

but considerably more dikes and dike-fragments (Fig. 1). The relationship of two smaller kimberlite clusters towards the west (Maltahöhe) and south-west (Bethanien) of the Gibeon Kimberlite Field has not been finally resolved, but it is possible that these clusters are related to the same hotspot track (Vema or Discovery). The age of the Gibeon kimberlites scatters at about 70 Ma (Spriggs, 1988; Davies *et al.*, 1991; Hoosen, 1999; Kurszlaukis *et al.*, 1999) and preliminary data from Hoosen (1999) suggest a slightly younger age for a diatreme from the Maltahöhe cluster, supporting the hotspot model as suggested by Spriggs (1988) and Davies *et al.* (1991).

The kimberlites are classified as non-diamondiferous, off-craton Group 1 kimberlites. There is, however, a close genetic relationship in space and time to carbonatites which seem to be concentrated at the margins of the field. It is interesting to note that the occurrence of carbonatites is commonly linked to dome structures such as Gross Brukkaros (Lorenz *et al.*, 1995, 1997, 2000) at the southern margin of the Gibeon Kimberlite Field and the Hatzium dome at its northern margin. The Blue Hills Intrusive Complex (Kurszlaukis, 1994; Kurszlaukis and Franz, 1997; Kurszlaukis *et al.*, 1999) in the south of the Gibeon Kimberlite Field, inside the Gross Brukkaros Volcanic Field, is most probably also related to the same thermal event as the kimberlites.

Co-ordinates of the diatremes as well as whole-rock geochemical compositions are given in Kurszlaukis *et al.*, (1998b, c). Apart from early work of Janse (1969, 1975) and Mitchell (1984), other studies include the mineralogy of mantle nodules (Franz *et al.*, 1996a, b) and crustal xenoliths included in kimberlite and carbonatite diatremes (Rupperecht, 1997).

The Gibeon kimberlites are located in the Gibeon Plateau, a flat, featureless plain with an average altitude of 1000 m asl. The Gibeon Plateau is underlain by a relatively undisturbed foreland basin sequence of quartzites, shales and carbonates of the late Precambrian-early Cambrian Nama Group. Because of the regional dip of the Nama and Karoo sediments of a few degrees towards the east, the land surface, from west to east, shows a number of escarpments through the stratigraphy of the Nama sediments and eastwards up into the overlying late Palaeozoic-Mesozoic Karoo Supergroup (Grill, 1997). Post-kimberlite Kalahari sediments cover the easternmost portion of the Gibeon Field so that the actual boundary of the field towards the east is not precisely known. In the southeastern portion of the field, the sediments of the Dwyka and Ecca Groups of the Karoo sequence (Grill, 1997, Lorenz *et al.*, 2000) are intruded by the Keetmanshoop dolerites. To the north they are capped by Kalkrand Formation flood basalts, the effusive counterparts of the dolerites (Gerschuetz, 1996). The boundary between the northern diatremes containing xenoliths from the Kalkrand Basalt Formation and the southern diatremes containing xenoliths from the Keetmanshoop Dolerite Complex runs be-

tween the diatremes of Hanaus (north) and Deutsche Erde (south) (Kurszlaukis *et al.*, 1998c). Judging from the presence of specific sedimentary and volcanic xenolith types, together with the known stratigraphic thickness of the slightly eastward dipping Nama and Karoo strata, the maximum thickness of cover rocks eroded since eruption of the kimberlites is estimated at about 540 m (Grill, 1997; Lorenz *et al.*, 1997), which is in conformity with the estimates made for the Gross Brukkaros region. Because of the slight regional dip of the Nama and Karoo sediments to the east, it is assumed that the exposed emplacement level of the kimberlites becomes shallower towards the east. It can be further deduced from xenolith populations that some late Karoo erosion occurred before eruption of the Kalkrand basalts, since part of the Ecca Group lithologies is missing in the xenolith assemblage from the westernmost kimberlite diatremes (Grill, 1997).

Kimberlite dikes

The kimberlite dikes are generally less than 2 m thick (commonly less than 60 cm) and have a length of up to several hundred metres. The dike system at Deutsche Erde, for example, has a length of 850 m, while that at Fingerklip/Mukorob exceeds 1000 m (Fig. 2). Petrographically the latter dike is a carbonatite. Frankel (1956) interpreted this rock as a carbonatised olivine melilitite. However, Haggerty and Fung (1998) point out that the Mukorob dike represents a highly differentiated kimberlite. The kimberlite in the dikes is usually strongly decomposed and displays relatively few xen-

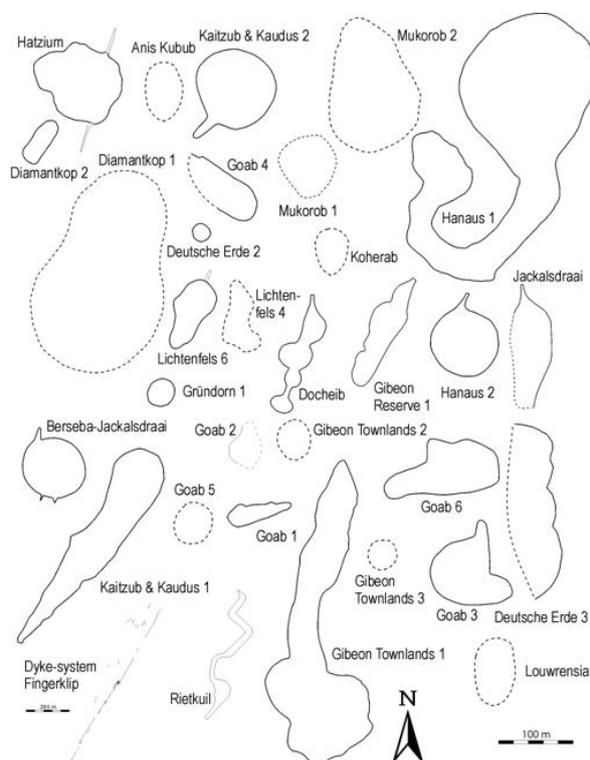


Figure 2: Outcrop plan view of the Gibeon kimberlite diatremes.

ocrysts and xenoliths. Olivine phenocrysts are usually totally serpentinised, while phlogopite shows distinct bleaching and chloritisation. Orientation of elongated crystals parallel to the dike walls is commonly observed. Vesicles are totally absent in the dikes, even in fresher samples from marginally rapidly-chilled locations.

Signs of multiple intrusive activity within the kimberlite dikes have not been recognised. This is probably due to poor outcrop quality and the high degree of alteration of most of the kimberlites. The only exception is the carbonatitic dike near Mukorob, which shows vertical planar zonation. The intrusive facies types within this dike can be distinguished by different amounts of either xenoliths or juvenile minerals. Calcite diapirs, as described by Donaldson and Reid (1982) for some carbonate-rich dikes near De Beers mine, Kimberley, are also observed. These diapirs point inwards from the dike margins and suggest relatively slow cooling after emplacement of the dike.

Most diatremes are located on and cut downwards into dikes and, therefore, the dikes in all probability represent the feeders for the diatremes. The diatremes are often elongated in outline and strike in the same direction as their feeder dikes.

As a feature characteristic of the kimberlites of the Gibeon Field, both the dikes and diatremes show an updoming of country rock beds along their margins, similar to the observations of Wagner (1914, 1971) for kimberlites in southern Africa. This is typically absent in the vicinity of carbonatite dikes and diatremes surrounding Gross Brukkaros. Updoming is most obvious along dikes and diatremes intruded into the Nama succession; for kimberlite bodies intruded into Karoo rocks, marginal updoming is less evident which could be a result of poor outcrop quality. Updoming of country rocks has affected a zone up to 15 m wide in the contact to diatremes but normally only 6 m wide in the vicinity of dikes. Dislocation of sediments becomes stronger on approaching the kimberlite body. Directly at the contact to the body the country rock strata may dip vertical or, more commonly, dip between 40° and 70° away from the contact. Neither the degree of dislocation nor the width of the affected country rock zone correlate strictly with the thickness of the intrusive body. Thin dikes, for example, may show dislocation of the adjacent beds for up to several metres, whereas larger dikes may only show relatively small zones of updomed country rocks. Since updoming is visible not only along dikes but also along their related diatremes, updoming is clearly related to the intrusive kimberlite and does not represent pre-existing linear, anticlinal structures which are also present in the area and which the kimberlite could have intruded. It is thought that the updoming was generated by upward drag because of post-emplacment volume increase of the kimberlite during serpentinisation of olivine and kimberlite matrix.

The kimberlite dikes and elongated diatremes frequently strike NNE/SSW and may have used a pre-ex-

isting joint pattern of the country rock striking in the same direction. The preferred orientation of dikes and diatremes appears to be determined by important Cretaceous crustal structural control in the area of southwestern Africa (Franz *et al.*, 1996a). The structural trend is oriented parallel to the mid-oceanic ridge of the South Atlantic, to the western continental margin of southern Africa and also to the margin of the South African craton. Although the opening of the Atlantic occurred about 50 million years before the emplacement of the Gibeon kimberlites, it is possible that the kimberlite intrusions used pre-existing structures of weakness generated by the stress field during the opening of the South Atlantic.

Kimberlite diatremes

Most kimberlites of the Gibeon Volcanic Field may be grouped in clusters with up to eight diatremes in one cluster (Fig. 1). Outcrop plan views of kimberlite diatremes (Fig. 2) show approximately circular (e.g. Hanaus 2: Fig. 3), highly irregular (Hanaus 1: Fig. 4) or elongated (e.g. Gibeon Reserve 1: Fig. 5) shapes. Most of the elongated diatremes and their feeder dikes are oriented in a NNE trending direction (see above). A number of elongated diatremes coalesce, such as the four single blows (in the sense of Wagner, 1914, 1971) that make up the Docheib pipe (Fig. 2 and Kurszlauskis *et al.*, 1998a) and are all located on the same feeder dike. The diatremes differ in size between some tens of

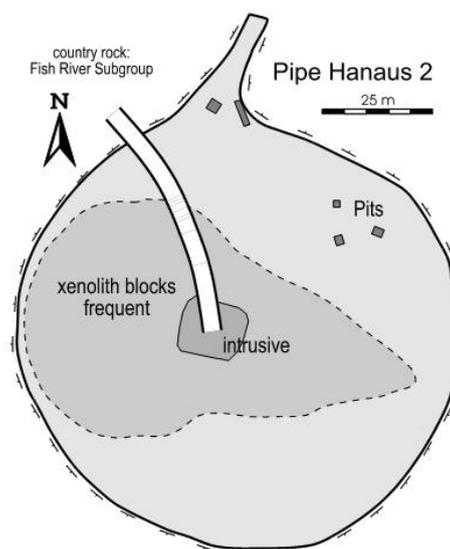


Figure 3: Schematic map of the kimberlite diatreme Hanaus 2. The country rock consists of red-brown shales of the Rosenhof Member of the Fish River Subgroup, Nama Group. Marginally to the diatreme and the magmatic kimberlite dike the shales are updomed. The area marked „xenolith blocks frequent“ to a large extent consists of blocks of subsided country rocks, i.e. lava flows and shales and sandstones from the Karoo. From the central plug of intrusive/hypabyssal kimberlite of diatreme Hanaus 2 several samples were taken and successfully used for experiments on phreatomagmatic/thermo-hydraulic explosions (Kurszlauskis *et al.*, 1998d; Lorenz *et al.*, 1999a, b).

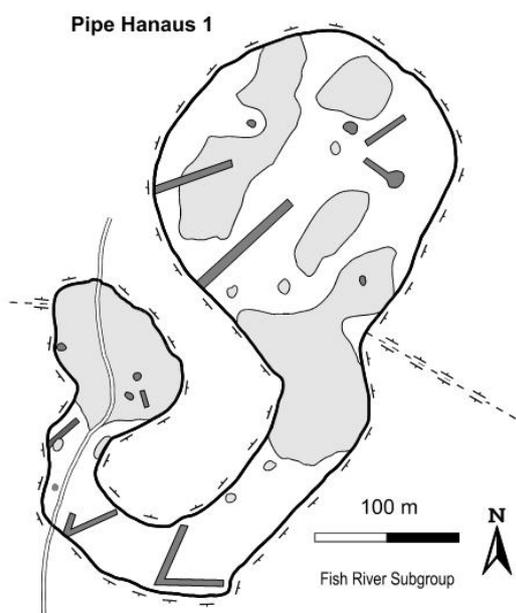


Figure 4: Schematic map of the kimberlite pipe Hanaus 1. The country rocks consist of red-brown shales of the Rosenhof Member of the Fish River Subgroup, Nama Group. Marginally to the diatreme are two marked joints along which the shales are updomed. The grey areas inside the diatreme to a large extent consist of blocks of subsided country rocks; i.e. lava flows and shales and sandstones from the Karoo. The dark rectangles and small circular areas represent exploration trenches and pits. The diatreme Hanaus 1 is exposed several tens of metres below the base of the Karoo sediments.

metres and 400 m in maximum dimension, with most of the pipes having an average diameter of about 100 m. The relative small size of the diatremes compared to their South African or Siberian counterparts at relatively shallow erosion levels suggests a shorter eruptive life, following the phreatomagmatic model of the growth of maar-diatreme volcanoes (Lorenz, 1985, 1986, 1998; Lorenz and Zimanowski, 2000).

The diatremes are mainly composed of clastic diatreme facies rocks (TKB in the nomenclature of Clement, 1982). Intrusive, or hypabyssal, kimberlite is rare. Matrix material is usually highly altered and does not allow discussion of its original composition and fabric. It is thought that the matrix primarily consisted of ash, both juvenile and derived from country rocks. Xenoliths as small as 1 cm are still discernible in the matrix, depending on the degree of weathering of the kimberlite host. In fresh kimberlite diatreme facies, xenoliths of only a few millimetres can be detected easily. The xenolith fraction with sizes between some millimetres and centimetres normally consists uniformly of sediments, originating either from Nama, Dwyka or Ecca strata. Basalt or dolerite fragments from the Karoo succession frequently exceed sizes of 1 m. The spectrum of basement xenoliths (gneisses, pyroxenites, amphibolites, pyriclasites) varies greatly and is described in detail by Rupprecht (1997).

The percentage of xenoliths varies between near zero and about 70%, depending on the diatreme and facies.

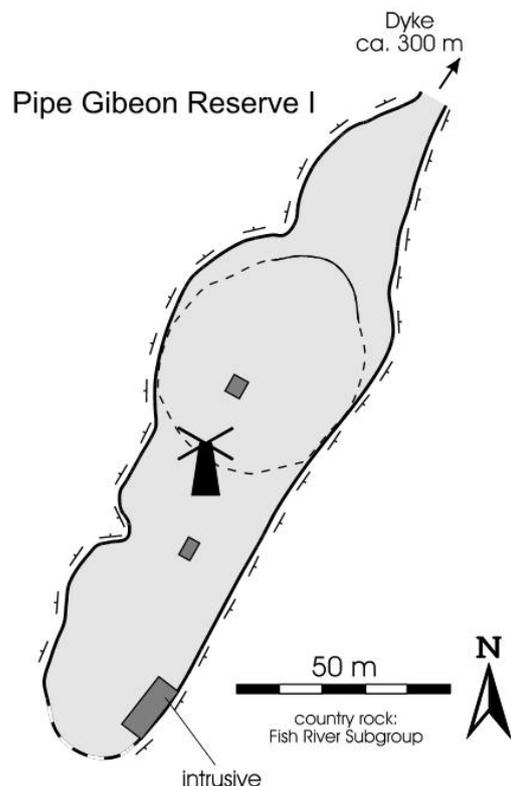


Figure 5: Schematic map of the kimberlite pipe Gibeon Reserve 1. The country rocks consist of red-brown shales of the Rosenhof Member of the Fish River Subgroup, Nama Group. Marginally to the diatreme and the magmatic kimberlite dike the shales are updomed. The grey rectangles represent exploration pits. The solid and dashed line marks the approximate area of the hypabyssal kimberlite plug which intruded the diatreme.

An enrichment of subsided blocks of country rock at the margin of the diatreme is well displayed at Gibeon Townlands 1 and Hatzium. There, megaxenoliths of Karoo sediments and basalts may reach diameters of 20 m. The blocks may be unbrecciated or may be veined and disrupted by kimberlite. Enrichment of subsided xenoliths along the margins is also observed in kimberlite diatremes of other fields (e.g. Novikov and Slobodskoy, 1979) and seems quite typical for upper diatreme facies kimberlites. Nucleated autoliths and pellet lapilli, (i.e. spherical lapilli) are recognisable in less weathered diatremes and do not normally exceed diameters of 4 cm. They may have a xenolith fragment as kernel (normally consisting of a basement rock), a serpentinised olivine grain, or a single, sparry, well rounded carbonate crystal. Without exception, the kimberlite mantling the kernel is nonvesicular.

The transition from diatreme to root zone kimberlites has not been recognised, nor have any primary bedded pyroclastic kimberlite or any epiclastic crater-lake sediments been found – either because of advanced alteration and weathering or because of erosion of the pipes to levels underlying such bedded sequences. Latestage magmatism is indicated by intrusions of magmatic (hypabyssal) kimberlite plugs into diatreme facies.

Such late plugs were emplaced in the diatremes Anis Kubub, Hanaus 2, and Gibeon Reserve 1 (Kurszlaukis *et al.*, 1998a-c). The diameter of these plugs varies between 40 m (Anis Kubub, Kurszlaukis *et al.*, 1998) and about 0.5 m (Hanaus 2). Plugs are exposed inside the diatremes at about 320 m (Anis Kubub), 400 m (Hanaus 2), and 420 m (Gibeon Reserve 1) below the original surface. Intrusive kimberlite of the respective diatremes is distinctly depleted in country rock xenoliths but may show a relatively strong enrichment in mantle fragments (best visible in Anis Kubub). It is devoid of vesicles, even in the very marginal (chilled) facies of diatreme Gibeon Reserve 1. Kimberlite from the plug inside the Hanaus 2 diatreme was used in experiments on thermohydraulic explosions resulting from the interaction of remelted kimberlite with injected water (Kurszlaukis *et al.*, 1998d; Lorenz *et al.*, 1999a, b; see also Buettner and Zimanowski, 1998).

Formation of diatremes by phreatomagmatic explosions

It is evident that juvenile kimberlite in the Gibeon Field, occurring in dikes, diatremes, intrusive plugs and spherical lapilli, is devoid of vesicles. Although post-emplacment alteration and/or weathering may obscure such evidence, sufficient fresh kimberlite has been examined (e.g. Gibeon Reserve 1) to rule out the existence of vesicles.

The spherical shape of the lapilli and autoliths indicates that the kimberlite was still largely molten at the time of eruption and was not part of a fragmented precursor dike. If vesiculation would have been the dominant eruption mechanism, then vesicles should have been preserved within the chilled juvenile clasts. Furthermore, vesicles are absent in the kimberlite matrix of the diatreme fill. Since most of the diatremes are located on their feeder dikes, indicating a penecontemporaneous activity of dike and diatreme formation, it is hard to explain how these diatremes, with their root zones at even greater depths, should have developed by magmatic explosions, i.e. ultrarapid exsolution of the volatile phases leading to fragmentation not only of the kimberlite magma but also of large amounts of country rocks but without preservation of any vesicles in the chilled diatreme clasts. The neighbouring feeder dike neither shows vesicles in the chilled marginal facies nor brecciation of the dike. Thus, it is concluded that a thermohydraulic explosion mechanism is required to provide an explanation for the localised formation of the diatremes on the feeder dikes and their specific features (content of country rock clasts and lack of vesicles in the juvenile clasts). See also discussion of the phreatomagmatic model of the formation of kimberlite diatremes (Field and Scott Smith, 1999; Scott Smith, 1999; Lorenz *et al.*, 1999a, 1999b).

Lorenz (1985, 1986, 1998, 2000) notes that diatremes are commonly emplaced on sites where dikes intersect

a zone of structural weakness. Those zones may have been hydraulically active. This model would provide a local supply of water and would explain why intrusive and explosive volcanism can be located in close proximity. That abundant groundwater was present at the time of kimberlite uprise is difficult to independently assess, but it has been shown for the Gross Brukkaros Volcanic Field at the southern margin of the Gibeon Volcanic Field that the Karoo stratigraphic sequence and the intrusive and volcanic rocks within and on top of the Karoo sediments in all probability contained several aquifers and that groundwater and some surface water fed a substantial caldera lake at Gross Brukkaros itself (Lorenz *et al.*, 1997, 1999). Moreover, fractures and fissure systems traversing the country rocks in the whole region are lined with abundant hydrothermal minerals, such as drusy quartz, calcite and barite. Finally, the highly amygdaloidal and distinctly jointed nature of the Kalkrand Basalts that cap the Karoo cover points to their highly permeable nature after eruption, and quantities of water sufficient to drive phreatomagmatic explosions may well have been stored at this level. It is therefore quite probable that circulating groundwater was available throughout the Gibeon Kimberlite Field and its localised interaction with uprising magma led to the formation of diatremes by thermohydraulic, i.e., phreatomagmatic explosions.

At Hanaus 2, Anis Kubub, and Gibeon Reserve 1, there was not sufficient groundwater available during the whole period of kimberlite magma rise. After an initial phreatomagmatic phase, lack of further influx of groundwater enabled magma to intrude and form a plug inside the diatreme and close to the original surface. That the melt of this magma would have been able to erupt phreatomagmatically has been shown by an experimental investigation: a sample (130 ml) from the intrusive plug of Hanaus 2 was remelted and water (10 ml) was injected. The resulting thermohydraulic explosion – one of the strongest so far in the Wuerzburg volcanic laboratory – not only fragmented the kimberlite melt and formed spherical lapilli, but also fragmented the brittle crucible, the equivalent of the country rocks (Kurszlaukis *et al.*, 1998d; Lorenz *et al.*, 1999a, b).

Mixing of clasts of country rocks from different stratigraphic levels is also typical for phreatomagmatic explosive activity (Lorenz, 1998; White, 1991) and thus another strong argument in favour of the phreatomagmatic eruption model for kimberlite diatremes. This process is accomplished by repeated upward ejection of debris through the diatreme fill and thus incorporating some of the diatreme fill, associated with repeated collapse of the tephra ring surrounding the crater and subsidence of the resulting mass deposits inside the diatreme (Lorenz, 1985, 1986, 1998, 2000).

At first sight, perpendicular or oblique faults or prominent joint zones cutting the dikes at the localisation of the diatremes are not present. However, the country rock joint pattern in the Gibeon Volcanic Field is, to a

large extent, clearly oriented perpendicular to the dominant NNE/SSW trend of the dikes (Kurszlaukis *et al.*, 1998c). In addition, a number of NW/SE striking faults are generally present within the area of the Gibeon Kimberlite Field. Similar faults could also have been present in the overlying Karoo rocks. Joints and faults in hard rocks (both in sediments and volcanic rocks) usually store groundwater and it is groundwater from this joint aquifer we invoke to have caused the thermo-hydraulic explosions in the rising kimberlite magma.

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