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Timing of post-Karoo alkaline volcanism in southern Namibia

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Abstract – New radiometric age data are reported for alkaline centres in southern Namibia, and are discussed together with published age data in terms of models put forward to account for post-Karoo (Mesozoic–Recent) alkaline magmatism within the African plate. Agreement between K–Ar and Rb–Sr ages indicate emplacement of the Dicker Willem carbonatite in southern Namibia at 49 ± 1 Ma. Alkaline rocks associated with the Gross Brukkaros volcano show a discordant radiometric age pattern, but the best estimate for the age of this complex is 77 ± 2 Ma, similar to that obtained for the neighbouring Gibeon carbonatite–kimberlite province. The Dicker Willem carbonatite is therefore younger than the Luderitz alkaline province (133 ± 2 Ma), and the Gross Brukkaros volcano, but is older than the Klinghardt phonolite field (29–37 Ma). The new age data argue against a distinct periodicity in alkaline igneous activity in southern Africa, thereby ruling out possible controls by episodic marginal upwarping of the subcontinent. Although the available age data do not appear to be consistent with the passage of one or even two hotspots under southern Namibia, it is argued that the surface expression of hotspots under continents may be so large and overlapping that within-plate magmatism attributed to these thermal anomalies need not necessarily be confined to narrow linear belts or show an age progression. The role of hotspots in continental alkaline magmatism is most likely one of melt generation, while local crustal structure probably controls the distribution and timing of eruption. Major tectonic boundaries in the Precambrian basement underlying southern Namibia seem to have controlled the development of Tertiary alkaline centres in that region.

1. Introduction

Post-Karoo alkaline magmatism is well represented in Namibia, with the more spectacular occurrences being in northern Namibia (Damaraland) (Martin, Mathias & Simpson, 1960; Mathias, 1974). Less is known of the numerous central complexes, dyke and plug swarms believed to be of similar age in southern Namibia. We report here new K-Ar and Rb-Sr age determinations for two occurrences (Dicker Willem carbonatite and Gross Brukkaros volcano), and discuss these and other age data in terms of the nature and timing of alkaline activity in this region. In particular, the role of hotspot traces is evaluated, as southern Africa has featured prominently in the continuing debate on the controls of within-plate magmatism.

2. Geologic setting

The distribution of post-Karoo alkaline rocks in southern Namibia is shown in Figure 1. The country rock comprises gneisses of the Proterozoic Namaqua Province, which are structurally and stratigraphically overlain along the Atlantic coast by sediments and volcanics of the late Precambrian Gariep Province. Further inland to the east the gneiss basement is overlain by flat-lying sedimentary sequences of the late Precambrian Nama Group and late Palaeozoic–Mesozoic Karoo Supergroup.

Marsh (1975) has described late Karoo central complexes in the Luderitz Province, which were emplaced 133 ± 2 Ma ago, based on a K–Ar age (recalculated using revised decay constants in Steiger & Jäger, 1977) on biotite from the Granitberg Complex. The nearby Klinghardt Province includes phonolites of the Klinghardt Mountains, the Schwarzeberg nephelinite, and the Swartkop phonolite (Lock & Marsh, 1981). K–Ar ages of 29–31 Ma (A. J. Spriggs, unpub. Ph.D. thesis, Univ. Leeds, 1988) and 36 Ma (Kröner, 1973) have been reported for the Schwarzeberg nephelinite, and 37 Ma (Kröner, 1973) for the Swartkop phonolite. Alkaline rocks associated with the Gross Brukkaros volcano include both carbonatites and kimberlites (Janse, 1969). Allsopp & Barrett (1975) assign an approximate age of ~82 Ma to Gross Brukkaros, using Rb–Sr data from associated alkaline rocks. No age data were hitherto available for the Dicker Willem carbonatite complex, although Marsh (1975) suggested that this complex may be part of the Luderitz Province.

The Dicker Willem complex intrudes Namaqua Province gneisses, which were last metamorphosed ~1000 Ma ago (Jackson, 1976). The absence of the

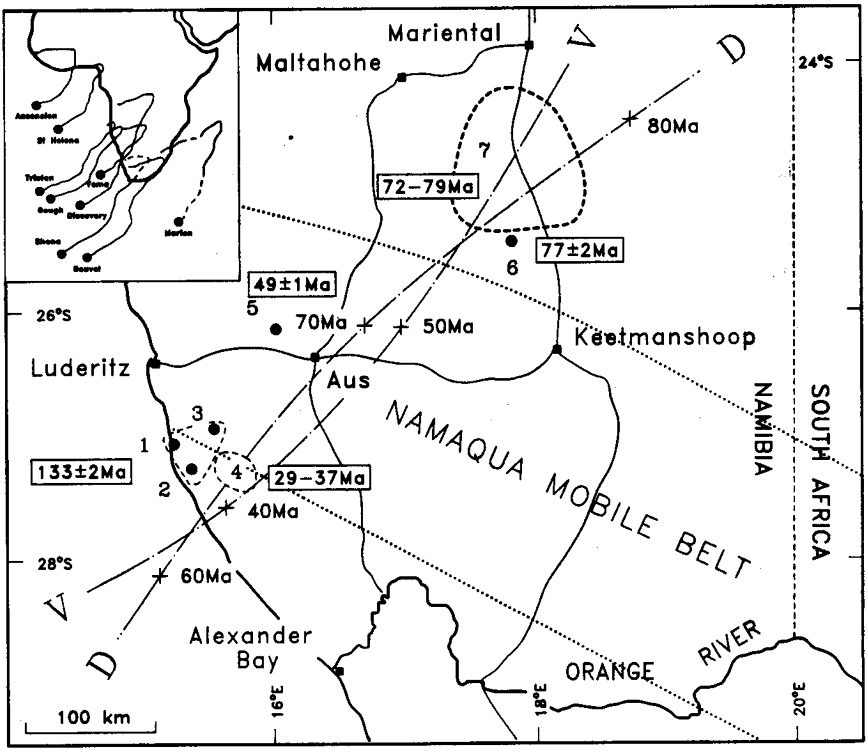

Figure 1. Locality map of southern Namibia, showing the location of Dicker Willem, Gross Brukkaros and other post-Karoo alkaline rocks. 1 (Pomona), 2 (Granitberg) and 3 (Drachenfels) comprise the Luderitz Province of Marsh (1975), 4, Klinghardt phonolite field; 5, Dicker Willem; 6, Gross Brukkaros; 7, Gibeon kimberlite-carbonatite field. Available age-data for some of the alkaline centres are given in boxes next to the locality. Approximate traces of the Vema (V) and Discovery (D) hotspots are superimposed, together with their locations in 10 Ma intervals (after le Roex, 1986). The two heavy dotted lines approximately locate the boundaries of the Namaqua mobile belt in southern Namibia (after Blignault *et al.* 1974).

Nama and Karoo cover rocks allow little control on an upper age-limit. Cooper (1988) describes Dicker Willem as a circular (diameter 3 km) subvolcanic composite intrusion of carbonatite, consisting of coarse-grained silicate-, oxide- and phosphate-bearing sovite, intruded by later sheets of fine-grained microsovites or alvikites which make up the bulk of the complex. The core of the complex is dominated by pipes of explosively emplaced carbonatite breccia. Remnants of a pre-carbonatite ijolite–syenite phase occur as xenoliths and thin screens near the margins of the complex. Biotite and calcite from the coarse sovite were chosen for the K–Ar and Rb–Sr study.

Sample AFC-213 (Table 1) is from a lens within the sovite, rich in cumulus magnetite, biotite, aegirine-augite, apatite, pyrochlore and zircon, while AFC-084 represents the more common variety of biotite-bearing sovite that makes up the bulk of the early intrusive phase (Cooper, 1988). Samples DLR-D and AFC-041 are from sovite xenoliths enclosed in later alvikites on the western side of the complex. AFC-041 contains coarse euhedral biotite crystals up to 15 mm in diameter.

The Gross Brukkaros crater is developed in late Precambrian Nama strata, and an associated carbonatite dyke intrudes neighbouring Karoo strata, thereby providing a lower age limit (Janse, 1969). Morphologically Brukkaros has a volcanic form but the present structure is in fact an eroded remnant of the original crater (Miller & Reimold, 1986). Direct dating of Gross Brukkaros is not possible because of the lack of suitable material, and we have followed earlier workers (Allsopp & Barrett, 1975; Ferguson *et al.* 1975) in collecting material from the nearby intrusion of porphyritic monticellite-bearing peridotite at Blue Hills (Janse, 1971). The massive hypabyssal peridotite of the Blue Hills intrusion contains zones of alteration characterized by abundant phlogopitic mica and carbonate. Mica and calcite from such a zone was apparently studied by Allsopp & Barrett (1975), and mica has been separated from additional samples collected by the present authors.

3. Results

Biotites from Dicker Willem and Blue Hills have been analysed by conventional K–Ar techniques (Briden *et al.* 1979). Coexisting biotite and calcite from Dicker Willem have been analysed by conventional Rb–Sr techniques (Harmer, 1985). Analytical results are listed in Table 1.

K–Ar ages of three biotites from Dicker Willem all

Table 1. Potassium–argon and rubidium–strontium data obtained in this study

Sample	K (%)	Vol ^{40}Ar rad ($\times 10^{-5}$ scc/g)	^{40}Ar rad (%)	Age (Ma)
Dicker Willem				
AFC-041 (bi)	6.74	1.3125	51.6	49±2
AFC-084 (bi)	6.83	1.2759	51.9	47±2
AFC-213 (bi)	5.82	1.1015	57.8	48±2
Gross Brukkaros				
MP (phlog)	8.45	2.5982	88.6	77±2
(Duplicate)		2.5942	67.0	77±2

Sample	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	Age (MA)
Dicker Willem					
AFC-041 (bi)	333.7	214.4	4.502	0.706540	49.7
AFC-084 (bi)	448.1	144.9	8.945	0.708163	37.8
(cc)	0.41	9285.0	0.0001	0.703358	
AFC-213 (bi)	325.3	206.3	4.562	0.706605	49.9
(cc)	1.12	5533.0	0.0006	0.703370	
DLR-D (bi)	252.1	67.3	10.842	0.709587	40.9
(cc)	4.24	1073.0	0.0114	0.703359	

agree within error, and indicate an age of 48±2 Ma. Rb–Sr ages of three biotites have been calculated using the coexisting calcite data for initial Sr correction. Since the three calcites analysed have identical Sr isotope ratios, the fourth biotite was corrected using an average calcite value derived from the first three. Two samples (AFC-213 and AFC-041) have Rb–Sr ages which agree closely with the K–Ar data. Samples AFC-084 and DLR-D have a slightly lower Rb–Sr age of 39 Ma. Regression of the Rb–Sr data plotted in Figure 2, using the method of York (1969), indicates an isochron age of 49.8±0.8 Ma (MSUM = 0.05) for the older samples, and an errorchron age of 39.3±1.0 Ma (MSUM = 6.15) for the younger samples. The initial ^{87}Sr/^{86}Sr ratio of 0.70336±4 is virtually identical to the average of the measured calcite ratios.

The K–Ar age of the Blue Hills phlogopitic mica is 77±2 Ma, slightly higher than the mica–calcite Rb–Sr age of 68 Ma, calculated from the original data in Allsopp & Barrett (1975). The Blue Hills Rb–Sr data are displaced to higher initial ^{87}Sr/^{86}Sr (0.7041±2), compared with the Dicker Willem data (Fig. 2).

4. Discussion

4.a. Age of the Dicker Willem carbonatite

Agreement between K–Ar mica and Rb–Sr mica–calcite ages indicates an age of 49±1 Ma for the Dicker Willem carbonatite complex. One of the two

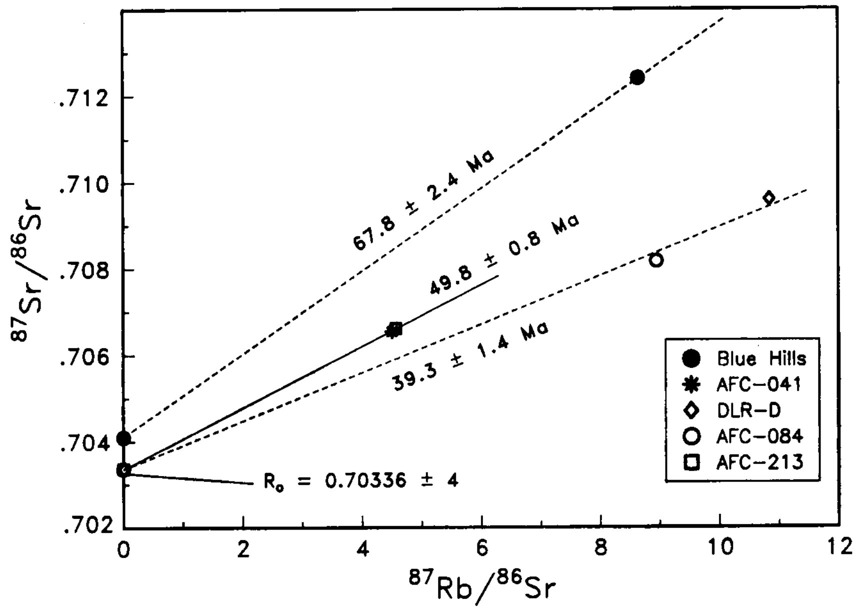

Figure 2. Rubidium–strontium isochron diagram for micas and calcites from Dicker Willem (data from Table 1) and Gross Brukkaros (data from Allsopp & Barrett, 1975).

micas with the lower Rb–Sr age (sample AFC-084) has a K–Ar age which agrees with the others, suggesting that this sample may have lost radiogenic Sr, a feature which is perhaps consistent with the significantly lower Sr content (Table 1). Sample DLR-D was collected from a slightly weathered outcrop of sovite and insufficient mica was available for a separate K–Ar analysis. This fourth sample had the lowest Sr content of all. An alternative explanation, assuming a significantly lower initial $^{87}Sr/^{86}Sr$ ratio (estimated to be 0.7019 assuming an age of 49 Ma), is considered unlikely in view of the constant value obtained from three calcite samples. Moreover, such a low value of 0.7019 (at 49 Ma) has not been recorded even in the most depleted modern oceanic mantle sources.

4.b. Age of the Gross Brukkaros volcano

K–Ar and Rb–Sr data pertaining to the Gross Brukkaros volcano reported here and in Allsopp & Barrett (1975) are from alteration zones within the Blue Hills intrusion. These alteration zones have transitional boundaries with the host peridotite, and do not extend out into the Nama country rock. There was no compelling evidence therefore to regard the alteration event to have significantly post-dated the intrusion of the peridotite, a conclusion also reached by Janse (1971) and Ferguson *et al.* (1975). The K–Ar age of 77 ± 2 Ma obtained during this study may be compared with the Rb–Sr age of ~82 Ma quoted in Allsopp & Barrett (1975), although the analytical data actually yield a lower age of 68 ± 2 Ma (see Fig. 2). To compound the problem, the monticellite peridotite itself yields a K–Ar whole rock age of 116 Ma (A. J. Spriggs, unpub. Ph.D. thesis, Univ. Leeds, 1988).

The lack of independent age constraints prevents any obvious choice between the discrepant radiometric ages obtained for the Blue Hills intrusion. The discrepancies may be due to a variety of causes. For example, whole-rock samples from rapidly cooled hypabyssal mafic intrusions have often retained excess argon, resulting in high K–Ar ages (Dalrymple & Lanphere, 1969). Allsopp & Barrett (1975) warn that the Rb–Sr age of the calcite–biotite pair from Blue Hills assumes that the minerals are cogenetic. Certainly a lower initial $^{87}Sr/^{86}Sr$ ratio of 0.703 would cause the Rb–Sr age of the mica to approach more closely its K–Ar age. The pattern obtained by the Blue Hills intrusion is similar to that already described for Dicker Willem, where some of the micas may have lost small amounts of radiogenic strontium. The same process could have also affected Gross Brukkaros. At present the K–Ar age of 77 ± 2 Ma obtained from mica in the Blue Hills intrusion is considered the best estimate of the emplacement age, and by inference the age of the Gross Brukkaros volcano.

Rb–Sr mica–whole-rock isochron ages of 72–79 Ma have been obtained by A. J. Spriggs (unpub. Ph.D. thesis, Univ. Leeds, 1988) from various kimberlites in the neighbouring Gibeon field. While possibly subject to the same problems as found for the Blue Hills and Dicker Willem samples, these ages do suggest emplacement of the Gibeon kimberlites, Gross Brukkaros and Blue Hills between 70 and 80 Ma ago. Judging from the regression errors on the Rb–Sr data reported by Spriggs in his thesis, the K–Ar mica age of 77 ± 2 Ma is close to the average value, and is therefore suggested as being representative of this alkaline subprovince as a whole.

4.c. Alkaline igneous activity in southern Namibia

The age obtained for the Dicker Willem complex is distinct from that obtained for the Granitberg alkaline complex, and therefore argues against incorporation of Dicker Willem in the Luderitz Province, as proposed by Marsh (1975). Moreover, Dicker Willem is older than the Klinghardt phonolites, and younger than the alkaline magmatism at Gross Brukkaros. Both the Luderitz and Klinghardt alkaline provinces appear therefore to be confined to the Atlantic coast, and the Dicker Willem complex represents the product of a separate igneous event. Gross Brukkaros appears to be part of the larger Gibeon kimberlite–carbonatite province.

It has been suggested that alkaline igneous provinces in southern Africa are the result of hotspot traces (Duncan, 1981; Morgan, 1983; Hartnady & le Roex, 1985; le Roex, 1986). The currently known age distribution of the alkaline rocks in southern Namibia (Fig. 1) clearly indicate no link with a single hotspot trace, but constructions of both Morgan (1983) and le Roex (1986) show that southern Namibia has passed over at least two hotspots (Vema and Discovery) at different times. The ages of the Klinghardt phonolite field and the Dicker Willem complex would be consistent with the Vema hotspot, but not Gross Brukkaros, as its assigned age of 77 Ma is too old for its position relative to the 49 Ma old Dicker Willem. Rather, Gross Brukkaros, Blue Hills and the Gibeon kimberlite field may be related to the Discovery hotspot, over which southern Namibia passed some 20–30 Ma before Vema.

However, neither the Vema nor the Discovery hotspot can explain the Luderitz Province at the Atlantic coast at 133 Ma. It is tempting to relate the Luderitz Province to magmatism that was more directly associated with the breakup of Gondwanaland, since its age is closer to those established for the late-Karoo Etendeka and Damaraland provinces (Siedner & Miller, 1968; Siedner & Mitchell, 1976). Control by a specific hotspot at that time is less clear.

Doubtlessly as further age determinations on Namibian alkaline centres become available, the alleged relationship between such within-plate magmatism and South Atlantic hotspots will be continuously challenged. It is, however, considered pertinent here to discuss in more general terms the hotspot model as it applies to Namibia, and also possible alternative models involving more local control.

Linear belts of igneous centres showing an age progression across continents presupposes (amongst other things) that the activating asthenospheric plume has a surface expression sufficiently small to allow resolution in the 10–100 km range. Some recent estimates of the surface expression of plumes are much larger, of the order of 1000 km (White & McKenzie, 1989). Specifically these authors postulate the influence of the 'Walvis Hotspot' to explain the voluminous magmatism associated with the opening of the South Atlantic 130–120 Ma ago. If all the other South Atlantic hotspots postulated by other workers have (or had) comparable surface expressions then it is questionable whether within-plate magmatism would necessarily show any coherent age or distribution pattern. The problem is further compounded if it is accepted that the subcontinental lithosphere may not behave as passively as the hotspot model would imply.

The role that asthenospheric hotspots play in continental within-plate alkaline magmatism is probably more indirect, in the sense that the associated thermal anomaly provides a means of melt generation. Just how and where the melts enter the continent and erupt may be controlled more by the local geology. In southern Namibia, the Luderitz Province can be explained by low degrees of melting in the southern periphery of the thermal anomaly responsible for the Etendeka and Parana provinces, as postulated by White & McKenzie (1989). The Damaraland alkaline centres could perhaps represent an analogous belt trending northeast away from the thermal anomaly, following the structural grain in the underlying Precambrian basement (Pan-African Damara mobile belt).

Subsequently, as the African plate drifted over other South Atlantic hotspots during Tertiary times, the resuting thermal anomalies triggered low degrees of melting in either the slightly decompressed asthenospheric plume or the overlying lithosphere. Eruption of the melts was controlled by ancient flaws in the crust. Both the Klinghardt phonolites and Gibeon Province appear to have exploited contact zones between adjacent Proterozoic crustal subprovinces, that are buried beneath the Nama and Karoo cover sequences. An extension of the Namaqua mobile belt into southern Namibia forms a linear belt bounded to the southwest by the Tantalite Valley Shear Zone and Fish River Thrust, and to the northeast by the Lord Hill–Excelsior mylonite belt and the geophysically traced extension of the Namaqua Front (Blignault *et al.* 1974, 1983; Hartnady, Joubert & Stowe, 1985). These two crustal boundary zones underlie the Klinghardt and Gibeon provinces respectively. Dicker Willem is more problematic in that it is situated in the middle of the Namaqua Province gneiss terrane, although the poor exposure and Namib sand cover prevents recognition of any fundamental lineaments in the immediate vicinity.

Le Roex (1986) has reported several trace element and radiogenic isotope patterns that have allowed the various South Atlantic hotspots to be chemically characterized. It is conceivable therefore that these geochemical signatures may be reproduced along the trace of a particular hotspot, even on to the continent, thereby providing a means of correlation. Le Roex (1986) has already highlighted the possibility that the Cretaceous kimberlites of southern Africa may in some way be related to hotspots under the subcontinent at that time. Several factors make such an attempt at correlation premature at this stage. For example, it has yet to be demonstrated that any one hotspot trace does in fact show a reproducible geochemical signature even within its oceanic sector. Under the continents the hotspot-derived geochemical signatures could be significantly modified by interaction with the lithosphere. Finally, no geochemical data are available for the Vema hotspot, which has been invoked as being responsible for some of the southern Namibian alkaline provinces studied here. Notwithstanding the many uncertainties, however, geochemical characterization of igneous products along hotspot traces in the South Atlantic and adjacent portions of Africa appears to be an interesting area for future study.

An alternative control on alkaline igneous activity, whereby the continental extensions of oceanic fracture zones mark subcrustal zones of weakness exploited by within-plate magmas, as suggested by Marsh (1973), can explain alignment of centres, without the requirement of age progression. While no detail of just how melt is produced or is extracted was put forward by Marsh (1973), the idea does merit attention, as there must be some reason for the existence and location of transforms along a spreading ridge that was responsible for continental break-up. Should the future location of transforms be indeed governed by crustal structure, then this same structure could continue to play an influential role in the distribution of later within-plate alkaline magmatism. The problem of melt generation still remains and in this respect the fracture-zone model may not actually constitute an alternative. In other words, melt generation may still require the presence of hot spots to provide the thermal anomaly, but the surface expression is controlled by the same zones of crustal weakness that were responsible for the transforms.

Moore (1976) has offered a third alternative to explain the alkaline igneous activity, which involves periodic marginal upwarping of the subcontinent. In this model the age of alkaline magmatism corresponds to marine regressions, and defines four events, each with a specific time duration since the Cretaceous Period. Gross Brukkaros was included within the period during which many of the Kimberley kimberlites were emplaced (~90 Ma), although the revised date of 77 Ma for this Namibian complex rules out such a correlation. The age of Dicker Willem requires the emplacement of this complex *between* the 58–60 Ma and 36–38 Ma events as defined by Moore (1976). The episodic nature of alkaline igneous activity near the margins of the subcontinent is therefore not substantiated. Again, the precise nature of how melt is generated and erupted in this model was not discussed, although upwarping of the continent can presumably cause extension at the base of the crust or lithosphere. The resulting decompression may allow melting but the problem would then be one of erupting that melt through the complementary compressional regime in the upper zone of the continent.

To summarize, the current debate as to the size of asthenospheric hotspots argues against their surface traces across continents being necessarily linear belts of igneous centres showing age progressions. Hotspots are probably essential to promote melting under the continents, while uprise and eruption of the melts are controlled by the local geology. Tertiary melting under southern Namibia was probably caused by its passage over the Vema and Discovery hotspots. Major boundaries between Proterozoic crustal provinces in southern Namibia coincide with the location of many of the Tertiary alkaline igneous centres.

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