The petrogenesis of the alkaline rocks of the Judith Mountains, central Montana
by Paula Jean Barrick

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Earth Science
Montana State University

Abstract:
The Judith Mountains are part of the central Montana alkaline province. , Intrusive igneous activity began in the Judith Mountains about 68-69 m.y. ago with the emplacement of alkali-calcic plutons. Volume-trically minor but widespread alkaline igneous rocks were intruded 62-65 m.y. ago in the same terrane. This study focuses on the origin of the second (alkaline) intrusive event, which emplaced two different suites of alkaline igneous rocks.

The alkaline rocks are divided into two groups based on silica saturation: 1) a quartz-bearing assemblage consisting of syenite which contains xenoliths of alkali gabbro; and 2) a nepheline-bearing assemblage which includes tinguaite (a textural variety of nepheline syenite) and xenoliths of nepheline pyroxenite or ijolite. The two assemblages may be termed "mildly" and "strongly" alkaline.

The parent magma may have been kimberlite, since carbonatite-kimberlite magmas are known elsewhere in the province and local alteration (fenitization) suggests the presence of a buried carbonatite body. However, quartz-bearing alkaline rocks cannot be derived from an undersaturated kimberlitic magma except under certain special conditions. Therefore, the mildly and strongly alkaline rocks either formed from separate parent magmas, or formed from a single parent magma under two very different sets of conditions. The nearly contemporaneous emplacement of the two groups suggests a single parent magma pulse.

The early separation of the parent magma into two sub-magmas followed by physical separation of the magma chambers to two different levels in the crust could explain the formation of these two divergent alkaline assemblages.

Fractional crystallization of the strongly alkaline rocks is indicated by cumulate textures and by the formation of a residual melt, represented by tinguaite. Fractional crystallization may have taken place relatively deep in the crust. At a shallower depth, quartzbearing syenite could have separated from alkali gabbro by the process of liquid immiscibility. Immiscibility is promoted by low-pressure environments and is known to produce bimodal felsic and mafic rocks, with the felsic fraction having a much higher degree of silica saturation. Syenite bodies containing xenoliths of alkali gabbro were the first alkaline rocks to be emplaced, tinguaite dikes containing ijolite xenoliths were emplaced later, although in rare instances this sequence is reversed, suggesting nearly contemporaneous emplacement of the two groups.

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# THE PETROGENESIS OF THE ALKALINE ROCKS OF THE JUDITH MOUNTAINS, CENTRAL MONTANA

by

PAULA JEAN BARRICK

A thesis submitted in partial fulfillment
of the requirements for the degree

of

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in

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## ABSTRACT

The Judith Mountains are part of the central Montana alkaline province. Intrusive igneous activity began in the Judith Mountains about 68-69 m.y. ago with the emplacement of alkali-calcic plutons. Volumetrically minor but widespread alkaline igneous rocks were intruded 62-65 m.y. ago in the same terrane. This study focuses on the origin of the second (alkaline) intrusive event, which emplaced two different suites of alkaline igneous rocks.

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Fractional crystallization of the strongly alkaline rocks is indicated by cumulate textures and by the formation of a residual melt, represented by tinguaite. Fractional crystallization may have taken place relatively deep in the crust. At a shallower depth, quartz-bearing syenite could have separated from alkali gabbro by the process of liquid immiscibility. Immiscibility is promoted by low-pressure environments and is known to produce bimodal felsic and mafic rocks, with the felsic fraction having a much higher degree of silica saturation. Syenite bodies containing xenoliths of alkali gabbro were the first alkaline rocks to be emplaced, tinguaite dikes containing ijolite xenoliths were emplaced later, although in rare instances this sequence is reversed, suggesting nearly contemporaneous emplacement of the two groups.

# INTRODUCTION

## Purpose

The purpose of this investigation is to study the petrogenesis of the alkaline igneous rocks of the Judith Mountains. This study deals with two alkaline rock assemblages, one strongly alkaline and nepheline-bearing, and one mildly alkaline and quartz-bearing.

Previous investigations of the volumetrically subordinate alkaline rocks are of limited scope and only the felsic alkaline rocks were described. Origins proposed for the alkaline rocks, such as laccolithic differentiation (Weed and Pirsson, 1896) and limestone assimilation (Wallace, 1953) do not adequately explain the relationships and rock types observed. A more detailed examination of the alkaline rocks of the Judith Mountains was undertaken to help understand the origin of these rocks. The discovery of numerous mafic alkaline xenoliths in the felsic alkaline rocks shed much light on the origin of these alkaline rocks.

The first portion of this paper is a brief discussion of the geology and tectonic setting of central Montana and the Judith Mountains, followed by a detailed description of the alkaline rocks. The petrogenesis of the strongly and mildly alkaline assemblages is then discussed, and compared with other similar alkaline complexes. Finally, a petrogenetic model is proposed to explain the origin of the alkaline rocks of the Judith Mountains.

## Location

The Judith Mountains are an isolated group of forested peaks in central Montana which rise 300 to 760 meters above the surrounding plains, reaching a maximum altitude of 1915 m (6,280 ft) at Judith Peak. Figure 1 shows the location of the Judith Mountains and the other ranges which make up the central Montana petrographic province. The study area for this thesis is limited to the northern portion of the range (Figure 2).

Topography in the study area varies from rugged cliffs and talus slopes to sparsely forested grassy hills. Several gravel roads and unimproved jeep trails pass through the area, which is easily traversed by foot. Poor rock exposures inhibit detailed mapping in some areas, but the more resistant rock units, notably the tinguaite dikes, form resistant cliffs and walls.

Although much of this area is under the jurisdiction of the Bureau of Land Management, some of the surrounding land, especially in the eastern part of the study area, is privately owned. Excellent access to the Judith Peak-Red Mountain area is provided by a paved highway and an improved gravel road which leads to the abandoned Air Force radar base at the top of Judith Peak. Anyone wishing to visit the easternmost portions of the study area, however, should first contact the local landowners.

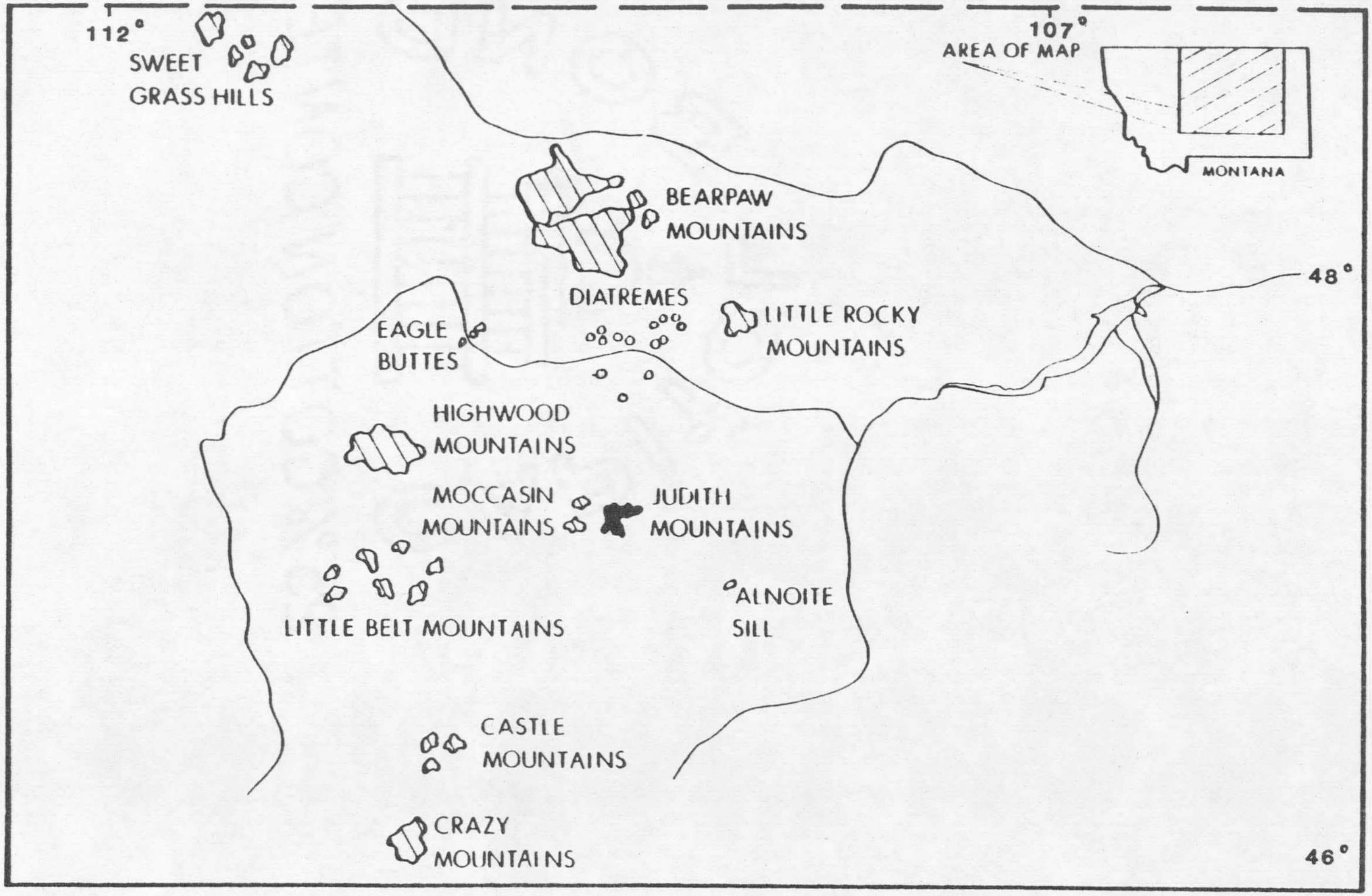


Figure 1. Location of the Judith Mountains, central Montana. Cretaceous-Tertiary igneous centers of the central Montana alkaline province are shaded in.

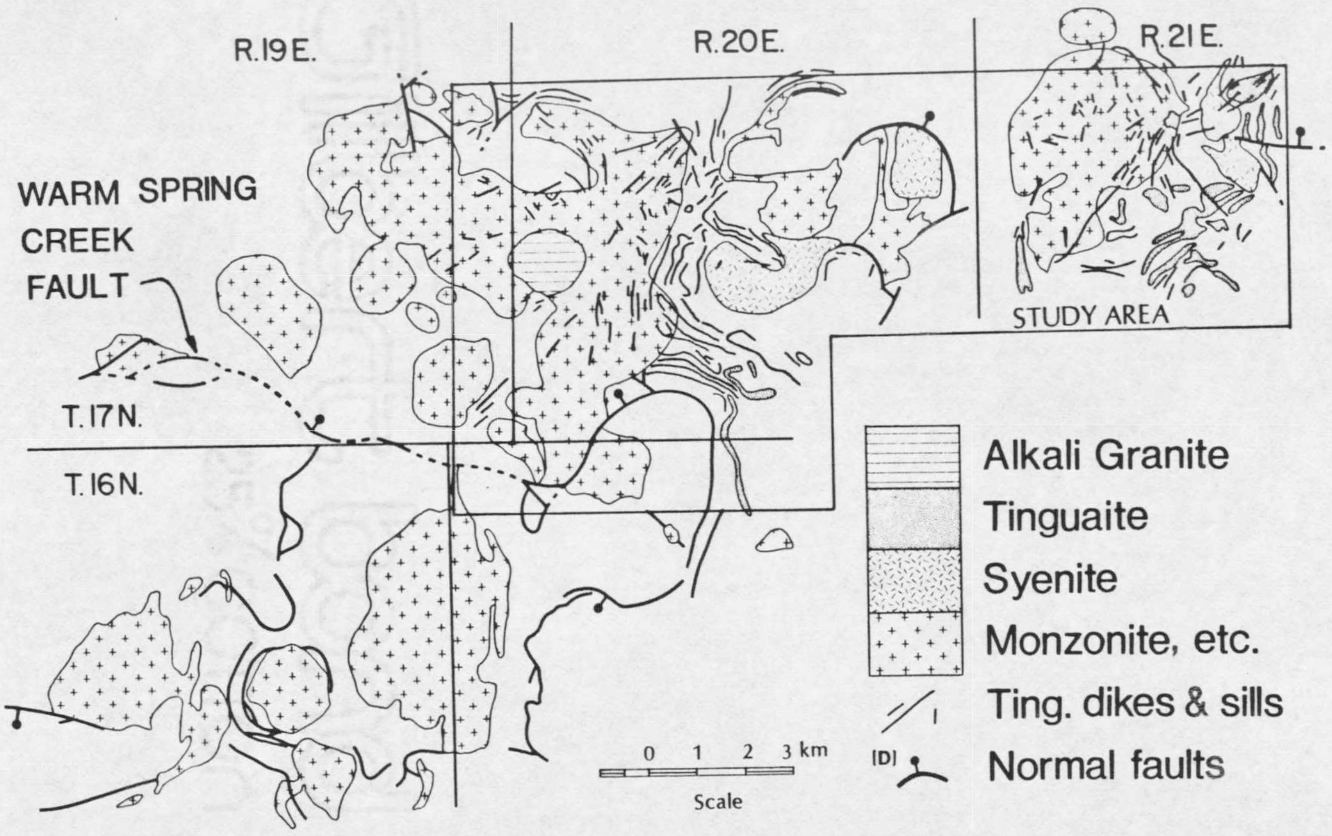


Figure 2. Generalized geologic map of the Judith Mountains (after Wallace, 1953). Study area is outlined.

## Regional Geology

A brief discussion of the regional geology will help to clarify the purpose for the current study. The Judith Mountains are part of a regional belt of igneous rocks widely scattered in isolated mountain groups east of the main trend of the Northern Rocky Mountains (Figure 1). Pirsson (1905) grouped these igneous centers into the central Montana petrographic province.

The province includes the Crazy Mountains (Wolff, 1938; Simms, 1966), Castle Mountains (Weed and Pirsson, 1896; Winters, 1968), Little Belt Mountains (Weed and Pirsson, 1895; Witkind, 1970), Judith Mountains (Weed and Pirsson, 1896; Wallace, 1953), Moccasin Mountains (Blixt, 1933; Miller, 1959), Highwood Mountains (Pirsson, 1905; Burgess, 1941; Larsen and others, 1941; Woods, 1976; Kendrick, 1980), Bearpaw Mountains (Weed and Pirsson, 1896; Bryant and others, 1960; Schmidt and others, 1967; Pecora, 1962; Hearn and others, 1964; Schmidt and others, 1962), Little Rocky Mountains (Weed and Pirsson, 1896; Emmons, 1908), and the Sweetgrass Hills (Weed and Pirsson, 1895; Truscott, 1975). Larsen (1940) also included the volcanic rocks of Yellowstone Park, the Absaroka Range and Adel Mountain volcanics (Lyons, 1944; Beall, 1973; Whiting 1974) in the province. Hearn (1969) included several diatremes along the Missouri River in the province.

The central Montana petrographic province is recognized as a group of igneous rocks related in space and time. The igneous rocks can be divided into subprovinces. The rocks within a subprovince display related chemical, mineralogical, and textural features, as well as similarities in the method of intrusion or extrusion and relation of the rocks to structural features.

The igneous rocks in the province vary from mafic to felsic and from calc-alkaline to alkaline in composition (Larsen, 1940). The calc-alkaline rocks are rhyolite, andesite and basalt and their intrusive equivalents. These rocks occur in Yellowstone Park and in the Crazy Mountains. Common minerals include quartz, calcic plagioclase, augite, hypersthene and olivine (Larsen, 1940).

Alkali-calcic rocks are widespread in Yellowstone Park, in the Absaroka and in the Adel Mountain area. Common rock types include trachybasalt, orthoclase gabbro, quartz monzonite, quartz latite and syenite (Larsen, 1940). Quartz latite from the Highwood and Bearpaw Mountains and quartz monzonite from the Judith Mountains and elsewhere also belong in this group.

Mafic alkaline rocks range from mafic-rich plagioclase shonkinite to plagioclase-free feldspathoidal rocks such as mafic phonolite. Felsic alkaline rocks include syenite, nepheline syenite, trachyte, phonolite and tinguaite. Feldspathoids, olivine, biotite, and orthoclase or sanidine are abundant; plagioclase, hornblende and quartz are rare. Diopsidic augite is by far the most abundant pyroxene, and is constant in composition from one part of the province to another.

Diatremes and intrusions of alkalic ultramafic rocks such as kimberlite and mica peridotite form isolated igneous centers in the alkalic province (Figure 1). These igneous features mark the waning phase of igneous activity in the central Montana alkaline province (Marvin and others, 1980).

Most of the alkaline rocks in the province have a high $K_2O/Na_2O$ ratio--that is, they are potassium-rich rocks, except for the Crazy Mountains, where alkaline rocks are rich in sodium. In the Judith Mountains, however, potassium-rich tinguaite contains xenolithic inclusions of sodium-rich ijolite. This association of potassium and sodium-rich rocks showing a coeval relationship is, so far as known, unique in the province, although examination of other tinguaite rocks in the province may show similar relations.

At many of the igneous centers of the central Montana alkaline province, two distinct periods of igneous activity occurred. The first produced alkali-calcic rocks; the second produced strongly alkaline rocks. For instance, in the Highwood Mountains, which lie 100 km west of the Judith Mountains, volcanic eruptions of quartz latite built a volcano several thousand feet high which was largely removed by erosion before new eruptions built a volcano of potassium-rich mafic phonolite (Larsen and others, 1941). Similarly, in the Judith Mountains, alkali-calcic intrusions of quartz monzonite (the intrusive equivalent of quartz latite) preceeded the emplacement of potassium-rich alkalic intrusions. A slight variation on this theme is found in the Bearpaw Mountains, where mafic phonolite and latite volcanics are unconformably overlain by analcime trachyte and mafic analcime phonolite (Larsen, 1940). The alkaline mafic phonolite was extruded earlier than the alkali-calcic latite. The significance of this relationship of alkali-calcic and alkaline rocks is not clear, but this pattern is a constant and characteristic feature of the alkalic province.

Magma sequences and evolution of rock types have also been repetitive in the region--alkaline rock types progress toward a late tinguaite magma; alkali-calcic types toward a rhyolite (Marvin and others, 1980).

The central Montana alkaline province is located in a tectonically stable region. The structure is dominated by broad arching or upwarping typical of the high plains east of the Rockies. Several west-northwest-trending fault zones, the "Lewis and Clark Lineaments" of central Montana (Fig. 3) are thought to reflect deep-seated lateral movement in the crust or upper mantle (Smith, 1965). Smith concludes that, on a regional scale, the igneous centers of the central

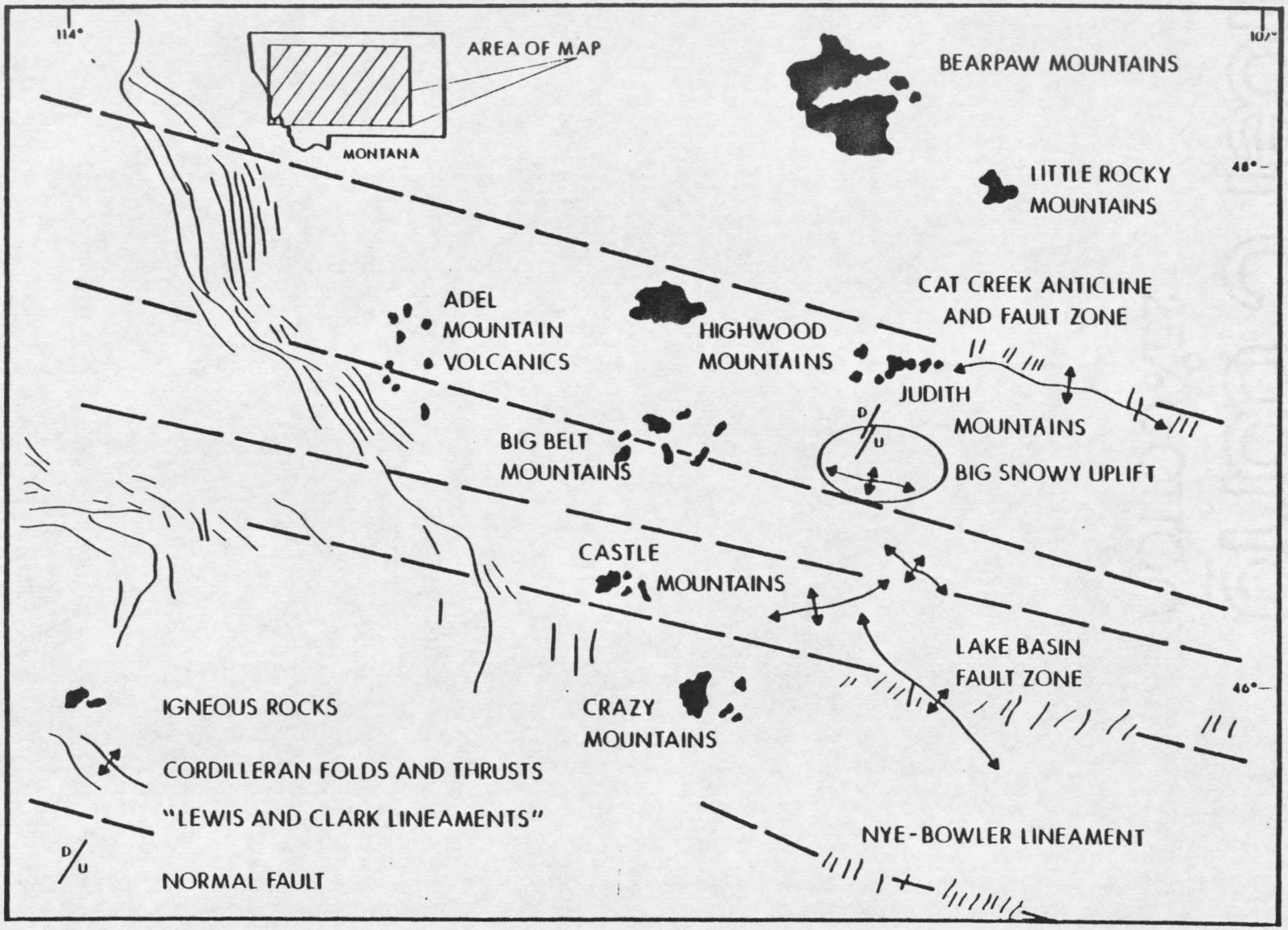


Figure 3. Tectonic map of central Montana showing "Lewis and Clark Lineaments" and associated features (after Smith, 1965).

Montana alkaline province are located on the edge of the stable craton where it is intersected by these deep-seated lineaments.

The Judith Mountains lie along the lineament marked at the surface by the Cat Creek fault zone (see Figure 3). Ore deposits in the Little Belt, Judith and Little Rocky Mountains also align with the northeast-trending Idaho-Montana Porphyry Belt or "Transverse Porphyry Belt" which contains many porphyry-type copper and molybdenum deposits (Figure 3), (Armstrong, 1978). This northeast-trending porphyry belt may correlate with a Precambrian basement structure inferred from aeromagnetic anomalies (Marvin and others, 1980).

A less prominent northeast structural trend is shown by two north-northeast-trending normal faults in the Big Snowy Mountains (Reeves, 1931) (Figure 3). The intersection of the Cat Creek fault zone and these northeast-trending zones may have controlled the emplacement of the igneous complex in the Judith Mountains.

## Previous Work

In the 1880's and 1890's, geologists first reported the fact that the outlying mountain groups east of the main trend of the Northern Rockies are composed of unusual alkaline igneous rocks (Iddings, 1892). Prompted by these reports, U.S. Geological Survey geologists visited the Judith Mountains in the early 1890's. The geology and mineral resources of the Judith Mountains were first described by

Weed and Pirsson (1896). They noted the lack of mafic igneous rocks in this area, a fact that makes the Judith Mountains unique in the alkalic province--"...there is not a single occurrence of what may be called a basic rock; they are all of light-colored feldspathic aspect, dark-colored pyroxenic rocks being absolutely wanting" (p. 557). They further speculated (p. 572) "... one must think that the basic types have not been erupted toward the surface and are still concealed below." They proposed "laccolithic differentiation" of the magma produced laccoliths of monzonitic material surrounded and cut by sills and dikes of tinguaite.

Wallace (1953) described the petrology of the igneous rocks of the Judith Mountains in a Ph.D. thesis published by the U.S. Geological Survey. Contrary to Weed and Pirsson (1896) who believed all the igneous rocks are laccoliths, Wallace concluded that nearly all the large bodies are stocks, citing the following evidence: 1) igneous-country rock contacts are often discordant or cross-cutting; 2) nearly all primary flow structures have steep dips; 3) the sedimentary roofs of many domes have been ruptured--in one area, vertical displacement of roof rocks is more than 1.5 km. Wallace (1953) believed limestone assimilation by the quartz monzonite magma desilicated the magma at depth to produce the alkalic rock types.

More recently, Hall (1977) studied a 700 m diamond drill core from the Judith Peak-Red Mountain area. He concluded that intense potassium metasomatism and late calcite-fluorite-quartz veins present in the bottom 400 meters of the core indicate that a carbonatite body is present at depth.

Early radiometric ages for igneous rocks in the central Montana alkaline province suggested that all these rocks were Eocene in age (Baadsgarrd and others, 1961; Marvin and others, 1973). Recent geochronologic work (Marvin and others, 1980) indicates that intrusive and extrusive activity in north-central Montana ranged from Late Cretaceous to Eocene time. In their study, Marvin and others (1980) found that igneous activity in north-central Montana started about 68-69 m.y. ago in the Judith Mountains. According to radiometric ages, the earliest intrusion, 68-69 m.y. ago was quartz monzonite, followed by monzonite and diorite, both 67 m.y. old. Alkali syenite, tinguaite and alkali granite samples yield ages of 65, 65, and 62 m.y. old, respectively. However, the age dates determined are discordant and subject to various interpretations. Marvin and others (1980) point out that the Judith Mountains are geochronologically more complex than the other igneous centers in central Montana. The sequence established radiometrically is, however, generally similar to the sequence established by Wallace (1953) from field relations.

## Methods

Field mapping and sampling during the summers of 1978 and 1979 provided a wealth of new data. Wallace's (1953) geologic map and his original air photos showed many of the field relationships and occurrences of the various alkaline rock types. Limited additions and corrections to Wallace's mapping were made by the author; the information on the geologic map (Plate 1) was largely taken from Wallace's air photos. Fourty-eight thin sections of alkaline rocks were examined by polarizing microscope and described. Chemical analyses of the alkaline rocks from Wallace (1953) and Weed and Pirsson (1896) are compiled in Table 5.

# GENERAL GEOLOGY OF THE JUDITH MOUNTAINS

## Sedimentary Units

The sedimentary rocks domed and displaced by igneous intrusions form a stratigraphic column about 1,800 m thick (Wallace, 1953). The oldest rocks exposed are the Cambrian Flathead Sandstone and Wolsey Formation (Wallace, 1953). From oldest to youngest, the other stratigraphic units which surround the igneous rocks are the Mississippian Madison and Big Snowy Groups, the Jurassic Ellis Group and Morrison Formation, and the Cretaceous Kootenai Formation, Colorado Group, Telegraph Creek Formation, and Eagle Formation (Wallace, 1953).

## Warm Spring Creek Fault

The Warm Spring Creek normal fault (Figure 2), which bisects the mountains, was active between Mississippian and Jurassic time, and was reactivated when igneous bodies were intruded along the fault in Late Cretaceous time. Earlier activity on this fault is indicated by an abrupt change in the stratigraphic section north and south of the fault (Wallace,1953). The Mississippian Big Snowy Group is almost entirely absent from the upthrown south side of the fault where it was removed by erosion prior to the deposition of Jurassic rocks (Wallace, 1953). Several rhyolite bodies lie along the fault and the small igneous body east of the surface trace of the fault suggests an eastern continuation at depth, although the fault, as reactivated, now curves southward at the eastern end (Figure 2).

The igneous complex is elongate in an east-west direction, especially in the northern part of the range (Figure 2; Plate 1). The Warm Spring Creek fault also trends generally in an east-west direction. These trends suggest near-surface crustal weaknesses with similar east-west orientations.

## Alkali-Calcic Igneous Rocks

The alkali-calcic rocks constitute 60-70% of the the igneous rocks (Wallace, 1953), and form stocks and plugs which coalesce in the north-central part of the range to form a large irregular pluton (Figure 2). Rock types include quartz monzonite, monzonite, quartz diorite, diorite, syenite and rhyolite (Wallace, 1953; Forrest, 1971). Rhyolite is the youngest rock in the sequence. These rocks are Late Cretaceous (67-69 m.y. old) (Marvin and others, 1980).

The alkali-calcic rocks are all porphyritic; the groundmass material is aphanitic. Phenocrysts include large orthoclase or sanidine feldspar, smaller plagioclase (oligoclase in the quartz monzonite, sodic andesine in the rhyolite), quartz, hornblende (usually much altered) and diopside in the quartz monzonite (Wallace, 1953).

## Alkaline Igneous Rocks

Alkaline rocks form dikes, sills and large tabular bodies and cut the alkali-calcic rocks. The alkaline rocks occur mainly in the northern portion of the mountains and are volumetrically subordinate compared to the alkali-calcic rocks.

The oldest alkaline rock exposed is quartz-bearing syenite. The largest alkaline intrusion is the syenite mass at Maginnis Mountain (Plate 1). Flat flow structures in the lower part of the intrusion indicate that it is a floored intrusion (Wallace, 1953). Discordant upper contacts, however, show that it is not a true laccolith (Wallace, 1953). The alkaline syenite masses at Lewis Peak and west of Lookout Peak are probably floored intrusions resembling laccoliths or thick sill-like bodies with slightly arched roofs. The sill-like nature of these bodies is shown by the concordant contacts with country rocks and by the flat dips of flow structures (Wallace, 1953).

Gray and green tinguaite bodies cut the syenite intrusions. Green tinguaite dikes form two crudely radial dike swarms in the north-central and northeastern parts of the mountains, within the boundaries of the study area (Plate 1). The dikes range in thickness from a few centimeters to over 30 meters, and can have an outcrop length of a few meters to more than a kilometer. Sills of green and gray tinguaite are particularly numerous within shale beds in the Cretaceous Colorado Group. Sills average about two meters thick and some can be traced for more than 4.5 km. Several small round bodies of gray tinguaite are found near the eastern boundary of the study area.

The largest has an elliptical shape and measures about one kilometer along the long axis (Plate 1).

The youngest alkaline rock type in the Judith Mountains is alkali granite which occurs as a circular stock (according to Wallace, 1953) or a cone sheet (according to R. Leonardsen, verbal comm., 1979) 1.6 km in diameter at Judith Peak (Plate 1). The peripheral part of the stock is composed of fine-grained alkali granite. In the east-central portion of the intrusion, this fine-grained facies is cut by a coarse-grained facies. Both types are cut by an intrusion breccia.

# PETROLOGY OF THE ALKALINE ROCKS

## Introduction

Classification. Syenite is classified according to the modes of its leucocratic minerals (Streckeisen, 1976). Tinguaite, which is a textural variety of phonolite, has the composition of nepheline syenite (Streckeisen, 1976). The terminology employed for the ijolitic rocks is pyroxenite-95-melteigite-70-ijolite-30-urtite-5-nepheline rock where figures refer to color indices or percent mafic minerals. The term "nephelinite" refers to the fine-grained extrusive equivalent of melteigite and is often used to describe primary nepheline-pyroxene mafic magmas. The alkali gabbro contains plagioclase, pyroxene, biotite, amphibole, and potassium feldspar. Some rocks classified as alkali gabbro could be designated as essexite, theralite, or feldspathoid-bearing monzonite. For simplicity, the term 'alkali gabbro' is preferred in this study.

The alkaline rocks can be divided into two groups--'strongly' alkaline (tinguaite and ijolitic rocks) and 'mildly' alkaline (syenite and alkali gabbro). The syenite, which is quartz-bearing, may be termed 'mildly' alkaline, when compared to the tinguaite, which is strongly undersaturated with respect to silica and contains nepheline. The division of alkaline rocks into mildly or strongly alkaline groups, based on the presence of quartz or nepheline is discussed by other authors, i.e. Williams (1970). The significance of coexisting mildly and strongly alkaline rocks will be developed further in the discussion on petrogenesis of the alkaline rocks.

Age Relations and Emplacement Sequence. The alkaline rocks have been dated as Paleocene (65-62 m.y.) (Marvin and others, 1980). Alkali syenite, green tinguaite and alkali granite have ages of 65, 65, and 62 m.y., respectively (Marvin and others, 1980). These dates represent the best interpretations from a wide range of dates which were obtained. Even for individual samples, dates are conflicting, and subject to various interpretations. For instance, a fission track age on apatite in a sample of green tinguaite gave a Cretaceous age (73.3 m.y.). For the same sample, a sanidine K-Ar date gave an Eocene age (53.7 m.y.). Because of intrusive field relations, the green tinguaite was assigned an age of 65 m.y., and the two radiometrically determined dates were considered spurious (Marvin and others, 1980). Additional age dates on the tinguaite as well as the other alkaline rocks are needed.

The intrusive sequence of the alkaline rocks appears to be as follows: alkali gabbro; syenite; ijolitic rocks; gray tinguaite; green tinguaite; carbonatite (?); alkali granite.

Syenite is the oldest alkaline rock exposed in the study area, but the mafic alkali gabbro xenoliths in the syenite must have crystallized at depth before the syenite was formed. Gray tinguaite intrusions followed the emplacement of syenite, since gray tinguaite dikes cut syenite bodies. However, in one area, a gray tinguaite sill is cut by a syenite dike, indicating a nearly contemporaneous relationship of syenite and gray tinguaite. Green tinguaite dikes cut both syenite and gray tinguaite. Both the gray and green tinguaite contain xenoliths of ijolitic rocks, which must have formed at depth before the formation of the tinguaite. The intrusion of the green tinguaite was followed closely by the formation of intrusion or explosion breccia in the Red Mountain area. A few small green tinguaite dikes cut the breccia, but have been altered or metasomatized along with the breccia and other rocks in that area. The emplacement of alkali granite was the final episode in the intrusion of the alkaline rocks. Calcite-fluorite-quartz veins found in a diamond drill hole below 300 meters are thought to be related to a buried carbonatite (Hall, 1977). The age relations between the alkali granite and the carbonatite(?) are not known, but the alkali granite intrudes the metasomatized rocks, and probably post-dates the carbonatite, since the metasomatism is thought to have been caused by the carbonatite.

## Mafic Xenoliths

The Judith Mountains contain several types of mafic alkaline rocks not previously described. Especially important are two suites of mafic alkaline rocks contained as xenoliths in the syenite and tinguaite. These xenoliths are composed essentially of pyroxene, amphibole, and nepheline or plagioclase. The xenoliths can be classified as rocks of the ijolite series and as alkali gabbro.

The ijolitic rocks occur as xenoliths in the tinguaite; the alkali gabbro occurs as xenoliths in the syenite. All the xenoliths appear to have a plutonic origin: they have a more or less uniform massive fine- to medium-grained massive texture. Their dark color causes them to stand out against the felsic rocks in which they are contained. They form rounded inclusions ranging in size from 1.5 mm to over 50 cm in diameter. One-third of the tinguaite and syenite rocks studied in thin section contain microscopic xenoliths which were not apparent in hand specimen. The abundance and unique mineralogy of these xenoliths underscores their importance in interpreting the petrogenetic history of the alkaline rocks.

### Alkali Gabbro

The modal mineralogy of the alkali gabbro is somewhat variable (Table 1). In hand specimen, the alkali gabbro occurs as massive, fine- to medium-grained black to dark brown xenoliths in the syenite (Figure 4). In thin section (Figures 5 and 6), pale green diopside commonly constitutes about 20% of the rock. The diopside forms small

| | 2JPS1 | 2LPS1 | 2FMS1 | 2FMS2 | 2FMS3 | 2FMS4 |
|---|---|---|---|---|---|---|
| Diopside | 13 | -- | 23 | 20 | 17 | 15 |
| Amphibole | 10 | -- | -- | 15 | 20 | 30 |
| Biotite | 10 | 45 | 20 | 15 | 3 | 5 |
| Plagioclase | 40 | 10 | 26 | 25 | 35 | 27 |
| Orthoclase | 15 | tr | 10 | 20 | 15 | 15 |
| Analcime & zeolites | -- | 7 | 3 | 2 | 2 | 3 |
| Magnetite | 10 | 3 | 5 | 3 | 5 | 2 |
| Apatite | 2 | 1 | 2 | 2 | 2 | 3 |
| Sphene | tr | tr | -- | -- | tr | tr |
| Calcite | -- | 10 | -- | -- | -- | -- |
| Chlorite | tr | 20 | 12 | -- | -- | -- |
| Garnet | -- | 5 | -- | -- | -- | -- |

Table 1. Modes of Alkali Gabbro (estimated in thin section).

Figure 4. Photograph of syenite containing inclusions of alkali gabbro. Sample on left contains two small rounded inclusions; sample to right is syenite with a large alkali gabbro xenolith. Figure 5 is a photomicrograph of the large alkali gabbro xenolith.

Figure 5. Photomicrograph of alkali gabbro, plane light. Sample contains diopside, diopside intergrown with magnetite, and biotite. Light minerals are plagioclase and orthoclase, (X 150).

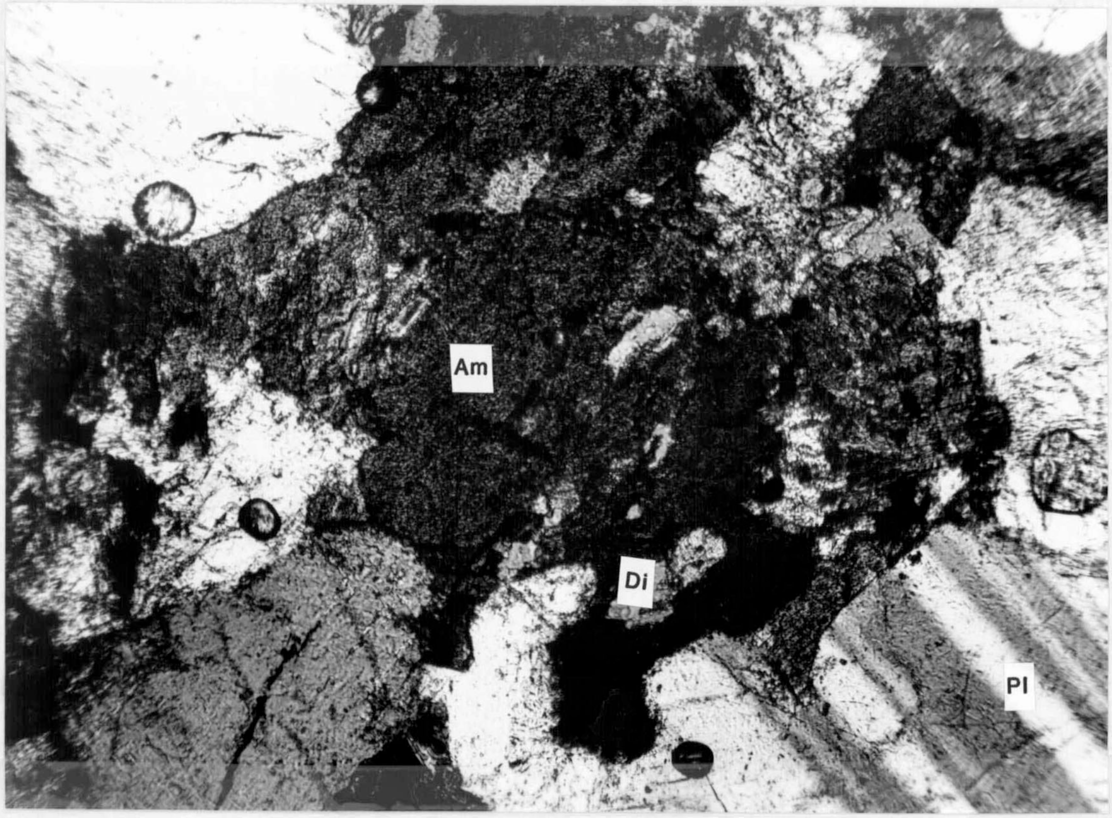


Figure 6. Photomicrograph of alkali gabbro; polarized light. Contains diopside, arfvedsonite amphibole enclosing diopside remnants, and twinned plagioclase. (X 150).

anhedral to subhedral crystals ranging from less than 0.1 mm to about 5 mm in diameter. Some crystals show exsolution of thin opaque rods, possibly ilmenite. The diopside can be complexely intergrown with opaque iron oxide in a subgraphic texture. These graphic 'grains' contain as much as 40-50% opaque oxide, probably ilmenite or titanomagnetite. Magnetite also occurs as separate octahedra within the gabbro.

Amphibole (X=deep greenish brown, Y=deep brownish green, and Z=pale greenish brown) occurs as subhedral grains and as patches on the edges of pyroxene. The amphibole has a small 2V (10°), and nearly parallel extinction. These properties best fit arfvedsonite, a sodic amphibole (Deer and others, 1975). Amphibole varies from being totally absent to forming more than 30% of the rock, making it more abundant than pyroxene in some samples. Amphibole occurs as a marginal overgrowth or replacement of pyroxene in some samples, other samples contain subhedral crystals of amphibole which appear to have formed directly from the magma.

Biotite (X=Y=greenish brown to brownish red, Z=pale golden brown to pale orange) is found in all the gabbroic rocks. The reddish brown color probably indicates a high titanium content (Deer and others, 1975, p. 213). Biotite forms patches on the edges of both the pyroxene and amphibole; it also occurs as plates 1 to 4 mm long poikilitically enclosing rounded blebs of embayed, optically continuous pyroxenes. At least some, and perhaps all, of the biotite replaces pyroxene and amphibole. In some samples, biotite and diopside are the only mafic minerals present, in others, diopside, biotite and amphibole occur together. The amount of biotite is extremely variable, and some samples show biotite-rich zones.

In some samples, green chlorite occurs as optically continuous overgrowths on the edges of biotite. Chlorite ranges from trace amounts up to 20 percent and is probably secondary.

Plagioclase occurs as equidimensional crystals averaging 1.5 mm. Plagioclase is a significant component of the alkali gabbro, varying from 15 to 50%. The plagioclase in some samples is zoned from An58 to An32 (as determined by extinction angles). Plagioclase displays albite and pericline twinning; in some crystals, sodic overgrowths are untwinned. In one sample, plagioclase forms continuous interstitial patches poikilitically enclosing pyroxene grains. Orthoclase is subordinate in amount to plagioclase, and forms small wedge-shaped patches between other minerals, averaging 5-15% of the rock. Isotropic analcime(?) is present in trace amounts in most samples.

All of the alkali gabbro samples contain needles and hexagonal prisms of apatite up to 1.5 mm in diameter. Euhedral sphene is present in trace amounts, and secondary calcite is common.

Textural evidence indicates the sequence of crystallization was as follows (Figure 7): diopside began to crystallize first, but the diopside intergrown with magnetite appears to have formed after diopside alone. Amphibole then began to crystallize and some of the diopside was altered to amphibole. Plagioclase began to crystallize before all the amphibole had formed, and biotite formed as an alteration of pyroxene and amphibole after those minerals had ceased to crystallize. Orthoclase crystallized after plagioclase, and biotite became altered to chlorite. Analcime(?) occurs as a late-stage small-scale alteration mineral. The sequence diopside-amphibole-biotite requires increasing amounts of water, possibly evolved from the parent magma, but more likely leached from crustal sources as crystallization proceeded.

### Syenite

There are two major types of syenite in the Judith Mountains (Wallace, 1953). The major difference between the two types is that one type contains only sodic amphibole as a mafic mineral and the other type contains both diopside and amphibole. There are several other kinds of syenite scattered throughout the study area, in addition to the two major types. The syenite bodies on the geologic map (Plate 1) are not differentiated, but are all shown simply as syenite. Table 2 shows the modal mineralogy of several syenite samples.

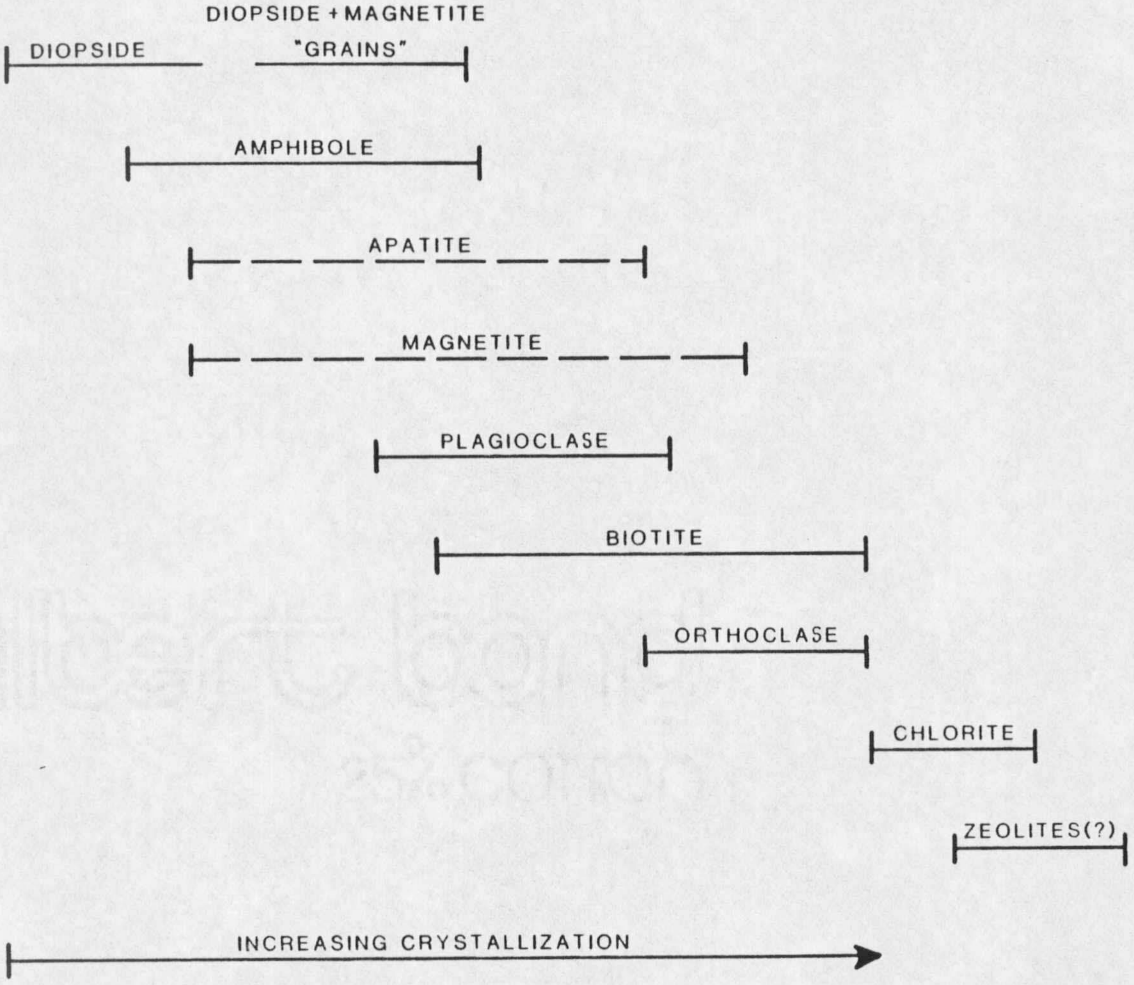


Figure 7. Crystallization sequence of alkali gabbro.

| | 2DTG | 2LPS1 | 2DS | 2JPS1 | 2FMS4 | 2LPS2 |
|---|---|---|---|---|---|---|
| Groundmass | 60 | 57 | 55 | 10 | 40 | 55 |
| Orthoclase | 10 | 3 | 5 | 30 | 15 | 15 |
| Plagioclase | 15 | 25 | 25 | 40 | 30 | 15 |
| Amphibole | 3 | 10 | 10 | tr | 2 | 6 |
| Diopside | 12 | -- | -- | 7 | 12 | -- |
| Biotite | -- | 2 | -- | tr | 1 | tr |
| Quartz | -- | 3 | 5 | 10 | 2 | 1 |
| Magnetite | tr | tr | tr | 3 | 3 | 3 |
| Sphene | tr | tr | tr | tr | tr | tr |
| Calcite | -- | -- | -- | -- | -- | 5 |

Table 2. Modes of syenite (estimated in thin section).

The most voluminous type of syenite is the "Lewis Peak type" (Wallace, 1953). This syenite makes up the large mass at Lewis Peak and the two bodies west and southwest of Lookout Peak (Plate 1). This syenite is a light to medium gray fine-grained porphyritic rock, commonly crowded with small equidimensional feldspars averaging 2 mm in size. The amount of plagioclase (An 32-An 36) and orthoclase is about equal. Conspicuous needles of sodic amphibole measure 2 to 5 mm. Sodic amphibole is the only mafic mineral in this type of syenite. Sphene, apatite and magnetite are present in trace amounts. Small scattered nests of quartz are present in the groundmass.

Although most samples of Lewis Peak syenite appear fresh in hand specimen, mafic minerals are commonly altered to aggregates of calcite and magnetite. Wallace (1953) stated that the mafic mineral in this syenite is hornblende, but, where identifiable, the amphibole is the same sodic variety present in the alkali gabbro (arfvedsonite). Figure 4 shows hand specimens of syenite containing alkali gabbro xenoliths.

The second type of syenite, Wallace's "Maginnis Mountain type" crops out at Maginnis Mountain and in the Linster Peak area (Plate 1). The rock is pale yellowish-brown, fine-grained and porphyritic. Orthoclase phenocrysts range from 4 to 7 mm. Plagioclase phenocrysts are smaller, averaging 2 mm. Figure 8 is a photomicrographic of Maginnis Mountain syenite. Diopside is the principal mafic mineral, constituting 12-15% of the rock, and measuring about 1 mm. Rare needles

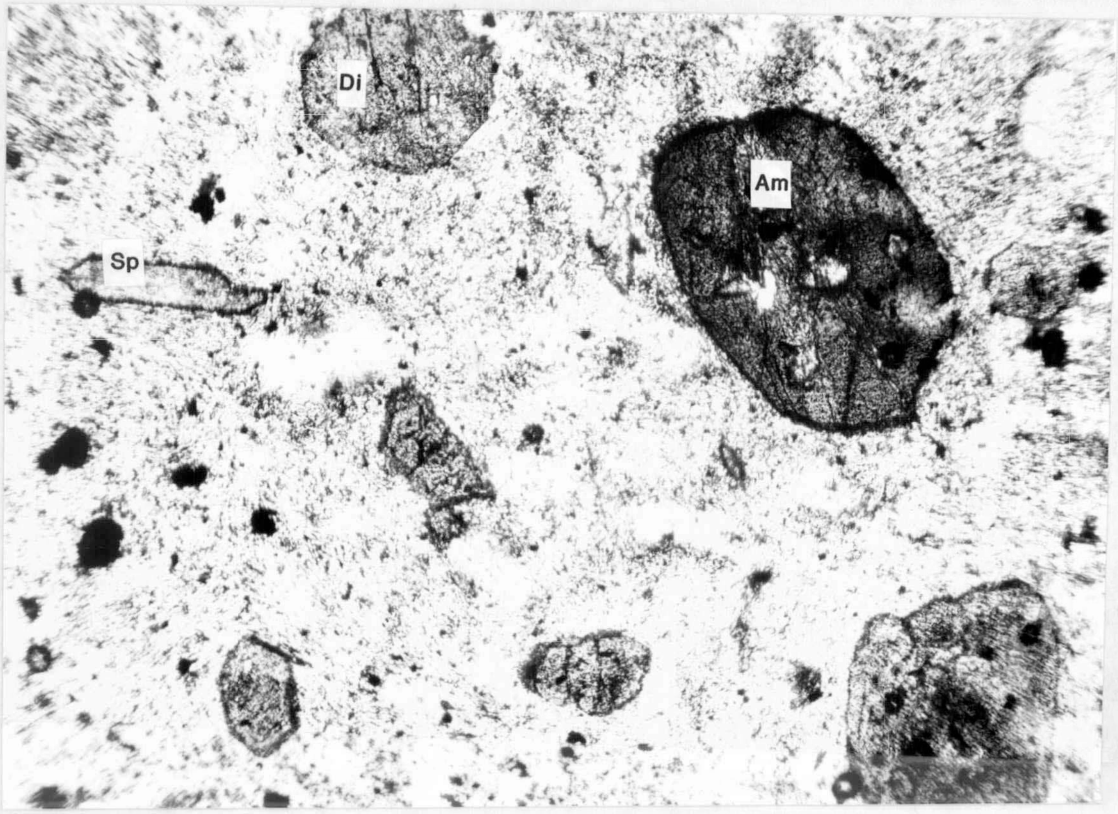


Figure 8. Photomicrograph of syenite; plane light. Large rounded phenocryst is sodic amphibole bordered by magnetite grains. Lighter gray phenocrysts are diopside, wedge shaped crystal is sphene. (X 150).

of amphibole and plates of biotite are scattered throughout the rock. Both biotite and amphibole show corrosion and are bordered by magnetite grains. Accessory minerals include sphene, apatite, magnetite, and quartz. The samples of "Maginnis Mountain syenite" are also somewhat altered, although to a lesser degree than the "Lewis Peak type." Mafic minerals and plagioclase show the strongest alteration effects and in many places are altered to magnetite, chlorite, sericite and calcite.

Scattered about the study area are exposures of other kinds of syenite in dikes, sills, and irregular and poorly exposed bodies. These types of syenite are not the same as the two major types, and not always similar in mineralogy to each other. Syenite also may be associated with the older large alkali-calcic plutons as a border phase (Forrest, 1971).

Several samples of various syenite bodies were studied in thin section. In these syenites, there are large orthoclase and smaller plagioclase phenocrysts. Some samples contain labradorite (An 55), some zoned plagioclase (An 48-An 32), and one sill contained albite (An 5), rimmed by orthoclase. One type of syenite contains crowded orthoclase zoned plagioclase phenocrysts which make up more than 80% of the rock. In individual samples, analcime, sodalite or calcite may occur in filled vesicles or fracture fillings. Quartz is found in some samples. Practically all the syenite contains pale green diopside and small magnetite octahedra. A very large dike of syenite southwest of Lookout Peak contains elongate xenocrysts of sodic amphibole (arfvedsonite) and numerous mafic alkali gabbro xenoliths.

Biotite, chlorite and calcite replace original mafic minerals in most of these rocks. One highly altered syenite sill in the roadcut west of Big Grassy Peak contains melanite garnet phenocrysts and aegirine needles in the ground-mass.

## Pyroxenite, Melteigite and Ijolite

In hand specimen, the ijolite-series rocks (including pyroxenite, melteigite and ijolite) are massive fine- to medium-grained greenish black xenoliths. They are composed of black lustrous pyroxene prisms with some interstitial nepheline. Thin veinlets of pure nepheline cut some xenoliths locally, giving specimens a gneissoid appearance. These veinlets do not cut the host rock, which is always gray or green tinguaite. Figure 9 shows a large xenolith of ijolite enclosed in gray tinguaite.

In thin section, these rocks show highly variable mineral percentages even within the space of a few centimeters. Modes of samples studied in thin section are shown in table 3.

Figure 9. Large ijolite inclusion in gray tinguaite. The upper left part of the inclusion and the separate sample to the right show nepheline veinlets which give the ijolite a gneissic appearance.

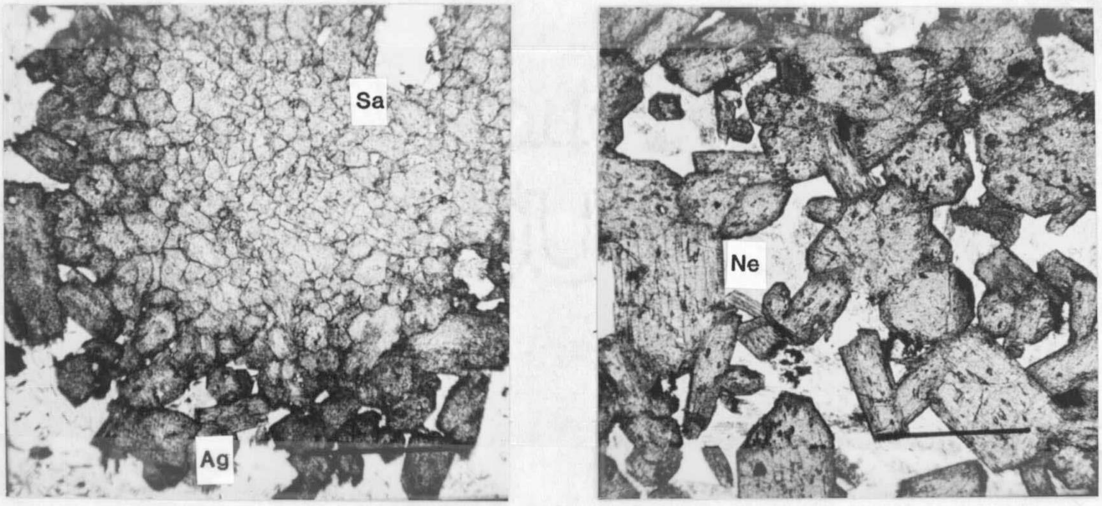
| | Pyroxenite | Melteigite | | | | Ijolite | | | |
|---|---|---|---|---|---|---|---|---|---|
| | RMT11 | AT3 | RMT3 | LPT3 | FMT6 | LPT11 | RMT10 | AT13 | LPT4 |
| Pyroxene | 95 | 60 | 20 | 20 | 43 | 42 | 55 | 65 | 55 |
| Nepheline | 3 | 10 | 10 | -- | 15 | 25 | 25 | 25 | -- |
| Analcime & zeolites | 2 | 5 | 2 | 2 | 5 | 30 | 20 | 9 | 40 |
| Melanite | -- | -- | 60 | 75 | 10 | tr | -- | -- | -- |
| Magnetite | -- | 15 | 5 | 3 | 20 | 2 | 1 | 1 | tr |
| Sphene | -- | 10 | 3 | tr | 2 | 1 | 3 | -- | 5 |
| Biotite | -- | -- | -- | -- | -- | tr | tr | tr | -- |
| Chlorite | -- | -- | -- | -- | -- | tr | tr | -- | -- |
| Apatite | -- | -- | -- | -- | -- | tr | tr | -- | -- |
| Calcite | -- | -- | -- | -- | -- | tr | tr | -- | -- |
| Pectolite | -- | -- | -- | -- | -- | -- | tr | -- | -- |
| Cancrinite | -- | -- | -- | -- | -- | tr | tr | -- | -- |

Table 3. Modes of ijolitic rocks (estimated in thin section).

The pyroxene content varies from nearly 100% (rarely) to about 20%. The pyroxenes in the pyroxenite form a mosaic of anhedral crystals 0.05 to 0.5 mm in size (Figure 10A). Melteigite and ijolite samples contain subhedral to euhedral pyroxene prisms 0.5 to 2 mm in length. Figures 10B and 11 are photomicrographs of melteigite and ijolite. The pyroxenes commonly exhibit a prominent zonation from pale green cores to deep green margins. The pleochroic scheme is X=pale green, Y=pale green, Z=pale brown within the cores of the zoned crystals; X=emerald green, Y=bluish green, Z=pale greenish brown on the margins of the zoned pyroxenes. The angle Z C varies from 38° in the cores to 85° near the margin. The index of refraction $n_y$=1.705 in the cores of the crystals, and a 2V of about 60° indicate that this pyroxene is diopsidic augite (salite) (Deer and others, 1975), the common pyroxene of the alkalic province. The salite is rimmed by aegirine-augite with nearly parallel extinction.

Rarely, biotite occurs as patches within the pyroxene grains. The biotite probably represents a small-scale replacement of the pyroxene.

Nepheline varies from 3% to over 25% in the ijolite. The nepheline is interstitial, and rarely more than 2 mm across. Nepheline is altered to analcime, natrolite and other zeolites. Nepheline and its alteration products may account for as much as 55% of the leucocratic



A.

B.

Figure 10. A. Photomicrograph of a pyroxenite inclusion, plane light. Small anhedral crystals in center of inclusion are salite. Near the margins of the inclusion, salite grains are zoned to deeply pleochroic aegirine-augite. Large white area in center of inclusion is a hole in the slide. Bar is 1 mm.

B. Photomicrograph of melteigite, plane light. Shows classic cumulate texture with salite crystals zoned to dark aegirine-augite margins. Interstitial phase is nepheline and/or alteration products of nepheline. Bar is 1mm.

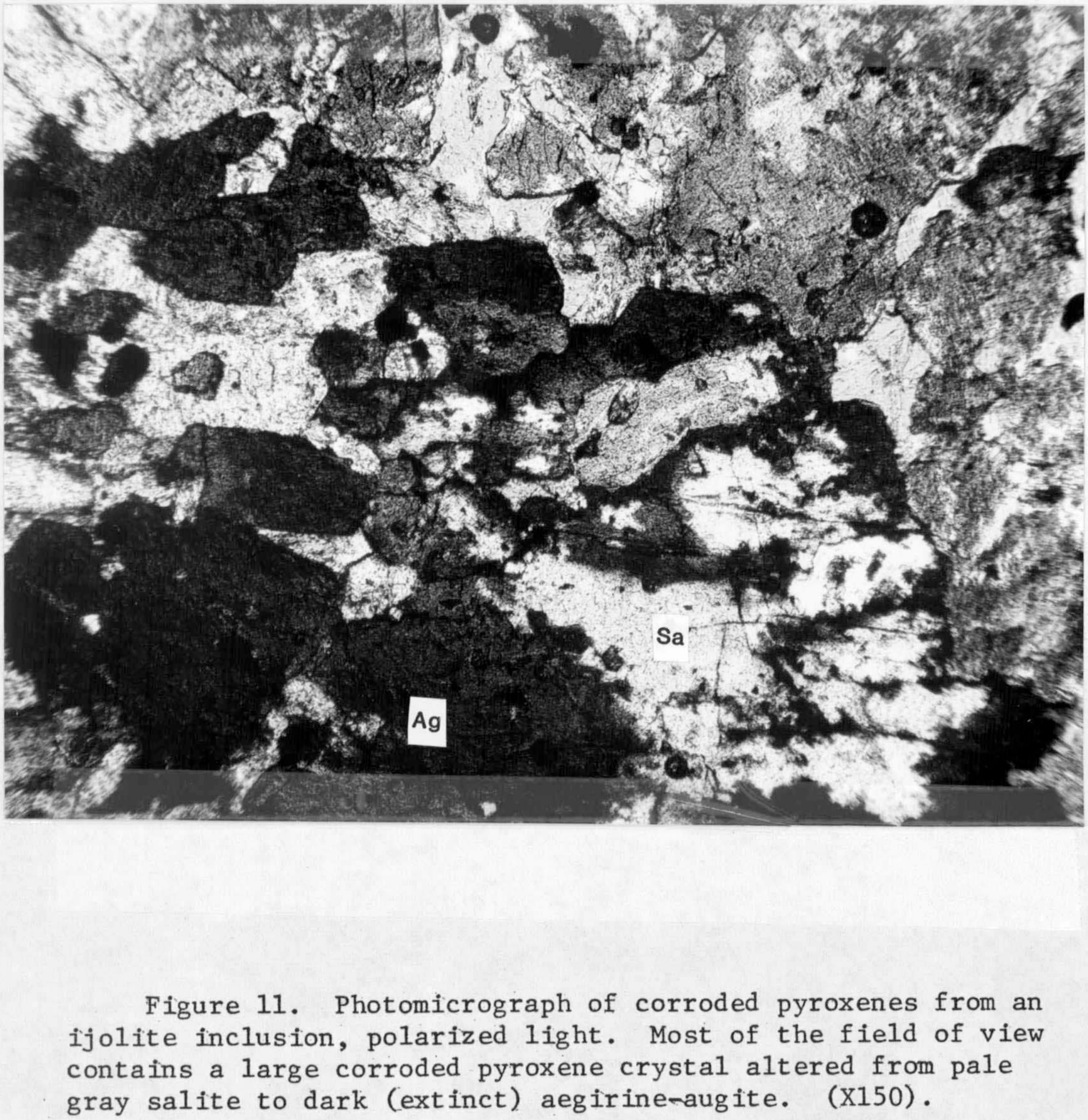


Figure 11. Photomicrograph of corroded pyroxenes from an ijolite inclusion, polarized light. Most of the field of view contains a large corroded pyroxene crystal altered from pale gray salite to dark (extinct) aegirine-augite. (X150).

minerals in the ijolite. As the amount of nepheline in a sample increases, the pyroxenes show a tendency to be zoned to more sodic (or more aegirine-rich) rims. The introduction of nepheline appears to be an essential feature of the transformation of salite to aegirine-augite in the melteigite and ijolite.

Zoned melanite garnet (Ti-rich andradite) is a highly variable component of these rocks and may be entirely absent or may form major portion of the rock. Euhedral melanite encloses pyroxene, sphene, magnetite and altered inclusions of nepheline. The sporadic distribution of melanite is a characteristic feature of ijolite.

Euhedral sphene, magnetite and apatite are ubiquitous accessories. Secondary calcite, chlorite and pectolite have also been observed.

Salite began to crystallize first (Figure 5); sphene was also an early phase. Salite became zoned to aegirine-augite with continued crystallization. Magnetite, apatite and additional sphene crystallized after most of the pyroxene had had formed. Nepheline crystallized later than pyroxene, and is an interstitial phase. Nepheline is more or less altered to analcime, fibrous natrolite and cancrinite or other zeolites. Melanite is a late-formed mineral, most of it crystallized after the nepheline.

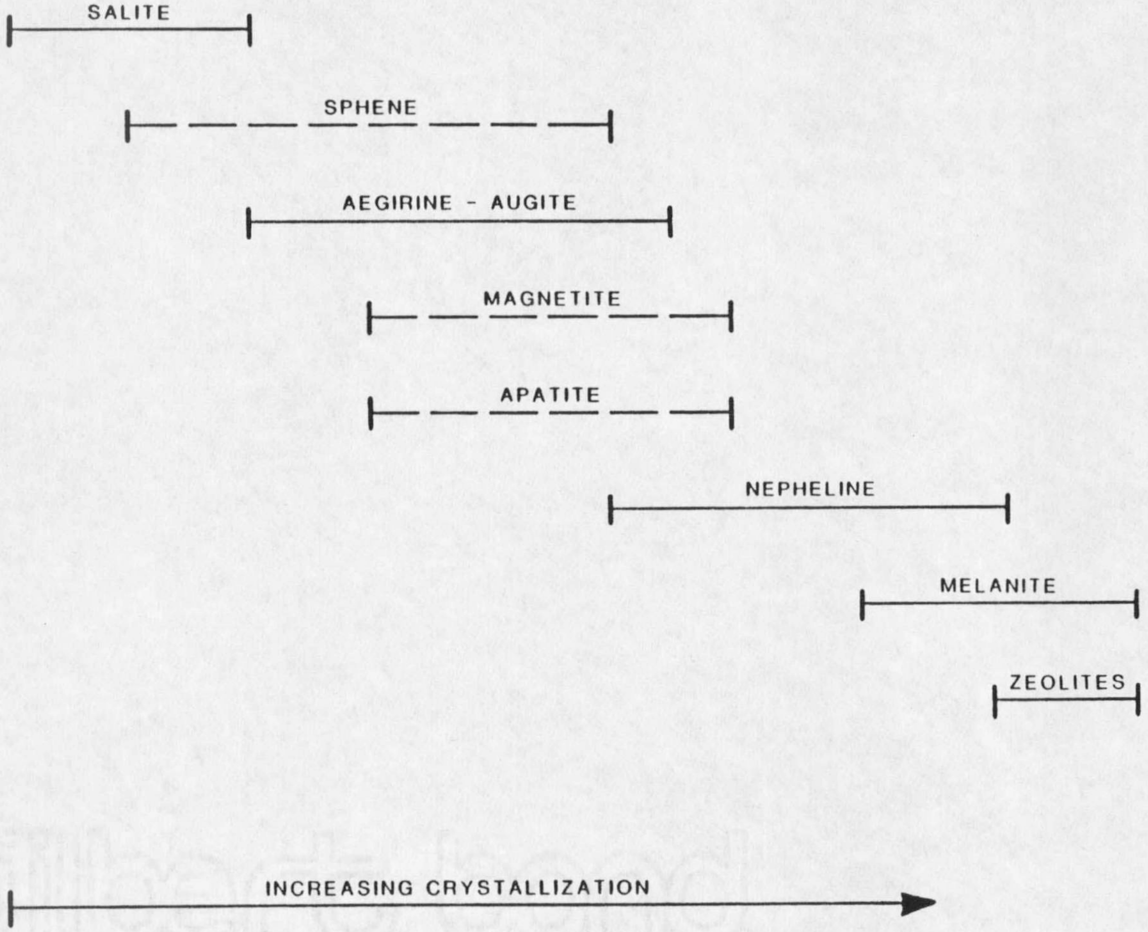


Figure 12. Crystallization sequence of pyroxenite, melteigite and ijolite.

## Tinguaite

Tinguaite forms very resistant outcrops. Dikes are marked by lines of boulders or stand out as walls; sills form hogback ridges (Figure 13A). The distinctive porphyritic texture makes tinguaite easy to identify in the field. There are two types of tinguaite, gray (see Figure 13B) and green (see Figure 14). The gray tinguaite primarily forms sills and the larger round bodies in the eastern part of the study area (Plate 1). The green tinguaite forms numerous dikes which make up the two crudely radial dike swarms in the study area, but the green tinguaite also forms numerous sills in the Cretaceous Colorado Group shales.

The differences between the gray and the green tinguaite are mineralogical. Essentially, the green tinguaite evolved from the gray tinguaite. Aegirine needles eventually began to crystallize in the tinguaite, imparting a green color to the groundmass of the rocks which crystallized later. The major mineralogical differences between the gray and green tinguaite are that the green tinguaite contains: 1) larger and fewer pyroxene phenocrysts; 2) numerous aegirine needles in the groundmass; 3) more nepheline and zeolites; and 4) somewhat larger and more abundant sanidine phenocrysts. Modes of tinguaite are tabulated in Table 4.

In hand specimen, the most conspicuous feature of the tinguaite is the large alkali-feldspar phenocrysts it almost invariably contains.

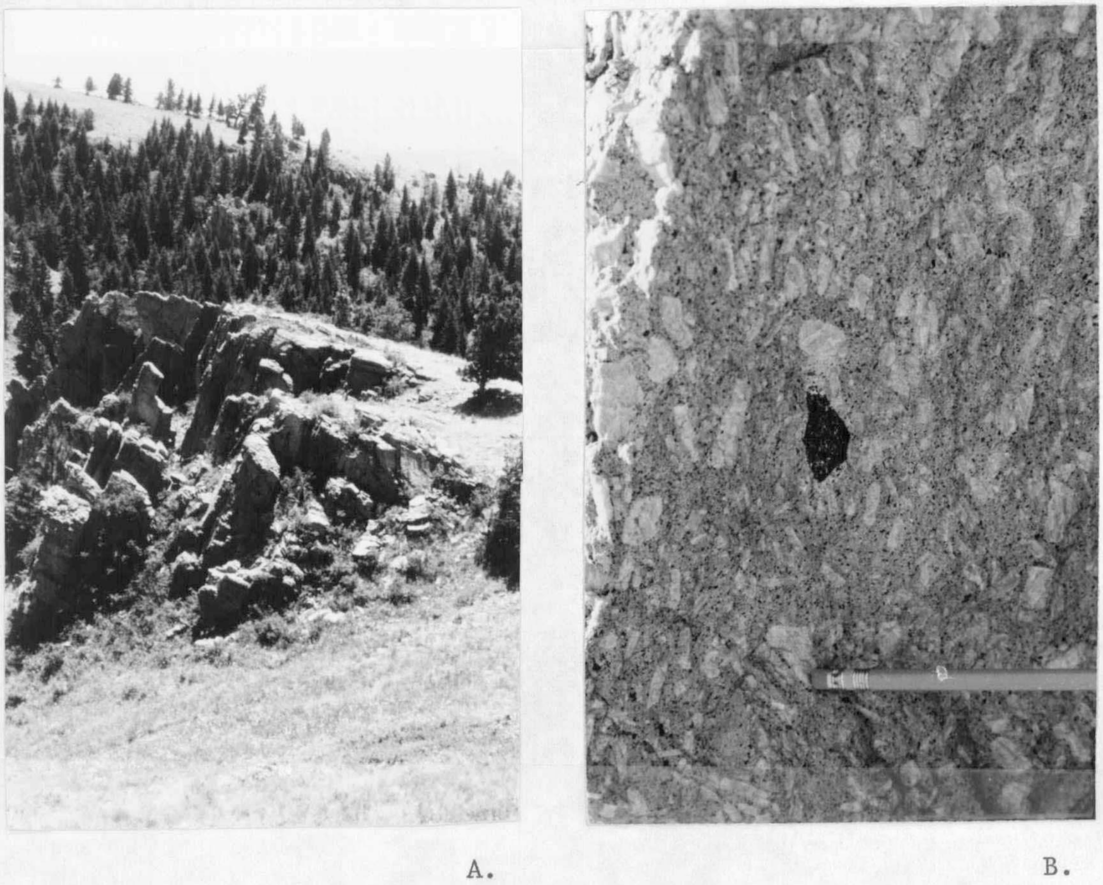


Figure 13. A. Photograph of a resistant sill of gray tinguaite southeast of Lookout Peak. Tree growing on top of sill is about four meters high.

B. Photograph of gray tinguaite with white sanidine phenocrysts, smaller black diopside and melanite phenocrysts. Small black inclusion is ijolite. Near Lookout Peak.

A.

B.

Figure 14. A. Photograph of green tinguaite with large white sanidine tablets displaying flow structure. Lens cap is 7 cm.

B. Photograph of green tinguaite with small sparse sanidine phenocrysts.

| | Gray Tinguaite | | | Green Tinguaite | | | | |
|---|---|---|---|---|---|---|---|---|
| | FMT10 | LPT4 | 2LPT11 | AT3 | RMT7 | BGT5 | LPT3 | SPT1 |
| Groundmass | 55 | 45 | 52 | 60 | 40 | 56 | 58 | 80 |
| Sanidine | 30 | 40 | 35 | 30 | 25 | 10 | 2 | 15 |
| Nepheline | -- | -- | -- | 2 | -- | 30 | -- | tr |
| Pseudoleucite | -- | -- | -- | -- | 27 | -- | -- | -- |
| Analcime | -- | -- | -- | -- | -- | -- | 27 | tr |
| Pyroxene | 10 | 12 | 10 | 6 | 8 | 3 | 1 | 10 |
| Melanite | 5 | 2 | 1 | 2 | tr | 1 | 2 | 1 |
| Magnetite | tr | 1 | 1 | tr | tr | tr | tr | 1 |
| Sphene | tr | tr | 1 | tr | tr | tr | tr | 1 |
| Apatite | -- | -- | tr | tr | tr | -- | tr | tr |
| Sodalite | -- | -- | tr | tr | -- | -- | -- | tr |
| Chlorite | -- | -- | -- | -- | -- | tr | -- | -- |
| Biotite | -- | -- | tr | -- | -- | -- | -- | tr |

Table 4. Modes of tinguaite (estimated in thin section).

Most samples are crowded with these tabular phenocrysts, which vary from 2 mm to over 8 cm in length. Some samples of green tinguaite contain few or no feldspar or other phenocrysts, as illustrated in Figure 14B; but commonly, the feldspar accounts for 15 to over 50% of the volume of the tinguaite. These milky white feldspar tablets are aligned in a conspicuous flow structure, the white tablets are especially obvious against the dark green groundmass of the green tinguaite (Figure 14A). Tablets are usually parallel to walls of dikes and sills, but locally they form circular or random patterns (Figure 15).

In thin section, the feldspar shows the small negative 2V of sanidine, and X-ray diffraction studies show them to have the composition of Or 76 Ab 24±4% (Wallace, 1953, p. 72). The feldspar is microperthite of the sanidine-high albite series; for convience, they will be referred to as sanidine in this study. Some of the sanidine phenocrysts show alteration to analcime, natrolite and other zeolites; the sanidine commonly appears somewhat cloudy. A few crystals have been albitized. Rarely, albite forms overgrowths on sanidine crystals. The sanidine encloses pryoxene and sphene crystals.

A green tinguaite dike west of Lookout Peak (Plate 1) contains small aggregates of sericitized potassium feldspar and analcime or nepheline which appear to be pseudomorphic after leucite, and which form an estimated 20% of the rock. The pseudomorphs average 5 mm in

Figure 15. Photograph of green tinguaite sill with white sanidine tablets, displaying a sweeping circular flow pattern. Top of sill is up. South of Armell Creek. Lens cap is 7 cm.

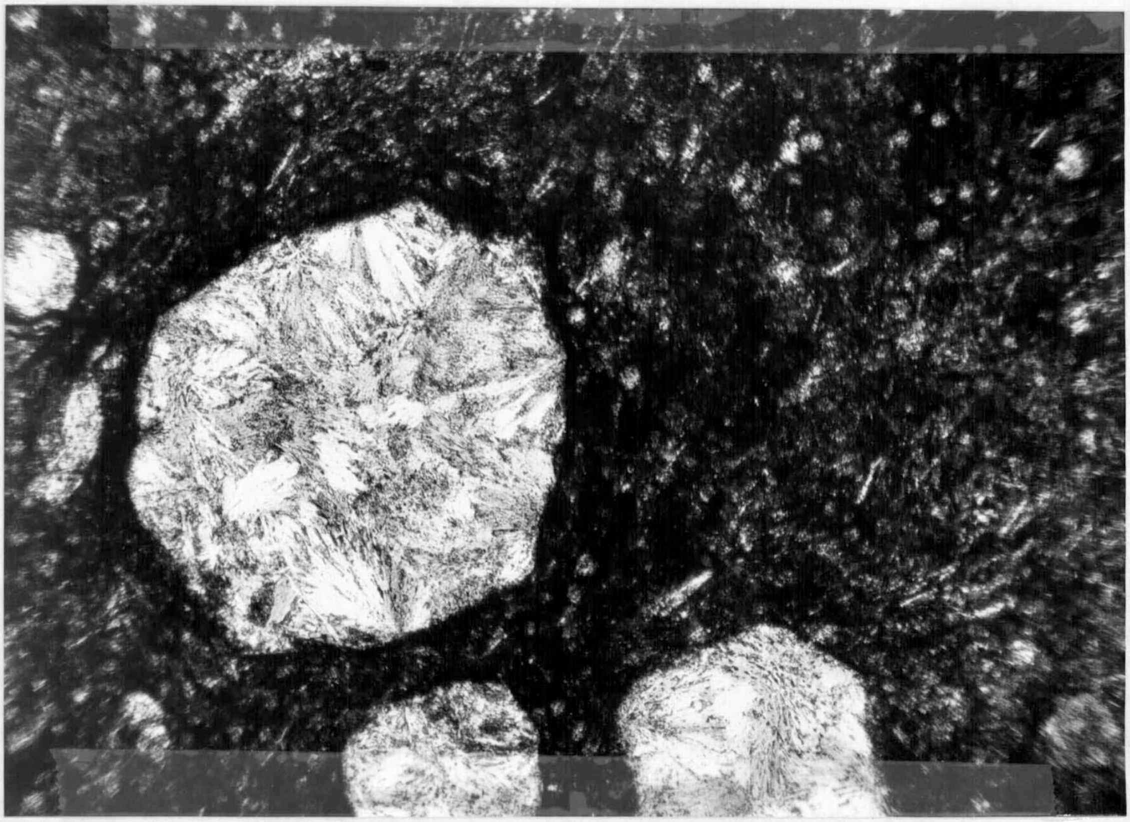


Figure 16. Photomicrograph of green tinguaite containing pseudoleucite 'crystals,' polarized light. Pseudoleucite consists of the replacement minerals nepheline, analcime, and potassium feldspar, all arranged in radial aggregates. Numerous small round shapes in groundmass are also suggestive of the former presence of leucite. (X 150).

diameter, have 8 sides, and are composed of replacement minerals arranged in radial aggregates (see Figure 16).

Small euhedral to hexagonal to rectangular nepheline crystals are present in a few sections of green tinguaite. One sample contains almost 30% nepheline phenocrysts, averaging about 5 mm. The nepheline alters to analcime and other zeolites.

Most tinguaite samples contain a few percent of pyroxene phenocrysts averaging one to three millimeters. These phenocrysts are almost invariably zoned from pale green cores to deep green margins. These pyroxenes are identical to those described from the ijolite, and have salite cores and aegirine-augite margins. Alteration of the salite to aegirine-augite occurs along fractures and cleavage traces as well as on the margins of the phenocrysts. Ragged overgrowths of aegirine needles commonly surround the zoned crystals. Abundant small needles of aegirine impart a green color to the groundmass of the green tinguaite. Rarely, pyroxene is altered to biotite.

Figure 17 is a photomicrograph of gray tinguaite, showing abundant small phenocrysts of pyroxene and larger melanite phenocrysts. In the green tinguaite (Figure 18) pyroxene phenocrysts are larger and less abundant; numerous aegirine needles display the micro-flow structure of these rocks.

Melanite garnet, zoned alternating light and dark reddish-brown, occurs as dodecahedra ranging from 0.2 to 3 mm. Melanite usually ac-

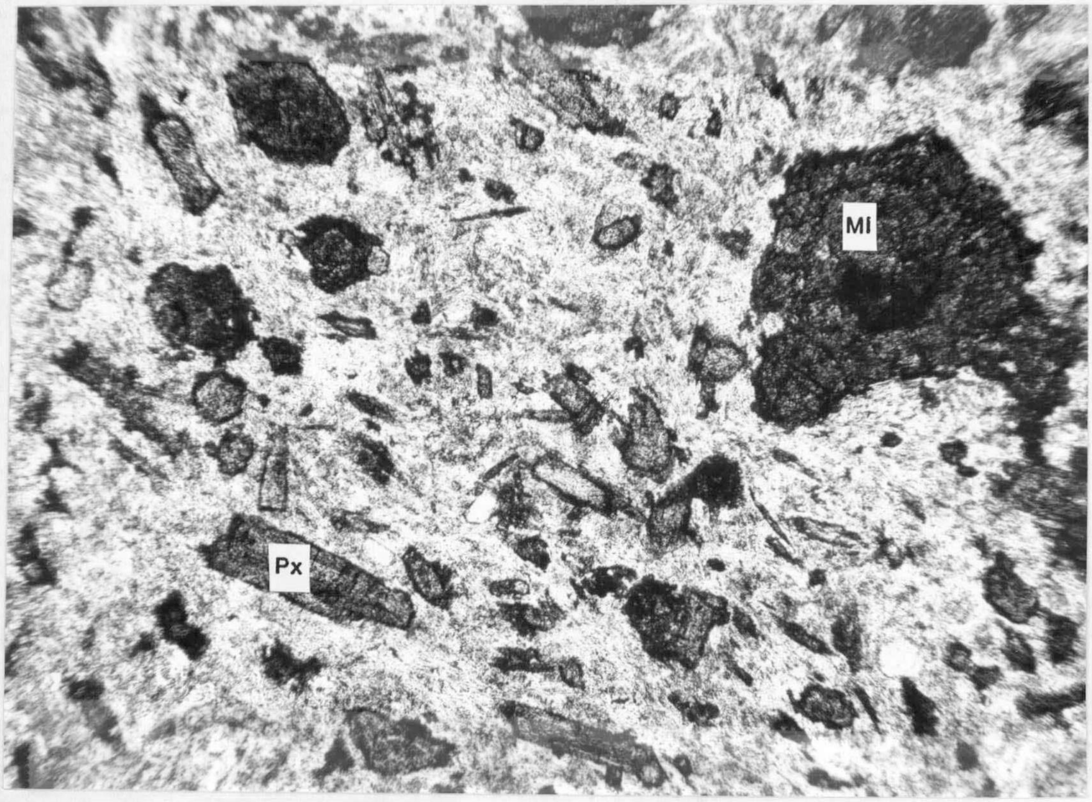


Figure 17. Photomicrograph of gray tinguaite, plane light. Phenocrysts are melanite garnet, pyroxene, and sphene. (X 150).

Figure 18. Photomicrograph of green tinguaite, polarized light. Zoned phenocrysts are salite rimmed by aegirine-augite (extinct). Needles of aegirine and microlites of sanidine and zeolites define a micro-flow structure. Bar is 1 mm.

counts for one percent or less of any sample. Zonation is melanite is probably caused by varying amounts of Titanium (Erickson and Blade, 1963, p. 74). Sometimes, melanite encloses pyroxene, sphene, nepheline and zeolites, indicating that it formed at a late stage in the tinguaite magma. However, a few highly altered melanite crystals were found along the contact of a green tinguaite dike within quartz monzonite. This melanite occurs several millimeters from the tinguaite, although the contact is somewhat gradational. This melanite appears to be a replacement mineral formed in the monzonite from solutions emanating from the molten tinguaite. Melanite also occurs as coroded phenocrysts surrounded by coronas of a fibrous mineral too fine-grained for identification. Some crystals are also mantled by aegirine needles or rimmed by aggregates of magnetite. These coroded melanite crystals appear to be out of equilibrium with the surrounding tinguaite, and are most likely xenocrysts, formed elsewhere, and incorporated into the tinguaite.

A late-stage fibrous amphibole is found in many samples of tinguaite. This amphibole has nearly parallel extinction and is highly pleochroic (X=deep bluish green, Y=yellowish green, Z=pale yellow green). It is a sodic amphibole, or arfvedsonite, but the pleochroic scheme of this arfvedsonite shows that it must have a slightly different composition than the arfvedsonite in the syenite, which is brown in color. This arfvedsonite forms fibrous tufts and overgrowths on pyroxenes in the tinguaite. In many samples, the arfvedsonite, which has a 6-sided cross-section, forms as overgrowths on 8-sided pyroxenes.

Sodic amphibole which replaces amphibole is often called uralite (Deer and others, 1975). Uralitization of pyroxenes in both the gray and green tinguaites is widespread. Uralitization often results in the formation of primary amphibole as an overgrowth on pyroxene, with the C-axis of the amphibole parallel to that of the pyroxene (Heinrich, 1965; Deer and others, 1975).

Euhedral sphene, magnetite and small apatite needles are ubiquitous accessories. Fluorite is rare. Secondary minerals include sericite, chlorite, zeolites, hematite and calcite.

The major portion of most tinguaite samples is groundmass. The groundmass accounts for an average 60% or more of the tinguaite, and some samples of green tinguaite are nearly 100% groundmass material (Figure 14B). The groundmass consists of microlites of clear sanidine, minute grains of anisotropic nepheline, isotropic analcime and considerable quantities of secondary zeolites. In the green tinguaite, the groundmass is pierced in every direction by numerous tiny needles of aegirine. These aegirine needles and the groundmass microlites outline small round shapes in some samples which may indicate the former presence of leucite in these rocks. The groundmass exhibits a felty to sub-trachytic texture, and elongate microlites wrap around phenocrysts in a micro-flow texture (Figure 18).

The mineralogy of the tinguaite is strikingly similar to that of the ijolitic rocks. The pyroxene, sphene, magnetite and melanite crystals are petrographically indistinguishable from the same minerals in the ijolite. These phenocrysts are commonly found in glomeroporphyritic aggregates (see Figure 19). Ijolite inclusions exhibit all degrees of mechanical disintegration; many of the large ijolitic inclusions show clumps of minerals near their margins which have apparently separated from the main inclusions. It appears, therefore, that many of the phenocrysts in the tinguaite could be xenocrysts derived from an ijolite source at depth, or that these phenocrysts did not have time to settle to the floor of the magma chamber before the tinguaite was injected toward the surface.

### Alkali Granite

The alkali granite post-dates all the other alkaline rocks, and occurs as three separate phases or facies. The outer portion of the intrusion is composed of the fine-grained facies, in turn cut by the coarse-grained facies, with both cut by an intrusion breccia (Plate 1).

The fine-grained facies of alkali granite is a light gray microcrystalline rock. In some areas, ferromagnesian minerals have been

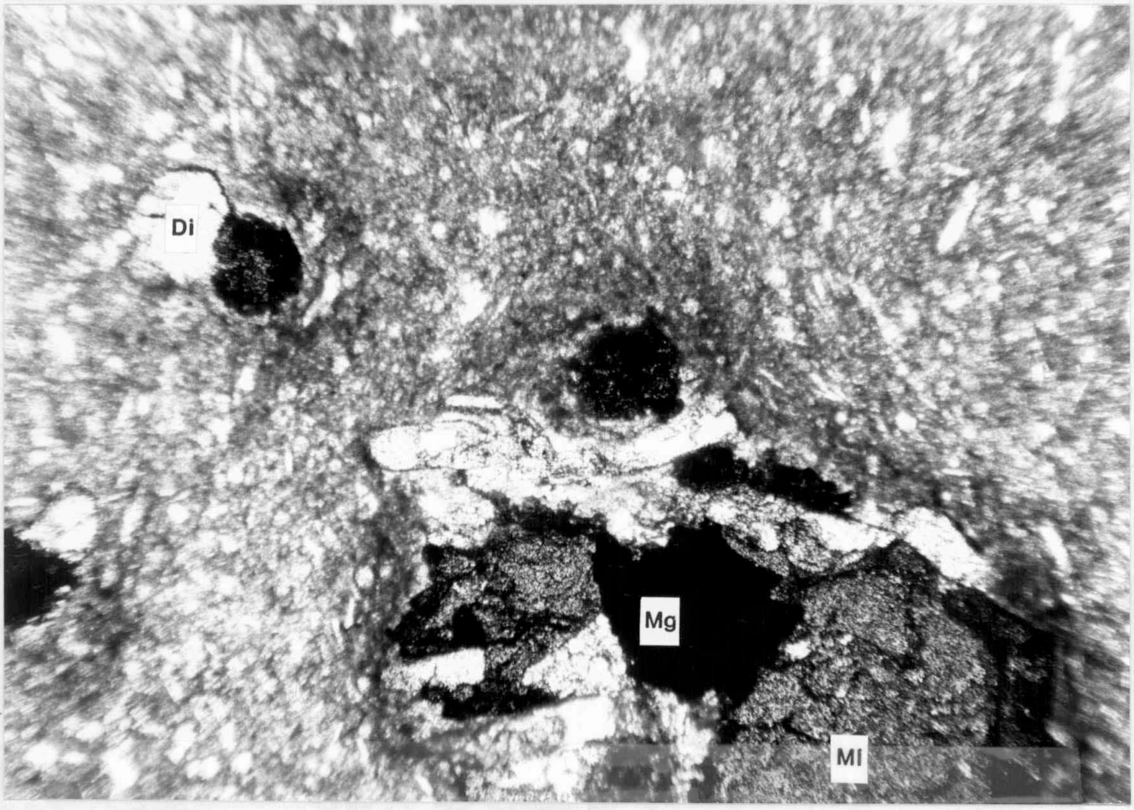
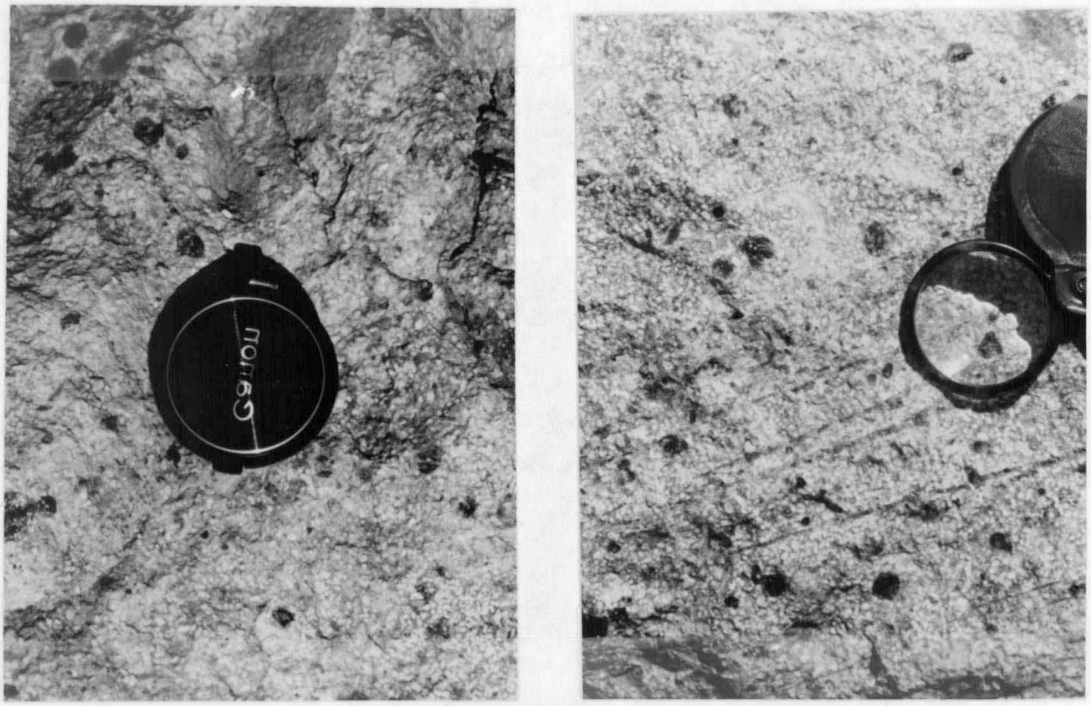


Figure 19. Ijolite clump in green tinguaite, plane light. Phenocrysts are large dark zoned melanite garnet, pale diopside, and opaque magnetite. Tiny aegirine needles are present in the groundmass. (X 150).

oxidized, giving the rock a tan to pinkish color. Disseminated quartz gives the rock a sparkling appearance. The rock is highly fractured and contains stringers and veinlets of dark grayish-purple quartz. Quartz veining is especially common near the edges of the intrusion. Veins range from microscopic to over 15 cm in width.

The coarse-grained facies of the alkali granite contains large grayish-purple doubly-terminated quartz phenocrysts which make up about 5% of the rock. These crystals can be as large as 27 mm, and average about 10 mm. The dark quartz bi-pyramids contrast sharply with the buff to light greenish groundmass, giving the alkali granite a "spotted" appearance (Figure 20). Small abundant phenocrysts of buff to white sanidine tablets are closely packed, averaging 4 mm in length. A few prisms of pyroxene up to 10 mm in length are scattered throughout the rock. The groundmass constitutes 25 to 40% of the coarse-grained facies; it is greenish gray where fresh and buff-colored on weathered surfaces.

In thin section, the sanidine phenocrysts contain inclusions of rectangular albite crystals identical to those in the groundmass (Figure 21). These crystals are oriented parallel to the crystal faces of the sanidine. Some albite crystals are observed half within the sanidine and half projecting into the groundmass. The groundmass has a



A. B.

Figure 20. A. Photograph of alkali granite. Dark 'spots' are smoky doubly-terminated quartz phenocrysts. Small white crystals are closely-packed sanidine. Lens cap is 7 cm.

B. Photograph of alkali granite. Phenocrysts are as above, in addition, sample contains numerous quartz veinlets. Lens is 5.5 cm.

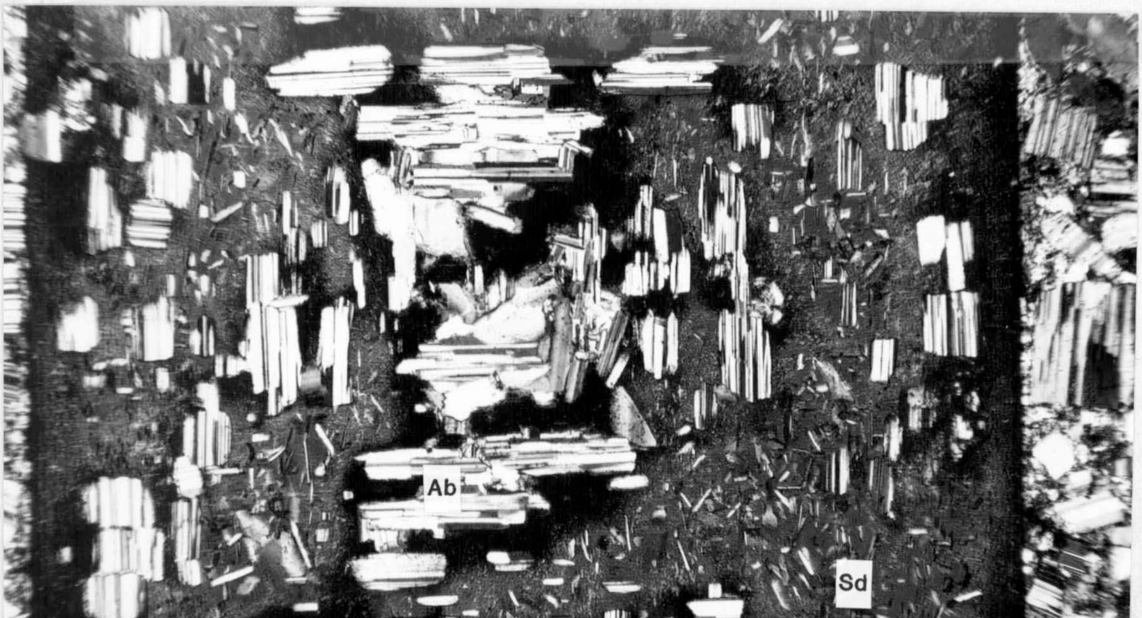


Figure 21. Photomicrograph of alkali granite, polarized light. Rectangular large dark crystal is sanidine with small albite inclusions oriented parallel to the sides of the sanidine. Identical albite crystals occur in the groundmass, giving the rock a microporphyritic texture. (X 150).

microporphyritic texture with small equidimensional albite phenocrysts (An 3) averaging 0.1 to 0.4 mm in size. Microcrystals of pyroxene and quartz form the rest of the groundmass (Figure 22). Excluding the albite, the groundmass forms a very small percent of the rock. This suggests that the magma was subject to some filter-press action. Bent and ruptured sanidine and quartz crystals present further evidence of filter-pressing.

## Metasomatized Rocks and Intrusion Breccia

Metasomatized and brecciated rocks crop out in the Judith Peak-Red Mountain area (Plate 1). The area is a complex association of rock types including quartz monzonite, syenite, tinguaite and intrusion or explosion breccia containing fragments of all of these rocks, all affected by varying degrees of metasomatism, silicification, and cut by alkali granite, alkali granite dikes, and various late-stage veins (Wallace, 1953; Hall, 1977). Brecciation and fracturing were followed by metasomatism which introduced large amounts of potassium to the country rocks, giving the metasomatized rocks an average $K_2O$ content of 12.28% (Hall, 1977). This type of metasomatism is called fenitization or feldspathization. Metasomatic fluids also introduced large amounts of pyrite; various samples contain trace amounts of sphalerite, rutile, covelite, marcasite, pyrrhotite, and galena (Hall, 1977). Late veins containing calcite, fluorite, quartz, barite,

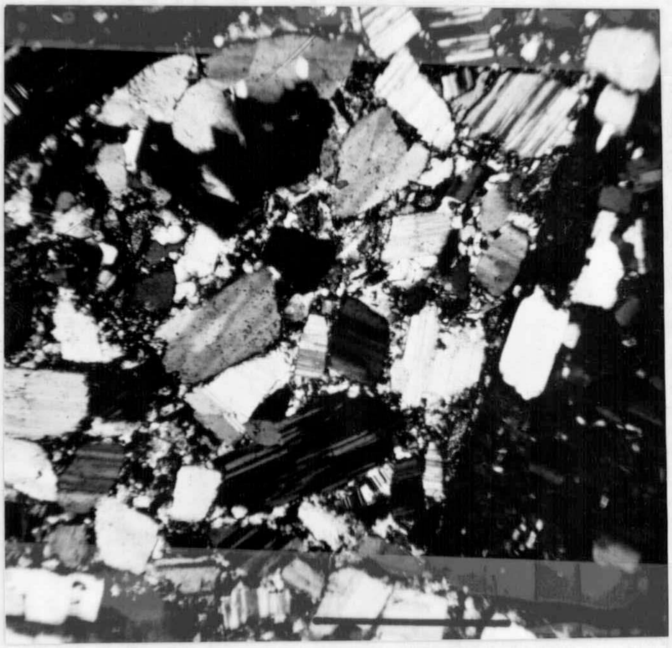


Figure 22. Photomicrograph of alkali granite, polarized light. 'Groundmass' of alkali granite containing closely-packed albite crystals with interstitial quartz and rare pyroxene. Bar is 1 mm.

rutile, aegirine, and scapolite are present in the Judith Peak-Red Mountain area below 300 m (Hall, 1977). Hall concluded that the potassium-rich fenite , the calcite-fluorite-quartz veins and the secondary pyrite and other minerals indicate the presence of a carbonatite at depth.

# CHEMISTRY

The first intrusive event in the Judith Mountains emplaced alkali-calcic rocks which are quartz-rich, mafic-poor rocks. $Na_2O+K_2O$ typically averages 8-9%, $SiO_2$ approaches 73%. Chemistry and normative mineralogy for both the alkali-calcic and alkalic rocks are summarized in Tables 5 and 6. Since this paper deals only with the second, alkaline instrusive event, the chemistry of the alkali-calcic rocks will not be discussed. Tables 5 and 6 also include values for average tinguaite, ijolite and alkali gabbro. Analyses of the ijolite and alkali gabbro from the study area are not available.

The alkaline rocks are distinctly different from the alkali-calcic rocks both in chemical composition and mineralogy. In general, the alkaline rocks are characterized by low silica (57-60%), and high alkalis ($Na_2O+K_2O$=10-15%).

On the basis of the chemical analyses, the syenite and tinguaite form two separate groups. The syenite is oversaturated with respect to silica and contains some quartz, while the tinguaite is strongly undersaturated and contains nepheline and zeolites. Therefore, the quartz-bearing syenite and its related alkali gabbro inclusions can be considered as 'mildly alkaline.' The tinguaite and related ijolitic rocks represent a 'strongly alkaline' group, characteristically nepheline-bearing. The association of mildly and strongly alkaline series

|  | Quartz Monzonite |  |  | Rhyolite | Syenite | Syenite | Gray Tinguaite | Gray Tinguaite | Green Tinguaite | Green Tinguaite | Average Tinguaite | Average Ijolite | Average Alkali Gabbro | Alkali Granite | Average Fenite |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| $SiO_2$ | 65.37 | 65.96 | 69.42 | 73.35 | 60.64 | 58.05 | 57.63 | 60.01 | 58.11 | 57.63 | 54.08 | 42.58 | 43.94 | 73.88 | 56.23 |
| $Al_2O_3$ | 16.30 | 15.74 | 14.58 | 13.88 | 16.60 | 15.63 | 14.54 | 17.14 | 16.74 | 17.53 | 18.65 | 18.46 | 14.87 | 13.44 | 17.41 |
| $Fe_2O_3$ | 1.95 | 1.12 | 1.02 | 0.90 | 1.91 | 2.56 | 4.02 | 2.40 | 3.03 | 3.46 | 3.92 | 4.01 | 4.35 | 1.16 | 4.66 |
| FeO | 1.66 | 1.52 | 1.23 | 0.58 | 3.94 | 3.24 | 1.84 | 2.07 | 1.38 | 1.18 | 2.28 | 4.19 | 7.80 | 0.47 | 0.62 |
| MgO | 1.02 | 0.68 | 0.66 | 0.24 | 1.33 | 1.37 | 1.96 | 0.60 | 0.58 | 0.22 | 1.07 | 3.22 | 9.31 | 0.11 | 0.75 |
| CaO | 3.23 | 2.74 | 2.94 | 1.42 | 4.17 | 4.66 | 3.14 | 3.16 | 1.94 | 1.35 | 2.77 | 11.38 | 12.37 | 0.05 | 2.20 |
| $Na_2O$ | 5.01 | 4.68 | 4.86 | 4.07 | 4.85 | 4.12 | 3.18 | 5.08 | 6.73 | 5.86 | 8.18 | 9.55 | 2.32 | 5.41 | 2.61 |
| $K_2O$ | 3.92 | 4.04 | 3.12 | 4.45 | 5.33 | 5.04 | 8.72 | 7.50 | 7.68 | 9.16 | 5.52 | 2.55 | 0.92 | 5.08 | 12.28 |
| $H_2O^-$ | 0.05 | 0.12 | 0.03 | 0.13 | 0.06 | 0.55 | 1.14 | 0.12 | 0.05 | 3.22 | 0.23 |  |  | 0.04 | 0.59 |
| $H_2O^+$ | 0.31 | 1.13 | 0.45 | 0.67 | 0.42 | 1.68 | 1.36 | 1.12 | 2.78 |  | 2.10 | 0.55 | 0.66 | 0.32 |  |
| $TiO_2$ | 0.42 | 0.14 | 0.67 | 0.10 | 0.23 | 0.65 | 0.66 | 0.52 | 0.52 | 0.23 | 0.54 | 1.41 | 2.86 | 0.11 | 0.59 |
| $P_2O_5$ | 0.18 | 0.08 | 0.10 | 0.03 | 0.23 | 0.26 | 0.20 | 0.06 | 0.06 |  | 0.20 | 1.52 | 0.44 | 0.01 |  |
| MnO | 0.07 | 0.08 | 0.10 | 0.05 | 0.14 | 0.14 | 0.10 | 0.12 | 0.10 |  | 0.22 | 0.20 |  | 0.01 | 0.12 |
| $CO_2$ | tr | 1.59 | 0.10 | 0.16 | 0.21 | 1.39 | 0.53 |  |  |  | 0.06 | 0.38 |  |  |  |
| BaO | 0.10 | 0.16 | 0.15 | 0.09 | 0.27 | 0.14 | 0.48 | 0.15 | 0.19 |  |  |  |  | 0.11 |  |
| S | 0.04 | 0.04 | tr | 0.02 | 0.03 | 0.03 | 0.06 | 0.03 | 0.07 |  |  |  |  | 0.03 |  |
| $ZrO_2$ | 0.05 | 0.03 | 0.09 | 0.02 | 0.02 | tr | tr | 0.02 | 0.03 |  |  |  |  |  |  |
| $F_2$ | 0.02 | 0.01 | 0.03 | 0.03 | 0.03 | 0.07 | 0.02 | 0.07 |  |  |  |  |  | 0.01 |  |
| $Cl_2$ |  | tr |  |  |  | tr | 0.05 | tr | 0.08 | 0.08 |  |  |  |  |  |
|  | 99.70 | 100.94 | 99.55 | 100.19 | 100.41 | 99.57 | 99.23 | 100.26 | 100.07 | 99.92 | 99.82 | 100.00 | 99.84 | 100.24 | 98.06 |

Table 5. Chemistry of the alkaline rocks of the Judith Mountains (samples 1-10, 14; Wallace, 1956). Average chemical analyses of tinguaite (11; LeMaitre, 1976), ijolite (12; Nockolds, 1954), and alkali gabbro (14; Nockolds, 1954). Sample 15 is the average chemistry of the fenite near Judith Peak (Hall, 1977).

|  | Quartz Monzonite |  |  | Rhyolite | Syenite | Syenite | Gray Tinguaite | Gray Tinguaite | Green Tinguaite | Green Tinguaite | Average Tinguaite | Average Ijolite | Average Alkali Gabbro | Alkali Granite | Average Fenite |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Q | 13.86 | 20.04 | 23.10 | 29.40 | 2.04 | 7.80 | 1.26 |  |  |  |  |  |  | 23.52 |  |
| C |  | 2.55 |  | 0.10 |  |  |  |  |  |  |  |  |  |  |  |
| Or | 22.80 | 23.91 | 18.35 | 26.69 | 31.14 | 29.17 | 51.71 | 44.48 | 45.59 |  | 32.63 | 10.00 | 5.60 | 30.02 | 56.88 |
| Ab | 42.44 | 39.82 | 41.39 | 34.58 | 41.39 | 34.58 | 25.15 | 35.63 | 22.53 |  | 26.03 |  | 12.10 | 40.35 | 6.86 |
| An | 10.56 | 5.56 | 8.62 | 5.84 | 7.78 | 6.67 | 0.28 | 1.67 |  |  |  |  | 27.50 |  | 0.06 |
| Lc |  |  |  |  |  |  |  |  |  |  |  | 3.90 |  |  | 14.17 |
| Ne |  |  |  |  |  |  |  | 3.98 | 11.08 |  | 21.22 | 43.70 | 4.00 |  | 7.40 |
| Ac |  |  |  |  |  |  |  |  | 8.78 |  | 2.90 |  |  | 3.70 | 1.77 |
| Ns |  |  |  |  |  |  |  |  | 0.37 |  |  |  |  | 0.24 |  |
| Di | 3.80 |  | 3.75 |  | 9.60 | 4.66 | 9.29 | 5.47 | 7.71 |  | 7.24 | 22.50 | 17.00 | 2.13 | 6.20 |
| Wo |  |  |  |  |  |  |  | 2.67 | 0.35 |  | 1.26 |  |  | 0.12 | 1.55 |
| Hy | 1.70 | 3.55 | 0.31 | 0.73 | 3.34 | 3.82 | 0.60 |  |  |  |  | 6.40 | 7.20 |  |  |
| Ol |  |  |  |  |  |  |  |  |  |  |  |  | 12.70 |  | 1.13 |
| Mt | 3.02 | 1.62 | 1.39 | 1.39 | 2.78 | 3.71 | 3.48 | 3.48 |  |  | 4.22 | 5.80 | 6.30 |  | 2.23 |
| Hm | 0.76 | 0.15 | 1.37 |  |  |  | 1.60 |  |  |  |  |  |  |  |  |
| Il |  |  |  | 0.15 | 0.46 | 1.37 | 1.37 | 0.91 | 0.91 |  | 1.03 | 2.70 | 5.50 | 0.15 | 1.17 |
| Ap | 0.34 | 0.34 | 0.34 |  | 0.34 | 0.67 | 0.34 | 0.34 | 0.34 |  | 0.48 | 3.60 | 1.00 |  |  |
| Cc |  | 3.60 | 0.20 | 0.50 | 0.05 | 3.20 | 1.10 |  |  |  | 0.13 | 0.90 |  |  |  |

Table 6. Normative mineralogy, sequence same as in Table 5.

at one complex has been recognized elsewhere, i.e. in Kenya (Saggerson, 1970; Williams, 1970; Rock, 1976). The significance and implications of the association of two series of alkaline rocks in the same area will be discussed later.

The sequence of formation of the alkaline rocks was: alkali gabbro, syenite, ijolitic rocks, gray tinguaite, green tinguaite, alkali granite. The chemical analyses (Table 5) show several distinct trends. CaO sharply decreases from a maximum of 4.66 in the syenite to a low 0.05% in the alkali granite, while CaO in the alkali gabbro and ijolitic rocks may be as high as 11 or 12%. Potassium and sodium are both concentrated in the green tinguaites, although potassium is more abundant than sodium. The tinguaite contains significantly more potassium than average tinguaite, which reflects the potassium-rich nature of the alkalic province. Pirsson (1905) pointed out the potassium-rich nature of the central Montana alkalic province in his "general law of the province":

> The petrographic province of central Montana is characterized by the fact that in the most siliceous magmas the percentages of potash and soda are about equal; with decreasing silica...the potash relatively increases over the soda, until in the least siliceous magmas it strongly dominates.

This generalization does not hold for the ijolite in the Judith Mountains. Ijolite is composed of pyroxene and and nepheline, neither of which contain potassium, except as a limited substitution. Therefore, in the least siliceous rocks in the Judith Mountains, sodium is more abundant than potassium. The presence of sodium-rich alkaline rocks in the Judith Mountains makes them unusual in the province, where the alkaline rocks are either all rich in sodium, as in the Crazy Mountains, or all rich in potassium, as in the Highwood Mountains. The significance of the occurrence of sodium- and potassium-rich rocks together is not clear, but will be examined further in the section on petrogenesis.

A general trend in enrichment of sodium and potassium with decreasing age can be observed on an AFM diagram (Figure 23). This diagram shows the weight percentage of $Na_2O+K_2O$, Fe oxides, and MgO on a triangular diagram with the totals recalculated to 100% (Figure 23). The AFM diagram shows smooth variation from early to late rock types along a slightly curved line. There is a strong trend toward a simultaneous increase in alkalis and a decrease in iron and magnesium. Sodium and potassium are concentrated in the younger, residual magmas; magnesium decreases slightly and iron decreases dramatically in the younger rocks.

A rapid, late decrease in iron on an AFM diagram indicates that the P $O_2$ or P $H_2O$ of the magma was low, or that the magma had a low water content (Hyndman, 1972). If the water content of a magma is

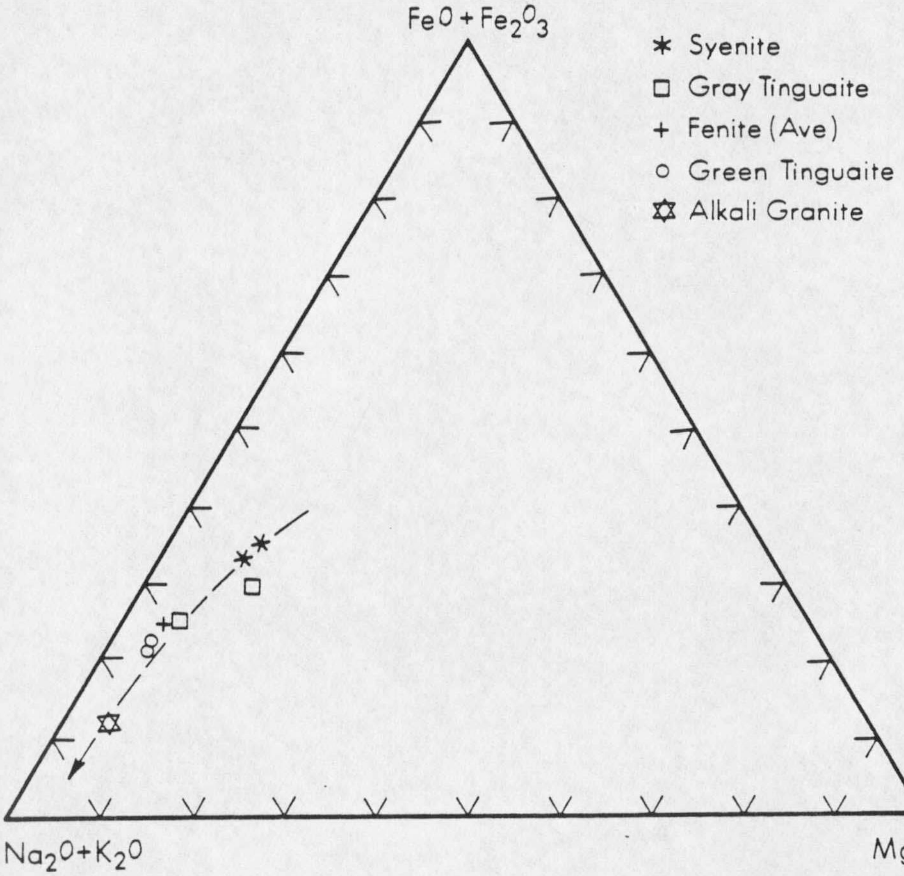


Figure 23. AFM diagram of the alkaline rocks of the Judith Mountains. Arrow points in direction of increasing crystallization and decreasing age.

high, iron is continually oxidized, and largely removed in the form of magnetite. In a dry magma, or one with a low P $O_2$ or P $H_2O$, iron remains in the melt, is not oxidized, and crystallizes at a late stage into iron-bearing silicate minerals (Hyndman, 1972). It appears from the diagram that the water content of the parent magma for the alkaline rocks from the Judith Mountains was a fairly dry one. The lack of wall-rock alteration next to the tinguaite, and the lack of significant amounts of hydrous alteration products in the alkaline rocks, especially the tinguaite, lends further support to the idea of a dry parent magma.

# PETROGENESIS OF THE ALKALINE ROCKS

## Generation of Alkalic Magmas

Most continental alkalic provinces are located in tectonically stable regions of the crust (Sorensen, 1974). Alkaline rocks are commonly found in updomed crustal areas, as is the case with the central Montana alkaline province, the Siberian alkaline provinces, and in west Africa (Sorensen, 1974).

Pressure-relief melting of mantle material caused by crustal upwarping is regarded by Bailey (1964) as a mechanism of producing alkaline magmatism. Thorpe and Smith (1974) suggest that mantle plumes can also cause crustal swelling and alkaline magmatism. Structural variations in the crust may give rise to alkaline magmatism due to an uneven thermal blanketing effect, leading to local "highs" in isotherms (LeBas, 1977). Mantle inhomogeneity, demonstrated by Hutchinson and others (1975) also can cause magmatism in stable areas by the growth of radioactive hot spots (Anderson, 1975). In order to initiate magmatism by this method, the inhomogeneity of the mantle has to be preserved. "Hot spot" conditions

> ... would not normally develop sufficiently to 'tip the balance' and set magmatism in motion. Any mantle stirring would reduce the critical heterogeneity, and it seems reasonable to assume that the mantle below a continental plate would be less stirred than under a midocean ridge or zone of subduction, and thus strongly alkaline magmatism characteristically occurs within continents (LeBas, 1977, p. 105).

There is generally a close connection between alkaline igneous activity and major tectonic features such as fault zones, intersections of fault zones, or rift zones (Sorensen, 1974). The association of alkaline rocks with such fault zones favors tapping deep-seated ultrabasic magmas.

In the region containing the Judith Mountains, crustal upwarping in the late stages of the Laramide orogeny may have caused relief of lithostatic pressures and triggered partial melting of mantle material. The intersection of fault zones provided a conduit which allowed deep-seated magmas to rise to the upper portions of the crust.

### Parent Magma

There is widespread evidence from strontium, carbon and oxygen isotope studies that alkaline magmas are mantle-derived (Rock, 1976; Deines and Gold, 1973; Bell and others, 1973. Powell and Bell (1970, 1974) conclude that strontium isotope ratios in alkalic rocks from central Montana point to a mantle origin for these rocks. The occurrence of peridotitite xenoliths in the Bearpaw Mountains, Eagle Buttes and various diatremes also suggests a mantle origin for all the alkaline rocks of the province (Marvin and others, 1980). The absence of mantle-type xenoliths in the Judith Mountains may be the result of a relatively slow rise from the mantle, as demonstrated by the large degree of differentiation shown by these rocks. However, based on the relationship of the Judith Mountains to the other alkaline rocks in the province, the alkaline rocks in the Judith Mountains also probably originated in the mantle.

Larsen (1940) suggested that all of the alkaline rocks in the central Montana alkaline province were derived from an alkali basalt parent magma which assimilated different amounts of crustal material from place to place, accounting for differences in rock types and chemistry between the igneous centers of the province. To test this idea, Woods (1976) examined the Rb/Y ratios of rocks from two areas in the province--the Big Belt and the Highwood Mountains. Crustal assimilation should affect the Rb/Y ratios since the yttrium content of crustal material and alkali basalt is similar, but rubidium contents differ by a factor of two (Woods, 1976). These rocks show no crustal assimilation, according to their Rb/Y ratios (Woods, 1976). The parent magma was most likely not alkali basalt, according to Woods (1976). Woods proposed partial melting of a garnet peridotite upper mantle, followed by fractionation of eclogite, giving rise to a kimberlitic parent magma for the Highwood Mountains. The presence of kimberlitic diatremes and other intrusions in the alkaline province lends support to the idea of a kimberlite parent magma for the entire province.

Kimberlitic magmas may be produced by partial melting of less than 5% of mantle rocks such as peridotite or eclogite, at depths of 100 km or more, and at pressures of 30 kb or greater (Yoder, 1975;

Green, 1973). At lesser depths, ijolite and phonolite may be further derivatives of kimberlite (Yoder, 1975). Primary nephelinite or ijolitic magmas are also thought to form by partial melting in the mantle (Green, 1973). Green (1971) believes that "the small liquid fraction present in the low-velocity zone is highly undersaturated olivine nephelinite or olivine melilite nephelinite." Many mafic alkaline-carbonatite complexes which contain rocks such as pyroxenite, melteigite, ijolite and tinguaite are believed to have nephelinite parent magmas--i.e. Fen, Norway (Mitchell and Brunfelt, 1975), Iron Hill, Colorado (Nash, 1972), and Oka, Quebec (Watkinson and Wyllie, 1971).

The exact nature of the parent magma is a matter of conjecture. The alkaline rocks of the Judith Mountains are probably differentiates of a kimberlitic or possibly nephelinitic magma generated by partial melting in the mantle.

### Differentiation of the Syenite and Alkali Gabbro

Alkaline igneous activity began in the Judith Mountains with the intrusion of the 'mildly' alkaline series, represented by syenite and alkali gabbro. Quartz-bearing syenite and alkali gabbro are not widespread rock types in the central Montana alkaline province. Shonkinite (nepheline-orthoclase gabbro with mafic minerals greater than 60%) is a typical mafic alkaline rock in the province. The alkali gabbro is too poor in mafic minerals and feldspathoids to be classified as shonkinite. Most of the syenite in the alkaline province is nepheline or feldspathoid-bearing, and does not contain quartz.

In general, two very different differentiation mechanisms can be employed to explain the differentiation of the syenite and alkali gabbro. The first mechanism is fractional crystallization, and the second and most recently proposed mechanism is magma immiscibility.

Fractional Crystallization. Crystal settling or fractional crystallization causes early-formed crystals such as olivine, pyroxene, or other minerals to settle to the floor of a magma chamber if they have a greater density than the magma. Minerals like plagioclase may have a lower density than the magma and rise to the top of the magma chamber. Crystal settling results in features such as rythmic layering with the intrusion, and cumulate textures in the rocks involved. Such layering is not present on surface outcrops of the syenite in the Judith Mountains, although such features could be present at depth. The syenite and alkali gabbro also do not have cumulate textures.

During fractional crystallization of a mafic-rich magma, the mafic minerals crystallize early, resulting in a felsic differentiate. The felsic liquid will generally contain fugitive elements and volatile constituents which do not easily fit into the early-formed minerals. The enrichment of incompatible elements into the felsic fraction is very different from the elemental partitioning which occurs during differentiation by liquid immiscibility. Element partitioning will be discussed further below. Although no evidence exists to prove the mechanism of fractional crystallization, a negative line of evidence may be utilized to disprove the mechanism of fractional crystallization for the syenite and alkali gabbro. The strongest argument against differentiation by fractional crystallization for the syenite and alkali gabbro involves the oversaturation with respect to silica of the syenite. An initially undersaturated alkaline magma cannot produce a differentiate like the syenite, which contains quartz, by fractional crystallization. The reason involves the ternary system silica-nepheline-kalsilite, a characteristic of which is the 'thermal divide' of the feldspar join. This thermal divide separates the depressions into which liquids descend by fractional crystallization. It is clear that liquids with a low silica content will approach the ternary system on the undersaturated side of the thermal divide. As crystallization proceeds, the remaining melt moves compositionally away from silica down the liquidus surface. According to this ternary system, an undersaturated alkalic magma may never produce a differentiate containing quartz by the differentiation process of fractional crystallization.

Liquid Immiscibility. A differentiation mechanism of liquid immiscibility has recently been proposed for the Square Butte and Shonkin Sag laccoliths in the Highwood Mountains and many other alkalic complexes containing coexisting syenite and mafic alkaline rocks (Kendrick, 1980; Edmond, 1981; Philpotts, 1976; Currie, 1972; Ferguson and Currie, 1971). The presence of spherical bodies of felsic material (ocelli) found in some fine-grained basic alkaline rocks implies the existence of two immiscible silicate liquids of divergent composition (see, for example, Kendrick, 1980; Philpotts and Hodgson, 1968; Ferguson and Currie, 1971).

Chemically analyzed pairs of felsic ocelli and mafic matrix rocks define a field of immiscibility which separates basic and felsic magmas (Philpotts, 1976). The basic rocks range in composition from lamprophyre to quartz diorite, the felsic rocks range from nepheline- and quartz-syenite to granite. Significantly, Philpotts (1976, p.1174) states "all analyzed pairs of ocelli and matrix show the ocelli to have higher degrees of silica saturation." In other words, the differentiation mechanism of liquid immiscibility can produce an oversaturated (quartz-bearing) differentiate from an undersaturated magma.

In experimental systems, a region of silicate liquid immiscibility occurs at geologically reasonable temperatures and pressures in several petrologic systems (Koster van Groos, 1975a, 1975b; Koster van

Groos and Wyllie, 1973, 1969, 1968, 1966; Visser and Koster van Groos, 1979, 1976). Immiscibility is best developed in potassium-rich systems (Naslund, 1976). The field of immiscibility expands markedly in the presence of volatile-related compounds such as $P_205$ and $TiO_2$ (Irvine, 1976). Low pressures also appear to induce immiscibility (Philpotts, 1976). All of these conditions could have prompted immiscible separation of the syenite and alkali gabbro of the Judith Mountains.

Certain elements behave differently depending on whether they formed by processes of fractional crystallization or by liquid immiscibility. Partitioning of elements between immiscible melts has been reported (Watson, 1976; Naslund, 1977; Ryerson and Hess, 1978). In immiscible melts, Al, K, and Cs concentrate in the Si-rich melt, whereas phosphorous is most strongly fractionated into the mafic melt. Rare-earth elements, magnesium, calcium, chromium, titanium, manganese and zirconium also concentrate in the mafic fraction (Watson, 1976). In fractionally crystallized rocks, phosphorus and titanium are most abundant in intermediate and acid rocks (Nockolds and Allen, 1953). Apatite is fairly abundant in the alkali gabbro, so it appears that phosphorus was fractionated into the mafic melt, as would be expected from immiscibility, and not into the felsic rocks, as would be expected from fractional crystallization.

Liquid immiscibility has recently been proposed as the mechanism which formed the Square Butte and Shonkin Sag laccoliths in the Highwood Mountains (Kendrick, 1980; Edmond, 1981). Previously, fractional crystallization was proposed as the cause of differentiation of these bodies (Nash and Wilkinson, 1970; Hurlbut and Griggs,1939). These laccoliths are all similar and consist primarily of shonkinite with an overlying nepheline syenite (Hurlbut and Griggs, 1939). In the Square Butte laccolith, large ocelli or felsic globules up to 10 meters in diameter are suspended in a mafic-rich shonkinite matrix; element partitioning in these rocks is also consistent with liquid immiscibility theory (Kendrick, 1980).

In summary, many characteristics of the syenite and alkali gabbro of the Judith Mountains support an origin by liquid immiscibility: 1) The syenite is oversaturated with respect to silica, a situation that cannot occur as the result of fractional crystallization of an undersaturated alkaline magma, but that has been demonstrated to occur as the result of immiscible separation of an undersaturated magma; 2) The apparent divergence in composition of the syenite and alkali gabbro is consistent with liquid immiscibility theory; 3) These rocks are potassium-rich, which tends to enhance immiscibility; 4) Minerals such as sphene and apatite in the alkali gabbro contain volatites, which expand the field of immiscibility; 5) The alkali gabbro contain an abundance of water-bearing minerals such as biotite, amphibole and chlorite, and the parent magma was mantle-derived and probably deficient in water. Therefore, these rocks probably differentiated at a high level in the crust, where surface waters could be added to the magma. Such a low-pressure environment would permit immiscible separation of the syenite and alkali gabbro; 6) The presence of up to 3% apatite in the alkali gabbro, a large percentage for what is usually an accessory mineral, shows that phosphorus has been fractionated into the mafic melt, consistent with immiscibility theory. These six characteristics, along with evidence supporting immiscibility in other alkaline rocks in central Montana, suggests that immiscibility could have formed these rocks. Clearly, more work needs to be done on the mildly alkaline rocks of the Judith Mountains in order to better understand their origin.

## Differentiation of the Pyroxenite, Ijolite and Tinguaite

The second, 'strongly' alkaline igneous phase resulted in the formation of a mafic (ijolitic) body or bodies of unknown size at some depth beneath the present surface, and in the intrusion of tinguaite containing ijolitic inclusions. These rocks evolved from anhydrous pyroxenite to melteigite and ijolite with progressive crystallization and the introduction of nepheline. Further differentiation produced the tinguaite phase, which evolved from a gray to a green phase, as potassium and sodium became more concentrated and late-stage aegirine needles crystallized in the green tinguaite.

Fractional crystallization or crystal settling probably formed this group of rocks. Textural evidence for such an origin, particularly cumulate textures, abounds in these rocks. Pyroxenite, formed by the settling of early-formed salite phenocrysts, represents a cumulate phase or crystal mush which could not have formed from a melt of its own composition. Melteigite and ijolite also display cumulate textures, with euhedral, zoned pyroxene crystals surrounded by an interstitial nepheline phase. The chemical composition of the tinguaite (chemically similar to nepheline syenite) represents a residual melt whose composition corresponds to the low-melting area or cotectic trough in the nepheline-quartz-diopside system. Such a composition would be expected from fractional crystallization, where the crystallization and separation of early-formed minerals would cause the remaining melt to change in composition along a liquidus surface toward a cotectic trough.

Anhydrous pyroxenite was the first mafic phase to form. The pyroxenite represents a cumulate phase formed by the sinking of early-formed salite crystals. A cumulative origin for pyroxenite elsewhere has been suggested by Upton (1967), LeBas (1977), and Dawson and Smith (1973).

A photomicrograph of a pyroxenite inclusion (Figure 10A) shows many small packed anhedral salite crystals. These crystals do not display zonation to sodic aegirine-augite rims, as do the melteigite

(Figure 10B) and ijolite (Figure 11). Only the outermost crystals on the pyroxenite inclusion display the zonation to sodic rims, demonstrating that the pyroxenite mush was successfully separated from the magma.

As the melt continued to crystallize, melteigite and ijolite were formed. Separation of salite caused the melt to change in composition and become more enriched in sodium and potassium. Since pyroxene belongs to a solid solution series, the pyroxene in the melteigite and ijolite is zoned from calcic salite cores to sodic aegirine-augite margins (Figures 10B and 11). As the melt became increasingly saturated with sodium, nepheline began to crystallize and form the interstitial phase (Figures 10B and 11). Veinlets of pure nepheline appear in some of these rocks, giving some samples a gneissic appearance. Some of the melteigite and ijolite inclusions do appear to be gneiss, at first glance (Figure 9).

In other ijolite complexes around the world, pyroxenite is described as "invariably the earliest member of the entire sequence" (King and Sutherland, 1967, p. 102), and it almost never forms extensive outcrops, but is often found as xenoliths in later types (King and Sutherland, 1967; Dawson and Smith, 1973). In general, the more nepheline-rich members of the ijolitic series vein and intrude the pyroxene-rich members (Bailey, 1974).

Extreme variability in texture and mineral percentages, even within the space of a few centimeters, and the irregular and sporadic distribution of melanite (Ti-garnet) are typical properties of ijolite (LeBas, 1977; King and Sutherland, 1967). According to Bailey and Schairer (1966) the wide variability of minerals in ijolitic rocks probably reflects their high content of volatiles. Mineral segregation in clots and bands, pegmatites and associated intrusion breccia, make these rocks particularly intractible to mapping or to generalizations about their composition.

The tinguaite represents the final silicate stage in the evolution of the ijolite series. Nepheline syenite (compositionally analogous to tinguaite) corresponds to the low-melting area or cotectic trough in the nepheline-quartz-diopside system (Sorensen, 1974). A melt of tinguaite composition may therefore be regarded as a residual liquid, squeezed out of the crystal mush to form an upper layer in the magma chamber. Such an upper magmatic layer often appears as late dikes (Hyndman, 1972). Nepheline syenite does appear at the top of an ijolite pluton in the Ruri Hills, East Africa (LeBas, 1977). Late tinguaite often occurs in the form of dikes, plugs and sheets, for instance, in the Fen complex (Barth and Ramberg, 1966), and in the Magnet Cove complex (Erickson and Blade, 1963).

Potassium accumulated in the residual tinguaite melt, since none of the mineral phases which crystallize early in an ijolite accomodate significant amounts of potassium. Analyzed tinguaite from the study area shows a very high potassium content when compared to average tinguaite (8.25% versus 5.25%, see Table 5). This high percentage of potassium is consistent with the potash-rich nature of the petrographic province. The presence of large amounts of potassium is reflected in the rock by the presence of large sanidine phenocrysts in both the gray and green tinguaite.

Liquids with compositions near that of potassium feldspar cannot form this mineral as a direct product of crystallization (Deer and others, 1975). In a potassium-rich liquid, leucite is the first phase to crystallize. The behavior of the cooling tinguaite magma is illustrated in Figure 24, where a melt of composition A, on cooling, intersects the liquidus surface at B, where leucite begins to crystallize. As the temperature continues to fall, and leucite continues to crystallize, the composition of the melt moves along the liquidus curve until it comes to the peritectic or reaction point at P. At this point, the liquid reacts with the leucite to transform it to potassium feldspar. Deer and others (1975, p. 373) remark that it is almost certain that the feldspar crystals that form experimentally in this system are the high temperature form, or sanidine. The presence of pseudoleucite in some of the tinguaite dikes confirms the fact that leucite did, in fact, crystallize in the tinguaite magma.

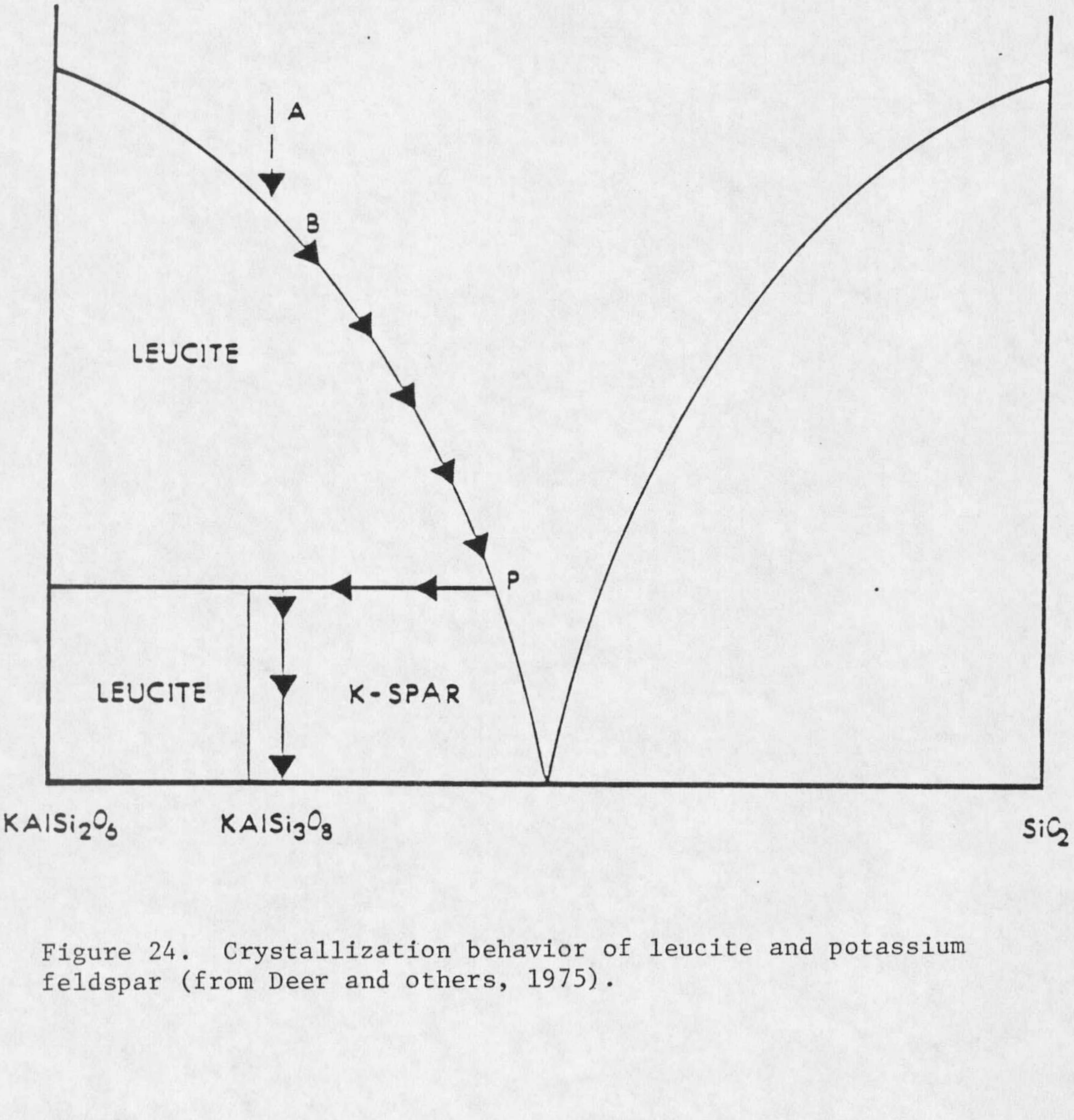


Figure 24. Crystallization behavior of leucite and potassium feldspar (from Deer and others, 1975).

As the tinguaite melt continued to crystallize, the concentrations of both sodium and potassium continued to increase. The tinguaite evolved from a gray to a green phase as sodium and potassium crystallized into late aegirine needles, nepheline and zeolites.

Melanite garnet crystallized more or less continuously during the formation of the ijolite and tinguaite. Some melanite apparently crystallized metasomatically along the margins of tinguaite dikes. In the ijolitic complex at Iron Hill, Colorado, Larsen (1942, p. 54) suggests that melanite "is in part a late magmatic and deuteric mineral, but it continued to crystallize into the hydrothermal stage."

The pyroxene, sphene, magnetite, and some of the melanite phenocrysts in the tinguaite are petrographically indistinguishable from the same minerals in the ijolite. All degrees of mechanical disintegration of ijolite inclusions are observed in the tinguaite. The individual phenocrysts as well as the clots of ijolitic phenocrysts are most likely subtle contamination features or "xenocrysts" derived from an ijolite source at depth or resulting from the disintegration of ijolite inclusions. A similar origin for such phenocrysts in phonolite lavas was proposed by LeBas (1977, p. 155). He concluded that "the majority of the porphyritic minerals of the phonolite are xenocrysts derived from the ijolitic wall rocks of the magma reservoir."

### Carbonatite (?)

Potassium-rich metasomatism and emplacement of intrusion breccia have most intensely affected the Judith Peak-Red Mountain area. This is the area where Hall (1977) concluded that a carbonatite body exists at depth. The metasomatized rocks are described by Hall as potassium-rich fenite. Fenitization is a type of alteration characteristically occurring adjacent to alkalic or carbonatite intrusions. According to Hall's chemical analyses, this fenite averages 12.28% $K_2O$ and 2.61% $Na_2O$. Potassium-rich fenite is also described from the Bearpaw Mountains, surrounding an exposed carbonatite (Pecora, 1962). In core from a diamond drill hole in this area, late veins containing calcite, fluorite, quartz and barite are present below 300 m (Hall, 1977). Veins containing calcite, fluorite, quartz and barite are common associates of carbonatite (i.e. Bailey, 1966).

The existence of ijolitic rocks in this area, as discovered by this study, provides further evidence that a carbonatite body could be part of the alkaline complex. Carbonatite is almost invariably associated with mafic and ultramafic alkaline rocks, most commonly, pyroxenite, ijolite, melteigite, jacupirangite (magnetite pyroxenite), biotite pyroxenite or essexite (orthoclase-nepheline gabbro). Normally these carbonatite-mafic alkaline complexes occur as zoned ring complexes with pyroxenite, ijolite or jacupirangite cores, a central plug of carbonatite, and an envelope of nepheline syenite and metasomatized rocks or fenite. Barth and Ramberg (1966, p. 250) state that "tinguaite dikes also seem to be universally present" in carbonatite complexes.

### Alkali Granite

The body of alkali granite at Judith Peak was the final igneous rock unit to be emplaced and it is possibly the most unusual rock type in this suite of unusual rocks. The origin of this alkali granite is beyond the scope of this thesis. Suffice it to say that its high silica content (73.88%) and very low CaO (0.05%) make it a very unique rock type in the alkaline rock association. Texturally, too, it is quite unusual (Figure 21). A study of this rock type is currently being undertaken by Gail Kerchner of the University of Montana.

### Petrogenetic Model

The major problem to overcome in any petrogenetic model for the alkaline igneous rocks in the Judith Mountains is the occurrence of the nepheline-bearing, strongly alkaline rocks showing a contemporaneous relationship with mildly alkaline quartz-bearing rocks. It is a well-known fact of igneous petrology that initially undersaturated magmas cannot produce differentiates containing free silica by normal crystallization processes, such as fractional crystallization (i.e. Edgar, 1974). The question, then, is whether or not all of the alkaline rocks had the same parent magma, and, if they did, how did two such distinctly different rock series arise from one source magma.

Normally, strongly alkaline magmatism and mildly alkaline activity are restricted to separate complexes or provinces, and do not occur together. In some areas, however, two types of alkaline magmatism do occur together, and current literature on these areas suggests several hypotheses to explain the occurrence of mildly and strongly alkaline rocks at the same center.

Some authors suggest that major variations in rock chemistry at the same center can result from tapping different levels of primary magmas (Johnson, 1966). In other words, separate parent magmas produce the different alkaline rocks. But it seems simpler and more reasonable to have a single parental magma for all of the alkaline rocks in the Judith Mountains, especially in the light of the contemporaneous emplacement of the syenite and gray tinguaite, which would seem to indicate a single igneous episode. Most authors believe that associated mildly and strongly alkaline rocks are derived from a single parental magma (Rock, 1976; Tilley and Yoder, 1967; Philpotts, 1976). If this is true, the differences between the mildly alkaline syenite and gabbro and the strongly alkaline tinguaite and ijolite must arise from different conditions at the site of crystallization of these rocks.

Rock (1976) concluded that mildly and strongly alkaline volcanic rocks at Mount Meru in East Africa derived from a single parental magma whose course of crystallization differed acording to the carbon dioxide/water ratio of the volatile phase of the magma. The sequence of events at Meru, envisioned by Rock (1976) is as follows: An initial water-rich gas phase in the magma allowed formation of a hydrous gabbroic or basaltic lineage; then a gradual decrease in the carbon dioxide/water ratio led to an anhydrous, strongly alkaline nephelinite phase.

It appears from the AFM diagram of the alkaline rocks of the Judith Mountains that the parent magma was fairly dry, which is not surprising, because the mineralogy of most alkaline suites implies that the parent magmas are rich in carbon dioxide and deficient in water, so Rock's (1976) hypothesis may not be applicable to these rocks. Some of the water in the gabbroic melt could have evolved from the magma, but it seems more likely that most of the water came from crustal sources. Therefore, it does not seem plausible to derive all the alkaline rocks from the Judith Mountains by differentiation within a single magma chamber under changing carbon dioxide/water ratios in the volatile phase. The mineralogy of each series is distinctively different, and the syenite and tinguaite intrusions occur as separate and distinct bodies.

A better hypothesis for the origin of the strongly and mildly alkaline rocks might involve early separation of the parent magma into two sub-magmas, giving rise to two separate rock series. It is apparent that the differentiation processes which formed the two series were very different. One resulted in a late differentiate which is nepheline-bearing (tinguaite). The other resulted in the formation of a quartz-bearing syenite as the final phase. Fractional crystallization probably formed the ijolitic rocks and the tinguaite, while a different mechanism, possibly involving magma immiscibility, formed the syenite and alkali gabbro.

The differences in differentiation mechanisms may be related to different depths of differentiation of the two sub-magmas. This is the hypothesis favored by Philpotts (1976) to explain the occurrence of mildly and strongly alkaline rocks at the same center in the Monteregian alkalic province. According to Philpotts (1976), who is an advocate of liquid immiscibility, a single alkaline parent magma can produce both mildly and stongly alkaline rocks if extensive differentiation at different depths strongly affects the final composition. Philpotts summarizes this idea:

> Nepheline and quartz-bearing rocks can be derived from a commom parent magma by differentiation at different depths. At high pressures where there is no immiscibility, a critically undersaturated magma would fractionally crystallize to form a nepheline syenite residue. However, at low pressure, this same magma would separate an oversaturated immiscible liquid (Philpotts, 1976, p. 1117).

This model can be applied to the origin of the alkaline rocks in the Judith Mountains.

This petrogenetic model is schematically represented in Figure 25. One pulse of the parent magma rose to a relatively high level in the crust. Here, factors such as low pressure, a high level of volatiles and water in the magma (probably partly leached from crustal sediments), enhanced separation of the magma into two immiscible fractions--one gabbroic and one felsic and oversaturated with respect to silica. The silica-rich felsic globules of syenite rose and coalesced in the upper portions of the magma chamber while the mafic alkali gabbro crystallized below. The still-molten syenite was injected toward the surface largely after the alkali gabbro had crystallized, and carried gabbroic xenoliths with it.

Injection of the early gray tinguaite from a much deeper source began before the emplacement of the syenite was completed. At the depth where tinguaite and ijolite formed, pressure was higher, and liquid immiscibility did not occur. This sequence of rocks was formed by fractional crystallization. The tinguaite represents a low-temperature residual fraction of an ijolitic melt crystallizing pyroxenite,

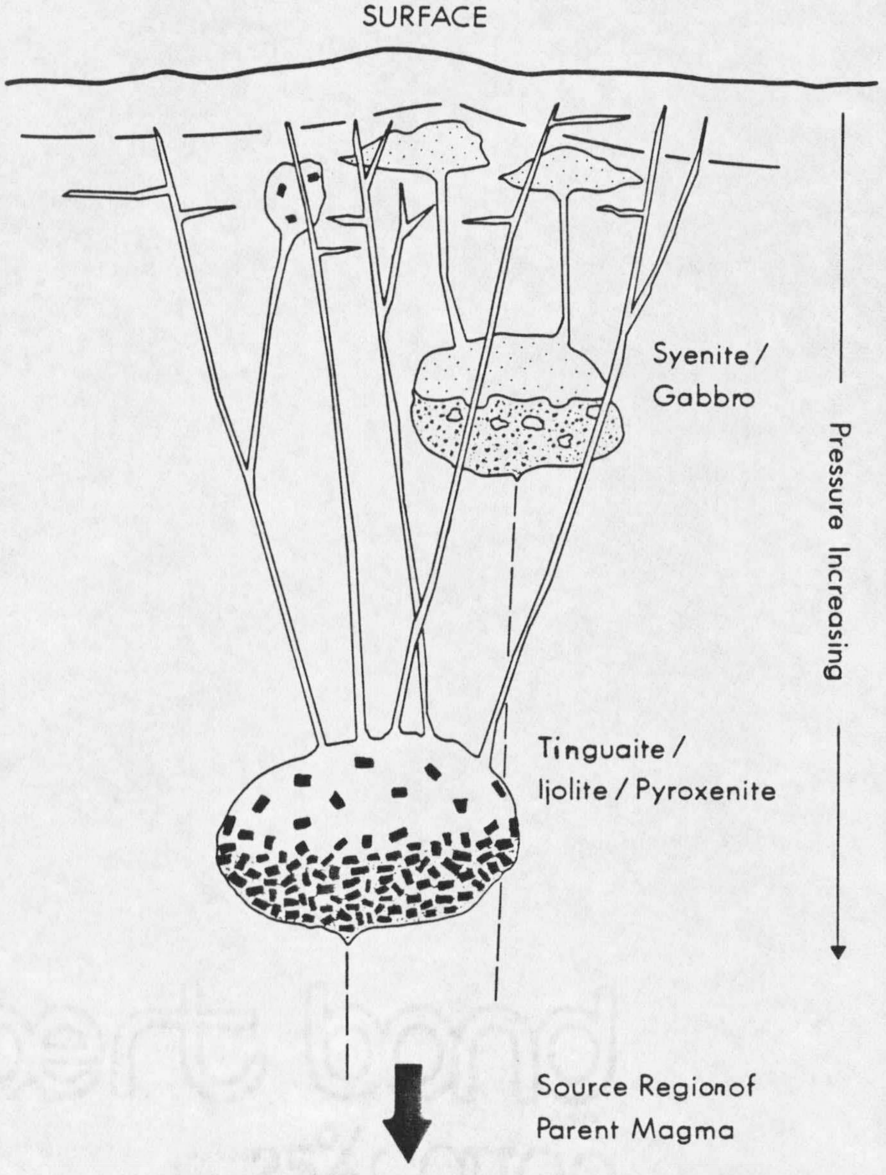


Figure 25. Schematic representation of alternate modes of differentiation of one parent magma to syenite or tinguaite residual phases (not to scale).

melteigite and ijolite at depth. As the melt accumulated in the top of the magma chamber, it was forcibly injected upward, ripping up and rafting along ijolitic inclusions and xenocrysts from the floor and walls of the magma chamber.

# SUMMARY

The igneous rocks of the Judith Mountains of central Montana are related to other Cretaceous and Tertiary igneous centers in that region. The province is characterized by alkaline igneous rocks. The igneous rocks of the Judith Mountains are unique in the province, because alkali-calcic rock types form the major exposed volume of the complex. In general, mafic alkaline rocks are more abundant than felsic alkaline rocks in the province. In the Judith Mountains, however, only felsic syenite and tinguaite crop out. Mafic alkaline rocks were found to exist as xenoliths in the felsic intrusions. Quartz-bearing syenite contains xenoliths of alkali gabbro. Rocks of the pyroxenite-melteigite-ijolite series are contained as xenoliths in the tinguaite. The emplacement of the syenite preceeded the emplacement of the tinguaite, although field relations indicate thate syenite and tinguaite were at least partly contemporaneous. The alkaline rocks are divided into two series--mildly alkaline alkali gabbro and quartz-bearing syenite and strongly alkaline nepheline-bearing tinguaite and ijolitic rocks.

The overall origin of the mildly and strongly alkaline rocks is not clear. However, quartz-bearing alkalic rocks such as the syenite can not be differentiated by processes such as fractional crystallization from the same undersaturated parent magma which forms nepheline-bearing rocks such as tinguaite. Therefore, either the two series of alkaline rocks arose from separate parent magmas, or they formed by very different processes from a single parent magma. The most reasonable hypothesis involves the early separation of a single alkaline parent magma, possibly kimberlitic, into two distinct sub-magmas. The magmas rose along crystal fractures or lineaments which represent deep-seated crustal weaknesses. These sub-magmas could have differentiated at different depths. Cumulate textures in the ijolitic rocks suggest that these strongly alkaline, nepheline-bearing rocks formed by fractional crystallization. The lack of cumulate textures in the alkali gabbro makes their origin a matter of speculation. It is possible that the mildly alkaline rocks were formed by liquid immiscibility processes. The strongly alkaline rocks may have differentiated at depth by fractional crystallization, while the mildly alkaline rocks formed nearer to the surface by liquid immiscibility processes.

A deeper level of erosion in the Judith Mountains would expose the mafic alkaline rocks and the carbonatite body which presumably exists at depth. It appears that the parent magma originated in the mantle and rose slowly from the source, allowing time for the extreme differentiation which produced this very diverse suite of alkaline rocks.

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Geology compiled in part from Walace (1953).

# PLATE 1

## GEOLOGIC MAP OF THE ALKALINE IGNEOUS ROCKS OF THE JUDITH MOUNTAINS CENTRAL MONTANA

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| Author: | P. BARRICK | Date: | 5-82 | Ref. No.: | |
| Datum: | C.I.: 50' | Scale: | 1'' : 3000' | Encl. No.: | |
| Drafted by: | SEP | Dr. No.: | | | |