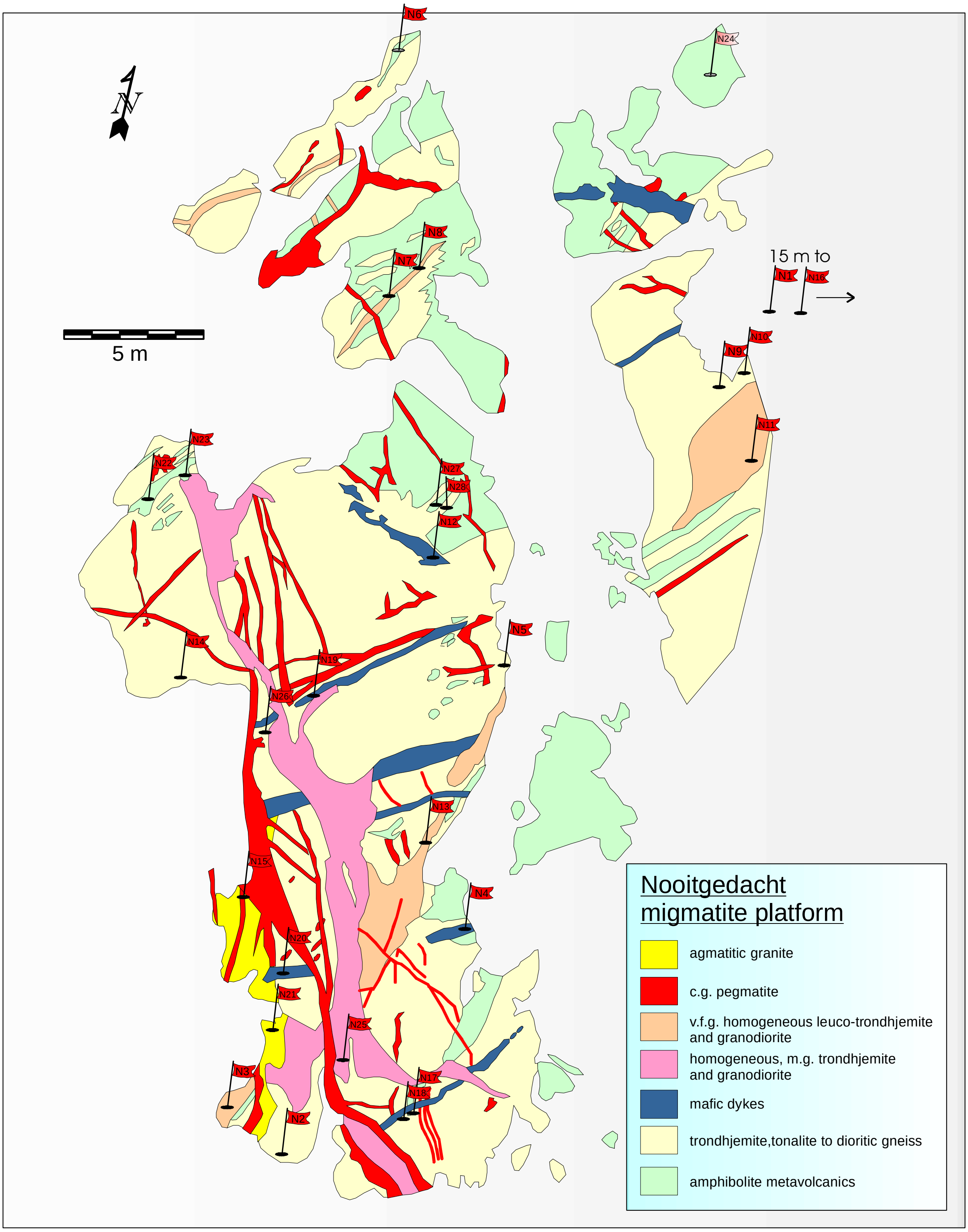

Figure 1b: *Simplified geology of the Nooitgedacht migmatite platform, showing sample locations, after Anhaeusser (1999).*

In this study, we focus on a detailed examination of a complex outcropping of the Johannesburg Dome (Fig.1a) from the central Kaapvaal Craton referred to as the Nooitgedacht migmatite-gneiss platform exposure (Fig. 1b), which was mapped and sampled in detail by Anhaeusser (1999), and the constituent lithologies subsequently dated by U-Pb in single zircon grains (Poujol and Anhaeusser, 2001). The Nooitgedacht migmatite platform is dominated by granitoids of various description, comprising tonalites, trondhjemites, and granodiorites, but also includes at least two generations of mafic dykes. One of these dyke sets displays a zircon population apparently dominated by inheritance from its host rocks (Poujol and Anhaeusser, 2001), but exhibits an unique geochemical signature, which suggests a more complex history.

GEOLOGICAL SETTING

The Johannesburg Dome is one of a number of gneissic domal structures which punctuate the northern Kaapvaal Craton (e.g., Robb and Anhaeusser, 1983), exposed amidst the extensive overlying Neoarchaean sedimentary packages such as the Witwatersrand and Transvaal Supergroups. Detailed mapping and age-dating of the dome (Anhaeusser, 1999; Poujol and Anhaeusser, 2001) indicated the intrusion at *c.* 3.34 Ga of trondhjemitic and tonalitic granitoids, hosting mafic dykes or relic greenstones (now amphibolitized) on the northern half of the dome. This episode was followed by the emplacement of a 3.2 Ga hornblende-biotite-tonalite gneiss in the south. A third magmatic event, consisting dominantly of granodiorites and occupying an area of batholithic dimensions extending across most of the southern portion of the dome, was dated at *c.* 3.12 Ga. The late mafic dykes exposed at Nooitgedacht are thought to comprise two generations on the basis of distinct orientations and geochemical characteristics (Anhaeusser, 1999), and are summarised in Table 1. It may be noted that the geochemical composition of sample N19 is intermediate between those for samples N12 and N20 and those for N4 and N18, albeit slightly closer to that of the latter group, with which it is included.

Table 1. Classification criteria for late mafic dykes at Nooitgedacht, based on Anhaeusser (1999)

Criterion	***Set 1 dykes***	***Set 2 dykes***
sample numbers	N12, N20	N4, N18, N19
orientation	060-090°	110-130°
major elements (in wt.%)	SiO_2 > 50, Al_2O_3 > 14, TiO_2 > 1; $Fe_2O_3^{tot}$ < 10, MgO < 7, CaO < 8	SiO_2 < 49, Al_2O_3 < 14, TiO_2 < 1; $Fe_2O_3^{tot}$ > 10, MgO > 9, CaO > 9
REE profiles	steep LREE, minimal Eu anomaly	flatter LREE, small -ve Eu anomaly

The dykes display greenschist to amphibolite-facies mineral assemblages, with a distinct internal fabric defined by alignment of biotite and hornblende grains, amongst saussuritised and sericitised plagioclase feldspar, with accessory sphene, magnetite, quartz, chlorite and apatite (Anhaeusser, 1999). The dykes crosscut the fabric in the tonalitic and trondhjemitic rocks, and are themselves crosscut by north-south-trending porphyritic leucogranodioritic dykes. Neither chilled margins in the dykes nor recrystallized margins in the granitoids have been recognized.

An attempt was made to date the dykes using zircons extracted from a sample taken from the northeast corner of the Nooitgedacht exposure. Although care was taken when sampling to avoid any potential leucosomic granitoid contaminant, the sample nonetheless contained mm-thickness leucocratic veinlets, which could be separated from one another after coarse crushing of the sample. Ultimately, the zircons, which were more abundant in the veinous material, all gave colinear discordant isotopic results which produced an age of 3117 ± 12 Ma, within error of the age of the cross-cutting porphyritic granodiorite at 3114.2 ± 2.4 Ma, and indistinguishable from intrusion ages of 3121 Ma for the granodiorites (Poujol and Anhaeusser, 2001). The zircons in the mafic dyke were therefore interpreted as "linked to the emplacement" of the leucocratic veinlets, which were correlated with the leucogranodiorite. The granodioritic rocks dated by Poujol and Anhaeusser (2001) contained largely dark pink zircons, but also smaller populations of pink translucent grains which typically gave more concordant results. In the case of the porphyritic granitoid specifically, the pink translucent grains were perfectly concordant, while the three dark pink grains were significantly discordant, although all colinear. The grains found in the mafic dyke were pink and fine-grained (30-50 µm long), but did not include a coarser-grained, darker pink population.

GEOCHEMISTRY

The major element characteristics of the granitoids, amphibolites and mafic dykes from Nooitgedacht have been presented by Anhaeusser (1999) in some detail. He noted the large range in MgO in the mafic dykes, from over 11 wt.% in N4 and N18, down to less than 5 wt.% in N20, and silica ranging from around 48 wt.% up to over 53 wt.%. A comparison of the granitoid compositions with those of the cross-cutting mafic dykes shows some unusual features. Figure 2 (a-c) illustrates the alkali contents of the Nooitgedacht assemblage. Of particular interest is the observation that the potassium content in the dykes is as high as that of the most enriched granitoids, with the exception of the late leucogranodiorite. The total alkali content is balanced out by the low sodium contents, and the dykes and amphibolites are appropriately low relative to the granitoids in Figure 2c. Figure 3 shows titanium variation, highest in the mafic rocks, consistent with their higher iron and magnesium contents, and with the abundance of hornblende, biotite and sphene in the rocks. In contrast, the mafic dykes are among the richest rocks in potassium and rubidium content relative to most of the granitoids, and inconsistent with their mafic character. Sample N20 is particularly enriched in Rb, but is well off the magmatic trend of K/Rb of around 230 (Shaw, 1968), around which most of the other samples cluster (Fig. 4). In terms of major elements and alkalis, the dykes are broadly consistent with tholeiitic basalts, but the Set 1 samples venture into the compositional range for lamprophyres. The only really unambiguous major element geochemical discriminant between tholeiites and lamprophyres (e.g., Nockolds *et al*., 1978) appears to be the FeO/Fe_2O_3 ratios, which unfortunately are not available for these samples. This distinction is evaluated further in the final discussion.

In terms of the typically compatible transition metals, their behaviour is consistent with depletion in progressively more siliceous rocks, as is expected from a siderophile affinity. Plots of silica against chrome and vanadium (Fig. 5a and c, respectively) are shown, but the same trends, with varying degrees of coherence, are exhibited by nickel, cobalt and scandium.

Of additional interest are the high field strength elements (HFSE), which, unlike the large ion lithophile alkali metals, are not prone to mobilization in typical hydrothermal or regional metamorphic environments. Figure 6 shows Zr vs. Nb and Zr/Nb ratio variation against silica, and while the abundances for all units are relatively heterogeneous in comparison with major and compatible element variations, three of the mafic dyke samples (both of "Set 1" above, plus N19) are richer in Zr than any of their host granitoids (Fig. 6a). Similarly, the same three samples are richer in Nb than their hosts. The observation that no individual unit shows a Zr-Nb distribution consisting of a straight line through the origin indicates that these elements are not behaving especially incompatibly in these rocks. There appears, however, to be no systematic variation between rock types in terms of the Zr/Nb ratio (Fig. 6b), so although a very general progressive increase in this ratio with increasing silica could be supported, the Zr/Nb ratio is unhelpful as a discriminant.

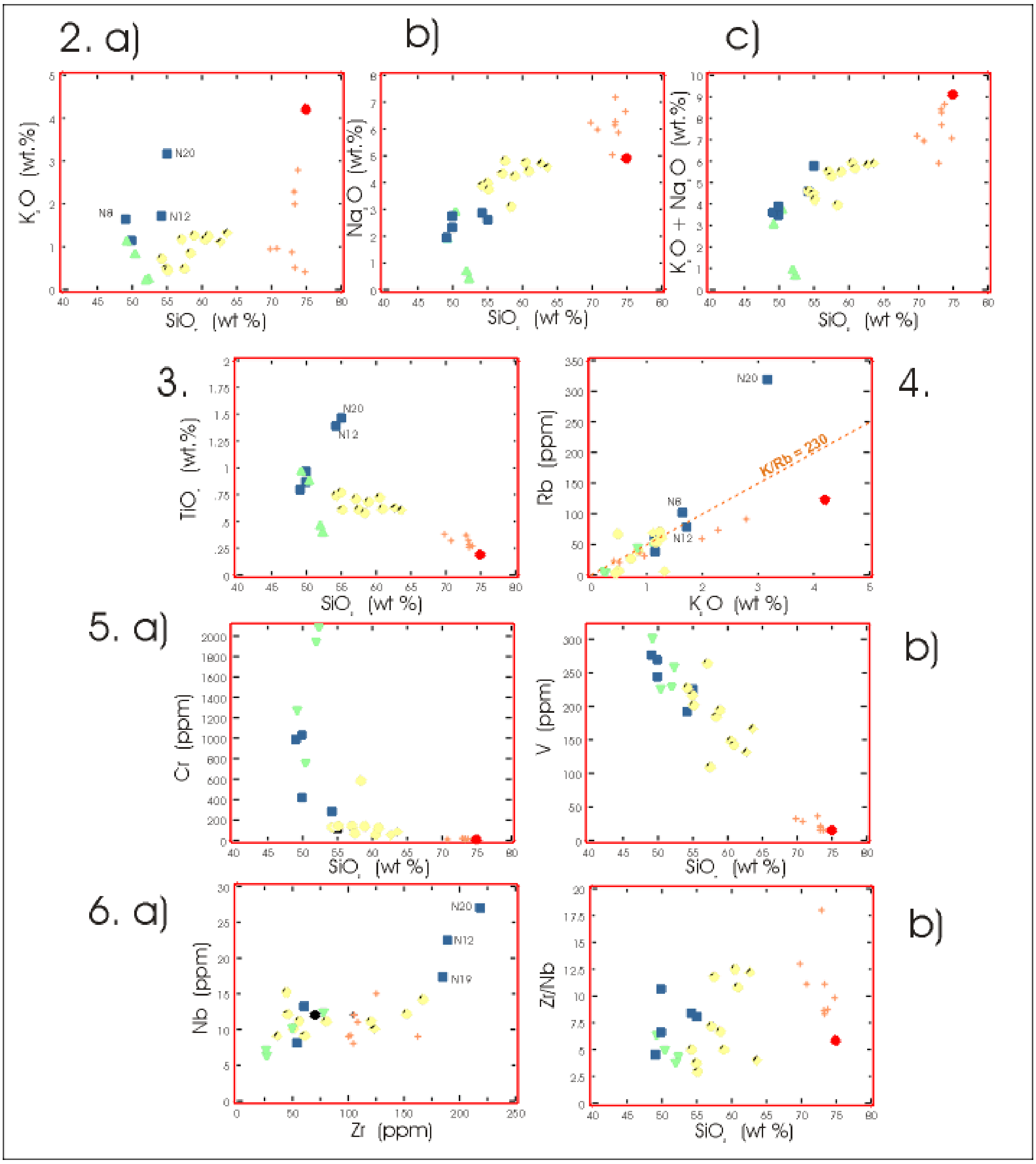

Figure 3. *Harker diagrams showing alkali compositions from Nooitgedacht. SiO_2 vs.(a) K_2O, (b) Na_2O, and (c) K_2O + Na_2O. Symbols are as given in Anhaeusser (1999): filled squares = mafic dykes, filled triangles = amphibolites, open circles = dioritic gneisses, open diamonds = tonalitic gneisses, plus signs = trondhjemites, filled circle = leucogranodiorite.*
Figure 3. *SiO_2 vs. TiO_2 for Nooigedacht samples. Symbols as indicated in Figure 2 caption.*
Figure 4. *Compatible elements: K_2O vs. Rb distribution for Nooitgedacht samples. Symbols as indicated in Figure 2 caption.*
Figure 5. *Compatible transition element variation in the Nooigedacht samples using silica vs. (a) Cr and (b) V. Symbols as indicated in Figure 2 caption.*
Figure 6. *HFSE variation, showing (a) Zr vs. Nb, and (b) silica vs. Zr/Nb ratio. Symbols as*

indicated in Figure 2 caption.

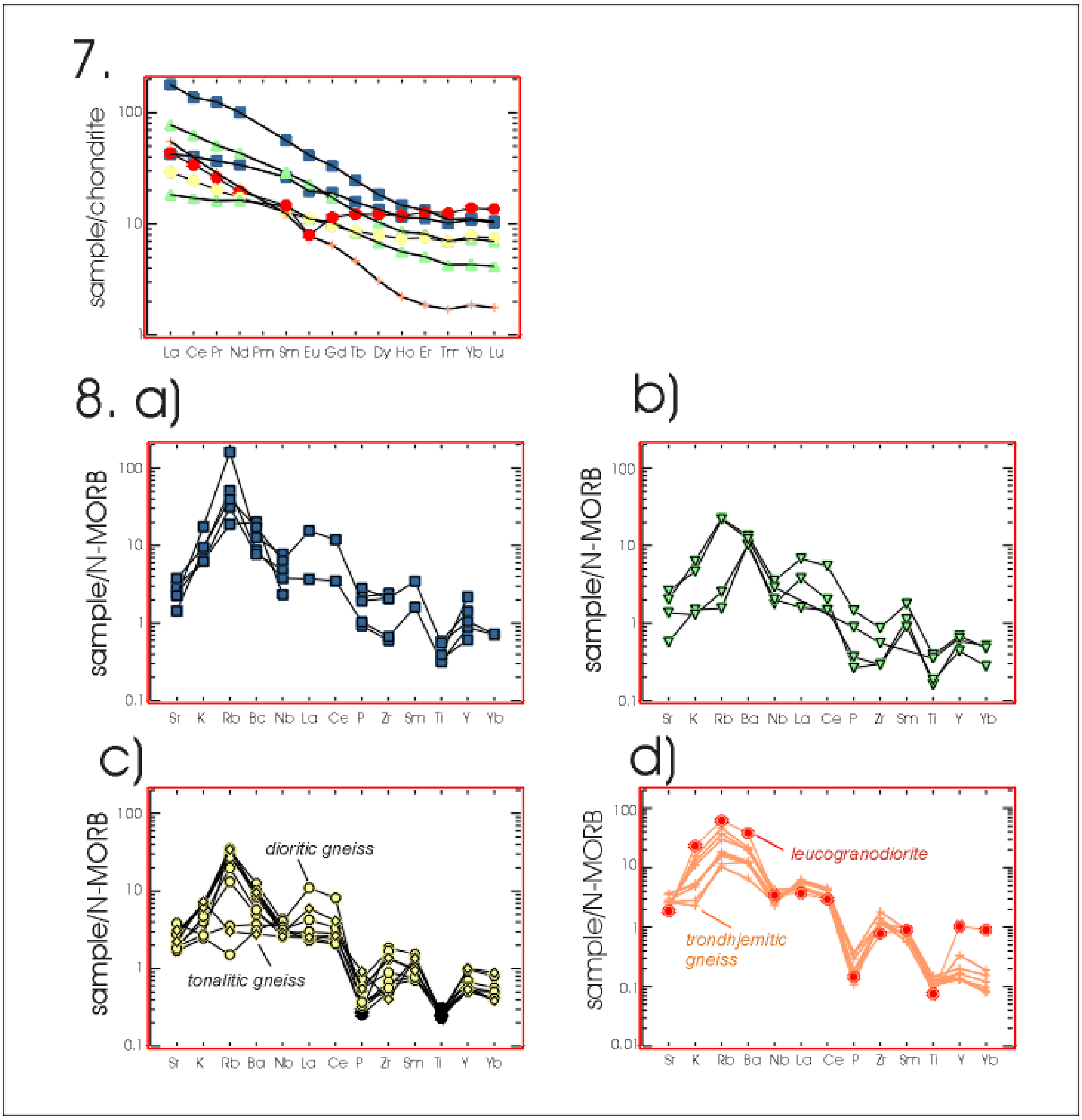

Figure 7. *Chondrite-normalised REE profiles for representative samples from Anhaeusser (1999), comparing mafic dykes (squares) with their host rocks. Symbols as indicated in Figure 2 caption.*
Figure 8. *Trace and incompatible element geochemical spidergrams for Nooitgedacht rocks, normalized to N-MORB (Pearce, 1983), showing (a) mafic dykes and amphibolites, (b) diorite and tonalite gneisses, and (c) trondhjemites and late leucogranodiorite. Symbols as indicated in Figure 2 caption. Note that REE data are not available for some samples in each diagram.*

The REE contents of the various lithologies were examined individually and characterized by Anhaeusser (1999), who noted the distinct patterns of the two mafic dykes analysed for REE (samples N12 and N18). These samples can be usefully compared directly with the compositions of their host rocks, and sample N12, in particular, is significantly more LREE-enriched than any of the granitoids (Fig. 7). In terms of both the slope of the REE profile (i.e., Ce/Yb ratio, or variants thereof) and the magnitude of the Eu anomaly, the mafic dykes are not otherwise distinctive. The trace element compositions may be further examined through the use of primitive mantle-normalized spidergrams (after Pearce, 1983), shown in Figure 8. The mafic dykes (Fig. 8a) are characterized by the enrichments in LILE and REE observed earlier, with a prominent positive spike for Ba, and a small negative spike for Ti. The amphibolite samples (Fig. 8b) show similar enrichment and depletion patterns to the mafic dykes, but less pronounced versions, and with lower overall abundances and typically flatter profiles. The dioritic and tonalitic gneisses (Fig. 8c) share the traits described for the mafic dykes, but in addition, display a small but ubiquitous depletion (negative spike) in phosphorus. Finally, the trondhjemitic gneiss and the late leucogranodiorite display patterns which are distinctive from the other lithologies, and virtually identical to one another (Fig. 8d), where the leucogranodiorite represents a more extreme version of the geochemical characteristics which define the suite. These rocks are characterized by a convex, rounded LILE profile, quite distinct from the more pointed or even slightly concave-sided profiles of the other lithologies. It is also characterized by a pronounced negative spike for phosphorus and titaniun. The leucogranodiorite is distinguished from the trondhjemites by a prominent HREE-enrichment (or perhaps a lack of HREE-depletion, reflecting a flatter normalized profile).

DISCUSSION

The issue under examination here is the nature of the geochemical enrichment of the Set 1 mafic dykes, and the possible implications, if any, regarding its zircon population. It has been established that the Set 1 dykes display enrichment in LILE and HFSE beyond that of any of the granitoid rocks into which they are emplaced or which intrude them. Possible mechanisms for enrichment include the following, which will be evaluated on the basis of the evidence presented above:

(1) secondary enrichment by metamorphism or hydrothermal alteration;
(2) syn-emplacement contamination; and
(3) enriched primary source characteristics.

Secondary enrichment by metamorphism or hydrothermal alteration

There is evidence to support remobilization of the more water-soluble elements, particularly the LILE. The medium-grade metamorphic assemblage, which characterizes the mafic dykes is almost certainly associated with an influx of fluids and hydration of an initially anhydrous pyroxene-plagioclase assemblage in the course of regional metamorphism. The observation that the K/Rb ratio of sample N20 (Fig. 4) is well above that of the ‘magmatic trend’ of Shaw (1968), which is appropriate for most of the rest of the Nooitgedacht suite, and consistent with other South African Archaean TTG rocks (e.g., Hunter, 1979) is consistent with secondary mobility. However, not only do the LILE-contents of the Set 1 dykes exceed those of their potential donors, the granitoid host rocks, the HFSE (including the REE) are similarly enriched, and they are typically immobile in such settings. Finally, a pervasive metamorphic overprinting should be reflected in rocks other than the Set 1 dykes, such as the adjacent lithologies, including the Set 2 dykes, as observed by Anhaeusser (1999). So while metamorphic enrichment of the LILE cannot be ruled out, it cannot be the sole enrichment process involved.

Syn-emplacement contamination

The simplest way to enrich a mafic intrusive rock in LILE and HFSE is through crustal contamination during emplacement, wherein relatively cold local crust is assimilated by the hot, intruding liquid. If the mafic dykes intruded the host granitoids while they were warm, as is perhaps suggested by the absence of chilled margins or contact aureoles, more wholesale assimilation might be expected. The fact that the tonalites and diorites have a fabric which is crosscut by the dykes, with a distinct fabric of its own, indicates that the country rocks were well-solidified and deformed prior to the emplacement of the dykes, possibly during a regional metamorphic episode (i.e., syn-deformational emplacement), in order to account for the fabric in the dykes which has failed to overprint that already present in the gneisses. The dykes would therefore have been emplaced into metamorphically heated country rocks, inducing localized partial melting of wet granitoid rocks along the dyke margins.

The similarity between the ages and morphologies of the zircon populations of the mafic dykes and the late granodiorite, and the absence of a darker pink, perhaps more obviously xenocrystic zircon population in the mafic dykes support the interpretation of Poujol and Anhaeusser (2001) that infiltration from melts derived from the later granodiorites has contaminated the dykes, perhaps along joints and fractures existing in the dykes at the time of granodiorite intrusion. However, the geochemical signatures of the granodiorites are sufficiently distinct from those of the older rocks, including the mafic dykes (re. Fig. 8), that significant contamination from the granodiorites cannot have occurred. Rather, the similarities between the tonalitic and dioritic gneisses and the mafic dykes suggests that these older (TTG) gneisses are the best candidate for partial melting and contamination of the dykes. Clearly, the observation that the Set 1 dykes have HSFE and LILE contents in excess of any of the granites requires that simple bulk contamination cannot account for the enrichment. This not only rules out infiltration by the late granodiorites (which are Zr poor), but also indicates that any contamination by promixal crustal rocks must have occurred via enriched partial melts of the contaminant.

While contamination by tonalite appears to be superficially inconsistent with the zircon population in the dykes, the TTG rocks dated by Poujol and Anhaeusser (2001) include a large number of relatively young zircons. The pink transluscent grains alone, from sample JHBD 98-8, a trondhjemitic gneiss sampled at the Nooidgedacht exposure, have an average $^{207}Pb/^{206}Pb$ age of 3116 Ma, and a regression through five of the six grains gives an imprecise upper intercept age of 3097 ± 24 Ma (Model 2 age of Ludwig, 1993). While these ages themselves may not be of great significance, they do suggest that zircons found within the older TTG rocks are contemporaneous (within error) with the zircon ages from the late granodiorites and the dyke-hosted zircons. The zircons in the mafic dykes are thus potentially consistent with zircons from the TTG rocks both in terms of morphology (colour and translucency) and age, as well as with those from the younger granodiorites. If the TTG rocks were locally melted and entrained within the dykes, the zircons would be juvenile, syn-emplacement crystals, rather than xenocrysts, which is consistent with their distinctive (small) size and the absence of older or darker xenocrystic grains.

Enriched primary source characteristics

In order to evaluate primary characteristics, the difference between the Set 1 and Set 2 dykes may be briefly examined. The REE profiles of sample N12 and N8 (Fig. 7) show a relationship wherein the LREE have been rotated upwards from Set 1 to Set 2, while the

HREE remain anchored. This requires contamination by material with HREE abundances around 10 x chondrite, and elevated LREE (> 200 x chondrite), and with minimal Eu anomaly. As illustrated in Figure 7, this immediately rules out the trondhjemites (near-chondritic HREE) and the late granodiorites (steep LREE, HREE-enriched) as potential candidates. The overall similarity between the trace element profiles and abundances in the tonalites and diorites and the mafic dykes would seem to require large-scale intermingling of a LILE-HFSE-enriched component of the former rocks.

The major element variation indicates that the Set 2 dykes may have been (prior to alteration) olivine-phyric tholeiitic basalts, as they are more magnesian (> 11 wt.%) than "normal" tholeiitic basaltic dolerite compositions (around 6-8 wt.% MgO; e.g., Nockolds *et al*., 1978), leaning towards picritic or komatiitic basalt compositions. This is also consistent with 15-20 wt. % normative olivine in the Set 2 rocks (Anhaeusser, 1999). While the high Mg and alkali enrichment are reminiscent of high-Ca boninites, petrogenetically linked with calc-alkaline lamprophyres by Rock (1991), the Set 2 dykes lack the characteristic depletions in Ti and P, are too enriched in HFSE, and have insufficient silica to otherwise suggest any boninitic affinity (e.g., Crawford *et al*., 1989). The Set 1 dykes, as suggested earlier, are within the realm of lamprophyric chemical composition. There is not an accepted overall set of geochemical criteria which characterize lamprophyres; they are volatile rich, and typified by LILE and HFSE enrichment (e.g., Rock, 1991), but with MORB-like HREE, Y and Ti, all of which are features of the mafic dykes, as shown in Figure 8a. The plot of MORB-normalized trace elements (Fig. 9a) and REE (Fig. 9b) also shows excellent agreement between the Set 1 dykes and an average of nearly 1600 calc-alkaline lamprophyres compiled by Rock (1991), as do the REE (Fig. 9b). While the Set 1 and Set 2 dykes are broadly consistent with lamprophyres and olivine-phyric basalts, respectively, in terms of their geochemistry, they do seem to define a continuum which cautions against over-classification. Finally, the suggestion that the Zr abundances in the mafic dykes are primary features suggests that their zircon populations could conceivably be *in situ* magmatic crystals, rather than inherited or acquired from contemporaneous felsic rocks.

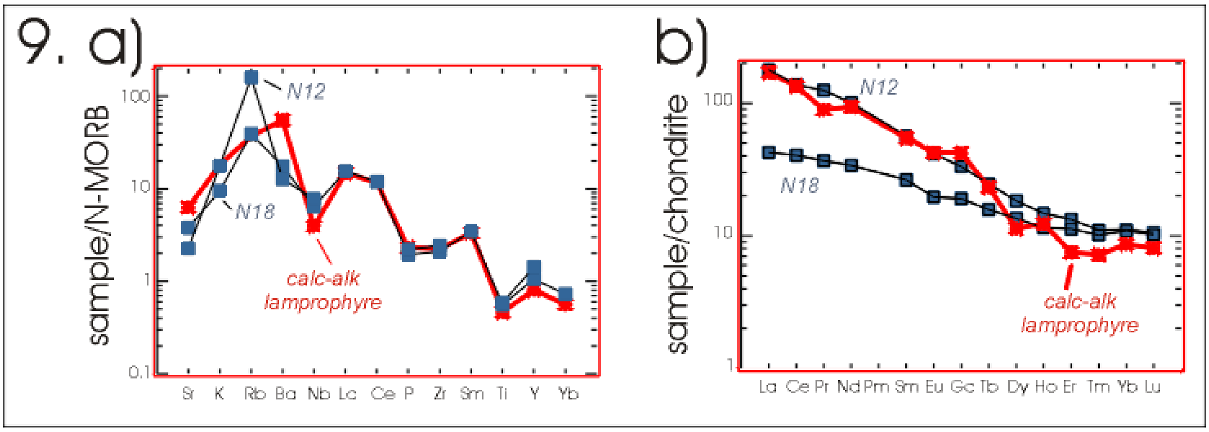

Figure 9. *NMORB-normalized spidergram (a) and REE profile (b) for selected mafic dykes and average calc-alkaline lamprophyre. See text for discussion.*

GENETIC IMPLICATIONS

As paraphrased after Rock (1991), lamprophyres routinely form the mafic members of dyke-suites, part of a compositional continuum from hornblendites and pyroxenites through to aplites and pegmatitites. Although commonly lamprophyric dyke-swarms immediately postdate their associated granitoid plutons, they may also bracket plutons in both time and space, such that the dykes appear as xenoliths in, and also cut, the granitoids, or they cut some phases of a polyphase pluton, but not others. The varieties of granitoid most commonly associated with calc-alkaline lamprophyres appear to be late- to post-orogenic, unfoliated bodies with a wide spectrum of basic-acidic granitoid compositions, from diorites to granites *sensu stricto*. These observations are entirely consistent with the observations from the Nooitgedacht exposure. The mafic dykes crosscut trondhjemitic rocks which include a *c.* 3120 Ma zircon population, in addition to older ones, and are cut by leucotrondhjemite, granodiorite, and pegmatite dykes and veins (Anhaeusser, 1999). The mapped relationships suggest possible crosscutting of the pegmatite in the southwest of the Nooitgedacht platform (near the N20 sample location), as well, but as this is near a termination of a pegmatitic vein, the relationship is ambiguous. The geochemical affinity between the mafic dykes and the tonalites is consistent with involvement with a process involving garnet fractionation, as has been proposed for lamprophyres (Rock, 1991). Garnet fractionation characteristically results in steep REE profiles with concave-upwards HREE or 'hockey stick-shaped' REE-profiles, which is a feature of the early granitoids and the mafic dykes from Nooitgedacht (but less so for the late granodiorites). A lower crustal or mantle origin is implied for lamprophyric rocks generally by their occasional employment as hosts for diamonds. Derivation of the TTG-dyke package at *c.*3120 Ma is therefore inferred to involve partial melting of an eclogitic (garnetiferous) lower crustal lithosphere, probably related to or instigated by basaltic lithospheric partial melting, in order to produce geochemically relatively primitive granitoid melts intergrown with olivine-phyric basaltic to lamprophyric dykes. This requires the existence of a thick lithospheric crust (> 30 km) by at least 3.2 Ga in the Kaapvaal Craton.

CONCLUSIONS

The mafic dykes, particularly those comprising Set 1, are defined by a generally more geochemically evolved signature, and have elevated LILE and HFSE abundances beyond that of any of their host rocks, which comprise a TTG assemblage. The dykes are interpreted, largely on the basis of their geochemistry, as a Mg-tholeiite basaltic to calc-alkaline lamprophyric suite emplaced at *c.* 3120 Ma with contemporaneous and probably partially consanguineous trondhjemitic to granodioritic felsic rocks. They were emplaced into older tonalitic, dioritic and trondhjemitic rocks (a TTG sequence), which may have been melted at depth in the process.

ACKNOWLEDGEMENT

Johan Kruger is thanked for constructive discussion.

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