GEOLOGIC HISTORY AND PETROGENESIS OF ALKALINE VOLCANIC ROCKS, MT. MORNING, ANTARCTICA

A Thesis
Presented in Partial Fulfillment of the Requirements for the Degree Master of Science

by

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Approved by

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Rocks exposed at Gandalf Ridge on the northern slopes of Mt. Morning represent the earliest documented evidence of volcanism in the Erebus volcanic province and the McMurdo Volcanic Group. K/Ar dating of samples from Gandalf Ridge suggests a mid-Miocene age (15.4 m.y. to 18.73 m.y.).

The rocks range in composition from trachyandesite to quartz trachyte and pantellerite. Two different trends, one non-peralkaline and one peralkaline, are recognized. The non-peralkaline trend is represented by a trachyandesite-quartz trachyte sequence and the peralkaline trend by a trachyandesite-comenditic trachyte-comendite-pantellerite sequence. Major, trace, and rare earth element data are consistent with the trachyandesite being derived from an alkali basalt parent by fractional crystallization of olivine, clinopyroxene, feldspar, opaque oxides and apatite.

The volcanism at Mt. Morning is believed to have been associated with the fracturing caused by an extensional tectonic regime. This regime is consistent with the widespread alkaline volcanism and the known crustal thinning in the western Ross Sea. These rocks are part of the McMurdo Volcanic Group.
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Gandalf Ridge is located at 78°20'S, 164°08'E on the northern slopes of Mt. Morning, Antarctica. Approximately 13 km to the west lie the foothills and 30 km to the west the crest of the Transantarctic Mountains which have a maximum elevation of approximately 3800 m. Gandalf Ridge lies on the western side of the Erebus volcanic province (Kyle and Cole, 1974) which includes Mt. Morning to the southwest and Ross Island to the northeast (fig. 1.1).

Previous work at Gandalf Ridge consists of a brief reconnaissance by P.R. Kyle in 1972 during which he collected a trachyte dike sample that yielded a 15.4 m.y. date (Armstrong, in press). This date made Gandalf Ridge the oldest known outcrop of the McMurdo Group.

Regional Geology

The basement in the Transantarctic Mountains consists of late Precambrian and early Paleozoic rocks together with a few isolated areas of an older crystalline complex (Elliot, 1975). A largely undeformed late Paleozoic-early Mesozoic platform sequence (Beacon Supergroup) overlies this basement (Elliot, 1975).

The exposed crystalline complex is mainly a high-grade metamorphic terrain consisting of gneiss, schist, quartzite, and marble, which is intruded by plutonic rocks ranging from gabbro
Figure 1.1 Map of the McMurdo Sound area showing the location of Gandalf Ridge and Mt. Morning.
to granite (Elliot, 1975). Exposures of the older crystalline complex in the Transantarctic Mountains have been recognized in northern Victoria Land (Geir and others, 1969), the Miller Range (Grindley, 1963; Gunner, 1969), and the Shackleton Range (Clarkson, 1972; Stephenson, 1966). The Shackleton Range rocks have been assigned to the upper of two structural stages recognized by Ravich (1972) for the East Antarctic shield.

The upper structural stage consists of complex fold systems within which there are local outcrops of the lower stage. Metamorphism did not exceed the amphibolite grade. Migmatites and associated intrusions are common.

The basement of late Precambrian and early Paleozoic age consists predominantly of metagraywacke, phyllite, and argillite, with slate, sandstone, polymict conglomerate and limestone occurring locally. Nowhere in the Transantarctic Mountains is a stratigraphic or structural contact with the older Precambrian crystalline complex observed (Elliot, 1975).

The upper Precambrian and lower Paleozoic basement in the central Transantarctic Mountains was deformed primarily during two orogenies: the Beardmore Orogeny and the Ross Orogeny. The Beardmore Orogeny (Grindley and McDougall, 1969) is the earliest widely documented phase of activity and is primarily recognized in the Beardmore Glacier area. The orogeny is defined by late

Structural stages are time-structural units and represent assemblages of rocks whose ages are assigned by metamorphic, structural, and compositional features.
Precambrian metamorphism and igneous activity, and stratigraphically by Cambrian beds unconformably overlying the deformed graywacke-shale sequence (Elliot, 1975).

The Ross Orogeny (Gunn and Warren, 1969) is the earliest documented phase of deformation in south Victoria Land. The orogeny is defined by early Paleozoic metamorphism and igneous activity and is bounded stratigraphically by undeformed Devonian strata (Elliot, 1975). The degree of metamorphism and deformation in south Victoria Land is higher than has been recorded elsewhere. Metamorphism in the Dry Valley area is in the uppermost amphibolite facies. Some of the metasedimentary rocks of the Dry Valley area, such as the augen gneisses described by Smithson and others (1970 and 1972), were involved in the Ross Orogeny but possibly are older and were involved in the Beardmore Orogeny.

The relatively undeformed Beacon Supergroup comprising the Taylor and Victoria Groups (Barrett and others, 1972) constitutes most of the exposed platform cover of the East Antarctic metamorphosed and deformed basement. It ranges in age from Devonian or older to Jurassic. The Taylor Group, the older group, ranges in age from pre-Devonian (?) to Late Devonian. It is best developed in south Victoria Land where it consists of quartzose sandstone with conglomerate and feldspathic and lithic sandstone at the base, and red and green siltstone locally at the top (Elliot, 1975). The top of the sequence is regarded as Late Middle Devonian (Helby and McElroy, 1969; McElroy and others, 1972; Ritchie, 1969) based on the fish remains and plant
microfossils found in the variiegated siltstones.

The Victoria Group is the younger of the two groups and ranges in age from Permian to Jurassic. This group lies disconformably on the Taylor Group or with nonconformity or angular unconformity on Precambrian and Lower Paleozoic basement in the Transantarctic Mountains (Elliot, 1975). The group is thickest in the Beardmore area. Here it consists of glacial strata overlain by a black shale unit. A massive deltaic sandstone which grades up into a well-developed floodplain sequence with abundant carbonaceous material overlies the black shale (Elliot, 1975). Fossil plants and palynomorphs indicate a Permian age. In south Victoria Land, the glacial beds are overlain directly by carbonaceous beds of a floodplain environment. In the area between Scott Glacier and north Victoria Land, Triassic clastic sediments representing an alluvial plain environment crop out. The basal beds are Lower Triassic in age (Elliot and others, 1970; Kitching and others, 1972), based on vertebrate faunas recovered from the beds overlying the Permian carbonaceous beds, and are overlain by beds ranging up to Middle and Upper Triassic (Kyle, 1977) based on plant microfossils and limited radiometric dating.

The Beacon Supergroup is intruded by sills and dikes and is overlain by lava flows of quartz tholeiite composition. These igneous rocks constitute the Ferrar Group which, based on radiometric dating by Elliot and others (in press), is
Jurassic in age (175 ± 5 m.y.).

The McMurdo Volcanic Group (Harrington, 1958) comprises
the Late Cenozoic volcanic rocks of Victoria Land, islands in
the western Ross Sea, and the Balleny Islands. The group
consists primarily of undersaturated alkaline volcanic rocks
and is divided into four volcanic provinces (Kyle and Cole,
1974): the Balleny volcanic province in the Balleny Islands;
the Hallett and Melbourne volcanic provinces in northern
Victoria Land; and the Erebus volcanic province in the McMurdo
Sound area.

The Gandalf Ridge and Mt. Morning area belongs to the
Erebus volcanic province. This province consists of
stratovolcanoes and cinder cones, with Mt. Erebus and Mt.
Discovery forming the main volcanic centers. The composition
of the rocks in this province is predominantly alkali basalt
together with subordinate associated differentiates, hawaiite,
mugearite, trachyte, and phonolite.

Tectonics

Antarctica can be divided broadly into two tectonic
provinces, East Antarctica and West Antarctica. The East
Antarctic shield consists of old continental crust overlain by
undeformed sedimentary strata, whereas West Antarctica consists
largely of Phanerozoic orogenic belts. Cenozoic volcanic
provinces are located in diverse tectonic settings in both
East and West Antarctica (Elliot, 1975). Five orogenies
have been documented in various places in the Transantarctic Mountain margin of East Antarctica, and range from late Precambrian to Cenozoic. Four orogenies ranging from early Paleozoic to Cenozoic have been documented in West Antarctica (Elliot, 1975).

The structural relations between East and West Antarctica were a persistent topic in early literature (Davies, 1956; Fairbridge, 1952; Gould, 1935; Taylor, 1940; Wade, 1937) and today they still remain the major problem in Antarctic tectonics. Geologic contrasts between East and West Antarctica suggests that there is a major structural break parallel to the Transantarctic Mountains (Elliot, 1975). This is also supported by the geography of the Ross and Filchner Ice Shelves and a marked erosional scarp along the Transantarctic Mountains.

Concern here is primarily with the tectonics of the Transantarctic Mountains in south Victoria Land and specifically with the Victoria Orogeny (Gunn and Warren, 1962) and its relation to the McMurdo Volcanic Group. The Victoria Orogeny is Cenozoic in age and is recognized by uplift of the Transantarctic Mountains.

A noticeable amount of relief is present on the front of the Transantarctic Mountains facing the Ross Sea. Many geologists believe that this front represents a major fault or fault zone. This however can only be clearly demonstrated at the mouth of the Shackleton Glacier where Beacon Strata have been downthrown between 2 km to 5 km by a fault subparallel to the front of the mountains (Barrett, 1965). Farther north
xenoliths of quartzose sandstone comparable to rocks of the Beacon Supergroup exposed in the Transantarctic Mountains occur in volcanic rocks near Cape Royds on Ross Island (Thompson, 1916), suggesting that Beacon rocks may have also been downfaulted adjacent to Ross Island (Kyle and Cole, 1974). On Leg 28 of JOIDES, marbles similar to those cropping out in the Transantarctic Mountains were cored in the Ross Sea (Hayes and others, 1973), again suggesting a major fault along the Transantarctic Mountains (Kyle and Cole, 1974).

Smithson (1972) and Woollard (1962) believe that the front of the Transantarctic Mountains represents an area of crustal thinning from 40 km to 27 km. Woollard (1962) arrived at this conclusion after considering seismic and gravity data which could not be explained by faulting alone. Smithson (1972) arrived at the same conclusion after considering gravity data. Faulting in this area may be associated with the crustal thinning. Smithson (1972) explains the crustal thinning by plate collision and subduction along the front of the Transantarctic Mountains in Late Precambrian times. Kyle and Cole (1974) disagree with this interpretation and believe that the Ross Sea more likely represents an area of crustal extension possibly due to rifting.

Kyle and Cole (1974) suggest that the pronounced topographic break on the east side of the Transantarctic Mountains may be the surface expression of the postulated McMurdo Fracture, a major structural break which may have formed during the initial separation of Australia and
Antarctica. Kyle and Cole (1974) also postulate crustal extension in the Transantarctic Mountains of northern Victoria Land where the Rennick Fault crosses the mountains diagonally and forms the western boundary of the Rennick Graben.

It was previously suggested (Harrington, 1965; McIver and Gevers, 1970; Gunn, 1963) that the McMurdo Volcanic Group volcanoes could be related to one major structural trend. Reconnaissance mapping (Warren, 1969; Gair and others, 1969) and aeromagnetic surveys (McGinnes and Montgomery, 1972) showed the volcanic rocks to be discontinuous and therefore Kyle and Cole (1974) proposed four volcanic provinces related to several structural trends of more local significance.

Kyle and Cole (1974) discuss the relation of the volcanoes to the volcanic provinces of the McMurdo Volcanic Group. They believe the volcanoes are mostly situated along fracture zones or faults that are roughly parallel to the front of the Transantarctic Mountains. The Balleny Fracture Zone, which is an oceanic fracture that probably is a transform fault offsetting the Indian-Antarctic mid-ocean ridge (Griffiths and Varne, 1972; Falconer, 1972) (see fig. 1.2) is the exception. In most cases however, the relationship of the volcanoes to the faults and fracture zones is inferred and not based on observed field relations.

Field Work

Field work was conducted as part of the Morning-Erebus
Figure 1.2 Simplified geological map of Victoria Land and the Balleny Islands, to show the relationship of volcanism to structure (after Kyle and Cole, 1974).
Volcanic Project 1977/78 of the Institute of Polar Studies, Ohio State University. The field party consisted of a two man team, Dr. Philip R. Kyle and H. Lee Muncy, who mapped and sampled for radiometric dating, petrographic analyses, and geochemical analyses.

The objectives of this study were to establish the geologic history and petrogenesis of the alkaline volcanic rocks of Gandalf Ridge and the possible relations of the McMurdo Volcanic Group to the uplift of the Transantarctic Mountains.

Field and laboratory work was supported by National Science Foundation grant DPP76-23440.
II. FIELD GEOLOGY

In the areas examined at Gandafj Ridge, glacial debris obscures much of the bedrock. Maps with scales less than 1:250,000 and contour intervals less than 200 m are not available. Mapping therefore was accomplished by preparing a geologic sketch map from vertical and oblique aerial photographs with detailed information coming from plane table maps prepared on site during the field season (fig. 2.1).

A brief reconnaissance was made to the area adjacent to Lake Morning where samples were collected for radiometric dating, geochemical analyses, and petrographic studies.

Basement Rocks

Basement rocks exposed on Gandafj Ridge consist of granitic intrusive rocks enclosing sheets or screens of metasedimentary schists. Both rock types belong to the Skelton Group. These rocks are exposed only in a small valley located transversely across the southern end of Gandafj Ridge and along the eastern flank of the ridge at low elevations where not covered by glacial debris.

The granite is a grayish white, medium-grained rock consisting predominantly of quartz, orthoclase, and biotite and is similar to intrusions around the head of the Koettlitz Glacier which have been termed the Crag Granite by D.N.B. Skinner (personal communication). The schist is a dark greenish
Figure 2.1 Simplified geologic sketch map of Gandalf Ridge, Mt. Morning, Antarctica. Numbers correspond to collection sites for K/Ar dated samples as follows: (1) 77M4; (2) 77M41; (3) 77M45; (4) 77M62.
gray, fine-grained rock which probably belongs to one of two formations, either the Cocks Formation (Skinner, 1978), or the Anthill Limestone (Gunn and Warren, 1962), both of which are part of the Skelton Group.

Trachyandesite and Dike Complex

A highly sheared and jointed trachyandesite unconformably overlies the basement and forms the majority of the exposed rock at Gandalf Ridge. The trachyandesite appears to be a massive sheet-like pile of flows which is extremely broken up and altered. The pile is approximately 100 m thick and dips gently northward. Lavas show relict flow banding and contain vugs commonly filled with zeolite. The mode of eruption of the trachyandesite is uncertain. P.R. Kyle previously postulated subaqueous eruption of what he called a pillow-palagonite breccia. The author believes the lavas were erupted subaerially because neither pillow structures nor evidence suggesting subaqueous eruption was observed at Gandalf Ridge.

Quartz trachyte and oversaturated peralkaline dikes intrude the trachyandesite and are the cause of its highly sheared nature. These dikes are best exposed at the northern end of the ridge where they generally trend east-west. The dikes are steeply dipping, vary in width from 0.2 m to 10 m, and are irregularly spaced apart. Most of the dikes are porphyritic with large phenocrysts of feldspar, but some finer grained types also occur.
It is probable that the dikes are part of a high-level subvolcanic complex in which the dikes were feeders for a now-eroded peralkaline trachyte volcano (Kyle and Muncy, 1978).

Breccia

A breccia or diamictite disconformably overlies the trachyandesite and dike complex. This rock unit is best exposed near the center of Gandalf Ridge close to its highest point. It forms a horizontal or near-horizontal tabular unit with a minimum thickness of 20 m, and caps part of Gandalf Ridge. The clasts are highly angular to sub-rounded, occasionally exceed 5 m in size, and all are volcanic, mainly peralkaline trachyte or porphyritic trachyandesite. The matrix is exceedingly altered and weathered.

The breccia is believed to be a sedimentary breccia deposited by mudflows transporting clasts of various sizes. The distance the constituents were transported is uncertain.

Younger McMurdo Volcanic Group

Younger trachyte and olivine-clinopyroxene basanite unconformably overlie the trachyandesite at the southern end of Gandalf Ridge. The contact is exposed in a small valley at the southernmost end of Gandalf Ridge near where the contact between the trachyandesite and basement is exposed. If the breccia is present on the southern side of the valley it has been completely covered by trachyte and basanite flows from
scoriaceous cones which form the majority of the surface not covered by ice or snow on the lower northern flanks of Mt. Morning. A trachyte sample collected by Kyle in 1972 near the summit of Mt. Morning yielded a 1.15 ± 0.02 m.y. date (Armstrong, in press). Thus the cones are likely to be younger than 1.15 ± 0.02 m.y. old.

Faulting

At Gandalf Ridge north-south trending faults are roughly parallel to the length of the ridge and cut basement rocks and the trachyandesite and dike complex. The amount of displacement and relative movement along the faults could not be determined due to lack of correlation between dikes across the fault planes; limited rock exposure due to ice cover; and the extremely broken up and altered nature of the trachyandesite and dike complex. The faulting may be local, associated with Mt. Morning volcanism, or of regional significance being associated with the uplift of the nearby Transantarctic Mountains.

The Gandalf Ridge faults are roughly parallel to the front of the nearby Transantarctic Mountains as are faults that are similar in trend mapped by D.N.B. Skinner (personal communication) along the foothills of the Royal Society Range. Together these faults may comprise part of a wide fault zone adjacent to the Transantarctic Mountains.

K/Ar dates on rocks cut by the Gandalf Ridge faults along with the fact that the faults do not cut the breccia
capping Gandalf Ridge or the younger trachyte or basanite suggest a Neogene age for the faults. This is believed to be the first documented evidence of Neogene faulting in the Ross Sea area.

These faults and their relation to the faults mapped by Skinner suggest, but do not prove, association with the uplift of the Transantarctic Mountains.

Hydrothermal Zones

Zones of intense hydrothermal alteration and silicification occur throughout Gandalf Ridge. These zones are commonly associated with the north-south trending faults which apparently provided paths for the migration of the hydrothermal fluids. Some of the hydrothermal zones extend for almost the whole length of the ridge. The hydrothermal zones vary in width from a few cm to an area approximately 125 m wide and 200 m long located at the approximate center of Gandalf Ridge.

Silicification of the rocks is the most common hydrothermal alteration at Gandalf Ridge.

Lake Morning Area

The Lake Morning area is characterized predominantly by highly dissected, reddish-black basaltic cones. Basalt is estimated to comprise more than 95% of the exposed rock in the Lake Morning vicinity. Older quartz trachyte and peralkaline silicic flows and dikes are exposed near the southwestern
hores of Lake Morning. These flows and dikes are very similar in appearance to the dikes at Gandalf Ridge. Two breccia pipes, which are approximately 100 m in diameter and rise about 150 m above the surface, are located just south and adjacent to the quartz trachyte and oversaturated peralkaline flows. The pipes contain volcanic clasts of various composition, the most common being trachyte. The size of the clasts varies from less than 1 mm to 2 m. The clasts have shapes which vary from angular to rounded.

Based on field relations, the breccia pipes are the oldest rocks exposed in the Lake Morning area.
III. RADIOMETRIC DATING

The purpose of the K/Ar dating of rocks from the Mt. Morning area was to:

1. establish the ages of the various lithologic units,
2. determine the time interval of igneous activity in this area,
3. confirm a previous date of 15.4 \( \pm \) 0.5 m.y. for a sample collected from this area, and
4. establish the amount of uplift in this area during the last 15 m.y.

Armstrong (in press) analyzed a sample collected by P.H. Kyle in 1972 and obtained a 15.4 \( \pm \) 0.5 m.y. date. The dated sample came from a dike which intruded what Kyle interpreted to be a pillow-palagonite breccia. If this interpretation was correct, the amount of uplift would be a minimum of 500 \( \pm \) m, which is the approximate present elevation of this area. However, the rocks in this area are subaerial and no specific amount of uplift can be implied.

K/Ar analyses on six different samples were done in the K/Ar laboratory of the Ohio State University under the direction of Dr. John Sutter. Potassium concentrations were determined by chemical separation of alkalis (Cooper, 1963) and single-channel flame-photometry using a Zeiss PF-5 flame photometer. All samples prepared for potassium were whole rocks crushed to -100 mesh and run in duplicate. The estimated precision of replicate analysis based on the last 100 analyses in the K/Ar laboratory is approximately 0.5 percent. Argon was
liberated from the samples in an extraction system using techniques described by Dalrymple and Lanphere (1969). Isotopic analyses of the argon were made with a nuclide mass spectrometer with 6-in. radius and 60° sector operated in the static mode. Radiogenic 40Ar concentrations were measured by isotope dilution using manifold-type (batch) 38Ar tracers.

Location of Samples

Of the six samples collected for K/Ar dating, four were collected from Gandalf Ridge (see fig. 2.1) and two were collected approximately 5 km west of Gandalf Ridge near Lake Morning. The Lake Morning area has never been mapped at a scale less than 1:250,000 and therefore a description of the collection site is presented here. Sample 77MB1 was collected from a quartz trachyte flow, and sample 77MB4 was collected from an oversaturated peralkaline dike which cuts the flows and breccia pipes present in the area. Both samples were collected just north and adjacent to the northernmost of two breccia pipes located on the SW side of Lake Morning. These pipes are resistant spines, approximately 100 m in diameter, rising 150 m above the surface. Their ochre color renders them very distinctive against the reddish-black basaltic rubble.

Data Interpretation

To interpret the data, it is necessary to determine if there is any real difference in the ages of the rocks. This is
Table 3.1. K/Ar Radiometric Ages for Rocks from Mt. Morning, Antarctica

<table>
<thead>
<tr>
<th>Sample</th>
<th>Locality and Description</th>
<th>%K</th>
<th>Moles rad. Ar/g x 10^-10</th>
<th>%Rad. 40Ar</th>
<th>Age bcd x 10^6 yr.</th>
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<td>4.49</td>
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<td>36.9</td>
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<td>Trachyandesite at Gandalf Ridge</td>
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<td>Peralkaline dike cutting trachyandesite at Gandalf Ridge</td>
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<td>1.229 1.227</td>
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<td>Quartz trachyte flow at Lake Morning</td>
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<tr>
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<td>Trachyte dike cutting trachyandesite at Gandalf Ridge</td>
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<td>1.178 1.162</td>
<td>24.0</td>
<td>15.40 ± 0.50</td>
</tr>
</tbody>
</table>
Table 3.1. K/Ar Radiometric Ages for Rocks from Mt. Morning, Antarctica (continued).

a. Whole rock analyses.

b. Constants used: $i_A = 1.804 \times 10^9$ yr.,

$$\frac{\lambda_A}{\lambda_P} = 0.1171,$$

$$40^\text{K} / \text{K total} = 1.167 \times 10^{-4} \text{ atom/atom}.$$

c. Indicates average age for sample.

d. Error estimate reflects analytical precision only; calculated in a manner similar to that described by Cox and Dalrymple (1967).

e. Sample dated by Armstrong (in press).

done by using the Critical Value test (Dalrymple and Lanphere, 1969). To claim a real difference in age, at 95-percent confidence, between two rocks, the apparent age difference must exceed the Critical Value; C.V. = $1.960 (\sigma_1^2/n_1 + \sigma_2^2/n_2)^{1/2}$, where $\sigma_1$ and $\sigma_2$ are the standard deviations of the ages and $n_1$ and $n_2$ are the number of measurements made on each rock. If the apparent age difference exceeds the Critical Value, it can be stated with 95-percent confidence that a real difference exists.

Before interpreting the dates reported in Table 3.1, a recalculation of the $15.4 \pm 0.5$ m.y. date is necessary. Armstrong (in press) used pre-1977 constants in calculating the above date. Recalculation using post-1977 constants increase the age of the trachyte dike he analyzed to $15.5 \pm 0.5$ m.y.

Application of the Critical Value test on the Gandalf Ridge samples suggests, but does not prove, that there is a
real age difference between the ages of the trachyandesite flows and the trachyte dikes. The date obtained for the trachyandesite sample suggests a minimum age of $18.73 \pm 0.32$ m.y. for the initiation of igneous activity in the Gandalf Ridge area. Field relations show that the dikes are younger. K/Ar dating yielded a maximum age of $17.56 \pm 0.56$ m.y. for intrusion, which continued until a minimum of $15.5 \pm 0.5$ m.y. ago. However when the Critical Value test is applied to the dates obtained by the author for the dikes and the date obtained by Armstrong, a real age difference is suggested between Armstrong's date and the author's dates. The unknown location of Armstrong's sample at Gandalf Ridge leads to uncertainty in interpretation of the data, and furthermore if more samples were dated, the apparent age difference might vanish.

The difference in ages between the Gandalf Ridge samples and the Lake Morning samples suggest that the volcanic rocks near Lake Morning are the result of a younger event than the volcanism at Gandalf Ridge. Unfortunately there are too few dates to say with confidence what the true time span of volcanism is.

The date reported by Armstrong (in press) for the dike at Gandalf Ridge extended the age of the Erebus volcanic province to $15.4 \pm 0.5$ m.y.. The dates reported in table 3.1 confirm that Gandalf Ridge is the oldest known outcrop of the Erebus volcanic province. The $18.73 \pm 0.32$ m.y. date gives a middle
Miocene age for the rocks at Gandalf Ridge, is the oldest age reported so far for the McMurdo Volcanic Group, and establishes a new minimum age for inception of volcanism.
IV. PETROGRAPHY

Petrographic analysis of the volcanic rocks of Gandalf Ridge and the Lake Morning area was conducted to ascertain their mineralogy as a prerequisite to the chemistry. Forty thin-sections of the volcanic rocks of Gandalf Ridge and six thin-sections of the rocks from the Lake Morning area were examined. Detailed petrography was completed on most samples. The results of the detailed examinations have been used to compile a general description of each rock type.

The mineralogy was determined by optical technique, together with x-ray diffraction data on certain phases. Anorthite content of the plagioclase was routinely estimated by the Michel-Levy technique. All rocks were named according to the chemical classification scheme of Coombs and Wilkinson (1969); (see chap. 5, nomenclature section).

Trachyandesites

Trachyandesite flows that form the majority of the exposed rock at Gandalf Ridge are medium gray, very fine-grained rocks that have felted to trachytic textures. The trachyandesites are comprised of plagioclase, augite, opaques, and apatite, with chlorite, calcite, and hematite occurring as secondary minerals.

Plagioclase forms subhedral laths and anhedral equant grains less than 0.1 mm in size. The laths have an average
composition of An$_{41}$ whereas the equant grains have an andesine core and are zoned to an oligoclase perimeter. Twinning in the form of Carlsbad and albite is present in the andesine laths. Most of the plagioclase appears relatively fresh and unaltered. Together the laths and equant grains make up about 50% of the trachyandesites. Augite grains are pale green to light brown in color. They commonly occur as interstitial grains that are less than 0.1 mm in size. Augite accounts for 10% to 15% of the rock. Black opaques less than 0.1 mm in size make up 10% of the rock. Minor amounts of prismatic apatite occur throughout the trachyandesites.

Green scaly grains of chlorite replace augite in some places. Grains are less than 0.1 mm in size and encompass 10% to 15% of the rock. Calcite occurs in minor amounts as veins. Hematite occurs throughout as an alteration product of the opaques.

Trachytes

The term trachyte is used here to refer to rocks of similar petrographic character but in fact distinguishable by differences in their chemical compositions. Trachyte, as used here, refers to quartz trachyte, comenditic trachyte, comendite, and pantellerite.

Trachyte dikes that intrude the trachyandesite flows are beige to light gray, fine-grained rocks that have porphyritic
intergranular textures. In these rocks sanidine phenocrysts are set in a matrix of anorthoclase, aegirine-augite, soda-amphibole, quartz, and opaques. Calcite occurs as a secondary mineral.

The sanidine forms euhedral phenocrysts ranging in size from 1 mm to 3 mm with an average size of 1.5 mm. Sanidine accounts for 5% to 10% of the composition of the trachytes. The phenocrysts commonly show Carlsbad twinning. The outer rims of some grains are zoned to more sodic composition. Exsolution of perthite occurs throughout the phenocrysts with the perthite being most noticeable in the interior of the grains. Alteration to a clay mineral is distinct in some grains.

Anorthoclase is the dominant phase and constitutes the bulk of the groundmass (approximately 50%) in the trachytes. It is distinguished from other feldspars by x-ray diffraction patterns and optically by a 2V of 30° to 45°. Anorthoclase forms subhedral laths that are less than 0.25 mm in length. Alteration to a clay is present. Aegirine-augite occurs as pale yellow, anhedral to subhedral grains less than 0.25 mm in size. It comprises approximately 10% of the trachytes. The grains occur interstitially to the feldspar laths. Anhedral grains of soda-amphibole that are less than 0.25 mm in size make up 10% of the rock. The grains are pleochroic from medium to dark green. The birefringence of the soda-amphibole is commonly masked by the color of the mineral. Both the aegirine-augite and soda-amphibole show slight alteration to limonite. Anhedral
interstitial quartz accounts for 5% to 10% of the composition of the trachyte. Three percent of the rock is made up by black opaques. Some rocks contain minor amounts of reddish-brown aenigmatite, suggesting that these rocks are peralkaline. Absence of aenigmatite in a rock however, does not indicate that the rock is not peralkaline. Aenigmatite occurs as anhedral to subhedral interstitial grains with high refractive indices. The grain size averages less than 0.1 mm.

Calcite and quartz occur in minor amounts as secondary material in amygdales and veins. Hematite is commonly found as an alteration product of the opaques.

Breccia Clasts

The breccia capping the central part of Gandalf Ridge is made up of two types of clasts: trachyte and trachyandesite. Trachyte clasts are beige to light gray, fine-grained rocks that have felted textures. Phenocrysts of sanidine and microphenocrysts of aegirine-augite lie in a matrix of alkali feldspar and aegirine-augite. Patches exist that are predominantly alkali feldspar and are devoid of ferromagnesium minerals.

Euhedral sanidine phenocrysts range up to 1 mm in size. Some grains show Carlsbad twinning and some are zoned to a more sodic composition along the edges. Alteration to a clay mineral is visible in some grains. Approximately 5% to 10% of the composition of the trachyte clasts is made up of sanidine.
phenocrysts. Aegirine-augite microphenocrysts are pale green, slightly pleochroic, subhedral grains that range up to 0.25 mm in size. They comprise about 5% of the trachyte clasts.

Over 50% of the rock is alkali feldspar that forms laths in the matrix. These laths are less than 0.1 mm in length. Carlsbad twinning is present in some grains. Considerable alteration of the laths to a clay mineral has occurred. Aegirine-augite in the matrix accounts for 15% to 20% of the composition. It occurs as interstitial grains less than 0.1 mm in size. The grains are pale green in color and slightly pleochroic. Some trachyte clasts contain up to 20% aenigmatite. The aenigmatite occurs interstitially as anhedral to subhedral, high refractive index grains that are strongly pleochroic from yellowish-red to reddish-brown. Grain size averages less than 0.1 mm for the aenigmatite.

Trachyandesite clasts are medium gray, porphyritic rocks that have very fine-grained matrices displaying trachytic textures. Plagioclase phenocrysts are set in plagioclase, augite, quartz, and opaques. Calcite commonly occurs as a secondary mineral.

About 5% of the trachyandesite composition is made up of plagioclase phenocrysts. The phenocrysts are euhedral to subhedral grains ranging from 0.5 mm to 3 mm in size. The average composition of the phenocrysts is An₅₇. However, most of the grains are zoned to an andesine composition. Some grains show albite, Carlsbad, or pericline twinning. Some of
the phenocrysts are resorbed. Alteration to clay or replacement by calcite is distinct in some grains.

The plagioclase in the groundmass forms subhedral laths that are less than 0.1 mm in size. It constitutes the bulk (approximately 50%) of the composition of the rock. The laths have an average composition of An₃₀. Some laths show albite and Carlsbad twinning. Alteration of the plagioclase to clay is distinct. Augite occurs as clear, anhedral to subhedral grains which make up about 15% to 20% of the rock. The average grain size for the augite grains is less than 0.1 mm. Fifteen to twenty percent of the rock is made up by black opaques that are less than 0.1 mm in size. Some of the opaques show alteration to hematite.

Minor amounts of quartz occurs interstitially. Calcite occurs as fillings in vugs and veins.

Basanite

Younger basanites cropping out at the southern edge of Gandalf Ridge are dark gray, fine-grained rocks that have porphyritic felted textures. Phenocrysts of olivine and augite are set in matrices consisting of plagioclase, augite, olivine, and opaques.

Approximately 10% of the basanite is made up by olivine phenocrysts. These phenocrysts commonly occur as fractured grains that range up to 1 mm in size. Five percent of the rock is augite that forms brownish, subhedral phenocrysts ranging up
to 1 mm in size. Some of the augite phenocrysts are resorbed and some have clear cores with purplish titaniferous rims. Zoning is present in some grains.

Plagioclase in the matrix occurs as subhedral laths that are less than 0.1 mm in length. These laths have an average composition of An₅₅. Most laths show albite twinning and a few show Carlsbad twinning. The majority of the grains appear relatively fresh and unaltered. Plagioclase accounts for approximately 30% of the composition of the basanites. Another 30% of the rock is made up by augite. It occurs interstitially as purplish-brown, anhedral to subhedral grains that are less than 0.1 mm in size. Clear, anhedral olivine grains that are less than 0.1 mm in size comprise 10% of the rock. Black opaque grains, less than 0.1 mm in size, make up 15% of the composition of the basanites.
V. GEOCHEMISTRY

Major and trace element analyses of samples from Gandalf Ridge and the Lake Morning area were made to:

1. characterize the bulk chemistry and classify the volcanic rocks,

2. compare Gandalf Ridge and Lake Morning rocks with other McMurdo Volcanic Group rocks, and

3. investigate the petrogenesis of the various rock types.

Analyses for most major elements and some trace elements were made by P.R. Kyle at Victoria University of Wellington using X-ray fluorescence. An assessment of accuracy and analytical precision is discussed in Appendix B. Determinations for rare earth elements (La, Sm, Yb, Lu, Sc), Na₂O, and MnO were made at the Nuclear Reactor Laboratory, Ohio State University using an instrumental neutron activation analysis method similar to that described by Laul (1977). Details are given in Appendix B along with details of the analytical precision. FeO determinations were made using wet chemical analysis identical to the method described by Shapiro (1975).

Forty-two specimens of volcanic rocks from Gandalf Ridge and the Lake Morning area were analyzed (Table 5.1). Specimens chosen represent trachyandesite flows, trachyte dikes and flows, and breccia clasts. Two specimens represent younger basanites which are part of a much later phase of volcanism; although considered in this chapter on geochemistry, they are not considered in the discussion of petrogenesis.
## Table 3.1 Chemical analyses of melon seed from different locations

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**Note:** All values are given as percentages.
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<th>K (ppm)</th>
<th>Na (ppm)</th>
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**Column 1**: Chemical analyses of minerals from the Nebo, Uinta, and Sanpetu mountains.

**Column 2**: F (ppm)

**Column 3**: Mg (ppm)

**Column 4**: Ca (ppm)

**Column 5**: K (ppm)

**Column 6**: Na (ppm)

**Column 7**: P (ppm)

**Column 8**: Fe (ppm)

**Column 9**: Si (ppm)

**Note**: The values are given in parts per million (ppm).

**Unit**: ppm

**Sample Location**: Nebo, Uinta, and Sanpetu mountains

**Method**: ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectroscopy)
Nomenclature

Classification using modal compositions (e.g., Streckeisen, 1978) is difficult because of the fine-grain size of the volcanic rocks. Therefore it is more reliable to use chemical composition. The classification scheme used in this thesis follows Coombs and Wilkinson (1969). The rocks are classified by major element analyses, differentiation indices (Thornton and Tuttle, 1960), and CIPW normative mineralogy. Oversaturated peralkaline rocks are not distinguished from trachytes in the above scheme, therefore the trachytes have been further subdivided according to the scheme used by Macdonald and Bailey, (1973) based on normative quartz content and the sum of felsic minerals.

Alkali volcanic rock series are divided primarily into sodic and potassic series (Coombs and Wilkinson, 1969; Irvine and Baragar, 1971). The distinction between the two series can be made on normative orthoclase content (Price, 1973; Irvine and Baragar, 1971) or by using the Na$_2$O/K$_2$O ratio (Macdonald and Katsura, 1964; Macdonald, 1960). The division based on the Na$_2$O/K$_2$O ratio is used in this study. When the bulk of the rocks from any one region have Na$_2$O/K$_2$O ratios of less than 2, then all the rocks are referred to the potassic series, even if some individual rocks have ratios greater than 2.

The bulk of the rocks from Gandalf Ridge and the Lake Morning area have Na$_2$O/K$_2$O ratios less than 2, and therefore fall into the potassic series (fig. 5.1). The potassic series can be divided into basalt (with normative labradorite),
Symbols used in figures 5.1 to 6.1

- basanite
- trachyandesite
- trachyandesite breccia clast
- quartz trachyte
- quartz trachyte breccia clast
- Lake Morning quartz trachyte
- comenditic trachyte
- Lake Morning comenditic trachyte
- comendite
- comendite breccia clast
- Lake Morning comendite
- pantellerite

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non-peralkaline trend
peralkaline trend
Figure 5.1 Plot showing division for potassic and sodic rock series.
basanite (with normative labradorite and nepheline),
trachyandesite (with normative andesine or oligoclase and
differentiation index less than 65), tristanite (with
differentiation index between 65 and 75), and trachyite (with
differentiation index greater than 75). The term quartz is
used as a modifier for rock types containing normative quartz.
Figure 5.2 shows the potassic series nomenclature applied to
the rocks from Mt. Morning.

Aquatic indices [mol/mol \( \text{Na}_2\text{O} + \text{K}_2\text{O}/\text{Al}_2\text{O}_3 \)] greater
than 1, the presence of normative aegirine, and modal contents of
soda-pyroxene, soda-amphibole, and aenigmatite \( \text{Na}_2\text{Fe}_5\text{TiSi}_6\text{O}_{20} \)
indicate that some of the high silica rocks are peralkaline,
therefore requiring further classification. MacDonald and
Bailey (1973) divide silicic peralkaline rocks into four
groups; comenditic trachyte, pantelleritic trachyte, comendite,
and pantellerite. The boundary separating comenditic and
pantelleritic trachytes from comendites and pantellerites
is taken at 10% normative quartz content. The line separating
comendite from pantellerite rocks is also arbitrary, with
pantellerite rocks being more mafic. The boundaries suggested
by MacDonald and Bailey (1973) are used here. The nomenclature
applied to the oversaturated peralkaline rocks from Mt. Morning
is illustrated in fig. 5.3. Even though the above nomenclature
is used, it should be noted that the Mt. Morning rocks straddle
the suggested boundaries and do not fall naturally into distinct
groups.
Figure 5.2 Classification scheme, based on normative mineralogy, for potassic series, alkaline volcanic rocks (after Coombs and Wilkinson, 1969). The term 'basanite' is used to refer to rocks containing normative nepheline, even though one basanite falls into the trachyandesite field. Peralkaline rocks (e.g., comenditic trachyte, comendite, and pantellerite) contain no normative anorthite, therefore they plot on the extreme right of the diagram. The peralkaline rocks have been further classified in figure 5.3.
Figure 5.3 Classificatory scheme for peralkaline, quartz normative rocks from Gandalf Ridge (after Macdonald and Bailey, 1973).
Major Element Chemistry

Variations of the major elements are depicted on plots of weight per cent oxide against anoplastic index \( \left( \frac{\text{Na}_2\text{O}+\text{K}_2\text{O}}{\text{Al}_2\text{O}_3} \right) \) (fig. 5.5). The choice of the weight per cent oxide/anoplastic index diagrams was influenced by the fact that two different trends (one for peralkaline rocks and one for non-peralkaline rocks) are recognized when the anoplastic index is plotted against the differentiation index (fig. 5.4). In the non-peralkaline trend the anoplastic index shows a positive correlation with the differentiation index, but for the peralkaline rocks the trend is just the opposite showing a negative correlation. The presence of two different trends of opposite character causes ambiguity in variation diagrams involving \( \text{SiO}_2 \) and differentiation index. In such diagrams only one trend is recognizable. When some major element oxides and trace element concentrations (e.g., \( \text{Al}_2\text{O}_3 \), \( \text{Na}_2\text{O} \), Th, Zn, and Zr) are plotted against the anoplastic index two different trends (one peralkaline and one non-peralkaline) are recognizable.

Silicon

\( \text{SiO}_2 \) ranges from about 42% in the basanites to about 70% in one of the quartz normative, trachytic breccia clasts.

Basanites contain up to 47% \( \text{SiO}_2 \), trachyandesites range from 45% to 52% \( \text{SiO}_2 \), quartz trachytes from about 62% to 70%, comendites from 62% to 67%, and pantellerites contain between 62% and 68% \( \text{SiO}_2 \).
Figure 5.4 Plot of aspatic index [(molecular (Na$_2$O+K$_2$O)/Al$_2$O$_3$)] against differentiation index for Mt. Morning rocks.
Figure 5.5 Plot of major element oxides against appaitic index.
Figure 5.5 (continued).
Titanium

$\text{TiO}_2$ tends to decrease in abundance as the appaite index increases (fig. 5.5) The younger basanites have the highest $\text{TiO}_2$ contents, ranging from 3.3% to 3.6%. Trachyandesites range from 2.4% to 2.9% $\text{TiO}_2$. The quartz trachytes, comenditic trachytes, comendites, and pantellerites all contain small concentrations of $\text{TiO}_2$ (from about 0.4% to 0.8%) relative to the trachyandesites and basanites.

The principal titanium-bearing phases identified in the Mt. Morning rocks are clinopyroxene and opaque oxides. In the peralkaline rocks aenigmatite ($\text{Na}_2\text{Fe}_5\text{TiSi}_6\text{O}_{20}$) is an additional titanium-bearing phase. The depletion of $\text{TiO}_2$ with increasing appaite index is probably due to the removal of the opaque oxides.

Alumina

The plot of $\text{Al}_2\text{O}_3$ against the appaite index (fig. 5.5) shows two separate negatively correlated trends. The smallest concentrations of $\text{Al}_2\text{O}_3$ occur in the quartz trachytes, which are the most evolved rocks of the non-peralkaline trend found at Mt. Morning. Pantellerites have the lowest abundances of $\text{Al}_2\text{O}_3$ in the peralkaline trend.

The quartz trachyte samples from Lake Morning (represented by "o" in the diagrams) have relatively high values for $\text{Al}_2\text{O}_3$, and appear to be a distinct group from the Gandalf Ridge samples. Concentrations range from 15.88% to 16.57% $\text{Al}_2\text{O}_3$ for the Lake Morning quartz trachytes.
$\text{Al}_2\text{O}_3$ concentrations range from 14.35% to 17.84% in the basanites, 14.35% to 17.97% in the trachyandesites, 10.11% to 12.97% in the quartz trachytes, 13.16% to 14.28% in the quartz trachyte breccia clasts, 12.86% to 15.43% in the comendites and comenditic trachytes, and from 11.65% to 12.50% in the pantellerites.

The feldspars are the important aluminum-bearing minerals in the Mt. Morning rocks.

Iron

Total iron, expressed as FeO shows a general decrease from the basanites and trachyandesites to the quartz trachytes and peralkaline rocks (fig. 5.5). The trend produced by the rocks other than basanites and the trachyandesites is somewhat scattered. Some of the pantellerites show a high concentration of FeO suggesting the presence of an increasing trend in the peralkaline rocks. One pantellerite however, has a significantly lower FeO concentration than the other pantellerites suggesting a somewhat decreasing trend. Total iron values for the basanites and trachyandesites are between 10.11% and 12.83% whereas the values for the Gandalf Ridge quartz trachytes and peralkaline rocks range from 3.79% to 9.47%. The Lake Morning quartz trachytes all have low values for iron (between 2.84% and 3.71%) forming a distinct group that is noticeably lower in total iron than all the other Mt. Morning rocks.
The trachyandesites have Fe$_2$O$_3$/FeO ratios between about 0.9% and 1.7%. The Fe$_2$O$_3$/FeO ratio increases in the more evolved rocks to values greater than 100.

Important iron-bearing minerals present in the trachyandesites are clinopyroxene and opaque oxides. Olivine is an additional iron-bearing phase present in the basanites. Among the quartz trachytes, comenditic trachytes, comendites, and pantellerites, aegirine-augite, aenigmatite and hematite are the common iron-bearing minerals present.

Manganese

Examination of the MnO versus apatite index diagram (fig. 5.5) shows that the MnO abundance is approximately constant. The basanites and trachyandesites contain between 0.17% and 0.25% MnO. All the other rocks show significant scatter, with MnO values ranging from 0.06% to 0.36%. The Lake Morning quartz trachytes contain between 0.04% and 0.09% MnO and once again form a distinct group separable from the Gandalff Ridge rocks.

Manganese is probably a minor component of all the mafic minerals present in the Mt. Morning rocks, among which are clinopyroxenes that are found in all the rocks from Mt. Morning plus magnetite in the basanites and trachyandesites and amphiboles in the quartz trachytes and peralkaline rocks. Olivine in the basanites and aenigmatite in the peralkaline rocks, may also contain minor manganese.
Magnesium

MgO decreases as the appaitic index increases. The MgO abundances in the basanites are scattered with contents ranging from 3.8% to 9.0%. The trachyandesites contain between 1.9% and 3.2% MgO. The quartz trachytes and peralkaline rocks are all relatively depleted in MgO containing less than 1% MgO, with the majority of the rocks containing less than 0.5%.

Olivine and clinopyroxene are the dominant MgO-bearing phases so that trends of depletion in MgO may be attributed to crystal fractionation processes involving these minerals.

Calcium

In figure 5.5, CaO shows a strong negative correlation with the appaitic index. CaO ranges from 9.14% to 11.18% in the basanites. The trachyandesites have lower CaO contents than the basanites and contain from 6.20% to 8.80% CaO. The quartz trachytes and peralkaline rocks contain between 0.32% and 2.48% CaO.

Plagioclase and pyroxenes are the important calcium-bearing phases present in the trachyandesites. The steady depletion of CaO as the appaitic index increases can be attributed to the removal of these minerals. Apatite is another calcium-bearing mineral that is found in the trachyandesites.

Alkali Elements

Figure 5.5 shows the variation of Na₂O and K₂O with the
appaitic index. Two trends are produced by the Na₂O diagram. The non-peralkaline trend shows a decrease in Na₂O from the trachyandesites to the quartz trachytes whereas the peralkaline trend shows a general increase in Na₂O as the appaitic index increases to the pantellerite range. The trachyandesites contain between 3.64% and 4.69% Na₂O, quartz trachytes between 2.47% and 4.03% Na₂O, and the peralkaline rocks contain from 3.55% Na₂O in one of the comendites to 6.40% in one of the pantellerites.

The K₂O versus appaitic index diagram shows an increase in K₂O from the trachyandesites to the quartz trachytes and peralkaline rocks. Once the more evolved compositions are achieved, the trend becomes more or less constant as the appaitic index increases. Basanites contain 1.17% to 1.56% K₂O, trachyandesites from 1.44% to 2.34% K₂O, and the quartz trachytes and peralkaline rocks contain between 3.20% and 7.24% K₂O.

Processes influencing the trends displayed in the alkali elements versus appaitic index diagrams by non-peralkaline and peralkaline rocks may be explained by fractionation of feldspars and will be discussed later under petrogenesis.

The principal alkali-bearing phase occurring in the basanites and trachyandesites is plagioclase. Among the quartz trachytes and peralkaline rocks anorthoclase, aegerine-augite, and soda-amphibole are the important soda-bearing phases. Aenigmatite is an additional soda-bearing mineral present in
peralkaline rocks. Alkali feldspar is the most important potassium-bearing phase present.

Phosphorus

$P_2O_5$ variation with appaitic index (fig. 5.5) shows a negative correlation. The basanites and trachyandesites have large concentrations of $P_2O_5$ (between 0.75% and 1.62%) relative to the quartz trachytes and peralkaline rocks (less than 0.1%). The larger amounts of $P_2O_5$ in the basanites and trachyandesites can be attributed to the minor amounts of apatite identified in this sections of these rocks. Since apatite is the only phosphorus bearing phase present, the depletion of $P_2O_5$ with increasing appaitic index must be due to the removal of apatite.

Trace Element Chemistry

Variations of the trace elements with the appaitic index are shown in figure 5.6. Although several of the variation diagrams show considerable scatter points, trends are still suggested. La, Sm, Yb, and Lu concentrations are normalized to chondritic abundances and plotted in figure 5.8.

Lead

Excluding the Lake Morning quartz trachytes and the breccia clasts, figure 5.6 shows that Pb decreases as the appaitic index increases. Pb abundances range from 6 ppm to 13 ppm in
Figure 5.6 Plot of trace element concentrations against aegpaitic index.
Figure 5.6 (continued).
Figure 5.6 (continued).
Figure 5.6 (continued).
the basanites and trachyandesites and from 1 ppm to 11 ppm in the quartz trachytes and peralkaline rocks exclusive of the Lake Morning rocks and breccia clasts.

\[ Pb^{2+} \] is intermediate in size between \[ Ca^{2+} \] and \[ K^+ \]. Therefore it is expected that the lead ion would substitute for calcium and potassium. The higher concentration of \( Pb \) in the basanites and trachyandesites relative to the quartz trachytes and peralkaline rocks may be attributed to \( Pb^{2+} \) readily entering the \( Ca^{2+} \) sites in plagioclase and apatite found in these rocks. The relative depletion in \( Pb \) in the peralkaline rocks may be explained by their high potassium concentrations. Although \( Pb^{2+} \) should be captured in \( K^+ \) sites, because of the double charge and smaller size, the more covalent character of the \( Pb-O \) bond relative to the \( K-O \) bond offsets such effects and allows potassium to be the dominant cation in potassium feldspars (Taylor, 1965).

The quartz trachyte breccia clasts and the Lake Morning quartz trachytes all have relatively high concentrations of \( Pb \) when compared to the other Mt. Morning rocks. The \( Pb \) abundances range from 16 ppm to 20 ppm for the Lake Morning quartz trachytes and from 15 ppm to 20 ppm in the breccia clasts.

Thorium

The abundance of thorium is shown by figure 5.6 to increase as the apaitic index increases. The basanites and
trachyandesites have relatively low concentrations between 2 ppm and 6 ppm. The quartz trachytes contain between 14 ppm to 24 ppm thorium, comenditic trachytes from 12 ppm to 21 ppm, comendites from 13 ppm to 26 ppm, and the pantellerites contain between 20 ppm to 25 ppm thorium. Since thorium is an incompatible element, it is expected to be concentrated in residual liquids, as illustrated by the Mt. Morning rocks.

Rubidium

Rubidium is very similar in size and chemical character to potassium, with which element it shows a well-known close association. Ahrens and others (1952) suggested that K/Rb ratios are uniform throughout a series. Increasing or decreasing K/Rb ratios within a series requires a special explanation such as extreme fractionation (Taylor and others, 1956). Taylor (1965) classified K/Rb ratios as "normal" if they fell within the 150-300 range. Ratios falling outside these limits call for special explanations. The Mt. Morning rocks have variable K/Rb ratios which fall between 500 and 250 (fig. 5.7). There is a marked decrease in the K/Rb ratios of the quartz trachytes and peralkaline rocks relative to the trachyandesites. The marked decrease is considered to indicate extreme fractionation, probably involving alkali feldspar (Noble and Hedge, 1970).

Figure 5.6 shows that the quartz trachytes and peralkaline rocks all contain large concentrations of rubidium (between
Figure 5.7  Relationship between potassium and rubidium for Mt. Morning volcanic rocks.
42 ppm and 160 ppm) relative to the basanites and trachyandesites which contain from 31 ppm to 44 ppm rubidium. The relative depletion of rubidium in the basanites and trachyandesites may be explained by the fact that those rocks contain no potassium feldspar which is the predominant rubidium-bearing phase present in the Mt. Morning rocks. The quartz trachytes and peralkaline rocks contain abundant proportions of potassium feldspar and are therefore more enriched in rubidium than the lower silica rocks.

Strontium and Barium

Figure 3.6 shows that the strontium and barium have similar behavior in the Mt. Morning rocks. Both are concentrated in the basanites and trachyandesites and relatively depleted in the quartz trachytes and peralkaline rocks. The trachyandesites contain from 570 ppm to 732 ppm strontium and 386 ppm to 927 ppm barium. The Gandalf Ridge quartz trachytes and peralkaline rocks contain only 1 ppm to 49 ppm strontium and 6 ppm to 180 ppm barium. The Lake Morning quartz trachytes however, show slightly higher concentrations of strontium (up to 202 ppm) and much higher concentrations of barium (between 799 ppm and 856 ppm).

Depletion in strontium is a common feature of highly evolved rocks from several localities. Gibson (1972) and Weaver and others (1972) report a depletion in strontium for pantellerites at Fantale Volcano, Sceal and Weaver (1971) for
trachytes at Paka Volcano, Noble and others (1972) for rhyolites in Mona County, California, Price (1973) for phonolites at Dunedin Volcano, and Barberi and others (1975) for comendites and pantellerites at Boina, Ethiopia.

Strontium is an important trace component in plagioclase, alkali feldspar, and apatite (Taylor, 1965; Wager and Mitchell, 1951). The depletion of strontium can be achieved by crystal fractionation involving feldspar and apatite (Noble and others, 1969), phases which are abundant in the Mt. Morning trachyandesites.

Barium ions substitute only for potassium among the common cations and is a minor component in alkali feldspars. The depletion of barium implies the removal of alkali feldspar. Strong depletion of barium in highly differentiated rocks has been reported by Noble and others (1972) for the rhyolites in California, Hewitt (1968) for the pantellerites on Mayor Island, Barberi and others (1975) for comendites and pantellerites at Boina, and Sceal and Weaver (1971) for trachytes at Paka.

Zirconium

Due to its large size and charge, zirconium has great difficulty entering normal silicate lattices. As a result zirconium becomes concentrated in residual magmas acting as a true residual element. In the Mt. Morning rocks the basanites and trachyandesites all have relatively low abundances (211 ppm
to 405 ppm) of zirconium. The quartz trachytes, comendites, and pantellerites all contain large concentrations of zirconium (up to 1782 ppm).

Since zirconium is a true residual element, a high concentration of zirconium would indicate that a rock is highly evolved. The high concentrations of zirconium in the quartz trachytes as well as the peralkaline rocks support the suggestion of two trends (one peralkaline and one non-peralkaline) being produced instead of one.

Chalcophile Elements: Copper and Zinc

The variation of these elements with the apagaitic index is illustrated in figure 5.6. Copper is relatively depleted in all the Mt. Morning rocks with abundances ranging from 5 ppm to 14 ppm. Zinc shows an increase in abundance from 90 ppm to 155 ppm in the trachyandesites, to 303 ppm in the quartz trachytes and 385 ppm in the pantellerites. Once again the Lake Morning quartz trachytes show anomalous concentrations, with values ranging from 59 ppm to 91 ppm zinc.

Wager and Mitchell (1951) arrived at the conclusion that acid rocks in volcanic series are often depleted in copper. Such is the case in the Mt. Morning rocks. The increasing abundance of zinc with the apagaitic index may be explained by zinc entering late Fe$^{2+}$ positions (Taylor, 1965). On the basis of size and bond covalence zinc should concentrate relative to iron during fractionation. Another possibility is that zinc
behaves as a residual element as it does in the Lovozero complex where it is concentrated into late liquids (Gerasimovsky and others, 1966).

Minor amounts of zinc in the trachyandesites occur in the iron-bearing phases such as opaques and clinopyroxenes. Large concentrations of zinc built up in the residual liquids during fractionation have been incorporated into the iron-bearing minerals such as aegirine-augite and aenigmatite in the highly evolved rocks.

Ferromagnesian Elements: Nickel, Chromium, and Vanadium

The Gandalf Ridge and Lake Morning rocks are relatively depleted in nickel and chromium and show a strong negative correlation of vanadium with the aegaptic index (fig. 5.c).

In basic rocks, Ni$^{2+}$ prefers to enter the olivine structure, where divalent cations are readily accommodated, because of the ease of charge balance (Taylor, 1965). Cr$^{3+}$ and V$^{3+}$ preferentially enter minerals such as clinopyroxenes where trivalent ions are readily accepted (Taylor, 1965). The early entry of Ni$^{2+}$ into olivine and Cr$^{3+}$ into clinopyroxene therefore depletes the remaining liquids in nickel and chromium during the early stages of fractionation. Since there are no genetically related rocks found at Gandalf Ridge more basic than the trachyandesites, it is believed that the low concentrations of nickel and chromium are due to early fractionation of phases bearing these elements prior to the
trachyandesite stage. The somewhat higher concentrations of vanadium in the trachyandesites are due to the fact that V$^{3+}$ has a larger ionic radius than Cr$^{3+}$, which is otherwise very similar. The larger size of V$^{3+}$ causes it to be concentrated in phases subsequent to the Cr$^{3+}$ phases. The rapid depletion of vanadium as the appaitic index increases suggests that the vanadium-bearing phases are still being removed between the trachyandesite stage and the quartz trachyte stage.

The Mt. Morning basanites contain abundant olivine which is a nickel-bearing phase. Minerals containing Cr$^{3+}$ and V$^{3+}$ in the trachyandesites are clinopyroxene and the opaques. In the quartz trachytes and peralkaline rocks, the clinopyroxenes are the predominant Cr$^{3+}$ and V$^{3+}$ bearing phases.

Scandium

Scandium shows a strong decrease in abundance as the appaitic index increases (fig. 5.6). The basanites contain between 16 ppm and 25 ppm scandium, trachyandesites between 14 ppm and 17 ppm, and the quartz trachytes and peralkaline rocks contain from less than 1 ppm to 4 ppm scandium.

Sc$^{3+}$ is the closest in size to Fe$^{2+}$ of the common cations and Sc$^{3+}$ should be captured in Fe$^{2+}$ positions. This should be aided by the more ionic character of the Sc-O bond relative to the Fe-O bond. The higher concentrations of scandium in the basanites and trachyandesites relative to the quartz trachytes and peralkaline rocks may be attributed to Sc$^{3+}$ substituting
for Fe$^{2+}$ in early pyroxenes (Wager and Mitchell, 1951; Borisenko, 1959).

The predominant scandium-bearing phases present in the Mt. Morning rocks are the clinopyroxenes which occur in all rocks found at Mt. Morning.

Rare Earth Elements and Yttrium

Chondrite-normalized REE patterns for the Gandalf Ridge and Lake Morning samples showing abundances of La, Sm, Yb, and Lu are illustrated in figure 5.8. All of the rocks are enriched overall in REE, and all show enrichment of the light REE relative to heavy REE.

There is a continuous enrichment in REE from the basanite to trachyandesites through the quartz trachytes and peralkaline rocks. Average concentrations of REE in the trachyandesites are about 200 times the abundance of La in chondrites, about 70 times the abundance of Sm, and about 17 times the abundance of Yb and Lu in chondrites. The quartz trachytes from Gandalf Ridge and the peralkaline rocks show up to 618 times the chondritic abundance for La, up to 752 times for Sm, and as much as 62 times the chondritic abundance for Yb and Lu. The Lake Morning quartz trachytes show extremely low abundances of REE relative to the Gandalf Ridge quartz trachytes. REE average abundances for the Lake Morning quartz trachytes are about 227 times the La abundance in chondrites, about 48 times the Sm value, about 16 times the Yb value, and
Figure 5.8  REE content of Mt. Morning rocks normalized to abundances of chondrites.
Figure 5.8 (continued).
Figure 5.8 (continued).
Figure 5.8 (continued).
about 18 times the Lu value in chondrites.

Yttrium variation with the appaitic index is illustrated in figure 5.6. The basanites contain about 28 ppm, trachyandesites contain between 31 ppm and 50 ppm, and the quartz trachytes and peralkaline rocks contain between 55 ppm and 108 ppm Y. The Lake Morning quartz trachytes once again have anomalous values with concentrations between 38 ppm and 40 ppm Y.

Yttrium and the rare earth elements behave very similarly (Taylor, 1965). The enrichment of REE and Y from the trachyandesites to the quartz trachytes and peralkaline rocks may be explained by the fractional crystallization of calcium-bearing phases. Since Ca$^{2+}$ is the common cation closest in size to the rare earth elements and Y$^{3+}$, the rare earth elements and Y$^{3+}$ can enter into Ca$^{2+}$ positions (Taylor, 1965). The more covalent character of the RE-O bond and Y-O bond relative to the Ca-O bond would concentrate the REE and Y in the residual melts. Wickman (1943) suggests that the difficulties of charge balance force the REE and Y to concentrate in the residual magmas.

The electronegativity and ionization potential values for the rare earth elements are all similar. The major difference between the rare earth elements is the steady decrease in ionic radii with increasing atomic number. The size difference becomes a major factor during fractionation, leading to the preferential entry of the smaller, heavier cations into the earlier formed fractions, enriching the residual melt in the
larger, lighter rare earth elements (Taylor, 1965). This effect will be superimposed on the general enrichment of REE in the residual melts caused by the more covalent character of the RE-O bond relative to the Ca-O bond (Ringwood, 1955).

Geochemical Comparison

The geochemical characteristics of various McMurdo Volcanic Group lineages are summarized on a total alkalis versus SiO$_2$ variation diagram (fig. 5.9). Trends A through F are visual fits of data summarized by P.R. Kyle (1976). Trend N represents the trachyandesite-quartz trachyte trend from Mt. Morning and trend F represents the trachyandesite-pantellerite trend.

The most noticeable feature about the total alkalis/SiO$_2$ variation diagram is the low alkali content of the Mt. Morning rocks relative to the McMurdo Volcanic Group lineages. In general, the Mt. Morning rocks increase in alkali content to about 63% SiO$_2$ where two trends develop (a peralkaline trend and a non-peralkaline trend). Rocks containing more than 63% SiO$_2$ show a decrease in alkali content, with the non-peralkaline, quartz trachytes showing a rapid depletion.

For the most part the Mt. Morning rocks contrast with other McMurdo Volcanic Group rocks. The only exceptions are the alkali basalts/basanite-quartz trachyte lineage (E) from the Hallett volcanic province and the quartz trachyandesite-quartz trachyte lineage (F) from Mt. Melbourne. Notable
Figure 5.9 Total alkali versus SiO$_2$ diagram showing the generalized trends for McMurdo Volcanic Group rocks (after P.R. Kyle, 1976).

A Sodic basanite-nepheline benmoreite lineage, The Pleiades
B Basanite-phonolite lineage (Kaersutite Lineage), Erebus volcanic province
C Nepheline hawaiite-anorthoclase phonolite lineages, Erebus volcanic province
D Mildly potassic trachyandesite-peralkaline K-trachyte lineage, The Pleiades
E Alkali basalt/basanite-quartz trachyte lineage, Hallett volcanic province
F Quartz trachyandesite-quartz trachyte lineage, Mt. Melbourne
N Trachyandesite-quartz trachyte (non-peralkaline trend; Mt. Morning, Erebus volcanic province
P Trachyandesite-pantellerite (peralkaline trend) Mt. Morning, Erebus volcanic province
similarities between these lineages and the Mt. Morning rocks are the trends for most major and minor elements including the unusual depletion of barium and strontium in the high silica rocks.

The Mt. Morning rocks, when compared to the Cenozoic volcanic rocks in Marie Byrd Land described by LeMasurier and Wade (1974), are more mildly alkaline. All of the Marie Byrd Land Cenozoic volcanic rocks belong to the highly sodic-basalt-sugargart-hemorite-trachyte series defined by Tilley and Muir (1964) (LeMasurier and Wade, 1974), whereas the Mt. Morning rocks belong to the potassic-trachyandesite-tristanite-trachyte series defined by Coombs and Wilkinson (1969). However, certain similarities in major elements (LeMasurier and Wade, 1974) and rare earth elements (LeMasurier and others, 1976) do exist in the quartz trachytes and peralkaline rocks of both regions.

Many of the major element and minor element trends produced by the Mt. Morning rocks are comparable to other provinces where comendites and pantellerites are found. Barberi and others (1975) report trends that are very similar to those shown by the Mt. Morning rocks for SiO₂, TiO₂, Al₂O₃, FeO, MgO, CaO, Na₂O, K₂O, P₂O₅, Sr, Ba, Rb, Zr, Zn, and REE in basalt-pantellerite and basalt-quartz trachyte sequences at Boina, Ethiopia. Major and minor element analyses similar to the Mt. Morning rocks have been reported by MacDonald and Bailey (1973) for comenditic and pantelleritic obsidians.
from several localities. Seasal and Weaver (1971) report similar analyses for salic rocks from Paka Volcano, Kenya.
Basaltic lavas are predominant in the Erebus volcanic province, which includes the Mt. Morning area. Gandalf Ridge is located on the northern slopes of Mt. Morning and the rocks at Gandalf Ridge represent the earliest volcanism in the McMurdo Volcanic Group. However, the most basic rock type found in this old volcanic complex is trachyandesite, which comprises the majority of exposed rock at Gandalf Ridge. Basanites are present in the area adjacent to Gandalf Ridge, but because of their much younger age, they are not discussed here. Quartz trachyte and silicic peralkaline dikes intrude the trachyandesites. This study is directed at establishing the relationships of the various rock types found at Gandalf Ridge and ascertain their origin.

Alkali basalt is considered to be the parental magma for the rocks from Gandalf Ridge. This is based on the close chemical similarities between the compositions of the trachyandesite breccia clasts and alkali basalts. Extrapolation of trends given by the Mt. Morning rocks in the variation diagrams (figs. 5.5 and 5.6) leads to compositions, on the low aaptite index part of the diagrams, comparable to that of alkali basalts, suggesting a possible relationship between the Mt. Morning rocks and alkali basalts. Basaltic lavas of highly alkaline character are the predominant rock type in the Erebus volcanic province and are considered the parent magma from which most of
the rock types in the province were derived. Other studies (Barberi and others, 1973; Macdonald, 1974; Bowden, 1974; and Bailey and Macdonald, 1970) suggests an alkali basalt parent for rocks similar to those at Mt. Morning.

Origin of Basalt

The consensus on the origin of basalt is partial melting of mantle material (Green and Ringwood, 1967; O'Hara, 1968; Kushiyo and others, 1972; and Frey and others, 1978). The composition of basic magmas appears to be controlled by the following factors (Green, 1971): the mineralogical composition of the mantle, which varies with pressure and temperature; the degree of partial melting and the P, T, and P/H$_2$O conditions when the magma segregates from the residual crystals; crystal fractionation processes operating as the magma ascends to the surface; and wall rock reaction processes. Recent work (Frey and others, 1978; Frey and Green, 1974; Egger, 1974) suggests the importance of CO$_2$, in addition to the above processes, for determining the composition of the basic magmas.

Many schemes have been developed for the petrogenesis of basalts, of which the most comprehensive are the schemes by O'Hara (1968) and Green and Ringwood (1967). O'Hara suggests that erupted magmas are not primary magmas, but the residual liquids of advanced crystal fractionation. O'Hara recognized three pressure regimes which are distinguished on the basis of subsolidus mantle mineralogy. The high pressure regime
corresponds to garnet peridotite, intermediate pressure regime to spinel peridotite, and low pressure regime to plagioclase peridotite. Partial melting of the mantle material will yield a hypersthene normative picritic liquid in the high pressure regime, a nepheline normative picritic liquid in the intermediate pressure regime, and three different liquids; an alkali olivine basalt-like magma, a high-alumina basalt-like magma, and a tholeiitic magma, in the low pressure regime. The three liquids correspond to subdivisions of the low pressure regime from lowest to highest pressure respectively. More advanced partial melting yields liquids which tend to be hypersthene-normative at all pressures. Various eruptive magmas can be produced from the parental liquids mentioned above, depending on the pressure-temperature-time paths by which the magma ascends to the surface.

The petrogenetic scheme of Green and Ringwood (1967) suggests that the composition of the magma is determined by the depth at which magma segregation from the residual crystals occurs and not by the depth of partial melting, even though magmas are considered to be a consequence of partial melting. For example, an olivine-rich tholeiite magma, which is assumed to represent 20% to 40% partial melting of the mantle peridotite may fractionate to produce three different magmas in clearly defined pressure regimes. These pressure regimes correspond to low pressure (0 to 5 kb) or shallow crustal fractionation (above 15 km) yielding quartz tholeiite liquids; moderate pressure (5 to 10 kb) fractionation at depths between 15 km and 35 km producing high-alumina magmas; and intermediate pressure
(10 to 20 kb) fractionation at depths of 35 km to 70 km yielding alkali olivine magmas.

To account for the large abundances of incompatible elements in alkali basalts, Green and Ringwood (1967) proposed the idea of wall-rock reaction processes. This simply involves a body of magma cooling by reaction with and solution of the lowest melting fraction of wall rock material with which it was in contact, enriching the magma in incompatible elements from the wall rock. However, for magmas such as basanites and nephelinites where the abundances of incompatible elements are frequently greater than 10 times that in tholeiites, Ringwood (1975) agrees with the proposal by Gast (1968) that these magmas are produced by direct partial melting of mantle rather than by fractional crystallization of olivine tholeiites.

Models for the origin of alkali basalt, based on the distribution of the rare earth elements, have been developed by Gast (1968), Kay and Gast (1973), Shimizu and ArulCUS (1975), Sun and Hanson (1975), and Frey and others (1978). Alkali basalts show a very strong enrichment of light REE relative to heavy REE (Kay and Gast, 1973). If a mantle source with a REE content 1 to 4 times the chondritic abundance is assumed, then formation of an alkali basaltic magma requires substantial enrichment of the light REE relative to heavy REE. Shimizu and ArulCUS (1975) suggests that the strong partition of heavy REE over light REE into garnets indicates that separation of garnet would give REE patterns similar to those seen in alkali
basalts. Kay and Gast (1973) propose that alkali basalts are the result of less than 3% partial melting of garnet-bearing mantle sources at depths greater than 60 km.

Carmichael and others (1974) however, believe that the lower degree of partial melting required by most REE models is too low to account for the volume of alkaline lavas in many island provinces. Recent REE models (Sun and Hanson, 1975; Frey and others, 1978) overcome these difficulties by suggesting that alkaline basaltic magmas form by 7% to 15% partial melting of mantle material which is already enriched in light REE.

Some agreement however, appears to have been reached between the REE models and experimental models without relying on wall-rock reaction or a REE-enriched mantle. Roy and others (1975) explained the origin of several Australian alkali basalts by less than 3% partial melting of pyrolite at 25 kb to 30 kb pressure with 2% to 7% H₂O present. The models were based on major element mass balance calculations and were consistent with REE abundances assuming an upper mantle source having twice the chondrite REE abundances.

In summary, alkali basalts would appear to be formed by partial melting of a hydrous garnet peridotite upper mantle source at depths greater than 60 km.

Origin of Mt. Morning Lavas

It is now the general concensus that there is no single
parent magma responsible for the formation of alkaline rocks such as trachyandesites, trachytes, and peralkaline rocks since they occur in many petrological associations. Suggested origins for these alkalic rocks include mantle and crustal anatexis, differentiation, resorption of minerals, assimilation, volatile enrichment, liquid immiscibility, and metasomatic processes (Sorensen, 1974).

As mentioned earlier, basaltic magmas are believed to originate by partial melting of mantle material. The trachyandesites, quartz trachytes, and peralkaline rocks at Gandalf Ridge are believed to be the result of differentiation of an alkali basalt parent. Differentiation is favored on the basis of: major and trace element variations compatible with fractional crystallization of mineral phases that are present as phenocrysts; linear correlation between pairs of residual elements (fig. 6.1); the fact that all the rock types occur together in a single volcanic structure, except for the assumed parent; and analogies of other volcanic provinces for which differentiation is the proposed mechanism by which rocks similar to the Gandalf Ridge rocks were formed.

Halpern (1969), Jones and Walker (1972), and Kurasawa (1975) have reported strontium isotope measurements on McMurdo Volcanic Group rocks. Fifty-one $^{87}\text{Sr}/^{86}\text{Sr}$ determinations on representative samples of the principal rock types in the Erebus volcanic province all have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the range of 0.7022 to 0.7048. Four determinations of Melbourne
Figure 6.1 Linear correlation between residual elements in Gandalf Ridge rocks.
volcanic province rocks average 0.7042.

Faure and Powell (1972) report that oceanic basalts, which are not contaminated by sialic crust, have an average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7035. The similar mean $^{87}\text{Sr}/^{86}\text{Sr}$ value for the McMurdo Volcanic Group samples (0.7036±0.0002) suggests that the McMurdo Volcanic Group are probably uncontaminated by crustal rocks and supports the magmatic differentiation explanations for the various lineages observed in the McMurdo Volcanic Group.

Figure 6.1 shows that there is a very good linear correlation between pairs of residual elements (La and Zr; La and Th; Zr and Th) for the rocks from Gandalf Ridge. Similar behavior in residual elements has been noted in basalt-pantellerite series in other locations; such as Boina (Barberi and others, 1975), the East African Rift volcanoes (Sceal and Weaver, 1971; Weaver and others, 1972), and Pantelleria (Villari, 1974). Treuil (1973) and Ferrara and Treuil (1974) point out that only a fractional crystallization process can maintain a constant ratio in the residual elements. Any other process, while producing a sequence of liquids of different composition, will modify the concentration of the residual elements. Therefore linear correlation could not be maintained.

It is believed that two different fractionation trends are represented in the Gandalf Ridge rocks. One trend leading from the trachyandesites to the quartz trachytes (non-peralkaline trend) and the other leading from the trachyandesites to the pantellerites (peralkaline trend). This is based on the
fact that several variation diagrams (fig. 5.5 Al₂O₃, Na₂O, versus agpaitic index; fig. 5.6 Th, Zn, Zr, versus agpaitic index) show two distinct trends. Both the quartz trachytes and pantellerites are enriched in the residual elements, displayed best by Zr, indicating that they are both highly evolved. The REE patterns displayed by the quartz trachytes and peralkaline rocks are further evidence supporting two distinct trends. Since the light REE are expected to be concentrated in the residual fractions, the high abundances of light REE shown by some quartz trachytes and pantellerites relative to other Gandalf Ridge rocks suggest that they are the most evolved rocks at Gandalf Ridge, indicating two residual phases instead of one.

The possibility of more than one trend developing from an intermediate rock is not uncommon. Bailey and Schairer (1964) have suggested that trachytes lie near a "cross-roads", which may lead to four kinds of residual: peralkaline oversaturated, peraluminous oversaturated, peralkaline undersaturated, and peraluminous undersaturated. Since alkali feldspar is the most abundant phenocryst in the majority of trachytic rocks, its composition strongly controls the fractionation paths that these rocks can follow. Slight departures from stoichiometry (ideal 1:1:0 formula) may influence the path a magma, critically balanced with respect to SiO₂, might take.

Lake Morning Quartz Trachytes

Quartz trachytes collected near Lake Morning forms distinct
group quite different from the Gandalf Ridge quartz trachytes and peralkaline rocks. They are noticeably younger in age than the Gandalf Ridge rocks. In nearly all of the variation diagrams, the Lake Morning quartz trachytes form a separated cluster of points. REE patterns for these rocks are slightly depleted relative to the Gandalf Ridge trachyandesites.

Postulation of an origin for the Lake Morning quartz trachytes would be speculative. All that can be said is that they represent a distinct phase of volcanism younger than and chemically distinct from the Gandalf Ridge volcanism.

Trachyandesite-Quartz Trachyte Trend

From trachyandesite to quartz trachyte there is an enrichment of SiO₂, K₂O, Th, Rb, Zr, Zn, Y, and the rare earth elements. In the case of the REE the chondrite normalized patterns are essentially all the same shape. Accompanying these enrichments are depletions in TiO₂, Al₂O₃, FeO, MgO, CaO, Na₂O, P₂O₅, Pb, Sr, Ba, V, and Sc. These geochemical features are best explained by a petrogenetic model involving fractional crystallization. Fractionation of plagioclase, clinopyroxene, and opaque oxides in the trachyandesites can account for most of the depletions of TiO₂, Al₂O₃, FeO, MgO, CaO, Pb, V, and Sc. The depletion of P₂O₅ can be attributed to the removal of apatite, a phase occurring predominantly in the trachyandesites. The decreasing abundance of Na₂O is probably caused by fractionation of sodic-plagioclase and anorthoclase.
The depletion in Sr and Ba can also be explained in terms of fractional crystallization. The initial separation of olivine and pyroxene from a basaltic magma would lead to a concentration of Sr and Ba in the liquid phase, but with the increasing crystallization of feldspar, concentrations of both Sr and Ba would rapidly become reduced in the residual liquids. Sr would enter preferentially into plagioclase and Ba into alkali feldspar.

Trachyandesite-Pantellerite Trend

For most part, the trachyandesite-pantellerite trend shows major and minor element variations very similar to those shown by the trachyandesite-quartz trachyte trend. The notable differences are the negative correlation between the aphytic index and differentiation index (fig. 5.4) and the increase of Na₂O with increasing aphyticity (fig. 5.5). Most of the observed variations in major and minor element chemistry can be explained by the same process suggested for the non-peralkaline trend (e.g. fractional crystallization involving plagioclase, clinopyroxene, opaque oxides, and apatite).

The increase in Na₂O may be caused by the fractionation of a more calcic (less sodic) plagioclase than was fractionated to form the non-peralkaline trend. The fractionation of plagioclase, which has incorporated calcium and alumina into sodic-feldspar crystallizing from a liquid with little or no normative anorthite component, has been called the "plagioclase effect" (Bowen, 1945). The plagioclase effect may have caused
the first peralkalinity of the Mt. Morning rocks to occur. Evidence for the plagioclase effect is shown petrographically by the occurrence of andesine cores in oligoclase grains observed in some trachyandesites. Once the peralkaline field is reached the crystallization of alkali feldspar will progressively increase the molecular excess of alkali over alumina.

Bailey (1974) suggests that the "plagioclase effect" can never provide more than a partial solution to the problem of peralkalinity. This is based on the fact that many basaltic magmas which have peralkaline tendencies (containing normative acmite, diopside, or wollastonite) originate at pressures beyond the stability of plagioclase. Bailey points out that clinopyroxene is the obvious source of alkalis among the solid phases throughout most of the upper mantle, since plagioclase, amphibole, and mica have only limited stabilities. Melting of clinopyroxene would tend to make the resultant magma acmite normative, or at least diopside or wollastonite normative, and potentially peralkaline.

Peralkalinity could also be initiated by fractionation of biotite (Carmichael, 1967), aluminous pyroxene (Schairer and Yoder, 1960), spinel, garnet, or Al-bearing iron oxides (Bailey and Schairer, 1966), or of non-stoichiometric alkali feldspar (Luth and Tuttle, 1966). The fact that many of these phases are not present in the Mt. Morning rocks, eliminates their influence. However, the possibility of a non-stoichiometric alkali feldspar causing peralkalinity is possible.
Conditions of Formation of Aenigmatite

Aenigmatite is generally considered to form under conditions of low oxygen fugacity (Abbott, 1967). Ernst (1962) and Thompson and Chisholm (1909) both synthesized aenigmatite under low oxygen fugacity conditions controlled by the iron-wustite buffer. Lindsley (1971) examined aenigmatite stability over a range of temperatures and oxygen fugacity conditions and found that aenigmatite is only stable under 900° C and at, or below the oxygen fugacities defined by the quartz-fayalite-magnetite buffer. Aenigmatite appears to be an effect of low oxygen fugacity conditions at the time of formation.
VII TECTONIC RELATIONS AND GEOLOGIC HISTORY

Since the Mt. Morning lavas represent the earliest documented volcanism in the McMurdo Volcanic Group, they are important in the interpretation of the regional tectonic history and in the geologic history of the McMurdo Volcanic Group.

Tectonic Environment of Mt. Morning

The Mt. Morning lavas represent a trachyandesite-quartz trachyte/peralkaline silicic rock association (chap.6). Alkali basalt associations, such as seen at Mt. Morning, are generally considered to be associated with tensional tectonism (Martin and Piwinski, 1972). Sorensen (1974) states that there is generally a close association between alkaline igneous activity and major tectonic structures such as rifts, intersections of fault zones, and folds. Peralkaline silicic magmatism, such as observed at Gandalf Ridge, is generally related to continental doming and rifting (Bowden, 1974). Le Bas (1971) points out that peralkaline magmatism can occur during the pre-rifting (epi-riftogenic doming), initial rifting (development of linear fractures and beginning of crustal attenuation), and continued rifting (extensive crustal attenuation leaving little or no sialic crust on the rift floor) stages.

Classification of the peralkaline silicic rocks using the scheme of Macdonald and Bailey (1973) suggests that the oversaturated peralkaline rocks from Gandalf Ridge are
essentially of comenditic affinity (see chap. 5, nomenclature section). Comenditic associations are typical products of epeirogenic doming (Bowden, 1974; MacDonald, 1974). Vincent (1965 and 1973) reports that alkali olivine basalts and comenditic associations are related to the epeirogenic uplift and faulting in Tibesti. In other areas, such as the East African rift zone in Kenya, comendites with peralkaline trachytes and pantellerites are commonly associated with the rifting in rift valleys (Bailey, 1974). Mohr (1970) points out that in the more evolved rift systems of Ethiopia, where crustal attenuation is very extensive, the proportion of comenditic rocks relative to pantelleritic rocks is small suggesting that the more evolved a rift system becomes, the more peralkaline the volcanism. Examples of pantelleritic associations in well-developed rift systems include the alkali trachyte-alkali rhyolite-pantellerite volcanic complexes at Fantale (Gibson, 1967). There the volcanic complexes are located on the rift floor within the Main Ethiopian Rift, overlying older alkali basalts. Barberi and others (1975) report a mildly alkaline basalt-trachyte-pantellerite association at Boina, which is located on the Afar Rift, Ethiopia.

Relationship of the McMurdo Volcanic Group to Tectonics

As mentioned earlier (chap. 1), the McMurdo Volcanic Group is comprised of four volcanic provinces (Kyle and Cole, 1974): the Balley volcanic province; the Hallett volcanic province; the Melbourne volcanic province; and the Erebus
volcanic province. Aeromagnetic surveys (McGinnis and Montgomery, 1972) showed that the volcanic rocks are discontinuous between provinces which suggests that the volcanism of each province is related to structural trends of local significance.

Kyle and Cole (1974) discussed the relationship of volcanism in the volcanic provinces to various structural features. In the Balleny volcanic province, the volcanoes are linearly distributed along the Balleny Fracture Zone, a transform fault which offsets the Indian-Antarctic Ridge (Falcomer, 1972; Kyle and Cole, 1974). Since the volcanoes in the Balleny volcanic province are related to the Balleny Fracture Zone and are not related to the tectonic feature responsible for the volcanism in the other volcanic provinces (e.g. crustal extension in the Ross Sea), the author believes that the Balleny volcanic province should not be included in the McMurdo Volcanic Group.

In the Hallett volcanic province, four volcanic piles, comprised predominantly of alkali olivine basalt and trachyte, produce a linear feature along the coast of northern Victoria Land (Harrington, 1967; Hamilton, 1972). Harrington (1967) suggests that the volcanoes were produced by tensional rifts in a monoclinal flexure. Kyle and Cole (1974) however, propose that the volcanoes are related to a major fracture which they termed the "Hallett Fracture". The nature of the crustal structure along the coast of northern Victoria Land strongly
favors relationship of the volcanoes to a fracture and will be discussed later in this section.

Nathan and Schulte (1968) described the field occurrances of the volcanic rocks of the Melbourne volcanic province and divided them into two suites: a Central Suite and a Local Suite. The Central Suite is the most abundant and consists of the large stratovolcanoes of Mt. Melbourne and Mt. Overlord and the cones of The Fleiades. The compositions of the rocks range from basanite to trachyte with 95% of the rocks having intermediate and trachytic compositions. Many of the lavas in the Central Suite are similar to the lavas found at Mt. Morning, especially the trachyandesite-oversaturated peralkaline rock lineage observed at The Fleiades. The Local Suite includes all other occurrences not part of the Central Suite. The predominant rock type in the Local Suite is olivine-bearing basanite.

The volcanoes of the Melbourne volcanic province show a more clear relationship to tectonics than do the volcanoes of either the Weddell or Erebus volcanic provinces. The volcanoes of this province are associated with the NW trending faults of the area (fig. 1.2) (Kyle and Cole, 1974).

There is no obvious tectonic feature with which the predominantly alkaline basaltic volcanoes of the Erebus volcanic province are associated. The main volcanic centers of Ross Island, Mt. Discovery, and surrounding areas are located in front of the eastern face of the Transantarctic Mountains at a point near a flexure in the physiographic trend. McIver and
Gevers (1970) suggested that Ross Island may lie at the intersection of a major north-south lineament (topographic break between the Transantarctic Mountains and the Ross Sea) and a subsidiary east-west fracture which passes through Ross Island and the smaller volcanic cones in the Taylor Valley. Kyle and Cole (1974) however, suggest that the Erebus volcanic province is situated at the junction of the southern extension of the Rennick Fault and a NE trending structure which in part may be the northern extension of the Hillary Fault postulated by Grindley and Laird (1969). The trouble with both suggestions is that the faults are based strictly on inferences.

It is evident however, that the front of the Transantarctic Mountains represents a major structural break (see chap. 1, tectonics). The most plausible explanation is that the front represents an area of crustal thinning (Woollard, 1962; Smithson, 1972) caused by extension of the crust (Kyle and Cole, 1974) because the gravity gradient across McMurdo Sound and the Transantarctic Mountains is too large to be explained by faulting alone. Bouger gravity anomalies (Woollard, 1962) and surface wave dispersion studies (Adams, 1972) indicate a crustal thickness of 25-30 km for most of the Ross Ice Shelf and Byrd Subglacial Basin, 32 km for Marie Byrd Land, and about 40 km for East Antarctica.

Cenozoic volcanism in Marie Byrd Land (LeMasurier and Wade, 1974) is similar to that observed in the McMurdo Volcanic Group suggesting a similar tectonic environment (e.g. crustal extension).
Kyle and Cole (1974) recognized radial symmetry about Mt. Erebus and Mt. Discovery, which suggested that these volcanic centers may have been formed by crustal updoming. The associated volcanic centers about Mt. Discovery; Mt. Morning, Minna Bluff, and Brown Peninsula; and the associated centers about Mt. Erebus; Mt. Terror, Mt. Terra Nova, and Mt. Bird, would in turn be associated with the fractures produced by the updoming. These fractures would occur at angles of 120° to each other, radiating from the center of greatest uplift, which in these cases are Mt. Erebus and Mt. Discovery.

In summary, the front of the Transantarctic Mountains probably represents a rift environment. The alkaline composition of the lavas which is generally associated with rifting and uplift; the pronounced change in crustal thickness; and the association of the Melbourne volcanic province lavas with faults; all point to a regime of crustal extension.

Geologic History of Mt. Morning

Based on field observations and subsequent laboratory investigations, the following chronology of geologic events in the Mt. Morning area can be postulated.

 Heating of the mantle beneath McMurdo Sound caused expansion and partial melting of the mantle. The overlying crust was uplifted as a result of the expansion and the near surface and surface rocks underwent brittle fracture.

 A volcano was built up consisting, presumably, of alkali
basalt and the differentiates trachyandesite, quartz trachyte, and oversaturated peralkaline trachyte; the volcanic edifice was cut by fractures along which magma was introduced and chilled to give sills and dikes, some of which were feeders. Only the trachyandesite flows and trachyte dikes have been preserved and are likely to be remnant in a flank of the volcano.

K/Ar dating of samples from Gandalf Ridge has suggested a minimum age of 18.75 m.y. for the extrusion of the trachyandesite lavas. A maximum age of 17.56 m.y. and a minimum of 15.5 m.y. has been suggested for the onset of trachytic and peralkaline volcanism at Gandalf Ridge. Trachytic and peralkaline volcanism continued in the Lake Morning area until 14.63 m.y. ago.

A period of faulting and silicic hydrothermal alteration followed the trachytic and peralkaline volcanism. The faulting occurred in a north-south direction approximately parallel to the face of the Transantarctic Mountains. The duration of faulting is unknown.

Subsequent to the volcanism and faulting was a period of quiescence characterized by erosion, deposition, and further erosion. The old volcanic complex consisting of trachyandesite and trachyte was eroded to a near horizontal surface. Deposition of a volcanic breccia covered the eroded surface. Later, erosion of the breccia and underlying volcanic rocks created a few small valleys exposing the stratigraphic sequence seen today.

A period of younger volcanism occurred subsequent to the
period of quiescence. Extrusion of predominantly basanitic lavas built up Mt. Morning and flank eruptions created the associated smaller cones on the slopes of Mt. Morning. This younger volcanism is believed to have commenced around late Pliocene time, based on the K/Ar date of 1.15 m.y. (Armstrong, in press) for a sample collected near the summit of Mt. Morning.

The present day geological processes occurring in the area are glaciation and erosion.
APPENDIX A
THIN SECTION DESCRIPTIONS

Basanites

Both samples of basanite (77M21, 77M23) were collected at Gandalf Ridge and are identical to the description of basanite given in chapter 4 (petrography).

Trachyandesites

All samples were collected at Gandalf Ridge. The description of trachyandesite given in chapter 4 applies to all four samples of trachyandesite (77M11, 77M17, 77M28, 77M41). K/Ar dating was performed on sample 77M41.

Trachyandesite Breccia Clasts

Both samples of trachyandesite breccia clast (77M59, 77M60c) were collected from the breccia capping the central part of Gandalf Ridge. Both samples are identical to the description of the trachyandesite breccia clast given in chapter 4.

Trachytes

A general description of trachyte is given in chapter 4. All the samples of trachyte collected at Gandalf Ridge are similar to that description. The differences between various samples and the general description are given below.

The following samples are identical to the description
given in chapter 4; 77M1, 77M15, 77M20, 77M26, 77M32, 77M33, 77M36, and 77M39. Samples 77M22, 77M27, 77M34, 77M37, 77M40, 77M44, and 77M62, differ only in that they have a more felty texture than that described in the general description. Some of the samples (77M4, 77M5, 77M30) contain larger sanidine phenocrysts (up to 6 mm in size) and have a slightly more felty texture than mentioned in the general description of trachyte. Samples 77M25, 77M30, 77M35, and 77M45, are coarser-grained than the grain-size mentioned in chapter 4 and they display a highly trachytic texture.

K/Ar dating was performed on samples 77M4, 77M45, and 77M62.

Trachyte Breccia Clasts

For most part the samples of trachyte breccia clasts (77M47, 77M50, 77M57, 77M58, 77M60, and 77M61) are very similar to the description of a trachyte breccia clast given in chapter 4. Samples 77M47 and 77M58 contain large amounts (up to 20%) of aenigmatite.
APPENDIX B

ANALYTICAL METHODS AND COMPARISONS

X-ray Fluorescence

Most major and trace element analyses were made by Dr. Philip R. Kyle at Victoria University of Wellington using x-ray fluorescence. Table B.1 is a comparison between major element analyses of USGS rock standards undertaken at Victoria University of Wellington and estimates reported by Flanagan (1976). Trace element analyses of USGS rock standards made at Victoria University of Wellington are compared to the estimates recommended by Flanagan (1976) in Table B.2.

Instrumental Neutron Activation Analysis

Analyses for rare earth elements (La, Sm, Yb, Lu), Sc, Na₂O, and MnO were made at the Nuclear Reactor Laboratory (NRL), Ohio State University using an instrumental neutron activation analysis (INAA) method similar to that described by Laul (1977).

Fifty-four 0.15 gram powder samples consisting of 44 rock samples and 10 USGS rock standards were analyzed. The samples were divided into two groups of 27 and irradiated for 5 hours in the central irradiating facility of the NRL. The samples were counted after decay times of 5 hours and 7 days using a Ge(Li) detector and multichannel analyzer at the NRL.

Table B.3 is a comparison between the rare earth element analyses of USGS rock standards made at the NRL using INAA.
and estimates recommended by Flanagan (1976). Table B.4 is a comparison between the analyses for Na$_2$O and MnO made at the NRL using INAA and those made at Victoria University using x-ray fluorescence.
Table B.1 Major element analyses of USGS rock standards.

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<td>P₂O₅</td>
<td>0.48</td>
<td>0.49</td>
</tr>
</tbody>
</table>

VW: analyses made at Victoria University of Wellington by P.R. Kyle

Accepted values: estimates recommended by Flanagan, (1976)
<table>
<thead>
<tr>
<th></th>
<th>AGV-1 VUV Accepted value</th>
<th>G-2 VUV Accepted value</th>
<th>G-1 VUV Accepted value</th>
<th>GSP-1 VUV Accepted value</th>
<th>BCR-1 VUV Accepted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>41 35.1</td>
<td>32 31.2</td>
<td>40 48</td>
<td>52 51.3</td>
<td>17 17.6</td>
</tr>
<tr>
<td>Th</td>
<td>5 6.41</td>
<td>26 24.2</td>
<td>44 50</td>
<td>100 104</td>
<td>4 6.0</td>
</tr>
<tr>
<td>Rb</td>
<td>78 67</td>
<td>169 168</td>
<td>200 220</td>
<td>258 254</td>
<td>54 46.6</td>
</tr>
<tr>
<td>Y</td>
<td>20 21.3</td>
<td>12 12</td>
<td>12 13</td>
<td>26 30.4</td>
<td>36 37.1</td>
</tr>
<tr>
<td>Zn</td>
<td>83 84</td>
<td>87 85</td>
<td>- 45</td>
<td>- 98</td>
<td>111 120</td>
</tr>
<tr>
<td>Cu</td>
<td>65 59.7</td>
<td>17 12</td>
<td>- 13</td>
<td>- 33.3</td>
<td>16 18.4</td>
</tr>
<tr>
<td>Ni</td>
<td>12 28.5</td>
<td>- 5.1</td>
<td>- 1</td>
<td>- 12.5</td>
<td>6 15.8</td>
</tr>
<tr>
<td>Ba</td>
<td>1220 1208</td>
<td>1864 1870</td>
<td>- 1200</td>
<td>1297 1300</td>
<td>676 675</td>
</tr>
<tr>
<td>Cr</td>
<td>10 12.2</td>
<td>8 7</td>
<td>- 20</td>
<td>12 12.5</td>
<td>12 17.6</td>
</tr>
<tr>
<td>V</td>
<td>114 125</td>
<td>37 35.4</td>
<td>- 17</td>
<td>50 52.9</td>
<td>350 399</td>
</tr>
<tr>
<td>Sr</td>
<td>675 657</td>
<td>475 479</td>
<td>256 250</td>
<td>230 233</td>
<td>323 330</td>
</tr>
<tr>
<td>Zr</td>
<td>230 225</td>
<td>304 300</td>
<td>204 210</td>
<td>500 500</td>
<td>172 190</td>
</tr>
</tbody>
</table>

VUV: analyses made at Victoria University of Wellington by P.R. Kyle

Accepted value: estimates recommended by Flanagan, (1976)
Table B.3 Rare earth element analyses of USGS rock standards.

<table>
<thead>
<tr>
<th></th>
<th>BCR-1</th>
<th></th>
<th>G-2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OSU</td>
<td>Accepted value</td>
<td>OSU</td>
<td>Accepted value</td>
</tr>
<tr>
<td>La</td>
<td>24</td>
<td>26</td>
<td>87.2</td>
<td>96</td>
</tr>
<tr>
<td>Sm</td>
<td>6.3</td>
<td>6.6</td>
<td>6.96</td>
<td>7.3</td>
</tr>
<tr>
<td>Lu</td>
<td>.50</td>
<td>.55</td>
<td>.11</td>
<td>.11</td>
</tr>
<tr>
<td>Yb</td>
<td>3.30</td>
<td>3.36</td>
<td>.05</td>
<td>.88</td>
</tr>
<tr>
<td>Sc</td>
<td>31.5</td>
<td>33</td>
<td>3.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>

OSU: analyses by INAA at Ohio State University
Accepted value: estimates recommended by Flanagan, (1976)

Table B.4 Comparison between Na₂O and MnO analyses made by INAA and XRF.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Element</th>
<th>VUW XRF</th>
<th>OSU INAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>77M41</td>
<td>Na₂O</td>
<td>4.68</td>
<td>4.61</td>
</tr>
<tr>
<td>Trachyandesite</td>
<td>MnO</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>77M20</td>
<td>Na₂O</td>
<td>3.72</td>
<td>3.62</td>
</tr>
<tr>
<td>Quartz trachyte</td>
<td>MnO</td>
<td>0.34</td>
<td>0.33</td>
</tr>
<tr>
<td>77M1</td>
<td>Na₂O</td>
<td>6.62</td>
<td>6.40</td>
</tr>
<tr>
<td>Pantellerite</td>
<td>MnO</td>
<td>0.36</td>
<td>0.35</td>
</tr>
<tr>
<td>77M45</td>
<td>Na₂O</td>
<td>6.18</td>
<td>5.86</td>
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<tr>
<td>Comendite</td>
<td>MnO</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>77M21</td>
<td>Na₂O</td>
<td>3.28</td>
<td>3.27</td>
</tr>
<tr>
<td>Basanite</td>
<td>MnO</td>
<td>0.20</td>
<td>0.18</td>
</tr>
</tbody>
</table>

VUW: Victoria University of Wellington
OSU: Ohio State University
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