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The Phalaborwa Syenite Intrusions along the West-Central Boundary of the Kruger National Park

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The geology of the Phalaborwa Complex is described and emphasis placed on the distribution of the large number of syenite intrusions. The petrography of the different textural types of syenites is discussed and it is shown that porphyritic, granular, gneissic and hypidiomorphic syenites are present. The petrography shows that the deformation textures, which are present in some of the syenites, may have formed during the emplacement of syenitic magmas which contained a high concentration of crystals. The geochemistry of the syenites is discussed and it is shown that they were not derived from an alkali basaltic magma through fractional crystallisation, but that they may rather represent alkali basaltic magmas which were contaminated by granitic material. The mode of emplacement of the Phalaborwa Complex is discussed and the relationship between the pyroxenites is explained.

Key words: Phalaborwa Complex, Proterozoic, syenites, pyroxenite, petrology, geochemistry.

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Introduction

The Phalaborwa Igneous Complex is a large, multi-stage intrusive complex, which occurs in the Letaba district, along the western boundary of the Kruger National Park (KNP). The complex consists of a large, multi-stage, central intrusion which is composed of a feldspathic pyroxenite, pyroxenite, various pegmatoidal intrusions and a central carbonatite complex. A large number of small, plug-like bodies of syenite crop out around the central pyroxenite intrusion and mark the terminal phase of the volcanism. According to Holmes & Cahen (1957) the pyroxenitic portion of the complex intruded roughly 2 060 Ma ago, and the geological evidence presented by Hanekom, Van Staden, Smit & Pike (1965) indicates that the syenites intruded more or less simultaneously with the pyroxenites. This complex is unique in that it is the only alkaline complex that is mined intensively for a large variety of raw materials, including copper, phosphate, uranium, thorium, zirconium, iron, titanium and limestone.

Prior to the mining activity this complex fell within the boundary of the Kruger National Park, but fortunately it was located that close to the western boundary that the land on which it occurs could be exchanged for land which is now included in the park. There are, however, still ten syenite intrusions which are located within the Kruger National Park, south of the Phalaborwa gate.

It is generally believed that the complex was first discovered by the famous South African explorer, Carl Mauch (Harger 1934). During his travels in the Transvaal and Zimbabwe, Carl Mauch carried out a systematic reconnaissance mapping of the country and between 1868 and 1871 he produced the first map of these territories. In Fig. 1 a small portion of this now famous map, showing the first documented discovery of the copper deposits in the Phalaborwa Complex, is reproduced.

Fig. 1. A copy of the original geological map of the Phalaborwa area by Carl Mauch, produced in 1868.

Since its original discovery by Mauch, this area has attracted a large number of archaeologists and geologists on account of the ancient, pre-historic copper smelters in the vicinity, as well as the occurrence of large phosphate, copper and iron ore deposits within the Phalaborwa Complex. It is of interest to note that all the major copper deposits in the Transvaal, such as Phalaborwa and Messina, were known to the pre-historic inhabitants of southern Africa and that these people carried out fairly extensive exploitation of the oxidised surface ores. Verwoerd (1956) described the presence of small smelting furnaces, freestone walls, built-up terraces and copper and iron ingots, which date from this early pre-historic mining period of South Africa in the Phalaborwa area. The identity of these early miners is unfortunately unknown.

Geomorphology

The Phalaborwa Complex is situated roughly halfway between the Drakensberg Escarpment and the Lebombo Mountains and lies in the Transvaal Lowveld at an average height of 350 metres above sea level. Around Phalaborwa the rather flat and monotonous topography is broken by the presence of a large number of scattered, small conical hills (Fig. 2). These hills rise approximately 100 metres above the surrounding Lowveld topography and form a typical inselberg landscape.

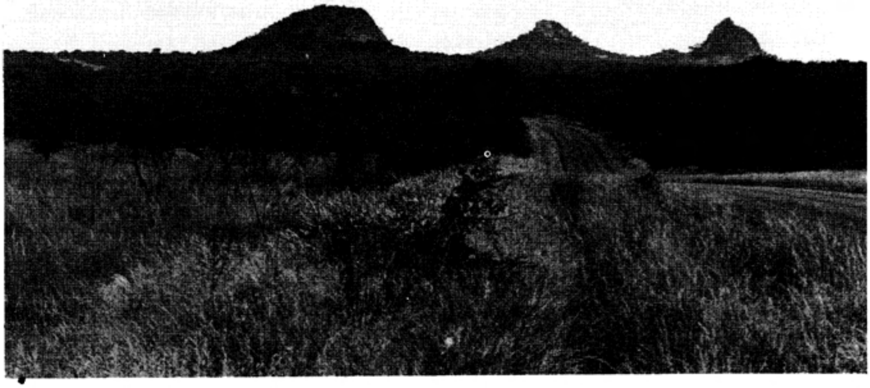

Fig. 2. Inselbergen consisting of syenite which forms small conical hills rising some 100 metres above the gentle undulating Lowveld topography.

The small inselbergen consist of syenite, a rock-type containing mainly orthoclase with accessory amounts of quartz, alkali-amphibole, aegerine-augite and biotite. They are intrusive into a basement consisting of pegmatitic granite and granite gneiss of Swazian age (3 000 Ma). The latter rocks are very coarse-grained and weather readily, whereas the syenite is more massive and more resistant to erosion. The formation of the present inselberg landscape is thus largely the result of differential weathering between granite and the syenite.

The entire area around Phalaborwa is covered by a thick blanket of granitic detritus and scree, which is mostly very sandy in composition, and which varies in thickness. The syenite intrusions usually outcrop well and no surface covering has developed on them. On the central portion of the Phalaborwa

Complex, which consists of mafic rock-types, a sandy blanket is invariably absent and a dark-coloured turfy soil containing calcrete has developed.

The major drainage system in the immediate vicinity of Phalaborwa consists of the Selati River, which has its source in the Drakensberg Escarpment and which is a perennial river. The area covered by the Phalaborwa Complex drains into the Selati River along a number of small tributaries which only carry water seasonally. The Selati River has a very shallow profile in this area. Its banks are low, and a thick blanket of sand has formed along the course of the river. All these features indicate a relatively low load competency of the river. Some 6 km to the south-east of the Phalaborwa Complex the Selati River runs into the Olifants River, which is one of the major rivers in the eastern Transvaal Lowveld. The Olifants River normally carries a large volume of flowing water and serves as the water reservoir to both the town of Phalaborwa and to the two large mines.

The granitic soil of the region is mostly vegetated by Mopani trees *Colophospermum mopane* with a fairly thick undergrowth, especially along the rivers and creeks. The mafic rocks of the Phalaborwa Complex are vegetated by an acacia flora, which forms mostly only a waist-high undergrowth.

Geology

A geological map of the Phalaborwa Complex, based on the work of Gevers (1949), Frick (1975) and Brandt (1948), is shown in Fig. 3. The complex consists of a large pyroxenite body, which is for the largest part rimmed by a thin border zone consisting of feldsphatic pyroxenite. The pyroxenite consists of clinopyroxene, titaniferous magnetite and apatite. The feldspathic pyroxenite contains microcline in addition to the above minerals and shows no evidence of a reaction relationship between the microcline and the pyroxene. The pyroxenite body consists of three bulges, possibly representing three separate intrusions. Large ring-shaped intrusions consisting of an assortment of pegmatoids and one intrusion of carbonatite are present within each of the three bulges. The carbonatite consists essentially of a volcanic rock composed of calcite, with smaller amounts of titaniferous magnetite, apatite, and copper-bearing minerals.

Beside the main, multiple intrusive centre forming the bulk of the Phalaborwa Complex, a large number of smaller intrusions consisting of separate, single-stage syenite plugs are present. These syenite bodies vary from 10 m to 300 m in diameter and are concentrated outside the main complex. The spatial distribution of the individual syenite intrusions shows no distinct preferred orientation, though an unusually high concentration appears to be arranged along zones which trend in a north north-west and south south-east direction and which radiate from the central complex. Most of the syenite intrusions consist only of single intrusions (Fig. 4), but in a few cases, notably at Malelene Hill and Spitskop, along the Tzaneen-Phalaborwa road, a series of four separate vents, which are connected to one another, are present.

A number of thin cross-cutting veins of syenite are also present within the central pyroxenitic portion of the complex, as well as in the feldspathic

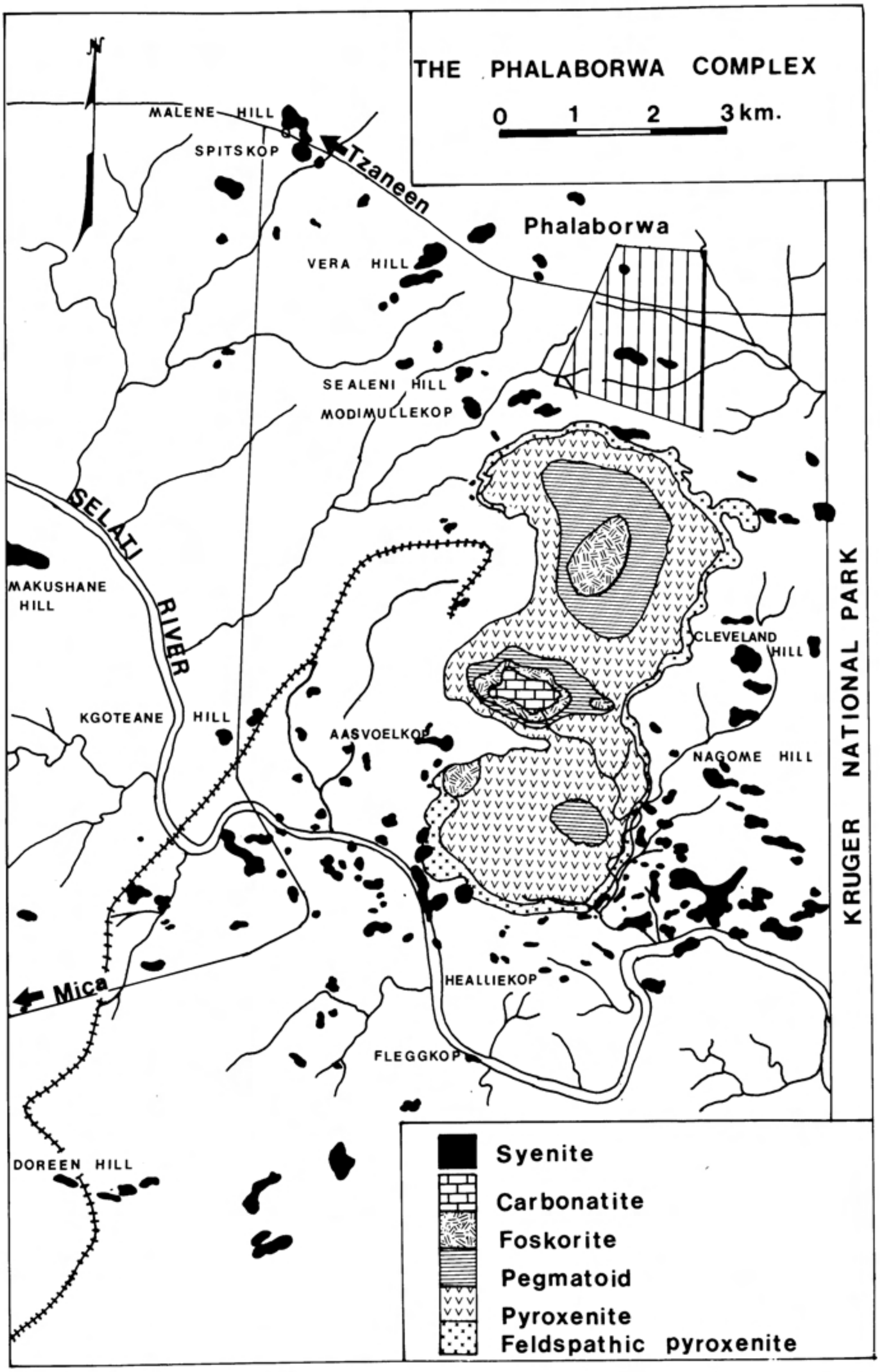

Fig. 3. A generalised geological map of the Phalaborwa Igneous Complex showing the distribution of the syenite intrusions.

pyroxenite pipe forming the old Guide Copper Prospect. The outer contacts of some of the syenite bodies with the surrounding granite are sharp, but in a few cases, notably at Vera Hill the granite along the outer margin of the intrusion is severely brecciated and consists of a heterolithic assemblage of rock-types (Fig. 5). The rock fragments in this breccia consist of biotite-granite, granulites, schists, amphibolites and leucogranite, whereas the matrix between the xenoliths, which often intrude into them, consists of orthoclase, quartz and accessory amounts of plagioclase. The contacts between the xenoliths and the invading syenitic veins are usually sharp along the outer peripheries of the brecciated zones, whereas towards the centres, the contacts become more diffuse and the individual xenoliths become more mafic.

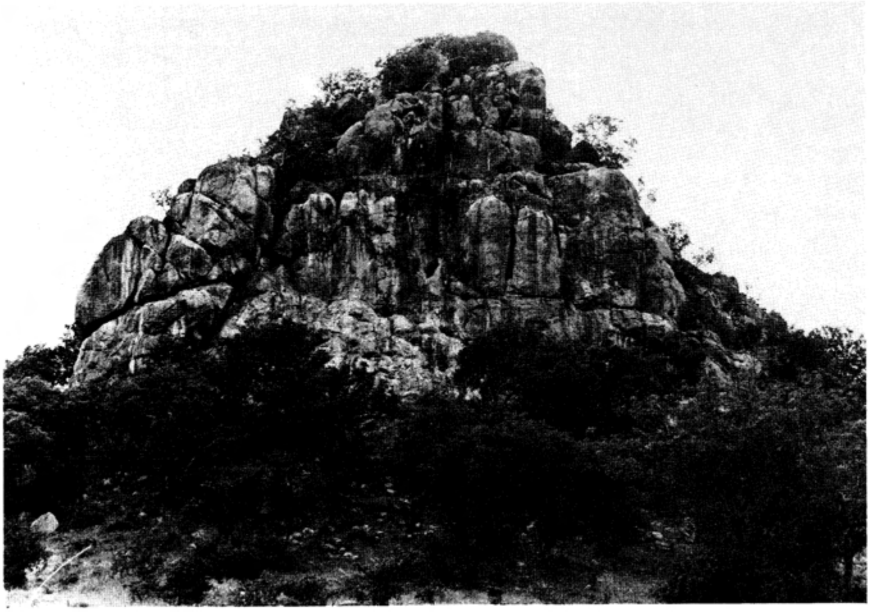

Fig. 4. A closeup view of one of the syenite intrusions which forms a small conical hill.

Where the syenite bodies have intruded into the pyroxenite, brecciated zones and deformed pyroxenite are generally absent, which, according to Hanekom *et al.* (1965), indicates that the pyroxenite was still plastic at the time of the emplacement of the syenite. Inclusions of pyroxenite are also present in the syenite which occurs close to the rim of the pyroxenite body. The latter inclusions are generally recrystallised and the clinopyroxene partly altered to aegerine-augite along the rims of the grains.

In the centres of some of the plugs, notably at Vera Hill, Aasvoëlkop and Malelene Hill, the xenoliths are much smaller than those along the outer rims of the intrusions, but they consist only of biotite and amphibole. This suggests that these relicts may represent much larger xenoliths which became accidentally enclosed in the syenitic magma and from which the minerals with low melting temperatures such as quartz, feldspar and possibly albite have been extracted and included in the syenitic magma.

Fig. 5. The breccia consisting of clasts of granite gneiss, granite and amphibolite around the Spitskop syenite intrusion.

The individual plugs contain syenite which shows a large variation in textural types. However, textures within each plug are uniform. The textural variations encountered include porphyritic, granular, hypidiomorphic (syenites with a typical granitic texture) and gneissic syenites (Fig. 6). The gneissic syenites show a distinct lineation which is occasionally orientated parallel to the lineation in the Swazian granite gneiss, but in most cases the lineation in the syenite is orientated parallel to the outer periphery of the intrusion. This indicates that plastic deformation took place in the syenitic magma during the emplacement thereof. The porphyritic, granular and hypidiomorphic syenites vary considerably in grain size and lens-shaped bodies and veins of pegmatite and aplite are also present in some of the plugs. In those examples where the outer contacts of the plugs are well exposed it appears that the syenite intrusions have steeply dipping outer contacts. This confirms the conclusion of Hanekom *et al.* (1965) that the syenite intrusions are pipe-shaped.

Petrography of the Syenites

The porphyritic syenite (Fig. 6A) consists of large euhedral to subhedral porphyres of K-feldspar (both microline and orthoclase) which often exceed 5 mm in diameter and are set in a finger-grained intergranular matrix. The latter usually contains small anhedral grains of orthoclase, quartz, aegerine-augite with accessory amounts of apatite, sphene, magnetite,

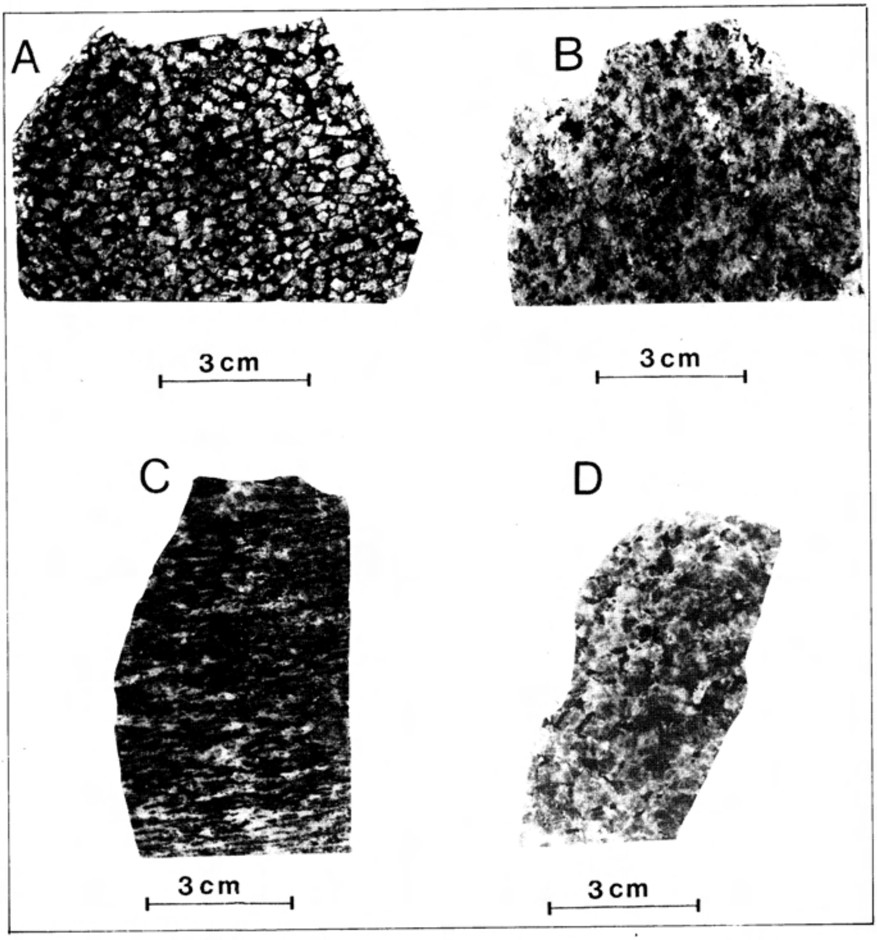

Fig. 6. Handspecimens of the different textural types of syenites from the Phalaborwa Complex. A is the porphyritic syenite, B the granular syenite, C the gneissic syenite and D the hypidiomorphic syenite.

alkaline amphiboles and secondary calcite and sericite. Needles of alkali-amphibole in the matrix are arranged in flow lines along the peripheries of the large orthoclase porphyries. The large porphyries are often recrystallised and partly deformed, especially in those instances where the porphyries are in direct contact with one another. It is also evident that the degree of deformation and recrystallisation of the porphyries increases as the amount of intergranular material decreases. It is concluded that the large porphyries crystallised at depth and that they became deformed during the emplacement of the syenitic magma.

The hypidiomorphic (Fig. 6D) syenites consist of orthoclase, microline, albite, alkali-amphibole, sphene, apatite, calcite and opaque oxides. They are very coarse-grained and show a typical granitic texture. The K-feldspar also consists of two generations, the older one being coarse-grained and the second generation being much finer grained and interstitial to the former.

Aegerine-augite is present as subhedral to anhedral grains which form wreaths around the first generation of K-feldspar crystals. The aegerine-augite is also often altered to a blue-green alkali-amphibole which contains exsolutions of chlorite and magnetite. Some of the hypidiomorphic syenites are also recrystallised and in these samples the first generation of orthoclase is more severely affected, especially along the grain boundaries.

The granular syenites (Fig. 6B) contain the same mineral assemblages as was observed in the other types of syenites. These syenites also contain large K-feldspar phenocrysts which are intensively recrystallised and consist of central cores of feldspar, which is intensively strained, surrounded by a halo consisting of fine-grained, equigranular, orthoclase grains showing an amoeboid texture. Some of the granular syenites have also been recrystallised to the extent that a flaser texture containing large K-feldspar augen has developed. In most of the granular syenites the smaller orthoclase, albite and quartz grains, which are intergranular to the larger grains, are also partly recrystallised, imparting an amoeboid texture to the rock. The aegerine-augite in the matrix is also often recrystallised and partly altered to alkali-amphibole. The recrystallised pyroxene is orientated parallel to the direction of elongation of the recrystallised feldspar porphyres.

The gneissic syenite (Fig. 6C) shows a distinct flaser texture in thin section with the development of a prominent lineation which is parallel to the orientation of the aegerine-augite grains. The orthoclase is recrystallised with the formation of a typical augen texture which is also elongated parallel to the main lineation. Even the quartz and feldspar in the matrix of these syenites are elongated parallel to the lineations. The aegerine-augite is present as small subhedral grains which show a typical nematoblastic texture. In places it is even recrystallised and a number of small needle-shape grains have resulted.

Geochemistry of the Syenites

In Fig. 7 the chemical analyses of the different rock-types from the Phalaborwa Complex have been plotted in a diagram showing the variation in the Na_2O+K_2O, MgO and $FeO+Fe_2O_3$ contents of the rocks. In addition, the variation in the composition of a basaltic magma with continued fractional crystallisation (Kuno 1968), and the composition of the K-feldspar in the feldspathic pyroxenite are also shown. Since the pyroxenite and feldspathic pyroxenite at the Phalaborwa Complex do not represent original magmas, but are the result of the accumulation of crystals which had crystallised from these magmas, they cannot be compared directly with the syenites, which probably represent magmas. It is thus clear that the tie-line between the composition of the pyroxenites and that of the K-feldspar, along which the feldspathic pyroxenite also falls, represents a mixing line, indicating that the feldspathic pyroxenite only resulted from the inclusion of K-feldspar in the pyroxenite. The syenites on the other hand define a trend which is more or less parallel to that normally observed in basaltic magmas, but this trend appears to be excessively enriched in alkalies.

As noted earlier, the contact relationships around the syenite plugs show that contamination of the pristine syenitic magmas by granitic material, and particularly the low melting fraction thereof (K-feldspar and quartz), took place. This contamination could cause a severe enrichment in alkalies in the syenitic magmas when compared to the pristine magmas and could explain the observed enrichment in alkalies in the syenitic trend compared to that of the normal fractionation trend of basaltic magmas. In addition, the large variation in the Fe-content of some of the syenite intrusions would suggest that the pristine magmas into which the granite was incorporated, did not have a uniform composition, but may have been fractionated with variable Fe-contents. Assuming that only orthoclase and quartz were the contaminants and that the evolution of the pristine magmas followed the fractionation curve suggested by Kuno (1968), a series of mixing lines can be drawn (lines between Or and B to D), which would suggest that the pristine magmas, which became contaminated, had a wide variation in compositions reflecting different degrees of fractionation.

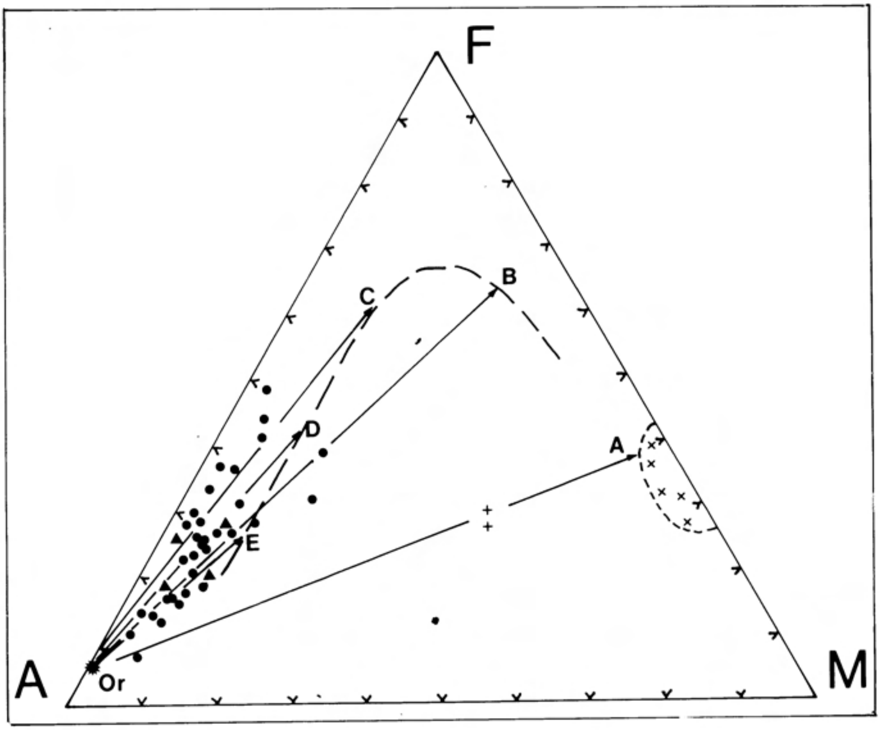

Fig. 7. The chemical variation of the rock-types in the Phalaborwa Complex in an AFM variation diagram. The compositions of the syenites (●), pyroxenites (x), feldspathic pyroxenites (+), the K-feldspar from the feldspathic pyroxenites (*), the Swazian basement granites (▲) and the fractionation trend after Kuno (1968)(/) are indicated.

In Fig. 8 the same analyses have been plotted in a variation diagram showing the molecular proportions of Al_2O_3, SiO_2 and Na_2O+K_2O in the rocks. This diagram also serves to distinguish alkaline from calc-alkaline rock-types. It shows that most of the syenites are moderately alkaline and that they vary in composition between the average composition of an alkaline basalt and that of K-feldspar. It is significant that the analyses of the Swazian granites also

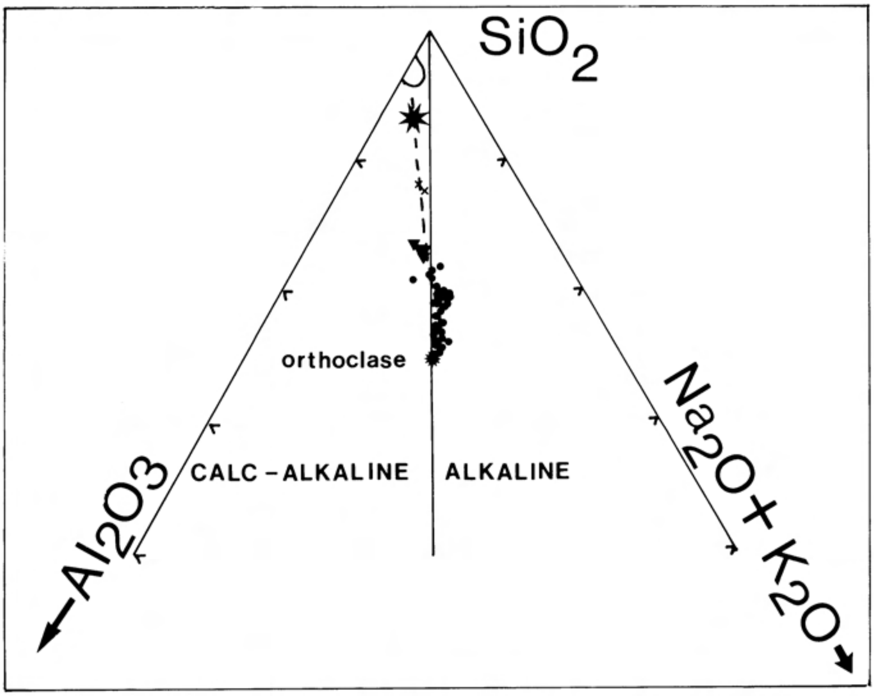

Fig. 8. The chemical variation of the rock-types from the Phalaborwa Complex plotted in a SiO_2-Al_2O_3-Na_2O+K_2O variation diagram. The compositions of the syenites (●), feldspathic pyroxenites (x), the average alkaline basalt (*), the Swazian basement granites (▼) and the orthoclase from the feldspathic pyroxenite are indicated.

plot along the same mixing line, but that the syenites are generally more enriched in alkalies than the granites, indicating that feldspar from the granite must have been preferentially added to the original alkali basaltic magma to yield the syenites.

Emplacement of the Phalaborwa Complex and the Genesis of the Syenites

In Fig. 9 a schematic cross section through the Phalaborwa Complex is shown, depicting the distribution of the major rock-types in this complex. Most of the rock-types which outcrop on the present surface are very coarse-grained, reflecting the fact that they cooled slowly and had sufficient time to form large crystals. It is thus clear that the present surface represents the plutonic stage of the Phalaborwa Complex. Observations by Goles (1975) and King (1965) in the East African Rift valley have indicated that the volcanic stage of alkaline plutonic complexes, such as the Phalaborwa Complex, must have erupted as alkaline basalts on the original land surface. This original surface on which the alkaline basalts erupted has long since been eroded and thus only the feeder channels and magma reservoir from where the eruption took place, are now exposed as the Phalaborwa Complex.

According to the diagramatic section it is clear that feeder channels other than the syenite intrusions, with their breccia haloes, are also present. According to Hanekom *et al.* (1965) at least one small plug-like body of

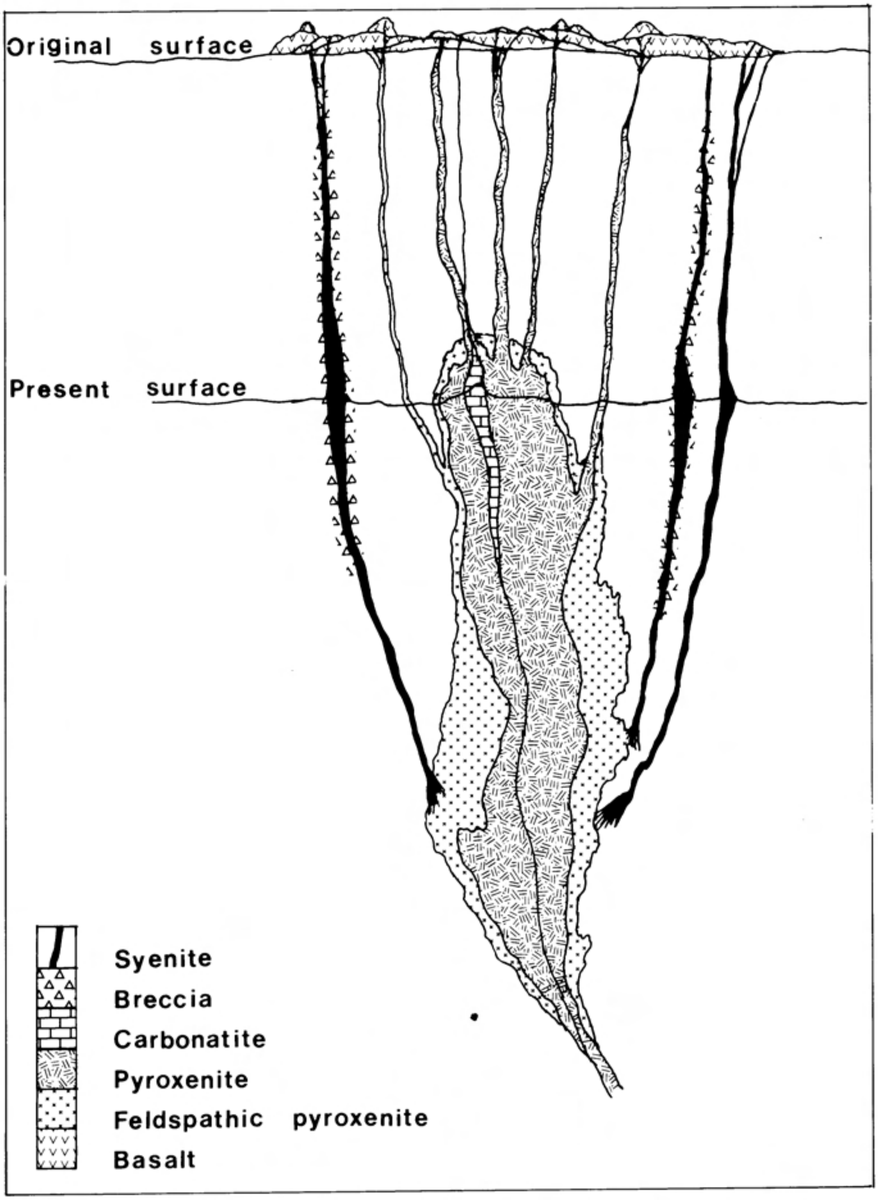

Fig. 9. A diagramatic cross section through the Phalaborwa Complex showing the shape and possible genesis of the Complex schematically.

feldspathic pyroxenite, the Guide Copper Prospect, and a similar one consisting of pyroxenite, west of Cleveland Hill, are also present between the syenite plugs. In addition, three late stage intrusion vents are also present within the Phalaborwa Complex and one of them consists of carbonatite.

It is thus suggested that the lavas which erupted on the original surface would have consisted of a large variety of magma types ranging from basaltic and carbonatitic to felsic lavas. It is further suggested that whereas the syenite plugs could be considered as the feeder vent for rather minor eruptions of felsic lavas on surface, the main pyroxenite body would have acted as a reservoir for a rather major eruption of alkali basaltic lavas.

The source of the alkali basaltic magmas, of which the pyroxenite body represents the subsurface crystalline phase, was probably the upper mantle of the Earth, some 35 km to 40 km below the surface. The source area for the syenitic magmas and for those which gave rise to the feldspathic pyroxenitic magmas, is more problematic. Three possible alternatives can be used to explain the origin of the latter magmas. They could also have derived from the upper mantle as separate magmas, they could have evolved as a consequence of fractional crystallisation from the main intrusion of alkali basaltic magmas or they may represent a reaction product between the alkali basaltic magma and the granitic crust into which it intruded.

The fact that the chemical compositions of the syenites do not appear to follow the normal fractionation trend for alkaline basalts, together with the fact that both inclusions of granite and gneiss are present along the marginal portions of the intrusions would suggest that contamination may in fact have caused the syenitic magmas to form. It is also significant that the feldspathic pyroxenites are only present along the rim of the pyroxenite body, suggesting that it also formed as a consequence of the assimilation of the basement granite and gneiss. The variation in the relative amounts of Fe and Mg in different syenites suggests that the pristine magmas which became contaminated may well have been a series of fractionated alkali basalts prior to emplacement and contamination.

It can thus be concluded that the Phalaborwa Complex represents the plutonic phase of a major period of volcanic activity which took place approximately 2 060 Ma ago. This episode started with the emplacement of large volumes of alkaline basaltic magma, from which the pyroxenite crystallised in the plutonic stage and the lavas erupted on surface. During the emplacement of the relatively hot (1 200 °C) alkali basaltic magma into the granitic crust, the low melting constituents such as the K-feldspar in the granite along the contact melted and were incorporated in the magma to crystallise as the feldspathic pyroxenite. Some of this contaminated alkali basalt magma also erupted on surface possibly giving rise to a more K-rich siliceous magma. During later emplacements of hot alkali basaltic magma, which may even have been fractionated, more reaction could have taken place resulting in even more siliceous and K-rich lavas, yielding the syenitic magmas. Further reaction took place between the syenitic magma and the granitic crust along feeder channels as was shown along the contact zones of the syenite plugs. The final phase of volcanism resulted with the eruption of carbonatitic magma, which may well result from fractionation within the sub-surface plutonic mass (magma chamber).

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REFERENCES

BRANDT, J.W. 1948. *Die geologie van 'n gebied in noordoos Transvaal, met spesiale verwysing na die verspreiding en petrografie van die rotssoorte van die Palaborastollingskompleks.* D.Sc. thesis, University of Stellenbosch, Stellenbosch.

FRICK, C. 1975. The Phalaborwa syenite intrusions. *Trans. geol. Soc. S. Afr.* 78:201-213.

GEVERS, T. 1949. Vermiculite at Loolekop, Phalaborwa, North Eastern Transvaal. *Trans. geol. Soc. S. Afr.* 60:244-250.

GOLES, G.G. 1975. Depths of origin of Kenyan basalts and implications for the Gregory Rift. *Nature* 255:391-393.

HANEKOM, H.J., C.M. v. H. VAN STADEN, P.J. SMIT and D.R. PIKE. 1965. The geology of the Phalaborwa Igneous Complex. *Mem. geol. Surv. S. Afr.* 54:1-185.

HARGER, H.S. 1934. An early Transvaal geological map by Carl Mauch. *Trans. geol. Soc. S. Afr.* 37:1-4.

HOLMES, H. and L. CAHEN. 1957. Geochronologie africaine, 1956. *Mem. Acad. r. Sci. colon.,* n Ser. T-S Fasc. 1:1-169.

KING, B.C. 1965. Petrogenesis of the Alkaline Igneous Rock Suites of the volcanic and intrusive centres of Eastern Uganda. *J. Petrol.* 6:67-100.

KUNO, H. 1968. Differentiation of basalt magmas. *In:* HESS, H.H. and A. POLDERVAART (eds.) *Basalts.* New York: John Wiley.

VERWOERD, W.J. 1956. Sekere Produkte van Primitiewe koper- yster- en bronssmelterye in Oos Transvaal met besondere verwysing na Phalaborwa. *Tegnikon* 9:91-104.

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