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A.PAPERS

GEOLOGY OF DICKER WILL EM, A SUBVOLCANIC CARBONATITE COMPLEX IN SOUTH-WEST NAMIBIA

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ABSTRACT

The Dicker Willem carbonatite complex intrudes Precambrian basement of the Namaqualand Metamorphic Complex. The main intrusion is composite, characterized by dismembered remnants of an ijolite-syenite suite enclosed within a circular sövite plug. Sövites, including magnetite, aegirine, biotite, apatite apd pyrochlore-bearing varieties and their associated cumulates have been disrupted by intrusion of a concentric suite of alvikite cone sheets and ring dykes. Alvikites range from microsövite-dominated varieties at the outer margin to dolomite-phyric types near the centre of the intrusion. Dykes of ferro-alvikite intrude the cone sheet sequence. Steep-sided, funnel-shaped pipes of carbonatite breccia intrude the central complex and are the source of ubiquitous dykes of microbreccia-tuffisite, yellow carbonatite and veins of calcite. Gneisses are patchily reconstituted to potassic fenites during sövite intrusion and are subsequently intruded by dykes, cone sheets and plugs of carbonatite, trachyte and their breccia equivalents. Intense brecciation, faulting and updoming of the gneisses and trachytes accompanied intrusion of the alvikites. Chilled margins and spinifex quench textures in alvikites, and open-space infilling of fractures formed during breccia pipe emplacement indicate a high level of intrusion. Dicker Willem is interpreted as a diatreme-like, subvolcanic carbonatite from which the uppermost effusive products have been removed by erosion.

1. INTRODUCTION

Dicker Willem (also known as Garubberg) is a circular, approximately 3 km diameter inselberg rising 600 m above the desert plain of the pre-Namib, 33 km north-west of the township of Aus in south-west Namibia.

On the eastern side of the mountain there is an extensive blanket of wind-blown dune sand. Elsewhere much of the lower flanks are covered by bouldery, calcite-cemented talus fans and calcrete. In contrast, the steep upper slopes provide excellent, although sometimes inaccessible, outcrop.

Rock types of Dicker Willem were originally described as limestone and quartzite (Beetz, 1924; Kaiser, 1926) and correlated with the Nama Group sediments. The west-facing escarpment of the flat-lying Nama Group occurs 56 km east of the mountain. Carbonate-rich rocks of Dicker Willem were first interpreted as carbonatites by De Villiers (1971).

Almost four weeks were spent mapping the mountain in March-April 1987. The following preliminary report is based largely on field observations, supplemented by petrographic study, X-ray diffraction and microprobe analysis.

2. GENERAL GEOLOGY

Dicker Willem comprises two major carbonatite bodies intruding high grade gneisses of the Namaqualand Metamorphic Complex (Fig. 1). The carbonatite centres are slightly elliptical in plan, with the major axes aligned north-east. The main complex has diameters of 2,8 and 2,1 km (area 4,83 km^2) and the satellite body on the south-east flank is 700m by 400m (area 0,16 km^2). Both centres have a steeply dipping concentric internal structure defined by flow banding. Basement gneisses and granitoids are exposed discontinuously around the entire perimeter of the lower slopes and are faulted, brecciated, fenitized, and intruded by peripheral plugs, dykes, and concordant cone sheets of trachyte, various carbonatites, and their explosively emplaced breccia equivalents.

Although minor intrusions are particularly abundant within 1 km of the carbonatite contact, sporadic thin dykes of carbonatite and breccia, often radial with respect to the central complexes, occur up to 2,7 km from the contact in the desert terrane north-east and south-east of the mountain. Solitary plugs and a thick dyke of trachyte also occur 2-2,5 km south and south-east of the carbonatite contact.

3. BASEMENT LITHOLOGIES

The country rocks of the carbonatite complex are high grade metamorphic gneisses, collectively referred to as the Garub Sequence (Jackson, 1976). Around Dicker Willem quartzo-feldspathic gneisses are dominant, with minor interlaminated mafic, calcareous and quartzose varieties. Concordant lenticular bands of garnet-bearing, pegmatitic, graphic granite are common, and are probably related to more extensive bodies of incipiently foliated granitoid, as exposed on the eastern flank of the mountain.

A single plagioclase-phyric basic dyke occurs as blocks within brecciated amphibolite gneiss on the north-west slopes of Dicker Willem. The petrological affinities of the dyke are unknown, but it is tentatively correlated with minor porphyritic basic dykes that occur throughout the Aus area (Jackson, 1976).

3.1 Petrography

Quartzo-feldspathic gneisses are dominated by the assemblage quartz-microcline-plagioclase-biotite, with

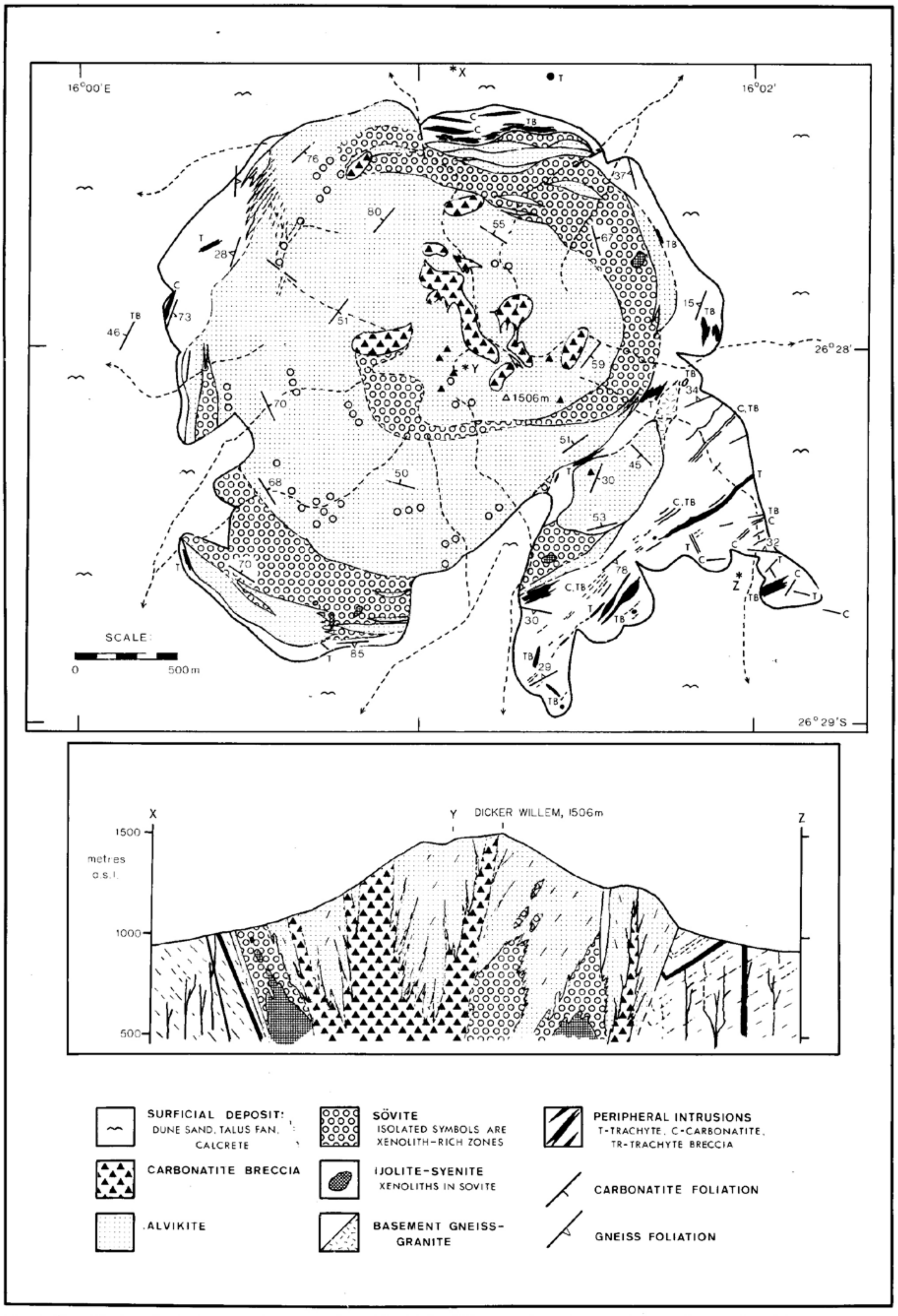

Fig. 1: Simplified geological map and cross section of the Dicker Willem carbonatite complex, south-west Namibia.

rarer garnet and sillimanite. Amphibolites comprise essential green or green-brown hornblende, biotite, plagioclase and quartz. A calc-silicate horizon in the north-east contact zone containing calcite, diopside, vesuvianite, grossular and sphene is fenitized to a pale-coloured amphibole-clioozoisite-prehnite-plagioclase assemblage adjacent to cross-cutting carbonatite veins. A comprehensive account of the Garub Sequence gneisses is given in Jackson (1976).

The dyke rock contains coarse (5 mm) phenocrysts or glomeroporphyritic clusters of andesine (An_{44}) in a medium-grained mafic aggregate of biotite, green hornblende (replacing a brown variety), equant and tabular opaque oxides and prismatic apatite with interstitial carbonate and quartz.

4. CONTACT RELATIONSHIPS

Garub gneisses form extensive outcrop only on the southeast flank of the mountain. Here the gneissic foliation strikes north-east and dips gently (7-30°) north-westwards, steepening to over 70° closer to Dicker Willem. Occasional, thin 1-2 m wide zones of gneiss breccia, consisting of a close-packed aggregate of randomly oriented, subrounded, carbonated clasts, cut otherwise coherent sequences. Such breccias are interpreted as local zones of fluidization. At several localities adjacent to the carbonatite contact the foliation is overturned, dipping steeply to shallowly in a south-east direction.

Fig. 2: Feldspar-phyric trachyte containing rounded xenoliths of sövite. Trachyte is intruded by late-stage carbonatite dykelet. North-west slopes of Dicker Willem. Knife 9 cm long.

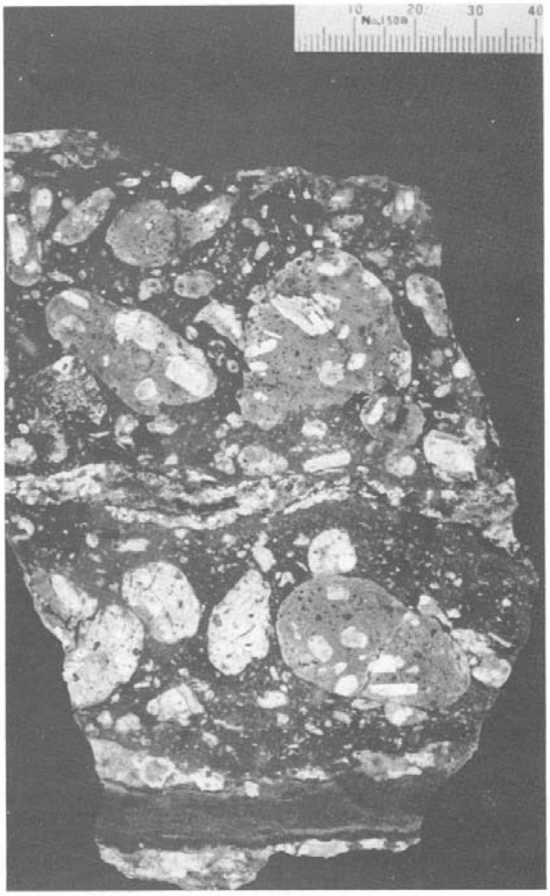

Fig. 3: Trachyte breccia composed of rounded pellets of feldspar-phyric trachyte enclosed in a fluorite-rich, carbonate matrix. Central band is thin septa of crushed basement granite, lower 1 cm band is fluorite-barite-quartz carbonatite. Western slopes. Scale bar in cm.

Elsewhere around the perimeter of the mountain the gneisses occupy such a narrow, poorly exposed zone that the attitude of the foliation, independent of effects of carbonatite emplacement, is impossible to determine. Foliation strikes approximately parallel to the carbonatite contact, suggesting some degree of rotation during intrusion.

Gneisses are variably fenitized and intensely intruded by dykes, plugs and concordant sheets of carbonatite, trachyte and their explosively emplaced breccia equivalents. The concordant sheets are appropriately sills or cone sheets. Dyke orientations can be radial with respect to either the main, or satellite, carbonatite centres, but are commonly random. Intrusions range in thickness from thin veins to substantial 20-30 m thick bodies. In many localities basement rocks are reduced to thin screens between intrusive sheets.

Basement rocks and trachyte intrusions are occasionally intensely shattered and brecciated, and have been concentrically faulted during the early stages of intrusion of granular-textured carbonatite cone sheets. Individual sheets have a crescentic outcrop pattern extending for up to 900 m along strike and attaining thicknesses of up to 60 m. Considerably thicker bodies are attributed to amalgamation caused by multiple intrusion. Cone sheets contain xenoliths of basement gneiss, trachyte, and sövite.

5. TRACHYTE AND TRACHYTE BRECCIA

Trachyte, previously unreported from Dicker Willem, forms an important peripheral component of the complex. Trachytic intrusions are particularly common in the basement gneisses close to the carbonatite (Fig. 2), but also occur up to 2,5 km south and south-east of the contact as 40 m-diameter plugs and a 400 m long dyke.

On the south-east flank of the mountain cone sheets and dykes of a pale brown, feldspar-phyric, occasionally spherulitic trachyte attain thicknesses of up to 16 m. However, trachytes are subordinate to breccias which are highly variable in terms of size, shape and composition of clasts, and the proportion and nature of the matrix. Clasts, composed of basement lithologies, trachyte, carbonatite (sövite), microsyenite and feldspar porphyry, are variously rounded to subangular and range in size from granules to 60cm diameter boulders. The matrix is often carbonate-rich, and with an increase in the matrix: clast ratio there is a natural gradation to carbonatite breccias. One of the most distinctive forms of trachyte breccia contains rounded pellets of feldspar-phyric trachyte, ranging in size between individual intrusions from 4-5 mm to 3 cm (Fig. 3), enclosed in a fluorite-bearing, carbonate-rich matrix that has undergone variable alteration to goethite/limonite.

5.1 Petrography

Trachytes are characteristically porphyritic with phenocrysts of sanidine and rarer zircon and magnetite. Flow-aligned microlites of alkali feldspar and acmitic pyroxene are set in a microcrystalline base that may, in some cases, represent devitrified glass. Xenocrystic microcline is ubiquitous. Xenoliths of sövite are typically mantled by a reaction zone of phlogopitic mica. A pale brown mica also occurs interstitially in several dykes and is often associated with calcite and fluorite.

Fluorite is a widespread late stage accessory mineral in both trachytes and associated breccias, occurring both close to the carbonatite contact, and in one of the isolated plugs 2,5 km south-east of the main complex. In the trachyte plug fluorite occurs as veins, segregations, and as a replacement of feldspar. It is unclear whether the fluorite is related to trachyte magmatism, or is introduced from carbonatitic fluids during brittle deformation associated with emplacement of the later alvikites.

6. PHONOLITE

A pale green volcanic unit occurs in the interior of a thick composite trachyte-trachyte breccia cone sheet on the south-east flank of the mountain. The rock is sparsely porphyritic containing a stubby tabular phase totally replaced by sericite, carbonate and zeolite; fresh and rarely hexagonal nepheline(?); and a common microphenocrystic phase that is also hexagonal, but totally pseudomorphed by alteration products. The groundmass is a flow aligned aggregate of sanidine microlites and aegirine prisms set in a base of analcime. Although the rock is clearly undersaturated, precise classification is difficult given the altered nature of the phenocryst species. The rock is tentatively described as an analcime phonolite.

Tinguaite dykes occur in the desert immediately east of the mountain (Kaiser, 1926). The dykes generally have a north-south strike, offset east-west striking carbonatite radial dykes, and would thus appear to be structurally unrelated to the Dicker Willem complex. Marsh (1975), however, suggested that both the carbonatite and tinguaite may be related to the early Cretaceous Lüderitz Alkaline Province.

7. IJOLITE-SYENITE SUITE

Rocks of the ijolite-syenite suite are a minor <0,12 % by area), but distinctive component of the Dicker Willem complex, restricted in occurrence to xenoliths within sövite. Xenoliths range in size from a few centimetres to large 100 m long rafts. The large size and local abundance of ijolite-syenite xenoliths is most likely the result of *in situ* disruption of an originally continuous silicate unit by sövite magma, with limited upward transport of xenoliths.

Widely different modal contents and grain sizes within large xenoliths and between adjacent blocks suggest a complex multi-intrusive form of the original ijolite. Some varieties are pegmatitic, with centimetre-size crystals of aegirine-rich pyroxene and/or wollastonite, others are fine-grained, occasionally in the form of thin dykes cutting coarser grained variants.

7.1 Petrography

Ijolites comprise combinations of nepheline, aegirine-augite, biotite, melanite, sphene and apatite, with variable and often abundant interstitial to poikilitic calcite and K-feldspar, and infrequent zircon and magnetite. Grain boundaries between calcite and nepheline are commonly, but not exclusively, marked by intermediate zones of cancrinite, a reaction product predicted by the phase relations determined by Watkinson and Wyllie (1971). K-feldspar occurs as clear interstitial pools, often enclosing corroded remnants of nepheline. Some rocks have K-feldspar dominant over nepheline, although it is not clear whether this is a primary feature, or due to subsequent replacement. Wollastonite occurs in two samples of feldspathic ijolite, coexisting with aegirine-augite, melanite, apatite, calcite and cancrinite.

8. CARBONATITES

A wide variety of carbonatites make up the central complexes, and the cone sheets and dykes intrusive into the surrounding basement gneisses. The mineralogy, texture, xenolith content and intrusive relationships are sufficiently distinctive in most cases to enable subdivision into five main groups. The classification used is that of Streckeisen (1979).

8.1 Sövite

White, calcite-rich rocks occupy a zone of subdued outcrop up to 400 m wide, commonly close to the outer margin of the complex. The sövite can be traced as a coherent, concentric unit for up to 2,5 km along strike, particularly on the north-east and south-west slopes of Dicker Willem. Elsewhere the sövite zone has been internally and marginally disrupted, occurring as dispersed xenoliths within banded alvikite.

Sövites are heterogeneous, with textures ranging from fine-grained and saccharoidal, through medium-grained and often banded, to coarse-grained varieties characterized either by interlocking stellate clusters, or broadly equigranular pegmatitic aggregates. Banding is defined by grain size variations, or by concentrations of mafic minerals (Fig. 4). Sövite foliation is rarely continuous for more than 20 m along strike, being distorted or folded, presumably by semiplastic flow, or broken by intrusion of other sövite varieties.

Sövites contain euhedra of magnetite, a pyroxene zoned from aegirine-augite cores to aegirine rims, and pyrochlore, together with tabular biotite and rounded prisms of apatite set in a granular aggregate of calcite. Aegirine is often overgrown and occasionally replaced by a pale green-blue amphibole, while apatite is marginally altered to dahllite. Other phases that occur, in order of decreasing abundance are zircon, K-feldspar, nepheline, and a colourless uniaxial mica (phlogopite?). The order of crystallization inferred from thin section textures is generally magnetite, followed by aegirine, biotite, pyrochlore, and finally calcite. Apatite appears to crystallize throughout the sequence.

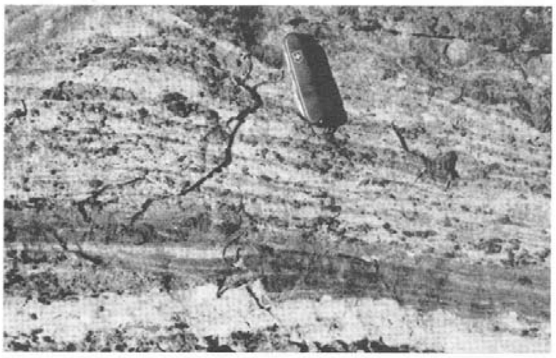

Fig. 4: Flow banding in sövite defined by concentrations of magnetite and aegirine, and by grain size variations in calcite. Lower band is pegmatitic. Knife 9 cm long.

Fig. 5: Weathered surface of sövite cumulate showing aggregate of octahedral magnetite. Northern slopes. Pencil thickness 0,7 cm.

In addition to xenoliths of ijolite, the sövite contains irregular segregations or pods, sometimes up to 60 m in length, composed of combinations of close-packed magnetite octahedra (Fig. 5), aegirine, biotite, pyrochlore and apatite. On the basis of the deduced order of crystallization these segregations are interpreted as sövite cumulates.

8.2 Alvikite

The dominant rock types of both carbonatite centres are fine-grained, buff to pale brown, occasionally banded and/or porphyritic calcite carbonatites that intrude the basement rocks and sövite zone as moderate to steeply dipping concentric cone sheets and ring dykes and occasional cross-cutting dykes. Although alvikites are mineralogically and texturally diverse, the fine scale interbanding prevents further subdivision of mapping units.

8.2.1 Texture

Porphyritic alvikites contain phenocrysts (up to 1 cm diameter) dispersed randomly through a granular calcite groundmass, or arranged as flow-aligned trails and

Fig. 6: Tabular, flow-aligned phenocrysts of calcite in fine-grained groundmass of alvikite. Western slopes. Pencil thickness 0,7 cm.

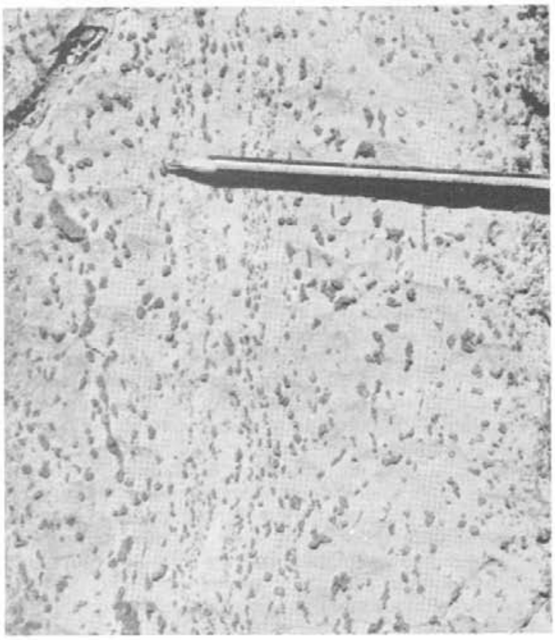

Fig. 7: Phenocrysts of dolomite in alvikite. Flow banding is perpendicular to pencil. North-west gully. Pencil thickness 0,7 cm.

segregations parallel to the margins of the unit (Figs 6, 7, 8). Banding is occasionally distorted into flow folds (Fig. 9).

In a thick dyke from the north slopes of Dicker Willem bands consisting of close-packed rhombohedra of dolomite and aggregates of fine-grained apatite alternate with calcite-rich layers containing occasional isolated, or amalgamated streaks of dolomite phenocrysts (Fig. 10). This banding is interpreted as cumulate layering with dolomite and apatite crystallizing early from successive intrusions of alvikite magma.

The calcite groundmass is typically granular, although 'spinifex' textures, defined by parallel or radiating interlocking aggregates of bladed crystals, are widespread (Fig. 11). By analogy with similar textures in komatiites (Donaldson, 1982) and in charges produced during experimental investigation of carbonate systems (Wyllie and Tuttle, 1960), such textures are interpreted as due to rapid growth, probably with some degree of supercooling. Although 'spinifex' textures are prominent in hand specimen, thin sections show that the bladed crystals have undergone subsolidus recrystallization to granular aggregates. Similar recrystallization of primary, typically tabular, calcite to finer grained granoblastic aggregates has been described by Zhabin (1978) as a widespread post-magmatic phenomenon in Russian carbonatites. Many alvikites also exhibit comb-layering and chilled margins.

8.2.2 Mineralogy

Phenocrysts include octahedral magnetite (Figs 8, 9) and pyrochlore, tabular calcite (Fig. 6), and rhombohedral dolomite (Figs 7, 8, 10). Dolomites are often zoned, with a clear core mantled by a more Fe-rich, limonitized rim. Grains carry rare inclusions of apatite

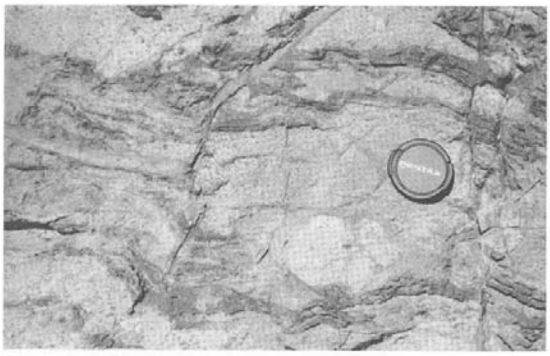

Fig. 8: Banding defined by concentrations of dolomite and magnetite in dolomite-phyric alvikite. White xenolith to lower left of lens cap is sövite. Alvikite is intruded by irregular late-stage yellow carbonatite dyke (left) and veins of calcite (right). North-west gully. Lens cap 6 cm across.

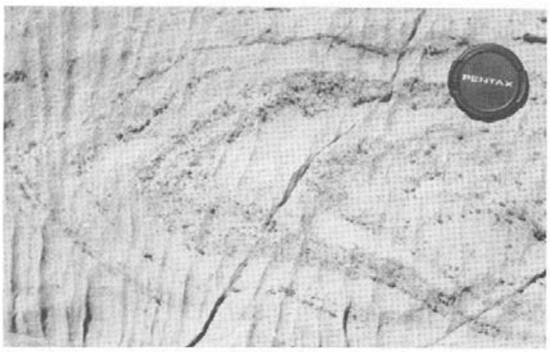

Fig. 9: Flow fold in alvikite. Banding is defined by concentrations of magnetite phenocrysts. Western slopes. Lens cap 6 cm across.

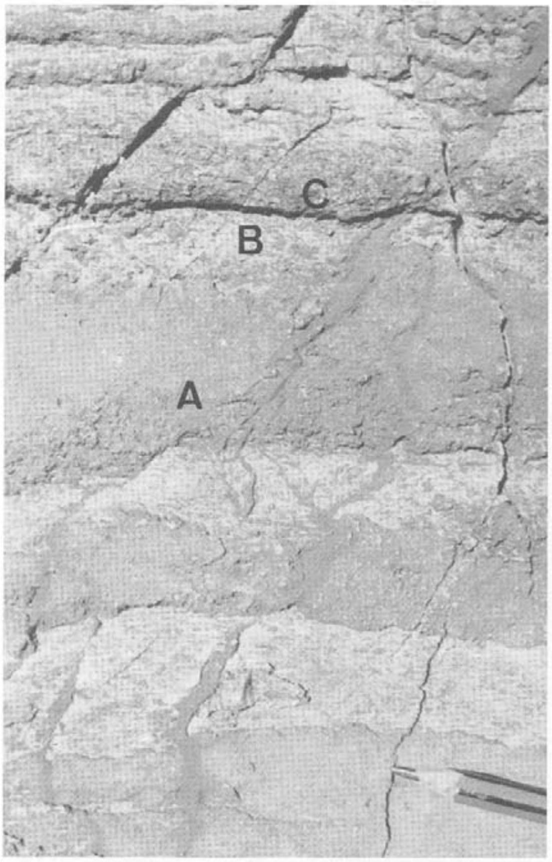

Fig. 10: Rhythmically banded alvikite. Lower portions of cumulate bands are close-packed rhombs of dolomite (A), grading rapidly upwards to pale-coloured tops containing sparse phenocrysts of dolomite in a spinifex-textured calcite groundmass (B). Sharp contact to overlying unit is defined by concentration of cumulate apatite and dolomite (C). North gully. Width of pencil 0,7 cm.

and a brown, reversely pleochroic tetraferriphlogopite. Such micas are widely reported from Al-poor carbonatites (Hogarth *et al.*, 1970; Puustinen,1973).

The alvikite groundmass is typically calcite, with some varieties containing minor amounts of limonitized dolomite.

Biotite (with normal pleochroism), an acmite-rich clinopyroxene, apatite, quartz, and barite are common, while fluorite occurs rarely in alvikites from both the central complexes and from distant radial dykes. Some varieties contain an intergranular residuum composed of a pale brown, isotropic to feebly birefringent, microcrystalline or fibrous aggregate.

Ellipsoidal pellets (up to 1 cm diameter) composed of prismatic apatite occur in several alvikites. The recrystallization of apatite and its alteration to dahllite adjacent to the alvikite groundmass indicates that the pellets are xenoliths.

Dolomite-poor alvikites containing magnetite, biotite, and aegirine commonly occur near the outer margin of the complex. These varieties are mineralogically microsövites, intruded at a higher level, or under volatile-poor conditions compared to the earlier sövites. Dolomite-bearing alvikites, lacking biotite and aegirine but containing accessory barite, are dominant in the interior of the complex.

8.3 Beforsite

An essentially monomineralic, 40 cm thick layer of dolomite in a dolomite-phyric alvikite cone sheet, and a metre thick unit exposed in cliff sections south of Dicker Willem summit are classified as beforsite. Constituent dolomite occurs as close-packed aggregates of rhombohedral grains which, like phenocrysts in alvikites (Section 8.2), contain inclusions of tetraferriphlogopite. Given that the low viscosities of carbonatites (Treiman and Schedl, 1983) enable efficient gravity settling of early-formed crystals, these beforsites are interpreted as cumulates.

More problematical are dark brown carbonatite dykes up to 15 cm thick intruding a late-stage breccia pipe on the north-west slopes of the mountain. The dykes are composed largely of dolomite with only minor interstitial calcite, barite, and pyrite. Although the dykes could represent dolomite-phyric alvikite from which most of

Fig. 11: Interlocking bladed aggregates of calcite defining a spinifex texture. Upper section of north-west gully. Scale bar in cm.

the calcite-rich liquid has been expelled by filter pressing, the dolomite is finely crystalline with only rare rhombohedral form. It is likely that beforsite magmas were generated during the final stages of carbonatite fractionation.

8.4 Ferro-alvikites

Dark brown to black, medium- to coarse-grained carbonatite dykes, reaching thicknesses in excess of 1 m intrude the banded alvikites throughout the complex. Dykes are randomly oriented and clearly post-date earlier carbonatite activity. The carbonatites are composed of calcite, with the dark colouration the result of disseminated goethite. Clear calcite, with barite and quartz occur in intergranular patches.

At Homa Bay, West Kenya, Le Bas (1977, 1987) describes similar, late-stage, calcite-rich rocks (mean whole rock CaO 46,29 wt%) as ferrocarbonatites, despite recommendations by Streckeisen (1979) that the term be restricted to rocks ‘essentially composed of iron carbonate minerals’. The late-stage dykes at Dicker Willem are not ferrocarbonatite; the term ferro-alvikite is suggested to describe their calcite-rich, but goethite-impregnated character.

8.5 Yellow carbonatite, microbreccia and tuffisite dykes

Thin yellow-brown carbonatite dykes and veins are, apart from a beforsite dyke cutting a breccia pipe, the latest phase of carbonatite intrusion on Dicker Willem. Yellow carbonatites are ubiquitous, occurring both within and exterior to the central complex, assuming greatest concentration adjacent to the various breccia pipes. They appear heterogeneous in outcrop, with the more resistant dykes, or segments of dykes, being more siliceous. Sharp interfaces between resistant and recessively weathered portions within a single dyke indicate that silicification was a late magmatic, or post-emplacement process.

Many of the dykes are microbreccias or tuffisites, having rounded xenoliths of wall-rock carbonatite enclosed in an orange-yellow, calcite-rich matrix. Central parts of dykelets are commonly occupied by white or pale blue calcite veins, which at several localities open out into 1-2 m thick lenticular segregations composed of radiating aggregates of coarse prismatic calcite. These open-space, late-stage, fracture fillings of calcite often have a radial orientation to breccia pipes, and can be traced along strike for up to 250 m.

X-ray diffraction studies and petrographic observation demonstrate that the yellow carbonatites are dominantly calcite, although some calcite-dolomite varieties have been recorded. Alteration to goethite is extensive. Carbonate textures are varied, ranging from equant, rhombic granules through to elongate flow-aligned laths. Interstitial areas are occupied by clear calcite, with common barite and quartz.

9. CARBONATITE-BRECCIA PIPES

The summit plateau and northern slopes of Dicker Willem are characterized by rounded outcrops of a yellow or orange-brown, carbonatite breccia. These internal breccia bodies, unlike the assorted breccias in the contact zone of the complex, are entirely carbonatitic, with no trachyte component.

Individual breccia units range from semicircular 10-30 m diameter bodies to more irregular, interconnecting complexes hundreds of metres across. Dyke-like apophyses of breccia radiate from many bodies, spawning yellow carbonatite dykes and calcite-filled fractures. The total area of all breccia bodies amounts to 0,18 km^2.

Adjacent to the breccias the surrounding carbonatites are typically fractured, invaded by an anastomosing stockwork of yellow carbonatite and microbreccia dykes and veins, and impregnated by haematite and secondary carbonate. Rarely the breccia contact is sharp, dips steeply inwards, with the wall rocks unaltered.

Fig. 12.: Carbonatite breccia in pipe on north-west slopes of Dicker Willem. White clasts are calcite-rich sövite; black resistant clasts are magnetite-rich sövite cumulates. Breccia is cut by several generations of yellow carbonatite dykelets and a late-stage beforsite. Lens cap 6 cm across.

Breccia margins are characterized by coarse, 30-40 cm diameter, spalled blocks of country rock with the clast size decreasing, generally to 2-5 cm, towards the interior of the body (Fig. 12). Well rounded to occasionally subangular clasts are composed of various carbonatite varieties, with sövite debris being particularly distinctive. Reworked clasts of breccia also occur. Breccias are typically structureless, but are occasionally cross-cut by cylindrical to irregular zones of fine-grained, well sorted microbreccia. Discordant microbreccias probably formed during late pulses of fluidization.

Breccia pipes are intruded by planar to irregular dykes and veins of calcite; yellow microbreccia carbonatite; silicified carbonatite; and rarely beforsite. Outcrops of breccia are commonly littered by a bouldery surface layer of chalcedony-rich gossan. Breccias contain clasts of calcite, apatite, magnetite, pyrochlore, biotite, and zircon, and lithic fragments of sövitic, alvikitic and dolomite-phyric carbonatites. Some carbonate clasts have a thin limonitized border or turbid reaction zone adjacent to a medium- to fine-grained calcite matrix.

9.1 Interpretation

Breccia bodies occur in an approximately central position in both the main Dicker Willem Complex and the satellite centre to the south-east. On the northern slopes of the mountain breccias have also been emplaced close to the contact between the sövite collar and the inner banded alvikite sequence. On the evidence presented, breccias are interpreted as fluidized pipe-like intrusions marking the site of repeated late-stage explosive carbonatite activity.

10. FENITIZATION

Characteristically, rocks adjacent to carbonatite complexes are metasomatically altered by processes collectively referred to as fenitization. At Dicker Willem, basement gneiss outcrops are most extensive on the south-east flank of the mountain and here fenitization is only patchily developed. Peripheral carbonatite cone sheets and dykes have produced few metasomatic effects on adjacent gneisses. The most intense fenitization appears to be restricted to zones where an original sövite (or ijolite?)-basement contact is relatively unmodified by later trachyte and alvikite intrusion. Thus, although most fenite aureoles are a few metres or tens of metres wide, the metasomatic zone reaches 100 m in granitoid sandwiched between the main and satellite centres on the south-east flanks, and along the northern contacf. Fenites are recognized in the field by the development of lime-green segregations and joint coatings rich in aegirine.

10.1 Petrography

Incipient fenitization occurs as fine-grained mosaics of turbid K-feldspar replacing plagioclase in crush zones formed during cataclastic deformation. Quartz is fractured and replaced by prisms of aegirine in veins and at grain margins. At the contact of the satellite carbonatite in the south-east, minor fluorite and barite are introduced, associated with intergranular films of carbonate.

At more advanced stages of fenitization plagioclase is totally replaced by K-feldspar, and quartz by pseudomorphic aggregates of colourless to deep green aegirine and a pale blue or blue-green amphibole. Brown biotite occasionally recrystallizes to a pale green variety, but is more commonly resorbed, initially with reaction along cleavage traces and at grain boundaries. Adjacent to quartz, corroded relics of biotite are mantled by an inner zone of K-feldspar and an outer radiating aggregate of aegirine. Alteration of biotite is occasionally accompanied by production of a colourless, effectively uniaxial, optically negative mica.

Eventually even microcline undergoes reconstitution, with corroded relics enclosed in a matrix of recrystallized K-feldspar. The end product of metasomatism at Dicker Willem is a fenite composed of K-feldspar, aegirine ± pale blue amphibole, with occasional relics of microcline and, in gneissic parent lithologies, rounded granules of garnet and sillimanite.

Although chemical analyses are not yet available, the dominance of K-feldspar in Dicker Willem fenites indicates that metasomatism is largely potassic. Feldspathization and phlogopitization, the dominant forms of potassic fenitization, are widely reported from carbonatite complexes interpreted as high level intrusions (Le Bas, 1977, p. 274-275). In contrast, deeper level carbonatites are often characterized by a sodic metasomatism involving albitization. The potassic character of fenitization at Dicker Willem is thus compatible with an immediately subvolcanic setting.

11. ECONOMIC GEOLOGY

Dicker Willem carbonatites contain potentially economic phases such as pyrochlore, apatite and fluorite. However, on the basis of concentrations assessed from field observations and preliminary petrographic examination, the likelihood of exploitation does not appear high.

12. INTRUSIVE HISTORY OF DICKER WILLEM

The history of intrusive activity at Dicker Willem can be summarized as:

1. Emplacement of a calcite-rich ijolite complex.
2. Intrusion of a circular, concentrically banded sövite. The ijolite was totally disrupted and incorporated as xenoliths. Basement gneisses and granitoids were reconstituted by potassic fenitization to K-feldspar-aegirine assemblages.

3. Intrusion of trachyte and trachyte breccia dykes, cone sheets and plugs in basement gneiss. Explosive fluidization produced breccias comprising rounded pellets of feldspar-phyric trachyte in a fluorite-bearing, carbonate-rich matrix.
4. Trachytes and host basement gneisses were extensively brecciated and concentrically faulted during multiphase emplacement of a major suite of alvikite intrusions. Alvikites disrupted and truncated the earlier carbonatite, with sövite blocks occurring in moderate to steeply dipping, often amalgamated cone sheets and ring dykes. Within the alvikite sequence there is a broad concentric zonation with outer parts dominated by magnetite-phyric, aegirine and biotite-bearing varieties (mineralogically resembling the sövites) while the inner part is dominated by dolomite-phyric varieties lacking alkali silicate phases. These dolomite-phyric alvikites contain, or are associated with, essentially monomineralic bands of beforsite formed by gravity settling of early-formed dolomite phenocrysts. Alvikites produce only localized fenitization.
5. Dark brown ferro-alvikite dykes of random orientation intruded the alvikite sequence.
6. The final phase of carbonatite activity involved the explosive emplacement of steepsided, funnel-shaped breccia or tuff pipes which dominate the central part of the complex. Breccias are generally structureless, comprising finely comminuted fragments of pre-existing carbonatites enclosed in a yellow carbonatite matrix. Cross-cutting, well sorted zones of microbreccias or tuff are interpreted as products of late-stage pulses of fluidization. Abundant late-stage dykes of yellow carbonatite, and microbreccia (tuffisite) occurring throughout the complex probably represent in part the same differentiated carbonatite magma that forms the matrix to the breccia. Dykes and veins have undergone a late- or post-magmatic silicification.

13. ORIGIN OF DICKER WILLEM

Dicker Willem exhibits many of the characteristics of central-type ijolite-carbonatite complexes, but is unusual in that ijolite and syenite collectively comprise less than 0,2 per cent of the outcrop area. With carbonatite occupying an area of close to 5 km^2, Dicker Willem would rate as one of the larger carbonatites in Africa, although still dwarfed by the breccias of the Kaluwe sheet, Zambia (1,8 km x 13 km x 240m; Bailey, 1966), and the Sangu Complex, Tanzania (three elongate carbonatites up to 1,6 km wide, distributed along a zone 26 km long; Coetzee, 1963). Like Dicker Willem, these and other large carbonatites essentially lack associated alkali silicate rock types.

The major silicate intrusive rocks of Dicker Willem are the trachytes and trachyte breccias, which were intruded after emplacement of the sövites but before the alvikites. Trachytes, often unusually potassic, are widespread in carbonatite complexes of central and east Africa, occurring at Tundula and Chilwa (Garson, 1966), Mbeya (Brown, 1964), and Torero and Toror Hills (Sutherland, 1965; King and Sutherland, 1966). Based on their close field association with potassic fenites, and their totally dissimilar alkali ratios to associated phonolites, trachytes are commonly interpreted as rheomorphic fenites (e.g. Garson op. cit., p. 39, 58). At Dicker Willem it is perhaps significant that trachytes are absent from the interior of the carbonatite complex, being restricted to the peripheral, fenitized basement.

The dominant rock types of Dicker Willem are alvikites exhibiting textures characteristic of rapid cooling. Phenocrysts of magnetite, dolomite, and pyrochlore are enclosed in a fine-grained, calcite-rich groundmass which is commonly characterized by spinifex-like textures, interpreted as a quench phenomenon. Many of the alvikite intrusions show pronounced chilled margins. Open-space infillings of calcite in radial fractures associated with emplacement of late-stage breccia pipes similarly argue for high level, near surface environments.

The extensive breccia pipes in the central part of the intrusion are exclusively carbonatitic, both in terms of clast lithology and matrix composition. As such, breccia pipes of Dicker Willem bear a striking similarity to those in carbonatite complexes of the Rufunsa province of Zambia (Bailey, 1966). One complex, Chasweta (Bailey op. cit., p. 139-143), is an eroded twin volcano in which tuff or breccia pipes intrude an earlier sövite plug. Interbedded dolomitic or ankeritic tuffs and agglomerates, exhibiting graded- and cross-bedding and ripple marks, are preserved at the margin of one of the pipes and are interpreted as forming subaerially during multiple effusive periods. Any effusive products from the central complex of Dicker Willem, either derived from the breccia pipes or, less likely, from the early alvikite magmatism, must have been similarly carbonatitic.

Early ijolite intrusion on the site of the Dicker Willem complex is followed by a possible differentiated carbonatite sequence ranging from sövite, through alvikite to dolomitic alvikite and carbonatite breccia; with each unit successively intruded to higher structural levels. It is likely that at least the last stage of breccia pipe intrusion (and possibly the earlier alvikite phase) resulted in subaerial eruption. Dicker Willem is thus interpreted as a diatreme-like, subvolcanic carbonatite complex in which only the uppermost effusive portion has been removed by erosion.

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