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
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Head, Major Department

Graduate Dean

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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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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.

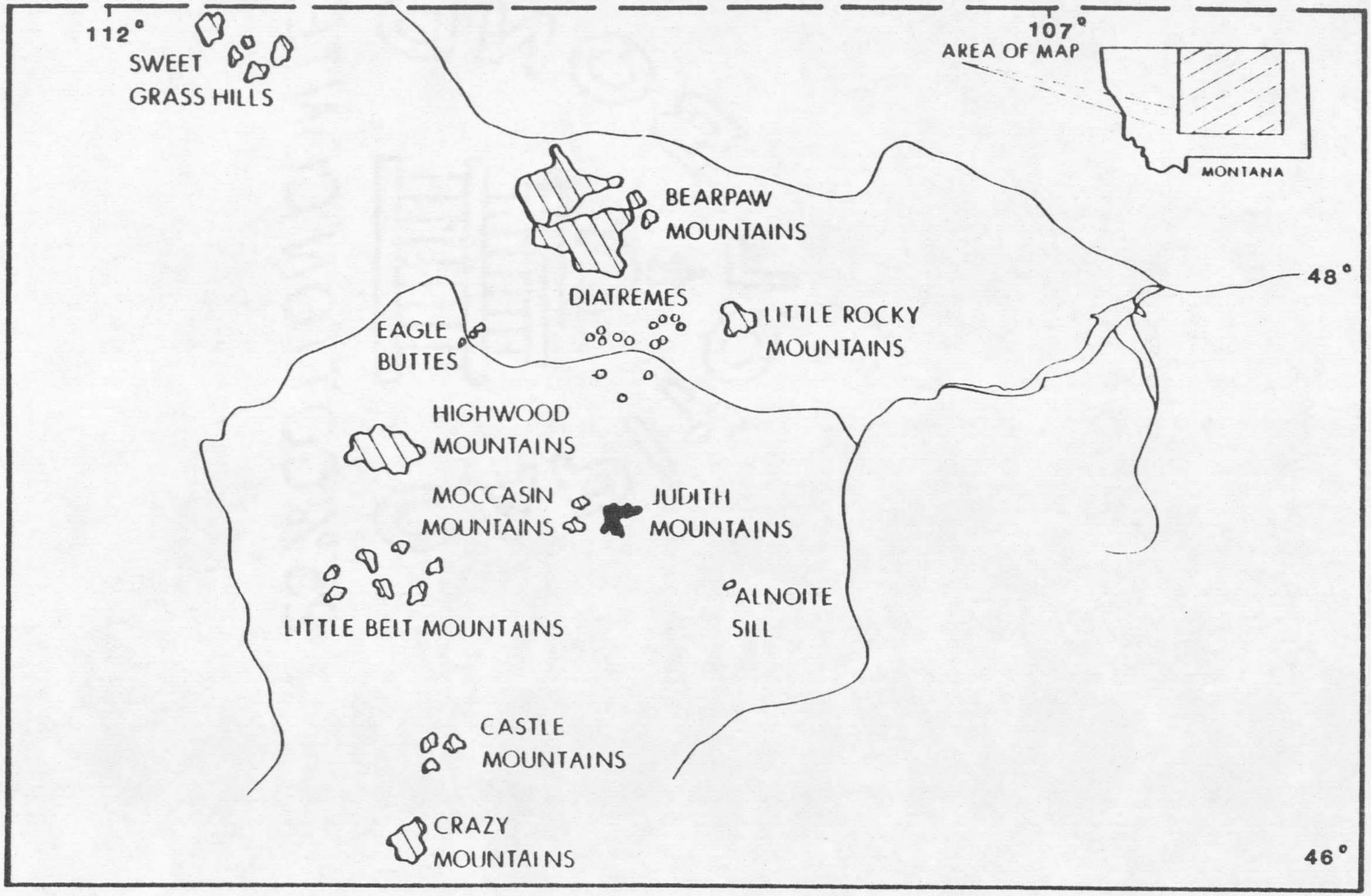

Figure 1. Location of the Judith Mountains, central Montana. Cretaceous-Tertiary igneous centers of the central Montana alkaline province are shaded in.

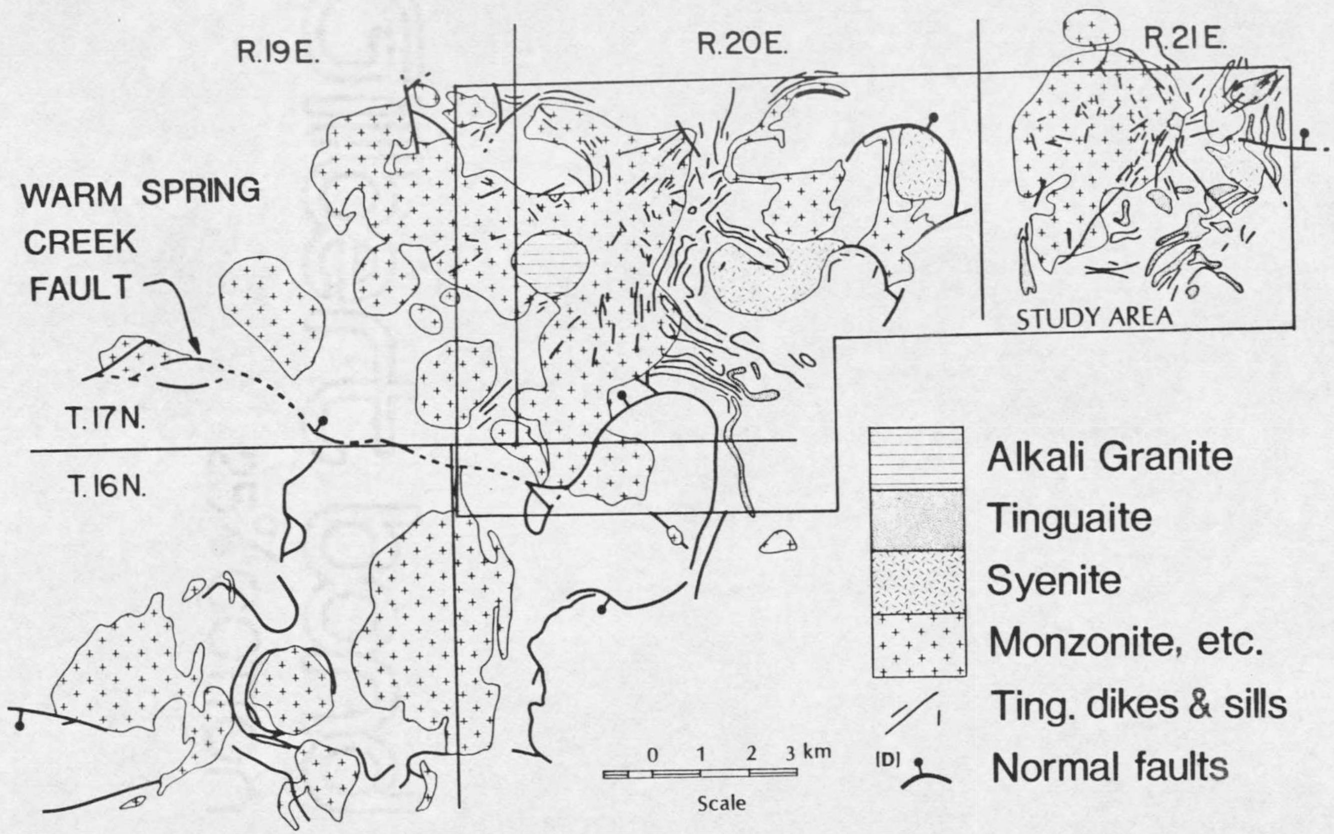

Figure 2. Generalized geologic map of the Judith Mountains (after Wallace, 1953). Study area is outlined.

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

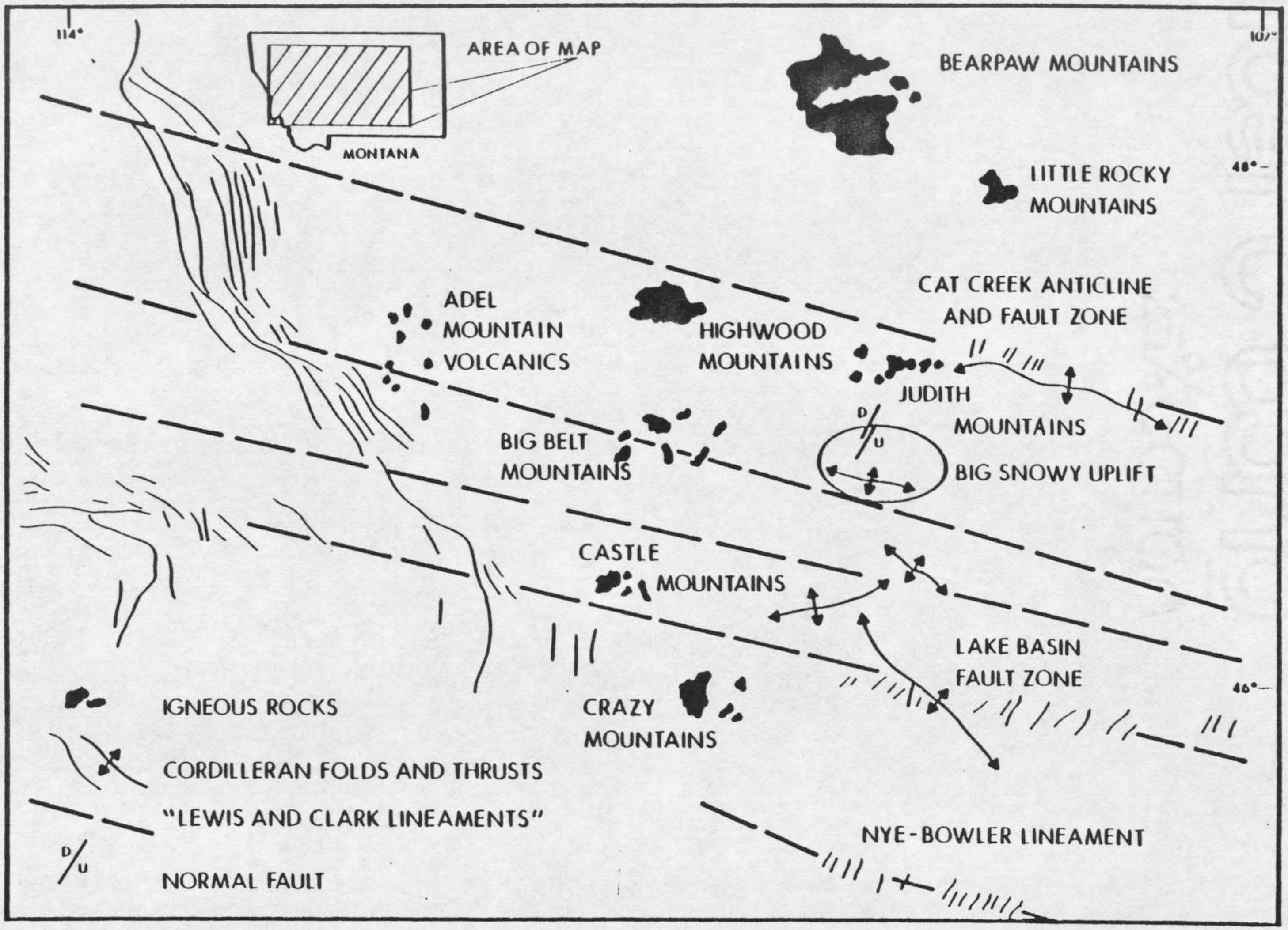

Figure 3. Tectonic map of central Montana showing "Lewis and Clark Lineaments" and associated features (after Smith, 1965).

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).

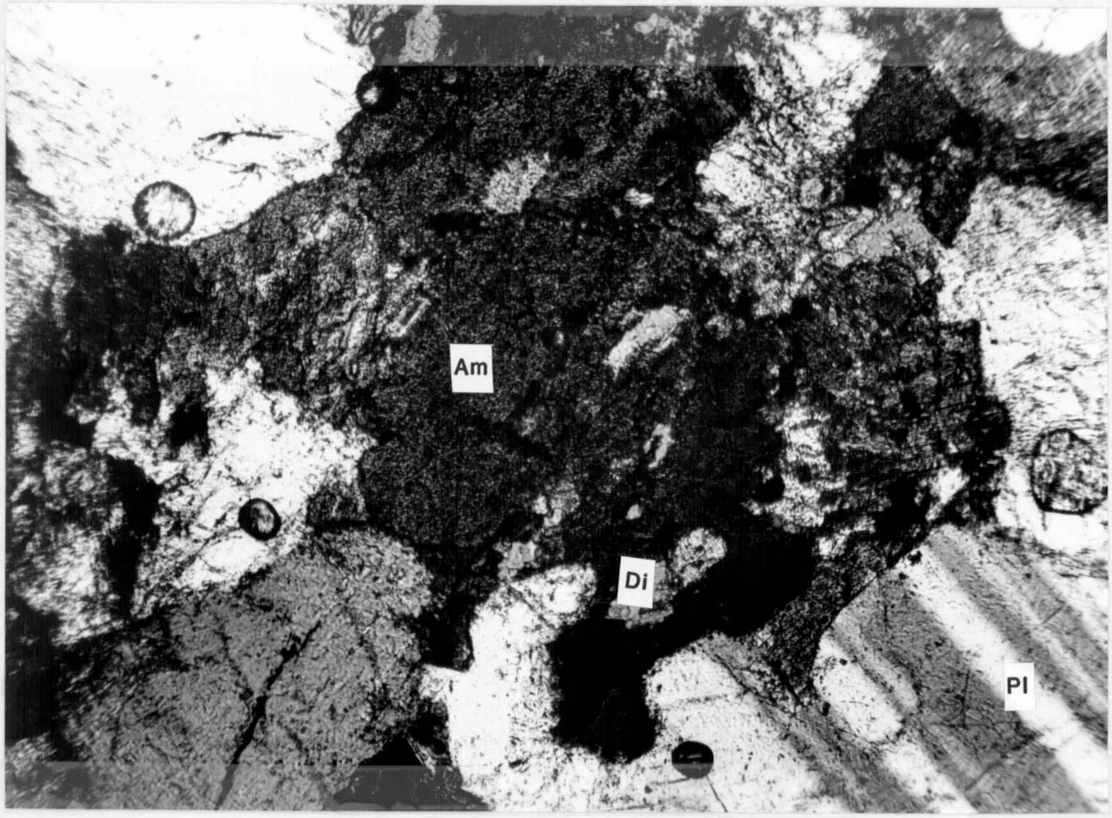

Figure 6. Photomicrograph of alkali gabbro; polarized light. Contains diopside, arfvedsonite amphibole enclosing diopside remnants, and twinned plagioclase. (X 150).

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.

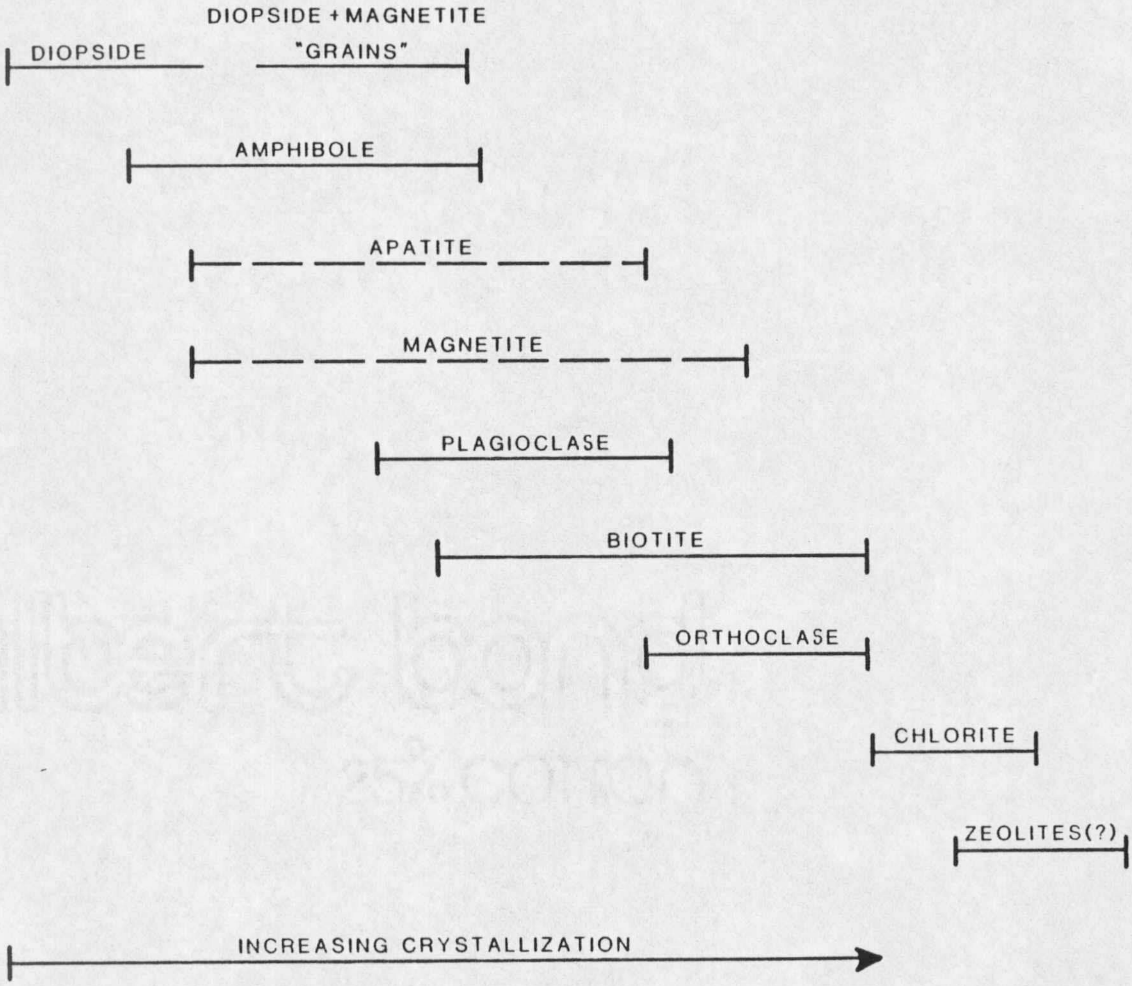

Figure 7. Crystallization sequence of alkali gabbro.

	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

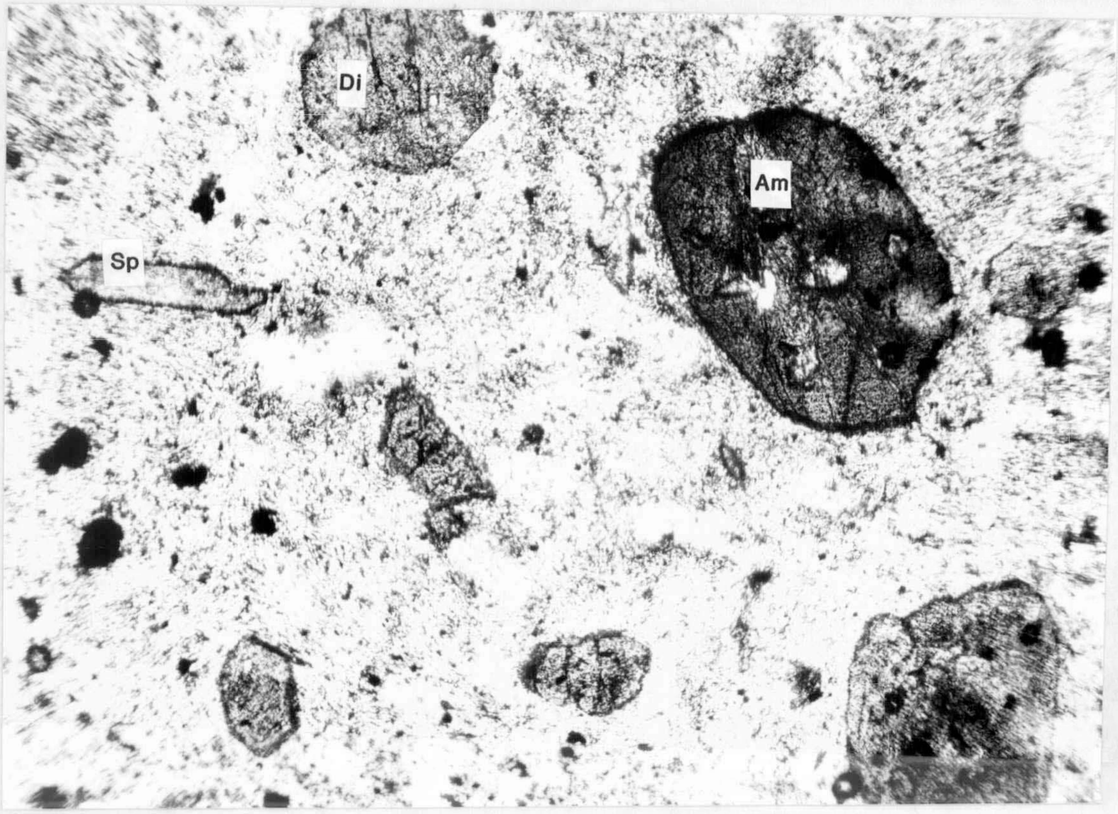

Figure 8. Photomicrograph of syenite; plane light. Large rounded phenocryst is sodic amphibole bordered by magnetite grains. Lighter gray phenocrysts are diopside, wedge shaped crystal is sphene. (X 150).

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