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Field relations petrology and mineralization of the Linster Peak dome Fergus County Montana

Gail L. Kirchner
The University of Montana

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FIELD RELATIONS, PETROLOGY, AND MINERALIZATION
OF THE LINSTER PEAK DOME, FERGUS COUNTY, MONTANA

By
Gail L. Kirchner
B.S. Duke University, 1977

Presented in partial fulfillment of the requirements for the degree of

Master of Science
UNIVERSITY OF MONTANA
1982

Approved by

Chairman, Board of Examiners

Dean, Graduate School

Date
Late-Cretaceous and Early-Tertiary calc-alkaline and alkaline magmatism produced the Linster Peak dome in the eastern Judith Mountains. The Linster Peak stock, a multiphase monzonite porphyry stock, forcefully intruded an east-west fault zone in Upper Paleozoic and Mesozoic sediments. Various consecutive phases of the stock produced an upper chill cap, a massive core, molybdenum- and copper-bearing intrusive breccias and dikes, and gold-bearing skarns.

Immediately following this calc-alkaline igneous event, nepheline-normative alkali-syenite porphyries and alkali-trachytes invaded the dome as a plug, irregular discordant bodies, sills, and dikes. No mineralization is attributed to this event. Late hydrothermal alteration produced carbonate-pyrite-fluorite veins and extensive carbonatization and pyritization along major shear zones, after crystallization of all igneous lithologies.

Differences in mineral and chemical constituents, fluid phases, and silica saturation indicate that the calc-alkaline and alkaline rocks of the Linster Peak dome did not evolve from the same source area or magma. Apparently minor magma mixing at depth produced the chemical and mineralogical anomalies present in these lithologies. Presumably the calc-alkaline and alkaline magmas, from crustal and mantle sources respectively, developed contemporaneously by the same tectonic mechanism of magma generation. Local decompression, in response to Late-Cretaceous and Early-Tertiary secondary tension and basement faulting, is suggested here as the most plausible mechanism for generating coeval calc-alkaline and alkaline magmas of the Linster Peak dome.
ACKNOWLEDGEMENTS

Many people from the University of Montana, U.S. Geological Survey, and private industry have been invaluable in generating data and ideas incorporated into this thesis. A special thanks go to thesis committee members: David Alt, Donald Hyndman, John Scott, and Carter Hearn for their ideas and comments on the progressing work and manuscript.

Carter Hearn, Richard Marvin, David Lindsey, and Zeke Rivera of the U.S. Geological Survey, and Randy Moore, Roger Kuhns, Bruce Otto, and Carleen Holloway supplied expertise, data, or facilities utilized in this study. I also wish to extend my sincere appreciation to Warren Rehn, John, Delores, and Bill Rife, and especially Fess Foster.

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Purpose and Approach

The Linster Peak dome, in the eastern Judith Mountains, exemplifies the problem of spatially and temporally associated calc-alkaline and alkaline magmatism in central Montana. In this study the petrogenesis of these magmas is evaluated in light of additional petrologic research and an examination of contemporaneous crustal deformation.

The two previously published studies in this area are reconnaissance evaluations of the entire Judith Mountain complex. The breadth of their approach completed the necessary correlative work to allow investigation on a more detailed scale. Weed and Pirrson (1897) concluded that the two igneous suites are related by some "inexplicable differentiation" from a common source magma. Wallace (1953) supported a model of limestone assimilation by calc-alkaline magmas to produce alkaline magmas.

This study involved detailed field, petrographic, chemical, and chronological work on one isolated dome which contained rocks of both suites. The conclusions presented here suggest that the calc-alkaline magmas of the Linster Peak dome evolved independently, but contemporaneously with alkalic magmas. Presumably, minor magma mixing produced slight mutual contamination of both magmas. Regional and local structures indicate that deep crustal shears and local faults, respectively, acted as conduits for rising magmas and allowed minor mixing. The relationship of the calc-alkaline and alkaline magmas of the Linster
Peak dome may represent one small, but significant, clue to the igneous history of central Montana. These conclusions must be kept in perspective, as applicable to the Linster Peak dome. Additional detailed studies should elaborate the processes which produced coeval calc-alkaline and alkaline magmas in central Montana.

Location

Central Montana hosts numerous alkalic igneous centers which are grouped into the petrographic province of Central Montana (Weed and Pirrson, 1905; Larsen, 1940). Within this province, the east-west-trending Judith Mountain range contains both calc-alkaline and alkaline igneous centers, including the Linster Peak dome (Figure 1). This dome occurs as a geographically isolated mass between Ross Pass and Black Butte (Figure 2). The study area occupies approximately 25 square kilometers in the northeastern portion of the Judith Peak 15-minute quadrangle and the southern portion of the Lewistown 1 SE advance 7.5-minute topographic print.

The Linster Peak dome includes both Bureau of Land Management land and privately owned land. The highest elevations are public, but the plains and flanking hills of the dome are private.
LOCATION OF THE LINSTER PEAK DOME
IN NORTH-CENTRAL MONTANA

Figure: 1
The Judith Range is composed of isolated and interpenetrating stocks and laccoliths in the central Montana Alkalic Province (Weed and Pirrson, 1897; Wallace, 1953). This province, occupying approximately 40,000 square kilometers, was delineated by the "cosanguinity of igneous rocks" occurring in an ovoid, northeast-trending zone (Weed and Pirrson, 1905; Larsen, 1940).

The representative alkalic lithologies include an unusual assemblage of Late-Cretaceous and Tertiary potassic varieties. They range from alkalic shonkinites, ultramafic rocks, and feldspathoidal syenites to peralkaline rhyolites and granites. Coeval igneous suites include a broad spectrum of rock types including: carbonatites (Pecora, 1962), ultramafic rocks and kimberlites (Hearn, 1968; 1979), and calc-alkaline lithologies (Wallace, 1953; Weed and Pirrson, 1895; 1896; 1897; Brock-unier, 1936; Larsen, 1940; and Witkind, 1973).

Throughout the province, alkaline magmatism generally post-dates calc-alkaline magmatism, although commonly the two suites are coeval. Magmatism began 69 to 68 million years ago and tapered off significantly 46 million years ago (Marvin and others, 1980).

Clearly the mafic alkaline, carbonatitic, and ultramafic lithologies are mantle-derived. The petrogenesis of the felsic alkalic and calc-alkaline rocks is still a puzzling problem of the Central Montana Alkalic Province. The Judith Mountains contain several phases of felsic
alkaline and calc-alkaline rocks (Weed and Pirrson, 1897; Wallace, 1953). The tectonic setting of the Judith Mountains will be discussed below to illuminate crustal processes which influenced local magmatism.
The petrogenesis of the igneous rocks of the Linster Peak dome cannot be adequately resolved without an awareness of the Late-Cretaceous and early Tertiary tectonic setting and structures in central Montana. Northeast tensional structures resulting from regionally pervasive Late-Cretaceous to early Tertiary east-northeast compression are interpreted to have influenced coeval magmatism in the Rocky Mountain foreland (Bookstrom, 1981; Smith, 1967; Smith, 1965; Stone, 1969; Rehrig and Heidrich, 1972).

The latent effects of these compressive and tensional regimes are far more subtle in the Rocky Mountain foreland than in the Cordillera itself. In the plains of central Montana, surface features are generally attributed to deformation deep within the crust. Here, numerous domes, uplifts, basins, folds, and en echelon fault zones, interpreted to reflect large-scale faulting of the Precambrian basement, include: the en echelon Cat Creek, Sumatra, and Lake Basin fault zones; the Big Snowy and Little Belt uplifts; the Cat Creek, Big Wall, Sumatra, Women's Pocket, and Wolf Creek anticlines; the Blood Creek and Sumatra synclines; and the Porcupine and Big Coulee-Hailstone domes (Figure 3) (Smith, 1962; Dobbrin and Erdmann, 1955; Smith, 1967; Chamberlain, 1919; Thom, 1923, Smith, 1965; Stone, 1969).

En echelon fault zones, folds, and domes are predictable surface phenomenon of deep-seated wrench faults (Wilcox and others, 1973; Moody, and Hill, 1956; Stone, 1969; Anderson, 1942). Stone (1969), Smith
(1967), Smith (1965), and Thom (1923) interpret the surface structures of central Montana to represent buried megashears, or wrench faults. The magnetic map of central Montana (Zeitz, 1980) also supports an interpretation of basement faulting for many of these features.

These hypothetical megashears trend approximately N70-75°W, as do most of their surface expressions (Figure 4). The northernmost megashear of Smith (1965) extends northwest from the Porcupine dome and the Cat Creek anticline, through the Northeastern Judith Mountains, in the immediate vicinity of Linster Peak. Local structures which are apparently related to this trend are discussed in the next chapter.

Stratigraphic evidence suggests that these northwest-oriented basement shear zones originated or were reactivated in response to 70 to 50 million year old Laramide east-northeast compression (Burchfiel, 1979; Stone, 1969; Smith, 1965; Smith, 1967). They are not to be confused with the Precambrian east-west shears of Winston (1982) and Thom (1923). Theoretically, this east-northeast Laramide compressive regime produced a shear couple oriented approximately N70°W. Thus, a secondary zone of tensional stress is expected to have formed in a northeasterly direction (Figure 4). Smith (1965) and Smith (1967) use geophysical, petrologic, and structural data to suggest that Late-Cretaceous igneous activity in central Montana utilized this "incipient rifting" environment to reach shallow crustal levails. These structures were presumably influenced by later, primary Tertiary tensional stresses.

In summary, the Rocky Mountain cordillera exhibits severe crustal deformation resulting from the Late-Cretaceous Laramide Orogeny while
Stress pattern in rocks overlying regional megashears

Lewis and Clark Lineaments (Surface traces of deep-seated megashears)

1. Nye-Bowler Lineament
2. Lake Basin Lineament
3. Osburn Lineament
4. Big Snowy Lineament
5. Cat Creek Lineament

Constituent Structures

6. Porcupine dome
7. Cat Creek anticline and fault zone
8. Big Wall anticline
9. Big Snowy uplift
10. Women's Pocket anticline
11. Show-Me anticline
12. Big Coulee-Maxtute dome
13. Lake Basin fault zone
14. Pryor terrace
15. Clark Fork en échelon folds
16. Osburn fault zone
17. Hope fault
18. Little Belt uplift
19. Judith Mountains intrusives

Compiled from The Tectonic Map of the United States, 1965.
the Rocky Mountain foreland exhibits only minor near-surface deformations. Yet the evidence of deep crustal deformation in the northern Rocky Mountain foreland should not be overlooked. Apparently, basement shears and a secondary tensional regime formed in response to Late-Cretaceous, east-northeast compression. The resulting surface phenomena in central Montana are en echelon fault zones, basement-cored uplifts, folds, and domes.

Presumably magma generation in central Montana is linked to this contemporaneous occurrence of deep-seated basement faulting and a secondary tensional regime.
LOCAL GEOLOGY

The Judith Mountains

Local structures and igneous centers of the Judith Mountains are characteristic of the regional structures and coeval alkaline and calc-alkaline magmatism in central Montana.

The chronological sequence of igneous rock types here, from oldest to youngest, is considered: quartz monzonite, syenite, rhyolite, tinguaite, and alkali-granite (Wallace, 1953). These lithologies decrease volumetrically in the same order. Generally, the calc-alkaline magmas, which are far more voluminous, produced porphyritic stocks, plugs, dikes, and breccia pipes whereas the alkaline magmas produced porphyritic laccoliths, plugs, dikes, and sills.

The stratigraphic position of the competent Madison limestone north and south of the Warm Springs Creek fault presumably controlled the mode of emplacement and possibly the type of magmatism in the area. Calc-alkaline rocks occur on both sides of the fault, whereas alkaline rocks occur only north of the fault (Figure 2).

Major faults in the Judith Mountains trend east-northeast or west-northwest (Wallace, 1953; Calvert, 1909) and comply extremely well with regional trends discussed in the previous section. The alignment of stocks in the northern Judith Mountains also exemplifies this trend. It is probable that the orientations of major faults and stocks in the Judith Mountains were strongly influenced by regional basement shears.
Gold mineralization is spatially related to contacts between calc-alkaline magmas and the Madison limestone, as well as at intersection of shear zones. Anomalous copper, molybdenum, silver, lead, and zinc values occur sporadically in hydrothermally altered areas.

Structure of the Linster Peak Dome

The Linster Peak dome is a sub-circular monzonitic stock which intruded and domed sediments of the Big Snowy Group, the Morrison, Ellis, and Kootenai formations, and the Colorado Group. This crystalline-cored dome is cut by a major east-west-trending normal fault which appears to have been active before, during, and after stock emplacement. North-south-trending shears, faults, and fractures attest to less dramatic structural elements active during and after stock emplacement, but prior to Eocene alkalic activity.

The domal structure of the Linster Peak stock is revealed by the occurrence of in situ sediments which flank the stock on three sides. These sediments have been tilted from their original sub-horizontal position by stock emplacement, although later faulting may have modified their orientations slightly. Roof pendants in the apical part of the stock indicate that the roof chamber is presently exposed. The domed strata and the occurrence of vuggy intrusive breccias attest to a near-surface, forceful emplacement, typical of other stocks and laccoliths in the northern Judith and Moccasin Mountains (Wallace, 1953; Lindsey, 1980).
The dominant fault of the Linster Peak dome is a vertical, east-west-trending normal fault (Plate 1). The fault trace is unaffected by topography, indicating a near-vertical dip. Its strike varies from N75°W to N80°E, paralleling the dominant regional trends. This fault is documented on the eastern flank of the dome by stratigraphic offset and faulted igneous and sedimentary contacts, while in the core of the dome it is recognized by aligned tectonic and intrusive breccias. To the west the trace of the fault is indistinguishable in the chaotic and altered monzonite porphyry-mixed unit, although abundant east-northeast and west-northwest fractures here indicate that splaying fractures and shears outlived the last pulses of monzonitic magma. Movement prior to crystallization of the stock apparently dominated the fault's history. Stratigraphic offset in Late-Mesozoic sediments indicates that the dip separation is approximately 450 meters (Figure 6). Since no significant offset occurred in the sub-horizontal contact of the fine- and coarse-grained monzonite facies (Plate 1), less than 155 meters of the 450 meters of displacement could have occurred after crystallization of the earliest monzonite porphyry phase. The alignment of at least five major stocks, including the Linster Peak dome, along an east-west line in the northern Judith Mountains suggests that a large fault or shear controlled Late-Cretaceous to Paleocene stock emplacement and local faulting. This structure could be a subsurface extension of the Cat Creek anticline and fault zone (Figure 3).
### Explanation for Cross Sections

*(Figures 5 and 6)*

<table>
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<th>Qu</th>
<th>Undivided alluvium, colluvium, and talus</th>
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<tr>
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<td>Alkali-Trachyte</td>
</tr>
<tr>
<td>Tasp</td>
<td>Alkali-Syenite Porphyry</td>
</tr>
<tr>
<td>Tmpm</td>
<td>Monzonite Porphyry, mixed</td>
</tr>
<tr>
<td>Tib</td>
<td>Intrusive Breccia</td>
</tr>
<tr>
<td>Tmpc</td>
<td>Monzonite Porphyry, coarse-grained</td>
</tr>
<tr>
<td>Tmpf</td>
<td>Monzonite PORphyry, fine-grained</td>
</tr>
<tr>
<td>Kc</td>
<td>Colorado Group</td>
</tr>
<tr>
<td>Kk</td>
<td>Kootenai Formation</td>
</tr>
<tr>
<td>Jme</td>
<td>Morrison Formation and Ellis Group</td>
</tr>
<tr>
<td>Mbs</td>
<td>Big Snowy Group</td>
</tr>
<tr>
<td>Mm</td>
<td>Madison Formation</td>
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Cross Section B to B'
LINISTER PEAK DOME
Fergus County, Montana

Cross Section D to D'
LINISTER PEAK DOME
Fergus County, Montana
Fault movement contemporaneous with intrusion of the monzonite porphyry stock is most clear in the center of the dome. There, an oblong, N80°E-trending zone of consecutive monzonitic and latitic phases and intense argillic alteration and pyritization occur along the fault trace. In Plate 1, this complex zone of weakness is contained within the unit monzonite porphyry-mixed.

Post-crystallization fractures along the fault are documented by a local offset, tectonic breccias, and gauge in the monzonitic rocks. Late-stage quartz-pyrite-fluorite and calcite-pyrite-fluorite veins, oriented N80°E and N75°W in the Golden Jack and Lucky Strike adits (Plate 2) respectively, attest to post-monzonite fracturing along the fault zone. Within monzonite lithologies to the east, undeformed Eocene age alkalic dikes intruded along the fault.

Another less dominant structural trend is a sub-vertical shear-fault-fracture system that trends N5°W and is responsible for localization of late monzonitic magmas and hydrothermal alteration and mineralization. Shearing with this orientation is exposed at the Landheim prospect, aligned faulting is exposed at the Kirby prospect, and aligned fracturing is exposed in the Golden Jack adit and Edward's Creek prospects (Plates 1 and 2). Extensive quartz veining, reaching thickness of 1 centimeter, also occurs along this trend (Plate 3). Alteration, mineralization, and intrusive breccias are most intense at intersections of east-west- and north-south-trending faults and shears.
In summary, the dominant structural trends of the Linster Peak dome are N75°W to N80°E and N5°W. The comparison of these trends with those of the entire Judith Mountain range mapped by Wallace (1953) and regional trends (Smith, 1967; Thom, 1923; Smith, 1965; Dobbrin and Erdmann, 1955) suggest that regional tectonic forces controlled the faulting and shearing pattern of the Linster Peak dome. These pre-existing zones of weakness appear to have been active before, during, and after emplacement of the Late-Cretaceous - Early-Paleocene monzonite stock. Younger, Eocene alkalic magmas utilized these zones, but there is no evidence of post-Eocene displacement or fracturing along these trends.

Description of Rock Units

The study area includes Paleozoic and Mesozoic limestones and clastic rocks, four phases of associated monzonite porphyry and latite, two varieties of phonolitic to syenitic lithologies, and undifferentiated Quaternary alluvium. With the exception of Quaternary alluvium, these rocks will be described in order of decreasing age.
Pre-Intrusion Faulting

The timing of major faulting in the Linster Peak dome is bracketed by offset on Late-Cretaceous sediments and undeformed Eocene dikes. Local faulting, nearly coincident with stock emplacement, is approximately coeval with the Cat Creek anticline. The pre-intrusion faulting in the Linster Peak area could have resulted from basement shearing along the anticline, the pressure of rising monzonitic magma, or both.

Emplacement of the Linster Peak Stock

Passive and forceful modes of emplacement were controlled by depth, and possibly rock type. At depth, in the Precambrian gneisses and Paleozoic limestones, stoping was apparently a significant mechanism of emplacement while shallow levels, in the upper Paleozoic and Mesozoic strata, forceful intrusion occurred by doming and brecciation.

The uppermost 150 to 210 meters of the stock chilled rapidly, forming an impermeable cap rock, the fine-grained monzonite porphyry. The monzonitic magma crystallized gradually in satellite bodies and peripheral portions of the stock. In the apical portions, below the chill cap, water, fluorine, sulphur, silica, and metals accumulated in magmatic fluids. The contact between the fine-grained porphyry chill cap and the coarse-grained core of the stock is extremely complex. In some locations, the coarse-grained porphyry brecciated the fine-grained porphyry. Elsewhere, it appears to have remelted the overlying fine-
grained porphyry, so that both rocks quenched simultaneously with loss of volatiles. In these areas, extensive hydrothermal alteration is indicated by silification, pyritization, and cation leaching.

As volatiles, silica, and metals accumulated in the roof zone, the effective pressure also increased. Eventually, hydrostatic pressure overcame lithostatic pressure along the fault zone and the stock fractured, resulting in quench textures in the coarse-grained porphyry and intrusive breccias, dikes, and hydrothermal alteration in the overlying fine-grained porphyry (Figure 5). Related faulting played a significant role in releasing magma and fluids. Sporadic copper, molybdenum, lead, and zinc porphyry-type mineralization accompanied decompression. The most pronounced skarn development also occurred during decompression events. Younger small spurts of magma continued to intrude the crystallizing stock, producing fine-grained latites.

The origin of the hydrothermal fluids is difficult to assess. It is possible that they are totally magmatic, or dominantly meteoric. The apparent "dryness" of the fine-grained porphyry chill cap is perplexing in light of the excess water required to form skarns and hydrothermal fluids. A felsic magma, carrying four percent water at significant depth, is undersaturated in water (Whitney, 1974; Hyndman, 1981). Whereas, in the epizonal environment, it is oversaturated with respect to water (Figure 7A). This phenomenon could explain why the monzonitic magma was able to rise to the hypabyssal environment yet expell volatiles and crystallize before it breached the surface. It is likely that at least some of this water was adsorbed from the lower Paleozoic
FIGURE 7: TWO SCHEMES FOR EXSOLVING A VOLATILE PHASE
MONZONITE PORPHYRY OF LINSTER PEAK

A. MAGMATIC VOLATILES:
- decreasing hydrostatic pressure promotes increasing volatile pressure
- lack of contact metamorphic zones skarns, up to 60 meters thick

B. MAGMATIC AND METEORIC VOLATILES:
- water diffuses to the zone most undersaturated in water
horizons at depth. With continued rising, when the magma reached a particular horizon (hereafter called the "A" horizon), the reverse process occurred (Figure 7B). This shift in water diffusion at different lithostatic pressures and temperatures is totally dependent on temperature and the relative partial pressures of water in the magma and host rocks. Small amounts of water and fluorine may also have accumulated during the destruction of hornblende.

During the waning stages of crystallization, alkali-trachyte porphyry and alkali-trachyte magmatism began. Nearly everywhere the intrusion of the alkaline magmas clearly post-dates crystallization of the stock. A few gray alkali-trachyte dikes carry anomalous, fractured plagioclase crystals and orthoclase megacrysts and contain less aegirine than the characteristically green alkali-trachytes. They are apparently a product of magma mixing or assimilation.

In one locality and in drill core, minor amounts of rhyolitic breccias represent the final magmatic event of unknown origin. The rhyolite in the drill core carries clasts of alkali-trachyte, thus dating the rhyolite as the youngest magmatic rock in the Linster Peak dome.

Alkalic Magmatism

Alkali-syenite porphyries intruded passively and violently coincident with the last stages of the Linster Peak stock. Alkalic magmatism was confined to sedimentary host rocks or fractures in the crystallized stock. Alkali-syenite porphyry magmas intruded first whereas alkali-trachyte dikes and sills intruded very shortly afterwards. Field and
petrographic characteristics of the alkali-trachytes indicate that they are fine-grained equivalents of the alkali-syenite porphyries. But chemical analyses indicate that the alkali-trachytes display unique chemical characteristics. Relative to the alkali-syenite porphyries, they are slightly enriched in potassium and depleted in calcium and silica. It is possible that the original alkali-syenite magma was identical in composition to the alkali-trachyte magmas but contamination by monzonitic material produced a composition equivalent to that of the alkali-syenite porphyries.

Evidence of a minor, late, carbonate-, alkali-, and water-rich fluid phase is indicated by analcrite and carbonate amygdules in the alkaline rocks, although low water pressures and high temperatures characterized the alkaline magmas. Fenitization and contact metamorphism are absent, although brecciation of host rocks is common. No significant mineralization is attributed to these magmas.

**Faulting and Late Hydrothermal Activity**

Faulting continued after crystallization of the Linster Peak stock where it offset portions of the earlier crystallized stock and produced oriented fractures in the younger stock lithologies. The alkaline magmas utilized the Linster Peak fault as a conduit, resulting in alkali-trachyte dikes oriented along the original fault trace.

Hot fluids may have travelled periodically or continually for a significant period of time after crystallization of the stock. Early episodes of hydrothermal alteration and veining occurred with magmatic
decompression and is dominated by a quartz-rich fluid. A later period of alteration is younger than the rhyolite breccias and alkali-trachytes and contained a carbonate-rich fluid. Likely sources for the quartz-rich phase are combined meteoric and magmatic fluids, whereas probable sources for the carbonate-rich fluid are primarily meteoric and may be linked to the occurrence of bedded travertine in the Judith and Moccasin Mountains. The late carbonate-rich hydrothermal alteration completed the sequence of "magmatic" events of the Linster Peak dome.
Upper Paleozoic and Mesozoic Sediments

Paleozoic and Mesozoic stratigraphy is critical to interpretation of stock morphology and faulting. Table 1 is a brief description of the stratigraphy of the northern Judith Mountains, as proposed by Wallace (1953) and Lindsay (1980).

Upper Paleozoic and Mesozoic strata occur on the Linster Peak dome as flanking sediments, roof pendants, and stope blocks (Plate 1). The oldest in situ formations exposed in the area are limestones, sandstone, siltstones, and shales of the Upper Mississippian Big Snowy Group. Younger rocks include the Jurassic, Swift, and Ellis Formations, Cretaceous Kootenai Formation, and Colorado Group. All of these formations occur in direct contact with igneous rocks of the dome.

Roof pendants include all of the above-mentioned formations. Generally they are attached to strata at the base of the dome, although occasionally they exist as islands in monzonite porphyry. Their orientation distinguishes rotated stope blocks from in situ pendants. All stope blocks are comprised of thickly bedded gray limestone, and are tentatively correlated with Mississippian Madison limestone. Their similarity to a section of massive limestone of the Big Snowy Group makes this correlation tenuous, and tactite development further complicates their stratigraphic correlation.
<table>
<thead>
<tr>
<th>PERIOD</th>
<th>FORMATION</th>
<th>THICKNESS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRETACEOUS</td>
<td>EAGLE SANDSTONE</td>
<td>140'</td>
<td>Light-gray to yellowish-gray massive, medium-grained sandstone with some layers of yellowish-gray sandy shale. Locally crossbedded.</td>
</tr>
<tr>
<td></td>
<td>TELEGRAPH CREEK</td>
<td>205'</td>
<td>Light olive-gray sandy shale, thinly laminated. Sand content increases upward.</td>
</tr>
<tr>
<td></td>
<td>COLORADO SHALE</td>
<td>1525'</td>
<td>Dark-gray to black fissile shale with a few thin ridge-forming sandstone layers. Cat Creek sandstone 75 feet thick at the base, and Mowry beds 140 feet thick are 350 feet above the base. Mowry consists of fine-grained sandstone and limy shales that weather light-gray and contain abundant fish scales in some layers.</td>
</tr>
<tr>
<td></td>
<td>KOOTENAI FORMATION</td>
<td>320-500'</td>
<td>Characterized by black and maroon mudstone in the upper part, and ridge-forming coarse-grained salt-and-pepper sandstone in the lower part.</td>
</tr>
<tr>
<td>JURASSIC</td>
<td>MORRISON FORMATION</td>
<td>220'</td>
<td>Red and brown mudstone, siltstone, and sandstone; gray micritic limestone; and near the top, impure coal.</td>
</tr>
<tr>
<td></td>
<td>SWIFT FORMATION</td>
<td>55'</td>
<td>Thin-bedded brownish-gray arkosic sandstone; some layers contain abundant glauconitic grains.</td>
</tr>
<tr>
<td></td>
<td>PIEDMONT FORMATION</td>
<td>90'</td>
<td>Light- to dark-gray sandy, limy shale with a few thin layers of limy sandstone.</td>
</tr>
<tr>
<td></td>
<td>PIPER FORMATION</td>
<td>120-230'</td>
<td>Interbedded dark-gray limestone and shale, locally some red shale.</td>
</tr>
<tr>
<td>MISSISSIPPIAN</td>
<td>KIDBEE SANDSTONE</td>
<td>0-110'</td>
<td>Light-brown to yellowish-gray sandstone with thin beds of red shale.</td>
</tr>
<tr>
<td></td>
<td>MADISON LIMESTONE</td>
<td>1350'</td>
<td>Massive gray limestone; contains gray to black chert in some layers and some thick layers of brecciated limestone.</td>
</tr>
</tbody>
</table>

**Table: 1** Upper Paleozoic and Mesozoic stratigraphy of the Lister Peak dome area, after Wallace (1953) and Lindsey (1980).
Late-Cretaceous age sediments dominate the north part of the dome, while sediments as young as Upper Mississippian are exposed south of the fault. Stratigraphic offset here is approximately 450 meters.

**Quaternary Alluvium**

Quaternary alluvium is mapped as undifferentiated alluvium (Qu) on the map of the Linster Peak dome (Plate 1). These deposits include both colluvium and alluvium. Talus is mapped as the rock type of which it is composed, and contacts covered by talus are dashed.
PETROLOGY OF THE IGNEOUS ROCKS

Descriptions for Late-Cretaceous to Eocene igneous rocks of the Linster Peak dome are divided into four sections: field occurrence, mineral composition, texture, and interpretation. Rock unit descriptions are based on field observation, petrographic studies, and x-ray diffraction analyses.¹

MONZONITE PORPHYRY - Fine-Grained

Field Occurrence

Fine-grained², gray to brownish-gray monzonite porphyry (Plate 4) is a cap rock on the Linster Peak stock. At the apex of the dome this unit attains a maximum thickness of 215 meters. The upper contact is not exposed and the base forms a sub-horizontal contact with the coarse-grained phase of monzonite porphyry. The contact is commonly intrusive, although on Cone Butte and parts of Linster Peak it is clearly gradational. Field distinction between these two units is based on the abundance of potassium feldspar megacrysts; the fine-grained monzonite porphyry contains less than two percent megacrysts whereas the coarse-grained analogy contains more. A gradational phase containing zero to two percent megacrysts may range from 50 to 75 meters thick.

¹ Detailed accounts of laboratory procedures are filed in Appendix 1.
² Prefixes for fine- and coarse-grained porphyry are used to describe phenocryst size, not groundmass size. Grain sizes used in this report are: very coarse = > 8 mm; coarse = 4-8 mm; medium = 2-4 mm; fine = 1-2 mm; very = 0.2-1 mm; and aphanitic = < 0.2 mm.
A. Fine-grained Monzonite Porphyry

B. Coarse-grained Monzonite Porphyry
The fine-grained monzonite porphyry also occurs as dikes and sills.

Mineral Constituents

Phenocrysts of the fine-grained monzonite porphyry (Table 2) in order of decreasing abundance, are andesine (An\textsubscript{50-55}), hornblende, biotite, diopsidic aegirine-augite, quartz, biotite, and orthoclase. Medium-grained, black, prismatic hornblende phenocrysts are identified as a member of the hastingsite group on the basis of pleochroism, 2V, Z \& C, and X-ray pattern. Hornblende and biotite have reaction rims of fine-grained magnetite and clinopyroxene. Diopsidic-aegirine-augite, light green in thin section, characteristically occupies one-half to one percent of the rock. Its unusual occurrence in an igneous rock composed primarily of andesine and hornblende is discussed below. Rare, very coarse orthoclase megacrysts may reach dimensions of three to four centimeters. Minor quartz occurs as interstitial anhedral grains rarely visible in hand sample. With the exception of groundmass quartz, it occupies less than four percent of the rock.

Accessory minerals include ubiquitous magnetite, as well as sphene, apatite, limonite, tourmaline, and zircon. Sphene is very abundant and unusually coarse-grained. With the exception of limonite and magnetite, all accessory minerals are euhedral and crystallized early in the melt.
<table>
<thead>
<tr>
<th>Mineral/ color (H.S.)</th>
<th>Percent of rock</th>
<th>Grain size</th>
<th>Grain shape</th>
<th>Properties</th>
<th>Alteration products</th>
<th>Textures/ Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesine/ milky white</td>
<td>12 to 55%</td>
<td>medium to fine-grained, 0.5 to 2 mm</td>
<td>euhedral</td>
<td>An(48-50) *cores; An(30-44) *rims or -2V= 55-65°;</td>
<td>kaolinite, calcite, rarely sericite.</td>
<td>Oscillatory zoning, An-rich cores, Ab-rich rims; albite and carlsbad twins.</td>
</tr>
<tr>
<td>Hornblende (Tschemikite Group) black</td>
<td>3-7%</td>
<td>medium to fine-grained, 1-4 mm long</td>
<td>euhedral, prismatic with diamond or hexagonal cross-sections</td>
<td>-2V= 60°; ZA C= 15°, 16°; pleochroism: x=gold y=green to olive z=dark olive 60°/120° cleavage</td>
<td>carbonate, epidote, magnetite, chlorite, biotite, clinopyroxene</td>
<td>Generally lineated; prismatic shape is characteristic; may be glomerocrystic; in upper zone, rims of magnetite and cpx.</td>
</tr>
<tr>
<td>Diopsidic aegerine-augite/ black</td>
<td>Trace -2%</td>
<td>fine-grained, 0.5-0.75 mm</td>
<td>euhedral, square or hexagonal cross-sections</td>
<td>+2V=60°; bifr.=0.25; higher relief than hornblende; pleochroism: x=light green, y=light green, z=pale yellow-green; Z C=88°; 90° cleavage</td>
<td>calcite, epidote, magnetite, hornblende</td>
<td>very pale to light green; similar to cpx in trachyte, syenite and mafic inclusions; may be shattered or replaced by hornblende.</td>
</tr>
<tr>
<td>Biotite/ black</td>
<td>Trace - 3%</td>
<td>fine- to medium-grained, 0.5-3 mm</td>
<td>blocky, bladed, or pseudomorphic after hornblende</td>
<td>low -2V, parallel extinction; mod. high birfr., birds-eye texture, pleochroic: x=beige to light brown, y= brown, z= dk. brown</td>
<td>not observed</td>
<td>Generally pseudomorph after hornblende; rarely as individual euhedral grains.</td>
</tr>
<tr>
<td>Orthoclase/ glassy to opaque white</td>
<td>Mecacrysts &amp; pheno.; 0-2%, rarely greater than 0.5%</td>
<td>very coarse to very fine-grained; 0.1-40 mm</td>
<td>megacrysts and phenocrysts are euhedral, interstitial grains are anhedral</td>
<td>-2V=50°-60°; low (-) relief; low birefringence</td>
<td>sericite</td>
<td>Oscillatory zoning; rarely interpenetration twins; less than 2% is diagnostic.</td>
</tr>
<tr>
<td>Quartz/glassy</td>
<td>1-4%, increasing downward</td>
<td>fine-grained, 0.1-0.5mm</td>
<td>anhedral, commonly in aggregates</td>
<td>uniaxial (+); low birefringence; relief is low to nil</td>
<td>not observed</td>
<td>interstitial grains and aggregates.</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------</td>
<td>------------------------</td>
<td>---------------------------------</td>
<td>-----------------------------------------------</td>
<td>-------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Groundmass/brownish-gray</td>
<td>40-80%</td>
<td>fine-grained to aphanitic</td>
<td>euhedral plagioclase is minor to anhedral quartz and orthoclase</td>
<td>carbonate, kaolinite, sericite, quartz</td>
<td>Disseminated limonite causes brownish cast in hand sample; groundmass is very dark at chill margins</td>
<td></td>
</tr>
</tbody>
</table>

Accessory minerals include magnetite, sphene, limonite, tourmaline, calcite, apatite, and zircon in order of decreasing abundance.

* centered bisectrix method, Troger (1959)

Table 2: Detailed description of Tertiary Monzonite, porphyry fine-grained
Textures

Lineation of prismatic hornblende is common, although on outcrop scale, its orientation is too variable to map. This lineation is attributed to alignment of phenocrysts during magma flowage.

Mafic inclusions are ubiquitous, and generally constitute one to three percent of the rock. Predominantly hornblende, these inclusions may be rounded or slightly angular. Their foliation is visible in thin section, and locally in hand sample. Commonly they show resorbed and assimilated borders, although the adjacent magma shows little variation.

Mineralogical textures include oscillatory zoning of plagioclase with Ab-rich rims. Hornblende phenocrysts may be zoned and exhibit rims of fine-grained magnetite and clinopyroxene, as does biotite. Wallace (1953) attributed these reaction rims to represent instability of hydrous minerals in a very dry magma. Carmichael and others (1974) attribute the disequilibrium of hornblende to a fairly high temperature, low pressure environment. Aegirine-augite crystals are commonly ratty-looking or shattered.

This lithology weathers in plates averaging 3 to 10 centimeters thick. Alteration ranging from incipient kaolinization to pervasive cation leaching, silicification, and pyritization is more intense near the apex of the stock and intersection of major fault zones.

In summary, the fine-grained monzonite porphyry is easily recognized by its brownish-gray color, medium- and fine-grained plagioclase
and prismatic hornblende phenocrysts, and dearth of orthoclase megacrysts. In thin section, hornblende and biotite rimmed by magnetite and clinopyroxene is typically observed. The occurrence of anomalous diopsidic aegirine-augite and sphene is also characteristic. Flow-foliation may be observed in hand sample, and platey weathering may be recognized in outcrop.

Interpretation

The unusual occurrence of light green diopsidic aegirine-augite and anomalous sphene are important features of this lithology. Both minerals are optically identical to the aegirine-augite cores and coarse-grained sphene of the younger alkalic trachyte and syenite porphyry. The absence of reaction rims on aegirine-augite indicates that it is not in disequilibrium with the monzonitic magma. Either it represents original phenocrysts or xenocrysts from a chemically compatible rock or magma. The consistent, pervasive occurrence of disseminated limonite is responsible for the brownish cast of the groundmass. It apparently represents a very late increase in oxygen fugacity.

Magnetite-clinopyroxene rims on hornblende and biotite attest to the instability of these hydrous phases during late-stage crystallization. Hornblende xenocryst and glomerocrysts, optically indistinguishable from hornblende in the mafic inclusions, can be seen breaking off the inclusions. Possibly, all of the hornblende in this rock is accidental or xenocrystic.
In summary, the fine-grained monzonite porphyry magma is the earliest exposed phase of monzonite porphyry of the Linster Peak dome. The magma chilled rapidly, as a cap rock over the more voluminous coarse-grained phase. Anomalous diopsidic aegirine-augite and sphene indicate that the monzonitic magma acquired these minerals from alkalic magma and/or mafic inclusions, both of which are abundant in the area. Hornblende was assimilated as xenocrysts from these inclusions. A late-stage increase in oxygen fugacity represented by ubiquitous limonite is probably due to the abundance of meteoric water present in the near-surface host rocks of the Linster Peak area or rapid expulsion of an aqueous phase during chilling.
MONZONITE PORPHORY, Coarse-Grained

Field Occurrence

The light to dark gray, coarse-grained monzonite porphyry (Plate 4) is the dominant lithology of the Linster Peak stock. The base of this unit is not exposed, but drill core and topography indicate that the stock is more than 275 meters thick. Commonly, coarse-grained porphyry intrudes the overlying fine-grained unit whereas in other areas it grades into it. Although the coarse-grained porphyry most frequently represents the rather homogeneous "body" of the stock, it also outcrops as dikes, sills, and intrusive breccias.

Mineral Constituents

Field identification depends on the occurrence of at least two percent orthoclase megacrysts (Table 3). Otherwise, the mineral composition is analogous to that of the comagmatic fine-grained monzonite porphyry. Coarse- to medium-grained andesine is the dominant phenocryst. Less abundant orthoclase megacrysts reach lengths of eight centimeters. Medium-grained, black hornblende is the dominant ferromagnesian mineral. The stubby habit of hornblende differs from the elongate prismatic hornblende in the fine-grained porphyry, although these hornblende crystals also exhibit magnetite-clinopyroxene reaction rims. Diopsidic-aegirine-augite is also present, although it is slightly more pleochroic and altered than in the fine-grained porphyry. The aegirine component of this mineral ranges from 20 to 30 percent, using methods of Troger (1977). Here also, it is not clear whether the clinopyroxene is an
<table>
<thead>
<tr>
<th>Mineral/ color (H.S)</th>
<th>Percent of rock</th>
<th>Grain size</th>
<th>Grain shape</th>
<th>Properties</th>
<th>Alteration products</th>
<th>Textures/ Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesine/ milky white</td>
<td>pheno.: 5-40%, average 25%</td>
<td>medium-grained: up to 3 mm</td>
<td>euhedral, blocky</td>
<td>+ or - 2V = 55°; An (42-47)*; low + relief</td>
<td>epidote kaolinite sericite carbonate</td>
<td>Oscillatory zoning, also, more Ab-rich rims; twinning is by the albite law</td>
</tr>
<tr>
<td>Orthoclase/ milky to glassy</td>
<td>megacrysts: 2-15%</td>
<td>average = 8-10 mm, but up to 8 cm</td>
<td>euhedral</td>
<td>- 2V= 55°-65°, rarely as low as 12°; low - relief</td>
<td>sericite</td>
<td>megacryst; good foliation of megacrysts, and groundmass around megacrysts; zoned; plagioclase inclusions</td>
</tr>
<tr>
<td>Hornblende (Tschermikite Group)/ black</td>
<td>pheno.: 4-8%</td>
<td>medium-grained: up to 4 mm</td>
<td>euhedral, stubby</td>
<td>-2V= 60°-65°; ZAC=15,17°; pleochroism: x=gold, y= green to olive, z= dark olive; 60°/120° cleavage</td>
<td>carbonate, epidote magnetite, chlorite biotite, clinopyroxene</td>
<td>Stubby crystals are diagnostic; difficult to discern from cpx in hand sample, reaction rims of magnetite and cpx; as xenocrysts, glomerocrysts</td>
</tr>
<tr>
<td>Diopsidic aegerine-augite/ black</td>
<td>1-1.5%</td>
<td>fine to medium grained, up to 1.5 mm</td>
<td>euhedral, blocky</td>
<td>+2V=60°; birefringence=0.25; higher relief than hornblende; pleochroism: x=light green, y= light green, z= pale yellow-green; Z C= 0-80°, aegirine content= 20-30%</td>
<td>calcite, epidote, magnetite</td>
<td>Broken grains; sphene inclusions; may be altered; anomalous grains</td>
</tr>
<tr>
<td>Biotite/ black</td>
<td>0-2%</td>
<td>fine-grained</td>
<td>euhedral, pseudomorph after hornblende</td>
<td>Low -2V; high birefringence; pleochroism: x=light brown, y= brown, z= dark brown; bird's eye textures</td>
<td>magnetite and cpx</td>
<td>reaction rims of magnetite and cpx; xenocryst and possibly primary</td>
</tr>
<tr>
<td>Quartz/glassy</td>
<td>1-4%</td>
<td>fine- to medium-grained</td>
<td>anhedral; may occur in clumps</td>
<td>Uniaxial +; relief = nil, low birefringence</td>
<td>not observed</td>
<td>As small interstitial grains. Abundant in silicified rock</td>
</tr>
<tr>
<td>--------------</td>
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<td>---------------------------------------------</td>
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<td>------------------------------------------</td>
</tr>
<tr>
<td>Groundmass/light-dark gray</td>
<td>30-85%; average = 45%</td>
<td>aphanitic to fine-grained</td>
<td>some euhedral feldspars</td>
<td>plagioclase, orthoclase, and quartz</td>
<td>epidote, carbonate, sericite, kaolinite, quartz</td>
<td>commonly invaded by hydrothermal carbonate</td>
</tr>
</tbody>
</table>

Accessory minerals include magnetite, sphene, pyrite, tourmaline, apatite, and Fe-rich chlorite in order of decreasing abundances.

* centered bisectrix method, Troger (1959)

Table 3: Detailed description of Tertiary Monzonite Porphyry, coarse-grained
early magmatic ferromagnesian mineral or a remnant xenocryst. In the coarse-grained porphyry all ferromagnesian minerals are so altered that it is impossible to tell if the aegirine-augite was in disequilibrium with the magma, or affected by later deutric or hydrothermal alteration. Biotite and quartz occur in minor amounts.

Accessory minerals include: magnetite, pyrite, coarse-grained sphene, tourmaline, and apatite. Primary pyrite occurs in place of magnetite adjacent to intrusive contacts. In hydrothermally altered areas pyrite is clearly secondary, pseudomorphically replacing hornblende.

The groundmass of the coarse-grained porphyry contains tiny euhedral crystals of plagioclase, quartz, and potassium feldspar.

Textures

Particular hand sample and microscopic textures are diagnostic for the coarse-grained porphyry. Flow foliation is readily measured on outcrop scale where orthoclase megacrysts are abundant. This foliation of megacrysts and gradual development from fine- to coarse-grained porphyry phases clearly proves their magmatic origin. Phenocryst and groundmass sizes are generally coarser than in the fine-grained unit, and variability is attributed to local rates of quenching and volatile loss. In the more “quenched” rock, phenocrysts are small, megacrysts and ferromagnesian minerals are rare, and the groundmass has a glassy diaphanous appearance. Associated pyritization and brecciation is common. The quenched texture most commonly occurs in dikes and apophyses of coarse-
grained porphyry, in highly fractured and altered fine-grained porphyry, or adjacent to skarns.

Chilled zones near contacts with sandstones and shales contain medium-grained hornblende, dwarfed andesine, coarse, rather than very coarse, orthoclase megacrysts, and differ from the quenched zones adjacent to skarns. The aphanitic groundmass of the chilled variety is dark gray.

As in the fine-grained porphyry, mafic inclusions are ubiquitous, averaging one to two percent of the rock. Their size and shape resemble those in the fine-grained porphyry. Again, hornblende crystals may be seen "breaking" off of the mafic inclusions during assimilation.

Alteration of the coarse-grained porphyry is variable, ranging from mild kaolinization to pervasive cation-leaching, silicification, and pyritization. Orthoclase megacrysts resist alteration, allowing identification of this unit in areas strongly attacked by hydrothermal processes.

Typically this unit weathers in very thick plates, similar to but thicker than that of the fine-grained porphyry. Generally it forms bold outcrops and cliffs, and is much more resistant to weathering than the fine-grained porphyry.

**Interpretation**

Although the mineral compositions of the coarse- and fine-grained porphyries are nearly identical, several textures indicate that certain processes were unique or more dominant in one phase. Orthoclase
megacrysts, rare in the fine-grained porphyry, probably represent the effects of water saturation and continued crystallization below the temperature of crystallization of fine-grained cap. Anomalous diopsidic aegirine-augite and coarse-grained sphene occur in both lithologies, although in the coarse-grained phase the clinopyroxene is more hydrothermally or deuterically altered. If magma mixing is responsible for these crystals it occurred prior to emplacement of the Linster Peak stock. The parallel occurrence of mafic inclusions in both lithologies also represents an early event. Accidental hornblende resulting from partial assimilation of these inclusions has affected both rock types.

Processes unique to the coarse-grained phase include extensive contact metamorphism and internal hydrothermal alteration. Skarns and pyritized leached zones form where the coarse-grained porphyry intrudes limestones and fine-grained porphyry, respectively. Gold, silver, and copper mineralization, as well as fluorite, pyrite, and quartz, are introduced into the host rock in many instances. Clearly, the coarse-grained porphyry was able to develop an independent fluid phase, unlike the fine-grained porphyry.

In summary, the coarse-grained porphyry formed from the same magma as the fine-grained impermeable cap rock, which allowed the coarse-grained phase to accumulate water and volatiles. Locally, rapid decompression produced quenches phases, contact metasomatism, and hydrothermal alteration.
LATITES

Field Occurrence

Blue-gray, phenocryst-poor latites occur rarely in the Linster Peak dome as dikes, and are not indicated on the map as an independent map unit. They form a minor but unique lithology in the mixed monzonite porphyry unit, representing a third comagmatic phase of the Linster Peak stock. Latites commonly brecciate contacts locally where they intrude the fine-grained monzonite porphyry.

Mineral Constituents

The minerals noted in hand sample are similar to those of the fine-grained monzonite porphyry or the quenched coarse-grained porphyry. Medium- to fine-grained hornblende phenocrysts and fine plagioclase microlites appear to float in a glassy diaphanous blue-gray groundmass. Commonly hornblende is replaced by chlorite or pyrite, and plagioclase is replaced by clays.

Texture

The latites have the appearance of a rapidly quenched volcanic magma. These rocks are clearly intrusive, and interpreted to have chilled rapidly in the hypabyssal environment. Incipient phenocryst growth in the latites encourages one to interpret them as a rapidly quenched phase of the monzonite magma. Additional chemical analyses are necessary to validate this assumption. Large, foliated, angular mafic xenoliths are abundant in the unit and reach dimensions of 20 by 25
centimeters.

**Interpretation**

Latites appear to be a minor, late, comagmatic phase of monzonite porphyry. Presumably, this magma intruded forcefully from a deep, highly molten magma, through fractures and other zones of weakness in the crystallizing monzonitic stock. It brecciated host rocks and quenched rapidly in a hypabyssal environment. Unrelated origins of this magma seem unlikely, but should be considered until further chemistry demonstrates a genetic relationship to the more abundant monzonitic phases.
MONZONITE PORPHYRY, Mixed Unit

General Description

On the map, the monzonite porphyry-mixed unit represents a complex zone of multiphase intrusions which occurs at the intersection of the N5°W and N75°-80°E structural trends. At least three phases of comagmatic monzonite porphyry magmas utilized this weak zone in fine-grained monzonite porphyry as a conduit for anastamosing dikes and apophyses of coarse-grained porphyry, intrusive breccia, and latites. Intense contemporaneous or post-intrusion hydrothermal alteration further complicates the geologic picture in this area.

Remnant host rocks in this zone are altered fine-grained porphyry and thickly bedded gray limestone stope blocks. Coarse-grained porphyries intruded these host rocks, producing dikes and apophyses from the central magma chamber below. Intense metasomatism, including pyritization and silicification, accompanied these intrusions. Commonly brecciation also occurred. Host-rock metasomatism, intrusive brecciation, and quenched textures in the intruding lithologies attest to the tremendous release of pressure and volatiles which accumulated in the magma chamber below the crystallized fine-grained porphyry cap. All fine- and coarse-grained porphyry contacts in this area are intrusive. Latites here are clearly younger than the fine-grained porphyry, but their relationship to the coarse-grained porphyry is unclear.
Fracturing and possible splay faulting off the major N75-80°E normal fault structurally deformed the area after crystallization of the latites and coarse-grained porphyry magmas. Late-stage quartz-pyrite-fluorite, calcite-pyrite-fluorite, and quartz veins crystallized in fractures produced after all monzonite magmas crystallized. Earlier quartz-pyrite veining is contemporaneous with metasomatism from decompression of the coarse-grained porphyry.

Poor exposure and the small scale of these geologic features require that this unit be mapped as a "mixed zone". For purposes of this study, the exact dimensions of these small irregular intrusive bodies are far less significant than the type and sequence of events in this area, summarized as follows:

1) Injection of early fine-grained monzonite porphyry.
2) Fracturing of crystallized fine-grained porphyry, emplacement of coarse-grained porphyry dikes and intrusive breccias, quartz-pyrite veins, and contemporaneous metasomatism.
3) Contemporaneous or later emplacement of latites.
4) Fracturing, intense hydrothermal alteration, and late-stage veining (possibly very late).

Thus, this complex area resulted from intrusion and alteration in a zone of weakness throughout the history of stock emplacement. Located at the intersection of a shear zone and the major fault zone, this weak area appears to have controlled magmatic activity and hydrothermal alteration and mineralization in the Early-Tertiary.
MAFIC INCLUSIONS IN MONZONITIC ROCKS

Field Occurrence

Mafic inclusions occur in all igneous rocks of the Linster Peak dome, but they are particularly abundant in the calc-alkaline lithologies. In these rocks they account for 0.2 to 2 percent of these rocks, and range in size from sub-microscopic to fifteen centimeters long. Although commonly rounded to subrounded, the occurrence of angular fragments indicates that originally these inclusions were crystalline clasts (Plate 5).

Identical inclusions occur in syenitic-monzonite porphyry of the White Cow intrusion of the northern Little Rockies, about eighty miles to the north. There, the mineral contents and textures of inclusions match mafic layers of gneisses in exposed Precambrian basement rocks (Roemmel, 1982). This suggests that inclusions in the Linster Peak stock could also be remnants of Precambrian gneisses.

Mineral Constituents

Hornblende, apparently hastingsite, occasionally with ferropargasite cores, accounts for forty-five to ninety-five percent of the inclusions (Table 4). It is indistinguishable from the hornblende of the magma by optics or x-ray diffraction. Andesine is abundant commonly, and potassium feldspar and quartz are minor or lacking. Colorless to light green diopside occurs in a few samples. Titanobiotite or rarely brown biotite may replace hornblende, and secondary carbonate is common.
A. Mafic Inclusions in Monzonitic Rocks

B. Mafic Inclusions in Alkaline Rocks
### MAFIC INCLUSIONS IN MONZONITIC ROCKS

<table>
<thead>
<tr>
<th>Mineral/ color (H.S)</th>
<th>Percent of rock</th>
<th>Grain size</th>
<th>Grain shape</th>
<th>Properties</th>
<th>Alteration products</th>
<th>Textures/ Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hornblende (Hastingsite-barkevikite)/ black</td>
<td>45-75%; average = 65%</td>
<td>fine-to medium-grained, up to 2 mm long</td>
<td>stubby, euhedral; diamond or hexagonal cross-sections</td>
<td>-2V=60-70°; ZAC=14'-19°; pleochroism: x=light-gold, y=green, z=olive brown; green, or rust-brown; moderate birefringence; extinction angles &lt; 40°; 60/120° cleavage angles</td>
<td>augite or aegerine-augite, brown biotite or titanobiotite, magnetite, carbonate, chlorite</td>
<td>Commonly well foliated; rarely lineated; often has barkevikite cores and hastingsite rims; grains may be in inclusions, glomerocrysts, or free-floating; reaction rims of magnetite and clinopyroxene</td>
</tr>
<tr>
<td>Diopside/ black</td>
<td>0-3% or 20-35%</td>
<td>fine-to medium-grained, up to 2 mm long</td>
<td>stubby; euhedral; commonly shattered</td>
<td>+2V=55-60°; ZAC=42-58°; pleochroism: x=light-green, y=light-green, z=light-yellow-green; inclind extinction &gt; 40°; moderately high birefringence; 90° cleavage angles; colorless rarely</td>
<td>not observed</td>
<td>ZAC increases slightly with minor amounts of aegerine-augite content and green color; generally it is minor and not foliated</td>
</tr>
<tr>
<td>Andesine An (35-44) white</td>
<td>10-20%</td>
<td>fine-to medium-grained, up to 1.5 mm</td>
<td>subhedral</td>
<td>+ or -2V=50°-60°; ZAC=010=18-20°; X=010=38°; low birefringence</td>
<td>carbonate, kaolinite, sericite</td>
<td>Not zoned; occasionally albite twins; broken crystals may be found in adjacent magma</td>
</tr>
<tr>
<td>Titanobiotite, brown biotite/ black</td>
<td>0-4%</td>
<td>fine-grained, up to 0.5 mm</td>
<td>subhedral to anhedral</td>
<td>small -2V; pleochroism: x=colorless to beige, y=light brown to red-brown, z=dark-brown to dark-red-brown; bird's eye texture</td>
<td>not observed</td>
<td>Alteration of hornblende and inclusions in hornblende; may be foliated</td>
</tr>
<tr>
<td>Carbonate/white</td>
<td>0-5%</td>
<td>fine-grained</td>
<td>interstitial</td>
<td>small -2V; e &gt; w; dolomite: e bisects 60° twin angle, calcite: e bisects 120° twin angle</td>
<td>not observed</td>
<td>Interstitial, late-stage grains; alteration of hornblende and plagioclase</td>
</tr>
<tr>
<td>-----------------</td>
<td>------</td>
<td>--------------</td>
<td>--------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Potassium feldspar/white</td>
<td>0-4%</td>
<td>fine- to medium-grained, up to 1.5 mm</td>
<td>subhedral to anhedral</td>
<td>variable -2V; low birefreingence; low (-) relief</td>
<td>not observed</td>
<td>medium-grained and sparse in monzonitic hosts</td>
</tr>
</tbody>
</table>

Accessory minerals, in order of decreasing abundance are: magnetite, sphene, quartz, apatite, and rarely epidote and garnet

* centered bisectrix method (Troger, 1959)

Table 4: Detailed description of mafic inclusions in monzonitic rocks
Coarse-grained sphene dominates the accessory mineral assemblage, followed by magnetite, apatite, and rarely garnet.

In comparison, some Precambrian gneisses exposed in the northern Little Rockies contain mafic and felsic layers of similar mineral content. Mafic layers are dominantly hornblende which is optically indistinguishable from hornblende in the Linster Peak mafic inclusions and calc-alkaline igneous rocks. These dark layers also contain andesine, quartz, and potassium feldspar. Felsic layers also are composed of quartz, andesine, and potassium feldspar, but lack the hornblende. Thus, the mineral assemblages of the mafic inclusions in the Linster Peak dome and the northern Little Rockies, as well as gneisses exposed in the northern Little Rockies, are too similar to overlook. Similar textures discussed below further support a genetic relationship.

Textures

Hornblende and biotite are foliated in most of the mafic inclusions from the Linster Peak dome and the northern Little Rockies, as well as the Precambrian gneisses. Only rarely is this foliation recognized in hand samples of Linster Peak inclusions. But, with the aid of a microscope, foliation of hornblende and biotite, as well as alignment of crystallographic axes for quartz, plagioclase, and potassium feldspar can be observed. Clearly, the preferred orientation and mineral content of these inclusions demonstrate a regional metamorphic history for these xenoliths. Reaction rims of clinopyroxene and magnetite are abundant on the edges of the hornblende-rich mafic inclusions, and resemble those of the hornblende and biotite crystals floating free in the magma.
Interpretation

Assimilation of basement xenoliths by monzonitic magmas of Linster Peak may be observed in many stages. Hornblende, biotite, and sphene crystals are frozen in place, partially dislodged from the inclusions. Nearby, free-floating crystals and glomerocrysts suggest that much, if not all of the hornblende, biotite, and sphene in the monzonitic rocks are xenocrysts from inclusions or restites. If so, the original magma composition was leucocratic monzonite or quartz-monzonite with anomalous diopsidic aegirine-augite.

Although the magmas were clearly influenced by the mafic inclusions, little evidence supports that the reverse relationship existed. Reaction rims of clinopyroxene and magnetite surround the inclusions where magma contacts hornblende or biotite, but these reaction products do not permeate the interior of the inclusion. Andesine in the cores may be primary or secondary. Faintly twinned, weakly oriented, and homogeneous, they resemble feldspar in regionally metamorphosed rocks, unlike their strongly twinned and zoned magmatic analogues.

Thus, the presence of mafic xenoliths in the monzonitic magmas profoundly influenced the mineral compositions of the magmas. Reaction rims around hornblende and biotite indicate that these hydrous minerals existed in disequilibrium with the dry magma prior to crystallization.

The similar mineral contents of hornblende-andesine-orthoclase-quartz monzonite porphyries of Linster Peak to hornblende-andesine-quartz gneisses of local basement terrains strongly suggest that these xenoliths are accidental clasts or restite inclusions of the underlying crustal rocks.
ALKALI-SYENITE PORPHYRY

Field Occurrence

Light gray Tertiary alkali-syenite porphyry is considered the coarse-grained equivalent of the alkali-trachyte unit. These two lithologies exhibit related spatial, temporal, and mineralogical characteristics, although subtle chemical differences exist. Four major occurrences of this rock type include: the laccolithic body in the northeastern part of the dome, the altered and autobrecciated plug near Log Gulch, the thick sills on the southeastern part of the dome, and small dikes which cut fine- and coarse-grained porphyry (Plate 1). The alkali-syenite porphyry is clearly younger than the monzonite yet it appears to be slightly older as well as contemporaneous with its fine-grained counterpart, the alkali-trachyte.

Mineral Constituents

The characteristic rock-forming minerals of the alkali-syenite porphyry (Table 5) include the following varieties, in order of decreasing abundances: sanidine, aegirine-augite and aegerine, analcite, melanite garnet, and carbonate. High-temperature sanidine, the dominant mineral phase, comprises 75 to 80 percent of the rock. X-ray diffraction peaks support petrographic identification of this potassium feldspar, and indicate that significant albite (molecule) is trapped in the sanidine lattice. Aegirine-augite and aegerine, present in lesser amounts, exhibit a characteristic prismatic form. The phenocryst cores range in composition from diopsidic aegirine-augite to aegerine, yet in all cases
Table 5
Tertiary Alkali-Syenite Porphyry (Tasp)

<table>
<thead>
<tr>
<th>Mineral/color(ge)</th>
<th>Percent of rock</th>
<th>Grain size</th>
<th>Grain shape</th>
<th>Properties in thin section</th>
<th>Alteration products</th>
<th>Textures and Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanidine, white</td>
<td>18-65%</td>
<td>very fine to 20 mm by 3 mm</td>
<td>euhedral phenocrysts, laths in groundmass</td>
<td>biaxial negative, 2V = 10-14°, low (-) relief; tabular form</td>
<td>late-magmatic alt. to nepheline &amp; carbonate; sericite</td>
<td>excellent trachitic texture: replacement by nepheline; sanidine accounts for 75-85% of the rock.</td>
</tr>
<tr>
<td>Aegerine-augite &amp; aegerine, black</td>
<td>4-8%</td>
<td>very fine to 5 mm</td>
<td>prismatic, hexagonal &amp; square cross-sections</td>
<td>90° clv. angles; pleochroic: x=bright green y= green z= greenish-gold uniaxial (-) or (+) 2V= 55-85°; ZAC av. 80° in rims, 50° to 85° in cores</td>
<td>not observed</td>
<td>zoned; aegerine-rich rims, some augite cores. Total phenocryst composition ranges from aegerine-augite to aegerine; good lineation</td>
</tr>
<tr>
<td>Analcite, colorless</td>
<td>3-8%</td>
<td>very fine to 2 mm</td>
<td>subhedral, some good crystal faces</td>
<td>abnormal uniaxial negative, 2V=6-15°; nearly isotropic; mod. (-) relief; no twinning</td>
<td>not observed</td>
<td>occurs as small phenocrysts, sanidine replacement, with carbonate in amygdaloidal fillings, and interstitial grains.</td>
</tr>
<tr>
<td>Melanite garnet black</td>
<td>trace to 3%</td>
<td>fine to 1.2 mm</td>
<td>euhedral</td>
<td>isotropic; color in t.s. is golden-brown; high granular relief</td>
<td>not observed</td>
<td>may exhibit zoning or zonal arrangement of inclusions</td>
</tr>
<tr>
<td>Groundmass light-gray</td>
<td>25-43%</td>
<td>very fine to fine</td>
<td>euhedral sanidine laths, aegerine needles, subhedral nepheline</td>
<td>dominantly sanidine with 1-4% aenerine, 2-5% nepheline</td>
<td>not observed</td>
<td>trachitic alignment of sanidine; sanidine and nepheline may be intergrown; miarolitic cavities up to 3 mm long.</td>
</tr>
</tbody>
</table>

Accessory minerals in order of decreasing abundance are: magnetite, sphene, carbonate, apatite, and zircon.

Table 5: Detailed description of Tertiary alkali syenite porphyry
the rims are aegirine. This zonation, coupled with the presence of aegirine needles in the chilled groundmass, attest to the increasing peralkalinity of the magma with continued crystallization. Analcite ranges from 1 to 8 percent of the rock as interstitial grains, replacement of sanidine, and with carbonate in amygdaloidal fillings. Other minor and accessory minerals include abundant magnetite and euhedral sphene and lesser coarse-grained euhedral apatite, carbonate, and zircon. The groundmass consists of a fine mat of sanidine laths, aegirine needles, and subhedral interstitial analcite.

Textures

The alkali-syenite porphyries exhibit classic trachytic orientation of sanidine plates (Plate 6). Rarely vesicles and amygdules, up to three millimeters long, flattened parallel to the foliation, are observed in hand sample and thin section. The amygdaloidal fillings are zoned, with analcite rims and carbonate cores. Mafic inclusions are ubiquitous, as in the other igneous rocks of the dome. The magma shows signs of violent emplacement only in the alkali-syenite porphyry plug. This plug experienced extensive hydrothermal alteration, autobrecciation, and veining, either coeval with or after its crystallization. It intruded explosively, brecciating host rocks at the contacts. These destructive processes have obliterated all original textures except the trachytic habit of the resistant sanidine phenocrysts. Other alkali-syenite porphyry masses show no sign of explosive activity or alteration, and appear to have been emplaced passively.
A. Alkali-Syenite Porphyry

B. Alkali-Trachyte with miarolitic cavities
Interpretation

Zoned amygdules with analcite rims and carbonate cores suggest that the magma contained a late alkali-rich water and carbonate vapor phase. The lack of early magmatic hydrous minerals and igneous contact haloes suggest that the magma was also undersaturated with water until the very last stages of crystallization, although it may have contained abundant carbon-dioxide. The amygdules could also be post-magmatic cavity fillings.

High temperature sanidine and miarolitic cavities suggest that the alkali-syenite porphyry and alkali-trachyte magmas crystallized in the hypabyssal environment at an approximate theoretical minimum temperature of 675°C, above the alkali feldspar solvus for relatively dry magma (Bowen and Tuttle, 1950). Since the magma was presumably undersaturated with water, at least until the last stages, the scarcity of leucite is attributed to a magma temperature below 1,150°C ± 20°C (Schairer and Bowen, 1955). The transition of the clinopyroxene phase from aegirine-augite to aegirine indicates the increasing peralkalinity of the magma with continued crystallization. Presumably, analcite and carbonate amygdaloidal fillings attest to the existence of a vapor-phase rich in alkalis and carbonate, with minor water and silica, the antithesis of the silica-water-rich fluid phase of the coarse-grained monzonite porphyry.
ALKALI-TRACYTHE

The distinctive alkali-trachytes have been previously described as tinguaite (Weed and Pirrson, 1987; Wallace, 1953; Kinnaird, 1979). Many do exhibit typical tinguaiteic texture and mineral character (Sørenson, 1974). Other rocks of the same suite to not contain abundant feldspathoids or show the typical green color of the classic tinguaite. In an effort to use a more precise and widely understood name, these rocks are called alkali-trachytes.

Field Occurrence

Gray to green alkali-trachytes (Table 6) occur only as dikes, sills, and small irregular intrusive masses on the Linster Peak dome and are found to cross-cut all other igneous lithologies, except minor rhyolitic intrusive breccias. Alkali-trachytes are most abundant in the northeastern part of the dome, near the plug and laccolithic body of alkali-syenite porphyry. A vague, radial pattern of alkali-trachyte dikes intersects at the alkali-syenite porphyry plug (Plate 1), yet it is unclear if they originated contemporaneously from the same magma as the plug or used earlier-formed radial fractures. Regardless, the two lithologies are nearly identical in mineral and chemical constituents and age.

The geologic map shows only dikes of considerable size. The width of these dikes is slightly exagerated on the map. Generally they range in width from six to ten meters. Many smaller dikes exist that do not appear on the map.
Table 6
Tertiary Alkali-Trachyte (Tat)

<table>
<thead>
<tr>
<th>Mineral/color(hs)</th>
<th>Percent of rock</th>
<th>Grain size</th>
<th>Grain shape</th>
<th>Properties in thin section</th>
<th>Alteration products</th>
<th>Textures and Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanidine, white</td>
<td>0-25%</td>
<td>very coarse grained; 6-20mm</td>
<td>euhedral, phenocrysts, laths in groundmass</td>
<td>biaxial negative, $2V = 10-14^\circ$; 10$^\circ$ relief; tabular form</td>
<td>late-magmatic lit. to nepheline &amp; carbonate; sericite</td>
<td>excellent trachitic texture; replacement by nepheline; rarely perthitic</td>
</tr>
<tr>
<td>Aegerine-augite &amp; aegerine, black</td>
<td>2-6%</td>
<td>very fine to 2 mm</td>
<td>prismatic, hexagonal &amp; square cross-sections</td>
<td>$90^\circ$ clv. angles; pleochroic: $x =$ bright green, $y =$ green, $z =$ greenish-gold</td>
<td>not observed</td>
<td>zoned; aegerine-rich rims, some augite cores. Total phenocryst composition ranges from aegerine-augite to aegerine; glomerocystic</td>
</tr>
<tr>
<td>Analcite/colorless</td>
<td>Trace to 2%</td>
<td>very fine to 0.5mm</td>
<td>subhedral, to anhedral</td>
<td>abnormal uniaxial negative, $2V = 8-10^\circ$; nearly isotropic; mod. (-) relief; no twinning</td>
<td>not observed</td>
<td>occurs as small phenocrysts, sanidine replacement, with carbonate in amygdaloidal fillings, and interstitial grains.</td>
</tr>
<tr>
<td>Melanite garnet black</td>
<td>trace to 4%</td>
<td>fine to 0.1mm</td>
<td>euhedral</td>
<td>isotropic; color in t.s. is golden-brown; high granular relief</td>
<td>not observed</td>
<td>may exhibit zoning or zonal arrangement of inclusions</td>
</tr>
<tr>
<td>Groundmass light-gray to green</td>
<td>70-98%</td>
<td>very fine to</td>
<td>euhedral sanidine laths, aegerine needles</td>
<td>dominantly sanidine with 1-4% aegerine,</td>
<td>not observed</td>
<td>trachitic alignment of sanidine laths and aegerine needles, rapidly chilled</td>
</tr>
</tbody>
</table>

Accessory minerals in order of decreasing abundance are: magnetite, sphene, carbonate, apatite, and zircon.

Table 6: Detailed description of Tertiary Alkali-Trachyte
Mineral Constituents

The alkali-trachytes are composed of sanidine, aegirine-augite to aegirine, melanite garnet, analcite, and rarely pseudoleucite. Tabular sanidine phenocrysts are coarse- to very coarse-grained. Zoned aegirine-augite with diopsidic aegirine-augite-rich cores and aegirine rims indicate the increasing peralkalinity of the magma with increasing crystallization. Minor analcite occurs as late-stage filling in mafiolitic cavities and fractures.

Accessory minerals include carbonate, magnetite, sphene, and apatite. Sphene may form unusually large cigar-shaped crystals up to 1.2 millimeters long, as in the previously mentioned calc-alkaline lithologies. Rarely, fractured plagioclase and orthoclase xenocrysts occur in the gray dikes.

Textures

Alkali-trachytes of the Linster Peak dome are easily recognized by the excellent trachytic texture of white sanidine phenocrysts in a dark green or gray aphanitic groundmass (Plate 6). Occasionally sanidine phenocrysts are lacking or present in only trace amounts. In dikes and sills, foliation of sanidine is parallel to contact surfaces, grading to a more irregular orientation away from the contacts.

Ubiquitous mafic inclusions are less abundant in the alkali-trachytes than the monzonitic magmas, apparently due to greater assimilation by the higher temperature alkaline magmas, or a smaller original number of inclusions present. Inclusions of fine- and coarse-grained porphyry attest to the younger age of the alkaline magmas.
Miarolitic cavities occur in many dikes and sills, and are commonly lined with analcite and calcite (Plate 6). Alteration of these dikes is rare, except near the intersection of the major east-west and minor north-south fault and shear zones.

Alkali-trachyte dikes and sills weather to thin friable plates adjacent to contacts and accumulate carbonate in the fractures. Calcite, nearly always present, could be late-magmatic or secondary.

**Interpretation**

The alkali-trachyte dikes and sills of the Linster Peak dome intruded after crystallization of the monzonite porphyry stock and alkali-syenite porphyries, but prior to young phases of hydrothermal alteration along the east-west fault. Diagnostic characteristics in hand sample are sanidine and aegirine-augite phenocrysts in an aphanitic gray to green groundmass. Melanite garnet is diagnostic in thin section, and caliche weathering occurs on outcrops. Gray dikes with less peralkaline minerals and plagioclase and orthoclase xenocrysts apparently experienced contamination by mixing with monzonitic magmas or assimilation of monzonitic rocks.
MAFIC INCLUSIONS IN ALKALINE ROCKS

Field Occurrence

Mafic inclusions in alkaline rocks of the Linster Peak dome are less abundant than in the monzonitic rocks. They may occupy zero to one percent of the total rock, and range in size from single grains to inclusions 30 centimeters long. They are always rounded, and show greater degrees of assimilation than their calc-alkaline counterparts (Plate 5). Due to the influence of the alkaline magmas, it is impossible to correlate these mafic inclusions with the inclusions in the monzonite porphyry or with Precambrian gneisses.

Mineral Constituents

As in the foliated gneissic inclusions, the dominant mineral phase of the mafic inclusions (Table 7) is hornblende (hastingsite in solid solution with ferropargasite). Diopsidic-aegirine-augite is abundant in large grains, commonly broken. In comparison, hornblende is very fresh and euhedral. Biotite occurs adjacent to or within hornblende. Sardine laths and carbonate needles permeate the inclusions and give the appearance of a "groundmass" texture. Actually, this "groundmass" is nearly identical to the groundmass of the surrounding alkalic rocks. Sphene is minor or absent, but apatite and pyrrhotite or magnetite are abundant accessory minerals.
<table>
<thead>
<tr>
<th>Mineral/Color (H.S.)</th>
<th>Percent of Rock</th>
<th>Grain Size</th>
<th>Grain Shape</th>
<th>Properties</th>
<th>Alteration Products</th>
<th>Textures/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hornblende (Hastingsite)/black</td>
<td>40-65%</td>
<td>fine-to medium-grained, up to 2 mm long</td>
<td>stubby, euhedral, diamond or hexagonal cross-sections</td>
<td>-2V=60-70°; ZAC=14-19°; pleochroism: x=light gold, y=green, z=olive brown, green, or rust brown; moderate birefringence; 60/120° cleavage angles</td>
<td>augite or aegirine-augite, brown biotite or titanobiotite, magnetite, carbonate, chlorite</td>
<td>Commonly well foliated; rarely lineated; grains are only in inclusions; discrete hornblende-rich zones and aegirine-augite-rich zones; may have ferromagnesian cores</td>
</tr>
<tr>
<td>Diopsidic aegirine-augite/greenish-black</td>
<td>20-45%</td>
<td>coarse-to medium-grained, up to 3 mm long</td>
<td>stubby; euhedral; commonly broken</td>
<td>+2V=60-80°; ZAC=58-65; pleochroism: x=light green to green, y=light green, z=light yellow-green; moderately high birefringence; 90° cleavage angles</td>
<td>not observed</td>
<td>ZAC increases with aegirine-augite content and green color; not foliated, origin may be due to alkalic magma</td>
</tr>
<tr>
<td>Phlogopite/brown; biotite/black</td>
<td>0-4%</td>
<td>fine-grained, up to 0.5 mm</td>
<td>subhedral to anhedral</td>
<td>small -2V; pleochroism: x=colorless to beige, y=light brown, z=dark brown; bird's eye texture</td>
<td>not observed</td>
<td>Inclusions in hornblende</td>
</tr>
<tr>
<td>Sanidine/white</td>
<td>10-25%</td>
<td>fine-grained, up to 1 mm</td>
<td>anhedral or in laths</td>
<td>low -2V; low birefringence; low (-) relief</td>
<td>not observed</td>
<td>Radiating bundles of unoriented laths; intermixed with carbonate; interstitial; very similar to groundmass material of alkalic rocks</td>
</tr>
<tr>
<td>Carbonate/white</td>
<td>10-12%</td>
<td>fine-grained</td>
<td>interstitial</td>
<td>small -2V; e &gt; w; occasionally observed: calcite, e bisects 120° twin angle</td>
<td>not observed</td>
<td>Interstitial, late-stage grains; may be inherited from magma</td>
</tr>
</tbody>
</table>

Table 7: Detailed description of mafic inclusions in alkalic rocks.
Textures

Unlike the inclusions in monzonitic rocks, hornblende in these inclusions is not foliated. Individual grains do not float free in the alkaline magma, and clinopyroxene-magnetite reaction rims are not present. Evidently the original minerals of the inclusions have been completely assimilated by the high temperature alkaline magmas, rather than remaining as xenocrysts.

Interpretation

It is possible that the mafic inclusions in the alkaline rocks are metasomatized equivalents of the inclusions in the monzonitic rocks. Differences in mineral content and texture preclude any accurate estimation of their origin. It is impossible to definitively identify these inclusions as basement clasts, restites, or ocelli.
INTRUSIVE CONTACT RELATIONS

The intrusive contact relationships in the Linster Peak dome are unique to the individual lithologies, although the trends for the calc-alkaline and alkaline lineages are follow consistent trends. Variability in these trends seem to be a function of: mode of intrusion, cooling rate, and volatile content. Specific textures, mineral constituents, contact zone widths, and "type" locations are summarized in Table 8.

Monzonite Porphyry

Presumably the initial phase of monzonite porphyry in the Linster Peak stock intruded the overlying sedimentary package passively, approximately 600 to 1,000 meters below the Late-Cretaceous ground surface. This porphyrytic rock formed a fine-grained, chilled, cap rock which extended at least 150 to 210 meters below the upper intrusive contact. Clastic sediments are unaffected or slightly baked at the fine-grained porphyry contacts and limestone roof pendants are often recrystallized, but rarely metasomatized. One narrow skarn was noted on the summit of Linster Peak.

Chilled textures and lack of brecciation and metasomatic contacts indicate that the fine-grained monzonite porphyry chilled rapidly and contained almost no appreciable volatile-rich gas or liquid phase.

On the other hand, the coarse-grained monzonite porphyry intruded more violently and contained a volatile-rich vapor phase. Coarse-grained porphyry contacts with limestone roof pendants and stope blocks produced fractured, fine-grained, mineralized skarns locally rich in
<table>
<thead>
<tr>
<th>Intruding Rock</th>
<th>Host Rock</th>
<th>Contact Width</th>
<th>Original Mineralogy</th>
<th>Recrystallized</th>
<th>Metasomtized/ Recrystallized</th>
<th>Brecciated</th>
<th>Contact Facies</th>
<th>Assemblage</th>
<th>Representative Localities</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmpf</td>
<td>Cbs roof pendant Rm(?) stope blocks</td>
<td>3-4.5 mm</td>
<td>Yes</td>
<td>Rare; 1 skarn occurrence in stope block</td>
<td>Not observed</td>
<td>Marble</td>
<td>Calcite Epidote</td>
<td>Tremolite Chalcopyrite Pyrite</td>
<td>Duffy's Ridge; Skarn: Linster Peak Summit</td>
<td>Dominantly, limestones are marblized, not metasomatalized</td>
</tr>
<tr>
<td>Tmpc</td>
<td>&lt; 1 mm</td>
<td>No</td>
<td>Not observed</td>
<td>Not observed</td>
<td>Not observed</td>
<td>Not observed</td>
<td>Duffy's Ridge</td>
<td>This relationship attests that Tmpf and Tmpc magmas existed contemporaneously</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tmpf &amp; Tmpc</td>
<td>Jme, Kk, Kc (dominantly clastic)</td>
<td>0-3 mm</td>
<td>Rarely baked sediments + exotic limonite</td>
<td>Not observed</td>
<td>Not observed</td>
<td>Not observed</td>
<td>Log Gulch, Linster Creek, Edwards Creek area</td>
<td>Little to no reaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tmpc</td>
<td>Cbs mm(?)</td>
<td>15-60 m</td>
<td>Locally</td>
<td>Calc-silicate contact metamorphic assemblage and some metal mineralization</td>
<td>Common brecciation and fractioning</td>
<td>Epidote</td>
<td>Red Garnet(?) Fluorite Chalcopyrite Pyrite</td>
<td>Lucky Strike Scout, and Linster Peak Prospects</td>
<td>Tmpc may appear &quot;quenched&quot;; abundant limonite common</td>
<td></td>
</tr>
<tr>
<td>Intrusive Breccia (Tmpc or Tl)</td>
<td>Limestone</td>
<td>~15-60 m</td>
<td>Locally</td>
<td>Calc-silicate contact metamorphic assemblage and some metal mineralization</td>
<td>Yes</td>
<td>Epidote, Fluorite, Pyrite, Chalcopyrite, Calcite</td>
<td>Upper Landheim Prospect</td>
<td>Abundant limonite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------</td>
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<td>---------</td>
<td>-------------------------------------------------</td>
<td>-----</td>
<td>-----------------------------------------------</td>
<td>-------------------</td>
<td>------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tmpf</td>
<td>15-30 m</td>
<td></td>
<td></td>
<td>Matrix &amp; clast mineralization and silification; local cation leaching &amp; carbonate + metasomatism</td>
<td>Yes</td>
<td>SiO₂ hydrothermal clay, Epidote, Chlorite, Pyrite, Chalcopyrite</td>
<td>Lower Landheim Prospect</td>
<td>Zoned assemblage, silicified core with radiating SiO₂ stockwork into &quot;argillically&quot; or &quot;propilically&quot; altered porphyry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breccia Pipes</td>
<td>Tmpf</td>
<td>6-15 m</td>
<td>?</td>
<td>Minor alteration or Tmpf clasts</td>
<td>Yes</td>
<td>Exotic limonite in Tmpf</td>
<td>North side of Gulf Road; Log Gulch</td>
<td>These are not mineralized; the pipe intruding Tmpf appears to be rhyolitic; the pipe in Kk appears to be latitic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipes Rhyolitic or Latitic</td>
<td>Kk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tl</td>
<td>Tmpc</td>
<td>0-3 m</td>
<td>Not observed</td>
<td>Cation leaching pyritization silification</td>
<td>Yes</td>
<td>Pyrite, SiO₂ Hydrothermal Clays</td>
<td>Linster Creek; NE of Kirby's Prospect</td>
<td>Poorly exposed contacts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tat (Dikes &amp; Sills)</td>
<td>Cbs</td>
<td>0-15 m</td>
<td>Not observed</td>
<td>Occurrence of calc-silicate metasomatism</td>
<td>Common</td>
<td>Magnetite, Marble, Calc-Silicates</td>
<td>Upper Upper Landheim Prospect</td>
<td>Rarely skarns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jme</td>
<td>0-0.2 m</td>
<td>Baked sediments</td>
<td></td>
<td></td>
<td>Common</td>
<td></td>
<td>Flanking roof pendants</td>
<td>No fenitization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Depth</td>
<td>Contact</td>
<td>Observations</td>
<td>Chemical Examinations</td>
<td>Passive Emplacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>-----------------</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st (Uikes)</td>
<td>U-0.2</td>
<td>Not observed</td>
<td>Little to none</td>
<td>Occasional 1 occurrence of 10 cm pyritized zone</td>
<td>Lookout Peak, Lone Pine Gulch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tafsp plug</td>
<td>Kc</td>
<td>0-6 m</td>
<td>Not observed</td>
<td>Yes</td>
<td>No visible recrystallization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tmpf</td>
<td>0-30 m</td>
<td>Not observed</td>
<td>Intense Na₂, Ca leaching pyritization</td>
<td>Yes, Hydrothermal Clays, SiO₂, Pyrite, Exotic Limonite</td>
<td>Visible limonite &quot;halo&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tasp Laccolith &amp; sills</td>
<td>Kc</td>
<td>0-0.2 m</td>
<td>Commonly baked sediments</td>
<td>Not observed Not observed</td>
<td>Passive emplacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
copper, gold, silver, and fluorine. Minor areas of brecciated, silici-
fied limestone replaced by sphalerite and galena also occur. These con-
tact zones have been prospected on Linster Peak since the turn of the
century.

Contacts where the coarse-grained porphyry has intruded the fine-
grained porphyry are complex. The typical three to fifteen meter con-
tact zone exhibits leaching of calcium and sodium and patchy silicifica-
tion and pyritization of both lithologies. Commonly these two lithol-
ogies can only be distinguished by the occurrence of coarse-grained or-
thoclase megacrysts in the limonitic and clayey matrix of the coarse-
grained porphyry. Coeval quartz-pyrite, quartz-magnetite, and quartz-
fluorite veins and veinlets commonly occur in the fine-grained porphyry
within fifteen meters of the contact. Apparently the coarse-grained
monzonite intruded forcefully and carried a minor silica-metal-fluorine-
water-rich phase.

The few exposed latite contacts are always brecciated and chilled
or quenched. The latites may carry mixed clasts of monzonite porphyry,
carbonate + clastic sediments, mafic rocks and rarely massive pyrite.
This late phase, comagmatic with the other monzonite phases, intruded
forcefully, quenched rapidly, and may have contained a silica-rich vola-
tile phase. Intrusive breccias in the Linster Peak stock contain a
quenched, megacryst-bearing or latitic matrix. From the style of intru-
sive contact relationships in the monzonite porphyry phases, there ap-
ppears to be a time correlative relationship between the age of the mag-
matic phase and the volatile content and force of emplacement. An
increase in these trends can be noted in the following chronological sequence, from oldest to youngest: fine-grained porphyry, coarse-grained porphyry-intrusive breccia-latite, and quartz-pyrite-fluorite veins.

The Alkaline Rocks

The exposed alkaline lithologies of the Linster Peak dome are hypabyssal and fine-grained. Host sedimentary and monzonitic rocks are rarely effected by these rapidly chilled alkaline magmas.

Alkali-trachyte dikes and sills occasionally show brecciated contacts, but almost always contain rounded, floating clasts of their host lithology. The forceful mode of emplacement, coupled with the occurrence of carbonate-zeolite lined mariolitic cavities support the conclusion that at low pressures these magmas probably contained a vapor phase containing alkalies, water, and carbon-dioxide.

In summary, the contact relationships in the monzonite porphyry comagmatic phases show a significant trend toward increasing force of emplacement and silica-water-metal-volatile-rich phases with time. Alkalic magmas contained a separate vapor phase at hypabyssal levels, more carbonate-rich.
MINERALIZATION

Introduction

Gold, silver, copper, and molybdenum prospecting has been active intermittently on the Linster Peak dome for nearly a century. Jack Lee initiated interest in the area in the late 1890's, shortly after the discovery of gold in the nearby Giltedge district. Exploration since the 1970's has concentrated primarily on copper and molybdenum, and less on gold and silver. Bear Creek Mining Co., Mine-Finders, Inc., Gulf Resources, Inc., Earth Resources, Inc., and Asarco, Inc. have explored with modern prospecting methods of geologic mapping, silt, soil, and rock-chip sampling, and drilling. Plate 2 shows the drill hole sites, adits, and prospect pits.

The results of this study have delineated three major types of mineralization in the Linster Peak area, including: porphyry-type degassing occurrences, limestone and skarn-hosted contact occurrences, and late hydrothermal veins. They are discussed below in context of location, mineral assemblages, structural control, metal values, and economic potential.

Mineralization Resulting from Porphyry-Type Degassing

The core of the Linster Peak stock shows evidence of degassing following emplacement of the stock. These late magmatic products were volatile-rich, pyritic, siliceous magmas. The coarse-grained porphyry intrusive breccias, dikes, and roof zone produced extensive hydrothermal alteration, silicification, pyritization, and commonly mineralization
and carbonatization of fine-grained porphyry host rocks.

The Landheim, Kirby, and Edwards Creek prospects (Plate 2) display this characteristic alteration and mineralization. The dominant hydrothermal mineral assemblage is pyrite, chalcopyrite, fluorite, quartz, calcite, malachite, azurite, limonite, and rarely sphalerite and galena. Copper-bearing minerals may be absent.

The sub-horizontal intrusive contact between the fine- and coarse-grained monzonite porphyry is propylitically to argillically altered, pyritized, and silicified in the core of the stock. Quartz-pyrite and quartz-magnetite veins and veinlets in the overlying fine-grained porphyry indicate that siliceous metal-bearing fluids filled unoriented fractures produced by hydrofracturing or contraction of the chill cap. East-west alignment of other veins is probably fault-controlled. Alteration is concentrated in an east-west zone along the major normal fault, and in a north-south zone along the major shear of the dome. The most intense alteration occurs at the intersection of these two zones, the Kirby prospect (Figure 8). Apparently, structural zones of weakness in the Linster Peak stock centralized alteration and mineralization of this type (Plate 3).

Copper, molybdenum, lead, zinc, gold, and silver values from silt, soil, rock chips, and drill core chips are available for many of these occurrences on the Linster Peak dome (Rife, pers. comm., 1981). For the Landheim and Edwards Creek prospects, the ranges of rock-chip and core-chip values are listed below. Anomalously high values are less than five percent of the total range.
FIGURE 8: SKETCH OF THE KIRBY PROSPECT PIT
LINSTER PEAK DOME

N 5° E, 35° SE
SHEAR ZONE

ALL ROCKS CONTAIN 0.5-2% DISSEMINATED PYRITE

DISSEMINATED PYRITE (3-4%)
QUARTZ-PYRITE VEINS & VEINLETS
EPIDOTE, DISSEMINATED AND IN CLUMPS, AFTER HORNBLende IN TMPc
Metal Values from Intrusive Breccias and Dikes
(Landheim and Edwards Creek Prospects)
Values in ppm
(Rife, pers. comm., 1981)

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Mo</th>
<th>Zn</th>
<th>Au</th>
<th>Ag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr-4200</td>
<td>4-225</td>
<td>5-110</td>
<td>Tr-0.07</td>
<td>.015-0.4</td>
<td></td>
</tr>
</tbody>
</table>

Values for tin and tungsten are extremely low. Fluorine values range from 0.1 to 0.44 weight percent.

All of the above-mentioned occurrences are products of decompression in the monzonitic magmas. A similar type of occurrence is present in the alkaline rocks. The alkali-syenite porphyry plug exhibits brecciated contacts, intense hydrothermal alteration and autobrecciation, and alteration of the adjacent monzonite porphyry. Two drill cores, 240 meters and 440 meters respectively, were sampled and analyzed for copper, lead, gold, and silver with the following results.

Metal Values from the Alkali-Syenite Porphyry Plug
Values in ppm
(Rife, pers. comm., 1981)

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Mo</th>
<th>Pb</th>
<th>Au</th>
<th>Ag</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-5533</td>
<td>1-625</td>
<td>30-180</td>
<td>0.1-0.23</td>
<td>0.3-4.4</td>
<td></td>
</tr>
</tbody>
</table>
With the exception of the alkali-syenite porphyry plug, all of the major porphyry-type alteration and mineralization in the Linster Peak dome is a product of the monzonitic stock.

Thus, presumably highly compressed volatile-rich magma from the interior of the cooling monzonite porphyry violently intruded the overlying fine-grained porphyry chill cap and sediments. These intrusions are concentrated along previously existing zones of structural weakness. Although the magmas quenched rapidly, metalliferous, highly-siliceous fluids invaded the host rock pervasively and in discrete veins. These metasomatic processes produced mineralized intrusive breccias, extensive hydrothermal alteration, silicification, and pyritization.

Efforts to successfully locate a copper-molybdenum or molybdenum target in the Linster Peak dome have been unsuccessful. The lack of severe hydrothermal alteration, as well as sporadic metal values and discouraging drill hole data, indicate that if a porphyry-type ore body exists, it lies at considerable depths. Also, discouraging is the low-silica, mildly alkaline chemistry of the monzonite porphyry which is not compatible with current compositional categories of molybdenum porphyry deposits (Westra and Keith, 1981; Mutschler and others, 1981). Despite the poor molybdenum potential of the Linster Peak stock, it is possible that mineralization, related to a more differentiated body, lies at depth.
Limestone- and Skarn-Hosted Contact Occurrences

Limestone- and skarn-hosted contact mineralization occurs in stopes blocks and roof pendants of Madison(?) limestone and a silty limestone of the Big Snowy Group. Skarns fifteen to sixty meters thick are characteristically a product of intrusion by the coarse-grained porphyry, as in the Lucky Strike, Landheim, and Kirby prospects (Plate 2). Contact metasomatism is minor to absent at fine-grained porphyry contacts. The skarn at the Scout prospect was found where an alkali-trachyte unit intruded a silty limestone of the Big Snowy Group.

Mineral assemblages of this contact metamorphic environment are dominated by epidote group minerals, pistacite, or clinozoisite, with lesser calcite, dolomite, chlorite, pyrite, chalcopyrite, and quartz. Specular hematite may occur in limestone nearby. This low-grade assemblage represents a low temperature and pressure environment consistent with the albite-epidote hornfels facies.

The only structural control of this mineralization is the random placement of stope blocks, roof pendants inside the stock, and breccia pipes, both inside and peripheral to the Linster Peak stock. Metal values from the Landheim, Kirby, Lucky Strike, and Scout prospects are listed below.

Metal Values in Skarns
Values in ppm and oz/ton
(Rife, pers. comm., 1981)

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Mo</th>
<th>Au</th>
<th>Ag</th>
</tr>
</thead>
<tbody>
<tr>
<td>ppm</td>
<td>70-140</td>
<td>12-40</td>
<td>0.02-0.3</td>
<td>??</td>
</tr>
</tbody>
</table>
Massive galens and "black-jack" and "resin-jack" sphalerite replace brecciated and silicified limestone. This "high-grade" is found only in ore dumps at the Golden Jack and Kirby prospects.

Thus, despite the low molybdenum and copper values of the skarn-hosted mineralization, gold values here are the highest of the Linster Peak dome. The highest skarn-hosted gold values occur at contacts between coarse-grained porphyry and presumed Madison limestone. The contact between the contaminated alkali-trachyte and the Heath formation limestone contain lower gold values.

In contrast to the molybdenum targets, skarn-hosted gold occurrences may have potential for small ore bodies. Although the volume of exposed skarns in limestone roof pendants and stope blocks is small, the intrusive contact between the Madison limestone and monzonite porphyry probably lies at accessible depths. Unfortunately all drilling has been targeted for porphyry-type mineralization.

A contact-hosted gold target is also appealing in light of nearby ore bodies currently in production. Gold in the Spotted Horse Mine in the southeastern Judith Mountains, and the Kendall Mine in the North Moccasin Mountains, appears related to contacts between the Madison limestone and syenitic, monzonitic, or rhyolitic intrusive bodies. In light of interesting gold values as high as 0.3 ounce per ton, and nearby contact-type ore bodies, the skarn-hosted gold occurrences of the Linster Peak dome hold the greatest potential for small- to moderate-sized economic deposits.
Late-Stage Veins

Late-stage quartz-pyrite-fluorite and carbonate-pyrite-fluorite + quartz + chalcopyrite veins cross-cut all monzonitic rocks exposed on the Linster Peak dome but show no evidence that they are genetically related. Old adits follow these veins in the Golden Jack and Lucky Strike prospects. Massive barren quartz veins occur along Edwards Creek and in the alkali-syenite porphyry plug (Plate 3).

The consistent orientation of these mineralized veins is N80°E to N75°W and N7°W, consistent with the dominant east-west fault and north-south shear in the area. These veins filled open fractures after faulting of crystallized fine- and coarse-grained porphyry. Drill core evidence indicates that some carbonate-pyrite-fluorite veining post-dates crystallization of alkali-trachytes and late rhyolite breccia pipes.

The quartz-pyrite-fluorite veins may be dominantly magmatic in origin. They correspond well with the quartz, pyrite, and fluorite introduced by late-stage intrusive breccias and dikes. On the other hand, the carbonate-pyrite-fluorite + quartz + chalcopyrite veins appear to have crystallized late in the history of the dome. They may represent precipitation from carbonate-fluorine-metal-bearing fluids derived from the underlying Paleozoic carbonate rocks. It is also conceivable that they are a product of carbonate remobilized from altered ferromagnesian minerals. Hall (1976) and Barrett (1979) interpret the carbonate-fluorite veins in the Judith Mountains to represent carbonatitic fluids. This origin is unlikely due to the dearth of distinctive rare-carbonatitic elements in the veins and the lack of injection textures. A
meteoric source derived from heated limestone and porphyry is much more consistent with other contact-related gold-bearing veins and travertine deposits of the area. Although considered to be "high-grade" gold veins, metal values from these veins are not presently available.

Late-stage quartz-pyrite-fluorite and carbonate-pyrite-fluorite ± chalcopyrite veins require extensive geochemical sampling before their value can be adequately determined. These veins were the targets of early prospectors in the Linster Peak dome, but information on their volume and quality of ore is unavailable. The limited size and extent of these gold-bearing veins would presumably discourage all but the independent prospector.
Field relations of the Linster Peak dome and age dates on related rocks in the Judith Mountains effectively delineate the sequence of igneous events of the Linster Peak dome. Potassium-argon dating (Appendix II) and preliminary work on rubidium-strontium dating on the Linster Peak rocks produced anomalous ages which unfortunately are common in dating the Judith Mountain rocks (Marvin, pers. comm., 1982).

Field relationships indicate that the sequence of intrusive rocks in the Linster Peak dome is: fine- and coarse-grained monzonite porphyry, alkali-syenite porphyry, alkali-trachyte, and rhyolitic breccias. Late-stage carbonate-fluorite-pyrite veining is younger than all the igneous rocks exposed on the Linster Peak dome and attributed to a later hydrothermal event. Fine- and coarse-grained porphyry are contemporaneous in age, although the fine-grained chill-cap crystallized before the coarse-grained interior of the stock. The alkali-syenite porphyry, presumably analogous to Wallace's (1953) gray tinguaitae, apparently existed before and coeval with the alkali-trachytes.

Despite the problems of dating the Judith Mountain rocks accurately, Marvin and others (1980) utilized potassium-argon, fission track, rubidium-strontium, and uranium-thorium-lead methods to adequately date many igneous events in the Judith Mountains. The "quartz monzonite" stock of Black Butte, adjacent to the Linster Peak stock, apparently represents an analogous igneous event. Marvin and others have dated the stock at Black Butte as 69 to 68 million years old. This is compatible
with other dates for quartz monzonite stocks in the Judith Mountains. The alkali-syenite of Big Grassy Peak was dated at 67 million years, and the tinguaite of Collar Gulch was estimated to be 65 million years old. These dates are consistent with the intrusive relationships exposed on the Linster Peak dome. Igneous activity on the Linster Peak dome began 69 to 68 million years ago with the intrusion of the monzonitic Linster Peak stock. Presumably, less than two million years later the alkali-syenite porphyry intruded the area, immediately followed by the alkali-trachytes. Considering the standard deviation of the age dates, cooling time of the magmas, and a perspective of geologic time, these sequential events are nearly contemporaneous. In the perspective of the Central Montana Alkalic Province, these igneous events belong to the initial pulse of igneous activity in the Judith Mountains, as well as all of central Montana (Marvin and others, 1980).
Chemical Analyses and Results

Quantitative whole-rock and trace-element analyses were performed on igneous rocks of the Linster Peak dome to examine the chemical relationship between the alkaline and calc-alkaline varieties. Nineteen samples were analyzed for major and minor oxides by quantitative x-ray fluorescence, atomic absorption, and wet chemical methods. Rubidium, strontium, zirconium, niobium, and yittrium were also analyzed by x-ray fluorescence. Averages of major and minor oxide percents and trace elements in parts per million are listed in Table 9. Individual analyses are listed in Appendix I.

Harker variation diagrams proved the most useful in examining geochemical trends in the four major rock types: fine-grained porphyry, coarse-grained porphyry, alkali-syenite porphyry, and alkali-trachyte (Figures 9 and 10). Consistently, the Harker plots of the calc-alkaline and alkaline rocks of the Linster Peak dome produce clusters of points in distinct domains. The alkaline rocks are enriched in alkalis, aluminum, titanium, rubidium, strontium, and zirconium and depleted in silica and calcium relative to the calc-alkaline rocks. No perceptable differences were noted for total iron, manganese, phosphorous, yittrium, or niobium.

The slightly erratic and inconsistent trends in both suites for magnesium, calcium, and total iron defeated attempts to incorporate results of these elements in ternary plots. This may be due wholly or
### TABLE 9: WHOLE ROCK
Rb/Sr, AND
Zr, Y, Nb ANALYSES

<table>
<thead>
<tr>
<th>Oxide*</th>
<th>Total Tmpf (4)</th>
<th>Tmpc (5)</th>
<th>Tasp (4)</th>
<th>Tat (5)</th>
<th>White Cow Intrusion</th>
<th>Little Rockies (4)</th>
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<td>SiO₂</td>
<td>63.90</td>
<td>63.27</td>
<td>60.73</td>
<td>58.33</td>
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<td>Al₂O₃</td>
<td>17.64</td>
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<td>17.83</td>
<td>19.25</td>
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<td>TiO₂</td>
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<td>0.51</td>
<td>0.49</td>
<td>0.30</td>
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<tr>
<td>Fe₂O₃</td>
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<td>2.62</td>
<td>2.47</td>
<td>1.63</td>
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<td>FeO</td>
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<td>2.35</td>
<td>2.55</td>
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<td>MgO</td>
<td>1.15</td>
<td>0.68</td>
<td>0.77</td>
<td>0.75</td>
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<td>MnO</td>
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<td>0.13</td>
<td>0.14</td>
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<tr>
<td>CaO</td>
<td>4.32</td>
<td>4.30</td>
<td>3.10</td>
<td>1.98</td>
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<tr>
<td>Na₂O</td>
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<td>4.85</td>
<td>4.92</td>
<td>5.29</td>
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<tr>
<td>K₂O</td>
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<td>7.37</td>
<td>8.66</td>
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<td>P₂O₅</td>
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<td>0.10</td>
<td>0.12</td>
<td>0.08</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
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(ppm) (ppm) (ppm) (ppm) (ppm) (ppm)

| Rb†#       | 107            | 113      | 182      | 178     |
| Srt†#      | 591            | 679      | 706      | 564     |
| Zr†        | 193.1          | 220.9    | 247.4    | 285.6   |
| Y†         | 22.0           | 24.6     | 25.0     | 12.4    |
| Nb†        | 16.4           | 21.7     | 23.2     | 16.9    |

Rb/Sr†# 0.18 0.16 0.25 0.31
Fe₂O₃/FeO# 0.84 0.93 1.10 0.96

*University of Oregon + Washington State - Pullman
†U.S. Geological Survey
#University of Oregon
Figure: 9

MAJOR OXIDES vs SiO₂ (wt.%)  
ALKALINE AND CALC-ALKALINE 
ROCKS OF THE LINSTER PEAK DOME

- ▲ ALKALI TRACHYTE
- △ ALKALI SYENITE PORPHYRY
- ○ MONZONITE PORPHYRY - FINE GRAIN
- ● MONZONITE PORPHYRY - COARSE GRAIN
Figure: 10

MINOR ELEMENTS (wt.%) AND TRACE ELEMENTS (ppm)
vs SiO₂

Zr

Sr

Rb

TiO₂

P₂O₅
in part to variable compositions and abundances of partly assimilated mafic inclusions and hornblende xenocrysts. The assumption that all of the hornblende in the monzonitic rocks is accessory, either in xenoliths or xenocrysts, requires a re-estimation of their original chemical constituents. Table 10 displays the impact of the hornblende crystals on the whole-rock composition of the coarse-grained porphyry. Six percent hornblende crystals in the coarse-grained monzonite account for 100 percent of the magnesium, 47 percent of the total iron, 15 percent of the calcium, and less than 8 percent of the total silica, aluminum, and alkalis. Thus, a hypothetical uncontaminated magma would be slightly enriched in silica, aluminum, sodium, and potassium, and noticeably depleted in iron, magnesium, and calcium; a leucocratic quartz-syenite or quartz-monzonite.

Chemical Evidence Against Generation From a Common Source Magma

Plots of chemical variation of calc-alkaline and alkaline rocks of the Linster Peak dome are incompatible with present theories of differentiation. Harker diagrams, plotted with major oxides versus SiO₂, indicate the infeasibility of volatile transfer, magma immiscibility, crystal settling, and limestone assimilation to produce these two rock types from a common magma.

Accepted enrichment trends stimulated by volatile transfer in both experimental and natural systems require a contemporaneous enrichment of silica, alkalis, and halogens (Hildreth, 1979; Burnham, 1979) contrary to the Linster Peak trends. The expected depletion of iron and
### TABLE 10

Percent Major Oxides Accounted for by Hornblende Inclusions and "Xenocrysts" in Coarse-Grained Monzonite Porphyry

<table>
<thead>
<tr>
<th>Major Oxides</th>
<th>Percent Major Oxides for Avg. Hornblende</th>
<th>Avg. Percent Major Oxides in Tmpc</th>
<th>Percent Major Oxides in Tmpc Accounted for by 6% Hornblende in Inclusions, Glomerocrysts, and Free Floating</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>48.0</td>
<td>63.3</td>
<td>4.5</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>8.7</td>
<td>18.2</td>
<td>2.8</td>
</tr>
<tr>
<td>FeO</td>
<td>16.4</td>
<td>2.1</td>
<td>47.1</td>
</tr>
<tr>
<td>MgO</td>
<td>11.5</td>
<td>0.7</td>
<td>98.6</td>
</tr>
<tr>
<td>CaO</td>
<td>10.9</td>
<td>4.3</td>
<td>15.1</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.4</td>
<td>4.9</td>
<td>0.02</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.1</td>
<td>4.1</td>
<td>0.02</td>
</tr>
<tr>
<td>H₂O</td>
<td>2.1</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
magnesium do not accompany alkali enrichment in the alkali-trachytes and alkali-syenite porphyries. Furthermore, both alkaline and calc-alkaline magmas were originally quite dry. One would not expect a dry magma to result from differentiation utilizing volatile transfer. Also, the occurrence of two different volatile compositions for these suites is not consistent with this concept of differentiation.

The enrichment of andesine and quartz in the calc-alkaline rocks and the sanidine, aegirine-augite and melanite in the alkaline rocks cannot be explained by crystal settling.

The unusual combination of alkali-enrichment and silica depletion discourages consideration of magma immiscibility as the differentiation mechanism between the two igneous suites of the Linster Peak dome. Lack of significant enrichment trends in titanium, phosphorus, and iron further discount this theory of differentiation for the Linster Peak alkaline and calc-alkaline rocks. Furthermore, the chemical constituents of the two magmas do not place them in an immiscible field depicted by Visser and Koster Van Groos (1979) or Freestone (1978). Daly's hypothesis of limestone assimilation (1910) was used by Wallace (1952) to explain the generation of younger alkalic rocks from older calc-alkaline rocks in the Judith Mountains. This mechanism is no longer believed capable of producing compositional changes in significant volumes of magma (Gittens, 1979; Hyndman, 1981).

Chemical plots for the range of calc-alkaline rocks of the Judith Mountains (Figure 11) indicate that a distinct trend of typical calc-alkaline differentiation occurs with increasing time and silica
Figure: 11
MAJOR OXIDES vs SiO$_2$ (wt.%) 
ALKALINE AND CALC-ALKALINE 
ROCKS OF THE LINSTER PEAK-DOME

- ▲ ALKALI TRACHYTE
- △ ALKALI SYENITE PORPHYRY
- ○ MONZONITE PORPHYRY - FINE GRAIN
- ● MONZONITE PORPHYRY - COARSE GRAIN
- ■ OTHER CALC-ALKALINE ROCKS OF THE JUDITH MOUNTAINS (Wallace, 1952)
- □ WHITE COW INTRUSION, LITTLE ROCKIES (Roemmele, 1982)
percentages. These typical calc-alkaline trends are not compatible with a hypothetical alkali-trachyte - alkali-syenite porphyry - monzonite porphyry "trend" that might be construed from the Harker plots.

On the Harker plots, commonly alkali-syenite porphyry, intermediate in age, lies on a line between the two end members. In all cases it is most closely linked to the alkali-trachytes. This intermediate position suggests either a genetic relationship or magma mixing to explain the position of the alkali-syenite plots. Minor contamination of the alkaline magma by a small volume of monzonitic magma could produce the chemical trends exhibited by the alkali-syenite porphyry. Coexistence in space and time further support this possibility. The preferred explanation of magma mixing rather than differentiation to produce the alkali-syenite magma is also supported by the lack of any explicable differentiation mechanism to produce this rock type from a monzonitic parent.

Thus, chemical evidence indicates that the alkaline and calc-alkaline magmas of the Linster Peak dome developed independently. Permissive evidence does suggest that the alkali-trachyte magma was slightly contaminated by the calc-alkaline magma, producing the alkali-syenite porphyry. The occurrence of intermediate rock types elsewhere in the Judith Mountains supports varying degrees of magma mixing (Wallace, 1953). Contemporaneous evolution of two magmatic suites in an area of local crustal tension and basement faulting are consistent with chemical evidence of magma mixing.
ORIGINS OF THE LINSTER PEAK MAGMAS

Origin of the Calc-Alkaline Magma

The monzonitic rocks of the Linster Peak dome are the earliest series of intrusive rocks in the Judith Mountains. Their age and chemical composition indicate that they are the most primitive rocks of the Judith Mountain calc-alkaline suite.

Currently accepted theories for the genesis of monzonitic magmas point to mantle and crustal origins. A mantle source for the monzonitic magmas involves differentiation of a felsic magma from mantle-derived basaltic parent. The tectonic environment, chemical composition, and lack of exposed basaltic material collectively discredit this theory in the Judith Mountains. Calc-alkaline magmatism resulting from differentiation of a basaltic magma commonly occurs in a continental arc setting. Yet in the Early-Tertiary, the continental arc existed about five hundred kilometers west of the Judith Mountains (Burchfiels, 1979; Lipman and others, 1972). The small quantity of igneous rocks in the Judith Mountains discourages a mantle-plume type mechanism for generation of magmas as well.

The chemical compositions of the Linster Peak monzonite are significantly lower than basaltic differentiates of equivalent silica content (Carmichael and others, 1974). If all of the hornblende is xenocrystic and these elemental comparisons are even less compatible. The lack of mafic rocks exposed at the surface in the Judith Mountains is significant. Since the monzonitic rocks are fairly dry, one
would expect that a basaltic parent magma would also be dry. A water-undersaturated basalt should be able to breach the surface prior to crystallization. The lack of spatially associated mafic rocks, incompatible geochemical values, and inappropriate tectonic environment, discourage consideration of a mantle origin for the calc-alkaline rocks of the Linster Peak dome.

Crustal assimilation by the alkaline magmas to produce the monzonitic magmas is also unlikely. Calc-alkaline lithologies are significantly more voluminous, and the degree of crustal assimilation required is extremely large. The heat required to melt this quantity of material would induce rapid crystallization, probably in the mesozonal or catazonal environment. Although this mechanism cannot produce the monzonitic rocks, minor contamination of the original alkaline magmas may have occurred.

Crustal sources for the monzonitic rocks appear more favorable than mantle origins. Composition of the monzonites and quartz monzonites (or hypothetical leu-co-monzonites) of the Judith Mountains are compatible with compositions of partial melts from plagioclase-orthoclase-quartz-bearing rocks. Partial melting of crustal gneisses requires decreasing pressure, increasing temperature, or the addition of volatiles; conditions which may apply to central Montana during the Late-Cretaceous. A decrease in pressure may accompany tensional forces. Basement block faulting should have also dramatically reduced pressures locally in the crust. Hyndman (1981) notes that release of pressure by fracturing may initiate magmatism without a change in temperature or
FIGURE 12  DECOMPRESSION MECHANISM FOR MAGMA GENESIS

- Basalt (P_{CO2}*)
- Basalt (Dry)*
- Granite (6% H2O)*
- Granite (2% H2O)*

Approximate crustal thickness in central Montana (Smith, 1967)

* from Hyndman (1981)
** from Winkler (1979)

Pressure (kibars) vs. Depth (kilometers)

Temperature (degrees centigrade)

[Diagram showing the relationship between pressure, depth, and temperature for magma genesis.]

Approximate crustal thickness in central Montana (Smith, 1967)

- * from Hyndman (1981)
- ** from Winkler (1979)
(see Figure 12). Some anomalous heat flow is typical of tensional areas, regional or local tension in central Montana may have resulted in an Late-Cretaceous - Early-Tertiary heat flow greater than the average crustal value. Coeval, mantle-derived alkaline magmas may also have increased heat flow due to basaltic underplating. The low water compositions of the monzonitic rocks of the Judith Mountains suggest that volatiles did not play a significant role in their genesis, although small amounts of rising volatiles from the early-formed alkaline magmas may have contributed to anatexis. Thus, the expected pressure increase, temperature increase, and possible minor contribution of volatiles indicate that partial melting of the quartzofeldspathic basement gneisses is a likely origin for the Linster Peak stock. The composition of the basement rock, temperature, pressure, and volatile constituents would determine the depth of magma generation. The abundance of partly assimilated foliated hornblende xenoliths could be restite fragments, or later-assimilated inclusions. Heat and volatiles from the contemporaneous alkaline magmas may have contributed significantly to this event.

**Origin of the Alkaline Magmas**

Recent field and theoretical investigations in alkaline rocks and in the Central Montana Alkalic Province have aided in an understanding of these rocks. Mechanisms pertaining to crustal origins include partial melting of the crust, melting induced by rising mantle fluids, or contamination of the monzonitic magmas. Differentiation or contamination of the monzonitic magmas to produce the alkaline magmas is highly
highly unlikely. As shown above, the composition of both lithologies negates any method of differentiation to derive the alkaline rocks from the calc-alkaline rocks. Contamination of the monzonitic magmas by limestone syntaxis is not capable of deriving appropriate volumes of alkaline magma from calc-alkaline magma (Gittens, 1979). Minor contamination may have influenced the alkali-syenite magmas, but their compositional variation from the alkali-trachytes is very subtle. Crustal melting to derive the alkaline magmas is difficult to explain due to their depletion of silica. Partial melting induced by volatiles from the mantle is a more acceptable mechanism of genesis from crustal material.

Kimberlites, carbonatites, and mantle-derived mafic alkaline rocks occur in central Montana. Thus, mantle material has managed to reach the surface in the Alkaline Province. The likelihood that the felsic alkaline rocks of the Linster Peak area are mantle-derived is quite reasonable. They could have developed directly by partial melting of mantle material, or by differentiation from a mafic alkaline parent. Their mineral and chemical similarity to syenites from shonkinite-syenite laccoliths in central Montana (Kuhn, 1982; Kendricks, 1980) suggests that the Linster Peak rocks too may have differentiated from a mafic parent. The whole-rock chemical characteristics of the alkali-trachytes and alkali-syenite porphyries are compatible with differentiation from a mafic parent by crystal fractionation, volatile transfer, or magma immiscibility.
Mineralogical, chemical, and spatial characteristics suggest that a mantle origin or contamination of deep crustal rocks by mantle fluids is the most appropriate explanation for the genesis for these magmas. Mafic inclusions in these magmas could be ocelli or restites from a more basaltic magma or rock, as well as recrystallized basement xenoliths. The unusual occurrence of melanite garnet is further suggestive of a mantle origin. The factors which may have controlled the common spatial and temporal relationships of the alkaline and calc-alkaline magmas are discussed below.

Common Factors Involving Petrogenesis of Alkaline and Calc-Alkaline Lineages

The differences in mineral, chemical, and fluid-phase compositions of the two Linster Peak igneous suites indicate that they evolved from different source areas. The likelihood of crustal and mantle origins for the monzonitic and alkalic rocks, respectively, further supports a theory of independent genesis. Yet these magmas intruded the same area nearly contemporaneously.

The occurrence of Late-Cretaceous basement faulting and secondary tensile stresses must have locally decreased pressures in the crust. Bailey (1964) indicates that crustal warping alone may induce partial melting of the crust by decreasing hydrostatic pressure. Hyndman (1981) suggests that extensive fracturing of the crust may create felsic magmas by partial melting of the gneissic basement rocks. Presumably, decreased pressure promoted melting of gneissic basement rocks. Figure 12
depicts this mechanism. Assuming an average geothermal gradient of 20°C/km, a partial melt of granitic composition with three percent water would develop at 35 kilometers. A slightly less silicic melt, such as a quartz-bearing monzonite, would require slightly higher temperatures, more water, or less pressure. Anomalous sphene, hornblende, and mafic inclusions in the monzonitic rocks could reflect primary restite as well as accidental xenoliths.

Presumably, if pressures decreased in the lower crust due to basement faulting and/or tension resulting decompressional zones would occur in the upper mantle. This mantle decompression could promote rising of molten mantle material, volatiles, or a mantle-derived partial melt. Presumably, the alkali-trachytes and alkali-syenite porphyries are a direct or indirect product of melting induced by decompression in the mantle.

If generation of calc-alkaline and alkaline magmas was contemporaneous, responding to decompression in the crust and mantle, respectively, calc-alkaline magmas may reach the upper crust first, having less distance to travel. Denser, less viscous alkaline magmas presumably would follow very soon after intrusion of the calc-alkaline magmas. If basaltic underplating contributed to anatexis, the two magmas should intrude nearly simultaneously. The above-mentioned temporal relationships are precisely what is seen in most alkaline/calc-alkaline sub-provinces of central Montana.
Evidence of Magma Mixing

Indicators of magma contamination by magma mixing occur in both the alkaline and calc-alkaline rocks of the Linster Peak dome. In the monzonitic rocks, hornblende and sphene can be attributed to assimilation of mafic inclusions, but the aegirine-augite remains an enigma. If clinopyroxene had formed early in the crystallization history, augite would have formed using calcium that was later incorporated into plagioclase. Instead, andesine formed and aegirine-augite represents the clinopyroxene phase. Either the aegirine-augite formed after crystallization of the andesine, or it occurs as an accidental mineral. The similarity of the aegirine-augite in the monzonitic rocks, and the cores of the aegirine-augite of the alkaline rocks points to magma mixing to explain this phenomenon. The shattered and ratty appearance of the monzonitic hosted aegirine-augite further supports a mechanism of magma mixing. Sphene abundances, partly attributed to assimilation of mafic inclusions, may also be a refractory product of magma contamination.

Contamination of the alkali-trachyte magma by monzonitic magma can be seen chemically from Harker plots of whole-rock and trace-element chemical analyses. For nearly all elements, the alkali-syenites, the earliest rocks, show a subtle affinity for the calc-alkaline suite. Since no feasible differentiation trend can relate them, magma contamination must be the reason for their similarities. Also, gray trachyte dikes, weakly enriched in aegirine, often contain fractured plagioclase and orthoclase crystals. These crystals could have been incorporated by magma mixing late in the cooling history of the trachytes or they could
exist as xenocrysts from partly assimilated stock lithologies. Curiously, the youngest alkali-trachytes are far more enriched in aegirine, and show no evidence of magma contamination.

A younger, evolving suite of syenites and alkali-granites in the Judith Mountains is clearly the product of magma mixing (Wallace, 1953). Thus, all stages of magma mixing between the alkaline and calc-alkaline suites may be observed in the Judith Mountains. In comparison, it appears that the rocks of the Linster Peak dome represent the oldest, least contaminated, and most primitive magmas exposed in the Judith Mountains. All other igneous rocks in the area can be linked to the rocks of Linster Peak by differentiation or contamination.
CONCLUSIONS

In central Montana during the Late-Cretaceous, extensive basement faulting produced the following surface features: regional folds, basement-cored uplifts, en echelon fault zones, and other smaller, similarly-oriented faults. Presumably, these basement faults controlled the formation of local surface features and produced localized decompression in the earth's crust. A theoretical, secondary zone of tension apparently trended northeast through central Montana and may have contributed to zones of weakness and low pressure.

Normal faulting in the Linster Peak area, which parallels this regional trend, displaced Paleozoic and Mesozoic rocks prior or during to emplacement of the Linster Peak stock. This fault apparently remained a zone of structural weakness, and localized late magmatic pulses, hydrothermal alteration, and mineralization in the Linster Peak dome.

During the very Late-Cretaceous and Early-Tertiary, monzonitic magmas forcefully intruded this area, producing a multi-phase stock. These phases include a fine-grained chill cap, more coarsely crystalline porphyritic core, and late-stage dikes, intrusive breccias, and intrusive latites.

The upper chill cap crystallized early, allowing minor volatiles, silica, and metals to accumulate in the apical portions of the still-molten body of the stock. Thin, gold-bearing skarns formed at contacts between the more hydrous phases of the stock and Paleozoic limestones. Intrusive breccias, latites, and coarse-grained porphyry dikes produced
small-scale "porphyry type" copper, molybdenum, lead, and zinc accumulations, pyritization, silicification, carbonitization, and argillitization of the host rocks. These late-magmatic phases concentrated along the major east-west and north-south shear zones in the Linster Peak dome.

Emplacement of alkaline magmas began immediately following the crystallization of the Linster Peak stock. Nepheline-normative alkali-syenite porphyries and alkali-trachytes intruded the dome as a plug, irregular discordant bodies, dikes, and sills. With the exception of the argillically altered and brecciated plug, no mineralization is associated to these alkalic intrusions. Two small occurrences of rhyolitic breccias post-date alkaline activity.

Later hydrothermal alteration produced extensive carbonitization, and pyritization along the faults and shear zones of the Linster Peak dome. All igneous lithologies host this alteration, including the alkali-trachytes and rhyolitic breccias. High-grade, gold-bearing veins of carbonate-fluorite-pyrite + quartz + chalcopyrite apparently formed as fracture fillings during this event. The late occurrence of these veins indicates that they may be related to the same hydrothermal events which produced post-magmatic travertine deposits in the Judith and Moccasin Mountains.

Previous explanations of the nearly contemporaneous calc-alkaline and alkaline suites in the Judith Mountains by differentiation or assimilation have been re-examined by using field studies, laboratory analyses and research. The following results and speculation are the
product of this investigation.

Differences in mineral constituents, chemical trends, late-magmatic fluid phases, and degrees of silica saturation indicate that these two suites of igneous rocks cannot have originated from the same source area, or magma, as previously thought. The two magmas were derived from different source terrains, apparently crustal for the monzonitic rocks, and mantle related for the alkaline rocks. The same tectonic mechanism of magma generation probably initiated simultaneous magmatism in both areas. Basaltic underplating by the alkaline magmas may have greatly influenced anatexis of the crust and production of calc-alkaline magmas.

Chemical and mineral anomalies in both suites can be explained by minor contamination; presumably magma mixing at depth. The utilization of basement shears for conduits for both rising magmas would allow, if not necessitate, some degree of contamination. Mineral and chemical constraints suggest that mixing occurred after andesine began crystallizing in the monzonitic melt, and before aegirine rims formed on aegirine-augite in the alkalic melts. Younger intrusive rocks in the Judith Mountains more readily exhibit magma mixing between felsic alkalic and calc-alkaline magmas.

The occurrence of Late-Cretaceous basement shearing and secondary tensional zones support a simple model of magma generation by crustal decompression in central Montana. Crustal and mantle melting, initiated by local low-pressure zones, could produce small volumes of magma without the existence of anomalous heat flow or volatile constituents.
PHASE 1:
Late-Cretaceous basement faulting generates partial melting (by decreasing pressures) of crust and mantle rocks.

PHASE 2:
Calc-alkaline magmas rise first, forming a stock. Alkaline magmas rise through (and mix in) the fault zone.

PHASE 3:
Crystallization and denudation of the dome result in its present appearance.

EXPLANATION
- CALC-ALKALINE MAGMA
- ALKALINE MAGMA
- ZONE OF PARTIAL MELTING
- FAULT

* Basaltic underplating may also have contributed.
Basaltic underplating could also have strongly influenced crustal anatexis. The volume and timing of the magmatic events, coupled with the tectonic picture of central Montana during the Cretaceous-Tertiary transition, are compatible with this mechanism of crustal decompression to produce the two coeval magmas.

Although this mechanism of magma generation is presently speculative (Figure 13) it represents a simple, feasible explanation for the existence of spatially and temporally related alkaline and calc-alkaline magmatism in the Linster Peak area. Additional work involving the mineral, chemical, chronological, and structural relationships of these coeval magmas will test this theory of magma generation in similar areas of the Central Montana Alkalic Province.
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APPENDIX I
LABORATORY PROCEDURES

1. Thin Section Analysis

Slide preparation involved orientation of randomly selected samples cut and ground to approximately 30 microns in thickness by Steve Balogh, University of Montana. Standard Zeiss polarizing microscopes were used for observation. References used for mineral identification and textures are Troger (1977), Deer and others (1975), Phillips (1971), and Williams and others (1954).

2. X-Ray Diffraction Analysis

X-ray diffraction studies were performed at the U.S. Geological Survey under the direction of Zeke Rivera, Denver, Colorado. Samples of monzonite porphyry and alkali-syenite porphyry were ground to a fine powder and mixed with acetone for unoriented slides. Slides were radiated by a Picker X-Ray Diffractometer with a copper alpha tube using 32 kilovolts, 18 milliamperes, and rotating at 2°/minute. Individual mineral separates (hornblende, plagioclase, potassium feldspar) were x-rayed, as well as non-magnetic "heavies" and bromoform "lights" from mineral separation procedures.

3. Whole Rock and Trace Element Chemical Analyses

Sampling

All samples for geochemical analyses were collected randomly from the freshest rock available. A minimum of 4.5 kilograms/sample was collected, with the exception of a few fine-grained rocks for which 2.3 kilograms/sample was collected. All visible weathering rinds and mafic inclusions were removed prior to pulverizing the rocks. Longitudes and latitudes for geochemical samples are listed below in Table 1a.

Crushing and Pulverizing

Samples, broken to less than 2 inches in diameter, were crushed in a Chipmunk crusher to less than 1 centimeter in diameter. These chips were ground to less than 1 millimeter in a disc pulverizer with porcelain plates. Crushing and pulverizing mentioned above were performed using the facilities at the University of Montana and the U.S. Geological Survey in Reston, Virginia. Care was taken to avoid contamination and to crush, then split the entire 4.5 kilograms of samples to insure the random distribution of minerals. Entire splits of less than 1 millimeter size fractions were ground by hand, using a porcelain mortar and pestle, to less than 230 mesh. Care was taken to avoid any loss of material by sieving.
### Table 1a: Location of Geochemical Samples

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<th>Number</th>
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<td>Tmp</td>
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<td>109°04'55&quot;</td>
</tr>
<tr>
<td>JM-79</td>
<td>Tasp</td>
<td>47°14'44&quot;</td>
<td>109°02'00&quot;</td>
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<td>JM-124</td>
<td>Tasp</td>
<td>47°13'30&quot;</td>
<td>109°02'45&quot;</td>
</tr>
<tr>
<td>JM-82</td>
<td>Tasp</td>
<td>47°14'40&quot;</td>
<td>109°01'30&quot;</td>
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<tr>
<td>JM-84</td>
<td>Tasp</td>
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<td>JM-32C</td>
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<td>JM-16</td>
<td>Tat</td>
<td>47°13'08&quot;</td>
<td>109°04'50&quot;</td>
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<td>CBM-7</td>
<td>Tat</td>
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<td>JM-2A</td>
<td>Tat</td>
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<td>109°01'20&quot;</td>
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<td>JM-135</td>
<td>Tat</td>
<td>47°13'44&quot;</td>
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<td>JM-80</td>
<td>Tat</td>
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<td>109°02'00&quot;</td>
</tr>
</tbody>
</table>

Latitude values are accurate within: 02".
Longitude values are accurate within: 05".
Chemical Analyses

1. University of Oregon, Eugene, Oregon: Four samples, one of each rock type, were analyzed quantitatively under the supervision of Lance Peterson at the University of Oregon. Nine major elements were run on an x-ray spectrometer. Standard rocks were run in parallel with these samples to enable calculation of precision and accuracy. Sodium was analyzed by atomic adsorption and ferrous and ferric iron were determined by titration. Precision and accuracy of XRF analyses for major elements (except MgO) is 1% relative or less, 2% for MgO, and slightly higher for minor elements. Results are listed in Table 1b.

Trace elements Rb, Sr, Y, Zr, and Nb were also analyzed by XRF at the University of Oregon for the above-mentioned samples. Results are tabulated below in Table 1c.

2. Washington State University, Pullman, Washington: Twenty whole-rock samples were analyzed for ten major elements at Washington State University (W.S.U.), Pullman, under the direction of Peter Hooper. Less than 1 millimeter size pulverized rock was further prepared at W.S.U. and analyzed by standard XRF procedures. The results of these analyses are listed below in Table 1d. Accuracy and precision data are not available on these values, but they correspond well with results from the University of Oregon. The SiO₂ value for sample JM-105 appears to be anomalously high in comparison to other samples of similar rock type, and analysis of the same rock at the University of Oregon.

3. U.S. Geological Survey, Denver, Colorado: The following rubidium and strontium values were determined by x-ray fluorescence under the direction of Carl E. Hedge, U.S. Geological Survey, Denver, Colorado. These results are listed in Table 1e.
<table>
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<tr>
<th></th>
<th>Sample JM-84</th>
<th>Sample JM-89</th>
<th>Sample JM-105</th>
<th>Sample JM-106</th>
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</tr>
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<td>1.54</td>
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<tr>
<td>MnO</td>
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<tr>
<td>MgO</td>
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<td>0.95</td>
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<tr>
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<td>Na$_2$O</td>
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<td>4.17</td>
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<td>4.91</td>
</tr>
<tr>
<td>K$_2$O</td>
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<td>3.99</td>
<td>9.34</td>
<td>4.09</td>
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<td>P$_2$O$_5$</td>
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<tr>
<td>Total</td>
<td>99.04</td>
<td>98.94</td>
<td>100.10</td>
<td>98.03</td>
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### TABLE 1c: RESULTS OF TRACE ELEMENT ANALYSES IN PPM

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<tr>
<th>Sample Number</th>
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<th>Y</th>
<th>Zr</th>
<th>Nb</th>
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<tr>
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<td>285.6</td>
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**ABUNDANCES**

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<th>Y</th>
<th>Zr</th>
<th>Nb</th>
</tr>
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**ERRORS**
### TABLE 1d: WHOLE-ROCK ANALYSES FROM W.S.U. (PULLMAN)

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<th>Sample Number</th>
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<th>TiO₂</th>
<th>FeO*</th>
<th>MnO</th>
<th>CaO</th>
<th>MgO</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>P₂O₅</th>
<th>Total%</th>
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<td>3.92</td>
<td>4.02</td>
<td>0.13</td>
<td>100.08</td>
</tr>
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</table>

*Total Fe

†Mafic inclusion from alkali-syenite porphyry dike.
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<th>Sr (ppm)</th>
<th>Rb/Sr</th>
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<td>139</td>
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<td>0.24</td>
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Rb and Sr values determined by x-ray fluorescence under the direction of Carl E. Hedge, U.S. Geological Survey, Denver, Colorado.
APPENDIX II

Age Dating

Mineral separates were collected under the supervision of Zeke Rivera (U.S. Geological Survey, Denver, Colorado) for potassium-argon isotope dating of the fine-grained monzonite porphyry (JM-89) and alkali-syenite porphyry (JM-84). The results of these determinations on feldspars and hornblende are tabulated below. These analyses were performed by Richard Marvin, Branch of Isotope Geology, U.S. Geological Survey, Denver, Colorado.

United States Department of the Interior
Geological Survey
Isotope Geology Branch

K-Ar Age Determinations

Report No. 679 For Gail Kirchner Date March 5, 1982

Constants: $K_{40}^{\lambda} = 0.581 \times 10^{-10}/yr$ $\lambda_{8} = 4.962 \times 10^{-10}/yr$

Atomic abundance: $K_{40} = 1.167 \times 10^{-4}$

Potassium determinations made with an Instrumentation Laboratories flame photometer with a Li internal standard.

<table>
<thead>
<tr>
<th>Lab. No.</th>
<th>Field No.</th>
<th>$K_{2}O$ %</th>
<th>*Ar$^{40} (10^{-10}$ moles/gram)</th>
<th>$%Ar^{40}$</th>
<th>*Ar$^{40} / K_{40}$</th>
<th>Age m.y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3082S</td>
<td>GK-JM-84</td>
<td>9.77 avg.</td>
<td>8.479</td>
<td>84</td>
<td>0.00350</td>
<td>59.3+2.1</td>
</tr>
<tr>
<td>D3082H</td>
<td>GK-JM-84</td>
<td>0.33 avg.</td>
<td>0.2248</td>
<td>54</td>
<td>0.00275</td>
<td>46.7+3.9</td>
</tr>
<tr>
<td>D3083H</td>
<td>GK-JM-89</td>
<td>1.64 avg.</td>
<td>2.137</td>
<td>90</td>
<td>0.00526</td>
<td>88.3+3.2</td>
</tr>
<tr>
<td>D3083PI</td>
<td>GK-JM-89</td>
<td>0.79 avg.</td>
<td>1.063</td>
<td>76</td>
<td>0.00543</td>
<td>91.1+5.6</td>
</tr>
</tbody>
</table>

*radiogenic argon

S = sanidine concentrate
H = hornblende concentrate
PI = plagioclase concentrate

Analysts: R. F. Marvin, H. H. Mehnert, E. L. Brandt

Potassium determinations: 9.78 and 9.76% K$_2$O for D3082S
0.32 and 0.34% K$_2$O for D3082H
1.65 and 1.63% K$_2$O for D3083H
0.80 and 0.78% K$_2$O for D3083PI

Samples D3082S and D3082H, sanidine and hornblende concentrates, respectively, were obtained from specimens of alkali syenite porphyry that were collected at approximately 47°15'N, 109°50'W; Linster Peak Dome, Judith Mountains, Fergus County, Montana.

Samples D3083H and D3083PI, hornblende and plagioclase concentrates, respectively, were obtained from specimens of monzonite porphyry that were collected at approximately 47°15'N, 109°50'W; Linster Peak Dome, Judith Mountains, Fergus County, Montana.
MINERALIZATION OVERLAY FOR THE GEOLOGIC MAP
LINSTER PEAK DOME

EXPLANATION

- - Zone of pyritization and silicification
- Quartz veins < 1 cm thick ± pyrite
+ Quartz veins > 1 cm thick ± pyrite
- - Chalcopyrite
- - Sphalerite and galena
- - Fluorite

PLATE 3.
ROADS, ADITS, PROSPECT PITS, AND DRILL HOLES
LINSTER PEAK DOME

EXPLANATION

== Roads (4-wheel drive)
Y Adit
X Prospect pit
O Drill holes:
O1 Mine Finders
O2 Earth Resources DDH-2
O3 Earth Resources DDH-1
O4 Gulf DDH-2
O5 Gulf DDH-1
Plate I: Geologic Map of the Linster Peak Dome
Fergus County, Montana

EXPLANATION

- Qu: Undivided alluvium, colluvium, and talus.
- QL: Landslide debris.
- Strike and dip of beds.
- F: Foliation defined by parallelism of phenocrysts.
- F: Faults.
- S: Shear zones.
- G: Gradational contacts.
- Contacts accurate within 50 ft.
- Contacts accurate within 100 ft.

- T: Alkali trachyte.
- Tbp: Breccia pipe.
- Tbp: Intrusive breccia.
- Tmp: Monzonite porphyry-mixed.
- Tmp: Monzonite porphyry-coarse-grained.
- Tmp: Monzonite porphyry-fine-grained.

- Kc: Colorado group.
- Kk: Kootenai formation.
- Ume: Morrison formation and Ellis group.
- Msa: Big Snowy group.
- Mn: Madison formation.

Mapping by Gail Kirchner, 1981