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# The Etanenoberg Alkaline Complex, Namibia

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The Etanenoberg Complex is a small, circular alkaline ring complex with a probable diameter (the outer part is unexposed) of 7 km. It is situated near Kalkfeld in northern Namibia and belongs to the early Cretaceous Damaraland Igneous Province, ca 135 Ma in age. Concen¬tric rings around a central plug of tephritic phonolite comprise foyaite, white pulaskite and grey pulaskite. Contacts are intrusive except between the grey and white pulaskites which are presumed to belong to a single intrusion. Two sets of radial dykes concluded the eruptive history. Trachytic fluidal structure is commonly developed and modal as well as rhythmic layering occur sporadically. Xenoliths of sodalite syenite are interpreted as the products of volatile activity during an early stage of evolution. On the basis of mineralogy and geochemistry, the tephritic phonolite and some of the dykes approach the composition ofthe parent magma whereas the grey pulaskite has a modified, variable composition as a result of crystal accumulation. The most evolved peralkaline (but not agpaitic) liquids are represented by the foyaite and grey nepheline syenite dykes.

## Preamble

This paper is dedicated to the memory of Dr. Henno Martin who, in July 1956, first suggested to WJV that the prominent hill rising abruptly from the peneplain 21 km north of Kalkfeld might be another member of the post-Karoo Damaraland Igneous Province. At the time the first author was engaged in mapping the Kalkfeld carbonatite. He was joined in camp by Dr. Martin and two colleagues. The party of four climbed the hill and proved Dr. Martin's prediction to be correct. With characteristic generosity Dr. Martin left it to WJV to follow up the discovery despite the fact that Korn and Martin's definitive description of the Messum Complex had appeared shortly before and Dr. Martin had earned a.reputation as the foremost authority on the Damaraland complexes. WJV mapped the Etanenoberg Complex by plane-table and telescopic alidade on a scale of 1:5000 during 1956. Additional observations were made and samples collected during subsequent visits in 1965 and 1976. Unfortunately, publication of most of the results has been delayed till now.

## Introduction

Etanenoberg is a 300 m high inselberg with a symmetrical shape and a narrow shelf just below the summit, which is a topographic reflection of its concentric geological structure. An adjacent conical hill (Klein Etanenoberg, 160 m) forms part of a concentric zone. Steep, radial gulleys are truncated by a semi-circular dry water course with a diameter of 2.4 km in the surrounding sand-covered plain (Fig. 1). Although this circle appears to be structurally controlled, it is not the outer boundary of the complex. A high-resolution aeromagnetic survey (Eberle and Hutchins, 1996) reveals two more zones that are not exposed, giving a probable diameter of 7 km and confirming the almost perfectly ring-shaped structure (Fig. 2). If this is correct, the complex occupies an area of 38.5 km$^2$ of which only the central 2.5 km$^2$ crop out.

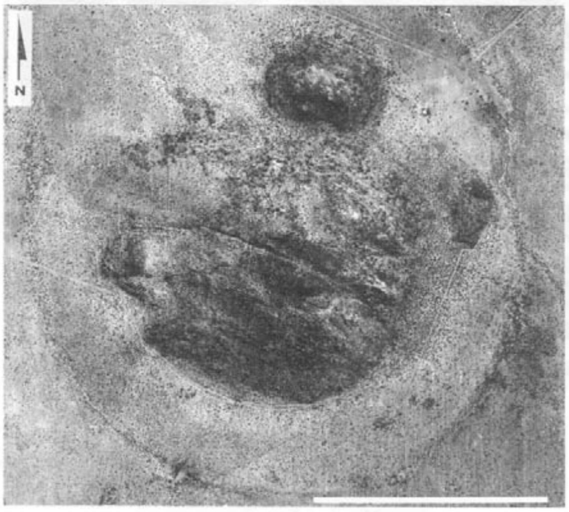


**Figure 1:** Vertical aerial photograph of the Etanenoberg. Apparent circular boundary marked by dry water course. Scale bar = 1 km.

The Etanenoberg Complex consists of several nepheline syenite and nepheline-bearing syenite components with spectacular igneous textures. An early Cretaceous Rb/Sr whole rock age (134±2.6 Ma) was recently obtained (B. Muller, Zürich, pers. comm., 1996). The complex is intrusive into the Northern Central Zone of the Damara Orogen, the country rock being Damara Sequence schist, marble and quartzite and coarse-grained, porphyritic, syntectonic Damaran biotite granite. The Etanenoberg belongs to the NE-trending belt of anorogenic volcano-plutonic intrusions (the Damaraland Igneous Province) which extends approximately 650 km inland if the sand-covered magnetic anomalies east of Grootfontein are included (Eberle and Hutchins, 1996).

## Previous Work

A preliminary account, based on our field work, was included in the review paper by Martin, Mathias and Simpson (1960). Five samples tram the farm Nordenberg 46 (Visser, 1964, pp. 55, 59, 215) have been re-analysed and the results show a much better correspondence between modes and CIPW norms. Mathias (1974) referred very briefly to Etanenoberg. Prins (1981) discussed certain geochemical aspects of the complex in relation to the province as a whole. There are three minor inconsistencies in the paper by Prins (*op.cit.*) that have caused confusion: “porphyritic” in the legend of his Figure 2 should be changed to “coarse-grained”; sample Et7 in Table 15 is the so-called “fine-grained core nepheline syenite” as quoted on p. 278, not “grey nepheline syenite”; and the sodalite syenite should be numbered Et11 as on p. 278, not Et12 as in Table 15. Rock names adopted in all these publications were tentative field identifications and are revised in the present study.

## Nomenclature

Petrographic nomenclature approved by IUGS (Le Maitre, 1989) is used in this paper with the following qualifications:

The core of the complex is a hypabyssal rock for which volcanic terminology is preferred because the texture, whilst varying from fine- to medium-grained, differs markedly from the plutonic textures in the rest of the complex. The “grey and black nepheline syenite dykes” are also hypabyssal and could be designated microfoyaite and porphyritic phonolite, respectively, but in view of their variable textures, the more neutral term nepheline syenite is given preference. Pulaskite is used instead of the cumbersome “nepheline-bearing alkali feldspar syenite”. The foyaite is characterised by its trachytoid texture.

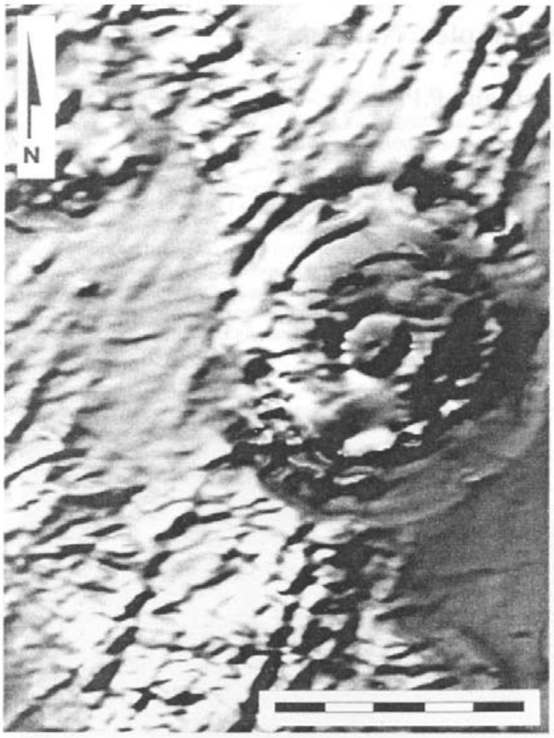
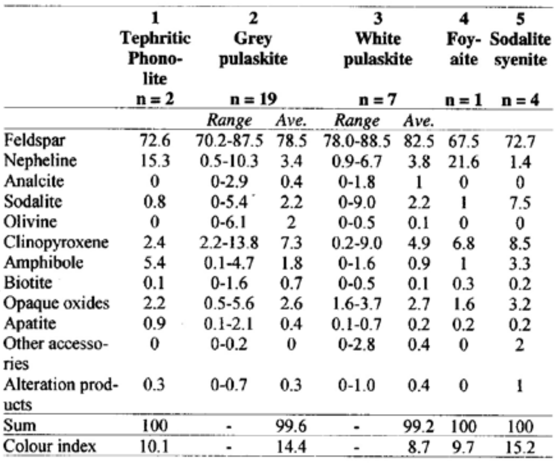


Figure 2: Regional aeromagnetic anomaly indicating unexposed outer rings and north-east trending linear magnetic pattern in metamorphosed Damara Sequence. Scale bar = 5 km. (Data stored by Geological Survey, Windhoek).

**Table 1:** Modal Compositions, Etanenoberg Complex



| | 1<br>Tephritic Phonolite<br>n = 2 | 2<br>Grey pulaskite<br>n = 19 | | 3<br>White pulaskite<br>n = 7 | | 4<br>Foyaite<br>n = 1 | 5<br>Sodalite syenite<br>n = 4 |
|---|---|---|---|---|---|---|---|
| | | *Range* | *Ave.* | *Range* | *Ave.* | | |
| Feldspar | 72.6 | 70.2-87.5 | 78.5 | 78.0-88.5 | 82.5 | 67.5 | 72.7 |
| Nepheline | 15.3 | 0.5-10.3 | 3.4 | 0.9-6.7 | 3.8 | 21.6 | 1.4 |
| Analcite | 0 | 0-2.9 | 0.4 | 0-1.8 | 1 | 0 | 0 |
| Sodalite | 0.8 | 0-5.4 | 2.2 | 0-9.0 | 2.2 | 1 | 7.5 |
| Olivine | 0 | 0-6.1 | 2 | 0-0.5 | 0.1 | 0 | 0 |
| Clinopyroxene | 2.4 | 2.2-13.8 | 7.3 | 0.2-9.0 | 4.9 | 6.8 | 8.5 |
| Amphibole | 5.4 | 0.1-4.7 | 1.8 | 0-1.6 | 0.9 | 1 | 3.3 |
| Biotite | 0.1 | 0-1.6 | 0.7 | 0-0.5 | 0.1 | 0.3 | 0.2 |
| Opaque oxides | 2.2 | 0.5-5.6 | 2.6 | 1.6-3.7 | 2.7 | 1.6 | 3.2 |
| Apatite | 0.9 | 0.1-2.1 | 0.4 | 0.1-0.7 | 0.2 | 0.2 | 0.2 |
| Other accessories | 0 | 0-0.2 | 0 | 0-2.8 | 0.4 | 0 | 2 |
| Alteration products | 0.3 | 0-0.7 | 0.3 | 0-1.0 | 0.4 | 0 | 1 |
| Sum | 100 | - | 99.6 | - | 99.2 | 100 | 100 |
| Colour index | 10.1 | - | 14.4 | - | 8.7 | 9.7 | 15.2 |

## Modal Composition

Modes of 33 rock samples are summarised in Table I. Most of these were taken along two traverses across the grey-white pulaskite boundary (Fig. 3) to investigate the possibility of a compositional trend in either a radial or vertical direction. No such regularity was found except the almost total disappearance of fayalitic olivine at this boundary. The variable proportions of the constituent minerals in the pulaskites are illustrated by Figure 4. This shows that the two types overlap, although the white pulaskite is generally more leucocratic; in addition there are textural differences.

## Petrology and Petrography

The concentric zones are described from the centre outwards. This is not necessarily the order of emplacement.

### *Tephritic Phonolite*

The core of the complex is a somewhat excentric, roughly oval body of dark-coloured tephritic phonolite, 300 m in diameter, forming the summit of Etanenoberg. Two facies can be distinguished: the central part is medium grained and mildly porphyritic; it grades into a second, finer grained peripheral facies with numerous well-orientated feldspar phenocrysts (Fig. 5). Several smaller isolated bodies of medium-grained phonolite are also present within the surrounding foyaite and white pulaskite, suggesting that the phonolite was engulfed and broken up by subsequent intrusions. Some outcrops are cut by veins of felsic material and the feldspar phenocrysts of the host may be aligned parallel to the contacts.

The texture of the coarser facies is hypidiomorphic with all the minerals relatively free from inclusions.

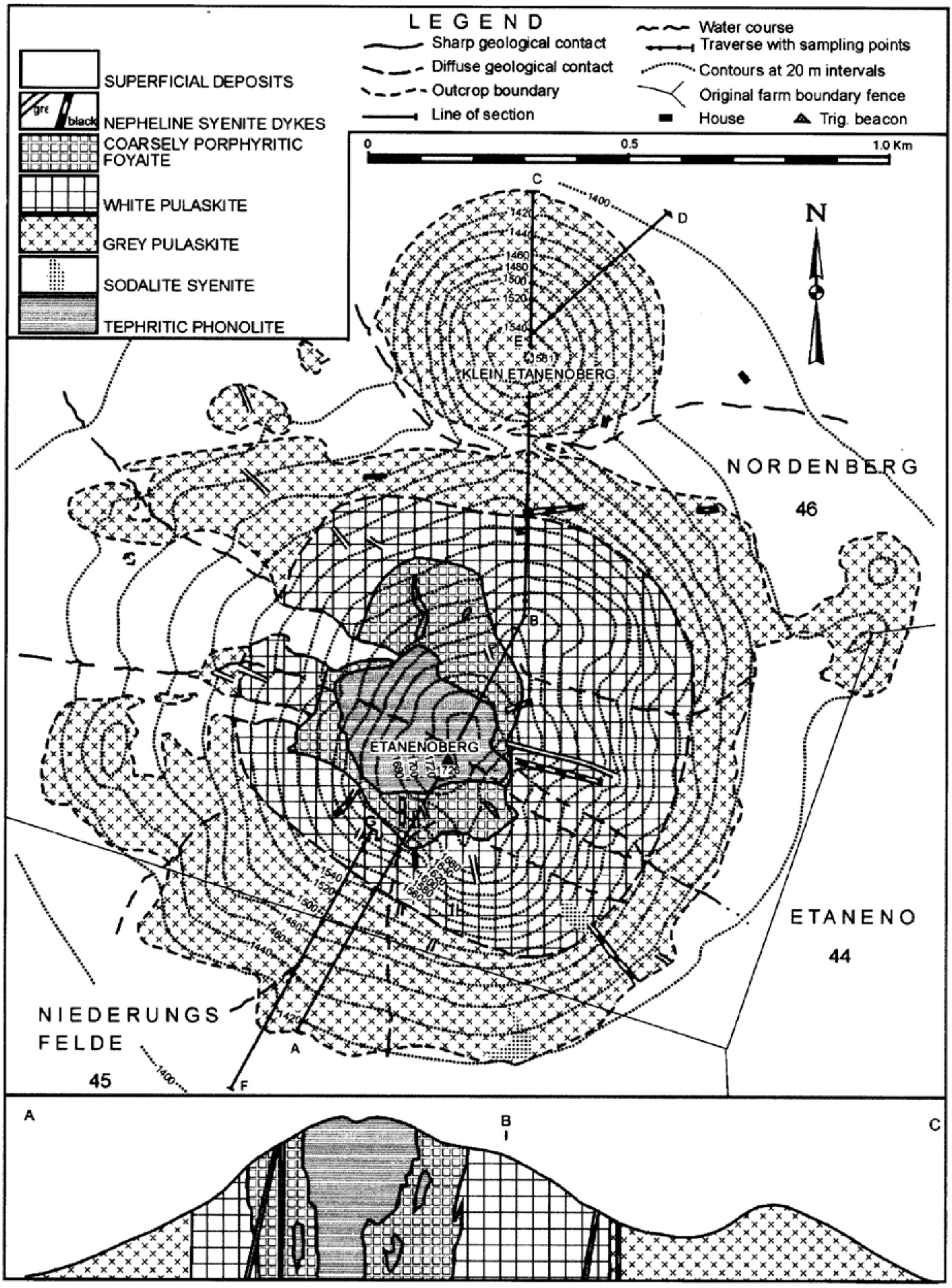


**Figure 3:** Geological map and section.

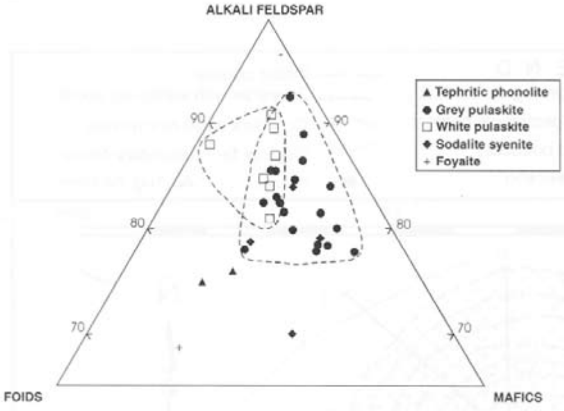


**Figure 4:** Triangular plot of modal compositions.

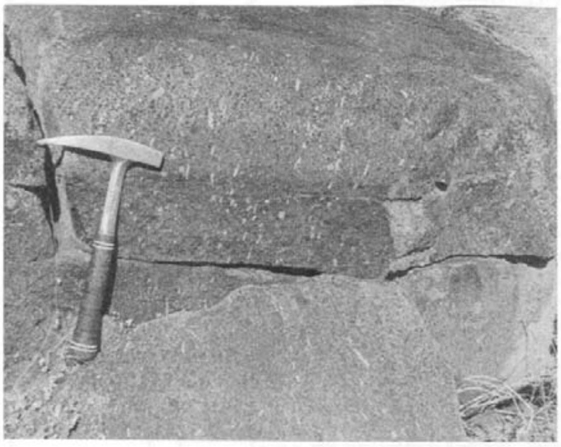


**Figure 5:** Tephritic phonolite (marginal facies) showing parallel orientation of tabular feldspar phenocrysts.

The finer-grained facies is allotriomorphic and the feldspars are riddled with nepheline, pyroxene, olivine and amphibole inclusions. The feldspar of both facies is strongly zoned primary plagioclase ($An_{35-65}$) which is commonly mantled by alkali feldspar. The mantles are usually optically homogeneous but some show very fine exsolved plagioclase stringers ending abruptly against the core. The relative proportions of plagioclase and K-rich alkali feldspar vary: in some specimens, plagioclase predominates greatly whereas in others the reverse relationship holds. In a few samples, partially exsolved, zoned K-feldspar is the sole feldspar phase. The cores of large feldspar phenocrysts (averaging 4 cm across) often contain dactylic intergrowths of K-feldspar and zeolite or sodalite. Nepheline is unaltered, subhedral and occurs mainly in the groundmass. Sodalite forms interstitial patches which corrode and replace the adjacent nepheline and feldspar. The principal mafic mineral is clinopyroxene of the diopside-hedenbergite and aegirine-augite series in the form of subhedral grains. Amphibole occurs mainly as coronas around pyroxene and olivine. Olivine ($Fa_{50-55}$) is sparingly present. Other minor constituents are biotite, iron oxides and apatite.

### *Xenoliths in tephritic phonolite*

Dark, rounded xenoliths from 1 to 13 cm in diameter occur sporadically in the phonolite. Contacts are sharp and no reaction phenomena have been observed. The xenoliths consist of inconspicuous feldspar, pyroxene and sparingly distributed nepheline phenocrysts in an aphanitic groundmass. Microscopically, the pyroxene and altered feldspar microphenocrysts, amongst which polysynthetically twinned plagioclase can be recognised, are rather closely packed in a dense (<0.01 mm) matrix. Very fine-grained aggregates that resemble so-called "pseudoleucite clots" in tinguaite are also present, as well as olivine, amphibole, biotite and iron oxides. The mineral constituents of these xenoliths are essentially the same as those of the tephritic phonolite. They are probably autoxenoliths derived from a slightly earlier, chilled hypabyssal phase or perhaps from a closely related tholoid or lava flow.

### *Foyaite*

This is a striking ornamental stone with greenish white feldspar laths reaching 8 cm in length, equant dull red nepheline crystals up to 1.5 cm in diameter and interstitial black aegirine-augite clusters. The feldspars often show Carlsbad and Manebach twins. The tabular feldspars are arranged in a sub-parallel fluidal texture (Fig. 6). The foyaite forms a collar around the tephritic phonolite and sends apophyses into the latter; small xenoliths as well as the large included blocks already mentioned bear further witness to an intrusive relationship. The foyaite also appears to be intrusive into the surrounding white pulaskite although the actual contact was nowhere seen. A banded contact facies is developed in the southern part of the foyaite against the white pulaskite, in which mafic schlieren with sparse nepheline and feldspar phenocrysts alternate with me-

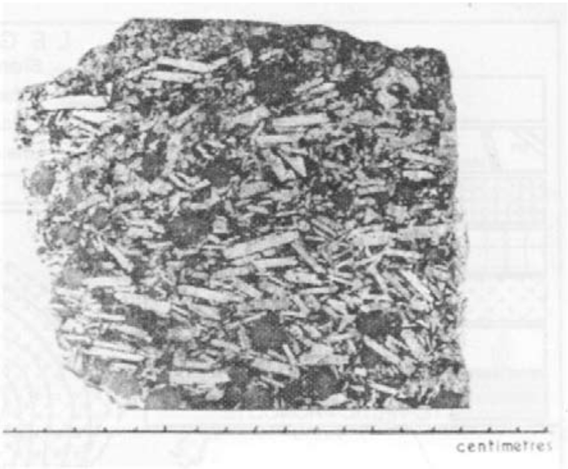


**Figure 6:** Foyaite. Polished slab showing well developed flow structure with white feldspar laths, red equant nepheline crystals and dark, pyroxene-rich groundmass.

dium-grained felsic schlieren. Elsewhere, the foyaite becomes coarser grained in proximity to the pulaskite.

The characteristic flow structure in the foyaite is vertical and parallel to the nearest contact but it may veer off and become perpendicular some distance away from the contact. Locally, nepheline may constitute the only phenocryst phase.

The alkali feldspar phenocrysts show only slight variation in the exsolution textures in different specimens. Plume, string and braid microperthite are common and micro-antiperthite not infrequent; albite twinned plagioclase may form a few large patches and many grains carry unexsolved, optically homogeneous areas. Herringbone textures are seen in Manebach-twinned phenocrysts. The groundmass feldspar varies from subhedral to anhedral. Nepheline phenocrysts are generally subhedral whereas the tiny crystals in the groundmass are euhedral. The nepheline is rather fresh, showing only limited sericitic alteration. Sodalite forms irregular blebs in the groundmass and partly replaces the small nephelines. The principal mafic mineral is strongly zoned aegirine-augite forming interstitial clusters of subhedral grains. Arfvedsonitic amphibole is sparse, as are biotite, the two accessories magnetite and apatite and the alteration products natrolite, analcite and calcite.

### *Grey and white pulaskites*

Although the two rock types can be clearly distinguished, they form a single intrusive unit that constitutes the major portion of the complex. Except where banded (see structure), the pulaskites have a homogeneous appearance.

The **grey pulaskite** is medium to coarse grained, allotriomorphic granular, with blue grey feldspar predominating over the mafic minerals. The subhedral habit of all the constituents contributes towards a massive character. Sparsely distributed rhomb feldspars bounded by the (110) and (201) crystal faces are especially characteristic of the outermost outcrops and the neck between the two hills. They show a reasonably well-developed preferred orientation. The rhombs are zoned: the cores are packed with minute but megascopically visible inclusions of pyroxene, olivine, amphibole, biotite and magnetite; surrounding sheaths are relatively free from inclusions. The sheaths are often incomplete and interlock with the surrounding minerals, indicating that they have grown *in situ*. The feldspars exhibit a moderately strong bluish schiller effect, but not as well developed as in the typicallarvikite of the Oslo region.

Feldspar is mainly anorthoclase and sanidine-anorthoclase micro-antiperthite. In general, it is blotchy due to a combination of weakly developed grid twinning, incipient exsolution, wavy extinction and irregular turbidity. A few primary plagioclase cores, strongly corroded by enclosing K-rich alkali feldspar, were observed in specimens from the outermost outcrops. The cores of the rhomb feldspars can be either plagioclase, or unexsolved to completely exsolved alkali feldspar. There are also a large number of grains with no exsolution: They nevertheless show a cloudy type of extinction under crossed polars, which probably relates to the schiller effect. Nepheline is scarce: a first generation occurs as poikilitically enclosed blebs in the feldspar, whereas a second generation occurs interstitially. Sodalite has a similar distribution. The mafic minerals are subhedral to anhedral and form interstitial aggregates, apart from the minute inclusions already mentioned. Olivine is fayalitic ($\text{Fa}_{65\text{-}100}$) and partly altered to deep yellow chlorophaeite (supposedly a mixture of chlorite, saponite and goethite). Clinopyroxene is weakly pleochroic (augite to aegirine-augite). Stringers and coronas of amphibole (both hornblende and pale bluish-green magnesiohastingsite) are present, as well as a little biotite, apatite and zeolite. Opaque oxides consisting of magnetite-ilmenite intergrowths are intimately associated with the mafic minerals.

The **white pulaskite** adjoins the grey pulaskite on the inside with a vague contact which can be described as neither sharp nor gradational. It is more like the type of boundary between units in a layered intrusion exhibiting cryptic or phase layering. On the northern slope of Etanenoberg, the outer margin of the white pulaskite is marked by a series of blocky tor-like outcrops in contrast with the exfoliation domes of grey pulaskite on Klein Etanenoberg. Megascopically the white pulaskite differs from the grey pulaskite by the lighter colour of the feldspars, their medium grain size and a hypidiomorphic granular texture. Rhomb feldspars are occasionally present but most are stubby prismatic crystals measuring up to 6 mm in length. Interstitial nepheline is visible and mafic minerals are distinctly less abundant than in the grey pulaskite. A slightly different facies forms a zone about 2 m wide against the foyaite: the feldspars are smaller and the nepheline changes habit from interstitial to euhedral as it becomes a primary precipitate.

Other differences between white and grey pulaskite become apparent under the microscope. Exsolution textures in the feldspar resemble those observed in the foyaite rather than those in the grey pulaskite. Patch or bead microperthite becomes more important inwards whereas the amount of unexsolved feldspar and of micro-antiperthite decreases. The K-rich feldspar is often turbid. The anhedral nepheline patches measure up to 4 mm in diameter; smaller crystals are enclosed by feldspar. Sodalite is still present (pseudomorphous after nepheline, in part) and analcite makes its first appearance interstitially. Olivine is a rare accessory, absent in most specimens. Clinopyroxene is strongly zoned, mildly pleochroic in green and richer in the acmite component than in the grey pulaskite. Apart from the usual accessory minerals (magnetite, amphibole, biotite and apatite), titanite and zircon are sporadically distributed.

### *Sodalite syenite*

Numerous xenoliths of sodalite syenite are grouped together in two elongated areas on the southwestern flank of Etanenoberg. The one group occurs in grey pulaskite and the other transects the boundary between the grey and white pulaskites. The xenoliths are mostly rounded with sharp contacts and range in size from a few cm$^2$ to many m$^2$. Macroscopically they appear to differ in texture from the other, typically igneous components of the complex. They are heterogeneous, relatively dark in colour and contain rather inconspicuous feldspar phenocrysts set in a fine-grained groundmass.

Marked variations in grain size and mineral proportions are seen even in one sample. Sodalite forms large poikilitic patches enveloping the other constituents. It also occurs as rounded inclusions in the feldspar phenocrysts. Nepheline is less common than sodalite, but has been identified as small vermicular bodies enclosed by feldspar. Some specimens carry pseudomorphic aggregates of sodalite and a zeolite which have presumably replaced nepheline in the groundmass. Analcite occurs interstitially; both cancrinite and calcite are rare. Embayed feldspar phenocrysts measure up to 15 mm and are microperthitic; alkali feldspar also occurs as an important constituent of the groundmass where the grains are subhedral to anhedral and equant. The mafic minerals (pyroxene, amphibole, biotite and opaques) are mainly confined to the groundmass. Aegirine-augite is the only mafic mineral that sometimes forms microphenocrysts less than 1 mm in size. A second generation of aegirine occurs as fine, acicular overgrowths on magnetite. Blue green arfvedsonitic amphibole is invariably present and may predominate over aegirine-augite in places. Titanite, both anhedral and euhedral, is the most common accessory mineral, together with apatite and zircon. The sodalite syenite carries the highest concentration of accessories of all the Etanenoberg rocks.

### *Nepheline syenite dykes*

The latest intrusions are two sets of dykes that are compositionally similar but clearly distinguishable in texture and colour. The grey type carries nepheline and tabular feldspar phenocrysts set in a groundmass that varies from fine to medium grained. In some cases the phenocrysts are so well orientated parallel to the dyke contacts and the groundmass so coarse that the rock resembles the foyaite already described; elsewhere the texture is more equigranular. The black variety exhibits a more pronounced porphyritic texture; the phenocrysts, with nepheline less -plentiful than feldspar, are dominated by a dense, very fine-grained, mafic groundmass. In one instance a grey nepheline syenite dyke transects a black one, which is therefore older.

The dykes vary from 1 to 3 m in width and from a few metres up to about 300 m in length. They are vertical or near vertical and the majority radiate from the central tephritic phonolite plug. The only exceptions appear to be four black dykes with an east-west (tangential) trend between the two hills. The dykes cut through every rock type except the central plug. Perhaps they propagated in predominantly horizontal directions and pinched out at higher elevations below the summit.

In general, dyke contacts are sharp and sometimes saw-toothed (Fig. 7), but in other instances interesting contact effects are observed. A zone of grey microfoyaite a few cm wide may separate the dyke from the host; this is not just a case of composite intrusion because veinlets of microfoyaite also penetrate the dyke (Fig. 8). The explanation appears to be mobilisation of the wall rock, even remelting, during intrusion. That some of the black dykes intruded while the pulaskite was not yet completely solid is proven by one dyke which was broken up and dismembered by movement which obvi-

**Figure 7:** Black nepheline syenite dyke with saw-tooth contact intrusive in white pulaskite.

**Figure 8:** Grey pulaskite transected by a black nepheline syenite dyke which, in turn, is cut by narrow stringers of microfoyaite originating at the contact by remelting ("back veining")

ously took place within the country rock after emplacement of the dyke. Both angular and well-rounded wall rock xenoliths are common in the dykes.

Feldspar in both types assumes any of the following habits: tabular phenocrysts averaging 10-15 mm in length, short stubby prisms, rounded crystals and anhedral grains. The predominant type of exsolution texture is micro- or crypto-antiperthite, but well developed microperthite and optically homogeneous feldspars are also present. The feldspar often carries inclusions of nepheline, sodalite and pyroxene. Nepheline ranges from large composite phenocrysts consisting of as many as five individuals with different crystallographic orientation, to zoned microphenocrysts, rounded grains and interstitial patches. The nepheline is occasionally replaced by sodalite. Sodalite as well as analcite also occurs interstitially in limited amounts. Augite, aegirine-augite, hastingsitic amphibole and magnetite are the common mafic constituents. Olivine and biotite are scarce and may be restricted to the black nepheline syenite dykes. The olivine forms anhedral microphenocrysts with biotite coronas associated with secondary iron oxides. Other minor constituents are apatite, titanite and zircon.

## Petrochemistry

Chemical analyses of the five constituent rock types are presented in Table 2. Prins (1981) also analysed the dykes and major rock types. Totals lower than 99.5 could be accounted for by $CO_2$ which was not determined because calcite and cancrinite are negligible in thin sections. Note that the CIPW norms (Table 2) are not directly comparable with the modes (Table 1) since the latter have been averaged. Nevertheless, the correspondence is quite good except for the lack of normative nepheline and sodalite (which should appear as nepheline plus halite in the norm) in the samples of grey pulaskite (WJ362) and sodalite syenite (WJ366) that were analysed. This can be explained by the considerable modal variability of these rocks. Norms of the same two rock types based on analyses by Prins (1981) carry 8.86 and 22.02 % nepheline respec-tively, whereas the average modal nepheline contents are 3.4 and 1.4 % (Table 1). The grey pulaskite sample (WJ362) probably represents a rather extreme composition, since modal nepheline ranges from 0.5 to 10.3 % in Table 1. Normative magnetite and ilmenite appear to be consistently too high.

No clear trend emerges from a total alkali versus silica (TAS) plot, where all the data points cluster on and adjacent to the tephriphonolite field. This is because $SiO_2$ content is restricted to the narrow interval between 49% and 58%. Thornton and Tuttle's Differentiation Index or D.I. (the sum of the felsic normative constituents excluding calcic plagioclase, i.e. "petrogeny's residua") provide a much better yardstick for the evolution of alkaline rocks than silica. In the case of Etanenoberg,

**Table 2:** Whole-rock major (wt.%) and trace element (ppm) chemical analyses and CIPW norms of selected samples from the Etanenoberg Complex

| **Sample no.**<br>**Rock Type** | **WJ351**<br>Tephritic Phonolite | **WJ354**<br>Foyaite | **WJ364**<br>White Pulaskite | **WJ362**<br>Grey Pulaskite | **WJ366**<br>Sodalite Syenite (Xenolith) |
|---|---|---|---|---|---|
| **$SiO_2$** | 51.08 | 52.33 | 58.33 | 56.88 | 55.01 |
| **$TiO_2$** | 0.94 | 0.57 | 0.64 | 0.85 | 1.17 |
| **$Al_2O_3$** | 19.36 | 20.45 | 18.33 | 17.97 | 16.53 |
| **$Fe_2O_3$** | 2.50 | 3.76 | 2.23 | 1.46 | 4.98 |
| **FeO** | 5.81 | 3.33 | 3.24 | 5.45 | 4.41 |
| **MnO** | 0.23 | 0.22 | 0.17 | 0.23 | 0.28 |
| **MgO** | 1.74 | 0.81 | 0.60 | 0.68 | 0.91 |
| **CaO** | 4.34 | 2.16 | 2.03 | 3.97 | 3.75 |
| **$Na_2O$** | 7.66 | 9.13 | 6.31 | 5.42 | 5.29 |
| **$K_2O$** | 3.61 | 4.48 | 5.05 | 3.99 | 4.53 |
| **$P_2O_5$** | 0.59 | 0.34 | 0.20 | 0.34 | 0.40 |
| **$H_2O^+$** | 1.22 | 1.26 | 1.18 | 0.73 | 0.45 |
| **$H_2O^-$** | 0.08 | 0.14 | 0.11 | 0.07 | 0.06 |
| **Cl** | 0.1 | 0.3 | 0.0 | 0.0 | 0.1 |
| **-O(Cl)** | -0.03 | -0.07 | - | - | -0.11 |
| **Total** | **99.23** | **99.21** | **98.42** | **98.04** | **97.76** |
| **Rb** | 86 | 129 | 107 | 176 | 263 |
| **Sr** | 939 | 373 | 407 | 566 | 384 |
| **Ba** | 1639 | 1033 | 1249 | 1455 | 1105 |
| **Y** | 41 | 32 | 44 | 92 | 129 |
| **Zr** | 324 | 210 | 393 | 910 | 1644 |
| **Nb** | 133 | 81 | 118 | 246 | 374 |
| **La** | 140 | 127 | 114 | 188 | 270 |
| **Ce** | 211 | 190 | 172 | 286 | 418 |
| **Nd** | 72 | 56 | 59 | 101 | 144 |
| **V** | 52 | 4 | 0 | 8 | 12 |
| **Cr** | 11 | 0 | 0 | 0 | 0 |
| **Ni** | 0 | 0 | 0 | 0 | 0 |
| **Cu** | 54 | 12 | 13 | 25 | 76 |
| **Zn** | 75 | 68 | 57 | 140 | 153 |
| **Ga** | 20 | 22 | 23 | 29 | 30 |
| **Mo** | 5 | 4 | 5 | 7 | 12 |
| **Pb** | 15 | 10 | 17 | 33 | 211 |
| **Th** | 21 | 12 | 21 | 43 | 63 |
| **U** | 6 | 3 | 4 | 11 | 18 |
| **Sc** | 4 | 4 | 0 | 5 | 6 |
| **Qz** | 0 | 0 | 0 | 0 | 0 |
| **Or** | 21.33 | 26.47 | 29.84 | 23.58 | 26.77 |
| **Ab** | 28.31 | 30.06 | 47.97 | 45.86 | 44.02 |
| **An** | 8.17 | 2.76 | 6.78 | 12.92 | 8.37 |
| **Ne** | 19.38 | 24.37 | 2.94 | 0 | 0 |
| **Hl** | 0.16 | 0.49 | 0 | 0 | 0.16 |
| **Di** | 8.01 | 4.77 | 1.69 | 3.95 | 6.33 |
| **(Wo)** | (3.97) | (2.39) | (0.83) | (1.90) | (3.18) |
| **(En)** | (1.48) | (1.07) | (0.26) | (0.36) | (1.48) |
| **(Fs)** | (2.56) | (1.31) | (0.60) | (1.68) | (1.67) |
| **Hy** | 0 | 0 | 0 | 3.08 | 0.25 |
| **(En)** | (0) | (0) | (0) | (0.55) | (0.12) |
| **(Fs)** | (0) | (0) | (0) | (2.53) | (0.13) |
| **Ol** | 5.80 | 1.56 | 3.00 | 3.34 | 1.07 |
| **(Fo)** | (2.00) | (0.66) | (0.86) | (0.55) | (0.47) |
| **(Fa)** | (3.80) | (0.90) | (2.14) | (2.79) | (0.59) |
| **Mt** | 3.62 | 5.45 | 3.23 | 2.12 | 7.22 |
| **Il** | 1.79 | 1.08 | 1.22 | 1.61 | 2.22 |
| **Ap** | 1.40 | 0.81 | 0.47 | 0.81 | 0.95 |

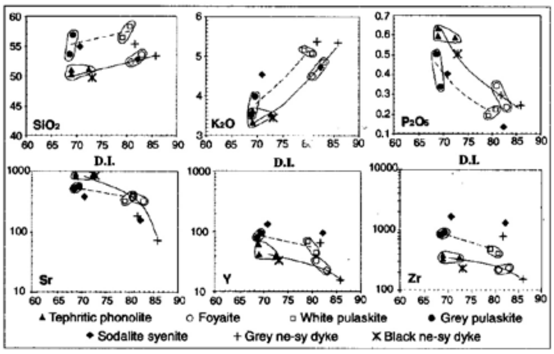


**Figure 9:** Selected major and minor element variation diagrams of the Etanenoberg rocks. D.I. = Differentiation Index of Thornton and Tuttle; symbols as in Fig. 4.

every chemical component of the tephritic phonolite plots at a low D.I. value and that of the foyaite at a high value, as expected (Fig. 9). This trend is continued beyond the foyaite by one of the grey nepheline syenite dykes (Et 5) which, therefore, appears to be the most highly evolved rock type. The other grey dyke (Et 1) is very different except for $P_2O_5$. It must represent another batch of magma, not related to the main trend. The black nepheline syenite dyke (Et 13) plots close to the tephritic phonolite but appears to be slightly less primitive (in terms of Ti, Fe, Mn, Ca, K, P, Cl, Y, Zr, Nb, Nd). With increasing fractionation along the main trend Si, Al, Na, K, CI, Rb and Ga increase and Ti, Fe, Mn, Ca, P, Sr, Ba, Y, Zr, Nb, La, Ce and Nd decrease.

The pulaskites are highly enriched in the high field strength elements (Y, Zr, Nb, REE) and depleted in the large ion lithophiles (Sr, Ba) compared to the main trend. The grey pulaskite is more primitive than the white pulaskite and these two rock types may represent a parallel subsidiary trend of their own. The sodalite syenites show even stronger enrichment and depletion of the same elements and because they differ rather widely from each other, they may also exhibit a separate evolutionary trend.

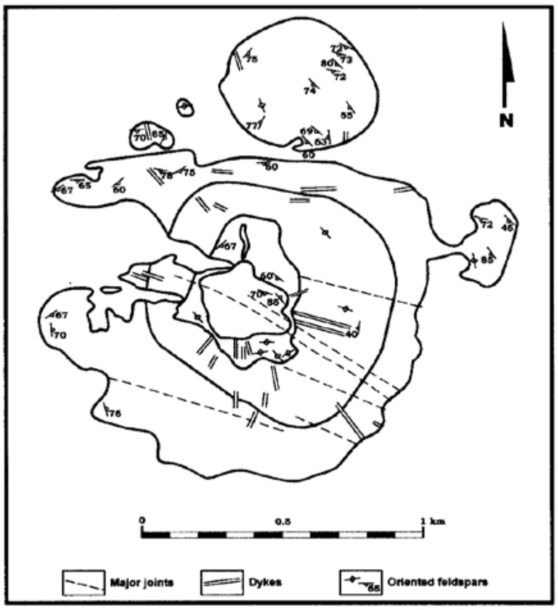


**Figure 10:** Structural map.

**Figure 11:** White pulaskite with vertically arranged undulating mafic streaks, southern slope of Etanenoberg.

## Structure

Several types of primary igneous structure (including small-scale layering) have been observed in the Etanenoberg Complex.

1. Preferred orientation of feldspar crystals is a common feature of the tephritic phonolite where porphyritic, of the foyaite ring and of the nepheline syenite dykes. In all these cases the feldspars are tabular and the orientation is undoubtedly due to magmatic flow within a confined space. The orientation is near-vertical except where affected by local obstructions. A less conspicuous orientation of rhomb feldspars is developed in the grey pulaskite, especially in some of the outermost outcrops. The dip is steeply inward (ca. 65°-75°) and the strike is more or less concentric (Fig. 10). This structure is interpreted as a form of igneous lamination probably due to side-wall accumulation of early crystals.
2. Mafic layers and streaks occur in dominantly feldspathic grey and white pulaskite but their distribution is sporadic. A group of five well developed parallel wavy mafic layers in white pulaskite and several intervening more poorly developed ones, are exposed along the southeastern slope of Etanenoberg (Fig. 11). Their thickness (1-3 cm) and spacing (5-50 cm) are variable; they can be followed for no more than 12-15 metres and they show some evidence of grading (Fig. 12). They have a near-vertical dip and their general trend appears to follow the concentric structure of the complex. Another locality where this type of structure can be seen is along the eastern slope of Klein Etanenoberg. Straight, curved, single and multiple mafic layers occur in grey pulaskite on a similar scale. On one particular rock face the curved and divergent layers interfere with each other in a pattern reminiscent of current cross-bedding; however, three-dimensional relationships could not be established (Fig. 13).
3. Rhythmic layering, showing a more or less regular stack of normally graded units ranging from 2 to 13 cm in thickness, was observed only in a 1 $^{m3}$ loose block of grey pulaskite on the eastern slope of Klein Etanenoberg (Fig. 14). Each unit consists of grey pulaskite grading downwards into a mafic (clinopy-

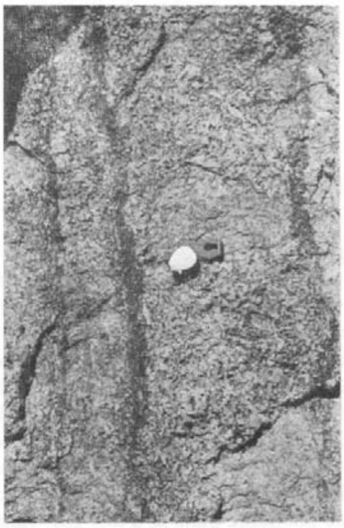


Figure 12: Close-up of mafic streaks in white pulaskite. Note sharp contact towards the left and gradational contact towards the right.

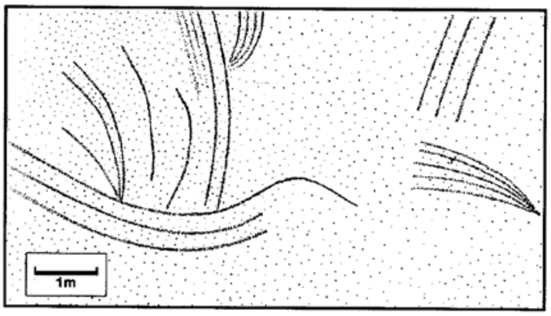


**Figure 13:** Sketch of mafic-rich layers in fine-grained grey pulaskite along eastern slope of Klein Etanenoberg. Rock face slopes about 40° away from summit. Curved, divergent and disconformable structures may have originated as magmatic current cross-bedding.

roxene, olivine, amphibole)-rich bottom layer with a sharp lower contact; the feldspars are not size-graded and do not show igneous lamination.

Such features on a much more extensive scale have been described in syenites from the Gardar Province, South Greenland, notably from the Nunarssuit Complex (Harry and Pulvertaft, 1963; Upton *et at.* 1996) and also from the Monteregian Province in Canada (Philpotts, 1974), where the Mt. Johnson intrusion is similar to Etanenoberg in size, petrology and structure. A recent review of all the mechanisms that have been proposed to explain primary igneous layering concludes that no single theory will suffice and that “some types of layering may be the result of multiple mechanisms operating at different stages of crystallization” (Naslund and McBimey, 1996).

Figure 14: Grey pulaskite with rhythmic layering, eastern slope of Klein Etanenoberg.

Numerous joints divide the outcrops into roughly rectangular blocks. It is noteworthy that the radial joints that were exploited by dykes were sealed in the process; they occur between radial gulleys and not within them. However, a set of master joints with a northwesterly trend cuts across Etanenoberg and most of them are deeply incised (Figs. 1, 3 and 10). They probably belong to a post-intrusive regional stress-field.

## Discussion

The three-dimensional relationship between the grey and white pulaskites appear to be somewhat problematic. The contact between the two rock types has already been described as neither sharp nor gradational, but readily mappable with a resolution of 1-2 m. The geological map (Fig. 3) shows that although it cuts across contours, it never deviates very much from the 1 500 m line and could therefore be either vertical or sub-horizontal. In the latter case, a major portion of the complex could perhaps be a layered intrusion; an interpretation suggested by the examples of phase layering, probable trough cross-bedding and rhythmic layering. However, these examples are few and far between, are often steep and nowhere accompanied by igneous lamination. Furthermore, white pulaskite is not present above 1 500 m on Klein Etanenoberg as expected in the case of a horizontal contact. It is concluded that the pulaskites are more likely to have been emplaced as a ring intrusion that underwent differentiation between two cylindrical or funnel-shaped boundaries during crystallization. The steep preferred orientation of rhomb feldspars in the grey pulaskite can be ascribed to upward drag (or sagging) against such a boundary. This implies that the contact is not far from the outermost outcrops and that the unexposed rings of the Etanenoberg Complex represent different intrusions that could be earlier or later than the pulaskite ring.

Klein Etanenoberg appears to owe its topographic prominence to the more massive and structureless character of the central than the marginal outcrops of grey pulaskite. No evidence could be found that it represents a separate conduit or intrusive centre.

There are also several unanswered petrogenetic problems. For instance, why does the grey pulaskite apparently have a composition as primitive as the tephritic phonolite (Fig. 10)? It is tentatively suggested that the hypabyssal tephritic phonolite that intruded first is actually the closest in composition to the parent magma. Both phonolite and pulaskite had their composition modified by incorporation of intratelluric crystals (mainly plagioclase). In the case of the grey pulaskite, crystal accumulation played a major role, at least against its outer boundary. The black nepheline syenite dyke analysed by Prins (1981) also has a relatively primitive composition, despite the fact that it intruded at a late stage. Conceivably, a small pocket of undifferentiated magma survived until after the bulk had crystallized.

The xenoliths of sodalite syenite are problematic because their composition suggests the accumulation of volatiles like chlorine, yet according to geological relationships they are just as early in the sequence as the tephritic phonolite. Furthermore, the mafic assemblage of the sodalite syenite points towards a lower temperature of crystalization than the tephritic phonolite and grey pulaskite, whereas the associated feldspar was formed under hypersolvus conditions. Lastly, the fine-grained groundmass appears to indicate rapid cooling which again contrasts with a high volatile content. If the sodalite syenite is related to the other rocks by fractional crystallization, it should not have evolved from the parental magma at the time when it did.

The answer probably lies in the absence of any textural evidence of early sodalite that could be compared with the standard interpretation of sodalite in the naujaites of Ilimaussaq. Textures strongly suggest that the Etanenoberg sodalite formed below the solidus. Kogarko and Ryabchikov (1969) ascribed the origin of some sodalite-rich rocks to immiscibility processes whereby an aqueous saline fluid separates from a silicate magma. According to their (Na,K) $AlSiO_4$ - (K,Na)$AlSi_3O_8$ - (Na,K)Cl phase diagram, crystallization of certain compositions in the field of primary carnegieite will result in the separation of a chloride-rich fluid. This fluid has an extremely low viscosity and will migrate into structurally favourable parts of the magma chamber where, with further cooling, it may react with primary nepheline to form sodalite. It is presumed that portions of such a reaction product were later picked up by various surges of alkaline magma and now appear as xenoliths. The variations in mineralogy, chemistry, texture and volatile content of these xenoliths probably depend on the time when the chloride-rich fluid was incorporated in the upward-moving nepheline-bearing magma. The coexistence of sodalite, nepheline and analcite in the xenoliths has a bearing on the temperature of crystallization and the NaCl content of the fluid. Experimental results at 1 kbar by Barker (1976) indicate that this assemblage is only stable below 550°C and that analcite cannot form if the mole fraction of NaCl in the fluid is high. The sodalite syenite of Etanenoberg thus truly has a hybrid origin.

## Conclusion

The magmatism that gave rise to the early Cretaceous Damaraland Igneous Province overlaps in age and is believed to be related to the main phase of Etendeka volcanism (135-132 Ma) as a result of mantle melting associated with the upwelling Tristan plume when it was located beneath central Namibia (Milner *et al.* 1995) Compared to the wide range of compositions from basalt to rhyolite, lamprophyre and carbonatite in the province as a whole, the Etanenoberg silicate magmas represent a very narrow interval indeed.

With peralkaline ("agpaitic") indices between 0.74 and 1.07, the analysed Etanenoberg rocks are on the border-line between alkaline and peralkaline (Edgar, 1974). In terms of mineralogy and trace elements they are certainly not agpaitic, but could be classified as miaskitic to intermediate. The proximity of the voluminous Ondurakorume and Kalkfeld carbonatites, that are further enriched in the elements that are incompatible with basalt, supports this view. However, the Etanenoberg Complex as exposed at present is devoid of carbonatite and/or fenite, and provides no geological evidence of a genetic connection with carbonatite. The nepheline syenites are hypersolvus types characterized by high-temperature assemblages; the magmas were either relatively dry (except with respect to the sodalite syenite) or a fenite aureole remains to be discovered.

The evolution of the Etanenoberg Complex is pictured briefly as follows. A local magma chamber filled with a mush of alkaline silicate liquid and early crystals once existed at a shallow crustal level beneath the present-day hill. The first batch to be intruded was the tephritic phonolite which filled a cylindrical conduit and may have reached the surface to form a tholoid, now eroded. The second and major intrusive pulse was the ring of grey and white pulaskite that probably solidified from the outside inward along a temperature gradient reflected by the gradual change in the nature of the alkali feldspar, disappearance of olivine and other textural features. Segregation of early crystals took place along the funnel-shaped (?) outer boundary. Sporadic remnants of rhythmic layering provide evidence of some form of fluctuating crystallization under tranquil conditions, whereas mafic layers and interference cross-bedding testify to the operation of localized magmatic currents or vortices. The third pulse was the foyaite ring that exploited the pipe-like boundary between the central plug and the white pulaskite. The final episode was the filling of radial tensional fractures shortly after consolidation, mostly by highly evolved residual nepheline syenite magma, but also by batches approaching the composition of the parent magma. It is not known what constitutes the outermost covered zones of this almost perfectly circular alkaline ring complex, which exhibits many classic magmatic features amenable to more detailed investigation.

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