Petrology, Geochronology, Mineralogy, and Geochemistry of the Beemerville Alkaline Complex, Northern New Jersey

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ABSTRACT

The Beemerville alkaline complex, New Jersey, occurs at the western end of the Cortlandt-Beemerville magmatic belt. The eastern end of the belt is defined by the Cortlandt complex, New York, which largely consists of ultramafic and mafic rocks. Between these two intrusive centers is a linear almost east-west trending zone of lamprophyre and felsic dikes. The Beemerville complex consists of two large nepheline syenite bodies, several diatremes, and associated lamprophyre and phonolite dikes, all of which intrude the shales and graywackes of the Ordovician Martinsburg Formation. The emplacement of these igneous bodies is post-tectonic and titanite fission-track ages indicate an emplacement age of 420 ± 6 Ma. The mean apatite fission-track age is 156 ± 4 Ma, which represents the time the rocks of the complex were last at temperatures of $60^{o}C$ to $100^{o}C$.

The major rock forming minerals are orthoclase, nepheline, and clinopryroxene. Minor minerals are biotite and titanite. Accessory minerals are sodalite, fluorite, calcite, and opaque oxides. Cancrinite alteration of nepheline is common. Based on electron microprobe data the pyroxenes range in composition from diopside through aegirine-augite to aegirine. The feldspars in the nepheline syenites and phonolites are orthoclase ($>Or_{80}$), with albite noted in some specimens. Two biotite populations can be identified: one encompasses the nepheline syenites and phonolites and the other the lamprophyre dikes and matrix material from the diatremes, an observation which suggests a genetic linkage between the lamprophyres and the diatremes.
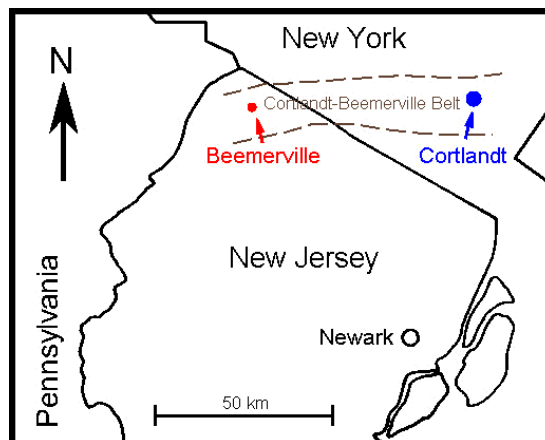
Based on textural, phase equilibria, and chemical criteria, the phases fractionating from the syenitic magmas were aegirine, nepheline, and titanite. The nepheline syenites are essentially crystal cumulates with some trapped interstitial melt. Few, if any, of the phonolites represent liquid compositions, and this is partly due to post-magmatic alteration. Nb/Ta and Zr/Hf ratios are very variable, in part due to the fractionation of titanite and in part due to hydrothermal alteration. Three distinct REE patterns are observed for the phonolites: uniform slope downwards from LREE to HREE, flattening at the HREE end, and U-shaped. These patterns are partly due to the fractionation of titanite, but a more detailed explanation most likely involves the role of fluids in altering these patterns.

INTRODUCTION

The Beemerville complex is a member of the Cortlandt-Beemerville magmatic belt (Ratcliffe, 1981). This belt extends approximately 100 km from the Peach Lake-Croton Falls area of Westchester County, New York, $S80^{o}W$ to Beemerville, New Jersey, (Fig. 1) and transects the structural grain of the Appalachians. The calc-alkalic to alkalic Cortlandt and Rosetown complexes mark the eastern end of the belt and the strongly alkalic Beemerville complex marks the western end, although the belt may extend farther to the west beneath Silurian strata. A 30 km wide belt of abundant mafic and intermediate dikes extends from Cortlandt to Beemverville. At the eastern end of the belt these dikes are weakly alkalic (spessartite, kersantite, andesite, and rhyodacite) while at the western end they are strongly alkalic (phonolite, and camptonite). Individual dikes typically have NE or NW strikes. Ratcliffe (1968, 1981) concludes that the Cortlandt complex was emplaced syntectonically relative to Taconic dynamo-thermal metamorphism and the Beemerville complex and associated dikes were emplaced post tectonically relative to folding and slatey cleavage in the Martinsburg. Nowhere (with a possible exception at Beemerville) have the rocks been observed to intrude strata younger than Ordovician age, thus fixing a

minimum age for this period of igneous activity. Ratcliffe (1981) suggests that the juncture of two distinct Taconic salients controlled the location of the belt and that the magmatic activity occurred in response to differential stresses that produced local rupturing of the continental crust and mantle. These stresses arose because of different directions or rates of plate consumption and collision during the Ordovician.

The Cortlandt complex, the largest of the alkalic – calc-alkalic complexes, intrudes metamorphosed Cambrian-Ordovician sedimentary rocks of the Manhattan Prong. Ratcliffe et al. (1982) subdivided the complex into geographic components, east of the Hudson River and Stony Point. East of the Hudson River the Cortlandt complex consists of 6 individual plutons: (1) hornblendite and kaersutite gabbro, (2) diorite, (3) clinopyroxenite, (4) cortlandtite and amphibole pyroxenite, (5) norite and biotite-amphibole norite, and (6) clinopyroxenite (Ratcliffe, 1968, 1982). The Stony Point portion of the Cortlandt complex consists of diorite, cortlandtite, and amphibole pyroxenite. The Rosetown complex consists of hornblendite, amphibole pyroxenite, diorite, and granodiorite. Models for the origin of these plutons have largely involved fractional crystallization plus crustal contamination of mantle-derived magmas

Figure 1. Location map for Beemerville and Cortlandt complexes and the Cortland-Beemerville magmatic belt. Modified from Maxey (1976).

(Domenick and Basu, 1982; Bender et al., 1984). Bender et al. (1982) suggested that large-scale liquid immiscibility may have played a role in the evolution of the granodiorite and diorite plutons of the Rosetown complex. The Beemerville complex consists of several nepheline syenite plutons, diatremes, and associated phonolite and lamprophyre dikes (Iddings, 1898; Aurousseau and Washington, 1922; Wilkerson, 1946; Davidson, 1948; Maxey, 1976; Eby et al., 1994). In this paper new mineralogical, geochemical, and geochronological data are reported for the Beemerville complex. The emphasis will be on the geochemistry and petrogenesis of the nepheline syenites and phonolites.

GEOLOGY OF THE BEEMERVILLE COMPLEX

The following geologic description of the Beemerville complex (Fig. 2) is summarized from Maxey (1976). The nepheline syenite occurs in two large bodies and as several small bodies, one located in the Shawangunk conglomerate and the other associated with the diatreme of Rutan Hill. The large bodies intrude the Ordovician Martinsburg shale and to the west are overlain by the Silurian Shawangunk conglomerate. The nepheline syenite that crops out in the Shawangunk is stratigraphically higher than the basal Shawangunk and may represent an intrusion of nepheline syenite from the southern large nepheline syenite body into the Shawangunk. The Martinsburg shale has been metamorphosed to a hornfels near the boundary with the nepheline syenite plutons, but actual contacts between the nepheline syenite and the shale are not observed. The nepheline syenite is medium- to coarse-grained and consists of nepheline, orthoclase, clinopyroxene, biotite, titanite, ±melanite, magnetite, apatite, and trace amounts of pyrite and zircon.

Several diatremes are found in the Martinsburg shale, and the largest comprises Rutan Hill. The diatremes consist of a variety of angular to subangular xenoliths and autoliths in a dark, dense matrix. Xenoliths noted by Maxey (1976) include shale and graywacke (Martinsburg Formation), fine-grained pale-blue dolomite (Kittatinny Formation?), cream-colored fine-grained limestone (Jacksonburg Formation), and gneiss (similar to that observed in the Reading Prong). Autolithic inclusions are nepheline syenite, micromelteigite, and carbonatite. The matrix consists of an extremely fine-grained

groundmass with fine-to coarse-grained megacrysts of biotite, diopside, aegerine-augite, orthoclase, magnetite, apatite, and nepheline. A nepheline syenite plug, approximately 30 m in diameter, intrudes the Rutan Hill diatreme. Fenitization of the greywacke in the Martinsburg is noted in a fracture zone associated with the small diatremes. The fenitized greywacke consists of albite, aegirine, sodic amphibole, and trace amounts of biotite and calcite.
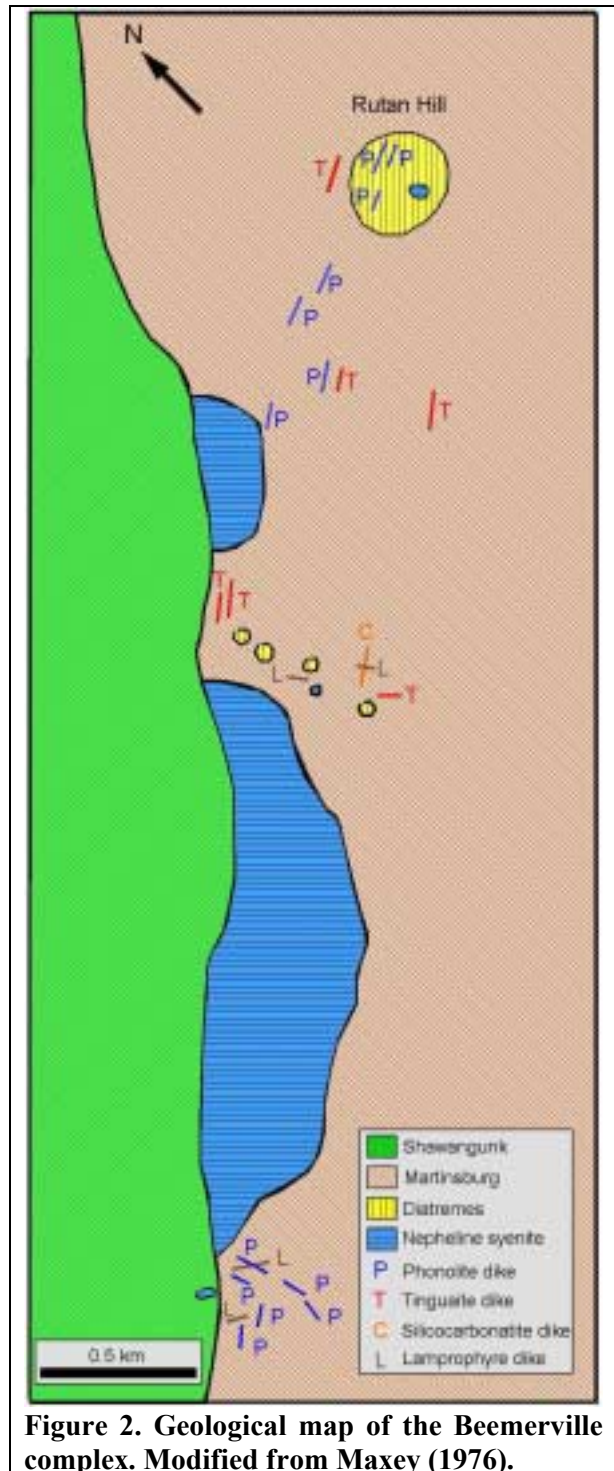
Phonolite, tinguaite and lamprophyre dikes occur in the Beemerville area. Phonolite dikes occur in the southern nepheline syenite body, crosscut diatremes, and intrude the Martinsburg Formation. Dikes vary from a few cm to up to 50 m in width and both fine-grained and porphyritic varieties are noted. The phonolites associated with the Rutan Hill diatreme are extensively altered. Tinguaite dikes are found in both nepheline syenite bodies and the Martinsburg formation. The dikes vary in width from 0.25 to 50 m. Most are porphyritic and the common phenocrysts are nepheline, orthoclase, clinopyroxene, and titanite. The lamprophyre dikes occur throughout the complex and range in width from 10 cm to 7 m and most trend northwest. Many of the dikes are extensively altered and the primary minerals are largely replaced. Where observable, the primary minerals are diopside, aegirine-augite, bioite, nepheline, orthoclase, titanite, melanite, magnetite, and apatite. Ocelli are common in some of the dikes.

Based on gravity data, plus supporting aeromagnetic data, Ghatge et al. (1992) modeled the Beemerville complex as a thin body near the surface that broadened and elongated with depth. The Beemerville body extends to the southwest and plunges at high angle to the southeast. From their data they also inferred the existence of a second, subsurface, intrusive body approximately 9 km southeast of the Beemerville complex.

PETROGRAPHY

Phonolite and tinguaite

Mineralogically phonolite and tinguaite are the same rock. Historically the distinction was based on the presence of phenocrysts (tinguaite). The term tinguaite is now considered archaic. As used on the geologic map (Fig. 2), phonolite indicates a fine-grained dike rock while tinguaite indicates the

Figure 2. Geological map of the Beemerville complex. Modified from Maxey (1976).

presence of phenocrysts in the dike rock. The major minerals in the phonolites are orthoclase, nepheline, and clinopyroxene. Minor minerals are biotite, titanite, and opaque minerals. A fine-grained phonolite,

with a texture indicative of rapid cooling, is illustrated in Figures 3a and 3b. In the porphyritic varieties, orthoclase, nepheline, clinopyroxene, and titanite are the common phenocryst phases (Figs. 4a, 4b).


Figure 3a. Phonolite dike at base of Rutan Hill (BEM16). Major minerals are nepheline and orthoclase with minor aegirine-augite. Plumose texture indicative of rapid cooling. Width of field, 2 mm. Plane light.
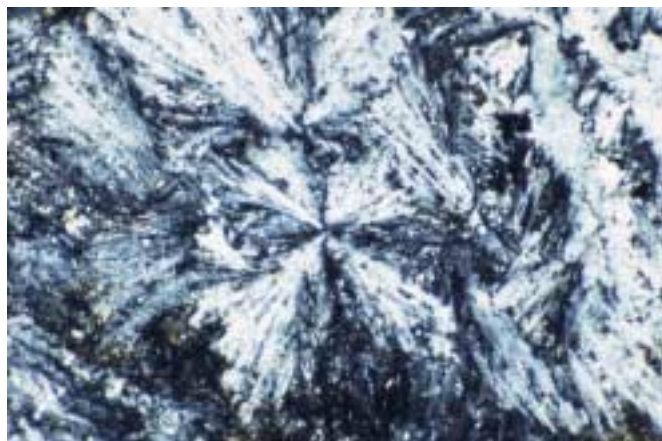
Figure 3b. Crossed polars.
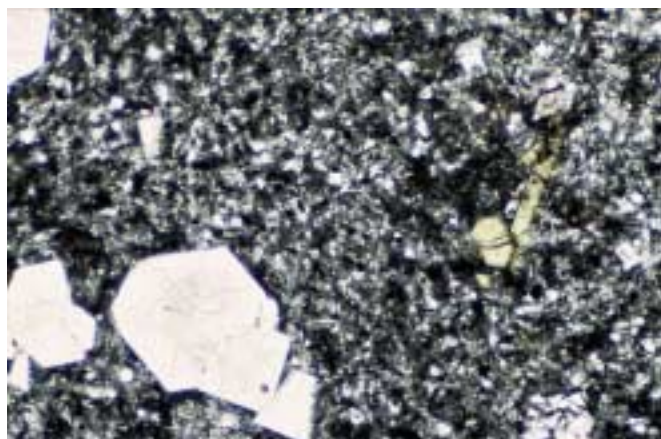
Figure 4a. Phonolite (*tinguaite*) dike (BEM19). Nepheline, aegirine, and titanite phenocrysts in a fine-grained matrix of nepheline, orthoclase, and aegirine. Width of field, 5 mm. Plane light.
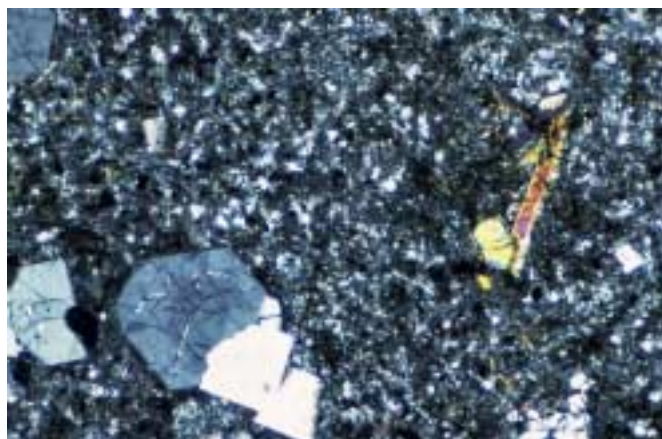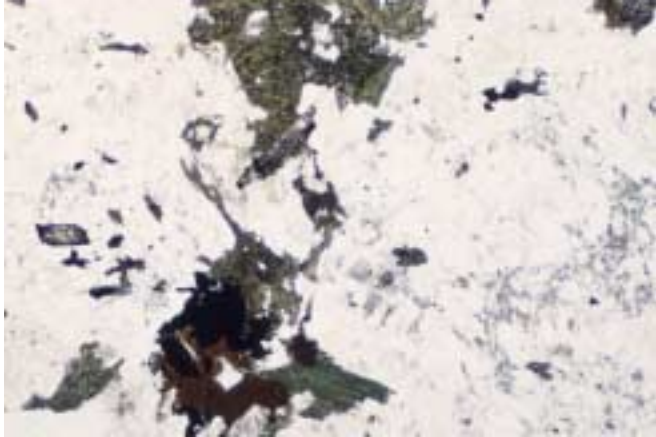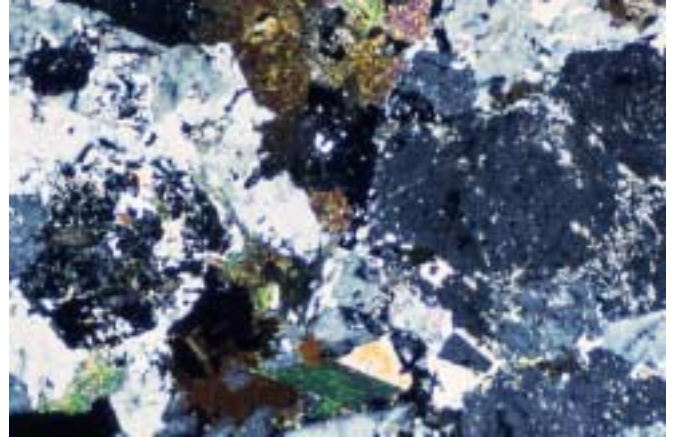
Figure 4b. Crossed polars.

Nepheline syenite

The nepheline syenite is medium- to coarse-grained, equigranular to subporphyritic. Major minerals are orthoclase, nepheline, and clinopyroxene. Minor minerals are biotite, titanite, ±melanite, fluorite, cancrinite, sodalite, calcite, magnetite, and apatite. Based on probe data, the feldspars are orthoclase ($\geq$ Or_{80}). Optically, the feldspars do not show unmixing textures. The pyroxenes vary in composition from diopside to aegirine. Zoned clinopyroxenes have diopside cores and aegirine-augite rims or aegirine-augite cores and aegirine rims. Biotite occurs as a minor mineral either replacing clinopyroxene or as discrete grains. Cancrinite and sodalite replace nepheline. Fluorite is a common trace mineral. Figures 5 – 8 illustrate the various types and textures of nepheline syenite.
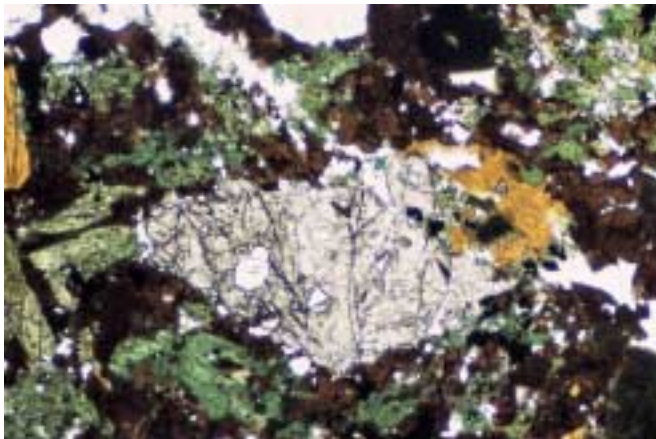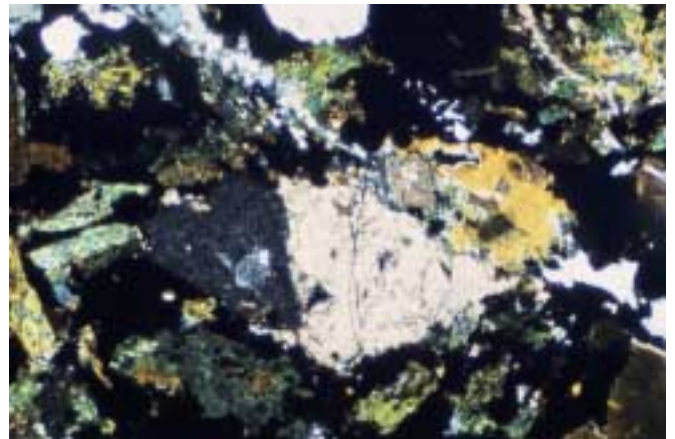
Figure 5a. Coarse-grained nepheline syenite (BEM4). Nepheline, orthoclase, aegirine-augite, and minor biotite. Width of field, 5 mm. Plane light.
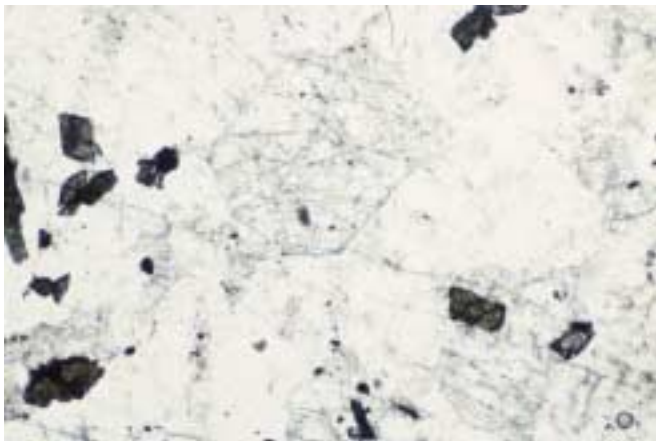

**Figure 5b. Crossed-polars. Sodalite replaces nepheline (isotropic mineral).**

Figure 6a. Nepheline syenite (BEM29). Intergrown melanite and aegirine-augite, minor biotite, feldspar, titanite. Width of field, 5 mm. Plane light.

**Figure 6b. Crossed polars. The high birefringence grain in the center of the field of view is calcite.**

Figure 7a. Nepheline syenite (BEM33). Euhedral to subhedral nepheline, aegirine-augite, and titanite in a large orthoclase. Width of field, 5 mm. Plane light.
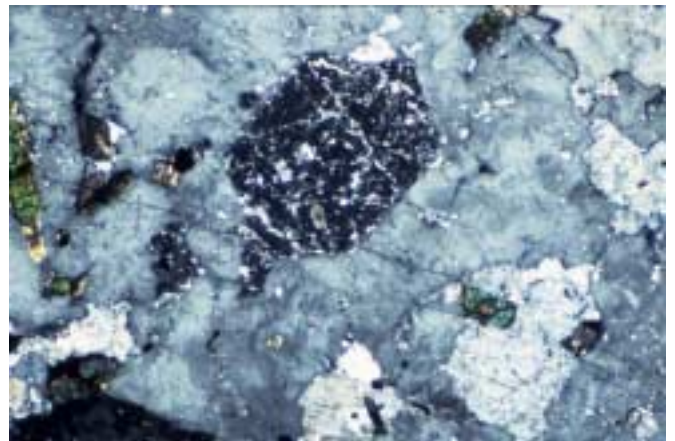

Figure 7b. Crossed polars. Note that the mineral inclusions in the orthoclase are the same as the phenocryst minerals in the phonolite (Fig. 4a,4b).
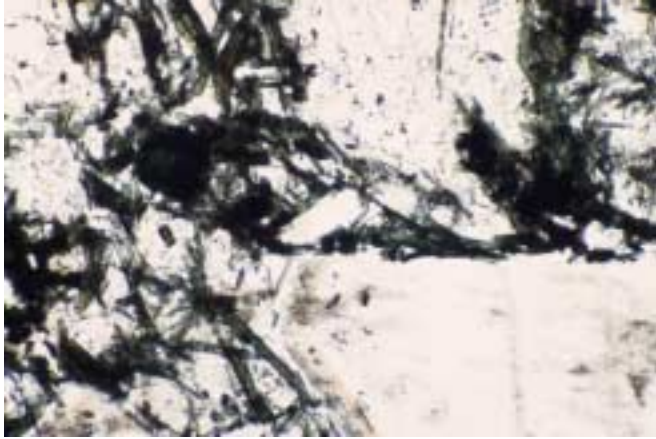
Figure 8a. Border phase of northern nepheline syenite body (BEM2). Phenocrysts of nepheline and orthoclase in a fine-grained matrix of feldspar and aegirine. The nepheline has been extensively altered by cancrinite. Width of field, 2 mm. Plane light.
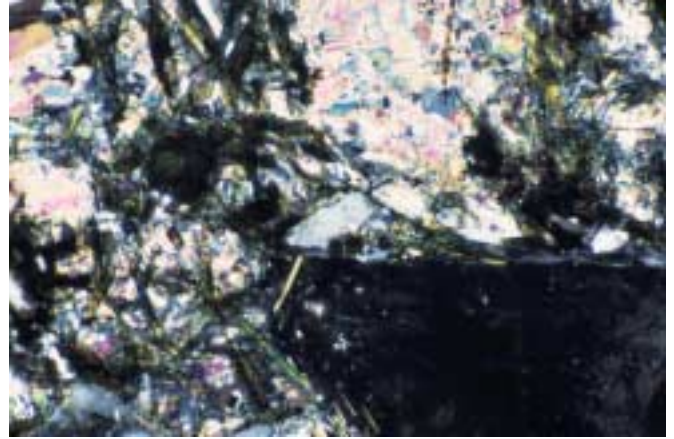
Figure 8b. Crossed polars. The high birefringence mineral is cancrinite.

Diatreme breccia

The diatreme breccias are heterogeneous at all scales and show a wide range of xenoliths and autoliths. Locally calcite is an important component. An example of this carbonate breccia is shown in Figures 9a and 9b.
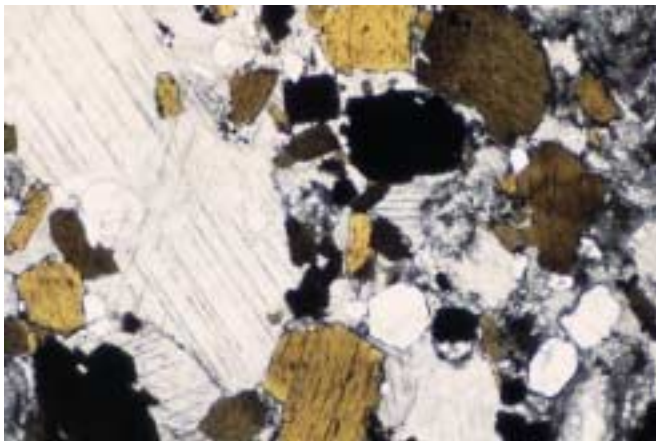

Figure 9a. Carbonate breccia from Rutan Hill (BEM11). Biotite, apatite, and opaque minerals in a coarse-grained matrix of calcite. Width of field, 5 mm. Plane light.
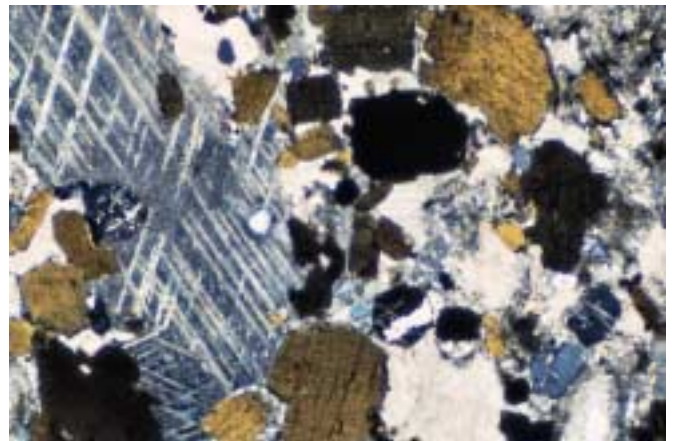
Figure 9b. Crossed polars.

Lamprophyre dikes

Many of the lamprophyre dikes are intensely altered obscuring the primary mineralogy. For relatively unaltered specimens the major minerals are diopside or aegirine-augite, and/or biotite phenocrysts in a fine-grained matrix of clinopyroxene, biotite, nepheline, orthoclase, titanite, magnetite, calcite, and apatite. Some of the dikes contain ocelli (Fig. 10a, 10b). A more complete description of the lamprophyre dikes will be given elsewhere.

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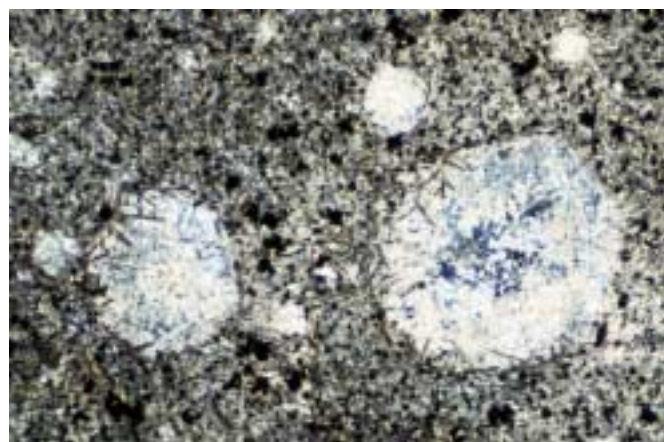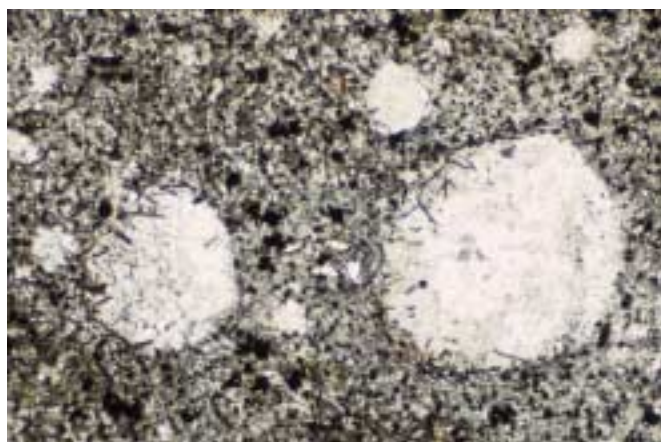
Figure 10a. Ocelli in lamprophrye dike (BEM20). Width of field, 5 mm. Plane light

Figure 10b. Crossed polars.

GEOCHRONOLOGY

Fission-track ages were determined for various lithologic units from the Beemerville complex. Apatite and titanite were separated using standard heavy liquid and electromagnetic techniques. Apatite fission-track ages were determined for nepheline syenites and the carbonate breccia from Rutan Hill using the population method. Titanite fission-track ages were determined for nepheline syenites using the external detector method. The zeta calibration method described by Hurford and Green (1983) and Hurford (1990) was used to calculate the fission-track ages. A detailed description of our procedures can be found in Eby et al. (1995). The analytical results are reported in Table 1.

TABLE 1. DATA FOR APATITE AND TITANITE FISSION-TRACK AGES

Sample	Number crystals	Spontaneous ρ_s (10^5 t/cm^2)	(N$_s$)	Induced ρ_i (10^5 t/cm^2)	(N$_i$)	Dosimeter ρ_d (10^5 t/cm^2)	(N$_d$)	Age (Ma) (± 1 σ)
				Apatite				
FC	100/50	1.37	(329)	4.78	(573)	3.01	(1877)	27.0±2.2
DUR	100/50	1.12	(266)	3.46	(415)	3.16	(1877)	31.9±2.7
BEM11	50/50	13.1	(1574)	7.92	(950)	3.02	(1877)	155.0±10.6
BEM13	50/50	12.8	(1534)	7.48	(898)	3.03	(1877)	160.4±11.4
BEM18	50/50	9.23	(1108)	5.76	(691)	3.04	(1877)	151.2±13.8
BEM20	50/50	1.53	(184)	0.93	(112)	3.06	(1877)	155.5±15.7
				Titanite				
DROM	8/8	52.3	(1005)	49.8	(957)	6.00	(4227)	99.0±2.5
FC	9/9	4.01	(346)	14.0	(1210)	6.39	(4227)	28.8±1.8
ESM1	10/10	5.46	(419)	1.21	(93)	6.03	(4227)	417±48
ESM2	8/8	5.44	(418)	1.25	(96)	6.42	(4227)	426±48
DROM	10/10	42.7	(1025)	2.17	(520)	3.16	(1877)	97.8±1.6
BEM4	10/10	11.8	(1136)	1.42	(136)	3.20	(1877)	410±63
BEM5	10/10	13.7	(1317)	1.61	(155)	3.24	(1877)	421±115
BEM18	12/12	8.44	(972)	1.02	(117)	3.28	(1877)	417±48
BEM29	10/10	10.6	(1019)	1.26	(121)	3.31	(1877)	428±75
BEM33	10/10	18.6	(1782)	2.25	(216)	3.35	(1877)	424±62

The mean apatite fission-track age for all samples is 156 ± 4 Ma. There is no statistical difference between the individual ages. Apatite shows a complex history of track retention as it cools from 120°C to 60°C through the partial annealing zone (PAZ). Above 120°C no tracks are retained and below 60°C all tracks are retained (Wagner, 1990). Thus, the apatite apparent age represents the time when the sample cooled through the PAZ. The exact significance of the age depends on the cooling history (long versus short) and can be addressed using a track length study (not done here).

The mean titanite age is 420 ± 6 Ma. The annealing temperature for titanite fission-tracks is ~275±25°C (Fitzgerald and Gleadow, 1988), similar to the closure temperature for the K-Ar biotite system. The Beemerville complex was emplaced in a post tectonic setting, and given that some of the phonolite dikes have quench textures, presumably at relatively shallow depths. Hence, it is reasonable to infer that 420 Ma is the emplacement age for the Beemerville suite. A Rb-Sr biotite age of 424 ± 20 Ma and a K-Ar biotite age of 443 ± 22 Ma were obtained by Zartman et al. (1967) for a syenite from the Beemerville complex. Within error these ages agree with the titanite fission-track age of 420 ± 6 Ma.

A large number of age determinations have been done for the various intrusions comprising the eastern end of the Cortlandt-Beemerville belt. Dallmeyer (1975) obtained [40]Ar/[39]Ar biotite and hornblende ages for the Cortlandt and Rosetown complexes ranging between 420 and 450 Ma. A K-Ar age of 448 ± 14 Ma was reported by Long and Kulp (1962) and a Sm-Nd isochron age of 430 ± 34 Ma was reported by Domenick and Basu (1982) for the Cortlandt complex. The most extensive set of geochronological data is found in Ratcliffe et al. (1982). These authors report Rb-Sr biotite ages of 417 ± 15 and 423 ±20 Ma for the Cortlandt complex and a Rb-Sr isochron age of 422 ± 18 Ma for the Rosetown complex. K-Ar ages reported by Ratcliffe et al. (1982) are listed in Table 2. If we eliminate the two significantly older K-Ar ages, the remaining K-Ar ages reported by Ratcliffe et al. (1982) give a mean age of 413 ± 12 Ma, in reasonable agreement with the Rb-Sr ages and the Sm-Nd isochron age. Given the data currently available it is reasonable to conclude that the Cortlandt-Beemerville belt intrusions were emplaced at about 420 Ma. This is a Silurian age, and the observation by Maxey (1976) that nepheline syenite appeared to intrude the Silurian Shawangunk conglomerate is in agreement with this age. However, a Silurian age is not in agreement with the syntectonic setting suggested for the Cortlandt complex and Ratcliffe et al. (1982) interpreted the younger ages as cooling ages. Resolution of these geochronological – geological discrepancies will most likely require the acquisition of high precision U-Pb zircon ages.

TABLE 2. K-Ar AGES FOR EASTERN INTRUSIONS

Sample	Mineral Dated	Age (Ma)
Stony Point		
OC4	Hornblende	483 ± 10
OC5	Biotite	422 ± 10
OC6	Biotite	396 ± 8
East of Hudson River		
OC9	Hornblende	496 ± 7
C1	Hornblende	419 ± 8
C6	Hornblende	426 ± 8
C6b	Biotite	412 ± 8

TABLE 2. K-Ar AGES FOR EASTERN INTRUSIONS

| Sample	Mineral Dated	Age (Ma)
Rosetown biotite rhyodacite dikes		
RD-1	Biotite	393 ± 14
RD-2	Biotite	423 ± 15
RD-3	Biotite	413 ± 14
Note: Ages are from Ratcliffe et al. (1982).		

MINERAL CHEMISTRY

The chemical composition of nepheline, feldspar, biotite, pyroxene, garnet, and titanite from the various lithologic units was determined by electron microprobe. The complete data listing (as Excel spreadsheets) is available on the author's website (http://faculty.uml.edu/Nelson_Eby). The feldspar, biotite, and pyroxene data will be discussed here and the nepheline data will be used in a later section.

Pyroxenes

Pyroxenes show a complete range of compositions from diopside through aegirine-augite to aegirine (Fig. 11). The compositional range is similar to that of other alkaline provinces (see Eby et al., 1998), with the notable exception of extreme iron enrichment in the more Na-rich compositions. Based on the existing data, there seems to be no distinction between pyroxenes from the nepheline syenites and pyroxenes from the phonolites, with the possible exception that Na-rich pyroxenes are more common in the phonolite. Also, pyroxenes from the southern nepheline syenite body show a more restricted range in composition (diopside to aegirine-augite) than those from the northern nepheline syenite body.
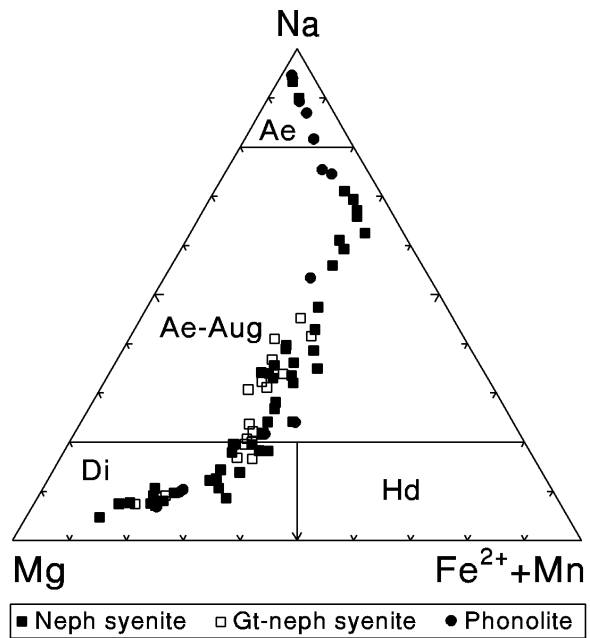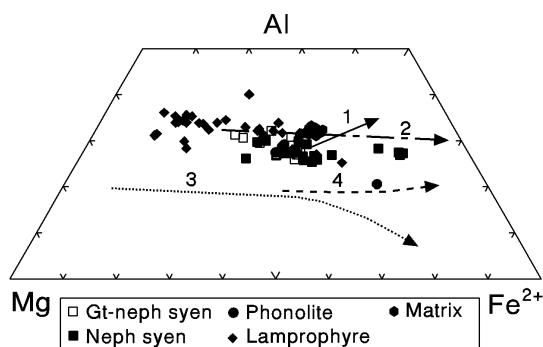

Figure 11. **Compositions of Beemerville pyroxenes projected into the Mg-Na-(Fe^{2+}+Mn) classification diagram.**

Feldspars

Feldspar compositions are plotted in the Ab-An-Or ternary feldspar diagram in Figure 12. Of note is that the feldspars from the nepheline syenites and phonolites have virtually no calcium and are K-rich (Or>80). At the microscopic level the feldspars are homogeneous, and if any unmixing has occurred it is submicroscopic (i.e., cryptoperthite). Feldspar solvi contoured on the diagram indicate that these are relatively low temperature feldspars. Only a few plagioclase grains (An<90) were analyzed and these were from a lamprophyre dike. Given the composition of the dike, these are not primary plagioclases, but are the product of hydrothermal alteration (albitization), which removed Ca from more Ca-rich plagioclases.
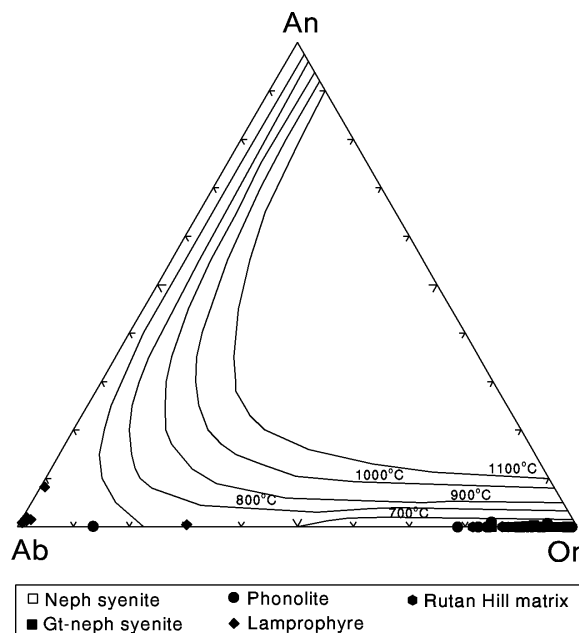
Biotite

The biotite compositions are projected into the Mg-Al-Fe^{2+} diagram in Figure 13. The Beemerville biotites tend to be more aluminous than those found in a number of other alkaline provinces. They are most similar to biotites from Igdlerfigsalik, South Greenland. There is a slight trend towards decreasing Al with increase in Fe^{2+}. Mn and Al (atomic) are plotted versus the Mg/Mg+Fe+Mn ratio in Figure 14. In terms of both of these elements the biotites form two groups: (1) lamprophyres and matrix material from the diatremes and (2) nepheline syenites and phonolites. The phonolite biotite analyses that plot in the mafic field are from the phonolite intruded into the Rutan Hill diatreme and the inference is that these are biotite xenoliths. A second inference is that the matrix material in the diatremes and the lamprophyres are related, while the nepheline syenites and phonolites represent a separate magmatic group.
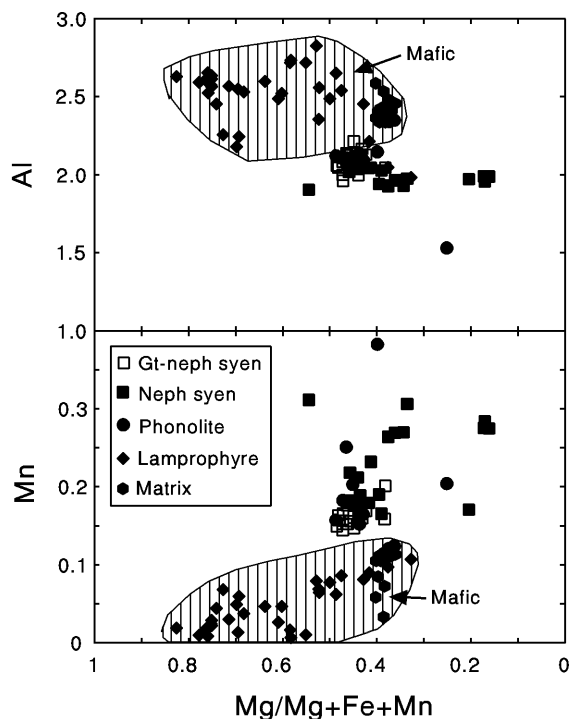

Figure 12. Feldspar composition plotted in the Ab-An-Or ternary. Feldspar solvi (^{o}C) are from Nekvasil (1992).

Figure 13. Biotite compositions plotted in the Mg-Al-Fe^{2+} diagram. Composition trends from other alkaline provinces are included for comparison. (1) Ilomba-Ulindi, North Nyasa Alkaline Province, Malawi (Eby et al., 1998); (2) Igdlerfigsalik, South Greenland (Finch, 1995); (3) Magnet Cove, Arkansas Alkaline Province, Arkansas (Flohr and Ross, 1990); (4) Junguni, Chilwa Alkaline Province, Malawi (Woolley and Platt, 1988).

WHOLE-ROCK GEOCHEMISTRY

Representative rock samples were reduced to fine powder using a jaw crusher (with hardened steel plates), a rotary pulverizer with ceramic plates, and final reduction by hand grinding in an agate mortar. Major elements were determined by X-ray


Figure 14. Al and Mn atomic for biotites plotted versus the Mg/Mg+Fe+Mn ratio.

fluorescence (XRF) analysis of fused beads using standard techniques. Trace elements were determined by XRF on pressed powders and by instrumental neutron activation analysis (INAA). Replicate analysis of international rock standards returned expected precision and accuracy for these analytical methods (XRF major elements, ± 2%; XRF trace elements, ± 5-10%; INAA trace elements, ± 5-10%). LOI was determined by drying the samples at $1000^{\circ}C$ for 1 hour. CO_2 was determined using a CNH analyzer. A listing of the chemical analyses can be found on the author's website.

In agreement with the observed mineralogy, chemically all the nepheline syenite and phonolite samples are silica undersaturated (Fig. 15). There is an inverse relationship between the silica abundance and the percent foidal minerals. This is not an unexpected result, but the important point is that given the silica content, many of these samples, even in the case of many of the phonolite dikes, cannot represent liquid compositions.

Harker diagrams are plotted for the nepheline syenites and phonolites in Figures 16a and 16b. There is considerable scatter in the data, but TiO_2 and CaO decrease with increasing SiO_2. A phonolite trend (dashed line) can be defined for CaO, but not for TiO_2. Ca principally resides in the titanites and
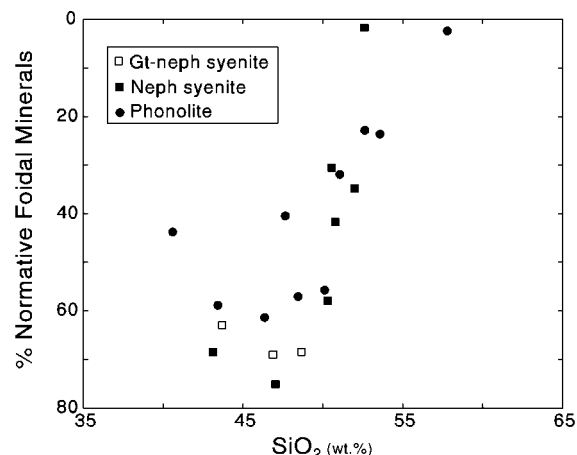
Figure 15. SiO_2 versus % normative foidal (nepheline and leucite) minerals.
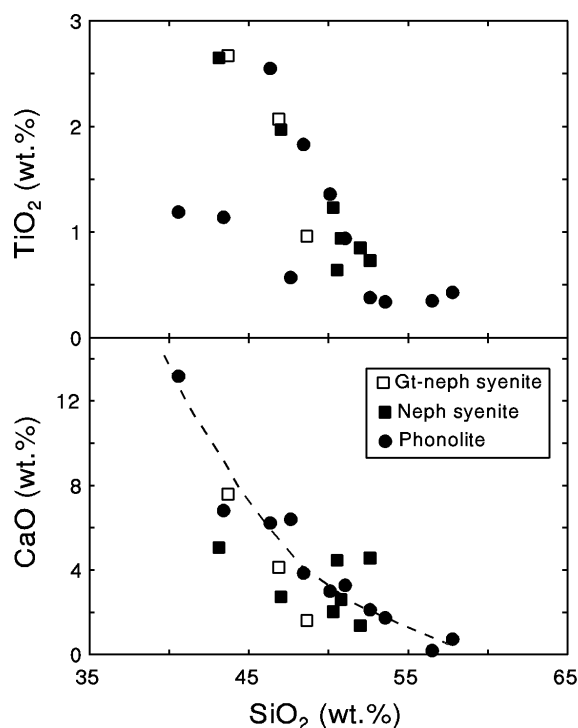
Figure 16a. SiO_2 versus TiO_2 and CaO
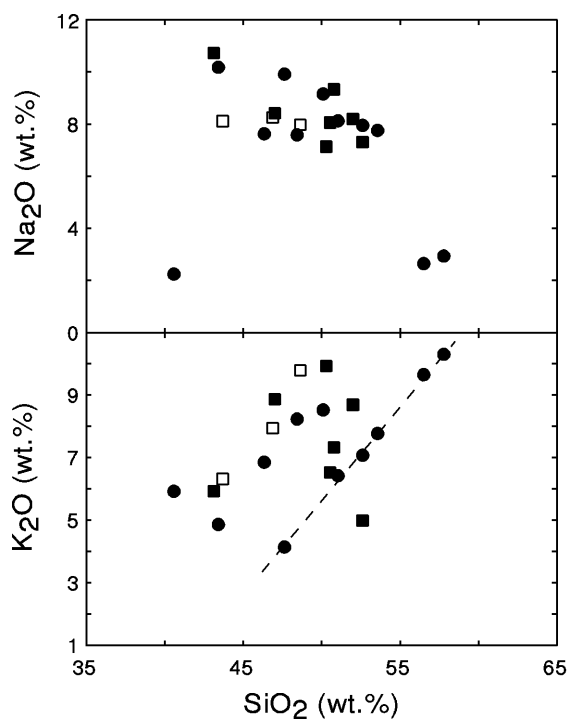
Figure 16b. SiO_2 versus Na_2O and K_2O.

Ca-clinopyroxenes while the major repository for Ti is titanite. A plot of CaO versus TiO_2 (not shown) shows that for most samples these two oxides covary. Hence, one should not interpret these variations as representing a liquid line of descent. For the alkalis, Na_2O decreases with increasing SiO_2 and K_2O increases with increasing SiO_2. As before, in the case of the nepheline syenites these variations are

largely due to changes in the modal abundance of clinopyroxene and alkali feldspar. For the phonolites, a K_2O trend (dashed line) can be defined for some of the samples, but as will be discussed subsequently there has been a significant amount of element mobility.
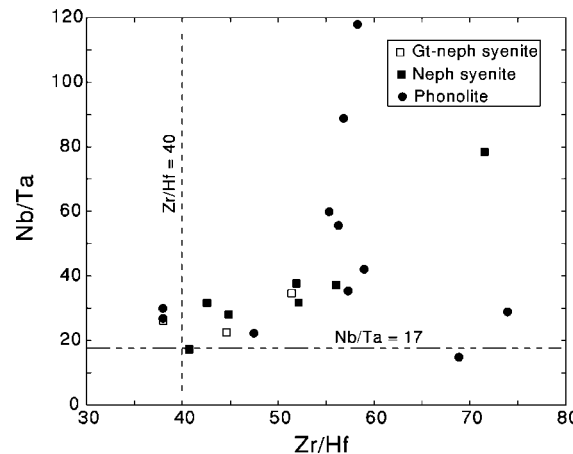
Nepheline syenite and phonolite compositions are projected into the 1 Kbar Neph-Or-Ab-Kal phase diagram in Figure 17. Also shown on the diagram is the composition field for the nephelines from the nepheline syenites and phonolites. The dashed line connects the average K-feldspar composition with the nepheline field. Of note is that many of the samples, particularly the nepheline syenite samples, lie along or near this line suggesting that the rock chemistry can largely be explained as a result of crystal accumulation

Figure 17. Nepheline syenite and phonolite compositions projected into the 1 Kbar Neph-Or-Ab-Kal phase diagram (from Henderson, 1984).

of orthoclase and nepheline. A few of the phonolite dike samples plot at what might be considered liquid compositions, at pressures >1 Kbar, but for most of the samples the inference is that the rocks do not represent liquid compositions. Maxey (1976) notes that many of the phonolite dikes have been albitized. In addition, cancrinite alteration of nepheline is common. Hence, there is ample evidence that the primary chemistry of the dikes has been modified by hydrothermal alteration.

Nb, Ta, Zr, and Hf are usually immobile elements in igneous rocks and the distribution of these elements has proven to be a powerful tool in unraveling petrogenetic histories. A standard ratio plot for these elements is shown in Figure 18. Typical mantle ratios are shown with dashed lines on the plot. Samples that plot in the upper right quadrant of the diagram are said to have "superchondritic" ratios, which is the case for virtually all the Beemerville nepheline syenite and phonolite samples.

Chondrite normalized rare earth element (REE) plots for nepheline and garnet-nepheline syenite (Fig. 19a), phonolites (Figs. 19b and 19c), and the rocks from Rutan Hill (Fig. 20) are shown below. None of the samples show

Figure 18. Zr/Hf versus Nb/Ta plot for nepheline syenites and phonolites.

either positive or negative Eu anomalies, which indicates that feldspar/plagioclase fractionation did not play an important role in the evolution of these magmas. Three types of phonolites (labeled I, II, and III) can be distinguished on the basis of REE patterns. Type I phonolites have a linear REE pattern, type II phonolites have patterns that flatten at the heavy REE end of the spectrum, and type III patterns are concave down (show a relative depletion in the middle REEs). The matrix material from Rutan Hill (Fig. 20) shows a linear REE pattern while the phonolite dike has a type II phonolite pattern.

Figure 19a. Chondrite (Nakamura, 1974) normalized REE patterns for nepheline syenite and garnet-nepheline syenite.

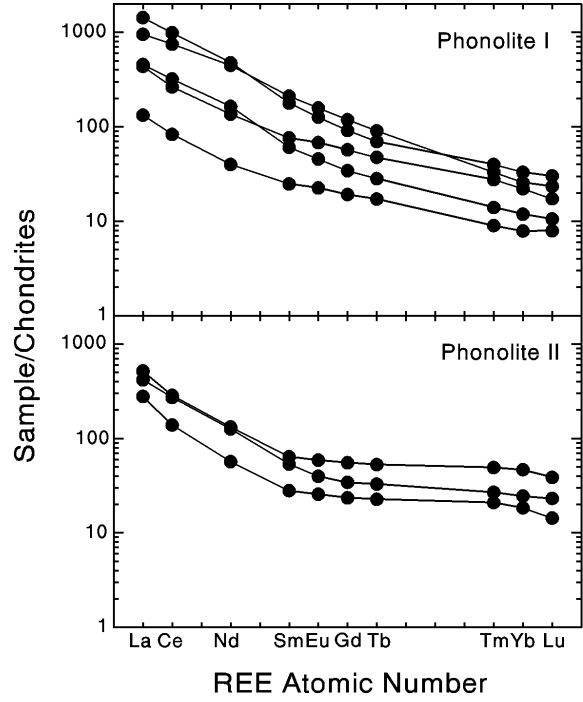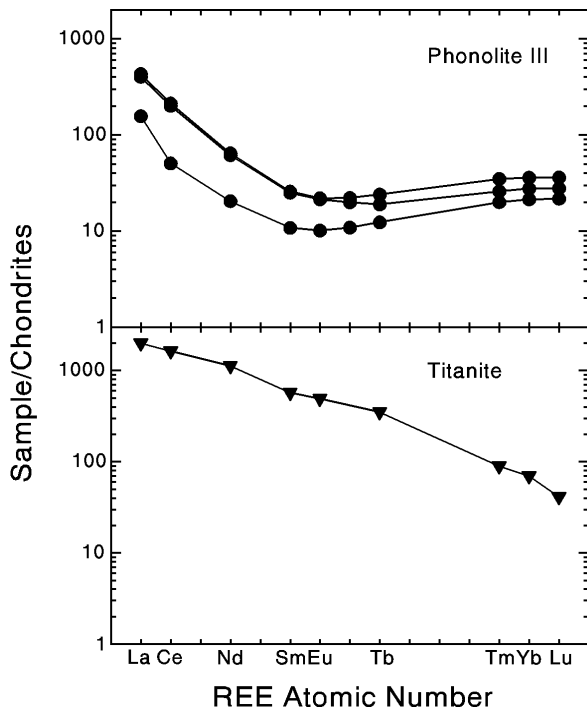Figure 19b. Chondrite normalized REE patterns for type I and II phonolites.

Figure 19c. Chondrite normalized REE patterns for type III phonolite and titanite from Beemerville nepheline syenite. Titanite data from Eby and Sclar (1993).
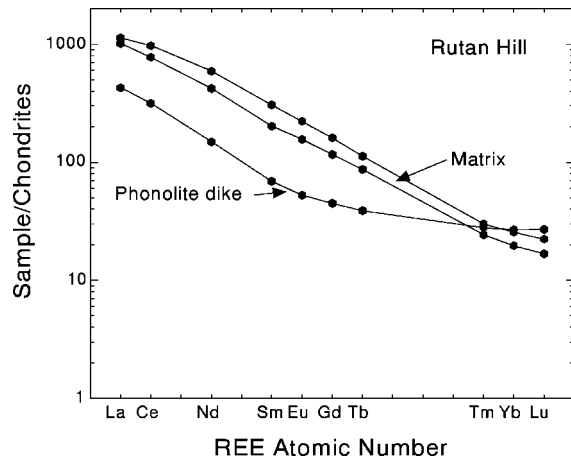

Figure 20. Chondrite normalized REE patterns for matrix material and phonolite dike, Rutan Hill.

DISCUSSION

The major emphasis of this paper is the geochemistry and petrogenesis of the felsic alkaline rocks in the Beemerville complex, and this topic will be considered further here. The common phenocrysts in the phonolite dikes are nepheline, clinopyroxene, and titanite (Fig. 4). These minerals often occur as inclusions in orthoclase (Fig. 7) in the coarse-grained nepheline syenites. Hence, it seems reasonable to conclude that these are the major minerals fractionating from the syenitic melt. In this interpretation, orthoclase is not a fractionating phase, which agrees with the observation that none of the syenite or phonolite samples have negative (or positive) Eu anomalies. The presence of these anomalies would indicate that feldspar and/or plagioclase were fractionating (negative Eu anomaly) or accumulating (positive Eu anomaly) phases. Given this interpretation, the nepheline syenites are partially crystal cumulates and do not represent liquid compositions. As illustrated on the phase diagram (Fig. 17), many of the nepheline syenites can be explained as simple mixtures of orthoclase and nepheline.

So-called "chondritic" ratios are, Nb/Ta = 17 and Zr/Hf = 40. While the data for the lamprophyre dikes is not presented in this paper, it is worth noting that for the dikes the majority of the samples plot near the chondritic ratios with scatter towards higher ratios, but not as high as those obtained for the nepheline syenites and phonolites. If we consider the mineralogy of the nepheline syenites and phonolites, the only mineral that contains significant amounts of these elements is titanite (and garnet for the garnet-bearing nepheline syenites). Zircon is the other potential reservoir of Zr and Hf, but it is rare in the Beemerville suite compared to the almost ubiquitous occurrence of titanite. For a titanite from nepheline syenite, Nb = 3300 ppm, Ta = 164 ppm, Nb/Ta = 20, Zr= 4430. Hf = 14.4, and Zr/Hf = 308 (Eby and Sclar, 1993). Given the high Zr/Hf ratio for titanite, the presence of cumulate titanite could contribute to a high rock Zr/Hf ratio. The same is not the case for the Nb/Ta ratio. Green (1995) noted that in alkaline suites Nb/Ta ratios tended to fall into two groups: one characterized by consistent Nb/Ta ratios close to chondritic or mantle values and the other characterized by highly variable ratios that significantly exceed mantle values. The Beemerville nepheline syenites and phonolites belong to the latter group. Green and Pearson (1987) experimentally investigated the effect of titanite fractionation on the Nb/Ta ratio and concluded that fractionation of this mineral could increase the ratio by about 20%. Their experiments did not include silica-undersaturated liquids. Data obtained for glassy volcanic rocks (e.g., Weaver, 1990) suggest that titanite fractionation can lead to Nb/Ta ratios of 50 to 60. Given the titanite/liquid partition coefficients for Nb and Ta, fractionation of this mineral leads to a decrease in the absolute Ta abundance and an increase in the Nb/Ta ratio. For the Beemerville nepheline syenites and phonolites there is a crude inverse relationship between the absolute Ta abundance and the Nb/Ta ratio (plot not shown) and, thus, it is possible that some of the variation in Nb/Ta ratios can be explained by titatnite fractionation. However, the very high Nb/Ta ratios are not readily explained by this mechanism. Vard and Williams-Jones (1993) investigated inclusions in vug minerals found in phonolite sills. They concluded that the vug filling was the result of mineral precipitation from a primary orthomagmatic fluid and that this fluid was enriched in HFSE ions, particularly Zr, Hf, Nb, and Ti. Thus, it is possible that the high Nb/Ta ratios (and Zr/Hf ratios) may be due to late stage hydrothermal processes. This would be in agreement with the observed alteration in these rocks. Hence, the high Nb/Ta and Zr/Hf ratios may represent a combination of titanite fractionation (or accumulation) plus hydrothermal alteration.

The variety of REE patterns shown by the nepheline syenites and phonolites of the Beemerville complex have been observed in a number of other alkaline provinces, e.g., Monteregian Hills (Eby, 1984, 1985), Magnet Cove, Arkansas Alkaline Province (Flohr and Ross, 1990), and the North Nyasa Alkaline Province (Eby et al., 1998). Eby et al. (1998) discussed the possible origin of these patterns in some detail. This discussion will not be repeated here, other then to note that three possibilities were considered: titanite fractionation, zircon accumulation, and fluid transport. Fluid transport by F- and CO_3-rich solutions could modify primary linear REE patterns to HREE flattening and U-shaped patterns, and the authors concluded that this was the most likely process. It is, therefore, relevant to note the

occurrence of both fluorite and calcite in a number of the Beemerville nepheline syenites and phonolites, which provides mineralogical evidence for this process.

Given the degree of alteration of many of the samples, plus the variability of trace element distributions, it is difficult to draw any definitive conclusions about the petrogenetic history of the nepheline syenites and phonolites. However, based on textural evidence, we can conclude that nepheline, clinopyroxene, and titanite were the major fractionating phases. Both textural and phase equilibria arguments support the conclusion that the nepheline syenites are largely cumulates. We can also conclude that these rocks underwent significant alteration by late stage magmatic and F- and CO_3-rich hydrothermal fluids that significantly altered both the major and trace element chemistry. Whether or not the phonolites are the end result of fractionation of the magmas that gave rise to the lamprophyre dikes is still an open question, but mineralogical evidence suggests that there is a relationship between the lamprophyres and the magmatic phase of the diatremes.

ACKNOWLDGEMENTS

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