Gross Brukkaros (Namibia)—an enigmatic crater-fill reinterpreted as due to Cretaceous caldera evolution

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ORIGINAL PAPER

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Gross Brukkaros (Namibia) – an enigmatic crater-fill reinterpreted as due to Cretaceous caldera evolution

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Abstract At Gross Brukkaros a central depression has developed within domed Nama Group sediments and has functioned as a local depocenter, with a primary fill deposited during the Cretaceous and a small secondary fill by alluvial fans during the Tertiary and Quaternary. The diameter of the entire structure is about 10 km and that of the central depression is about 3 km. Within this depocenter the sedimentary sequence consists mainly of debris-flow and mudflow deposits, with minor intercalations of fluviatile (braided channel) sediments and fossiliferous lacustrine deposits. The sedimentary system represents a set of coalesced subaerial fans which formed a fringing sedimentary apron along the margin of the depocenter. This sedimentary apron passed distally and centrally into a permanent lake, which was characterized by a fluctuating water level. Facies transitions observed are typical of those described from modern and ancient fan delta systems. Contact relationships show the Gross Brukkaros sediments to be about the same age (Upper Cretaceous) as the surrounding carbonatitic volcanism. An Upper Cretaceous age is also consistent with the plant fossil association recently recognized within the lacustrine beds of Gross Brukkaros.

We attribute the genesis of the dome structure to the shallow intrusion of a laccolith-shaped, strongly alkaline to carbonatitic magma body. Subsequent depletion of the reservoir due to volcanic activity around and in(?) Gross Brukkaros led to subsidence resulting in the development of the Gross Brukkaros depocenter. Differences between Gross Brukkaros and the general caldera model consist of a radially oriented dike pattern and the formation of the caldera by downsagging rather than cauldron subsidence, as derived from the absence of ring faults and ring dikes. The first (radial dikes) may be attributed to comparatively strong initial doming; the latter (lack of ring faults) to the small size of the caldera, its incremental subsidence, and finally the sedimentary wall rocks instead of a rigid crystalline crust.

Key word caldera · crater sediments · debris-flow alluvial fan delta · Gross Brukkaros

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Introduction

Initial reports of the Gross Brukkaros complex (Rogers 1915; Cloos 1937) interpreted the structure as a volcanic vent. Janse (1969), who first mapped the structure in some detail, described it as a carbonatite volcano in the incipient stage, with the crater filled with "microbreccias" resulting from phreatic eruptions. No juvenile pyroclasts were observed. Since the first Kimberlite Conference (1973), however, it has become internationally renowned as a large enigmatic volcanic feature. Paradoxically, little detailed research has been undertaken on the structure itself or its fill. Ferguson et al. (1975) proposed formation of Gross Brukkaros due to bulging and subsequent disruption of the roof of a magma chamber by volatile overpressure. Miller and Reimold (1987), however, recognized an exclusively sedimentary origin of the "crater" fill, interpreting the entire sequence as lacustrine.

Our initial reconnaissance studies showed that the structure of the complex is not in accordance with the development of a single central vent. This has led to a re-evaluation of Gross Brukkaros, including a structural analysis of the country rocks and the first facies analysis of the sediment fill resulting in a new interpretation of the evolution of this enigmatic feature.

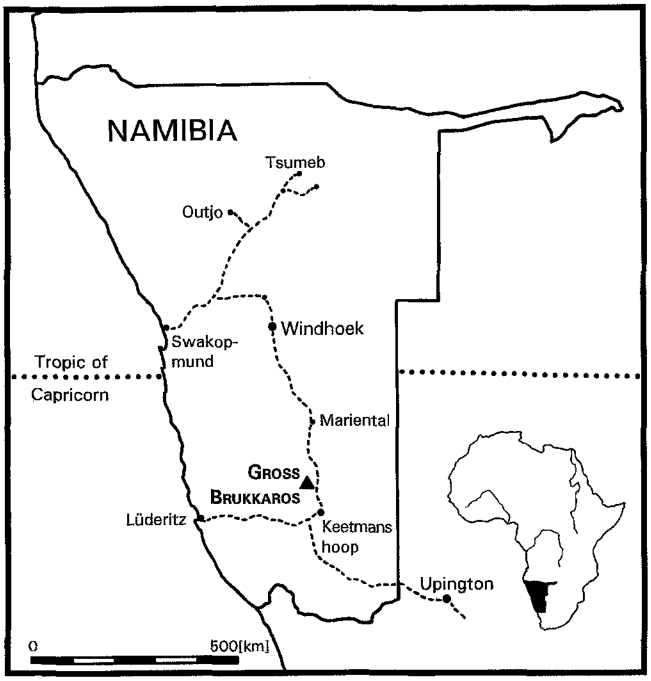

Fig. 1 Location of Gross Brukkaros in southern Namibia (aside the main road Windhoek – Keetmanshoop – Upington)

The Gross Brukkaros complex (25°52′S, 17°47′E) lies 370 km south of Windhoek in Namibia and about 40 km west of Tses and the main road from Windhoek to Keetmanshoop (Fig. 1). Gross Brukkaros is a crater-shaped inselberg (Fig. 2) which rises about 500–600 m above the surrounding Namaland plain. The entire hill has a diameter of about 7 km at its base; the crest line surrounding the central crater-like depression has a diameter of 3 km (Figs. 3 and 4).

Geologically Gross Brukkaros is located at the southern edge of the Gibeon Kimberlite-Carbonatite Province of Upper Cretaceous age (about 71.5 Ma, Davies et al. 1991). The carbonatitic activity in the Gibeon Province was almost exclusively restricted to the Gross Brukkaros Volcanic Field, that shows an obvious structural relationship with the Gross Brukkaros complex (Fig. 5). Based on Sr-Nd-Pb isotope studies, Spriggs (1988) and Davies et al. (1991) propose that heat transfer from the Vema hotspot induced melting at the asthenosphere–lithosphere boundary, with emplacement of the Gibeon kimberlites 7–10 Ma after the passage of the hotspot. However, isotopic characteristics of the Blue Hills monticellite peridotite (located at the southern flank of Gross Brukkaros) are consistent with melt generation within the lithosphere, due to conduction of heat from the plume into the lithosphere (Davies et al. 1991).

At Gross Brukkaros updomed quartzites and shales of the Early Cambrian Fish River Subgroup (Nama Group) form a ring-shaped anticlinal structure (about 4.5 km in diameter) with a central depression. The entire dome structure measures about 10 km in diameter. The crest line of Gross Brukkaros, with its steep outward-sloping cliffs, and the central depression comprise a sequence of epiclastic deposits (Fig. 6), whose origin is the main subject of this paper.

The Gross Brukkaros sedimentary fill

Four distinct lithologic associations are recognized within the Brukkaros sedimentary sequence. From their textural and structural characteristics each association can be attributed to either debris-flow and mudflow deposition, or fluviatile deposition, or lacustrine sedimentation.

The matrix-supported gravel/sandstone association (1): debris-flow and mudflow deposition

The first facies association comprises deposits ranging from massive mudstones, sandy mudstones and muddy sandstones, through massive diamictites and gravel and boulder-bearing sandstones, to matrix-supported breccias. Orientation bedding (swarms of platy fragments which are oriented approximately parallel to contacts, Fisher and Schmincke 1984) and clast-rich patches were observed. Vertical grain-size variations within single flows include reverse and normally graded units, as well as units in which reverse grading passes imperceptibly into normal grading. The thickness of individual units varies from about 10 cm to several meters. Debris-flow and particularly mudflow processes (with mudflows representing debris flows in which the entrained particles are mostly sand size or finer and in which mud is dominant, Friedman et al. 1992, p. 517) dominated to develop this association. Fines elutriated from mudflow deposits by rainwash between massflow events settled out in localized pools to deposit thin mudlayers which were subsequently dried to form desiccation cracks. These desiccated layers could resist shear imposed on them by the succeeding massflow to be preserved in situ, although in some cases mud flakes were incorporated into the subsequent deposits.

The clast-supported gravel and sandstone association (2): fluviatile deposition

This association comprises plane bedded and trough crossbedded (sets up to 30 cm thick) sandstones with lenses and layers of pebble to cobble breccia. Measurements of clast imbrication in these indicate sedimentary transport towards the center of Gross Brukkaros. Intercalations of matrix-supported breccias also occur. Clasts are dominated by pebbles and cobbles of siliceous mudstone and siltstone which vary from angular to rounded and these are joined by pebbly chert, quartzite, carbonate and crystalline (granitoid, dolerite) as

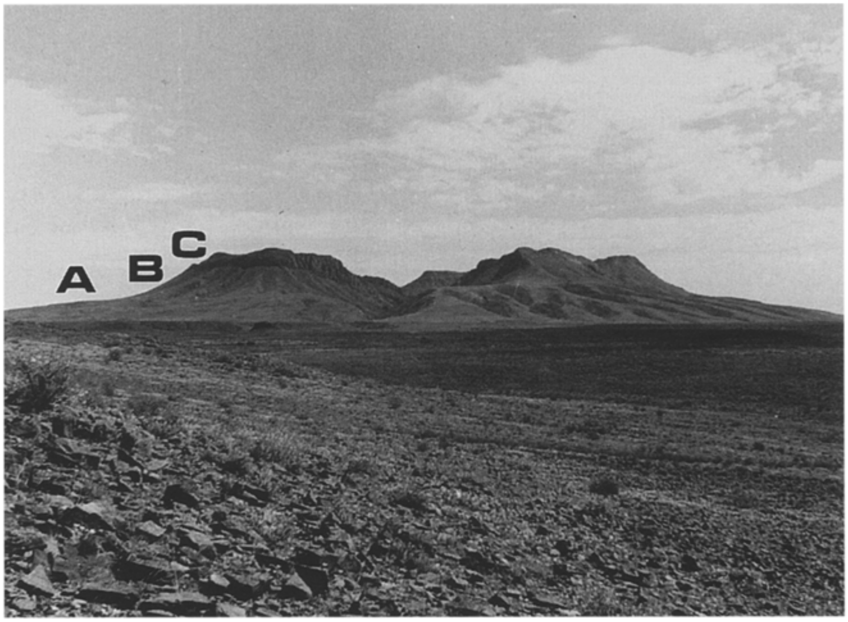

Fig. 2 Gross Brukkaros viewed from the S. The gentle lower slope of the hill is underlain by updomed Nama Group quartzites (*A*). Inward-dipping Nama Group shales (*B*) begin where the slope steepens. The steeply outward dipping to vertical cliffs along the crest line represent the inward-dipping epiclastic fill (*C*) of the Brukkaros depocenter

Fig. 3 Aerial view of Gross Brukkaros, looking towards the NW. The crater-shaped central depression has a diameter of about 3 km. The inward dip of the Brukkaros deposits can be recognized within the major gully ("Entrance Valley") at the south side of the hill (on lower left). The radial valleys (upper left) are cut within the updomed Nama Group quartzites

well as likely carbonatitic and pyroclastic fragments. The predominance of plane bedding indicates that flows tended to be shallow, as sheet floods or shallow braided streams. In such channels as developed, mega-ripple bed forms migrated and longitudinal gravel bars (Smith 1974) were deposited to form the clast-supported gravels.

The interbedded mudstone and sandstone (marginal and central) associations (3) & (4): lacustrine sedimentation

These associations are exposed in several areas at the basin rim (i.e. the present day erosionally degraded rim) and the inner slopes of Gross Brukkaros. They comprise a central facies association (4), in which normally graded turbidites are interbedded with fine-grained laminated mudstones, and a marginal facies association (3), where turbidites and laminated mudstones interfinger with fluviatile, mudflow, and debris-flow deposits (Fig. 7) similar to those described previously in the two coarser-grained facies associations.

Plane lamination and cross-lamination are developed as Bouma divisions B, C, and D within the turbidite units (Fig. 8) together with A and E divisions. The turbidite units vary in thickness from a few mm to several tens of cm and they contain grain sizes varying from gravelly coarse sandstone to fine sandstone and mudstone. Miller and Reimold (1987) report increasing carbonate contents towards the fine tops of individual graded sequences. Load casts, flame structures and water escape structures are common. The mudstone may

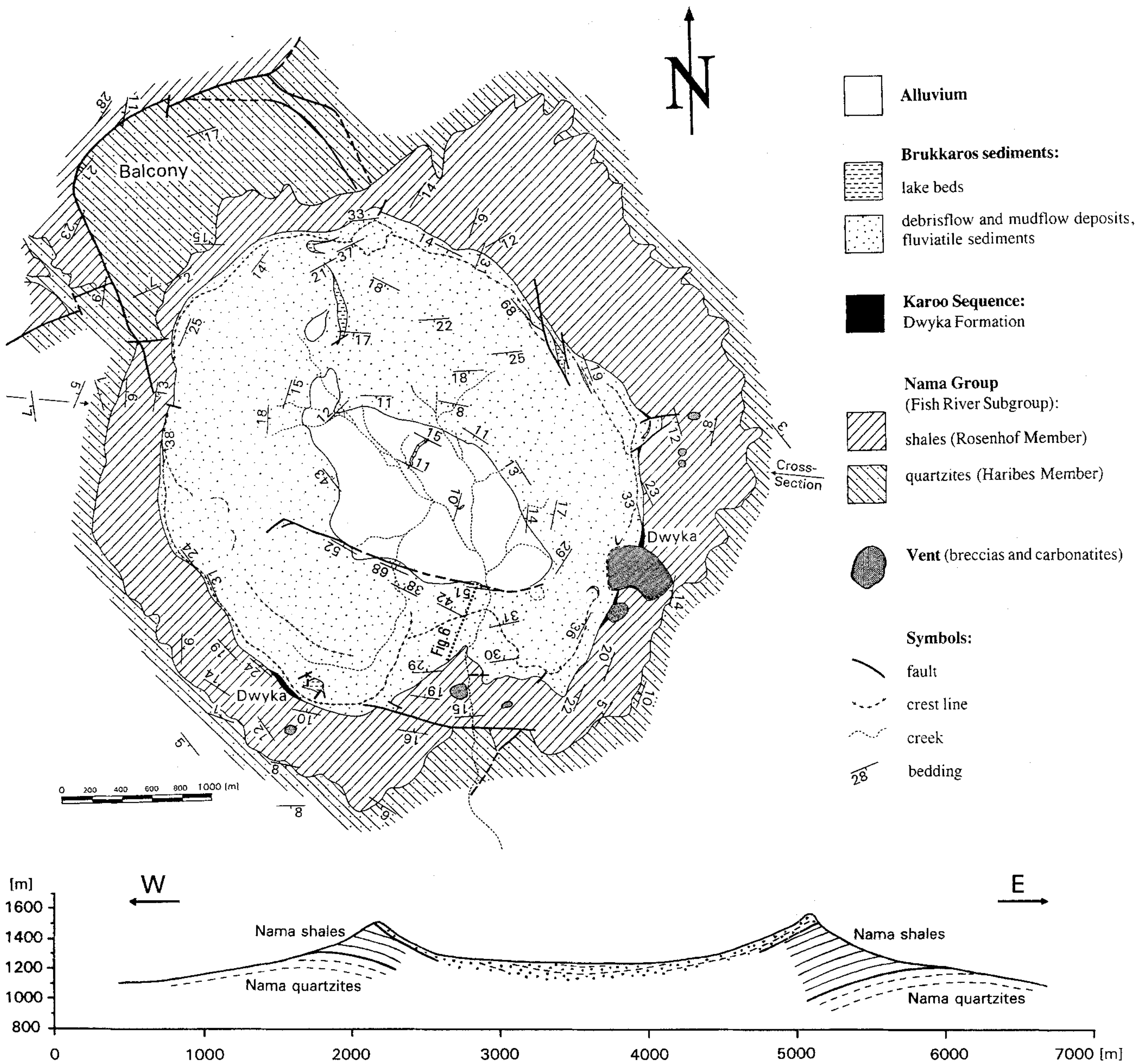

Fig. 4 Geological plan and cross-section of Gross Brukkaros (mapped on an aerial photograph base). Profile area for Fig. 6 is shown in the southern prominent gully (Entrance Valley)

show desiccation cracks and at several localities perfect raindrop imprints are preserved (Fig. 9) and in several others trace fossils of the Planolites type were observed. Within the central facies association large accumulations of fragmented plant fossils were discovered on bedding surfaces.

The central facies association developed as subaqueous deposits in the middle of a lake occupying the center of the basin into which the entire depositional system debouched. Turbidity currents were initially generated as subaerial massflows and converted into turbulent density flows on mixing with the water body (Lowe 1979, 1982). They commonly extended their deposition to the center of the lake. The marginal facies association developed where the turbidite sequence was joined by debris-flows and mudflows close to the edge of the lake. The existence of raindrop imprints and desiccation cracks on a few mudstone horizons between turbidites indicates that the lake level fluctuated dramatically. The preservation of plant fossils indicates maintenance of euxinic conditions within the lake, whereas the presence of trace fossils completes a picture of a stratified lake in which an aerobic upper layer could support life, whereas lower in the water column anaerobic conditions prevailed.

Spatial distribution

The debris-flow and mudflow deposits of facies association 1 form 80–90% of the rocks exposed on the outer

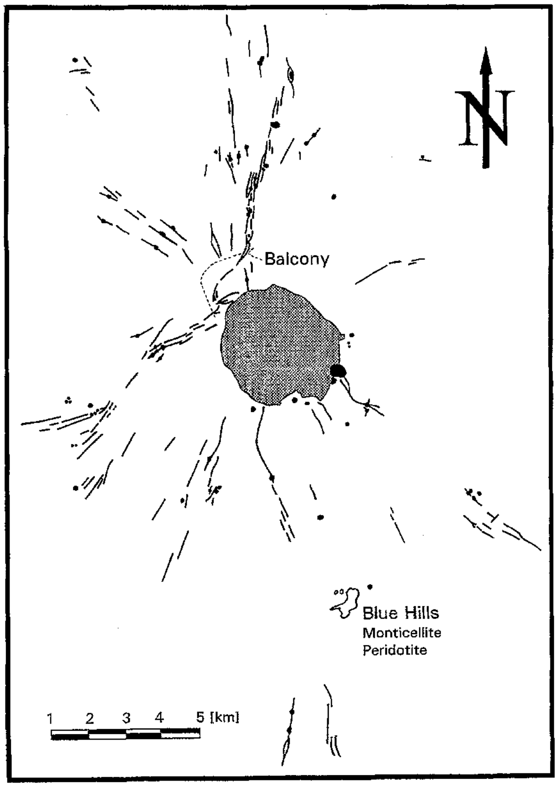

Fig. 5 The Gross Brukkaros Volcanic Field of the Gibeon Province (after Janse 1969; Kurszlaukis and Lorenz 1992, and own mapping). Gross Brukkaros (*gray area* indicates the outline of the depocenter) is surrounded by numerous radially oriented carbonatite dikes (*black lines*) with deeply eroded diatremes (*black dots*) located on them. Note the existence of several radially oriented zones with a particularly high dike density

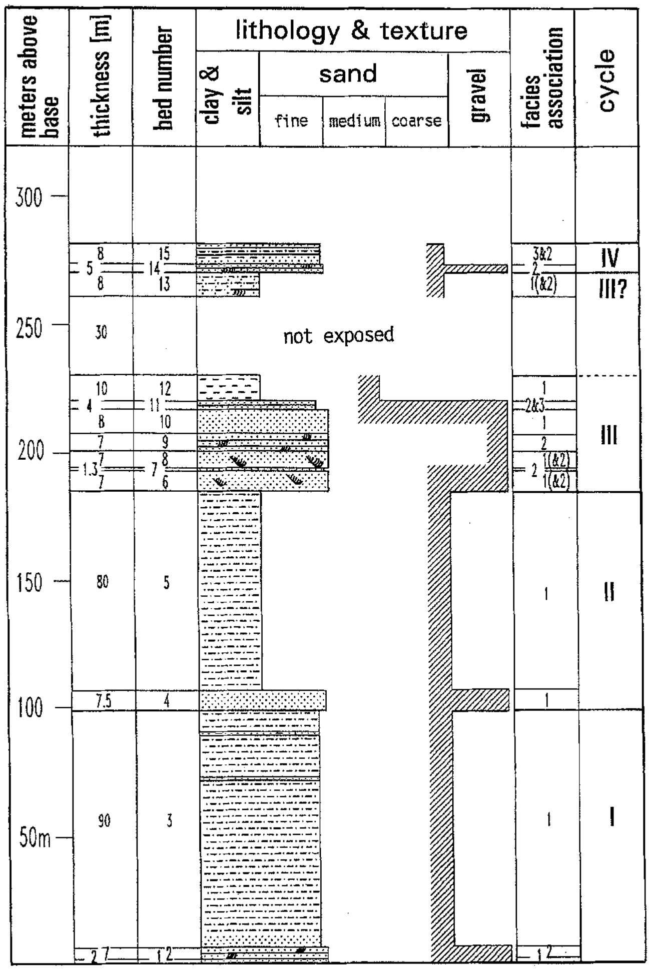

Fig. 6 Vertical section of the Gross Brukkaros stratigraphic sequence, as exposed along the W-side of the prominent gully in the S of the structure (profile area marked in Fig. 4). Both average (estimated) grain size (*patterned*) and maximum grain size (*hachured line*) are recorded. Levels with crossbedding are indicated

rim and inner slopes of the Brukkaros depocenter. Intercalations of fluviatile sediments (facies association 2) within the flow deposits show no preferred spatial distribution. Within facies association 1 and 2 the coarsest deposits were observed close to the rim of the depression. Towards the center the deposits are generally more fine grained. The downslope transition from debris-flow to mudflow dominated successions can be seen particularly well on the inner slope on the east side of Brukkaros. At the foot of the slope the mud-rich deposits became periodically flooded due to a fluctuating lake level, as documented by the intercalation of thin lake beds, imprints of grass leaves, bioturbation structures, desiccation cracks, and raindrop imprints. Thus transition towards the marginal lake facies (association 3) is also documented here.

The center of the structure is covered by a secondary alluvial fill of Tertiary and Quaternary age (Fig. 4). However, from the systematic facies transitions described above it may be concluded that the sequence beneath the secondary fill will be dominated by the deposits of a large central lake body, from which only marginal lobes are visible in the exposures of lake beds on the inner slopes of Gross Brukkaros.

Petrographic composition

The mineral constituents of the Brukkaros sediments consist to a large extent of angular to well-rounded quartz grains. The most highly rounded grains are so mature as to suggest an aeolian origin with a derivation from the Kalahari Basin (Stachel et al. 1994). Also found are angular to rounded plagioclase and augite grains (together up to 50 vol. %) derived from disintegrated Karoo dolerites of the Keetmanshoop dolerite complex (Siedner an Mitchell 1976), alkali feldspar and subordinate muscovite, opaque phases (magnetite, Ti-magnetite and ilmenite) and commonly rounded tourmaline grains. Small (<50 μ), hematite-stained dolomite rhombohedra and less common clear calcite rhombohedra occur in the otherwise unresolvable matrix. According to X-ray diffractometer analyses reported by Janse (1969), the sediment matrix consists of feldspar dust with small amounts of quartz, calcite and dolomite.

Fig. 7 Lacustrine sediments: marginal facies association (3). Debris-flow deposits (10–20 cm thick) are intercalated with normally graded turbiditic sandstones and plastically deformed laminated mudstone (e.g. between the lowermost debris-flow in the photo and the underlying turbidite units). Crest of southeastern basin rim

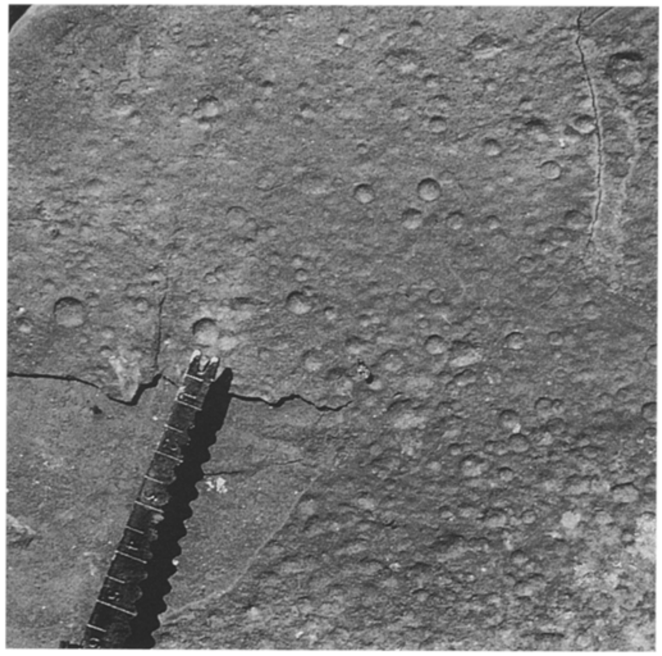

Fig. 9 Raindrop imprints on laminated mudstone (facies association 3), documenting a fluctuating lave level. Southeastern basin floor

Grain-supported fabrics are restricted to the fluviatile sediments. Within the massflow units the volume of the muddy matrix is variable and may reach up to approximately 80% (mudflow deposits).

Rounded sand-sized shale clasts are the dominant constituent in some beds. Angular pebble- and boulder-sized shale fragments are pale, partly bleached with red cores, or red. The pale clasts were probably derived from both Nama and Dwyka shales (lowermost Karoo, overlying the Nama shales), whereas the two latter obviously originated from the red-colored Nama Group

Fig. 8 Turbidite units developed as Bouma divisions B, C and D within (central) facies association 4. Lower inner slope, N side Brukkaros

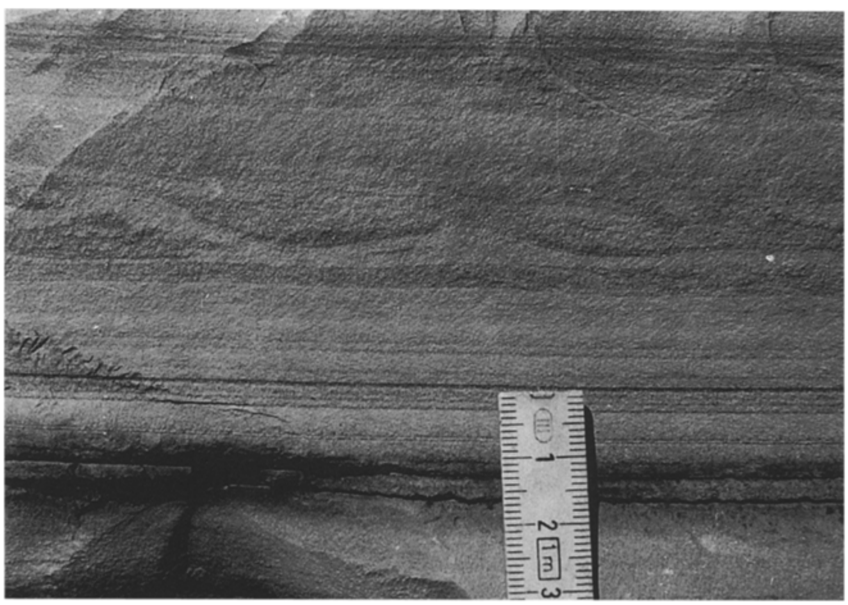

Fig. 10 Massive mudflow deposits (Entrance Valley, profile unit 5, Fig. 6) overlain by plane-bedded fluviatile sediments (base of unit 6) dipping towards the center of the structure. From the top of unit 5 a network of sedimentary dikelets extends downwards for several meters. Relative to the land surface of that time some of the dikelets are horizontal, suggesting that earthquakes may have been involved in their generation. Picture height is about 2 m

source rocks only. The spatial coexistence of bleached and unbleached clasts indicates bleaching of Nama Group rocks prior to deposition. Other lithic clasts include quartzitic sandstone and, even more rarely, dolerite, black chert, granitoid, and rounded quartzite pebbles, at least some of which originated from Dwyka Formation tillites. Some of the shale clasts are very angular with sharp pointed edges and thus may not have been transported over great distances. Therefore they are assumed to represent lithic pyroclasts derived from the surrounding carbonatitic diatremes of the Gross Brukkaros Volcanic Field (Fig. 5).

There are a few larger (up to 10 cm in diameter) pebbles and blocks obviously derived from carbonatitic intrusive rocks. The interpretation of finer clasts, which also have the orange color typical of carbonatitic rocks at Brukkaros, is uncertain, since they could in part also be altered shale clasts. Round, pebble-sized, grayish, greenish or brownish fragments are very common in several layers. Because of a different grain-size and composition of their altered groundmass relative to the enclosing sedimentary matrix they may be recognized as juvenile lapilli. Microprobe and XRF analyses (Stachel et al. submitted) show that the brownish lapilli are magnesiocarbonatites, the grayish lapilli calciocarbonatites, and the greenish lapilli fenitized calciocarbonatites. However, there are no magmatic phenocrysts present in these lapilli. The observed grains of quartz, clinopyroxene and plagioclase are minerals also present elsewhere in the Brukkaros sediments. Therefore they are regarded as xenocrystic inclusions which probably were introduced into the former melt by phreatomagmatic explosions. The fenitization of the Brukkaros sediments (e.g. aegirine and albite overgrowth), grading into hydrothermal crystallization of quartz, calcite, barite, and zeolite, is described in detail by Ferguson et al. (1975), Miller and Reimold (1987), and Stachel et al. (1994).

The petrography of the sedimentary fill clearly indicates dual sources: first the Nama, Karoo and Kalahari country rocks, and second, a minor component derived from tephra deposits dominated by lithic pyroclasts, which were available close to the edge of the depocenter. The predominance of country rocks indicates that these lithic and juvenile pyroclasts could represent reworked phreatomagmatic deposits. Ejection of the mostly non-vesicular pyroclastic deposits is attributed to the numerous small carbonatitic diatremes exposed around Brukkaros. However, additional vents may also be buried beneath the basin sediments.

Sedimentary fill/wallrock relationships

In general the basal contact of the Brukkaros sequence is erosional and sharp against the various units composing the collar. These are mainly Nama Group sediments, but at six localities in the SSW and ESE, the latter are overlain by Dwyka Formation rocks, not previously recognized in the collar. The Dwyka rocks overlie a regional unconformity. The uppermost few cm to m of the Nama shales beneath this unconformity commonly show upwardly increasing degrees of brecciation. Bleaching of the contact zone is a common phenomenon. Brukkaros-fill material has penetrated downwards up to 5 m below this unconformity surface along cracks to form dikelets (a few mm to about 20 cm thick). These branch to form entire networks. Some of the dikelets are horizontal, which implies that earthquakes have provided vertical momentum to cause their formation. Such earthquake-generated dikelets also are present within the Brukkaros sequence (Fig. 10), indicating that this was a recurring phenomenon.

At several outcrops of the basal contact a wallrock breccia is developed where Nama fragments (up to boulder size) are imbedded in a matrix of pulverized shale. These basal breccias may already contain fragments of bedded Brukkaros sediments. On the ESE and SW side of Brukkaros, where the Dwyka country rocks are in contact with the sedimentary fill, a gradation can be seen between in situ Dwyka Formation, disrupted Dwyka Formation developed as a crackle breccia, and Brukkaros beds in which Dwyka clasts show a degree of downslope transport.

Cycles of deposition

A deep gully (the "Entrance Valley", Fig. 3) drains the central depression of Gross Brukkaros towards the S. There, along the only footpath leading into the "crater", a profile (Fig. 6) of the Brukkaros sedimentary sequence is exposed with a total thickness of almost 300 m. The vast majority (almost 90%) of the sequence is composed of the mudflow and debris-flow deposits (facies association 1) with a few intercalated fluviatile successions (facies association 2). Towards the central depression, at the higher levels of the profile, fluviatile units (facies association 2) as well as mudflow units (facies association 1) are intercalated with lacustrine deposits (facies association 3) in layers 11 and 15 (Fig. 6).

Within the stratigraphic record depicted in Fig. 6 several fining-upwards sequences occur in which the average grain size decreases from medium sand (250–300 μ, layers 1, 2, 4, 6, 7, 8, 9, 10, 14) towards fine sand (175–200 μ, layers 3, 11, 15) or even down to silt- and clay-size (layers 5, 12, 13). The decrease in average grain size is accompanied by a decrease in the proportion and, to a lesser extent, also in the size of the pebble-sized clasts (maximum grain size). The repetition of decreasing grain size within the stratigraphic sequence is interpreted in terms of four sedimentary cycles (cycle I: layer 1–3; cycle II: layer 4–5; cycle III: layer 6–12 (or 13?); cycle IV: layer 14–15). The sedimentary cycles started with increased deposition of quartz-, shale-, plagioclase-, and clinopyroxene-rich (the latter two derived from Karoo dolerites) deposits, interpreted as resulting from rigorous incision into the walls of the depocenter and the overlying tephra deposits. These subsequently graded into fine mud-rich deposits. These cycles might reflect repeated reactivation of the system due to subsidence, although climatic changes also have to be considered.

Erosional contacts are frequently observed at the base of fluviatile sediments which overlie massflow deposits. The lateral significance of these angular discordances within the Brukkaros sequence is, however, difficult to assess, because single beds cannot be traced over great distances. At two localities contacts between adjacent cycles are seen to be angular discordances cutting down into the underlying well-bedded lake deposits: (1) On the inner N side of Gross Brukkaros, lake beds are cut out by erosion that preceded fluviatile deposition, and the fluviatile sediments dip into the depression 5° less steeply than the underlying lake beds. (2) On the crest line on the ENE side of Brukkaros a contact between lake beds and overlying fluviatile units develops into an angular discordance of about 30° over a few tens of meters in a direction concentric to the crater. Elsewhere, in the Entrance Valley section, such a cycle boundary is directly underlain by the earthquake cracks shown in Fig. 10. This evidence, together with the obvious significant rejuvenation of the depositional system, lead us to the conclusion that the cyclicity is controlled by synsedimentary subsidence phases in the central part of the Brukkaros structure.

Structure of Gross Brukkaros

At the present erosional level the dome structure of the Gross Brukkaros country rocks is outlined by the top of the Haribes Member quartzites, which forms a dip-slope of about 10° over most of the outside of the complex. However, at the foot of the topographic Gross Brukkaros dome structure, the quartzites continue to dip outwards below the less resistant Rosenhof Member shales. At the S side of Brukkaros bedding of the Nama Group sediments becomes horizontal only at about 2 km from the base of the hill. Thus, the structural dome is broader than the actual hill of Gross Brukkaros.

Approaching the crest of Gross Brukkaros the dip of the quartzites becomes horizontal, and 0.5–1 km from the collar the beds start to dip inward as documented again by the preservation of inwardly dipping Rosenhof Member shales (Fig. 4). At the discordant contact with the overlying Gross Brukkaros sedimentary sequence, the shales generally dip inward at about 15–20°. Only in the NNE-part of Gross Brukkaros (see Fig. 4) does the dip of the Nama beds not conform to the general structure. Here the contact between the Nama Group and the Brukkaros sedimentary sequence locally dips outward.

The simplistic picture is of a circular ring-anticline, disturbed only on the N side by the intensely faulted horst-structure of the "balcony" (Janse 1969). Since carbonatitic intrusives are affected by the tectonic brecciation associated with the balcony faults, the formation of the balcony must be penecontemporaneous with the Gross Brukkaros structure itself. However, the Brukkaros sediments themselves are not displaced by the balcony fault system, indicating that the balcony predates in-filling of the depression and is related to the initial doming of the country rocks.

In general, the contact between the Brukkaros sequence and the Nama shales or the Dwyka Formation is marked by a small angular discordance, whose dip is greater than that of either of the latter two. The Brukkaros sediments sit on top of and parallel to this discordance. Only on the E-side of the large Entrance Valley cutting through the S-side of Brukkaros do the younger sediments sit clearly on a surface steeply truncating into the Nama Group sequence. Bedded blocks of Brukkaros sediments, several meters in size, together with large blocks of Nama shale, occur very close to the steep contact. This may have resulted from a syndepositional landslide into the depocenter. Close to the depression rim bedding of the Brukkaros sequence characteristically dips between 25 and 30° inwards. Towards the center of the depression dips commonly decrease to well below 20° (Fig. 4). Steeper dips are observed only near faults, e.g. at the major ESE-trending fault in the southern half of Brukkaros, where dips of up to 68° indicate that the NE side is downthrown.

Volcanic activity around Gross Brukkaros

Several newly discovered diatremes filled with sedimentary material, either similar to that in or derived from Gross Brukkaros occur on the S- and SE-flanks of the hill (Fig. 4). The largest of these vents has a maximum diameter of almost 500 m and the filling consists of a megabreccia rich in blocks of fossiliferous lake beds, indicating that it formed within already partly consolidated sediments of the Brukkaros depocenter. Numerous small vents and dikes of carbonatitic composition oriented radially to Gross Brukkaros (Fig. 5) occur on the flanks and at the foot of Gross Brukkaros (Janse 1969; Kurszlaukis and Lorenz 1992; Kurszlaukis in prep.). In addition, two more diatremes with an assumed kimberlitic composition and the Blue Hills monticellite peridotite intrusive complex are developed within 7 km of the Gross Brukkaros depression (Janse 1969).

From field observations it would appear that subsidence and filling of the Brukkaros depocenter slightly postdates the peak of intrusive activity, since no dikes were found to cut the Brukkaros sedimentary sequence. However, at one locality (basal contact with Nama shales on the SSW side of the hill) a swarm of very thin (max. 1 cm thick) carbonatitic dikes intrudes the lowermost beds of the Brukkaros sequence exposed in this area. This, together with the diatremes filled with brecciated Brukkaros sedimentary material, suggests overall contemporaneity of sedimentation and volcanic activity at Gross Brukkaros. Thus, the Late Cretaceous ages given for the surrounding volcanism, 77 Ma for the Blue Hills (Reid et al. 1990) and 71.5 Ma for the Gibeon kimberlites (Davies et al. 1991), may equally be applied to the deposition of the Brukkaros sediments. The radiometric data are in agreement with the reported age (Cretaceous or post-Cretaceous) of newly discovered plant fossils from the lake beds within Gross Brukkaros (Kelber et al. 1993).

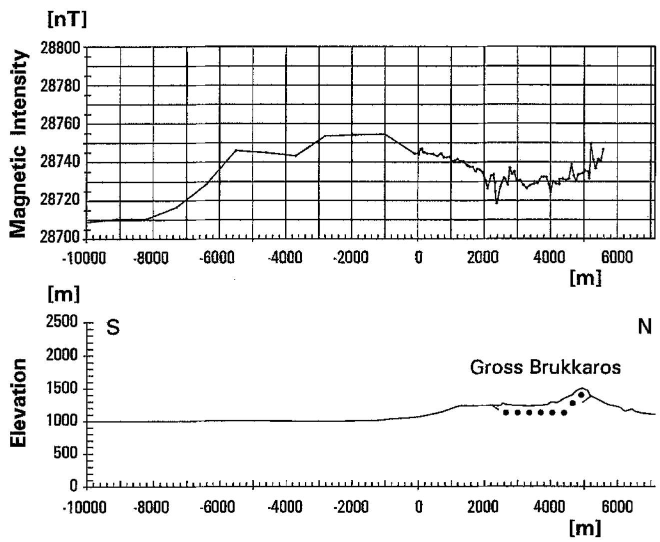

Fig. 11 Magnetic traverse (S–N) over Gross Brukkaros. *Heavy dots* represent the Brukkaros sedimentary fill. Distance 0 km refers to the southern hillfoot. Horizontal dip of the Nama Group sediments, outside the dome structure, is reached at about −2000 m

Magnetic Profile

In order to locate and determine the extent of possible intrusive magmatic bodies or diatremes concealed beneath the sedimentary cover, a 16 km N–S geomagnetic profile was surveyed across the Gross Brukkaros structure. The total intensity of the Earth's magnetic field was measured using a proton spin magnetometer. The data were corrected with an automatic base station to the local field at 5. 5. 1992, 4 p.m.

The measured N–S profile (Fig. 11) shows no significant anomalies indicative of shallow, highly magnetic bodies. The Brukkaros depression itself coincides with a shallow magnetic low (the total intensity goes down by about 25 [nT]), which may be attributable either to a primarily lower susceptibility of the Brukkaros sediments, compared to the surrounding Nama Group deposits, or to partial demagnetization of the rocks beneath the Brukkaros depression due to the metasomatic alteration (the high fO_2 during fenitization causes conversion of strongly ferrimagnetic magnetite into essentially nonmagnetic hematite). Two small positive magnetic anomalies (increase by about 10 [nT]) exist within the Brukkaros depocenter (at 2500–2900 m and at 4600–4700 m and may indicate the presence of vents buried beneath the Brukkaros sediments. However, a similar third positive anomaly (at 5200 m) lies just a few meters outside the depocenter on exposed Nama Group sediments, thus documenting the questionable significance of these small anomalies.

A decrease in intensity (about 35 [nT]) is present in a distance of −6000 to −8000 m (southwards) to the base of Gross Brukkaros. From geometrical considerations it is evident that a possible magma reservoir causing the Gross Brukkaros dome structure may not be broader than the dome structure itself and will have to become increasingly smaller with depth. Therefore, a direct connection of this southward decrease in intensity with Gross Brukkaros itself is rejected because of the distance involved. This anomaly might be related to a basement structure, possibly faulting. However, due to the insufficient N-extension of the magnetic survey the possibility of a similar decrease in magnetic intensity in this direction may not be ruled out. The resulting magnetic high of about 35–45 [nT] might then be attributed to a magma reservoir at a depth of several kilometers, not related to the Gross Brukkaros dome structure itself, but possibly related to volcanic activity within the

Gross Brukkaros Volcanic Field. However, a compilation of aeromagnetic data (5 km line spacing at Brukkaros) currently undertaken at the Geological Survey of Namibia does not reveal a noticeable concentric anomaly above Gross Brukkaros (D Eberle, personal communication).

Genetic Model

Gross Brukkaros represents a large structural dome (about 400 m high and 10 km wide) within Nama Group rocks, with a smaller central depression (3 km wide), in which Cretaceous sediments at least 300 m thick were deposited. The lithologies, textures, and structures of these sediments indicate that sedimentation was dominated by debris-flows and mudflows and associated shallow braided streams that debouched into a central lake. Facies relationships are typical of an alluvial fan delta/lacustrine depositional system.

The steep dips observed in the Brukkaros sediments (e.g. commonly 25–30° at the rim) suggest that they do not represent initial depositional angles. Thus, the subsidence which provided the Brukkaros depository continued after deposition and tilted the beds. This is confirmed by the presence of synsedimentary faults, angular discordances within the sequence, and repeated rejuvenation of coarse clastic deposition.

Janse (1969) suggested that the Brukkaros sediments (which he interpreted as mainly non-volcanic phreatic deposits) were deposited within a large maar crater-like structure, and that subsequent intrusive activity produced doming of the Nama beds. Subsidence in the diatreme due to compaction accompanied by intrusive doming of the Nama rocks would thus explain the tilting of the Brukkaros beds. Although a late intrusive stage is very common during the formation of maar diatremes (Lorenz 1985, 1986), it is normally restricted to the injection of rather small dikes, sills, or plugs within the diatremes. A dome structure, however, with about five times the diameter of the central "vent" forming during a late stage of diatreme evolution appears to be very unlikely. The absence of primary pyroclastic deposits within Brukkaros also contradicts the interpretation of the Brukkaros depocenter as a large maar crater-like structure. Finally, single maar craters are smaller in diameter than the central depression of Gross Brukkaros (Lorenz 1985). Only coalesced maars may reach the size of the present Brukkaros depression. However, the existence of lake beds at several localities along the crest of Brukkaros indicates that the original depression was even larger than the present diameter.

We interpret the formation of the broad and relatively flat Brukkaros dome with its associated radial intrusive and explosive activity (Janse 1969; Kurszlaukis and Lorenz 1992) in terms of a shallow intrusion of laccolith-like form (Fig. 12a). According to depth-width relations derived from finite element modeling (Komuro et al. 1984) the maximum depth of the intrusion responsible for the 10 km wide Brukkaros dome is 4 km. Within this possible depth range the basement-Nama boundary, about 1 km below the present surface (Janse 1969), represents a major interface between rocks of contrasting density and rheology, suitable to cause the rising magma to accumulate and to spread laterally. Depletion of this shallow magma reservoir by at least 4–5 km^3 (Fig. 12c), either during the formation of the numerous dikes and vents around Brukkaros, or during eruptions through hypothetical vents located centrally but not now exposed, caused subsidence in the center of the dome. Repeated phases of subsidence are documented by the rejuvenation of the system, reflected in the sedimentary cycles and in the evidence for strong synsedimentary earthquake activity. Within this developing caldera the Brukkaros sedimentary sequence was

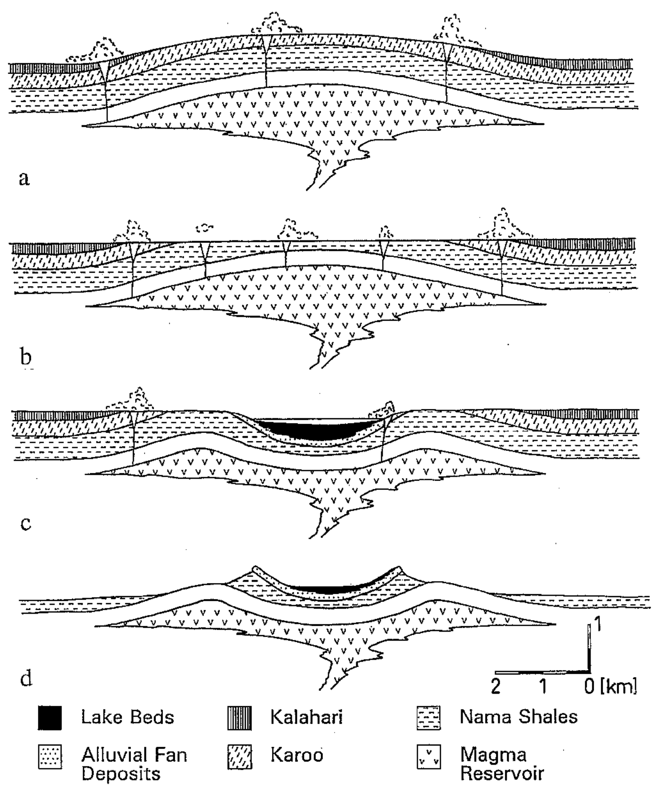

Fig. 12a–d Idealized model (true to scale) for the evolution of the Gross Brukkaros system. **a** A laccolith-shaped magma body intruded at shallow depth and domed the country rock stratigraphy. Erosion of the rising dome starts immediately. **b** The dome structure is quickly planated due to the easily erodible Kalahar Karoo and (at this time) Nama sediments. **c** Continuing volcanic activity (maar-type volcanism, dike intrusion, and perhaps lava flows) caused increasing depletion of the reservoir. Due to subsidence a centrally located caldera evolved, which formed the Brukkaros depocenter. The subsiding "crater" contained a permanent water body, within which deposition of lake beds occurred. A fluviatile system eroding backwards transported clastic sediments radially inward. The final shape of the caldera requires a mass deficit at depth of about 4–5 km^3. **d** Today Gross Brukkaros is a crater-shaped inselberg, which became protected against erosion by its cap of highly silicified sediments

deposited (Fig. 12c). The dips observed today within the fill sequence (Fig. 12d) are due to subsidence occurring during and after the deposition of the sediments.

Development of the dome structure and subsequent subsidence of the reservoir roof must have taken place over a considerable span of time. Denudation must have planated the rising dome (Fig. 12b) before deposition of the central "crater"-sediments, otherwise the ring structure would have worked as a morphological barrier restricting clastic input. The post-depositional tilt of the Brukkaros sediments indicates, however, that the youngest sedimentary fill units preserved were deposited prior to the cessation of magmatic activity at Brukkaros.

There are two important structural characteristics of Gross Brukkaros which do not conform with the general caldera model (Smith and Bailey 1968): (1) a radial instead of a concentric dike orientation and (2) the absence of field evidence for subsidence along ring faults.

Addressing the first point it may be noticed that both radial dikes and cone sheets result from upward magmatic pressure, but under very different stress distributions. Cone sheets are emplaced along shear fractures that are formed as result of dynamic stresses arising from the rapid expansion of the magma (Phillips 1974). No evidence for such catastrophic caldera eruptions exists at Brukkaros. The conditions for the formation of radial dikes, however, were met at Brukkaros, when the accumulation of magma within the laccolith-like chamber caused the swelling of the Brukkaros dome. During swelling the intermediate principal stress ($\sigma 2$) takes a radial orientation due to the weight of the rocks, which tend to slide off the dome (Phillips 1974). The maximum principal stress ($\sigma 1$) is approximately vertical or perpendicular to the ground surface; the minimum stress ($\sigma 3$) is consequently oriented concentrically to the dome. When further swelling of the dome reduces $\sigma 3$ to a magnitude such that the intrusive pressure of the magma exceeds the combined minimum principal stress ($\sigma 3$) and the tensile strength of the domed country rocks, radially oriented hydraulic fractures will be formed (Phillips 1974). A sufficiently high volatile pressure of the magmatic system at Brukkaros is also documented by radially oriented hydraulic breccia dikes described by Kurszlaukis (in prep.).

The observed radial dike pattern and its connection with magma intrusion below Brukkaros is also consistent with the scale model experiments of Komuro et al. (1984) simulating the rise of magma reservoirs from 15 km depth. When swelling of a dome structure at the surface began in their experiments, steeply dipping radial cracks started to grow outward from the center of the dome. Depending on the material used to model the Earth's crust, these radial cracks were or were not followed in time and linked by short and steep concentric cracks. Komuro et al. (1984) stress that the radial extension cracks formed during inflation of the dome structure represent optimum feeding routes of dikes, capable of tapping a rising magma reservoir in the deeper crust. The striking resemblance of the dike pattern around Brukkaros (Fig. 5) with the crack distribution in the scale model experiments (Komuro et al. 1984, Fig. 13) strongly supports our laccolith model. The experiments and the theoretically predicted stress distribution (Phillips 1974) suggest that the radially oriented dike pattern around Brukkaros was set up early, during swelling of the Brukkaros dome.

Within the standard model of caldera formation, cauldron subsidence causes the downward movement of a cylindrical block along a ring fault, but none of the characteristic structural features of cauldron subsidence, such as ring faults, vent rings, or ring dikes, were observed at Brukkaros. Walker (1984), however, describes a number of caldera-like volcanic depressions, that appear to have subsided by downsagging and where the subsided area is not contained within a ring fracture. The criteria for such "downsagged calderas" (Walker 1984) (a gradual inward slope without tangential fault scarps and centripetal dip of originally (nearly) horizontal caldera deposits) are both met at Gross Brukkaros. Comparing data on the size of calderas and cauldrons Walker (1984) suggests that only few of the smaller (<10 km across) calderas are linked with cauldron subsidence structures. In addition it would appear that cauldrons and ring dikes almost exclusively form within Precambrian cratonic crust, suggesting that a rigid, crystalline crust is required for their formation. Caldera formation at Gross Brukkaros, however, took place within sedimentary rocks. A further important factor leading to downsagging rather than subsidence along ring faults is incremental caldera growth, resulting from a succession of moderate-sized volcanic events, instead of catastrophic caldera formation (Walker 1984). For Gross Brukkaros incremental subsidence has been well documented during the present study.

Thus, Gross Brukkaros forms an important and unusual end-member type of caldera, whose specific features may be attributed to strong initial doming (dike pattern) together with incremental subsidence, comparatively small size, and formation within sedimentary wall rocks (downsagging with lack of major ring faults).

The composition of the melts intruded beneath the Brukkaros dome structure is not known directly. However, the lack of a positive magnetic anomaly at Gross Brukkaros, the fenitization of the crater sediments, and the carbonatitic composition of the radial intrusives (Janse 1969; Kurszlaukis and Lorenz 1992), suggest an Fe-poor, highly alkaline to carbonatitic melt composition. A magma able to fractionate melts such as the Blue Hills monticellite peridotite, which is rich in minerals with a high magnetic susceptibility (9 vol. % magnetite; Janse 1971), can be excluded.

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