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A reinvestigation of the Okenyenya igneous complex: a new geological map, structural interpretation and model of emplacement

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The Okenyenya igneous complex, of Mesozoic age and located in northwestern Namibia, is notable for its extremely wide range of rock types of both tholeiitic and alkaline affinities. The intrusive rocks, which range from highly alkaline, silica-poor lamprophyres through to quartz-syenite, have been emplaced by a variety of contrasting mechanisms. A detailed geological map of the igneous complex is presented, together with a structural reinterpretation of a number of the component intrusions. A model of emplacement is proposed comprising: *Stage 1*, emplacement of a tholeiitic gabbro-quartz monzodiorite sill or cone sheet complex, followed by *Stage 2*, the intrusion of picritic gabbro dykes; and *Stage 3*, the emplacement of alkaline gabbros into high level magma chambers. *Stage 4* involved the injection of syenite and quartz syenite as a series of dykes and sills, primarily in the southwest of the complex but including a major peripheral ring dyke. *Stage 5* saw the emplacement of concentric intrusions of nepheline syenite and essexite during the last major phase of magmatism, with the final magmatism of *Stage 6*, involving the emplacement of lamprophyric rock types as narrow dykes, small stocks and volcanic diatremes. The identification of a major peripheral ring fault is fundamental to a new model proposed for the evolution of the intrusive complex. The ring fault is interpreted as having formed during cauldron collapse of an overlying major volcano coincident with voluminous syenitic magmatism. The probability that significant vertical displacement has occurred along the fault poses difficulties in adjudging the exact nature and former extent of early gabbroic intrusions. Stresses, resulting from unequal displacement on different segments of the encircling fault, impacting on the structurally heterogeneous gabbroic rocks are believed to have significantly determined the geometry and distribution of the younger intrusions within the complex.

Introduction

Okenyenya (20°50'S., 15°20'E.) is one of numerous Mesozoic intrusive complexes occurring in a SW-NE zone across Damaraland, northwest Namibia. It exemplifies a "ring complex" with impressive ring-like structures evident from distant views (Plate 1), although these are commonly delineated in the field by quite subtle topographic features.

Although a mere 20 km^2 in area, the complex is of particular petrogenetic interest on account of the remarkable variety of igneous rocks exposed, ranging in composition from sub-alkaline to peralkaline, and including both silica-saturated and undersaturated types. With the exception of some small dykes, the rocks are of coarse grain-size indicating the plutonic nature of the intrusions. Isotopic dating has shown the magmatism to have extended for a period of at least 5 million years in the early-Cretaceous (Milner *et al.*, 1993; Watkins *et al.*, 1994). We interpret the complex to have been the sub-volcanic expression of a major central volcano.

The igneous complex was first recognised by Korn and Martin (1939) and was subsequently studied by Simpson (1950, 1952, 1954). Simpson (1954) presented a geological map which, whilst covering the entire complex, lacked detail and relied upon schematic representation for areas of complicated outcrop. Prior to the commencement of our recent studies, no other detailed geological investigations of the complex had been undertaken, and all references in this paper to earlier observations and interpretations relate to those presented by Simpson (*op. cit.*). The rekindling of geological interest in Okenyenya and, in particular, the initiation of detailed geochronological and petrogenetic studies (e.g. Watkins and Le Roex, 1990; Milner *et al.*, 1993; Watkins *et al.*, 1994), has revealed the urgent requirement for a new, more detailed geological map. Renewed geological mapping and also evidence from an extensive programme of geochemical analysis, the results of which will be presented in full elsewhere (Le Roex *et al. in prep.*), have further indicated the need for a new structural and evolutionary interpretation. This paper presents a more detailed map of the Okenyenya igneous complex. The map is based upon a continuing programme of detailed field investigation which has thus far been focused on those parts of the complex depicted only schematically on the previous geological map, or where current knowledge suggests the earlier structural interpretation might require revision. Simpson (*op. cit.*) described in detail the mineralogy and petrography of the various rock types in the complex and related them to two evolutionary series, one tholeiitic and one alkaline. It is not our intention in this paper to discuss further the mineralogy and petrology of the major rocks types, although we have taken the opportunity to simplify the terminology in line with modem usage (Le Maitre, 1989). Our recent field studies have confirmed the previously suggested sequence of emplacement, and the overall distribution of the major rock types shown on the new geological map broadly complies with that formerly proposed, and indeed is largely based upon confirmation of Simpson's original observations. However, recognition of the importance of a major peripheral ring fault (Watkins and Le Roex, 1991) in the evolution of the complex and an understanding of the precise structure of intrusive units such as the silica saturated and oversaturated felsic rocks and a suite of lamprophyre dykes, leads us to advance a new

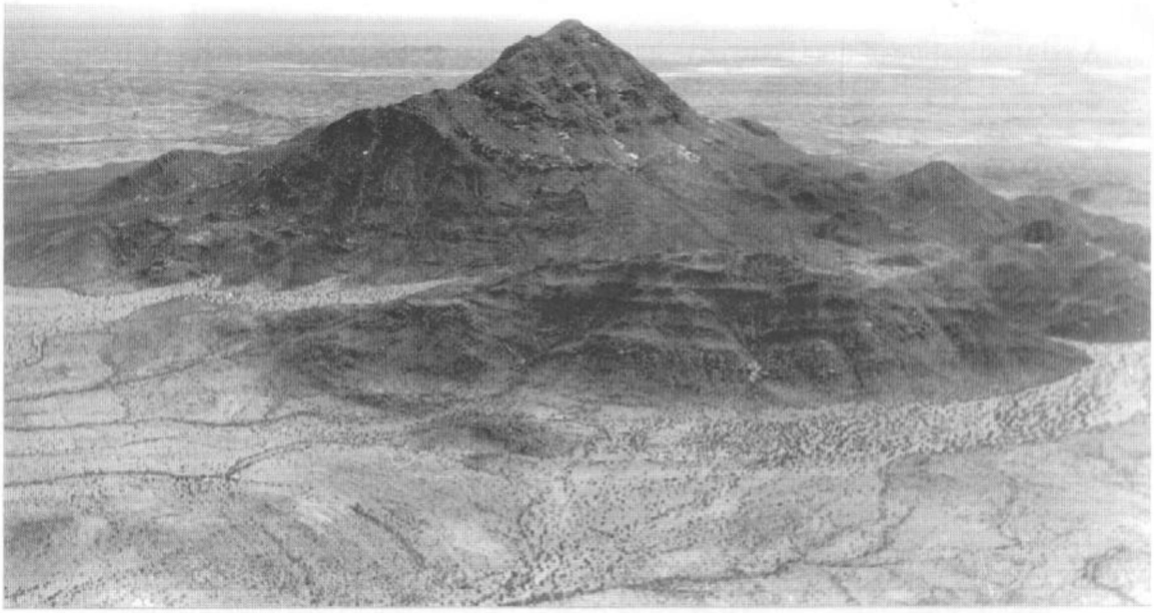

Plate 1: Aerial view of the Okenyenya igneous complex showing Johannes Berg in the foreground with arcuate gabbro and syenite ridges and Okenyenya Berg in the background, with the Adams Shoulder alkaline gabbros on the left. The central oligoclase essexite intrusion forming the summit of Okenyenya Berg is clearly visible, as is the surrounding nepheline syenite ring seen between the essexite and Adams Shoulder.

model for the evolution of the complex that is different, in significant aspects, from that previously proposed.

Geological map and structural reinterpretation

Table 1 compares the revised nomenclature adopted in this paper (after Le Maitre, 1989) with that formerly employed. A new geological map of the Okenyenya igneous complex is presented in Fig. 1. Numerous curvilinear features typifying an anorogenic ring complex are evident within the outcrop pattern and are related to intrusion coincident with, and subsequent to, the development of a major peripheral ring fault. Other curvilinear structures give rise to conspicuous ridges in early gabbroic bodies whose intrusion pre-dates the formation of the ring-fault. These ridges are particularly prominent in views of the Okenyenya complex (Plate 1; Simpson, 1954, *Plate XXIV*) and have been depicted (fine dotted lines) in Fig. 1. Interpretation of the structural significance of the various curvilinear features in intrusions of different ages, as well as attempts to account for the distribution of the major rock types and the location and orientation of abundant dykes and sills, form the basis of a new evolutionary model of the complex. Unfortunately, structural interpretation of the earliest gabbroic rocks, dated at approximately 130 Ma (Milner *et al.*, 1993; Watkins *et al.*, 1994), is most difficult based upon field relations alone. Interpretations of original intrusive structures through an exposition of present topographic form may be too simplistic in view of the possibility that significant vertical movement has occurred along the ring fault, changing the former attitude of the intrusive rocks.

Tholeiitic gabbro - quartz monzodiorite

The oldest rocks exposed in the Okenyenya complex are a series of tholeiitic gabbros, ranging from olivine gabbro to quartz monzodiorite. Exposures in the eastern part of the complex, in particular, form a series of broken arcuate ridges, and hence were formerly termed the "ridge gabbros" (Table 1). Between these ridges and the margin of the complex lies an equally broad region of monzodiorites in which there are few, if any, equivalent arcuate structures, the rocks instead producing a featureless terrain with little informative exposure. There are no conspicuous intrusive boundaries within the area of tholeiitic gabbro exposure. Although the 'inner' distinct gabbro ridges are formed of bare rock and are covered with only sparse vegetation, the bouldery outcrops preclude identification of more subtle geological discontinuities that could account for the ridges. Even when petrological differences between samples from adjacent gabbro ridges indicate the presence of a lithological boundary, there is no opportunity for detailed investigation of the contact. No screens of country rock or alternative intrusive rocks have been found, nor is there any clear evidence of fining of grain size that might indicate the margins of discrete gabbro intrusions.

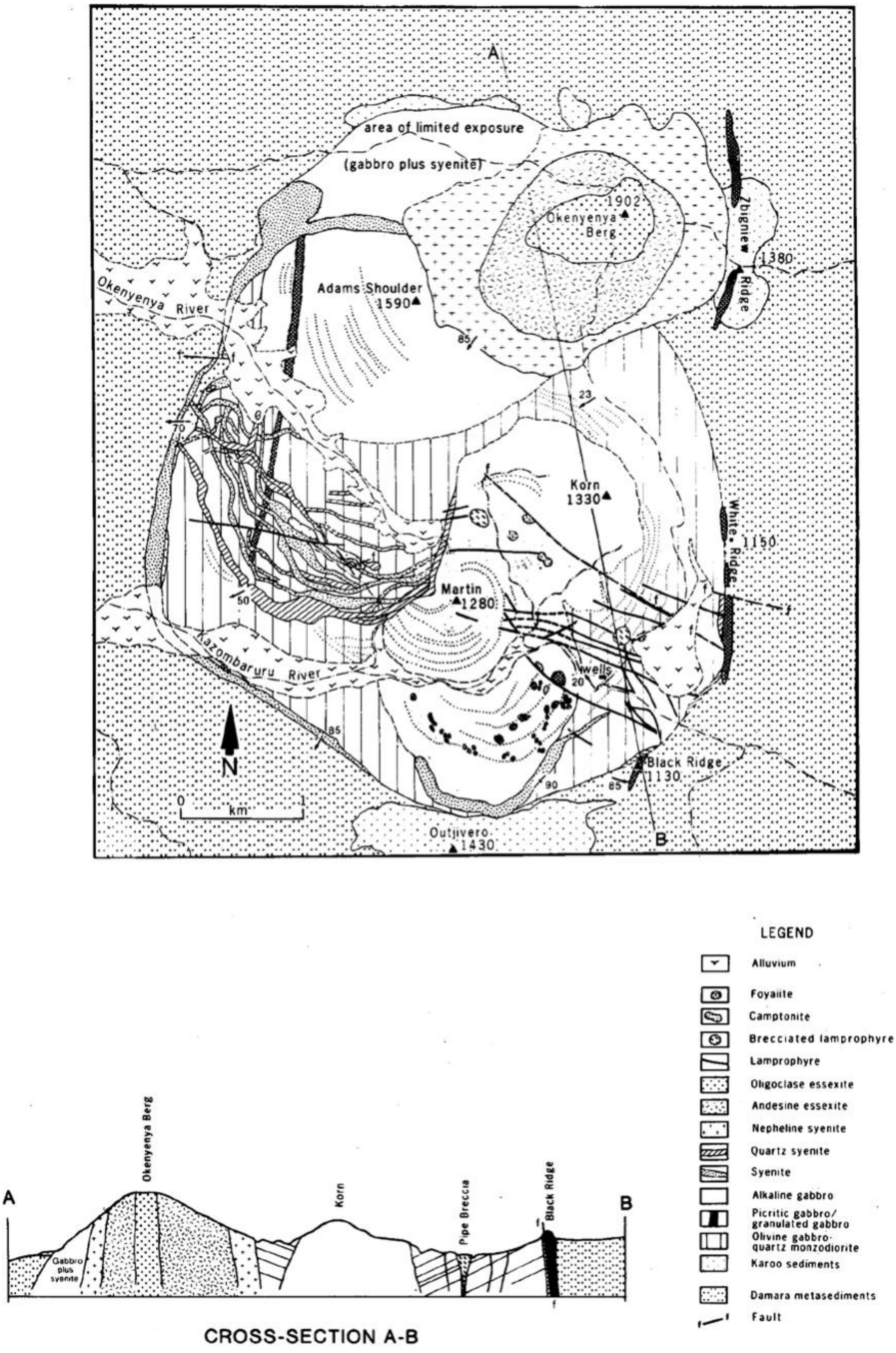

Figure 1: Geological map of the Okenyenya igneous complex. The map was compiled using the original map of Simpson (1954) which was modified and detailed using information from the present study, and that of Watkins and le Roex (1991). **A-B** shows line of cross-section.younger intrusions of Okenyenya Berg

Simpson (*op. cit.*) observed the gabbro ridges to define a roughly circular intrusion centred a little to the north of the present peak of Martin Hill (Fig. 1). On the basis of the general form of the ridges and the planes of lamination of tabular feldspars in the olivine gabbros and the adjacent monzodiorites ("ferrogabbros"), he proposed that the initial intrusion at Okenyenya had the form of "a saucer-shaped, multiple intrusion, elliptical in plan, probably emplaced by successive injection of a series of thin sheets" (Simpson 1954, page 17). That the intrusive 'sheets' were emplaced essentially contemporaneously during a single intrusive event is supported by the apparent absence of chilled margins and an overall regularity of compositional variation through the gabbros from the inner part of the complex outwards towards the margin. Given the centripetal dip envisaged by Simpson (1954), the trend of chemical and mineralogical variation across the gabbro outcrop is contrary to that expected from the differentiation of a single body of tholeiitic magma, reinforcing the case for multiple injection, rather than the *in-situ* differentiation of a single large magma body. The apparent 'inverted' nature of the gabbro body was explained by Simpson (*op. cit.*) by the growth of the cone-sheet complex through the accretion of successive intrusive sheets to its base.

Despite careful examination, we have been unable to observe directly any internal boundaries within the gabbro intrusion. Nevertheless, the general aspect of the arcuate ridges is difficult, if not impossible, to reconcile with a structure other than one exhibiting a centripetal dip. We can confirm that the ridge profiles and observed mineral laminations in the tholeiitic gabbros are consistent with an inward dip of the stratification of between 150-300 (Simpson, 1954), steepening to 450 were affected by hinge faulting on the southeast flank of Johannes Berg (Watkins and Le Roex, 1991). The results of systematic geochemical traverses through and within the tholeiitic gabbros confirm the overall trend to more evolved compositions outward through the gabbro complex (Le Roex *et al.*, in prep). However, in detail they reveal a more complicated geochemical sequence which repudiates a simple successive addition of intrusive sheets from a single fractionating body of magma (Fig. 2), and furthermore, points to a more varied pattern of emplacement including that of sheets within, and probably traversing, earlier sheets (Fig. 3). Elaboration of these geochemical complications is outside the scope this paper and will be addressed in detail elsewhere.

Watkins and Le Roex (1991) recognised the presence of a major fracture that presently encloses the greatest part of the igneous complex. The near-circular fracture would have been continuous in outcrop prior to the emplacement of the Okenyenya Berg (Figs 1 and 3). It is occupied for much of its length by a syenite ring dyke and has been interpreted (Watkins and Le Roex, *op. cit.*) as a major ring-fault formed during caldera collapse of an Okenyenya volcano concurrent with voluminous syenitic volcanism. The arc described by the tholeiitic gabbro ridges (Plate 1; Fig. 1) closely parallels the ring fault, raising the possibility that the inward dip of the earliest intrusive rocks may owe more to volcano-tectonic deformation than to the original form of the intrusion. Following this model, the inward dip of the sheeted gabbros may result from the upturn of an initially horizontal, or shallow-dipping, multiple sill intrusion, due to drag towards the margins during subsidence within the ring fault. Uncertainties regarding the thickness of sedimentary and/or volcanic rocks overlying the Damaran metamorphic basement during the Early Cretaceous, preclude a precise estimate of the amount of vertical displacement that may have occurred along the ring fault. However, comparison with other examples of cauldron subsidence (e.g. MacDonald, 1972) accompanying major episodes of syenitic or rhyolitic volcanism suggests that downward displacement of the rocks encircled by the ring-fault of several hundred to a thousand or more metres, could have occurred. This possibility, viewed together with the essential parallelism of the gabbroic ridges with the ring-fault, suggests to us that the present attitude of the gabbros is unlikely to be a wholly original feature. The presence of the peripheral ring fault further negates any realistic estimation of the original shape and aerial extent of the sheeted gabbro complex.

This Study	Simpson (1954)
Tholeiitic Suite.	Tholeiitic Suite:
Olivine Gabbro - quartz monzodiorite	*'Differentiated Suite' - Ridge Gabbro and Ferrogabbro*
Picritic Gabbro	*Gabbro Picrite*
Syenite *Quartz Syenite*	*Ridge Syenite* *Acid and Hybrid Rocks*
Alkaline Suite:	Alkaline Suite:
Alkaline Gabbro	*Core Gabbro*
Nepheline Syenite	*Pulaskite*
Essexite	*Essexite*
Nepheline Syenite (Foyaite)	*Foyaite*
Lamprophyre	*Lamprophyre*

Table 1: Nomenclature used in this study based on the IUGS recommendations (le Maitre, 1993), compared to that used previously by Simpson (1954).

Picritic gabbro

Intermittent dykes of distinctively dark-coloured, picritic gabbro (formerly "gabbro-picrite") appear on the earlier geological map as bodies adjacent and tangential to the eastern margin of the complex. They have the same composition as a hitherto unmapped, similarly broad, intermittently exposed, yet probably continuous, dyke trending NNW-SSE across the western part of the complex (Fig. 1), Numerous, very much smaller, outcrops of a rock of equivalent composition but finer

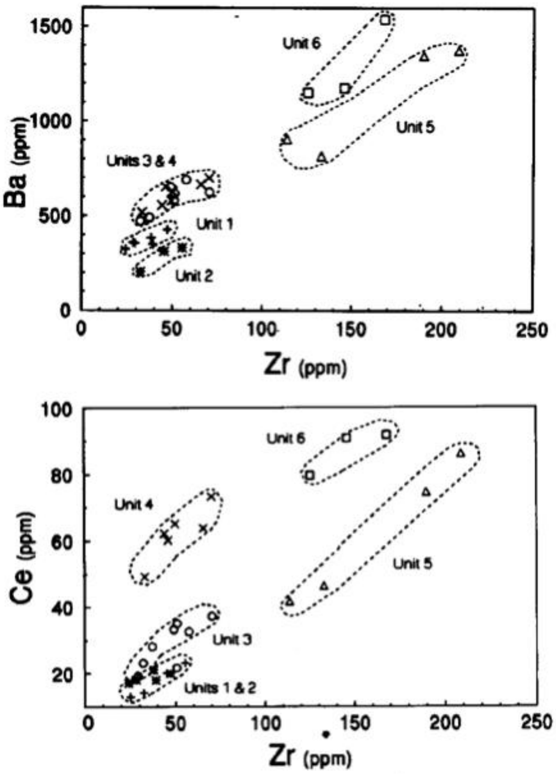

Figure 2: Variation of selected incompatible trace elements in samples collected from a transect across the tholeiitic gabbro - quartz monzodiorite body, showing the compositional differences between 6 intrusive units. Samples within each compositional unit were generally, but not exclusively, from adjacent neighbouring sampling sites along the traverse, and can thus be related to individual magmatic injections. Unit numbers increase towards the outer contact of the complex.

grain size, occur on the northern slope of Outjivero in the southern part of the complex and on the southern flank of Adams Shoulder in the northwest of the complex. The similar small outcrops in the southern part of the complex were designated "granulitic gabbro" by Simpson (1954) who considered them to represent the mafic portions of tholeiitic "ridge" gabbros disrupted and metamorphosed by the subsequent emplacement of a major body of alkaline gabbro, This interpretation is reflected in Simpson's schematic representation of the "granulitic gabbro" as a series of arcuate exposures of identical curvature to the tholeiitic gabbro ridges. Detailed reinvestigation of these small bodies (Le Roex *et al.*, *in prep.*) has confirmed the origin of the unusual, highly equigranular textures of these rocks through intense dynamic metamorphism during engulfment by alkali gabbro. However, although thoroughly recrystallised, the rocks show a close geochemical similarity to undisturbed picritic gabbro dykes elsewhere in the complex, supporting a formation through the disruption of one or more similar dykes.

The occurrence of the broad dyke traversing the complex throws doubt upon the previous interpretation of the broken outcrops of picritic gabbro around the eastern periphery of the complex as the remains of a ring dyke (Simpson, 1954). Rather, we interpret the exposures at Zbigniew, White and Black Ridges (Fig. 1) as belonging to one, or perhaps more than one, near-vertical and approximately North-South trending dykes that have been truncated by the ring fault (Fig. 3). Such an interpretation is consistent with Simpson's (1954, page 17) observation that Karoo sedimentary strata adjacent to the picritic gabbro north of Zbigniew Ridge are undisturbed, indicating "little or no differential movement" (*on the fault occupied by the gabbro-picrite ring dyke*).

Alkaline gabbro

According to the former structural interpretation, a massive body of alkaline gabbro ("core gabbro") punctured the sheeted tholeiitic gabbros to form a central plug within the older saucer-shaped intrusion. A second alkaline gabbro body was recognised to form the exposures of nepheline-bearing gabbro in the vicinity of Adams Shoulder in the north of the complex. A prominent feature in views of Martin Hill (Plate 1), is the presence of arcuate features of tight curvature encircling the summit. A single curving ridge is also apparent on the western side of Korn Hill. As in the case of the ridges of tholeiitic gabbro, no intrusive boundaries can be observed amongst the talus mantling Martin Hill. On close investigation, the topographic features responsible for the curving 'structure' are merely subtle breaks of slope and low, broken ridges, such as might be produced by the intersection of near-horizontal discontinuities in the alkaline gabbro with the hillside. The alkaline gabbro frequently exhibits marked crystal lamination and broad-scale variations in the mineral content or grainsize may well have given rise to differential rates of erosion and hence the apparent 'arcuate' features etched on the flanks of Martin Hill.

More obvious and complex layering on a fine-scale is seen in an alkaline leuco-gabbro on the summit of Martin Hill. This gabbro, however, has a trace element signature distinct from that of the gabbro forming the 'ridges' below (Le Roex *et al.*, *in prep.*). Furthermore, both are geochemically distinct from alkaline gabbros forming the hills in the vicinity of Korn Hill and intervening valleys. Consequently, whereas Simpson (1954) considered these central exposures of alkaline gabbro to be a single intrusion, we interpret them to represent a number of discrete intrusive bodies. Since no intrusive boundaries could be precisely located in the field between the petrographically similar rocks, no attempt has been made to demarcate the individual alkaline gabbro intrusions on Fig. 1.

Syenite and quartz syenite

Watkins and Le Roex (1991) identified a major ring fault peripheral to the main part of the Okenyenya complex. The fault describes a rounded pentagonal plan approximately 4.5 km across. Although presumably once continuous, the ring fault is presently truncated in the north by the younger intrusion of Okenyenya Berg (Fig. 1). Around the western half of the complex, and intermittently in the southeast, the fault plane is occupied by a syenite ring dyke. This major ring dyke, up to 75 m wide in the west, was included within the outcrop of "marginal acid and hybrid rocks" described by Simpson (1954). A plug-like body of syenite is situated on the ring fault in the northwest of the complex (Fig. 1). This steep-sided body is interpreted as a former magma conduit, whose location coincides with the intersection of the ring fault and the margin of the Adams Shoulder alkaline gabbro intrusion, and also the northwards extension of the picritic gabbro dyke (Fig. 1). To the north of Adams Shoulder syenite appears intermittently exposed in a region mostly covered by vegetation and colluvium (Fig. 1). There is thus the indication of a significant broadening of the syenite outcrop, the detailed structure of which is the subject of continuing detailed study.

The southwestern sector of the complex, centred on the elongate hill known as Johannes Berg (located to the WNW of Martin Hill - Fig. 1), is dominated by intrusive syenitic rocks of similar lineage to the main ring dyke. These rock types were formerly delineated and described in general terms as "acid and hybrid rocks" (Table 1). However, detailed mapping (Watkins and Le Roex , 1991) has shown them to comprise syenites and gabbro-contaminated quartz syenites emplaced within the tholeiitic gabbros as a series of arcuate dykes and shallow-dipping sheets, the outcrop patterns of which are shown in Fig. 1.

Nepheline syenite and essexite

The major peak of Okenyenya Berg (1902 m), located on the northern edge of the complex, comprises three intrusive units exposed in concentric arrangement. An outer ring of nepheline syenite (formerly "pulaskite") encloses two petrographically distinct varieties of essexite; an outer ring of andesite essexite and an inner plug of oligoclase essexite (Fig. 1). The contact of the outer ring of rather altered nepheline syenite with the alkaline gabbros of Adams Shoulder is well exposed in cliffs at the southwestern foot of Okenyenya Berg, where it is near vertical. On the geological map (Fig. 1) the internal boundaries of the nepheline syenite and andesite essexite units are undeflected where they cross the deeply gullied flanks of the mountain, indicating that these boundaries are likewise near vertical, and it is difficult to refute Simpson's (1954) interpretation that the Okenyenya Berg intrusions resulted from "multiple cauldron subsidences accompanied by magmatic intrusion" of first nepheline syenite magma, followed by essexite. The outer ring of nepheline syenite cross-cuts the alkaline gabbros of Adams Shoulder and the tholeiitic gabbros to the north of Korn Hill (Fig. 1), indicating that the silica undersaturated rocks of Okenyenya Berg represent the last major intrusive phase exposed within the complex.

Small, stock-like bodies of nepheline syenite (foyaite) and differentiated camptonite containing a variety of megacryst minerals, intrude the alkaline gabbros in the Auas Valley between the hills Korn and Martin (Fig. 1).

Lamprophyres and minor dykes

There are numerous minor intrusions within the igneous complex, the most abundant being dykes of various types of lamprophyre (alnoite, camptonite, monchiquite), nephelinite, phonolite and tephrite. The lamprophyre dykes cross-cut and therefore clearly post-date most of the other rock types within the complex. K-Ar dating of several lamprophyre dykes (Watkins *et al.*, 1994) supports our belief that they represent the final magmatic episode in the complex. Fig. 1 shows numerous of the lamprophyre dykes but many smaller dykes of various compositions have been omitted. Simpson (1954) recorded that there is a general radial distribution of these late dykes, although the present study indicates that the dominant, lamprophyric, dykes conform rather to a WNW-ESE trend. The lamprophyre dykes are mostly less than a metre in width, but are easily recognised by the very dark colour of the rock in surface colluvium. Individual dykes may be traced as far as 1.5 km across the complex, yet have not been found outside of the peripheral ring fault.

A volcanic diatreme ("pipe breccia" - Simpson, 1954) of approximately 100 m diameter is exposed southeast of Korn Hill (Fig. 1), and consists of brecciated ultramafic lamprophyre hosting numerous megacrysts, as well as gabbroic and mantle xenoliths. A less well exposed structure of roughly similar dimensions and appearing likewise to comprise brecciated lamprophyre, crops out in the Auas Valley, to the north of Martin Hill (Fig. 1). This second breccia pipe appears to lack mantle xenoliths. It is located in the vicinity of a zone of closely-spaced lamprophyre dykes where there has been profound alkaline metasomatism of the gabbro country rocks.

Model of Emplacement

The generally coarse grain size of the rocks of the Okenyenya complex, excepting some of the minor dykes, attests to their slow cooling at depth. The exact nature and thickness of the overburden during their emplacement in Early Cretaceous times is uncertain, yet is fundamental to a comprehensive understanding of the formation of the complex. At Okenyenya, as at other Mesozoic igneous complexes in Damaraland, the intrusive rocks presently rise well above the surrounding country rocks into which they have been intruded: the essexite of Okenyenya Berg projects approximately 900 metres above the metamorphic rocks and some 500 metres above remnants of Karoo sediments adjacent to the complex. The maximum thickness of Karoo

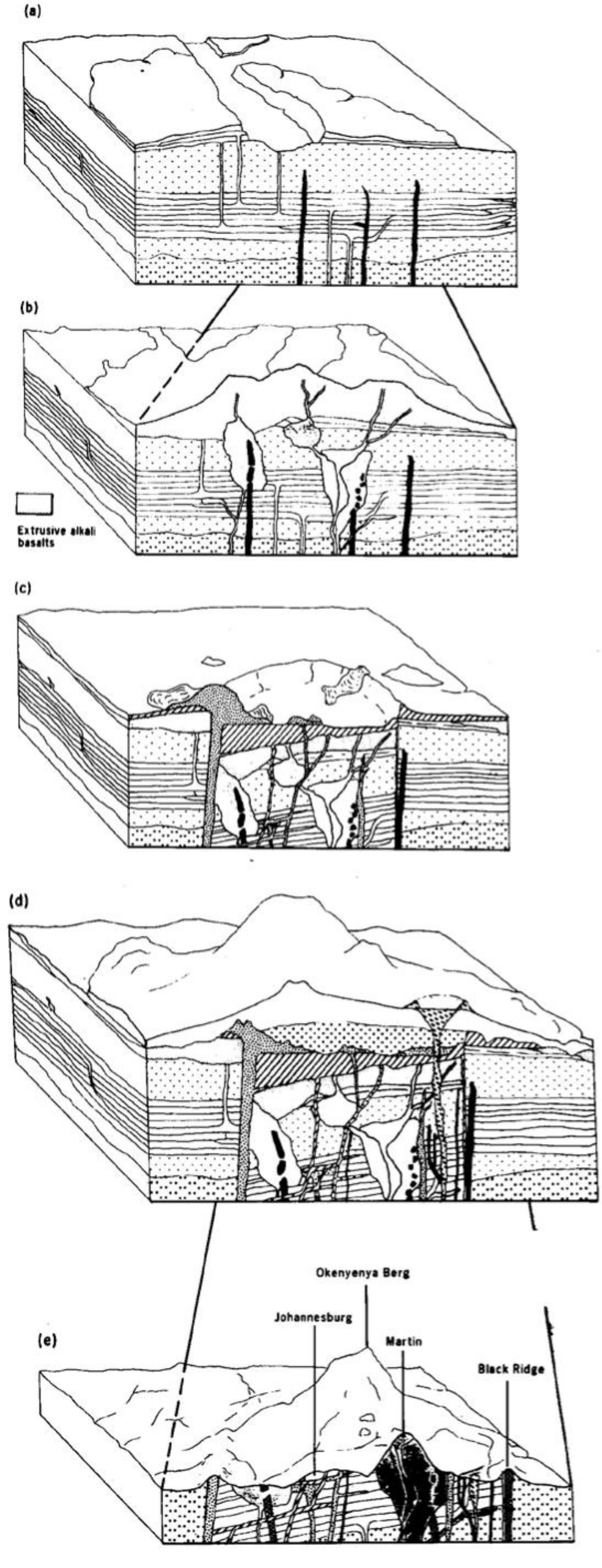

Figure 3: Simplified sketch block diagrams showing the evolutionary model proposed for Okenyenya igneous complex. The front faces of the blocks represent generalised sections through the centre of the complex in an approximately NW-SE direction. Since no volcanic rocks are preserved at Okenyenya, the extrusive features are necessarily speculative but are included to give some perspective to the intrusive structures. No accurate scale is implied by the diagrams which do not attempt to portray accurately the extent of surface denudation occurring during the 5 million years of development of the igneous complex. Individual block diagrams represent the stages of emplacement described in the text: **a**, emplacement of near flat-lying tholeiitic gabbro sheets; **b**, emplacement of high level magma chambers of alkaline gabbro; **c**, cauldron subsidence of the complex coincident with the injection of syenite and quartz-syenite magmas as a major peripheral ring dyke and a series of smaller arcuate dykes and sills. For simplicity, the tholeiitic gabbros are shown to dip uniformly to the west; **d**, emplacement of the Okenyenya Berg nepheline syenite/essexite intrusions on the northern margin of the former complex, flexuring of the central "plate" within the ring fault, and injection of highly alkaline magmas as dykes, plugs and pipes into the fractures thus produced; **e**, present day Okenyenya igneous complex. Ornamentation is the same as in Fig. 1.

sedimentary rocks preserved in the region is, however, only 400 metres on the Waterberg escarpment (Gevers, 1936). Basalt and quartz-latite lavas of the Etendeka Formation are some 900 metres thick at the type section of the Tafelberg (Milner *et al.*, 1992) and together with underlying sedimentary rocks form a similar thickness of Mesozoic strata in the Huab Valley to the northwest of Okenyenya. Milner and Ewart (1989) have suggested that lavas of the Goboboseb Mountain immediately to the north of Messum igneous complex were erupted from the complex and the Mesozoic igneous complexes of Damaraland in general have been regarded as subvolcanic in origin. Watkins and Le Roex (1991) considered that cauldron collapse of an overlying volcano could explain the complicated geometry of a series of syenite dykes and sills in the Okenyenya complex.

A model for the evolution of the Okenyenya igneous complex is illustrated in Fig. 3, in which it is assumed that the overburden during the greatest part of the intrusive history of the complex was provided by a superincumbent volcanic edifice of very large dimensions. The compositional variation within the Okenyenya igneous complex is equivalent to that recorded from many intra Plate igneous provinces, and is of a range present in only a relatively few composite volcanoes of the Central-type (e.g. Tenerife). Rb-Sr (Milner *et al.*, 1993) and K-Ar age data (Watkins *et al.*, 1994) indicate that magmatism at the complex extended for a period of at least 5 million years, consistent with the development of a major volcano. During this period, the mechanisms of emplacement appear to have been diverse reflecting both differing magma composition and localised tectonic stresses. An equally diverse evolution can be expected of the overlying volcano. However, no volcanic rocks are preserved at Okenyenya, and the surface expressions of the intrusive events shown in Fig. 3 are therefore merely speculative.

The proposed model of emplacement is as follows:

Stage 1 - Tholeiitic gabbro-quartz monzodiorite (Fig. 3a): The earliest intrusive episode for which there is evidence in the igneous complex gave rise to the tholeiitic gabbro - quartz monzodiorite rocks. These rocks constituted a multiple intrusion formed through the repeated injection of shallow-dipping cone sheets, or flat-lying sills, subsequently tilted inwards during subsidence (Fig. 3c). The rapid emplacement of the sheets to form a single cooling body is suggested by the absence of fine-grained margins within the sheeted intrusion. Any surface expression of this stage of development of the igneous complex may have been in the form of a low angle lava shield.

Stage 2 - Picritic gabbros (Fig. 3a): Picritic gabbro magma enriched in cumulus olivine was emplaced as a series of dykes, up to 50 m wide, in approximately north-south fractures in the sheeted tholeiitic gabbros and adjacent country rocks. It is suggested that local tumescence coincident with the onset of magmatism and the emplacement of the major sill complex gave rise to rapid surface denudation, removing much of the original superincumbent rocks.

Stage 3 - Alkaline gabbros (Fig. 3b): The alkaline gabbro magmas are interpreted to have been emplaced as a series of high level magma chambers beneath the growing central Okenyenya volcano. Such magma chambers are represented by the rocks on the hills Martin, Korn and Stanley. Crystal congelation, possibly adjacent to the roof of a magma chamber, may account for the fine-scale layering on the summit of Martin Hill. Another, larger, intrusion of more undersaturated gabbro magma was emplaced to the north, centred beneath Adams Shoulder. Room for the rising magma may have been generated partly by tumescence but also by significant stoping of the enclosing tholeiitic gabbros. Dykes of refractory picritic gabbro were engulfed and disrupted by the alkaline gabbro magma, and now remain as metamorphosed relics ("granulitic picritic gabbro").

Stage 4 - Syenites and quartz syenites (Fig. 3c): The emplacement mechanisms of the quartz-saturated and over-saturated syenitic rocks have been discussed in detail by Watkins and Le Roex (1991). Eruption of the syenite accompanied the formation of the ring fracture and cauldron subsidence. Syenite magma consolidated within the plane of the ring fault producing the ring dyke. Deformation of the rocks during cauldron subsidence was controlled by the heterogeneous nature of the foundering block. The older stratiform tholeiitic gabbros, possibly weakened from beneath by magmatic corrosion, appear to have been more prone to fracturing than the alkaline gabbro bodies. Tensional stresses resulting from the flexuring of the central block and greater subsidence in the southwest (Watkins and Le Roex, 1991) produced a complicated series of steeply inclined arcuate fractures and low-angled slip planes in the tholeiitic gabbros of Johannes Berg in the southwest of the complex, which were invaded by the syenite and gabbro-contaminated quartz syenite magmas. When stressed, the structural discontinuity between the sheeted tholeiitic gabbros and the more massive alkaline gabbros of Martin Hill gave rise to a further tensional fracture around the southern margin of the alkaline gabbro body which was invaded by syenite magma to form a broad curved dyke (the "ridge syenite" - Simpson, 1954).

Stage 5 - Nepheline syenites and essexites (Fig. 3d): The penultimate stage, and last major phase, of magmatic activity is preserved in the nepheline syenites and essexites of Okenyenya Berg. Post -erosional reactivation of magmatism on a major caldera ring fault is not unusual in large caldera volcanoes (McDonald, 1972) and we interpret the cylindrical intrusions as representing magmas intruded beneath a major silica-undersaturated volcano formed on the northern edge of the former volcanic complex. The concentric nature of the three major intrusions presently forming Okenyenya Berg, suggests that this later volcano also experienced episodes of cauldron collapse and crater/caldera formation. The two small stocks of nepheline syenite (foyaiite) exposed in the Auas Valley, in the central part of the complex, may have been emplaced during this magmatic episode, possibly representing conduits to satellite volcanic cones/domes.

Stage 6 - Lamprophyric rocks and related minor intrusions (Fig. 3d): Intrusion of the lamprophyres represented the last magmatic episode at Okenyenya for which there is evidence. These magmas were intruded as small stocks and abundant narrow dykes, the dykes being laterally persistent yet restricted to the area within the peripheral ring fault. A proliferation of long, narrow lamprophyre dykes in a WNW-ESE zone across the complex, as well as occasional faults parallel to the dykes, is interpreted as the result of flexuring of the central block, associated with the vertical emplacement of the major Okenyenya Berg intrusions in the north, and possible further subsidence along the pre-existing ring fracture in the southwest. At two localities, the volatile-rich lamprophyre magma became fluidised and eroded diatreme-like pipes. Percolation of alkaline hydrothermal fluids, believed to be associated with this final phase of magmatism, gave rise to secondary hydrated minerals, including rare zeolites, as interstitial and vuggy replacements in the camptonite exposed in the Auas Valley (Fig. 1) and to widespread metasomatic alteration of the gabbros, including the growth of plates of biotite, as much as 5 or more centimetres in size.

Summary

The intrusive igneous complex of Okenyenya is interpreted to be the subvolcanic remnant of a major central-type, composite volcano. The overall magmatic evolution of the complex shows a strong similarity to that characteristic of many oceanic volcanoes (e.g. Hawaii; Claque, 1987) in that alternating tholeiitic and alkaline phases of magmatism were followed by a final highly alkaline phase. Given this compositional progression, one may envisage an Okenyenya volcano to have grown in a similar fashion to other major central intraplate volcanoes (e.g. Hawaii, Tenerife) involving an early tholeiitic basalt shield with a subsequently more pronounced alkaline basalt cone; voluminous pyroclastic syenitic eruptions accompanied by caldera Formation; and finally, the late, post-erosional growth of undersaturated (phonolitic) cones and highly alkaline satellite cones and diatremes. The intrusive rocks presently cropping out in the complex formed for the most part beneath and within a volcano of major dimensions, with the broadly contemporaneous volcanic products providing overburden. The thickness of accumulated overlying volcanic rocks and the contribution to the overburden of Mesozoic sediments and/or volcanic products from other eruptive sites remains uncertain. Initial investigations involving fission track thermochronology have indicated that a considerable thickness of crustal rocks may have been rapidly denuded from this region of northwestern Namibia in the Cretaceous (Brown *et al.*, 1990). It is hoped that similar fission track studies to be directed at Okenyenya and neighbouring igneous complexes will provide valuable information, unrecorded in the present stratigraphy, on the depth of intrusion, as well as the extent and timing of denudation in Damaraland following continental break-up.

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