

## Update on carbonatites of South Africa and Namibia

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Brief descriptions are given of 43 carbonatite occurrences with emphasis on information that has come to light since 1967. This includes previously unpublished data on Keikamspoor, Welgevonden, Goudini, Mickberg, Weltevrede, Garub, Bokiesbank, Keishöhe, Teufelskuppe, and Kaukausib. The descriptions attempt to summarize data like location, size, geology, mineralogy, geochemistry, and geochronology of each carbonatite occurrence, if available. They are grouped in five age groups showing little overlap, ranging from early Proterozoic to Tertiary, and it is concluded that the subcontinent does not show a pattern of repeated alkaline-carbonatitic activity at the same place. Some doubtful and discredited cases are also mentioned.

Kort beskrywings van 43 karbonatietvoorkomste word voorsien, met die klem op inligting wat sedert 1967 verskyn het. Dit sluit voorheen ongepubliseerde gegewens in oor Keikamspoor, Welgevonden, Goudini, Mickberg, Weltevrede, Garub, Bokiesbank, Keishöhe, Teufelskuppe, en Kaukausib. Die beskrywings probeer data opsom met betrekking tot ligging, grootte, geologie, mineralogie, geochemie, en geochronologie van elke karbonatietvoorkoms, indien beskikbaar. Hulle word in vyf ouderdomsgroepe gegroepeer wat min oorvleueling toon, van vroeg Proterosoïes tot Tersiër, en die gevolgtrekking word gemaak dat die subkontinent nie 'n patroon van herhaalde alkaliese en karbonatiese aktiwiteit op dieselfde plek toon nie. 'n Paar twyfelagtige en gediskrediteerde gevalle word ook genoem.

### Introduction

The first comprehensive description of carbonatites in South Africa and South West Africa (now Namibia) listed 21 volcanic and subvolcanic occurrences and, in addition, 13 cases of doubtful status (Verwoerd, 1967a, Folder 1). At that time only one (Phalaborwa) had been dated by isotopic methods. Considerable progress has been made since then with regard to recognition, exploration, exploitation, and geochronology. Many (but not all) have been dated more or less reliably; one occurrence has been discredited; 23 new ones (including six major complexes) have been discovered or confirmed, bringing the total number up to 43 (Figure 1); and at least five cases that were tentatively linked to carbonatite in the past are no longer considered as such. These five exclude carbonate rocks associated with kimberlite, which qualify as carbonatite according to some definitions but will not be considered in this review with the exception of Premier Mine.

The origin and petrogenetic relations of carbonatite are now better understood than in 1967. However, there is still ample scope for more detailed geological, mineralogical, and geochemical studies of southern African carbonatites. The subject was briefly reviewed by Hunter (1981). In 1977 the author summarized the available data in a presidential address to the Geological Society of South Africa entitled: 'Karbonatiet in Suider-Afrika na Tien Jaar'. Aspects related to economic geology were eventually published (Verwoerd, 1986) but details about some of the less important occurrences have not yet appeared in print. It is the purpose of this paper to bring the information and list of references to southern African carbonatites up to date by complementing the two above-mentioned publications without undue repetition of content.

### Age groups

Southern African carbonatites range from early Proterozoic to early Tertiary in age. 'At least four periods of carbonatite

emplacement' were suggested by Verwoerd (1967a), mainly on geological grounds. Not every assignment of a particular occurrence to one of these groups has been confirmed by subsequent work, but in general the age categories have been substantiated by geochronology. One additional age group is now recognized: the late Proterozoic complexes in Namibia that appear to be related to the Damara orogenic belt. Thus, there is little doubt that the history of carbonatite emplacement in the subcontinent was discontinuous and episodic. The five groups described below are named in accordance with the IUGS approved chronometric time scale for the Precambrian (Cowie & Bassett, 1989).

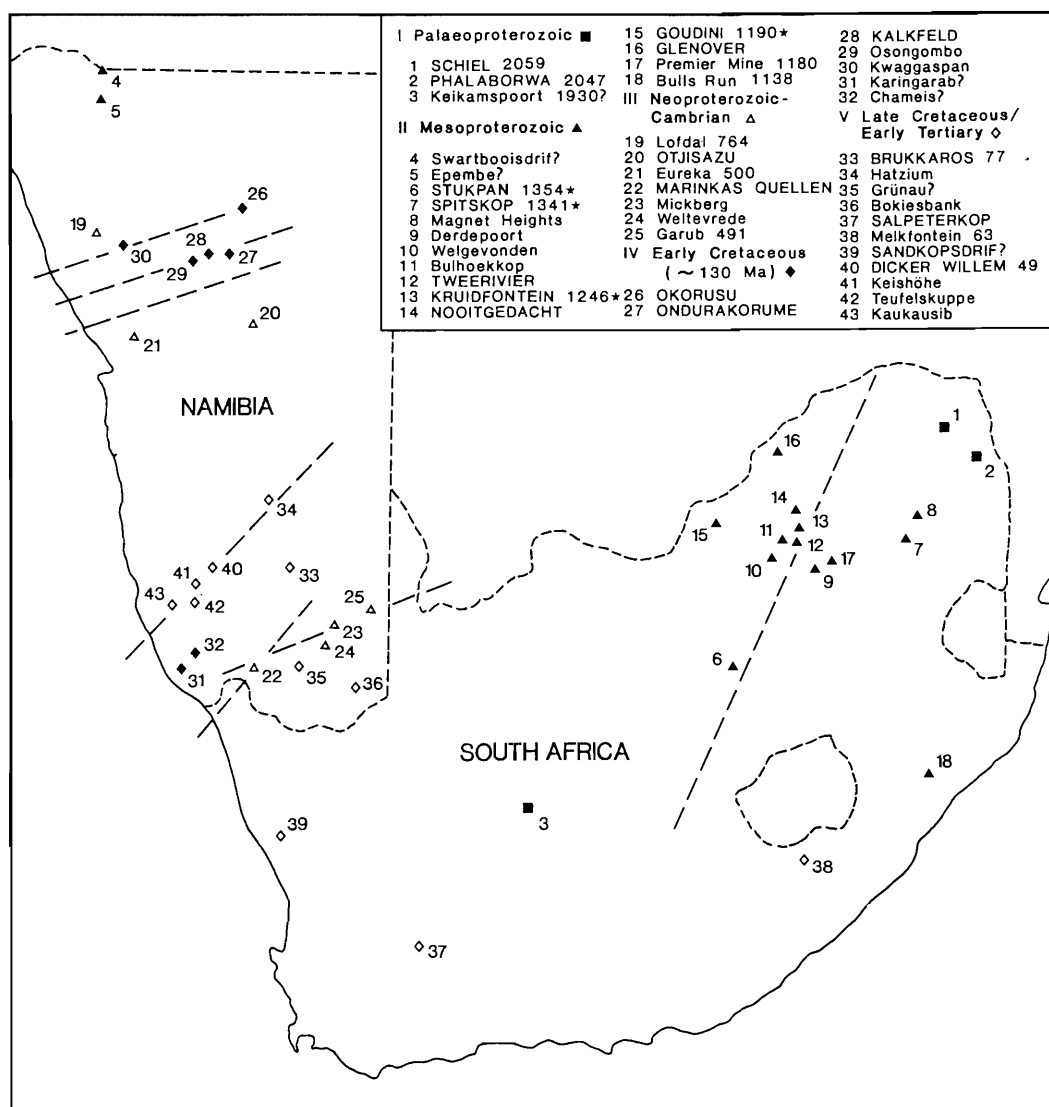
#### Palaeoproterozoic (2500 – 1600 Ma)

The three complexes grouped here are among the oldest known carbonatites on earth.

##### *Schiel (1)*

This is a syenitic complex occupying several hundred square kilometres, with subordinate carbonatite, foshkorite, pyroxenite, and syenogabbro. The main eastern body has been prospected for phosphate (Verwoerd, 1986; Brandl, 1987). Most of the complex is deeply weathered. Carbonatite (up to 10 m thick) was only intersected in boreholes. It is sövite, consisting of magnesian calcite with apatite, phlogopite, magnetite, clinopyroxene, rutile, and feldspar as accessories, with minor disseminated copper and iron sulphides. Trace elements have not been determined.

Preliminary Rb-Sr whole rock age determinations of the complex range from  $2572 \pm 26$  and  $2526 \pm 50$  Ma (South African Committee for Stratigraphy (SACS), 1980) to *c.* 2150 Ma (Barton *et al.*, 1983) but none of these figures are based on isochrons. New Pb-isotopic results on various lithological units show considerable scatter but, taken together, they allow a well-constrained errorchron of  $2059 \pm 35$ – $36$  Ma which is considered a best estimate for the age of the complex (Walraven *et al.*, 1992). This age confirms



**Figure 1** Carbonatites of South Africa and Namibia. Major occurrences (volcanoes or subvolcanic complexes) capitalized. Radiometric ages in Ma. Asterisk denotes previously unpublished Rb-Sr and Sm-Nd results by R.E. Harmer. Question mark signifies doubt about assignment to a particular age group. Well-established lineaments based on the alignment of intrusions also shown.

earlier opinions that Schiel and Phalaborwa are petrologically related (Verwoerd, 1986) and actually indicates that they are coeval.

The Pb-isotope work is part of a comprehensive geological and geophysical study of the Schiel Complex by the Geological Survey. It was remapped by R.T. Lubala and geophysically modelled by E.H. Stettler (Stettler *et al.*, 1993). Petrological investigations are also underway.

#### *Phalaborwa (Loolekop) (2)*

The Phalaborwa Complex is a composite ultramafic intrusion with a core of carbonatite. The other rock types are pyroxenite, feldspathic pyroxenite, glimmerite, foskorite, syenite, and fenite. It occupies an area of 16 km<sup>2</sup> excluding the separate syenite plugs. Geological descriptions of the important phosphate, copper, and vermiculite mines situated within the complex have appeared in many publications. The age has been determined by Rb-Sr and U-Pb mineral isochrons as 2047 ± 11–8 Ma (Eriksson, 1984; 1989).

The most up-to-date petrological account is that by Eriksson (1989), who comes out firmly in favour of an origin by interaction between magmas accompanied by very subordinate metasomatism. This paper provides isotope and major- and trace-element data on constituent minerals and rocks. Contrary to previous estimates, crystallization temperatures in excess of 1000°C are suggested. The conclusion is reached that the parental magma of the main complex was potassic and ultramafic and that there is no simple genetic relationship between this magma and the carbonatite. Both silicate and carbonate magmas were derived from mantle sources enriched in large ion lithophile elements relative to bulk Earth.

A useful summary of the economic geology of Phalaborwa appears in the text book on ore deposits by Park & MacDiarmid (1970). These authors classify the carbonatite-hosted copper sulphides as a magmatic segregation deposit, but admit that 'the copper appears to have been introduced by (closely connected) hydrothermal solutions'. Aldous

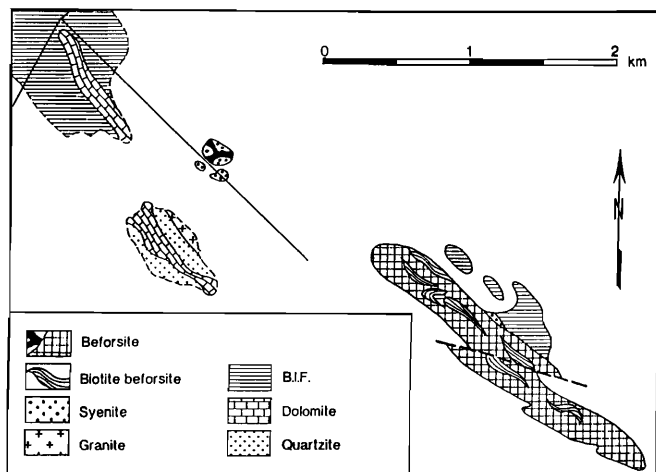


Figure 3 Geological sketch map of Keikamspoor carbonatite.

zons are known in the sedimentary succession. Despite the fact that the mineralogy is also somewhat atypical of carbonatites, the geochemical and geochronologic evidence leave little doubt that it is a Palaeoproterozoic carbonatite.

The dyke consists of brown-weathering quartz-apatite beforsite, quartz-feldspar beforsite, and micaceous lenses of an older (?) biotite-rich beforsite (Figure 3). The main constituent, ankerite, is almost uniformly fine-grained (less than 1 mm) to medium-grained (2 – 5 mm) in places. Calcite replaces ankerite, but is rare. Quartz is present in the form of microscopic veinlets and interstitial aggregates intergrown with apatite; also as transgressive quartz veins up to 1 cm thick. The apatite forms clots and segregations of a reddish colour that stand out on weathered surfaces. K-feldspar is likewise microcrystalline and reddish due to associated iron oxides which may weather dark brown to black. The two minerals are apt to be confused even in thin section, but individual K-feldspar grains are more often euhedral with rectangular outlines, they have lower relief and show simple twinning and perthitic texture under crossed polars. In the specimens studied, apatite and K-feldspar were not found together.

Rutile, in the form of minute (0.02 mm) yellow crystals, strings, and aggregates, is a characteristic accessory mineral. Disseminated cubes of pyrite are also quite common. Monazite tends to form lenticular aggregates up to 6 mm in length, rather than single crystals, and is not the green low-thorium variety commonly seen in carbonatites elsewhere. The carbonatite also contains specks (up to 1 mm) of chalcopyrite, sphalerite, and galena. Verwoerd (1986) gave assay results for Cu, Zn, Pb, and Ag of a non-representative malachite-stained sample from the southernmost outcrop. Small amounts of magnetite, zircon, fluorite, and perhaps strontianite have been identified tentatively, but the virtual absence of magnetite is notable. Pyrochlore was not found, but is suspected to be present in view of the 460 ppm and 355 ppm Nb reported by Anglo American in two of their samples.

Alkaline igneous rocks that may be linked to the Keikamspoor carbonatite are few and poorly known. A syenite plug and several syenite dykes following the same north-westerly trend (one of them along strike with the carbona-

tite) are shown on Du Toit's map between Keikamspoor and Prieska. A narrow strip of syenite or fenite consisting of K-feldspar without any dark mineral occurs for a short distance adjacent to the carbonatite. Similar rock forms a low outcrop 1 km to the northwest, where it is traversed by off-shoots from the main carbonatite. In addition, perfectly fresh sodalite-nepheline syenite (the Waterkop syenite) is exposed in a cutting along the Prieska-Copperton road, about 18 km from Keikamspoor, but the extent of the body is unknown.

Cornell *et al.* (1989) calculated a Sm-Nd depleted mantle model age of 1930 Ma for the Keikamspoor carbonatite and 1916 Ma for the Waterkop syenite, providing strong evidence that they are coeval. The alternative calculation according to the CHUR model is believed to be less appropriate for these samples. As the Sm/Nd ratios are extremely low and a mantle source is well-established for carbonatites, the uncertainties on these ages can be no more than 200 Ma. Lacking an isochron age, 1930 Ma is the best estimate at present.

#### Mesoproterozoic (1600 – 1000 Ma)

No less than 14 occurrences (including 7 large volcanic and plutonic complexes) belong here. Most are situated on the Kaapvaal Craton, and were previously assigned to the Pilanesberg Alkaline Province (Ferguson, 1973). On a geochronological basis the Mesoproterozoic group is considerably more extensive than this.

#### Swartbooisdrif(4) and Epembe (5)

A swarm of sodalite-rich carbonatite dykes occurs near Swartbooisdrif on the Namibia/Angola border (Menge, 1986). They consist of banded ankerite, sodalite, analcite, cancrinite, albite, and magnetite as principal constituents, and were intruded along pre-existing lamprophyre and syenite dykes. The sodalite has been exploited as semi-precious stone.

At Epembe, 40 km southwest of Swartbooisdrif, a broad apatite-bearing sövite dyke cuts across an oblong body of nepheline syenite accompanied by several smaller syenite and nepheline syenite stocks (Menge, 1986; Ferguson *et al.*, 1975b). The sövite is 6.5 km long and up to 250 m wide. Minor constituents are biotite, K-feldspar, plagioclase, magnetite, epidote, aegirine, riebeckite, and a betafite-like mineral.

These two occurrences have been linked as belonging to one alkaline igneous province but there is considerable doubt about its age. SACS (1980) classified Epembe as Phanerozoic. This was challenged by Menge (1986) on the basis of preliminary U-Pb (zircon) and K-Ar (biotite) data pointing to a minimum age of 1100 Ma for the alkaline rocks. The carbonatites are therefore included here in the Mesoproterozoic group despite their isolated position and the fact that all the others are situated on the Kaapvaal Craton. It should be noted that composite syenite-carbonatite dykes with sodalite have also been described from across the border in Angola, and are genetically connected with the Lupongola carbonatite ring complex only about 25 km from Swartbooisdrif (Lapido-Loureiro, 1973). Lupongola has not been dated, but the Angolan volcanoplutonic complexes are

generally considered to be Cretaceous or younger similar to their Namibian counterparts. This is supported by Rb-Sr isochron ages of  $104.3 \pm 0.8$  Ma and  $130.8 \pm 1.4$  Ma for the Njoio and Tchivira nepheline syenites respectively (Allsopp & Hargraves, 1985).

#### *Stukpan (6)*

This is the most recently discovered carbonatite in South Africa, and is documented in an accompanying paper (Verwoerd *et al.*, 1993). It has a reliable Rb-Sr isochron age of  $1354 \pm 11$  Ma. It is conjectured to be a pipe-like sövite body of up to 3 km in diameter but only a small part has been reached by drilling. Since it is overlain by approximately 200 m of younger Karoo cover, one may well wonder how many other carbonatites lie similarly concealed.

#### *Spitskop (7)*

Spitskop is a classic alkaline ring complex composed of successive intrusions of pyroxenite ijolite, nepheline syenite, and carbonatite with attendant fenitization of inclusions and country rocks belonging to the Bushveld Complex. The most recent account is a comprehensive petrological and geochemical study by Harmer (1992; 1993), who gives  $1341 \pm 37$  Ma as a best estimate of age based on Rb-Sr whole rock analyses on 34 samples of ijolite and nepheline syenite. It is therefore a member (the easternmost one) of the Pilanesberg Alkaline Province.

The Spitskop Complex measures about 5 km in diameter and the carbonatite, which forms an eccentrically situated plug, has a diameter of 1.5 km. The carbonatite is compositionally composite. According to Verwoerd (1967a), coarse-grained sövite was progressively replaced from a central axis outward by increasingly magnesium- and iron-rich solutions to form first dolomite sövite and finally beforsite. Harmer's (1992) alternative interpretation is that magnesiocarbonatite magma mingled with and transformed portions of the earlier calciocarbonatites, producing a hybrid 'dolomitic sövite' zone in between. This author concludes that the carbonatite as a whole intruded passively and had a low content of volatiles, since there is no evidence of disruption or metasomatism of the silicate rocks with which it comes into sharp, smooth contact. Apatite-rich zones occur in the dolomite sövite and beforsite. Other minor constituents are magnetite, soda amphibole, aegirine, albite, phlogopite, ancylite, monazite, sphalerite, and pyrite.

Sr and Nd isotopic data differ markedly between the silicate and carbonatite components of the Spitskop Complex. These data are not compatible with models which derive carbonatites as late stage differentiates of a carbonated silicate magma or through liquid immiscibility from nephelinitic or phonolitic melts (Harmer 1992; 1993). It therefore seems likely that separate and distinct parent magmas were involved.

Prospecting for nepheline as a potential aluminium ore and limited production of agricultural lime have taken place at Spitskop (Verwoerd, 1986) but economic prospects are not encouraging.

#### *Magnet Heights (8)*

Verwoerd (1967a) and earlier writers described two carbo-

natite dykes and at least five small diatremes with a calcareous matrix at Magnet Heights 22.5 km north of Spitskop. Albitite, analcite picrite, and lamprophyre may belong here as well. SACS (1980) renamed this the 'Mogashoa Suite' to avoid confusion with the Magnet Heights granite of the Bushveld Complex. However, the name of the locality has not changed and a formal nomenclature hardly seems necessary for a few intrusions with such limited distribution that they are not mappable units on any reasonable scale; confusion is more likely between the Derdepoort carbonatite and the Derdepoort gabbro, named after two different localities with the same name.

One carbonatite dyke is about 30 cm wide and 1 km long; it is made up of dolomite, calcite, quartz, chlorite, apatite, sphalerite, pyrite, and barite (?). No new information is available and the occurrence is still tentatively regarded as a satellite of the Spitskop Complex.

#### *Derdepoort (9)*

The Derdepoort carbonatite is situated on the outskirts of Pretoria. It is a minor occurrence associated with a breccia pipe and forms part of the Pienaars River 'Complex' (SACS, 1980). It was described in detail by Verwoerd (1967a) who regarded it as a satellite of the Roodeplaat volcano, within the PR'C'. The carbonatite itself occupies an irregular area of about  $0.5 \times 0.25$  km<sup>2</sup> and is intrusive in quartzite and diabase. It consists of dolomite with subordinate chlorite, quartz, feldspar, amphibole, calcite, apatite, pyrite, and hematite. White, red, and chlorite-rich varieties have been distinguished. Harmer (1985a; 1985b) found Sr contents of 1049 and 4645 ppm in two samples and determined the Sr isotopic composition of the carbonatite magma at its time of emplacement as between 0.70325 and 0.70366 which is identical with that of associated trachyandesitic lavas.

#### *Welgevonden (10)*

The discovery of a new carbonatite on the farm Welgevonden 131 JQ in the Rustenburg district is mentioned in an internal report of Anglo American Corporation dated 4-3-1969. Several low ridges consist of red fenite traversed by beforsite dykes. They partly adjoin a soil-covered depression 1–2 km in diameter which may conceal a carbonatite or related plug-like intrusion (Figure 4B). The locality is 10.5 km south-southwest of the very similar occurrence on Bulhoek (south) and in line with Bulhoekkop and Kruidfontein; this lineament diverges slightly from another prominent N-S alignment of related complexes (Figure 4A). On the 1:250 000 Geological Survey map 2526 Rustenburg (1981) it is shown as fenite surrounded by granophyre of the Rashoop suite within the Nebo granite, but no carbonatite is indicated. Thirteen samples were analyzed for Nb, La, U, and P by Anglo American Research Laboratory. Individual values of interest are 149 ppm Nb, 2370 ppm La, and 4.59% P<sub>2</sub>O<sub>5</sub> but the averages are lower: 44 ppm Nb, 494 ppm La, and 0.71% P<sub>2</sub>O<sub>5</sub>.

#### *Bulhoekkop (11)*

Bulhoekkop is a prominent (260 m) hill near the Tweerivier Complex; it represents an eroded carbonatite vent, the

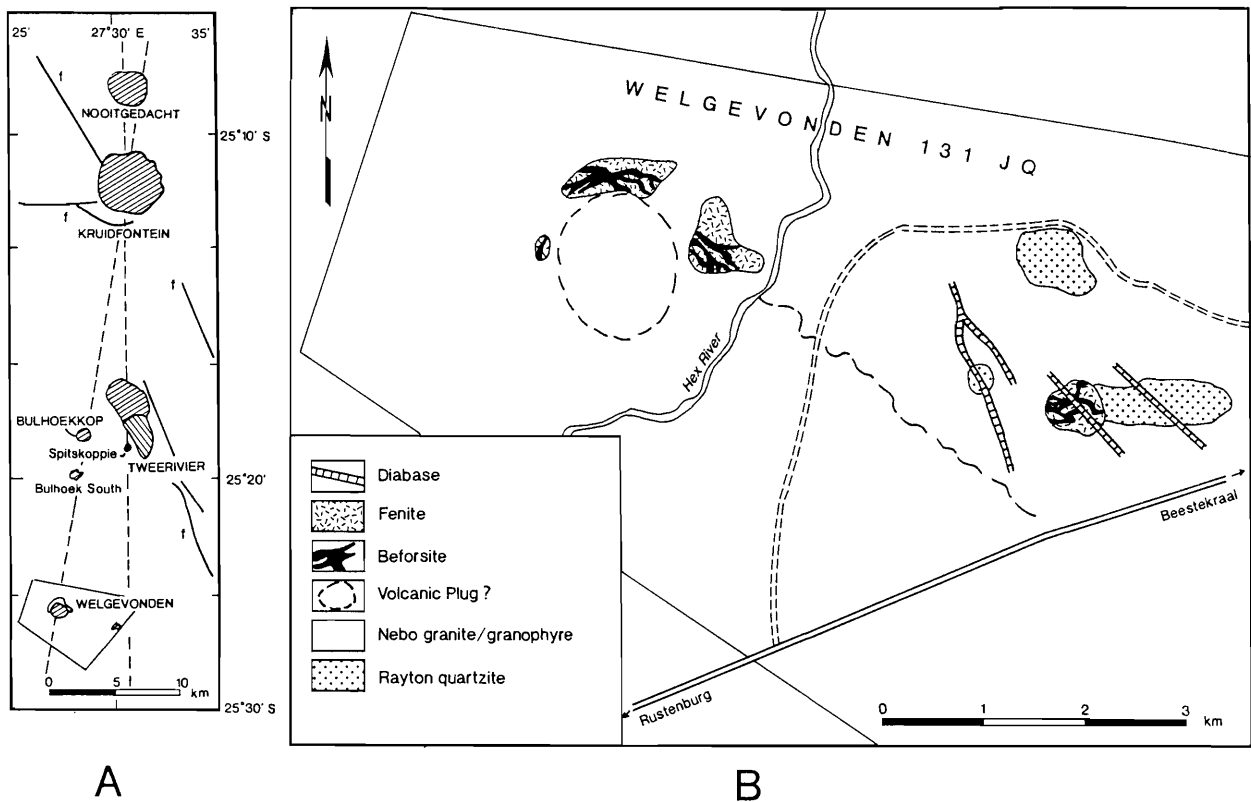


Figure 4A North-south and N10°E alignments of carbonatite centres east of Pilanesberg. Note also N30°W orientation of prominent faults. B Geological sketch map of Welgevonden carbonatite.

largest of three such occurrences grouped together here. The others are: 1) Spitskoppie, a circular diatreme containing granite and subordinate beforsite clasts; and 2) Bulhoek South, an irregular body similar to Bulhoekkop but only mapped schematically to date (Verwoerd, 1967a). The essential features of Bulhoekkop are poorly exposed volcanic breccia, brick-red fenitized Nebo granite and spectacular apatite-rich beforsite intrusions with drawn-out xenoliths. The breccia clasts are mostly derived from Bushveld gabbro which underlies the country rock granite in this area. The volcanic activity responsible for these vents probably corresponds to the last phase of the Tweerivier Complex.

#### *Tweerivier (12)*

This is a 'twin complex' named after the farm which straddles the confluence of two rivers, the Elands and Crocodile. It was mapped and described by Verwoerd (1967a) and no further work was done since then.

Tweerivier North has a concentric structure and aureole of fenitized Nebo granite. Undoubted carbonatite occurs on its northern boundary as a network of apatite-bearing ankeritic beforsite dykes. The rest of the oval-shaped body with its longer diameter of 3.5 km consists of various dolomitic rock types with tremolite. Large xenoliths of quartzite, hornfels, and metamorphosed banded iron formation, presumably derived from the floor of the Bushveld Complex, have been engulfed by the carbonate rocks.

Tweerivier South is an adjacent younger 'megabreccia' body consisting of Bushveld gabbro and anorthosite elevated to a higher level by the intrusion of sövite magma.

The sövite is characterized by the presence of magnetite, apatite, phlogopite, baddeleyite, olivine, and pyrite as accessories. Near the centre of the body which measures 3.5 × 1.8 km, there is a radioactive silicified zone.

Previous authors interpreted the tremolite-bearing dolomites of Tweerivier North as metamorphic and Verwoerd (1967a) recognized the possibility that this part of the complex could be 'hybrid'. More detailed investigations are called for in order to solve this problem.

Geological considerations led Verwoerd (1967a) to suppose that Tweerivier might be Triassic to Jurassic in age, but although reliable geochronological data are still lacking, it is now considered much more plausible that it belongs to the 1200 – 1400 Ma Pilanesberg group. Verwoerd *et al.* (1993) give an 'errorchron' estimate of 1269 ± 171 Ma for pooled data from five Western Transvaal carbonatite complexes which include Tweerivier and Nooitgedacht (Harmer, 1993).

#### *Kruidfontein (13)*

The complex has attracted more exploration activity and scientific attention since 1967 than any other South African carbonatite. It is a remarkable occurrence in at least two respects: 1) despite a Sm-Nd model age of 1246 Ma (Harmer, 1993), the volcanic superstructure has been comparatively little eroded; it was exhumed in post-Karoo time; 2) the volcanism exhibits two contrasting trends, one starting with basalt through intermediate compositions to rhyolite, and the other leading to carbonatite and fluorite mineralization, both sequences apparently erupted from the same conduit but not the same source.

The Kruidfontein volcanic complex is circular and 5 km

in diameter. It consists of an outer ring of overlapping volcanic breccias, minor sedimentary units, welded tuff, and lava flows of various compositions; the geochemical evolution of this silicate phase still awaits proper investigation. Within the outer zone is a 3 km-wide concentric sequence of bedded and massive carbonate rocks, generally agreed to have been deposited in a crater lake formed by caldera collapse. These rocks now consist of calcite, ankerite, K-feldspar, and chlorite with accessory fluorite, barite, apatite, anatase, pyrite, and quartz. Megascopic oolitic and pseudomorphic structures are prevalent. By analogy with Goudini, Verwoerd (1967a) argued that two waves of carbonatization (metasomatic replacement) of the tuffaceous sediments took place after deposition to form metasövite first and metabeforsite afterwards. Later authors (Clarke & Le Bas, 1990; Clarke *et al.* in press; Pirajno, 1992) think that carbonatitic ash deposits were erupted and subsequently affected by K-metasomatism. The geological map (Verwoerd, 1967a) remained essentially unchanged except for the addition of an orthoclase (K-fenite) lens and numerous faults of doubtful validity (Crocker *et al.*, 1988; Clarke *et al.*, in press).

As a result of prospecting, minor plugs and dykes of sövite, in addition to irregular intrusions previously described, were found to have intruded the metacarbonatites. These intrusions show magmatic characteristics (e.g. flow banding) and have an average content of 15 – 20% fluorite. They are considered by some to be the source of the penetrative carbonatization, as well as extensive secondary fluorite mineralization by replacement, which forms a halo in the adjoining metacarbonatites. Some of this replacement ore is stratabound, tabular, and extends semi-continuously for 3 – 4 km on strike. Between 1970 and 1982 two prospecting companies (Metallgesellschaft A.G. and Southern Sphere (Pty.) Ltd.) have established a reserve of about 200 000 t fluorite in the southern part of the metabeforsite zone (Crocker *et al.*, 1988). Soil sampling showed that geochemical anomalies for Cu, Pb, Zn, Ni, and Mo (of which Zn is the highest) also coincide with the carbonate rocks (Verwoerd, 1986). More recently, FOSKOR instituted a gold exploration programme on Kruidfontein. Inclusions of native gold, 1 – 8 microns in size were found in barite, Fe oxides, fluorite, and Y-bearing minerals (Pirajno, 1992). Gold enrichment reaches concentrations of up to 3.8 g/t in the weathered profile of the carbonate rocks and is associated with the breakdown of disseminated sulphides; it is thought to be supergene, not detrital (Pirajno & Winter, in press).

Some of the results of a Ph.D. study on the carbonatites and carbonatitic tuffs of Kruidfontein have been published by Clarke & Le Bas (1990) and Clarke *et al.* (in press). In addition to the minerals already mentioned, they identified synchisite and parisite in association with the fluorite. From a meticulous electron microprobe study of a minute (1 mm) pumice fragment showing a banded alternation of devitrified phonolitic, nephelinitic, and carbonatitic glasses, Clarke & Le Bas (1990) concluded that three, perhaps four, immiscible liquids were involved in the petrogenesis of the Kruidfontein Complex. Clarke *et al.* (in press) distinguished three types of magmatic carbonatite (sövite, alvikite, and fluorite-rich carbonatite) which, on the basis of trace and rare earth element ratios, are shown to be related by chemical frac-

tionation even though no intrusive sequence is evident. The metasövite of Verwoerd (1967a) is interpreted by them as recrystallized carbonatitic bedded tuff, which was simultaneously feldspathized (i.e. fenitized) and ankeritized to form the metabeforsite. Subsequently, extensive fluoritization of the tuff was caused by late-stage fluids. Oxygen and carbon isotope ratios indicate that there was a variable influx of ground water during all the secondary processes. The original magmatic geochemical characteristics can, however, still be recognized by trace element signatures.

A geochemical investigation of Kruidfontein rocks with the emphasis on REE distribution is currently underway by L.W. Schürmann of the Geological Survey.

#### *Nooitgedacht (14)*

This is a poorly exposed sövite plug about 3 km in diameter, with subordinate quartz-ankerite sövite, beforite, nepheline syenite, and microjelite. Aegirine-augite fenite and fenitized quartzite are also prominent. Apatite, magnetite, pyrochlore, monazite, phlogopite, pyrite (Verwoerd, 1967a), and clinohumite (Clarke *et al.*, in press) occur in the carbonatites.

Nooitgedacht is situated only 4.8 km north of Kruidfontein and Clarke *et al.* (in press) assume an intimate genetic connection between the two. These authors provide major, trace element, and stable isotope analyses of two sövite samples from Nooitgedacht. In view of the strong contrast in level of exposure (plutonic versus volcanic), Verwoerd (1967a) surmised that Nooitgedacht might be similar in age to Shawa in Zimbabwe (c. 200 Ma), but this is no longer tenable in the light of Harmer's Sm-Nd results (Harmer, 1993; Verwoerd *et al.*, 1993, Table 2) (cf. note on the age of Tweerivier above). It undoubtedly belongs to the Mesoproterozoic group although its relationship with Kruidfontein remains unclear.

Walraven (1981) renamed this complex 'Gelukshoek Carbonatite', without giving reasons, but presumably because SACS approved 'Nooitgedacht Member' as a lithostratigraphic subdivision of the Kango Group.

#### *Goudini (15)*

Verwoerd (1967a) described the Goudini volcano (or 'Yster-varkkop Carbonatite Complex' according to SACS, 1980) as a re-excavated Proterozoic maar with an outer ring of pyroclastic breccia and a crater-fill of indurated volcanoclastic sediments, varve-like tuff, intercalated calcite-rich layers, lava, and an ankeritic rock type (metabeforsite) formed by metasomatic replacement. A swarm of cross-cutting sövite dykes up to 1 m thick emanated from the metabeforsite area. Other evidence of carbonatitic affinity is fenitization of country rock norite and Na, Ti, Ba, Th, and REE enrichment. Of particular interest is the preservation of undoubted pillow structure in some of the carbonatized lava of the crater fill.

The complex has a roughly oval outline measuring 6 km north-south and 4.5 km east-west. Biesheuvel (1970) showed that it is marked by a negative gravity anomaly superimposed on a gravity high caused by the adjacent chromite-bearing Marico Bushveld lopolith which is 33 × 15 km in size. This implies that the Goudini eruption took

place above the deepest portion of the lopolith and may have utilized the same conduit. A Mesoproterozoic emplacement age for Goudini has been confirmed by Nelson *et al.* (1988) who obtained a Sm-Nd date of  $1190 \pm 80$  Ma and a similar but less precise Pb-Pb figure of  $1110 \pm 300$  Ma.

The southern part of the breccia ring (which has been interpreted as the remnant of a blanket deposit rather than a vertical pipe) contains exotic blocks of augite, magnetite, perovskite, and schorlomite-bearing rock that cannot be matched with any known outcrops. This problem was resolved, at least in part, when Falconbridge Explorations Ltd. drilled into a gravimetric/magnetometric anomaly on the farm Roodekopjesput immediately to the southwest of Goudini during 1977. The gravity peak covers an area of some 300 m<sup>2</sup> and is situated approximately 800 m west of the volcano rim. Borehole RK1 was sited close to the centre of the gravity anomaly. It intersected clinopyroxenite differing markedly from the bronzitites of the Bushveld Complex under a thin soil cover. The main constituent is titanite with variable amounts of hornblende, magnetite, ilmenite, melanite, biotite, apatite, and titanite. The pyroxenite is cut by minor intrusions of nepheline syenite and carbonatite but no ijolite was encountered. It is almost certainly related to the Goudini volcano and is shown as a substantial plug on a recent geological map of the area (Engelbrecht, 1990).

The crater fill at Goudini differs from that of Kruidfontein in several respects: an extensive area of bedded tuff escaped carbonatization, lava flows are intercalated with the sediments, and the metabasite consists of ankerite, albite, and aegirine to the exclusion of K-feldspar; accessories are rutile, biotite, sodahornblende, ramsayite, leucosene, calcite, fluorite, and barite. According to Verwoerd (1967a) the first stage of carbonatization was selective (metasövite layers along certain horizons) whereas the second stage was pervasive (the whole northwestern sector of the basin). However, the possibility that the calcite-rich layers represent recrystallized carbonatitic ash and that the gradational and interdigitating relationships have a sedimentary facies origin should be reconsidered.

Evidence that the original composition of the lava at Goudini was phonolitic nephelinitic will be published elsewhere.

The most promising mineralized portion of the Goudini volcano is in the vicinity of the farmyard just south of Goudinikop. A radioactive anomaly, barite veins, a silicified zone, and relatively coarse-grained sövite have been mapped here. During 1987/88 intensive geochemical exploration, trenching, and shallow drilling were carried out in this area by Anglo American Exploration Ltd.. As a result, a circular yttrium anomaly (two to five times background) was delineated and is considered to overlie a pipe-like zone of hydrothermal alteration. Satellite imagery utilizing a clay-iron prediction showed the alteration zone clearly but ground magnetometry and radiometrics were less successful. Yttrium and the heavy rare earths were found to occur mainly in carbonate minerals and in thorianite. Monazite is rare and a number of secondary rare earth carbonates (ancylite, burbankite or donnayite, synchisite, and doverite) were tentatively identified. Substantial decoupling of the light and heavy REE is indicated, with extreme HREE

enrichment compared to normal carbonatite values (Adrian *et al.*, 1989).

#### *Glover (16)*

This is an oval-shaped pyroxenite-carbonatite body, 4.7 and 3.5 km in diameter, which is poorly exposed. A borehole drilled in the northwestern quadrant by the Geological Survey in 1981 intersected biotite pyroxenite and carbonatite as expected. Coarse-grained sövite and magnesiocarbonatite contain apatite, magnetite, phlogopite, pyrochlore and late-stage quartz, synchisite, fluorite, barite, monazite, and columbite. The monazite provided an imprecise minimum age of  $1000 \pm 200$  Ma (Verwoerd, 1967a) but modern trace element and isotope studies have not been done. Verwoerd (1986) summarized more recent developments especially with regard to the interpretation and mining (from 1962 to 1983) of the secondary phosphate deposit near the centre of the complex.

#### *Premier Mine (17)*

Calcite-rich dykes in the Premier diamond mine have been described as carbonatite as long ago as 1925 (Daly, 1925). Since then the question whether or not minor carbonate-rich intrusions and segregations closely associated with kimberlite are carbonatite has been extensively debated. The author concurs with the views of Mitchell (1986) that in a modern mineralogical-genetic classification antecedents and co-magmatic rocks must be taken into account, and that characteristic isotope and trace element signatures indicate a common mantle origin but not necessarily a genetic relationship.

The Premier mine kimberlite has long been known to be Mesoproterozoic in age. The best available isochron figures are the virtually identical Rb-Sr and Sm-Nd ages of  $1180 \pm 30$  Ma obtained from diopside and garnet megacrysts and from mica in the nearby National kimberlite (Richardson, 1986; Jones, 1987). This date is towards the end of the protracted igneous event responsible for the so-called Pienars River Alkaline Complex (Harmer, 1985). In contrast with other kimberlites of southern Africa, the Premier mine cluster therefore belongs to a province (the Pilanesberg Province) dominated by undersaturated alkaline complexes and carbonatite. Thus, at least some justification exists for linking the Premier mine dykes to carbonatite, although the genetic connection with kimberlite seems to be closer (Robinson, 1975).

#### *Bulls Run (18)*

Scogings & Forster (1989) and Scogings (1991) first described gneissose carbonatite from the northern marginal zone of the c. 1100 Ma Namaqua-Natal mobile belt in Natal. The carbonatite is a minor component of the metamorphosed Bulls Run Complex which is 15 km long and 1.5 km wide, consisting of muscovite syenite gneiss, nepheline syenite gneiss, and albite syenite gneiss. The carbonatite gneiss occurs in the form of steep-dipping bodies up to 200 m long and 10 m wide, with xenoliths of the host muscovite syenite gneiss; they are therefore considered to be intrusive dykes that were subsequently involved in the regional metamorphism. At one of three localities the carbo-

natite forms pods and veins. The nepheline syenite gneiss yielded a Rb-Sr age of  $1138 \pm 45$  Ma for the complex.

The Bulls Run carbonatite is a sövite consisting of calcite, microcline, albite, biotite, and apatite with accessory pyrochlore, ilmenite, zircon, pyrite, and muscovite. Zircon crystals reach exceptional sizes of up to 1 cm. Apatite generally comprises up to 5 (exceptionally 10) modal per cent. Trace element content is typical of sövites e.g. 5700 – 9100 ppm Sr, 80 – 900 ppm Ba, 500 – 700 ppm Ce, 50 – 100 ppm Y, and 50 – 4000 ppm Nb.

This discovery extends the boundaries of the Mesoproterozoic group of carbonatites much further to the southeast than previously supposed, beyond the Kaapvaal Craton.

Neoproterozoic (1000 – 570 Ma) to Cambrian (570 – 510 Ma)

#### *Lofdal (19)*

A large swarm of north-east-trending carbonatite dykes (Miller, 1983a) is associated with the Lofdal nepheline syenite complex west of Khorixas near the northern edge of the Damara mobile belt in Namibia. Other associated intrusive rocks are gabbro, peridotite anorthosite, syenite, and quartz-feldspar porphyry. The carbonatite carries abundant fluorite in places and contains up to 180 ppm Th, 260 ppm W, and 1500 ppm Zn while up to 460 ppm Nb is recorded in the nepheline syenite (Miller, 1983b). Hawkesworth *et al.* (1983) obtained a reasonable Rb-Sr whole-rock isochron age of  $764 \pm 60$  Ma for the nepheline syenite. Although exposed within pre-Damara basement and thus not in contact with any Damara rocks, the Lofdal intrusions therefore belong to the earliest magmatic event (eruption of the Naauwpoort volcanics) in the deposition of the Damara succession; they are pre-orogenic and related to an intracontinental rift environment.

#### *Otjisazu (20)*

This major carbonatite complex was first recognized by R.J. Gunthorpe in 1976 and subsequently prospected for copper and phosphate by Tsumeb Corporation Ltd. (Gunthorpe & Buerger, 1986). It is situated 20 km east-northeast of Okahandja in Namibia, near the southern boundary of the highly deformed central zone of the Damara orogen. It has not been dated isotopically but can be bracketed rather closely on geological grounds. It is younger than the syntectonic granites of the major phase of deformation (550 Ma) and is cut by pegmatites inferred to belong to the Donkerhuk granite (523 Ma, Miller, 1983a).

The complex is elongated and approximately 12 km<sup>2</sup> in surface area. A core of sövite is surrounded by alkali pyroxenite and subordinate ijolitic and gabbroic rocks, all of which are intruded by leucocratic syenite and syenite pegmatite. The pyroxenite consists of aegirine-augite with subordinate K-feldspar, garnet, melanite?, apatite, titanite, calcite, and accessory monazite. The sövite has a complex megabreccia-like structure. It is locally rich in aegirine-augite, garnet, and apatite and contains xenoliths of schistose garnet-wollastonite rock. Apatite concentrations associated with traces of Cu sulphides are localized within both pyroxenite and sövite. Large tonnages of ore with an average grade of 3 to 5 per cent P<sub>2</sub>O<sub>5</sub> have been established.

The highest copper assay recorded in a drill core was 1670 ppm with averages in the range 200 – 600 ppm. It is interesting that the pyroxenite and sövite are both titanite-rich but devoid of magnetite, perhaps indicating crystallization under iron-poor reducing conditions. Large titanite and apatite crystals are especially notable in sheet-like mafic pegmatoids which are confined to the sövite and alkali pyroxenite as a late phase. Finitization of the surrounding pelitic and semi-pelitic schists of the Swakop Group is very limited.

#### *Eureka (21)*

Eureka is approximately 6.5 km north-northwest of Ebony siding on the Usakos-Swakopmund railway line, Namibia. Previous differences of opinion whether this famous monazite locality is related to marble, skarn, or carbonatite (Verwoerd, 1967a) have now been resolved through a Ph.D. study by T. Dunai (Dunai *et al.*, 1989; Ziegler & Dunai, 1991).

Low Th, high Ce monazite varying from minute rounded grains to platy aggregates up to 13 cm in length occur in several medium- to coarse-grained beforosite dykes with an average thickness of 1 – 2 m (maximum 7 m). The dykes intrude feldspathic quartzites interfingering with calc-silicate layers of the Nosib Group, and are intersected in turn by a tourmaline-bearing pegmatite of late Pan-African age. This leads to the conclusion that the Eureka carbonatites were emplaced at a time between 450 and 500 Ma. Selvedges of orthoclase up to 20 cm thick are interpreted as the result of finitization. A Sr-isotope study of four carefully selected carbonatite samples yielded a Sr content of 2.46 to 3.06 per cent Sr and initial <sup>87</sup>Sr/<sup>86</sup>Sr in the range 0,70286 – 0,70318. Nd isotope ratios have also been determined.

#### *Marinkas Quellen (22)*

Situated in a desolate part of southern Namibia, this important carbonatite complex was completely unknown until its discovery by H.J. Blignault in 1972. Geologist U.H. Schiefer and students K. Strauss and C. van Niekerk mapped it for Rio Tinto Exploration (Pty.) Ltd. between November 1972 and March 1973 (R. Cooke, pers. comm., 1976). It was indicated on the regional geological map of Blignault (1977) and briefly mentioned as a member of the Kuboos-Bremen line of intrusives (Figure 5) by Kröner & Blignault (1976), without description. The author paid a brief visit in 1976. Subsequent prospecting activity by Johannesburg Consolidated Investment Company Ltd. led to the recognition of uneconomic Mo, Pb, Zn, Cu fluorite porphyry-type mineralization in an adjacent alkali feldspar granite pluton (Killick & Odell, 1980; Bernasconi, 1981; 1986). The carbonatite complex was remapped by R.E. Schommarz for the Department of Economic Affairs of Namibia in 1988 and a Ph.D. thesis which included the petrology and geochemistry of the carbonatites was completed by R.H. Smithies in 1991 (Smithies & Marsh, 1992).

Some confusion exists about the spelling of the locality name. The definitive version adopted here is from South African 1:50 000 topographic sheet 2817 AB which extends across the border into Namibia. Historically it refers to the wells of the Bondelswart chief Jakob Morenga († 1907).



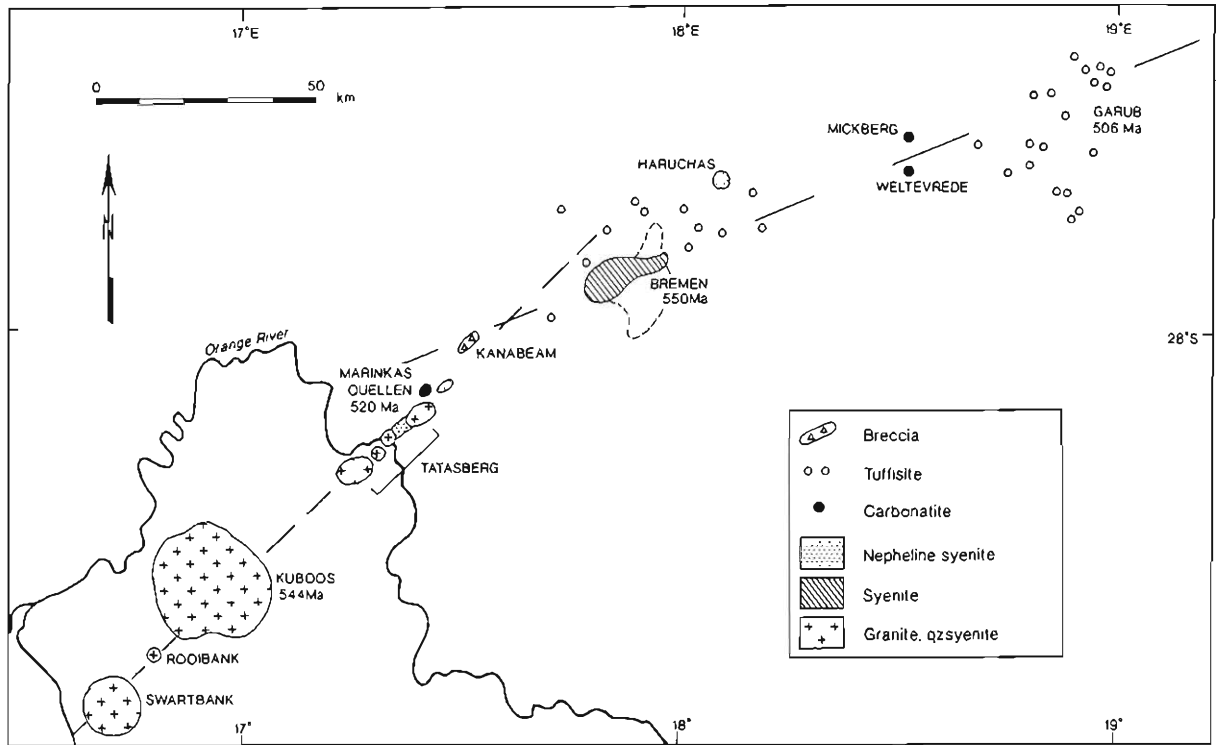


Figure 5 Kuboos-Bremen and Bremen-Garub lines of intrusions near the Orange River mouth.

Unfortunately the name has been further corrupted in the geological literature to 'Marinkas Kwela', apparently as a result of unfamiliarity with German.

The main body of carbonatite is a circular plug, 600 m in diameter, that crops out as a prominent brown peak more or less devoid of vegetation (Figure 6). A second arcuate body occurs to the northeast and sends off numerous dyke-like apophyses into the country rock and associated nepheline syenite (Figure 7B). A third carbonatite occurrence is shown further south on the map (Figure 7A) but this needs confirmation because it does not appear on text figures published later. There is also uncertainty about the extent of the nepheline syenite and of the fenitized aureole.

Smithies & Marsh (1992) give the order of emplacement as: 1) nepheline syenite, 2) sövite, 3) beforosite, 4) ferro-carbonatite (a small plug within the eastern beforosite), and 5) manganiferous carbonatite dykes. Geochemically the carbonatites appear to be depleted in most trace elements in a world-wide comparison, but the sövites are relatively enriched in HREE, the eastern beforosite in Nb and possibly HREE, and the manganiferous dykes in Zn. The latter are also high in Fe, Y, REE, and Th but not Nb, and are considered to represent highly evolved liquids. Minerals that have been identified in the carbonatites are aegirine-augite, ferro-richterite, perthite, chlorite, phlogopite, apatite, magnetite, pyrochlore, bastnaesite, synchisite, pyrite, sphalerite, galena, and fluorite.

The Marinkas Quellen Complex has not been dated but it seems to be intimately associated with members of the Kuboos-Bremen Province, notably the Tatasberg Complex. Three of these intrusions have been dated with varying reliability by both the U-Pb and Rb-Sr methods and they fall within the interval 550–490 Ma (Allsopp *et al.*, 1979). However, the possibility that the association is merely struc-

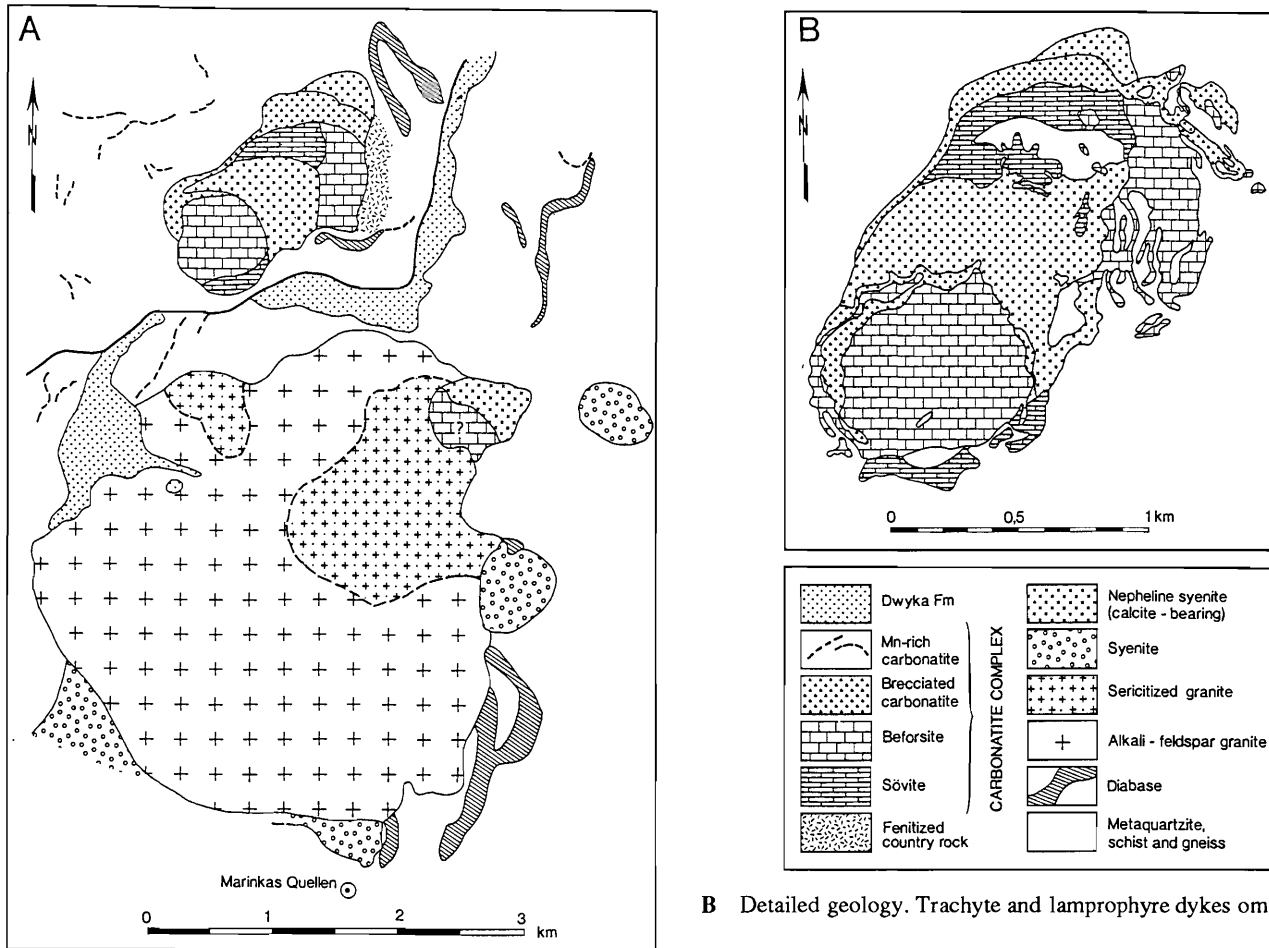
turally controlled and that Marinkas Quellen belongs to the younger group together with Dicker Willem should not be ignored.

#### Mickberg (23)

This carbonatite was first described by C.P. Schreuder (1975). Mickberg on the farm Mickberg 262, 20 km northeast of Grünau in southern Namibia is a double-crested hill, elongated in a north-northeasterly direction and rising about 100 m above the surrounding plain (Figure 8). It is built of gneiss that is brecciated in places and intruded by irregular bodies of dark brown ankeritic beforosite (Figure 9). Inclusions of gneiss, grit, and quartzite of the Kuibis Formation are embedded in the carbonatite. Some fragments of quartzite are light-blue in colour as a result of fenitization. The interlocking grains of quartz are seen under



Figure 6 Marinkas Quellen carbonatite as seen from the south.

**Figure 7** Marinkas Quellen Complex, based on mapping by Rio Tinto Exploration Pty. Ltd. in 1972/1973.**B** Detailed geology. Trachyte and lamprophyre dykes omitted.

**A** Regional geology. Porphyry-type sericitic alteration zones in granite after Bernasconi (1986).

the microscope to be replaced by tufts of crossite and a mosaic of new feldspar (microcline-perthite and albite/oligoclase). Blue soda amphibole also occurs in carbonatite north of the hill top. The main constituents of the carbonatite are ankerite (euhedral and anhedral), ferroan calcite, apatite, magnetite, biotite, and chlorite, as well as zircon, quartz, and feldspar derived from the surrounding gneiss. Insignificant amounts of malachite and chrysocolla occur at the southern tip of the composite plug.

A remarkable feature of the largest carbonatite body is the presence in places of spheroidal inclusions up to 15 cm in diameter (Figure 10). They consist of concentric shells made of fine-grained ankerite and angular fragments around a lithic nucleus that may vary from 1 to 7 cm in diameter. Between these 'balls' there is often a medium-grained silica-rich matrix consisting of quartz, microcline, and albite in a mosaic texture. The only explanation that can be offered at present is accretion in a fluidized vent.

#### Weltevrede (24)

On the farm Weltevrede 302 adjacent to Mickberg 262 there are two breccia plugs forming low rounded hills in a sandy flat. The northernmost one (Figure 11) measures 1 km in diameter, with several smaller subsidiary outcrops, and

consists of gneissic country rock fragments set in a gritty matrix with variable brown-weathering carbonate content. Beforsite dykes cut across the breccia and its boundary, and are also full of clasts. The second occurrence is similar with less ankeritic carbonate in the matrix. Several blocks of Kuibis quartzite and conglomerate, metres in diameter, are found in the breccia below the projected stratigraphic level where this formation used to be present. This plug is also associated with beforsite veins and a calcitic dyke up to 2 m wide that follows a zig-zag course along strike of the foliation in the country rock. At its southern extremity the carbonatite dyke contains sporadic galena, chalcopyrite, limonite, malachite, chrysocolla, and quartz (Schreuder, 1975, and personal observations).

#### Garub (25)

The farm Garub 266 in the Great Karas Mountains, Namibia, is the type locality for a series of ankeritic diatremes, dykes, and sills that are now known to extend over an area of 3000 km<sup>2</sup> towards the Bremen and Haruchas Complexes. Verwoerd (1967a, and unpubl. rep.) mapped about 60 separate occurrences and designated them as 'carbonatites of doubtful status'. A subsequent field and laboratory investigation was carried out by C.P. Schreuder (1975). He identified approximately 100 occurrences and studied 82 of them. The majority (65%) are intrusive into the Schwarzrand Formation of the Nama Group, 41% are in the form of sills, and 25% occur as pipe-like bodies.



Figure 8 Mickberg as seen from the south.

Figure 10 Spheroidal structures consisting of nuclei of gneiss surrounded by concentric layers of carbonatite, dust, and carbonatized fragments. Mickberg carbonatite.

Most of the diatremes and some of the dykes are filled with coarse breccia. The nature of the clasts proves that they were carried both upward and downward in the pipes. Some breccia clasts are well-rounded. In addition, accretionary lapilli and other spherical bodies 5 – 10 mm in size are common in many dykes, pipes, and sills, giving rise to 'pisolitic structure'. The groundmass and the pisoliths consist of medium-grained ankerite and subordinate calcite, chlorite, biotite, albite, and Fe-hydrates. Veinlets of non-dilatational type with similar composition penetrate the country-rock.

Evidence for a relationship with carbonatite is somewhat equivocal. Most sills and dykes consist at least in part of a relatively homogeneous, greenish-grey rock type with

10 – 20% CO<sub>2</sub> and about 25% SiO<sub>2</sub>. Under the microscope both phenocrysts and microcrysts of biotite, augite, kaersutitic hornblende, and ilmenite are seen in a matrix of ankerite. Carbonatized lath-shaped pseudomorphs (original melilite or feldspar?) are common. Irregular ferruginous patches may represent large olivines. Minor constituents are apatite, zircon, magnetite, leucoxene, pyrite, garnet, and quartz. On major element variation diagrams the Garub rocks do not coincide with South African olivine-melilitites or kimberlites. Trace elements (Ba, Sr, Nb, Zr, Y, and Rb) are low and do not show clear geochemical similarities with either carbonatite or kimberlite. Apart from their high carbonate content, they do show a similarity with alnöite. However, in the course of their geochronological work Allsopp *et al.* (1979) noted that the high Sr content (>1000 ppm) of their whole-rock sample from one of the

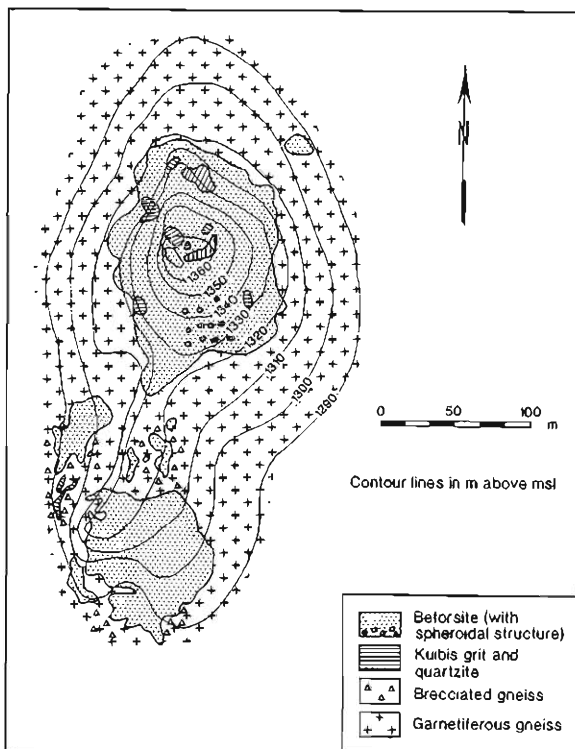


Figure 9 Geological map of Mickberg carbonatite after Schreuder (1975).

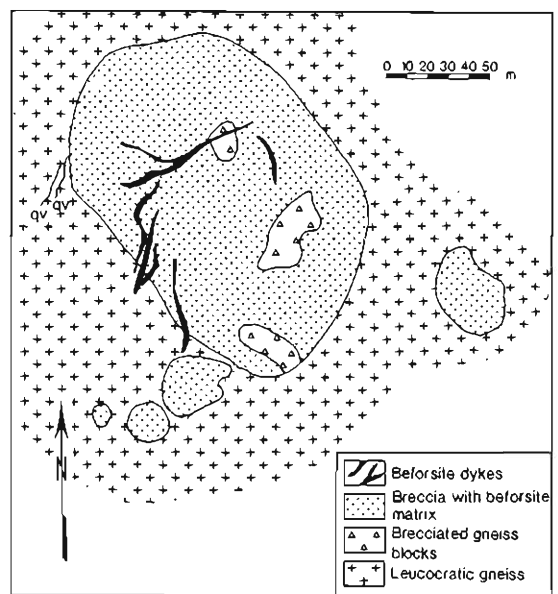


Figure 11 Geological map of the northernmost of two carbonatite-bearing breccia pipes on Weltevrede near Grünau after Schreuder (1975).

sills supported a carbonatitic affinity. They also found that the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of *c.* 0.708 is unusually high for carbonatite and, in view of the high Sr content, cannot have been seriously altered by contamination or internal isotopic rehomogenization. A carbonatitic origin is favoured with the observation of fenitization effects at two localities (replacement of quartz in the wall-rock by blue amphibole plus K-feldspar).

The age of the Garub eruptives is not well-constrained. According to Allsopp *et al.* (1979) the calculated Rb-Sr isochron age of  $491 \pm 8$  Ma, which they obtained from one whole rock and two impure (calcite-impregnated) biotite samples, should be interpreted as a minimum age for the emplacement of the sill. Likewise, their figures for the Nama Group, namely  $518 \pm 15$  Ma (definite) and  $553 \pm 13$  Ma (probable) are minimum ages. This implies that the Garub eruptives may perhaps post-date the rocks into which they were emplaced by approximately 50 million years, but that penecontemporaneity is not excluded. Such a possibility (namely that the Garub rocks are ancient peperites) was tentatively suggested by Verwoerd (1967a) but rejected by Schreuder (1975). It seems more likely that they belong to the alkaline magmatism of the Kuboos-Bremen line of intrusives. In view of many similarities, a detailed comparison of this field with the Miocene to Pleistocene Urach-Hegau-Kaiserstuhl volcanic district in Germany would be interesting.

#### Early Cretaceous (*c.* 130 Ma)

The next four localities are well-known in the geological literature (cf. earlier references in Verwoerd, 1967a). They are aligned along the east-northeast-trending Cape Cross lineament in Damaraland, northern Namibia, and are assumed to be of similar age to other volcanoplutonic complexes along this lineament that have been dated e.g. Messum (123 Ma) and Paresis (135 Ma). A geochronological study of Okorusu, Kalkfeld, and Ondurakorume by B. Müller at ETH, Zürich, is now in progress. Prins (1981) presented the results of a comparative geochemical investigation of the four carbonatites and their associated rocks.

#### Okorusu (26)

Okorusu is a poorly exposed ring complex 5 km  $\times$  6 km in diameter, consisting of syenite, nepheline syenite, and very subordinate carbonatite. The carbonatite occurs in the form of several isolated intrusions in the fenitized aureole but, according to Prins (1981), it occupies a larger area than previously thought. It is medium-grained sövite with apatite, aegirine-augite, pyrite, magnetite, celestite, quartz, and feldspar as accessory minerals. Trace elements (Sr, Ba, Y, Zr, Nb, La, Ce, and Nd) fall in the range typical of sövite, but Zr is rather low.

Two features of particular interest at Okorusu are: 1) the transformation of country rock quartzite and graywacke by pervasive metasomatism first to aegirine-augite fenite and afterwards to K-feldspar fenite; and 2) the widespread introduction of fluorite as replacements, veins, and disseminations. Ore reserves have been estimated at 7 – 10 Mt at a grade of  $> 35\%$   $\text{CaF}_2$  (Verwoerd, 1967a). After a lapse of 34

years fluorite mining at Okorusu was resumed in 1989; further particulars about the ore bodies are given by Notholt *et al.* (1990).

Prins (1981) found relatively low REE contents in the carbonatite and relatively high REE contents in the associated alkaline rocks compared to Kalkfeld and Ondurakorume. He suggested that the silicate magma at Okorusu retained large quantities of REE due to relatively high Na, F, and  $\text{CO}_2$  contents, whereas a more complete extraction of the REE into the carbonate liquid took place at Kalkfeld and Ondurakorume. Nevertheless, Okorusu presents several geological similarities to the world's largest REE deposit, Bayan Obo in China (Drew *et al.*, 1990). Both have extensive fluorite mineralization, Na- and K-metasomatism, magnetite ore bodies, and carbonatite. The possible existence of undiscovered niobium and rare-earth deposits at Okorusu should be tested by exploration.

#### Ondurakorume (27)

This is a composite intrusive carbonatite complex rising above the surrounding plain as a prominent inselberg. It is 1.4 km in diameter and sends dyke-like apophyses into the country rock of Damara marble, quartzite, schist, and granite. The only associated alkaline igneous rock is an adjacent plug of leucocratic nepheline syenite. The consecutive phases of intrusion are micaceous sövite, sövite, beforsite (in part apatite-rich), and REE-bearing riebeckite beforsite. This was followed by replacement bodies of radioactive hematite. The geological map (Verwoerd, 1967a) has been revised, one difference being the recognition of the REE-beforsite as a separate set of intrusions (Prins, 1981). Mineralogically, this late phase is characterized by a variety of carbonates (dolomite, calcite, pistomesite, strontianite, ancylite, carbocernaite) as well as riebeckite, pyrochlore, monazite, apatite, and cerianite. Ondurakorume has been considered to be a potential phosphate, niobium, rare earth, strontium, and thorium/uranium ore deposit (Verwoerd, 1986). The early micaceous sövites have the lowest Zr and highest Nb contents of the members of this complex, and there is a regular increase of Sr, Zr, Ce, and Ce/Y ratio with differentiation (Prins, 1981).

#### Kalkfeld (28)

The Kalkfeld Complex, about 15 km southwest of Ondurakorume, consists of a carbonatite plug followed outward by incomplete concentric rings of nepheline syenite, syenite, and fenite, accompanied by alkaline and subalkaline dykes. Prins (1981) and Verwoerd (1967a) consider associated granites to be part of the country rock. The complex is approximately 6 km in diameter and the carbonatite is oval with diameters of 2 km and 1.5 km. The carbonatite is a sövite with micaceous and apatite-rich zones. Accessory minerals are chlorite, albite, ankerite, apatite, pyrochlore, monazite, carbocernaite, barite, pyrite, and quartz. A replacement deposit of hematitic iron ore with a content of 0.5%  $\text{ThO}_2$  occurs in the centre of the carbonatite and was mined in the past (Verwoerd, 1967a). Prins (1981) found evidence of an Fe, Mg, Sr, Ba, and LREE enrichment trend in the Kalkfeld carbonatites, coupled with a decrease in Nb, Zr, and Y.

*Onsongombo (29)*

This occurrence is somewhat similar to Ondurakorume but much smaller (0.5 km). It differs in the relative importance of breccia (presumed to represent a volcanic level of exposure), which is intruded by beforite containing radioactive hematite ore. The beforite consists of manganiferous ankerite, apatite, quartz, feldspar, pyrochlore, rutile, calcite, and barite. Prins (1981) also analyzed sövite from Onsongombo and found that it is impoverished in Sr compared to the associated iron ore, but enriched in Nb, Zr, Ce, La, Nd, and Y.

*Kwaggaspan (30)*

Kwaggaspan is located at 15°15'E, 20°50'S, approximately 90 km west of Kalkfeld. It consists of several small plugs and associated calcite veins aligned along a 1.3 km long gently curving east-west oriented breccia zone in Kuiseb schist. The largest plug has a diameter of 150 m; it is mainly sövite associated with hematite. Green pyriboles in the schist may be the result of fenitization. The carbonatite is assumed to be of post-Karoo age (Miller, 1980).

*Karingarab (31)*

Not much is known about the carbonatite at this locality in the southern Namib, approximately 40 km northeast of Oranjemund. The author first heard about it at a Geological Society congress in 1979. Its age is uncertain but it may perhaps be linked to the carbonatite at Chameis 90 km distant.

*Chameis (32)*

Chameis (spelling adapted from the 1:1 000 000 geological map of SWA/Namibia, 1980) was described by Verwoerd (1967a) as a minor plug 100 m long and 50 m wide, 100 km northwest of Oranjemund. It is clearly intrusive in schist of the Gariiep Complex, but differs from the Tertiary carbonatites of the Luderitz area in composition and texture. It is therefore tentatively grouped with the great foyaite massif of the southern Namib called Granitberg (dated  $133 \pm 2$  Ma, Reid *et al.*, 1990) and with the early Cretaceous carbonatites of Damaraland.

It is a magnesiocarbonatite with miarolitic texture containing quartz, perthite, pyrite, zircon, rutile, amphibole, and biotite as accessories. No new information is available.

Late Cretaceous to early Tertiary (80 – 50 Ma)

*Brukkaros (33)*

Brukkaros Mountain is a prominent landmark 83 km north-northwest of Keetmanshoop, Namibia. Its 3 km-wide, crater-like aspect is the result of differential erosion, but geological investigations have shown that it was undoubtedly formed by explosive eruption. The absence of igneous material among the ejecta is striking. The best estimate of age is based on a K-Ar date of  $77 \pm 2$  Ma obtained from mica in the closely associated monticellite-bearing peridotite at Blue Hills (Reid *et al.*, 1990).

Brukkaros was described as a carbonatite volcano by Janse (1969) and as a kimberlite-carbonatite volcano by Ferguson *et al.* (1975a). The most recent geological map is

an unpublished one by M.J. Dodd and C.T.A. Hamman (in Miller & Reimold, 1987). The link with carbonatite is rather indirect: it rests on 1) numerous narrow carbonatite (beforsite) dykes that radiate from the mountain for distances of at least 90 km; 2) about 45 breccia-filled satellite vents with a carbonate matrix, sometimes closely associated with the dykes; 3) chemical and petrographic evidence of fenitization effects in the microbreccias and tuffs of the central crater; 4) late composite veins of dolomite, calcite, quartz, and barite in these sediments; and 5) the updoming and eventual rupturing of the surrounding strata which are indicative of a volatile-rich magma. The postulated relationship with kimberlite is equally tenuous: it is supported by 1) the Gibeon swarm of non-diamondiferous kimberlites and other ultramafic intrusions in the same general area and of the same age (Reid *et al.*, 1990); 2) pseudomorphic textures indicating that at least some of the radial dykes are carbonatized lamprophyres rather than carbonatites; and 3) enrichment of trace elements characteristic of both ultramafic and highly evolved magmas, in both microbreccias and dyke rocks, as in kimberlite. The conclusion seems justified that the distinctions between carbonatite magma and other mantle-derived volatile-rich magmas became blurred during the late Cretaceous magmatism in this craton-margin tectonic environment.

*Hatzium (34)*

The Hatzium dome 100 km almost due north of Brukkaros has been interpreted as a closely related cryptovolcanic structure 2.4 km in diameter (Heath & Toerien, 1962). Numerous small plugs and dykes of kimberlitic and carbonatitic affinity are known in the area. Consolidated Diamond Mines Ltd. drilled some boreholes here prior to 1988 but no further details are available; the core was stored at Kimberley.

*Grünau (35)*

According to Schreuder (1975) an oval-shaped pipe and two sinuous dykes of carbonatite were encountered on Grünau 16 in southern Namibia by G. Genis during a regional geological survey of the area in 1972. The pipe is about 30 m in diameter and consists of country rock fragments in a weathered matrix of calcite, apatite, and limonite. The dykes emanate from the pipe and extend for about 120 m to the southwest and northeast. This occurrence is not related to the Garub swarm, Mickberg, or Weltevrede to the northeast because it is post-Karoo in age: the carbonatite intrudes tillite, boulder shale, and limestone of the Dwyka Formation. A correlation with Brukkaros or Salpeterkop seems most likely.

*Bokiesbank (36)*

Haughton & Frommurze (1936) mentioned the existence of 'thin limestone veins, sometimes composite, cutting across the gneisses and amphibolites' on the farms Blydeverwacht 72, Hogeis 83, and Bokiesbank Ost 79 in the Warmbad district, southern Namibia. At the latter locality 'the veins are about 18 inches to 2 feet thick and are often bent and folded and sometimes broken by minor faulting. They are generally fine-grained but occasionally a coarse grain was

seen; where fine-grained they weather to a rusty brown, but the coarse-grained varieties remain grey. The veins are sometimes zoned, the central portion containing inclusions of angular feldspar, quartz, mica, and galena fragments.... On either side are narrow pegmatites with brick-red feldspars ... A thin section shows, set in a matrix of granular calcite, abundant large and small prisms of apatite, fragments of strained orthoclase showing secondary twinning, and a little limonite'. Elsewhere in the Warmbad district these authors described marble with garnet, quartz, apatite, and iron ores. Verwoerd (1967a) thought that, except for the folding, the brown-weathering veins resembled the ankeritic beforosite dykes of Brukkaros, but he never had the opportunity of visiting the locality. It was designated as a 'possible carbonatite of doubtful status'.

The existence of carbonatite dykes and dykelets on Bokiesbank can now be confirmed. Early in 1993 Dr. M.D. McMillan submitted a suite of samples to the author for investigation, including ankeritic beforosite from three 45 cm dykes near the Ariamsvlei road on Bokiesbank. Under the microscope the rock shows many of the features previously described in the Brukkaros dykes: pseudomorphs after olivine and biotite, scattered crystals of perovskite and magnetite, xenocrysts of K-feldspar and quartz, and chlorite intergrown with quartz and fluorite. Major and trace element analyses leave little doubt that the rock is a carbonatite (1810 ppm Sr, 328 ppm Ce, 223 ppm Zr, and 196 ppm Nb) but it is also enriched in the ultramafic indicator elements (281 ppm Cr and 206 ppm Ni).

In the vicinity of these dykes there are outcrops of granite and gneiss impregnated with calcite having no geochemical affinities with carbonatite. The analyzed specimen consists of 42% calcite, 33% albite (neglecting minimal anorthite), and 25% orthoclase with no quartz. From their description, Haughton & Frommurge (1936) obviously confused the two types of carbonate rock. The origin of the calcite-feldspar rock is problematic.

It must be concluded that there is either an undiscovered volcanic centre of similar type between Brukkaros and Salpeterkop, or the radiating swarm of Brukkaros dykes extends for 300 km southwards almost as far as the Orange River.

#### *Salpeterkop (37)*

Salpeterkop in the Sutherland district, Cape Province, has been identified as an eroded carbonatite volcano by De Wet (1975) and Verwoerd (1990). It has several features in common with Brukkaros (doming of the country rock, satellitic breccia plugs, crater remnant, radial carbonatite dykes) but is smaller. Associated rocks are intrusive K-trachyte and olivine melilitite. According to SACS (1980) the volcano is grouped together with other olivine melilitites and breccia plugs further afield into the so-called 'Sutherland Suite'. None of its members have been dated and they are only known to be younger than the Permian Teekloof Formation of the Beaufort Group penetrated by them. However, an age of the same order as Brukkaros ( $77 \pm 2$  Ma) is likely.

Carbonatite at Salpeterkop forms part of the southern rim of the crater and extends in the form of narrow dykes and

sills to a distance of at least 3 km from the volcanic centre. The carbonatite varies from sövite to ferruginous sövite with ankerite and hematite, biotite-sövite and alvikite. The following minerals have been identified in the carbonatites: calcite, dolomite, apatite, pyrochlore, biotite, zircon, hornblende, augite, K-feldspar, ilmenite, pyrite, and barite (De Wet, 1975). As a result of prospecting for niobium and other rare metals brookite, ilmenorutile, pyrophanite, molybdenite, aeschynite(?), eudialyte, yttrifluorite, xenotime, jarosite, graphite, goethite, magnetite, thorianite, thorite, and a trace of gold have also been found in deeply weathered borehole samples that include silicified magnetite-rich nepheline syenite (Verwoerd, 1986).

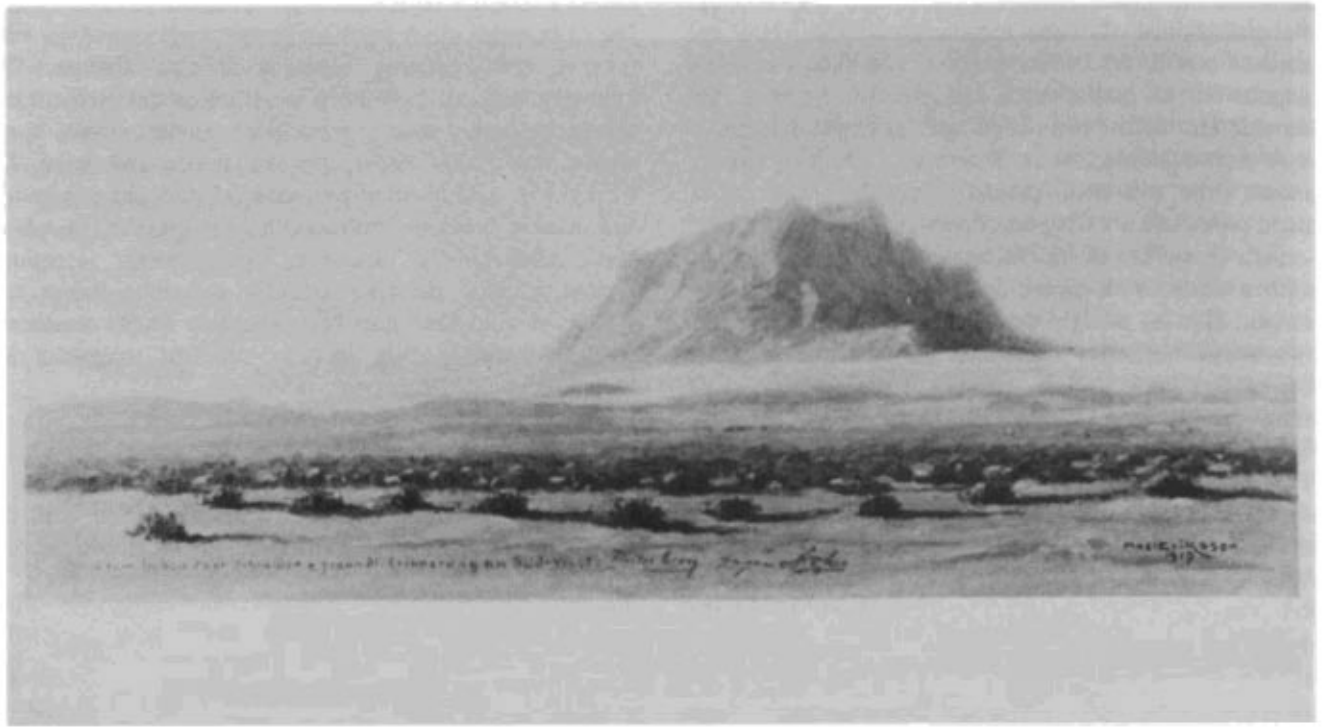
Recently the Geological Survey undertook a geophysical investigation of the Salpeterkop structure. Preliminary gravimetric, radiometric, and aeromagnetic results seem to support the interpretation of Verwoerd (1990) that the volcanic superstructure overlies an alkaline-carbonatitic ring complex of low density at comparatively shallow depth.

#### *Melkfontein (38)*

This locality, which had been prospected in vain for diamonds many years before, was first recognized as carbonate-rich tuff by Nixon (1975). It is situated 14 km south of Cedarville in East Griqualand adjoining Transkei. The tuff deposit is about 50 m thick and consists of cream-coloured calcite with numerous clasts of the country rock, basement, and lower crust. No associated carbonatite dykes or lavas have been observed (Nixon *et al.*, 1983). Detailed mineralogical study (Boctor *et al.*, 1984) has shown that clinopyroxene, amphibole, mica, plagioclase, magnetite, and apatite in the tuff were derived by disaggregation of garnet granulite inclusions, but that cognate magnetite and apatite also appear to be present. The tuff is enriched in the minor and trace elements characteristic of carbonatites (P, Sr, Ba, Ti, Zr, Nb, and LREE) but lacks minerals like pyrochlore, phlogopite, and perovskite, or evidence of fenitization. Zircon was recovered from a concentrate and yielded a  $^{206}\text{Pb} - ^{238}\text{U}$  age of 63.4 Ma (Davis, 1977). This means that Melkfontein is much younger than, and unrelated to, the East Griqualand kimberlites.

#### *Sandkopsdrif (39)*

Deeply weathered carbonatite complexes devoid of outcrops (like Sokli in Finland, Mt Weld in Western Australia and those of tropical climates) are unfamiliar in Southern Africa. Sandkopsdrif is one of them. It was first described by Moore & Verwoerd (1985). It is situated 26 km southwest of Garies, Cape Province, and gives rise to circular radiometric and aeromagnetic anomalies approximately 1 km in diameter. The main component is a secondary vermiculite-calcite-limonite glimmerite with pisolitic and brecciated structure. Minor dyke-like bodies of quartz-sövite and soda-amphibole sövite as well as manganese gossan are exposed within the pipe. Further evidence in favour of its interpretation as a carbonatite complex is the presence of primary and residual pyrochlore, secondary rare-earth mineralization (churchite) and fenitization of the country rock. Other minerals that have been identified during prospecting operations are manganoan calcite, goyazite,



**Figure 12** Dicker Willem: from a pastel painting by Axel Eriksson in 1919, reproduced as frontispiece in E. Kaiser: 'Die Diamantenwüste Südwestafrikas'.

gorceixite, carbonate-apatite, betafite, uraninite, and niobian rutile. Details about the economic potential with respect to phosphate, niobium, uranium, thorium, and rare earths were given by Verwoerd (1986).

The Sandkopsdrif Complex contains xenoliths of olivine melilitite and its location is in the centre of a cluster of olivine melilitite pipes. By inference Sandkopsdrif is of approximately the same age as the Biesiesfontein pipe dated by the K-Ar whole rock method at  $56 \pm 3$  Ma, which is corroborated by the 54 Ma zircon age on a neighbouring kimberlite (Moore & Verwoerd, 1985).

#### *Dicker Willem (40)*

This is another impressive landmark (Figure 12) that was only recently recognized as a carbonatite complex (De Villiers, 1971; Jackson, 1976). Also known as Garubberg, it rises 600 m above the Namib desert just north of the Luderitz-Keetmanshoop railway line and measures 2.5 km in diameter. It was shown as an outlier of Gariep limestone on the first edition of the 1:1 000 000 geological map of South West Africa (1963).

The geology, petrology, geochronology, and stable isotope geochemistry of this complex have been described in a series of papers by Cooper (1988), Reid *et al.* (1990), Cooper & Reid (1991), and Reid & Cooper (1992), with further work in progress. Virtually the entire mountain consists of calciocarbonatite: an earlier sövite phase intruded and broken up by multiple concentric ring dykes of medium- to fine-grained alvikite. Associated alkaline rocks are confined to xenoliths and screens of calcite-rich ijolite and nepheline syenite near the outer margin of the complex, as well as trachytic intrusions in the country rock. The

sövite is flow-banded with euhedra of magnetite, aegirine-augite, apatite, biotite, pyrochlore, zircon, K-feldspar, and nepheline. The alvikites have interesting and variable textures, often with phenocrysts of dolomite, calcite, magnetite, and pyrochlore in a groundmass of calcite, biotite, aegirine-augite, apatite, quartz, barite, and fluorite. Cooper & Reid (1991) present clear evidence of magmatic flow, gravity settling, and quench crystallization, compatible with the concept of a Ca-rich carbonatite magma carrying calcite and dolomite as cumulus phases. Oxygen isotope fractionation between silicate and oxide minerals in sövite cumulates indicate temperatures of 600–900°C. Detailed study of the carbon and oxygen isotope ratios of the different calcite and dolomite parageneses shows partial recrystallization in the presence of low-temperature hydrous fluids (Reid & Cooper, 1992). The final phase of carbonatite activity involved explosive emplacement of steep-sided, funnel-shaped breccia and tuff pipes in the central part of the complex, coupled with dykes and veins of yellow-brown carbonatite, micro-breccia, and tuffisite.

Excellent agreement between K-Ar and Rb-Sr isochron ages on biotite and calcite from Dicker Willem gives an emplacement date of  $49 \pm 1$  Ma (Reid *et al.*, 1990).

#### *Keishöhe (41)*

Approximately 4 km southeast of the old Keishöhe railway siding (Figure 13) there are low, scattered outcrops of brown-weathering dolomitic carbonatite (beforsite). Several shallow-dipping sills up to 2 m thick are cut by narrow beforsite dykes with country-rock xenoliths. Intrusive relations with gneiss and schist of the Namaqualand Metamorphic Complex can be seen in the west. Some specimens show

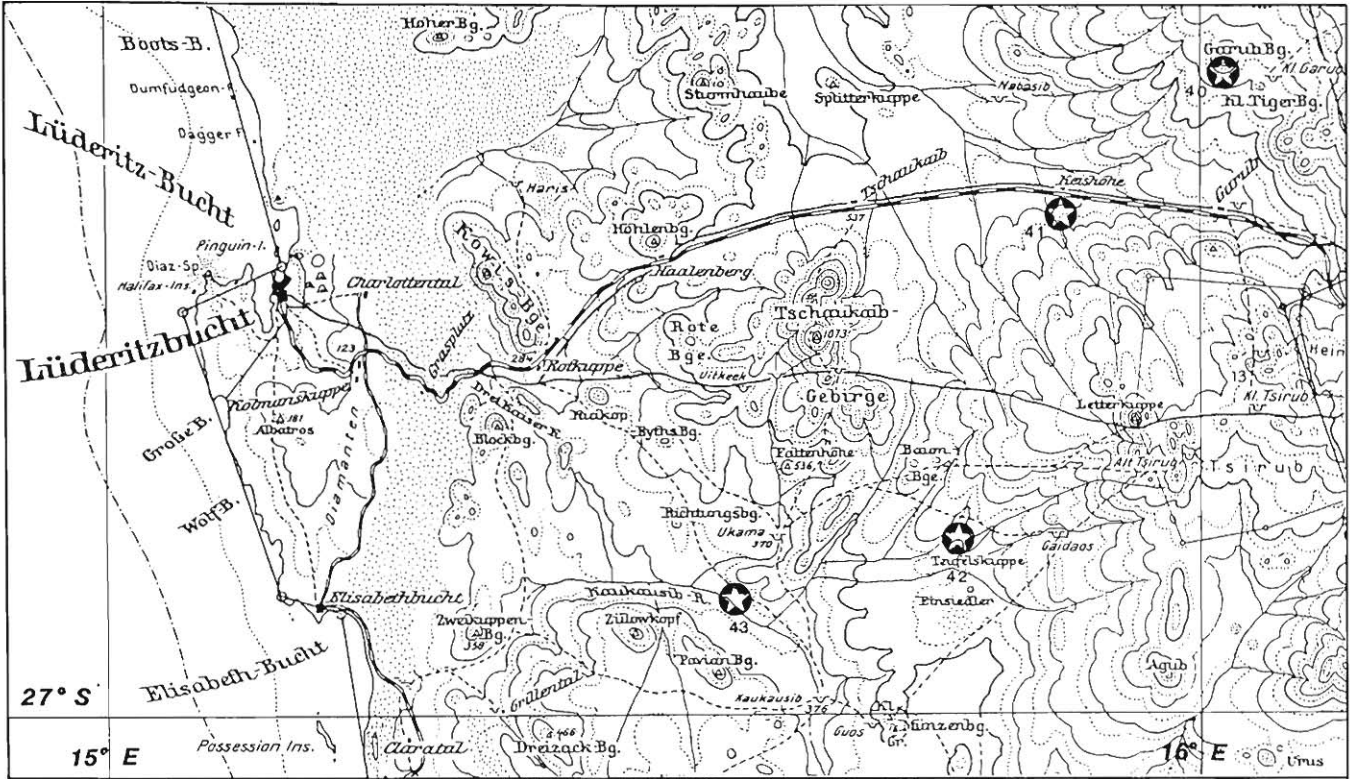


Figure 13 Portion of South West African 1:500 000 Ordinance Survey map of 1925, showing the location of four carbonatites between Aus and Luderitz. (The topographic survey was originally carried out for the Deutsche Diamanten-Gesellschaft m.b.H. and published on 1:100 000 by Dietrich Reimer, Berlin, 1913. On this map Keishöhe reads Kieshöhe, i.e. ‘Stony Height’, a more likely designation).

pseudomorphs of a glomeroporphyritic texture in a ferruginous groundmass and others appear to be microbreccias (McDaid, 1978; and own observations).

The extent of the outcrops is about 1.3 km long and 0.6 km wide, with the thickest sills and the largest concentration of carbonatite near the centre of the area, but no pipe-like body could be located. The trend is towards Dicker Willem 20 km to the northeast. Cooper (1988) only mentions sporadic radial carbonatite dykes up to 2.7 km from Dicker Willem, but Jackson (1976) also found fragments of carbonatite south of Koichab Pan 40 km west of the mountain. Although beforite dykes are a very minor feature of the Dicker Willem Complex, late in the sequence of intru-

sion, it seems most likely that the Keishöhe sills and dykes represent a satellitic body in depth.

*Teufelskuppe (42)*

Like the previous one, this occurrence is situated in Diamond Area No 1 and can only be visited with special permission. Teufelskuppe is a roughly circular group of hills 1 km in diameter and 120 m in height (Figure 14). The carbonatite appears to form a cone-sheet complex with inward dips of 5° to 25°. A conical hill in the north, associated with a band of black ferruginous oöoliths (accretionary lapilli?) at its base, is probably a volcanic neck. Both calcitic and dolomitic carbonatites with highly variable texture are

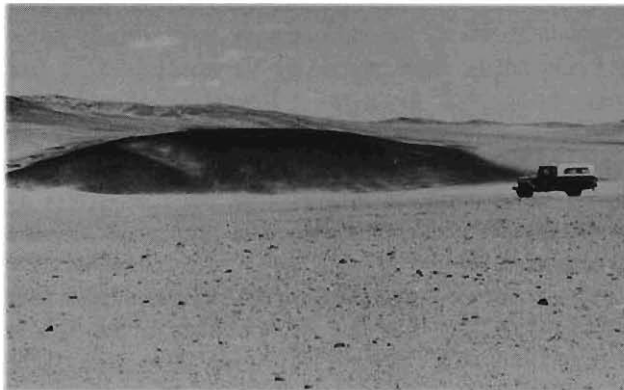


Figure 14 The Teufelskuppe carbonatite looking eastwards.

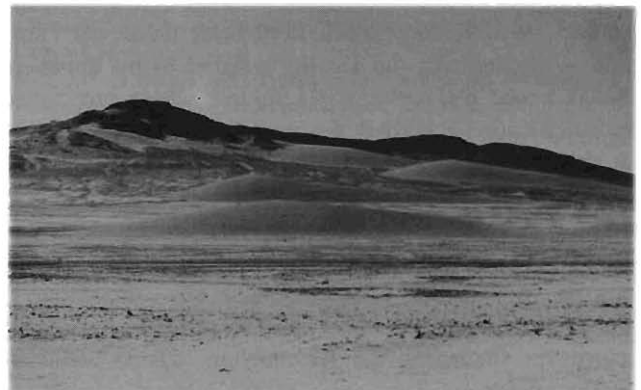


Figure 15 The Kaukausib carbonatite as seen from the south.



present in the cone-sheet complex, but alvikite seems to predominate. High Sr content has been reported. Some specimens resemble the Dicker Willem alvikite, with euhedral crystals of magnetite and apatite that stand out on the weathered surface. Others show a streaky flow-banding, a porphyritic texture with dolomite phenocrysts, or abundant fragments of country rock. Although contact relationships are obscured by scree, sand, and calcrete the carbonatites are undoubtedly intrusive in biotite schist and amphibolite of the Namaqualand Metamorphic Complex. Teufelskuppe is considered to be coeval with Dicker Willem (McDaid, 1978; and own observations).

#### *Kaukausib (43)*

This carbonatite was first recognized during a visit to the Luderitz area by P. Prins and the author in 1976. It is situated on the south flank of the broad Kaukausib valley, 20 km in a straight line west-southwest of Teufelskuppe. It forms a low rise 150 m in diameter (Figure 15), strewn with lateritic talus and a few outcrops of ferruginous silicified carbonatite. The occurrence is probably restricted to some minor beforite dykes in schist, gneiss, and migmatite.

#### **Doubtful carbonatites**

Descriptions of carbonatite that require substantiation appear from time to time in the geological literature and are briefly mentioned here.

Post-Transvaal age carbonatite dykes have been identified in some *Witwatersrand gold mines*, notably Vaal Reefs, Buffelsfontein, and Hartebeesfontein in the Klerksdorp area (Antrobus *et al.*, 1986). The dykes strike north-south and are packed with xenoliths. Their mineralogy is not distinctive (ankerite, dolomite, calcite, quartz, stülpnomelane, biotite, tremolite, hornblende, apatite, titanite, orthoclase, pyrite, and chalcopyrite) and geochemical analyses are not available. If confirmed, they could perhaps be related to Stukpan or an unexposed intrusion of the same age group.

Similar dykes are also known in the *Amandelbult section* of Rustenburg Platinum Mines, Ltd.. They are more frequent in the northeastern sector of the mine (Viljoen *et al.*, 1986) but have not been studied in detail. An unpublished chemical analysis (Univ. Stellenbosch) gave essentially calcite: 51,91% CaO, 2,48% FeO, 2,50% MgO, and 0,69% P<sub>2</sub>O<sub>5</sub>.

Vermaak (1970) mentioned the presence of magnesiocarbonatite dykes emplaced along faults in the area immediately northwest of Pilanesberg. One of these faults, the Frank Fault, is undoubtedly the locality referred to by Verwoerd (1967a) under the name *Witkleifontein* where brecciation and silicification preceded the introduction of ankerite, at that time considered to be doubtful as a carbonatite. On his geological map Vermaak (1970) also shows what appears to be a plug of 'carbonate rock' on the farm Groenfontein adjacent to Witkleifontein. Although the Pilanesberg Alkaline Complex itself is not known to have any carbonatite, it seems quite likely that these minor, somewhat doubtful, occurrences (including the Amandelbult dykes) could be directly related to it in view of the composition of the petrographic province as a whole.

Carbonatized breccia and carbonatized chlorite-quartz-

amphibole rock with dolomite and magnesite on *Olifantspoort* 328JQ near Rustenburg are described in an Anglo American company report of 1974. The carbonatization (of diabase?) is associated with the Rustenburg fault and an old copper prospect on a quartz vein. Sr contents of 235 to 575 ppm in the carbonate-silicate rocks may point to a carbonatitic parentage but they are obviously not carbonatites *sensu stricto*.

#### **Discredited carbonatites**

The spectacular maar-like crater known as the *Pretoria Saltpan* or Zoutpan Volcano, located 40 km north-northwest of Pretoria, was the first occurrence to be described as carbonatite in South Africa. This interpretation was supported by a few ejected blocks of carbonatite along the rim, and by the carbonate-rich composition of the brine forming the crater lake. However, several investigators have suspected in the past that it is a meteorite impact crater instead. As a result of a comprehensive study since 1988, which included drilling into bedrock at a depth of 151 m, the impact origin has now been established beyond reasonable doubt. Reimold *et al.* (1991; 1992) present convincing evidence of shock metamorphism, impact glass, and melt breccia in unconsolidated granitic 'sands' sampled between 90 and 143 m. In addition, a Precambrian fission track age has been determined for zircon from carbonatite ejects, whereas the impact glasses have fission track ages of  $220 \pm 52$  Ka, i.e. Pleistocene (Storzer *et al.*, 1993). This means that the presence of the carbonatite blocks must be regarded as coincidental, probably related to the so-called Pienaars River Complex.

Two other occurrences that were hitherto regarded as problematic have also yielded evidence of an impact origin: Roter Kamm in the southern Namib (Miller & Reimold, 1986) and Kalkkop near Graaff-Reinet (Hill, in prep., and Reimold, pers. comm. 1993).

*Roodeplaat* near Pretoria has been described as a carbonatite volcano by Verwoerd (1967a; 1967b), but this was based more on an analogy with Goudini and Kruidfontein, and on the likelihood that the Derdepoort carbonatite is a satellite intrusion, than on solid evidence. According to Frick & Malherbe (1986) Roodeplaat is a palaeocaldera complex with alkaline affinities, characterized by two distinct magmatic lineages leading to trachyte and quartz-trachyte respectively. These authors describe three small carbonatite dykes on the banks of the Pienaars river along the southern rim of the caldera; they were already known but could not be substantiated by Verwoerd (1967a). Until further evidence is forthcoming Roodeplaat should not be regarded as a carbonatite volcano. The unexposed Elandskraal volcano further north (Frick & Walraven, 1985) appears to be a related alkaline type but carbonatites and carbonatization phenomena have not been encountered in the boreholes.

The conclusion that banded carbonate veins in a small olivine basalt plug near the Spence shaft in the *Messina* copper mining area represent late Karoo carbonatite (Jacobsen & McCarthy, 1975) is unconvincing. The veins consist of calcite, dolomite, quartz, siderite, orthoclase, and barite. The Sr, Ba, La, and Ce contents of the carbonate rocks are

lower than those of the associated basalt. The veins are probably secondary alteration products of the olivine basalt.

Finally, Söhnge (1964) threw out the tentative suggestion that the Tsumeb CuZnPb ore body with its attendant calcitization of the surrounding Otavi dolomite might be related to the late Karoo (i.e. early Cretaceous) carbonatite activity in northern Namibia. This was disproved by Allsopp & Ferguson (1970) on the basis of strontium isotope and La and Ce analyses of a representative suite of samples, although the problem of the age of the pipe remained unresolved.

## Conclusion

Carbonatites, though volumetrically unimportant, can no longer be regarded as rare or exotic rock types. They are normal products of partial melting in the mantle or differentiation at higher levels. Since 1967 seven new discoveries have been made in South Africa and twelve in Namibia. Of the 43 occurrences described here, 18 are major carbonatite volcanoes or subvolcanic complexes; the others are small plugs, dykes, or dyke swarms. The majority occur in an anorogenic setting, but one group appears to be related to the Pan-African Neoproterozoic Damara orogen in Namibia; another (Bulls Run) was engulfed by deformation in the Tugela Terrane of the Namaqua-Natal Belt after its emplacement.

Geochronology has in general confirmed the relative ages deduced from geological relationships, although the range of ages within a particular alkaline province (e.g. the Pilanesberg Province) has been somewhat greater than expected. This review does not include alkaline magmatic activity where carbonatite was absent. For a full appreciation of the extent and periodicity of alkaline carbonatitic magmatism in southern Africa, the following closely related intrusions must also be considered: the alkali granites and nepheline syenites of the Vredefort-Parys area (Baviaanskranz, Lindeques Drift, Rietfontein, and Schurwedraai), the apgaitic Pilanesberg Complex, the Cape Cross-Messum-Okonjeje-Paresis-Brandberg group of volcanoplutonic complexes, Granitberg, the Auas and Klinghardt phonolites, the Bushmanland and other olivine melilitites, and the kimberlites. Of all these cases only Schiel, Vredefort-Parys, Kruidfontein, Messum, Okonjeje, and Brandberg show an association of undersaturated with saturated (basaltic or gabbroic) and oversaturated igneous rocks.

Whilst southern African carbonatites span 2000 million years from early Proterozoic to Tertiary, it is possible to distinguish clearly between five different age groups that show very limited overlap in time and space. Thus repetition of carbonatite activity through long-lived lithospheric control, as is the case along the East African rifts (Woolley, 1989), is not in evidence here. Only further discoveries and geochronological results can test the validity of this conclusion.

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