Geological Society of Namibia

Excursion to Granitberg and the Klinghardt Mountains, southern Namibia

23-26 October 1998

Field Guide

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INTRODUCTION

Three small subvolcanic intrusions (Granitberg, Pomona and Drachenberg) and associated dykes of Cretaceous age, occur between Bogenfels and Prinzen Bucht, S of Lüderitz, Namibia (Fig. 1). These rocks were mapped and described in considerable detail in the beautiful volumes by Kaiser(1926), who also gave an account of various other alkaline occurrences including the phonolites of the Klinghardt Mountains, E of Bogenfels. The alkaline rocks are of at least two distinct ages, as was recognised by Kaiser, and in writing about the older Cretaceous rocks, I referred to them as constituting the Lüderitz Alkaline Province (Marsh, 1973). In retrospect this very general name was perhaps a mistake as it refers to a geographical area and most would take it to include all the alkaline rocks present of whatever age.

This field trip will chiefly be concerned with rocks that have crystallized from magmas of nepheline syenite composition (see Table 1 for terminology). Day 1 focuses on the well-exposed Granitberg nepheline syenite and the wide variety of reaction phenomena at its contact with quartzites and dolomites on the margins and in the roof of the intrusion. Day 2 focuses on the volcanic equivalent of nepheline syenite - phonolite - which forms the eroded volcanic domes of Tertiary age in the Klinghardt Mountains. The main features to see here are volcanological, specifically the character of the volcanic landforms and how their eruptive forms can be deduced from ointing in the phonolite.

The Cretaceous alkaline rock occurrence is one of numerous sporadically preserved remnants of continental rift igneous activity that occurred between Cape Town and at least Luanda in Angola during rifting of South America from Africa at 125-135 Ma. The best preserved example of this activity is the Etendeka Igneous Province in NW NamibiaThe Klinghardt phonolites are a manifestation of widespread Tertiary alkaline igneous volcanism in western southern Africa between Windhoek in Namibia and the Alphard Bank off the southern Cape Coast. In particular the Klinghardt phonolites are very similar to the phonolites occurrences at Aris, just S of Windhoek and NW of Rehoboth, in terms of age, mode of occurrence and association, and volcanological character.

AGE OF ALKALINE IGNEOUS ACTIVITY

The Cretaceous age for the older alkaline rocks is based on an ancient K/Ar age of 130±2 Ma from biotite in the Granitberg nepheline syenite and requires confirmation by modern Ar-Ar or single crystal zircon U/Pb dating. The Klinghardt phonolites have also been dated by K/Ar (whole rock). A phonolite from the Swartkop outlier, just W of the Lüderitz-Oranjemund road, yielded an age of 37.1 Ma which is consistent with Kaiser's (1926) observation that this phonolite overlies a silcrete which he regarded as being of Eocene age. This

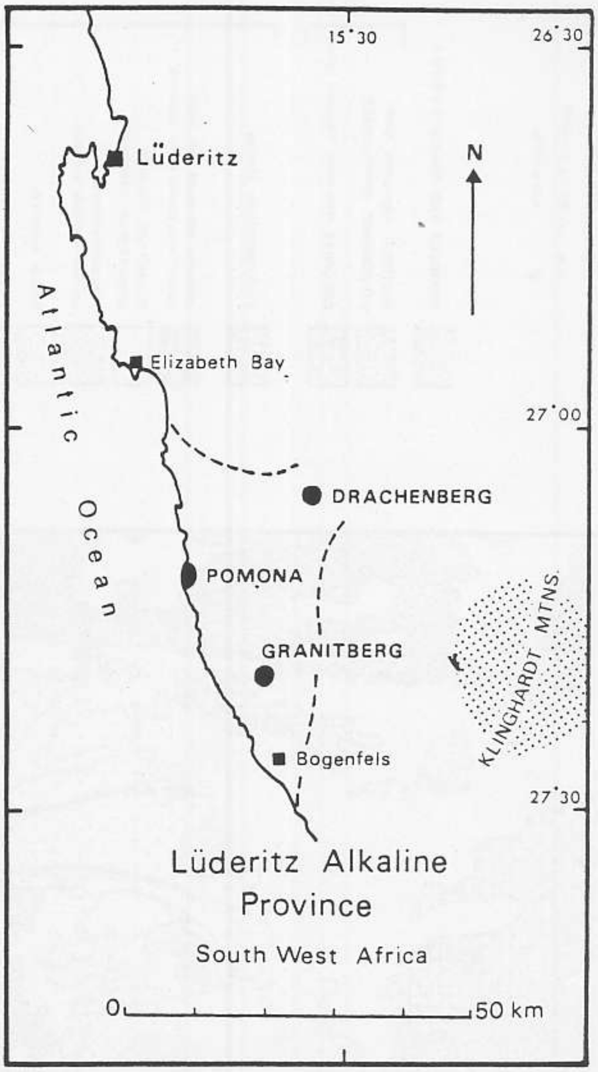
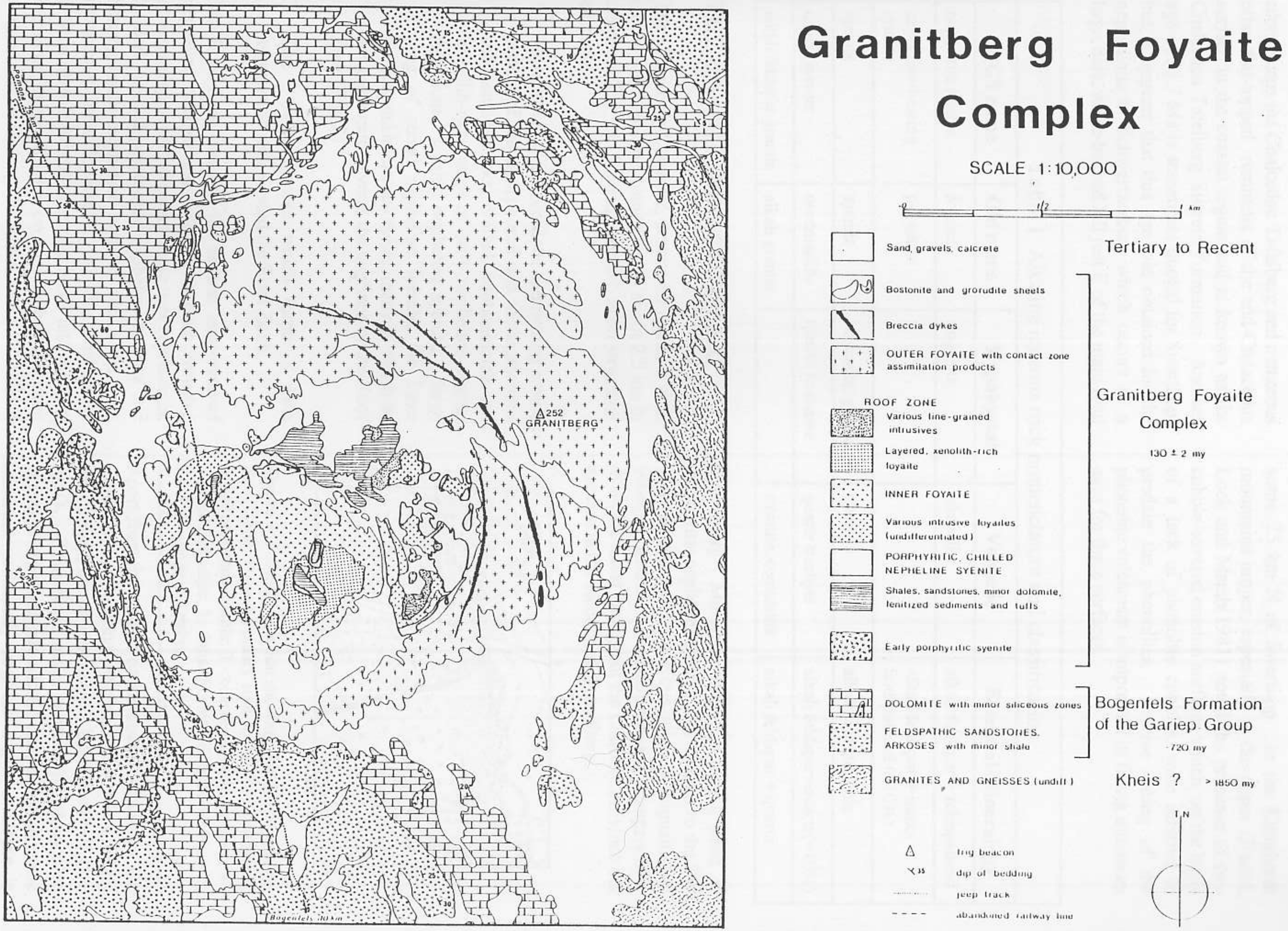


Figure 1: Location of the 3 complexes of the Lüderitz Province and the limits of the associated dyke swarm. The Tertiary phonolites occur in the Klinghardt Mountains further to the East.

Granitberg Foyaite Complex



mapped 5/70 and 7/71, drawn 1/73 by J.S.M.

silcrete caps the Chalcedon Tafelberg and numerous other flat-topped remnants of the end-Cretaceous surface in the coastal region and is known as the Chalcedon Tafelberg Silcrete Formation. Another age of 35.7 Ma is sometimes quoted for Swartkop, but it appears that this age was obtained for the nephelinite at Schwartzerberg which occurs as a large, dark, whale-backed hill just E of the main road some 25 km N of Swartkop. In the Klinghardt mountains proper, especially in the upper Glastal, Lock and Marsh(1981) noted the presence of two cobble-covered erosion surfaces which, on the basis of a lack of phonolite cobbles, were inferred to predate the phonolites. Precise dating of the phonolite volcanism is important in fixing minimum ages for these surfaces.

Table 1: Alkaline igneous rock nomenclature and classification

IUGS name	Old name	Hypabyssal	Volcanic	Essential Mineralogy
nepheline syenite	foyaite	tinguaite	phonolite	alkali feldspar + feldspathoid
nepheline-bearing syenite	pulaskite			alkali feldspar + minor feldspathoid (<10%)
syenite	syenite	bostonite, grorudite	trachyte	alkali feldspar only
quartz syenite	nordmarkite	quartz bostonite	quartz trachyte	alkali feldspar+quartz(<10%)
alkali feldspar granite	alkali granite		rhyolite, comendite	alkali feldspar + quartz

THE GRANITBERG COMPLEX

The Granitberg Complex, despite its name, is built entirely of nepheline syenite and is about 2.5 km in diameter (Fig. 2). It comprises two main structural elements

1. The near circular Roof Zone comprising a wide variety of metamorphosed and metasomatised sedimentary rocks, chilled, contaminated and xenolith-rich facies of early nepheline syenite intrusions, layered nepheline syenite, a large plug of zoned nepheline syenite, the Inner Foyaite, and numerous dykes, many of which do not propagate beyond the confines of the Roof Zone (Fig. 3)

2. The Outer Foyaite which forms a wide asymmetric ring around the Roof Zone.

The Roof Zone contains the earliest least-evolved nepheline syenites and at least two main intrusive phases are apparent: an earlier phase now represented by dark, chilled porphyritic nepheline-bearing and heterogeneous nepheline syenites and a the later intrusion of Inner Foyaite (Fig. 3). This whole mass is believed to have subsided as a block into the later intruding mass of highly evolved nepheline syenite magma, the Outer Foyaite, which forms the bulk of Granitberg. Minor intrusions include a sheet of porphyritic nepheline syenite that extends to the SW of the complex and numerous dykes of tinguaite and younger quartz bostonite/trachyte, Lamprophyre dykes are found throughout the Lüderitz Province but are rare in the vicinity of Granitberg.

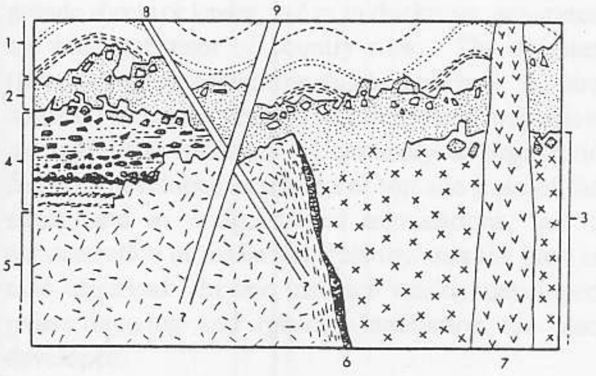


Figure 3: Schematic section showing relationships in the Roof Zone. 1 - sedimentary roof rocks; 2 - porphyritic, chilled nepheline syenite; 3 - coarse nepheline syenite; 4 - Layered Sequence; 5 - Inner Foyaite; 6 - igneous breccia; 7,8 & 9 - plugs and dykes.

Apart from the earliest contaminated intrusions, the nepheline syenites and the associated dykes are all peralkaline, i.e. on a molecular basis $Na_2O+K_2O > Al_2O_3$. Thus these rocks contain, in addition to essential nepheline and alkali feldspar, alkali mafic minerals, principally aegirine augite. Biotite is frequently present and common minor minerals include Ti-magnetite, sphene, and apatite. Nepheline syenites are well known for the extreme diversity of accessory minerals, many of which concentrate as essential structural constituents otherwise rare and trace elements. For example, more than 120 accessory phaseshave been reported from the highly peralkaline nepheline syenite complexes of the Kola Peninsula, Russia. At Granitberg, in both the Inner and Outer Foyaites, the following additional accessories occur: lavenite, zircon, eudialyte-eucolite solid solution, astrophyllite, arfvedsonite, aenigmatite, fluorite, sodalite and cancrinite. In both Foyaite intrusions there is a mineralogical zonation with regard to these accessories (and biotite). Thus for the Outer Foyaite one can distinguish an inner miaskitic zone with biotite+sphene+magnetite, from an outer agpaitic zone with aenigmatite + eudialyte + arfvedsonite + astrophyllite. There is a similar lesser developed but reversed zonation of accessories in the Inner Foyaite.

Contact relationships: feldspathic sandstones of the West Ridge

Along the SW and W margins of the complex the Outer Foyaite is in contact with thinly bedded feldspathic sandstones. The sandstones have been folded on a regional scale and along the West Ridge they dip towards the complex giving a zone 30-40m wide characterized by complex interfingering on all scales of igneous sheets that have been intruded along the bedding of the sandstones (Fig. 4). Dilation has probably been the dominant process allowing entry of the igneous sheets along the bedding, but there is evidence of stoping and assimilation having also played a role.

Features displayed along this contact can be conveniently discussed on the basis of a 3-fold subdivision of the contact zone (Fig. 4), although it is obvious that there is gradational variation of these characteristics across the zones.

Zone 1 has high syenite/sandstone ratios with the country rocks occurring as thin screens or xenoliths exhibiting extensive metasomatic/metamorphic effects. Igneous rocks are very coarse grained (anticipated fine-grained chilled margins are not found) syenites and nepheline-bearing syenites (perthite+ minor nepheline+biotite+sphene+Fe-Ti oxide) which grade inwards through increase in modal nepheline to normal Outer Foyaite. Adjacent to sandstone xenoliths quartz-bearing facies of the syenitic rocks may be developed.

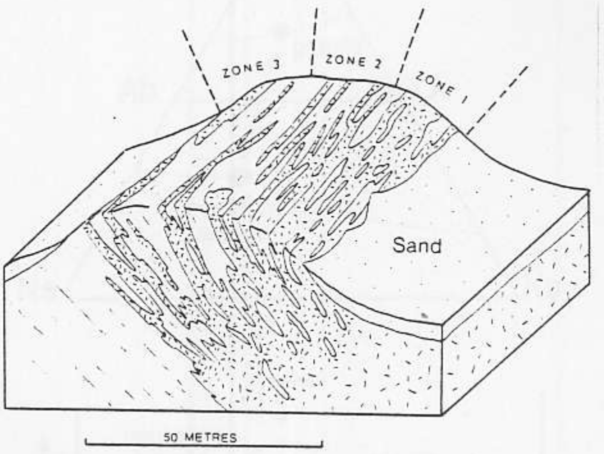


Figure 4: West Ridge contact zone showing relationship between inward dipping sandstones and intrusive contaminated magma.

Zone 2 has about equal amounts of igneous and country rock, and the igneous rocks are medium to coarse-grained quartz-syenites (perthite + little quartz + aegirine augite + arfvedsonite + sphene) with local gradations into alkaline granite.

Zone 3 is characterized by few intrusions of alkaline granite sheets or lenses, 1-2 m in thickness, separated by wide expanses of country rock. The granites (perthite+quartz+aegirine-augite+sphene) are medium to coarse grained and the sheets may show internal differentiation. Commonly a pegmatitic facies is developed at the top or top and base of the sheet, and in wedge-shaped terminations, and a concentration of mafic minerals towards the base is also observed. In one instance weakly developed phase layering and igneous lamination are also developed.

Assimilation reactions.

The overall compositional zonation in the igneous rocks from nepheline syenite through nepheline-poor syenite and syenite (sensu stricto) into quartz syenite to granite compositions across a contact zone with sandstones is strongly indicative of assimilation of quartz-rich material by nepheline syenite magma being an important process in the contact zone. This is illustrated schematically in Fig. 5 and relevant compositional data are given in Table 2. This process, obvious as it may seem, is not without difficulties because of the fact that phase relations show that syenites sit on a thermal ridge relative to granite and nepheline syenite (Fig. 5). Adding SiO_2 (quartz) to nepheline syenite liquid moves its composition into the feldspar field, forcing feldspar crystallization which simply drives the liquid composition back towards the nepheline syenite minimum ! Some type of gross disequilibrium assimilation process or one where fluid pressures are increased to suppress the temperature of the syenite ridge so that it can be overcome is required to generate a critically oversaturated syenitic liquid. Once this has been achieved there are no thermal obstacles to achieving granite compositions, either by further assimilation or by feldspar fractionation or a combination of these processes. The ubiquitous occurrence of pegmatitic patches and the very coarse-grained nature of the magmatic products in the contact zone are suggestive of a fluid-rich environment. These processes have been discussed in more detail in Marsh(1975)

Table 2

Major element data, and modes for contact magmatic rocks, West Ridge, Granitberg

	GM169	GM232	GM174	GM175	A	B
SiO_2	63.36	64.24	75.41	73.34	56.70	87.95
TiO_2	0.32	0.35	0.25	0.27	0.31	0.07
Al_2O_3	18.36	17.22	11.51	12.90	21.60	5.99
Fe_2O_3	1.25	1.27	0.94	0.97	1.21	0.41
FeO	0.47	0.43	0.25	0.33	1.09	0.37
MnO	0.10	0.11	0.08	0.08	0.19	0.00
MgO	0.25	0.86	0.25	0.25	0.20	0.48
CaO	1.25	1.16	0.26	0.55	0.85	0.22
K_2O	6.72	7.48	5.89	6.88	5.91	3.70
Na_2O	6.38	5.84	3.72	3.91	9.82	1.23
P_2O_5	0.10	0.09	0.00	0.00	0.01	0.02
H_2O^-	0.09	0.12	0.65	0.05		0.09
L.O.I.	0.73	0.34	0.30	0.31	1.11	0.31
	99.38	99.54	99.51	99.84		
molNa/K	1.44	1.18	0.96	0.86	2.52	0.52
mol(na + K)/Al	0.968	1.028	1.086	1.076	1.047	1.002
Alkali feldspar	93.6	92.9	63.2	67.9		
Quartz	—	1.7	34.5	27.2		
Nepheline	0.7	—	—	—		
Pyroxene	3.2	4.3	2.1	3.7		
Biotite	0.8	—	—	—		
Na-amphibole	—	0.8	0.1	1.1		
Sphene	—	0.3	0.1	0.2		
Other	1.7	—	—	—		

GM169	Pulaskite
GM232	Nordmarkite
GM174	Alkali granite
GM175	Alkali granite
A	average Outer Foyaite
B	average feldspathic sandstone

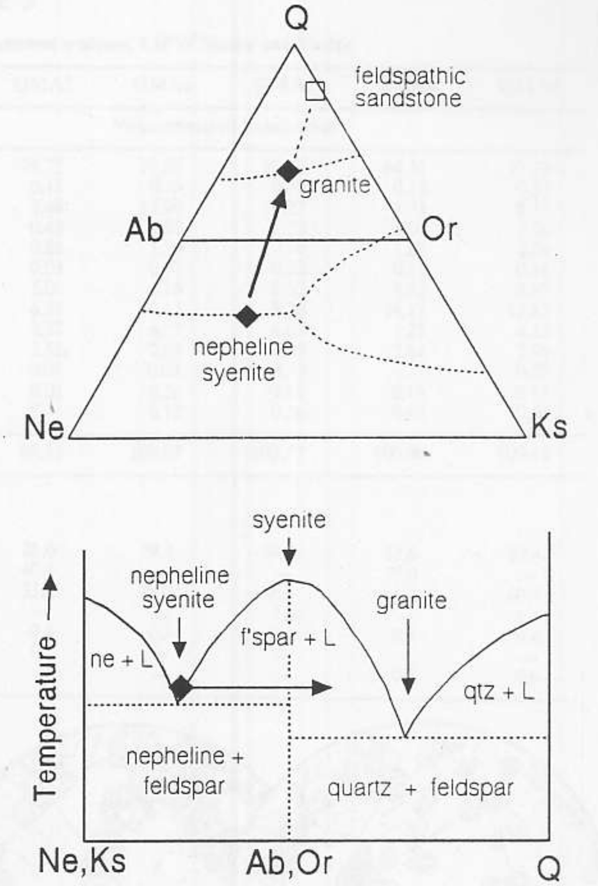


Figure 5: Schematic phase relations for contamination of nepheline syenite by sandstone. Note the thermal ridge between nepheline syenite and granite.

Metasomatism -Metamorphism of sandstones

Short-range metasomatism has affected the feldspathic sandstone of the West Ridge producing assemblages of perthite+clinopyroxene with or without quartz. Sandstone xenoliths in the nepheline-poor syenites exhibit the most intense metasomatism, the intensity of which falls off rapidly as one moves away from any sandstone-syenite contact. The extent of metasomatism is also controlled by discontinuities in the rock (joints, bedding planes, etc) and away from the contact pale green selvages to joints etc., can be observed with the bulk of the sandstone remaining unaffected.

Petrographic, modal and geochemical data relating to the metasomatic process is shown in Table 3 and Figs. 6 & 7. The onset of metasomatism is marked by the appearance of scattered, poikiloblastic, pale-blue crystals of amphibole. Increasing metasomatism

Table 3

Feldspathic sandstones and metasomatised sandstones: Major element analyses, CIPW Norms and Modes

	GMA1	GMA2	GMA3	GMA4	GMA5	GMA6	GMA7	GMA8	GMA9
	Feldspathic Sandstones				Metasomatised Sandstones				
SiO_2	87,58	87,15	89,13	85,56	75,75	59,80	59.70	64,32	57.79
TiO_2	0,05	0,09	0,06	0,06	0,11	0,16	0.30	0,15	0.37
Al_2O_3	6,03	6,32	5,56	6,21	5,48	12,99	11.27	4,78	8,12
Fe_2O_3	0,18	0,10	0,13	0,16	0,42	1,25	1.52	1,01	2.06
FeO	0,39	0,36	0,35	0,30	0,85	1,56	2.14	1,82	2.04
MnO	0,00	0.00	0,00	0,04	0,05	0,27	0.22	0,12	0.16
MgO	0,56	0,47	0,41	1,08	5,01	6,15	6.52	9,82	8.95
CaO	0,29	0,16	0,21	0,99	6,89	8,65	9,36	14,17	12,82
Na_2O	1,07	1,28	1,35	1,61	2,37	6,17	4.67	1,25	4.13
K_2O	4,10	4,02	2,97	3,82	2,52	2,68	4.05	2,61	2.96
P_2O_5	0,02	0.02	0,03	0,02	0,06	0,03	0,11	0,31	0,39
H_2O	0,10	0,07	0,09	0,07	0,01	0,26	0,15	0,14	0,13
LOI	0,41	0,27	0,25	0,21	0,41	0,72	0,56	0,44	0,50
	100,78	100,51	100,87	100,13	99,93	100,69	100,57	100,96	100,42
MODES									
Feldspar	36,5	30,7	27,4	34,5	26,0	59,4	49,5	13,6	37,4
Quartz	60,4	66,5	70,8	64,9	40,4	—	—	19,0	—
Cpx	—	—	—	—	33,2	38,0	48,4	66,2	60,7
Biotite	—	—	—	—	—	2,3	1,6	—	1.1
Sphene	—	—	—	—	0,4	0,3	0,5	0,4	0,4
Amphibole	—	—	—	—	0,1	—	—	—	—
Other	3,1	2,8	1,8	0.6	—	—	—	0,8	0,6

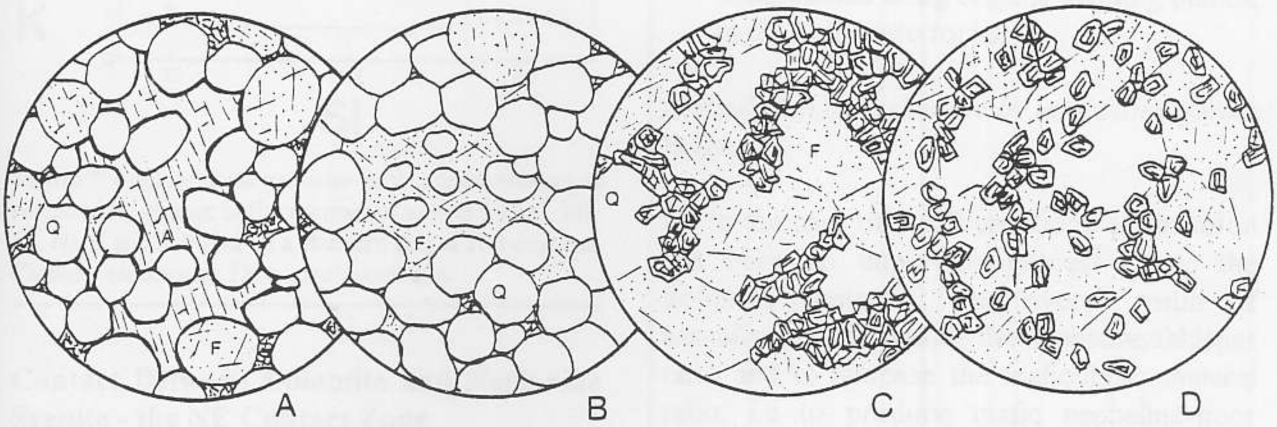


Figure 6: Metasomatites from the West Ridge contact zone. Q - quartz; F - feldspar; A - amphibole. A - poililoblastic amphibole. B - poililoblastic perthite. Note the diminished size of quartz grains. C - sinuous dipside aggregates with granoblastic perthite and quartz. D - dipersed aegirine augite aggregates with quartz and perthite. Diameter of field is 2.5 mm.

results in recrystallization and growth of feldspar at the expense of quartz and this process continues with the disappearance of amphibole and the growth of sinuous aggregates of colourless diopside leading to granoblastic rocks comprising perthite + diopside ± quartz. In the highest grade metasomatites the diopside aggregates become dispersed and diopside becomes mantled with thick rims of aegirine-augite. The geochemical data (Fig. 7) indicates that Ca and Mg introduction is an important aspect of the metasomatic process and this is manifested in the growth of diopside. This early stage of apparent introduction of Ca and Mg is unusual. More commonly the metasomatism (fenitization) associated with alkaline and carbonatite intrusions is dominated by introduction of Na, Fe and K. Experimental work has shown that chloride-rich solutions (regarded as fenitizing solutions in many other complexes) may contain considerable amounts of dissolved Ca and Mg.

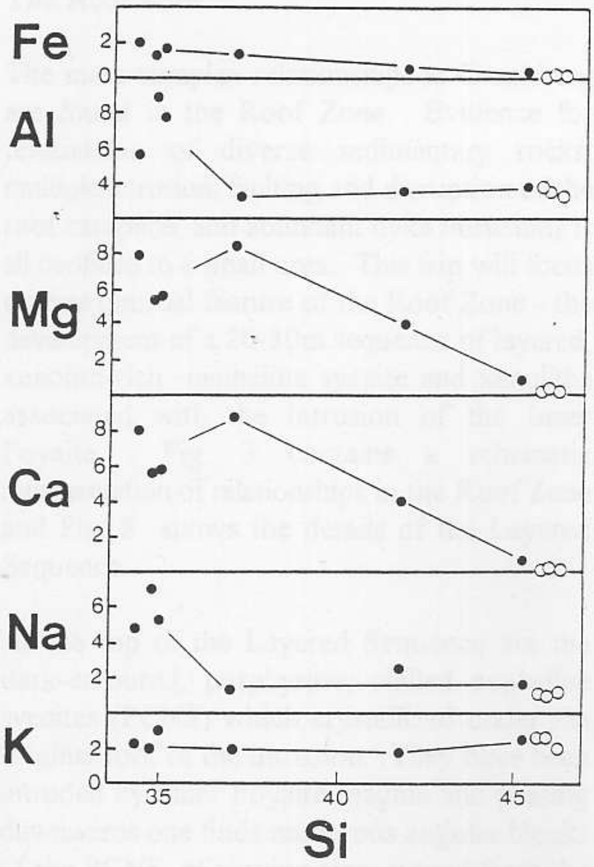


Figure 7: Compositional variation in the metasomatites as reflected by change in the number of ions of Fe, Al, Mg, Ca, Na, K and Si based on a standard cell of 100 oxygens. Circles - sandstones; Dots - metasomatites.

Contact Between Dolomite and Nepheline Syenite - the NE Contact Zone

Metamorphic - Metasomatic features in the contact rocks.

Around the NE and SE edges of the complex the nepheline syenites are in intimate contact with dolomitic rocks with widespread interfingering similar to that seen on the West Ridge. The dolomites are interbedded with thin argillaceous and arenaceous beds and the carbonate rocks themselves may be siliceous or marls. Metamorphic and metasomatic assemblages in these country rocks varies with the nature of the protolith as well as the proximity of magmatic intrusions. The following points summarise the main metamorphic/metasomatic features:

1. The most widespread assemblage is dolomite+calcite+forsterite+spinel±phlogopite.
2. Immediately adjacent to intrusions the assemblage is: calcite+diopside±spinel ±phlogopite±periclase.
3. Forsterite and diopside are never found together.
4. In the outer parts of the aureole tremolite and phlogopite dominate the mineral assemblages.
5. Aegirine and aegirine-augite occurs is bands in some coarse marbles along the inner zone of the contact aureole and are believed to represent metasomatic products of reaction between fenitizing fluids and a detrital silicate components, perhaps concentrated along original bedding planes, in the carbonate rocks.

Assimilation of carbonate by nepheline syenite magma

As in the case of the West Ridge assimilation has been an important process along the dolomite contact. The overall result of assimilation is to reduce the nepheline/feldspar ratio and to increase the mafic/felsic mineral ratio, i.e to produce mafic nepheline-poor rocks. Thus the most common magmatic rock in the dolomite contact zone is one I have called "shonkinite" but which, more correctly, should be called a mela nepheline-bearing syenite. It consists principally of perthite (55%) abundant biotite and zoned aegirine augite (together 35%), about 5% interstitial nepheline or cancrinite and minor Fe-Ti oxide, sphene and apatite. Gradations into more mafic and felsic facies are found. Using a standard cell for the basis of comparison it appears that assimilation results, not unexpectedly, in a decrease in Si, Al, Na, and an increase in Mg (dramatic), Fe, Ca, and Ti, with K remaining constant.

The Roof Zone

The most complex relationships at Granitberg are found in the Roof Zone. Evidence for fenitization of diverse sedimentary rocks, multiple intrusion, faulting and disruption of the roof carapace, and abundant dyke intrusions is all confined to a small area. This trip will focus on one unusual feature of the Roof Zone - the development of a 20-30m sequence of layered, xenolith-rich nepheline syenite and xenoliths associated with the intrusion of the Inner Foyaite. Fig. 3 contains a schematic representation of relationships in the Roof Zone and Fig. 8 shows the details of the Layered Sequence.

At the top of the Layered Sequence are the dark-coloured, porphyritic, chilled nepheline syenites (PCNS) which crystallized under the original roof of the intrusion. They have been intruded by Inner Foyaite magma and passing downwards one finds numerous angular blocks of the PCNS, of varying size, stoped from the roof and crowded into the foyaite. Descending further these xenoliths decrease in size and number and exhibit a degree of rounding. There is a corresponding gradation in the host foyaite from non laminated to strongly laminated textures and an associated tendency for the xenoliths to orient themselves with their long axes in the plane of lamination which is horizontal. The lamination in the foyaite is essentially due to parallel alignment of tabular perthite. This is the Xenolith-rich Laminated Foyaite unit in Fig. 8. In the central part of this unit the xenoliths are well rounded and sorted (3-7 cm in size) and, in places, weakly concentrated into layers. Towards the base of this unit the host retains its characteristics but the xenoliths increase in abundance and size and aggregates develop where xenoliths become packed together and show evidence of plastically distorting around one another. Where this happens the igneous lamination is disturbed and trails of perthite tablets drape around the xenoliths.

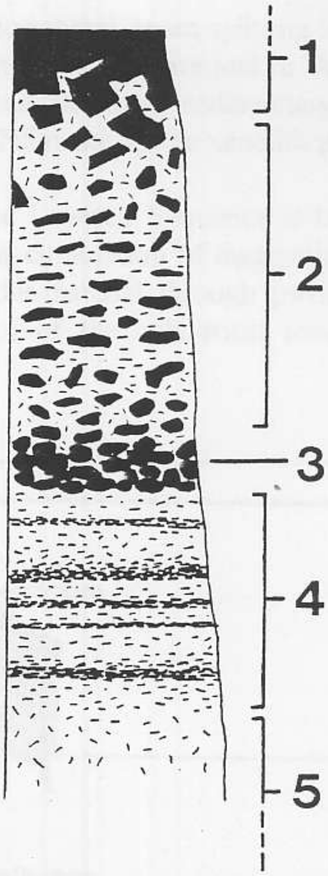


Figure 8: Schematic section through the Layered Sequence. 1 - PCNS; 2 - Xenolith-rich Laminated Foyaite unit; 3 - Xenolith Cumulate; 4 - Layered Foyaite unit; 5 - Inner Foyaite. Vertical scale is non-uniform.

At the base of the Laminated Foyaite unit is the Xenolith Cumulate which is a graded zone, 0.5 - 2.0 m thick, exhibiting all the characteristics one would expect of xenoliths accumulating on some "floor" as a result of gravity settling. The base of the cumulate has a sharp contact with xenolith-free Layered Foyaite. Within the cumulate the xenoliths are near-spherical, well-rounded, well-sorted and tightly packed.

The underlying Layered Foyaite unit is 3-4 m thick and is characterized by igneous lamination and inpersistent rhythmic mineral-graded layering achieved essentially by the sorting of feldspar and aegirine. This unit grades downwards, first by cessation of the layering and then through gradual disappearance of the igneous lamination into typical Inner Foyaite. Around the southern margin of the massif where these features are exposed the xenolith cumulate rests abruptly on non-laminated foyaite from which, in places, apophyses vein the overlying xenolith-rich rocks.

The relationships described above represent an ideal section through the Layered Sequence. Although the overall sequence is essentially constant, the character of the different units varies from place too place. In the westernmost outcrops sorting of xenoliths is poorer, the igneous lamination may show steep dips from the horizontal, seam splitting is observed in the Xenolith Cumulate and in the Layered Foyaite, and fenetized sedimentary rocks as well as PCNS make up the xenolith population.

Briefly, the Layered Sequence is believed to represent accumulation of magmatic sediment and xenolithic material, through gravity settling, in the roof of the cylindrical Inner Foyaite intrusion.

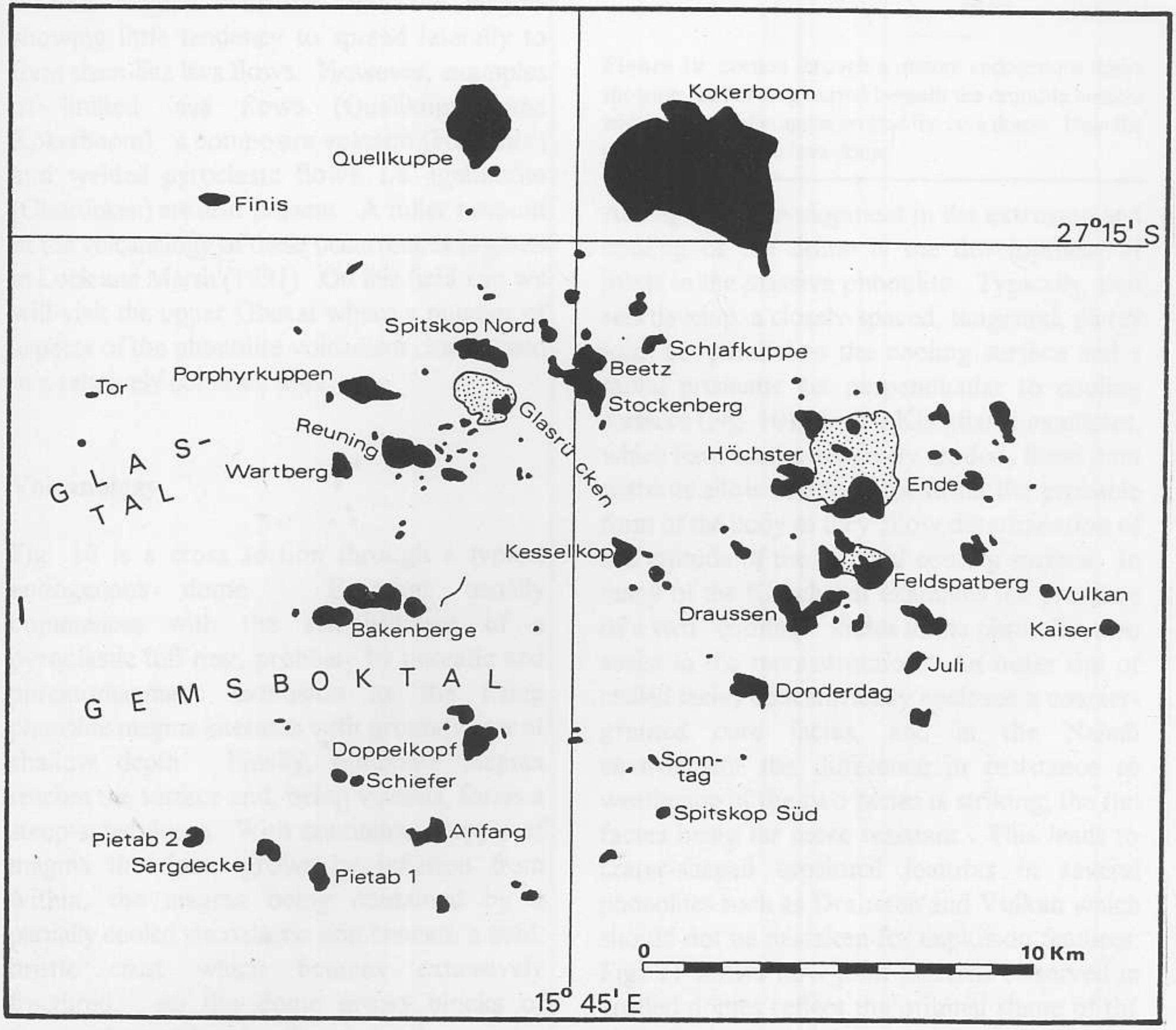


Figure 9: Map of distribution of phonolite bodies (black) and phonolite pyroclastic rocks (stippled) in the Klinghardt Mountains.

THE KLINGHARD PHONOLITES

Over 100 phonolite bodies are exposed in the area of Klinghardt Mountains (Fig. 9) with prominent outliers at Swartkop to the W and Namitsis to the S. These phonolites constitute an excellent example of an areal volcanic field. Nearly all the bodies are interpreted as erosional remnants of volcanic domes, specifically endogenous domes which grow by inflation of viscous magma over the vent, the magma showing little tendency to spread laterally to form sheet-like lava flows. However, examples of limited lava flows (Quellkuppe and Kokerboom), a composite volcano (Höchster) and welded pyroclastc flows, i.e. ignimbrite (Glasrücken) are also present. A fuller account of the volcanology of these occurrences is given in Lock and Marsh (1991). On this field trip we will visit the upper Glastal where a number of aspects of the phonolite volcanism can be seen in a relatively confined area.

Volcanology

Fig. 10 is a cross section through a typical endogenous dome. Eruption usually commences with the establishment of a pyroclastic tuff ring, probbaly by phreatic and phreatomagmatic explosion as the rising phonolite magma interacts with groundwater at shallow depth. Finally, phonolite magma reaches the surface and, being viscous, forms a steep-sided dome. With continuous supply of magma the dome grows by inflation from within, the magma being contained by a partially cooled viscoelastic skin beneath a cold, brittle crust which bcomes extensively fractured. As the dome grows blocks of fractured crust break off and develop a talus apron around the dome and new brittle crust develops. Depending on the amount of magma supply the talus apron may bury the pyroclastic explosion ring, as may the dome. For limited supplies of magma the dome and talus apron may be confined entirely within the crater of the tuff ring.

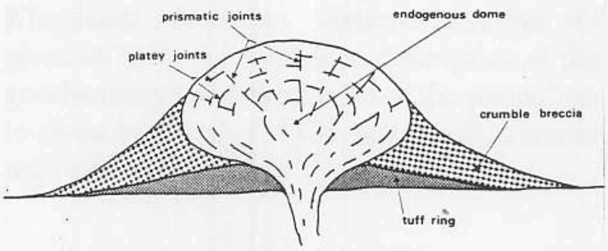


Figure 10: Section through a mature endogenous dome showing the tuff ring buried beneath the crumble breccia which forms a talus apron around the lava dome. Note the joint patterns in the lava dome.

An important development in the extrusion and cooling of the dome is the development of joints in the massive phonolite. Typically, two sets develop: a closely-spaced, tangental, platey joint set parallel to the cooling surface and a radial prismatic set perpendicular to cooling surfaces (Fig. 10). In the Klinghardt examples, which have been extensively eroded, these joint patterns allow one to reconstruct the probable form of the body as they allow determination of the attitude of the original cooling surface. In many of the Klinghardt examples the presence of a two “cooling” facies in the phonolite also assist in the reconstruction. An outer rim or chilled facies concentrically encloses a coarser-grained core facies, and in the Namib environment the difference in resistance to weathering of the two facies is striking; the rim facies being far more resistant. This leads to crater-shaped erosional features in several phonolites such as Draussen and Vulkan which should not be mistaken for explosion features. Fig. 11 shows how joint patterns observed in eroded domes reflect the original shape of the phonolite body, and demonstrates that the large body at Kokerboom is probably a dome that developed into a short thick lava flow.

In the Klinghardt the extent of erosion is such that in most instances only the lower parts of the dome remain preserved. The volcanogenic talus aprons and much of the outer parts of any phreatic tuff ring have long since disappeared. Unfortunately extensive "modern" talus slopes surround most of the occurrences so that the remnants of the tuff rings and their contacts with the phonolite are buried. One has to search in steep outwash gullys to find exposures, such as at Pietab II and Schiefer.

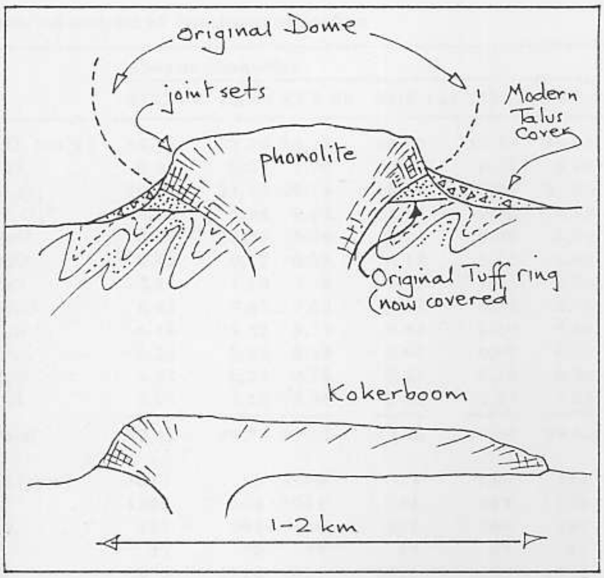


Figure 11: Examples of eroded domes in the Klinghardt Mountains indicating how the joint patterns allow one to decipher the original volcanic form and location of the vent area.

In the Glassrücken, in the northern part of the Klinghardt Mountains Kaiser (1926) recorded the presence of 5 lava flows and interbedded pyroclastics. The features referred to by Kaiser are, in fact, welded pyroclastic flows, or ignimbrite, of phonolite composition. The welded pyroclastic flows are an overall olive green colour on fresh surfaces and their fragmental texture is evident in broken phenocrysts, numerous accidental lithic fragments of both phonolite and basement lithologies, and fiamme, or collapsed pumice fragments, and an overall hard glassy matrix. Pyroclastic flows are commonly associated with dome-forming volcanoes.

Geochemistry

All the phonolites in the Klinghardt Mountains are true phonolites and have compositions which cluster around the low pressure "phonolite" minimum in the Q-Ne-Ks phase diagram (Fig 12). There are no trachytes in the Klinghardt Mountains. Selected analyses are given in Table 4. A detailed description of the geochemistry and petrogenesis of the phonolites is given in Marsh (1987), and I will mention only a few details here.

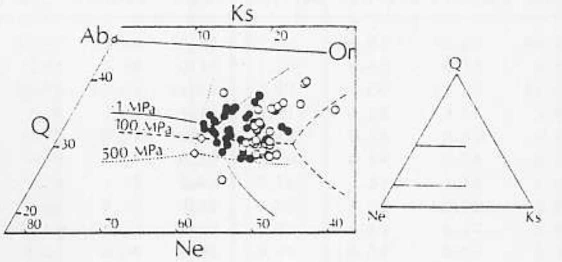


Figure 12: Part of the Ne-Ks-Q system showing the low pressure cotectics in the undersaturated volume and the phonolite minima. Klinghardt phonolites cluster around the minima. Dots - aphyric phonolites; cicles - phyric phonolites.

Many of the occurrences are essentially aphyric but porphyritic varieties also occur, some being quite spectacular with nepheline phenocryst up to 2 cm in diameter and tabular sanidines up to 8 cm across !. In porphyritic varieties both sanidine and nepheline (sometimes replaced by sodalite) are ubiquitous phenocrysts and the commonest mafic phenocryst is aegirine augite together with Ti-magnetite, sphene, and amphibole (rare). Groundmass phases are the same but include late stage aenigmatite. Despite the relatively constant major element composition the phonolites collectively constitute a very strongly differentiated suite with primitive samples having 1500-2000 ppm Ba and Sr and 500 ppm Zr, whereas highly evolved phonolites have close to close to 3500 ppm Zr and no Ba ans Sr. These enrichments and depletions are charcteristic of a fractional crystallization process dominated by alkali feldspar.

The geochemistry suggests that all phonolite occurrences are genetically linked to some common parental phonolite magma. There are many questions relating to this parent magma which remain unanswered - was it contained in a large Klinghardt-wide magma chamber ? or were there numerous smaller high-level subchambers connected at depth ? Phonolites are not regarded as primary magmas but derivatives of more mafic magmas generated by extensive differentiation processes. If this is the case why do we find no evidence of these possible parental magmas which must have had volumes 5-10 fold that of the phonolites ?

Table 4

Selected analyses of Klinghardt phonolites

	Aphyric phonolites							Porphyritic phonolites						
	KDO-43	KS-69	KTR-88	KDE-133	KQ-236	KJ-316	KH-341	KSC-28	KZ-82	KH-99	KSF-160	KOP-255	FEL-328	KH-355
SiO_2 (wt.%)	54.15	53.64	50.38	55.50	55.23	54.87	55.15	53.95	53.80	54.37	51.20	55.07	53.99	54.37
TiO_2	0.92	0.27	1.20	0.28	0.31	0.29	0.20	0.45	0.38	0.34	1.58	0.40	0.32	0.45
Al_2O_3	19.97	21.20	20.14	21.49	22.81	21.43	21.43	20.06	21.62	21.68	17.87	18.64	22.54	21.68
$Fe_2O_3^*$	4.72	3.04	6.02	3.14	2.30	3.19	3.22	5.38	3.57	3.39	6.71	4.28	3.25	3.40
MnO	0.25	0.39	0.34	0.39	0.35	0.34	0.46	0.32	0.31	0.29	0.29	0.18	0.32	0.31
MgO	0.80	0.47	0.81	0.13	0.11	0.40	0.25	0.74	0.21	0.21	1.79	0.64	0.24	0.25
CaO	3.52	1.69	3.79	1.15	1.01	1.20	1.01	1.46	1.38	2.03	5.26	1.53	1.35	1.40
Na_2O	6.45	7.67	7.63	9.35	9.75	8.70	8.74	6.06	8.77	7.42	4.52	7.72	10.52	8.38
K_2O	6.18	5.03	5.75	5.44	6.29	5.66	4.68	7.12	6.62	6.94	5.45	4.49	6.37	6.86
P_2O_5	0.23	0.02	0.28	0.02	0.05	0.03	0.01	0.05	0.04	0.04	0.49	0.05	0.05	0.06
H_2O	0.42	0.27	0.58	0.25	0.14	0.36	0.20	0.34	0.31	0.26	0.48	0.69	0.10	1.61
LOI	2.04	5.10	3.05	2.22	1.59	2.93	4.18	3.48	2.22	2.24	3.67	5.37	0.91	0.12
Total	99.65	98.79	99.97	99.36	99.94	99.40	99.44	99.41	99.23	99.21	99.31	99.06	99.96	98.89
Ba (ppm)	1043	52	2549	13	116	111	13	392	71	172	1373	496	165	164
Sr	1256	203	2951	151	555	570	163	1487	623	999	1569	391	862	700
Rb	182	343	184	299	249	246	349	226	190	208	150	142	217	213
Y	32	70	45	54	47	51	75	38	30	28	41	24	35	28
Zr	675	3218	1007	2416	1339	1853	3685	1177	1088	982	636	3136	1316	1118
Nb	151	706	237	456	360	356	781	225	265	198	169	753	267	298
Zn	83	267	159	236	164	205	300	191	163	147	90	184	171	151
Th	31	101	34	101	55	80	116	45	44	40	26	96	61	43
Pb	21	60	20	58	34	44	65	38	28	25	23	32	38	25
Ce	186	310	280	220	297	265	272	172	240	232	$255^{\dagger}$	135	278	213
Nd	59	100	95	59	83	73	86	48	56	42	$137^{\dagger}$	54	56	50
V	34	4	11	5	4	60	0	29	14	15	70	39	17	14

Erosion Surfaces and the Phonolites

The phonolites were emplaced in an area of considerable relief at about 37 Ma as far as we can tell. Within the Klinghardt Mountains it is possible to detect remnants of at least two old erosion surfaces with distinctive covering of surface sediments. One, at higher altitude, was noted in the upper Glastal and was characterized by the presence of abundant brown chalcedony (silcrete). A lower surface in the same area and around the NW side of Kokerboom is charcterised by unconsilidated cover of well-rounded cobbles and boulders (up to 30 cm in diameter) of quartzite, vein quartz, and rare chalcedony, with chatter marks on many of the boulders. Phonolite is absent from the clast population and Lock and Marsh (1981) inferred that these deposits were older than the phonolite volcanism.

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