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Volcanology of the Gross Brukkaros Field, southern Namibia

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Gross Brukkaros is a volcano-shaped inselberg rising 600 m above the Nama plain in southern Namibia. It evolved in several steps starting with the intrusion of a laccolithic body which caused uplift and radial fissuring of the overlying rocks, Cambrian, Permocarboniferous and Upper Cretaceous Kalahari sediments as well as Jurassic dolerite sills. On the radial fissures more than 100 carbonatite dykes and 74 carbonatite diatremes were emplaced. The eruption from these dykes and diatremes caused a mass deficiency in the laccolith and subsidence of its roof, i.e. a downsag caldera formed collecting thick reworked sedimentary and pyroclastic debris. The carbonatite diatremes point to phreatomagmatic explosive activity because of occurrence of only non-vesicular carbonatite ash grains and lapilli and because the hydrogeology was conducive to such explosive activity: a near surface groundwater table is indicated by unconsolidated Kalahari sediments and the free groundwater table of the caldera lake of Gross Brukkaros.

Introduction

The Gross Brukkaros Carbonatite Volcanic Field in southern Namibia has been studied repeatedly, e.g. by Rogers, 1915; Cloos, 1937; Janse, 1964, 1969, 1975; Ferguson *et al.*, 1975; Scheibe, 1973/74 and Miller, 1987. This paper summarises the results of our recent re-examination of the physical and geochemical volcanology of the carbonatite volcanic field and the structural formation of the Gross Brukkaros caldera and its sedimentary fill.

The Gross Brukkaros Carbonatite Volcanic Field

Gross Brukkaros is a volcano-shaped inselberg in southern Namibia rising 600 m above the surround-

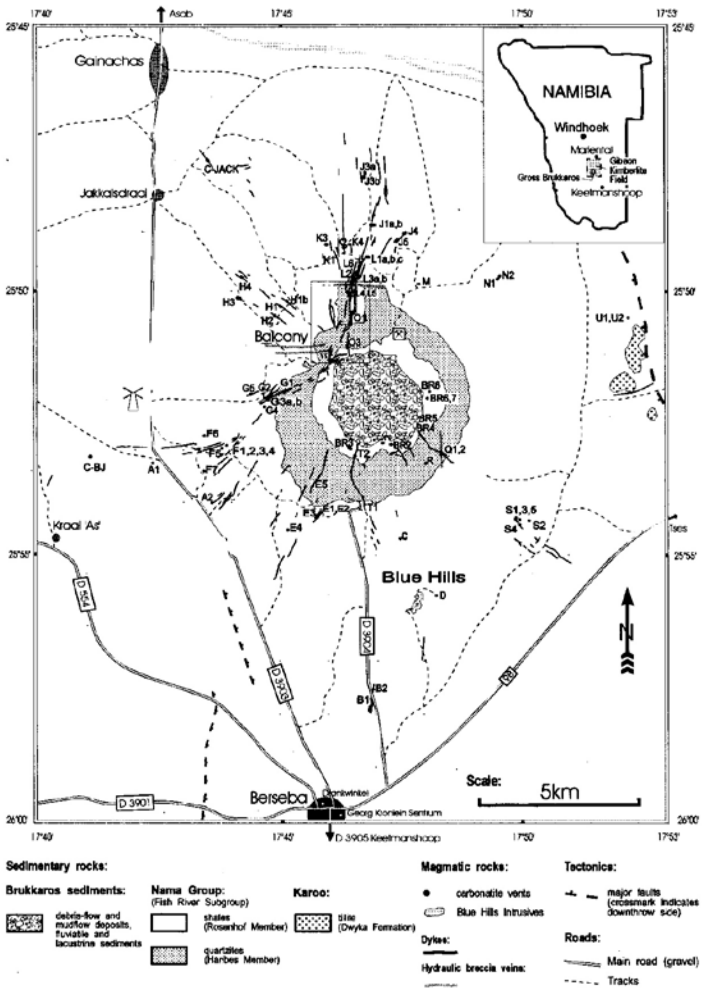

Figure 1 : Geological map of the carbonatitic Gross Brukkaros Volcanic Field; from Kurszlaukis, 1994. The diatremes are marked with letters according to the system introduced by Janse (1969).

ing Nama plain (Fig. 1). It is central to more than 100, almost radial carbonatite dykes and 74 associated diatremes (Kurszlaukis, 1994). At the original surface the volcanic edifices, which were fed from the dykes and the maars on top of the diatremes, formed a carbonatite volcanic field consisting of many monogenetic volcanoes (> 100) with the more complex Gross Brukkaros volcano in its centre. Since emplacement, erosion has removed as much as 650 m of the surrounding Nama and Karoo rock sequence below original surface as deduced from the known thickness of these rocks (Lorenz *et al.*, 1997). In the southern part of the Gross Brukkaros Volcanic Field a group of ultrabasic and carbonatitic hypabyssal rocks form the Blue Hills Intrusive Complex, a small laccolithic body, 800 m in diameter (Kurszlaukis, 1994; Kurszlaukis and Franz, 1997). The close geochemical relationships of this intrusive complex with the carbonatite field suggests that it was emplaced concomitantly with the Brukkaros Volcanic Field. Rb/Sr-age determination of several Blue Hills rocks and their minerals yielded an isochron age of 75.1 ± 0.6 Ma (Kurszlaukis and Franz, 1997). A similar age for the Gross Brukkaros Volcanic field is supported by plant fossils (Kelber *et al.*, 1993).

Gross Brukkaros

Brukkaros is located on a structural dome in red, Cambrian Nama Group quartzites (Haribes Member) and shales (Rosenhof Member). The dome has a basal diameter of 10 km, a crestal diameter of 4.5 km and a maximum amount of relative uplift of about 440 m (Lorenz *et al.*, 1997). The Brukkaros Mountain itself forms a pronounced ring-shaped ridge 3 km in diameter atop and in the centre of the dome. This circular ridge encloses a crater-like, intramontane basin. Sagging of the Nama sedimentary rocks and formerly overlying Karoo sediments and dolerite sills has resulted in a doughnut-like structure with a ring-shaped crestal anticline in these Nama rocks, the axis of which coincides approximately with the outer base of the ring-shaped Brukkaros ridge (Fig. 2) (Stachel *et al.*, 1994a, 1995; Grossnick, 1994; Werner, 1998a,b). At the base of the southern and eastern outer margins of the ring-shaped ridge are seven small occurrences of Dwyka sediments from the basal Karoo sequence. These unconformably overlie the red Nama rocks and are up to 19 m thick. The Cambrian and Karoo sediments of the inner limb of the antiform are unconformably overlain by up to 300 m of silica-cemented sediments, informally called Gross Brukkaros Group. In general, these sediments rest with a primary depositional contact on the Nama shales and Dwyka sediments. They form the crest of the ring-shaped ridge, are exposed in the outer almost vertical rocky walls (i.e. the upper steep slope) and on the more shallow dipping inner slope of the Gross Brukkaros "volcano" and in its "crater" (Fig. 2).

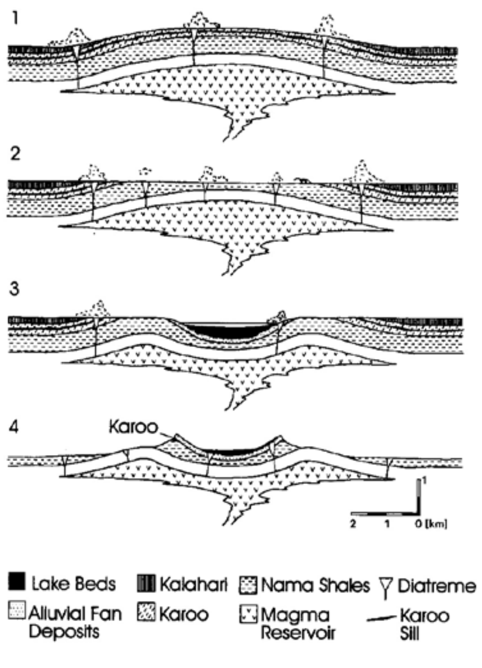

Figure 2 : Series of schematic cross-sections through the carbonatitic Gross Brukkaros Volcanic Field showing its evolution and including a cross-section of the present situation; modified from Stachel *et al.*(1994).

Originally, the Gross Brukkaros deposits were considered to be free of juvenile volcanic clasts and were thought to be of phreatic (Cloos, 1937) or CO_2-explosion (e.g. Ferguson *et al.*, 1975) origin. Miller (1987) recognised the sedimentary nature of the silica-cemented Gross Brukkaros deposits, described lacustrine and turbidite beds and likened the succession to crater-lake deposits above kimberlites in South Africa (Smith, 1987). It was consequently realised that the whole exposed sequence of the Gross Brukkaros deposits consists of reworked country rocks and reworked tephra (Stachel *et al.*, 1994b, 1995). These sediments consist of debris flows, mudflows and braided fluviatile and lacustrine deposits and were deposited in a local depocenter. The latter contain many turbidite beds and fragmented plant fossils which are probably of Upper Cre-taceous age (Kelber *et al.*, 1993). In the Brukkaros sediments there occurs a high proportion of dolerite detritus consisting of lithic clasts and of individual plagioclase and clinopyroxene grains. In addition, well rounded and highly spherical, monocrystalline quartz grains and small rounded shale clasts of fluviatile origin are characteristic features of the Brukkaros sediments. Haematite (that in part is clearly predepositional in origin) coats quartz and shale sand grains. Kurszlaukis (1994, 2000); Kurszlaukis *et al.* (1998b) and Stachel *et al.* (1994a, b) consequently suggested that the Karoo sediments in the Brukkaros area not only contained one or more extensive dolerite sills and that the Karoo sequence was already overlain by unconsolidated aeolian Kalahari sediments (Fig. 2). The well rounded, in part fresh, dolerite clasts and dolerite mineral grains indicate exposed dolerite areas and physical rather than chemical weathering on this dolerite surface during parts of the early Kalahari erosional and depositional period. Today dolerite sills are known from outcrop in excess of 50 km north-east and south-east and 80 km south of Gross Brukkaros (Miller and Schalk, 1990; Gerschuetz, 1996). The assumed aeolian Kalahari sediments provide the only likely source for the highly mature quartz grains and the many altered and fresh individual plagioclase and clinopyroxene mineral grains. As pointed out above, the small round shale clasts point to the existence of a fluviatile drainage system which probably was of low energy. Thus, in Upper Cretaceous time, there was a peneplained area characterised by some low-energy fluviatile drainage system and aeolian dunes. In addition, the lake and fluviatile beds in the Brukkaros sediments (which occur even at the "crater" rim) prove that there existed sufficient groundwater in near-surface levels, with the lake level representing the free groundwater table in this permeable environment.

Synsedimentary faulting (with downthrow towards the centre of Gross Brukkaros) and dips of the Brukkaros sediments up to 30° towards the centre (locally up to vertical), imply that the depocenter and its sedimentary fill subsided over an extended period of time. Thus the original landsurface and the original groundwater table must have been even above the present level of the "crater" rim, possibly at an elevation of up to 650 m above the present Nama plain. This original surface level above the present top level of Gross Brukkaros is supported by a regional peneplain surface cutting Gross Brukkaros at its highest elevation (Stengel and Busche, pers. comm., 1997). These results and interpretations are of great relevance to the hydro geological environment and thus to the volcanogenesis of the diatremes in the vicinity of Gross Brukkaros and in the adjacent Gibeon Kimberlite Volcanic Field.

Due to the formation of the radial carbonatite dykes and the possible eruption of lavas and scoria from these dykes and due to the eruption of typical maar tephra from the carbonatite diatremes, a growing mass deficiency must have evolved in the laccolithic magma reservoir and as a result the overlying roof rocks subsided over an extended period of time, resulting in a downsag caldera and consequently in the depocenter for the Brukkaros sediments (Fig. 2). The Brukkaros sediments, representing the caldera fill, only locally are in faulted contact with Dwyka sediments (south-east escarpment). In general they unconformably overlie in primary contact the Nama shales and Karoo sediments on soil-free, inward dipping, arcuate and locally also gorge-like, surfaces. This suggests that large-scale slumping of the walls of the caldera was an important process in the formation of the caldera (Lorenz *et al.*, 1997) and was probably related to more centrally located arcuate faults, while sagging of the caldera walls was an additional feature. In three areas of slumping of the caldera wall (east side of Gross Brukkaros and south-east side of the entrance valley of Gross Brukkaros) breccias consisting of blocks of Nama shales and Dwyka sediments as well as blocks of bedded Brukkaros sediments are additional features pointing to these important collapse processes in the evolution of the depocenter (Lorenz *et al.*, 1997). The Brukkaros sediments unconformably overlie this inward-dipping crater slope and lap onto this slope showing that towards the interior of the depocenter, older Brukkaros sediments probably occur, still hidden by the exposed younger beds. After deposition, subsidence and steepening of the Brukkaros sediments, they suffered strong post-depositional fenitisation implying a hot reservoir still in existence at this stage of the evolution of Gross Brukkaros (Stachel *et al.*, 1994a, b). The hydrothermal crystallisation of quartz, barite and calcite and the emplacement of an iron ore-barite vein containing a Nb-rich mineral has been studied by Werner (1998b).

Carbonatite Dykes

More than 100 carbonatite dykes (Fig. 1) are one of the characteristic features of the Brukkaros Volcanic Field. The dykes consist of either silicocarbonatite (Mg-rich) or magnesio-carbonatite, and in one instance of calciocarbonatite (Kurszlaukis, 1994, 2000; Kurszlaukis and Lorenz, 1997). This calciocarbonatite dyke is located near pipe Al 7 km away (WSW) from the centre of Gross Brukkaros. The carbonatite dykes are mostly radial to the northwestern margin of Gross Brukkaros, at the intersection of the Gross Brukkaros "crater" rim with the intensively block faulted area immediately to the north-west of Gross Brukkaros (Kurszlaukis, 1994; Stachel *et al.*, 1994a; Werner, 1998a, 1998b). This block faulted area was called the Balcony by Janse (1965). The individual dykes are up to 2 km long and are up to 0.5 m in width, rarely reaching 0.8 m. One dyke in the eastern Balcony area is 2.2 m thick. Vesicles (up to 30 vol.%) in a few dykes prove local exsolution of volatile phases and synchronous quenching of the vesicular melt (Kurszlaukis and Lorenz, 1997; Lorenz *et al.*, 1997). The carbonatite dykes extend up to 13 km away from Gross Brukkaros and are exposed at present at elevations of 1000 - 1500 m a.s.l., i.e. about 650 to 150 m below the original surface, which is tentatively taken at about 1650 m above present sea level. Because these dykes are rather long and exposed that close to the original surface it was suggested that they probably resulted in surface carbonatite volcanism - lava flows and scoria cones (Kurszlaukis and Lorenz, 1997; Lorenz *et al.*, 1997). Since juvenile carbonatite from the diatremes must have reached the original surface without thermal decomposition of the melt - otherwise the carbonatite lapilli could not have been redeposited intact into the Brukkaros depocenter (see above) - thermal decomposition of the carbonatite magma need not have been active and precluded the magma in the dykes to have reached the original surface. With respect to the emplacement of the carbonatite dykes, growth of the laccolith underneath Gross Brukkaros in several phases is assumed to have resulted in tensile fracturing of the overlaying roof rocks permitting the emplacement of the many radial dykes. A great proportion of basement xenoliths in the dykes (Kurszlaukis, 1994; Rupprecht, 1997) clearly points to an origin of the dykes and thus an intrusion level of their feeder laccolith largely within the uppermost basement (the Nama sediment/basement boundary is at about 1 km depth in the old near-by Berseba bore hole). Thus the level of intrusion of the laccolith could have been at a depth of about 2 km or more below the original surface.

Only locally at the southern margin of Gross Brukkaros, several thin carbonatite dykelets (found at the base of the ring-shaped ridge) intruded the presently exposed basal Brukkaros sediments Kurszlaukis, 1994; Stachel *et al.*, 1994). These dyke lets (and some diatremes with Brukkaros sediments in their topmost levels (Kurszlaukis, 1994, Stachel *et al.*, 1994) prove that there was some overlap between dyke (and diatreme) activity and sedimentation of reworked sedimentary and pyroclastic debris in the Brukkaros depocenter, especially since the Brukkaros sediments with the intruded dyke lets were not the first sediments deposited but were preceded by a thick sequence of Brukkaros sediments as already elucidated above.

Carbonatite Diatremes

The 74 carbonatite diatremes that surround Gross Brukkaros (Fig. 1) are from a few metres up to 200 m in diameter. Many, especially the larger ones, contain several facies (Kurszlaukis, 1994, 2000; Kurszlaukis and Lorenz, 1997; Lorenz *et al.*, 1997). In many instances the diatremes are located on and thus cut downward into their own feeder dyke. Thus, locally, diatremes became active on these dykes, probably initially at levels closer to the original surface, but systematically penetrating downward on their own active feeder dykes as suggested by Lorenz (1985, 1986), Lorenz and Kurszlaukis (1997) and Lorenz *et al.* (1997).

The clastic rocks of the diatremes, both bedded or unbedded, consist of carbonatite clasts and large amounts of country rock clasts set in a compact fine-grained carbonatite matrix. The juvenile carbonatite pyroclasts consist of mostly large ash grains and lapilli, both of spherical shape. A few spherical bombs exist. Depending on the carbonatite magma type, the spherical carbonatite clasts may contain tangentially oriented phenocrysts of phlogopite. There is a distinct lack of vesicles in these juvenile clasts, despite the fact that some of the carbonatite dykes and a few late intrusive bodies into the diatremes contain vesicles (Lorenz and Kurszlaukis, 1997). In those latter instances, volatile phases must have exsolved and through relatively rapid quenching of the melt of these small intrusions vesicles were preserved. The smaller juvenile pyroclasts are, the larger is their surface area relative to the volume. The resultant greater chilling effect would freeze any existing vesicles. Thus, the lack of vesicles within the carbonatite ash grains, lapilli and bombs points to a lack of exsolution of volatile phases just prior to and during formation of the spherical carbonatite clasts. As a consequence, a non-magmatic origin of the gas phases responsible for explosive fragmentation of the carbonatite magma and also of the copious amounts of country rocks is indicated. Therefore, a phreatomagmatic origin of the diatremes is strongly advocated here. The model for the phreatomagmatic formation of these carbonatite diatremes and also of the Gibeon kimberlite pipes follows the model for kimberlite pipes presented by Lorenz (1998) and Lorenz *et al.*, (1999a, b) which integrates field data and experimental studies of thermohydraulic explosions of metal, ionic and silicate melts with water (Buettner and Zimanowski, 1998; Lorenz *et al.*, 1994; Zimanowski *et al.*, 1986, 1991, 1997a-c). According to these experimental studies, the spherical shape of the carbonatite pyroclasts is the result of the action of hydrodynamic fragmentation between accelerated steam and melt.

The compact carbonatite matrix within which the carbonatite pyroclasts and country rock clasts are set, is suggested to represent recrystallised, fine-grained carbonatite ash. This assumption is supported by the facts that even the bedded carbonatite lapilli tuffs contain such a carbonatite matrix and that the grain size distribution of the juvenile pyroclasts, which extends from a few bombs via large and small lapilli to large ash grains, lacks the fine ash grains below about 0.5 mm. This recrystallisation, which certainly was of mixed hydrothermal and diagenetic origin, indurated the originally unconsolidated and permeable clastic diatreme fill as did late hydrothermal precipitation of quartz and some barite and calcite in remaining voids.

Xenoliths of diverse sizes in the diatremes provide evidence of the depth of origin and the stratigraphy of the country rocks penetrated by the diatremes, including that has been eroded from above the present level of exposure (Kurszlaukis and Lorenz, 1997; Kurszlaukis *et al.*, 1998a, b). Clasts derived from below present exposure levels are basement rocks and red Nama quartzites and shales. From the stratigraphy eroded since the time of formation of the diatremes are clasts of upper Nama sediments (quartzites and shales), the overlying Permocarboniferous Dwyka and Ecca sediments of the Karoo sequence (blocky diamictite material, cone-in-cone carbonate concretions, and shales) and Kalahari sediment (aeolian quartz grains) (Kurszlaukis, 1994, 2000). Dolerite clasts, up to 8 m in diameter, were derived from one or more Karoo dolerite sills intruded into Dwyka or Ecca shales (Fig. 3).

Those diatremes located closest to the Gross Brukkaros "crater" rim are now about 250-150 m below the original Upper Cretaceous land surface. Those diatremes exposed farthest away from Gross Brukkaros

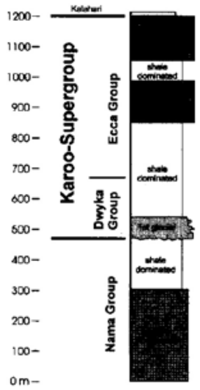

Figure 3 : Diagram of the stratigraphy of the Gross Brukarros area, Namibia, with the underlying preserved strata and the deduced former stratigraphy overlying the present surface of erosion in Upper Cretaceous times when the Gross Brukkaros Volcanic Field formed (from Lorenz *et al.*, 1997).

in the Nama plain must be slightly in excess of 600 m below that surface (Lorenz *et al.*, 1997). The high ratio of country rock clasts to juvenile carbonatite clasts suggests maars as the volcano type (Lorenz, 1985, 1986, 1998) with the maar craters cut into the basal Kalahari sediments and underlying Karoo rocks and surrounded by tephra rings and proximal and distal tephra beds. The tephra beds should have consisted mostly of base surge deposits with some ballistic fall deposits in the tephra rings and ash and lapilli fall deposits in the distal facies surrounding the tephra rings. In a few diatremes, as in diatreme C, subsided bedded pyroclastic rocks display evidence of base surge deposits (Kurszlaukis, 1994; Kurszlaukis *et al.*, 1998a, b). Judging from the diameters of the diatremes at the present level of exposure, the largest maar craters could have had diameters at the crater rim of approximately 500-600 m.

Continued eruption of carbonatite magma through the dykes and diatremes and the consequent depletion of the laccolithic magma reservoir should have led to repeated subsidence of the reservoir roof and a downsag caldera (Stachel *et al.*, 1994b) formed in the centre of the updomed roof. The thickness of the Brukkaros sediments in excess of 300 m and their facies require a source area larger than the area inside the crestline of the ring-shaped antiform. Formation of a peneplain on the updomed inconsolidated Kalahari sediments during formation of the dome is thus envisaged to have occurred. The repeated influx of floral debris in the turbidites at various levels of the Brukkaros sediments suggests a relatively large source area for vegetation and thus some regional influx of debris. This would only have been possible if the updomed area had become rather flat and integrated into the regional drainage system. The centripetal influx of thick debris flows into the depocenter shows on the other hand that the downsag caldera must have repeatedly established a centripetal and pronounced topographic gradient and resulted in erosion, especially in slumping, of the surrounding maar ejecta and of some unknown amounts of the underlying unconsolidated Kalahari and indurated Karoo sediments. Deposits in the Brukkaros depocenter also contain carbonatite lapilli and ash grains, a large fraction of individual Kalahari mineral grains and some lithics, and very angular clasts of Nama and Karoo sedimentary rocks. These latter clasts consist mostly of shales derived from the Karoo sediments and the underlying Rosenhof shale member of the Nama Group and some Karoo dolerite clasts, all of which were fragmented explosively inside the diatremes and then ejected onto the regional Upper Cretaceous Kalahari surface. It is not clear if any carbonatite clasts are derived from potential dyke-fed carbonatite lava flows or scoria.

The carbonatite ash grains and lapilli of the diatremes consist of magnesio-carbonatite (Kurszlaukis, 1994, 2000). In addition, redeposited magnesio- and calciocarbonatite ash grains and lapilli are present in the Brukkaros sediments. These were derived from reworking of the maar tephra from carbonatite diatremes and locally form up to 70 vol.% of the sedimentary rocks (Stachel *et al.*, 1994a, 1995). This indicates that the carbonatite magma did not decompose thermally on its final rise to the surface. It also indicates that the laccolithic reservoir underneath Gross Brukkaros contained different batches of carbonatite magma and may have been layered. The high proportion of calciocarbonatite lapilli in the Brukkaros sediments suggests that the main calciocarbonatite magma batch was located within the top and central part of the magma reservoir. Since the high proportion of redeposited calciocarbonatite ash grains and lapilli must have been ejected at the surface prior to redeposition in the depocenter it seems plausible to assume that their volcanic source was located close-by. This suggests that the volcanic feeders for most of these reworked calciocarbonatite clasts were located below the presently exposed depocenter of the Brukkaros sediments and that they had ejected their clasts to a large extent onto the Upper Cretaceous land surface surrounding the depocenter. The shape of the ash grains and lapilli, the lack of vesicles, as well as their content in xenocrystic quartz (Stachel *et al.*, 1994a) suggest that phreatomagmatic calciocarbonatite diatremes occurred above the central area of the laccolith, but below the depocenter and that these were active prior to deposition of those Brukkaros sediments which are exposed at present. The occurrence of high proportions of carbonatite lapilli in several levels of the Gross Brukkaros sediments might also point to the possibility of intermittent eruptions from diatremes, the tephra of which became in part or wholly reworked and incorporated in the overlying sediments.

Small rounded shale clasts in the Brukkaros sediments and the floral debris point to a fluvial system with surface water flow outside Brukkaros. The lacustrine beds at high elevations at Brukkaros also point to a high groundwater table in the surrounding country rocks: the unconsolidated Kalahari beds and the jointed Karoo dolerite sill(s), especially their chilled margins would have been good aquifers. The sandy diamictites and sandy esker deposits within the lower Dwyka would also have been aquifers, whereas the Ecca, Dwyka and Nama shales would have been aqua eludes.

Updoming during laccolith growth induced radial tension allowing groundwater from the various aquifers to flow or pour into the resulting radial fissures within which carbonatite magma was rising. As a consequence, contact between the two media is suggested to have induced thermo-hydraulic explosions at many localities. These explosions would have started in near surface environments forming an initial maar and an initial diatreme (Lorenz, 1985, 1986, 1998). With continuing rise of carbonatite magma and further influx of groundwater the level of these phreatomagmatic explosions would have penetrated downward resulting in the growth of the maar and underlying diatreme. Downward penetration of the diatreme resulted in the diatreme downcutting on its own active feeder dyke (Lorenz, 1985, 1986, 1998; Lorenz and Kurszlaukis, 1997).

At a number of diatremes, influx of groundwater ceased and, as a consequence, carbonatite magma intruded the diatreme forming dykes or plugs. Since the magmas at each diatreme stopped interacting explosively with groundwater at different stages of diatreme evolution, the size of the various diatremes varies from a few metres up to 200 m in diameter at the present surface. The root zone of pipe G3b has been described and discussed in detail by Lorenz and Kurszlaukis (1997). Although no evidence exists, some carbonatite dykes or plugs inside the diatremes may have extended upwards even into the level of the maar crater and formed a carbonatite scoria cone or lava lake.

Finally, it is postulated that, in principle, the carbonatite dykes and diatremes do not differ from dykes and diatremes related to ultrabasic and ultramafic magmas such as kimberlite and olivine melilitite (Lorenz *et al.*, 1994). The hydrogeological environment in Upper Cretaceous times would have allowed phreatomagmatic, i.e. thermohydraulic, explosions and thus formation of the carbonatite diatremes. From an experimental point of view there is no doubt that carbonatite melt can interact explosively with water rather easily (Lorenz *et al.*, 1994; Zimanowski *et al.*, 1986).

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