Geology and Geochemistry of the Coulee Dam Intrusive Suite and Associated Younger Intrusive Rocks, Colville Batholith, Washington

U.S. GEOLOGICAL SURVEY BULLETIN 1846

Prepared in cooperation with the
U.S. Bureau of Indian Affairs

Geology and Geochemistry of the Coulee Dam Intrusive Suite and Associated Younger Intrusive Rocks, Colville Batholith, Washington

By DIANE H. CARLSON

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U.S. Bureau of Indian Affairs

Geology and geochemistry of plutonic and hypabyssal
intrusive rocks northeast of Grand Coulee Dam, Washington

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Geology and Geochemistry of the Coulee Dam Intrusive Suite and Associated Younger Intrusive Rocks, Colville Batholith, Washington

By Diane H. Carlson

Abstract

Geologic mapping northeast of Grand Coulee Dam has resulted in the recognition of numerous intrusive units that can be grouped into two intrusive suites. An older suite, which is herein named the Coulee Dam Intrusive Suite, dates from about 54 Ma (million years) and represents a significant part of the Colville batholith. The Coulee Dam Intrusive Suite consists of five texturally distinct granitic units that, from oldest to youngest, are the Manila Creek Granodiorite (new name), Swawilla Granodiorite (new name), Keller Butte Granite (new name), granite porphyry, and garnet-bearing granite. The Coulee Dam Intrusive Suite is cut by a slightly younger (informally named) intrusive suite composed of hypabyssal dikes and plutons that are associated with Eocene volcanism and graben formation. The younger suite includes rhyodacite-dacite dikes, the Devils Elbow pluton, the Joe Moses Creek stock, and seriate granite.

Chemically, the Coulee Dam Intrusive Suite is silica-rich, strongly peraluminous, and defines a calc-alkaline differentiation trend of alkali enrichment with systematic depletion of total iron and magnesium. Rare-earth-element analyses show that overall the suite is depleted in REE and that the light REE are enriched relative to the heavy REE. There is a progressive decrease in REE and development of a negative Eu anomaly in the Coulee Dam Intrusive Suite. The youngest garnet-bearing unit of the Coulee Dam Intrusive Suite is anomalous in that it has a marked enrichment of heavy REE and a strong negative Eu anomaly. The suite is also characterized by low Rb/Sr, intermediate initial $^{87}Sr/^{86}Sr$ ratios, and a 1,700-Ma inherited Pb component.

The rocks of the younger intrusive suite can be subdivided based on their relative ages, spatial association, and chemical similarities. These rocks were emplaced during an early silicic episode, a middle intermediate episode characterized by high K_2O, and a late silicic magmatic episode. The younger suite is also enriched in light REE relative to heavy REE and, based on limited data, has slightly higher initial $^{87}Sr/^{86}Sr$ values than the Coulee Dam Intrusive Suite.

The Coulee Dam Intrusive Suite and the slightly younger suite of intrusive rocks probably evolved from a simple initial melt generated from lower crustal rocks which were, in part, Precambrian in age.

Manuscript approved for publication, February 4, 1988.

INTRODUCTION

This report presents the results of a study of the bedrock geology in a 135-mi^2 area in the central part of the Colville Indian Reservation in northeastern Washington (fig. 1). This study is part of a larger U.S. Geological Survey project to map the entire Colville Indian Reservation. The work was done as part of a cooperative program between the U.S. Geological Survey, the U.S. Bureau of Indian Affairs, and the Confederated Tribes of the Colville Indian Reservation. It consisted of geologic mapping during the summers of 1981–1983 in the south half of the Nespelem quadrangle and north quarter of the Grand Coulee Dam quadrangle (pl. 1).

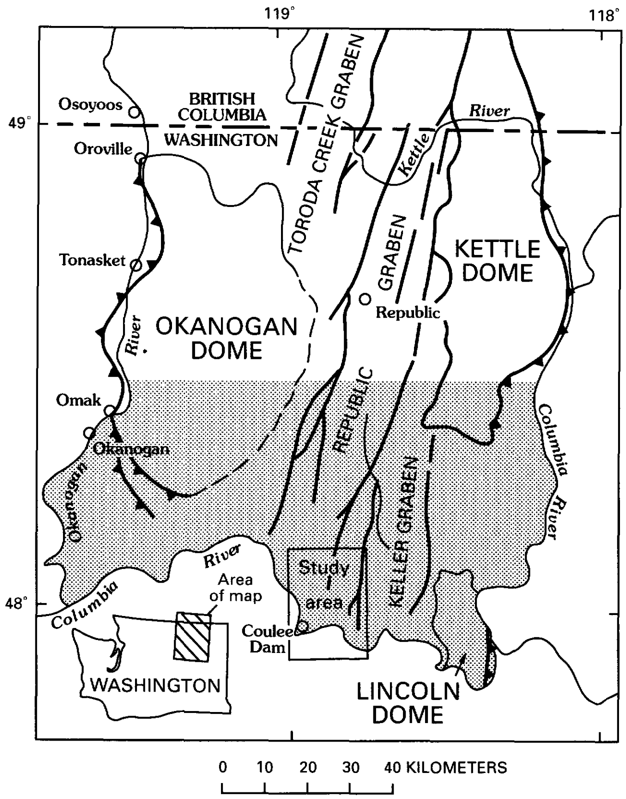
The Colville mapping project resulted in the recognition of numerous granitic units and plutons (fig. 2) that are part of the Colville batholith as defined by Pardee (1918) and later studied by Waters and Krauskopf (1941).

GEOLOGIC SETTING

The Colville batholith[1] is largely Paleogene in age based on K-Ar and U-Pb age determinations (R.J. Fleck and D.L. Parkinson, written commun., 1986). In the study area, it comprises an older (Coulee Dam) leucocratic intrusive suite and a slightly younger Eocene suite of plutons and dikes (pl. 1). The batholith is bounded by gneiss domes: on the west by the Okanogan dome (Fox and others, 1971, 1976, 1977; Hansen, 1983) and on the east by the Kettle (Cheney, 1980; Rhodes and Cheney, 1981) and Lincoln domes (Atwater and others, 1984). Waters and Krauskopf (1941) believed the Okanogan dome to be part of the protoclastic border of the Colville batholith and Campbell (1946) similarly interpreted the Kettle dome. Subsequent studies (Hansen, 1983; Atwater and others, 1984; Holder, 1986; Volk, 1986) have

[1]Names combined with the terms batholith, pluton, or stock, such as Devils Elbow pluton, are informal.

shown that granites of the older leucocratic suite are in fact gradational into the gneiss domes, suggesting that at least the last movement on the domes was Eocene in age. Kinematic indicators in the Okanogan dome give top-to-the-west sense of shear (Hansen, 1983; Parkinson and Kluitt, 1986) whereas those in Kettle dome give a top-to-the-east sense (Rhodes and Cheney, 1981). This final movement on the domes is contemporaneous with emplacement of granites of the older leucocratic suite and also with the development of the three en echelon graben structures that separate the Okanogan and Kettle domes (Atwater, 1985). The grabens trend north-northeast and from north to south are the Toroda Creek graben, Republic graben, and Keller graben (fig. 1). The grabens are volcanotectonic depressions that contain the O'Brien Creek Formation (54.5±1.5 Ma), Sanpoil Volcanics (53.8±1.8 Ma to 49.6±3.0 Ma), and the Klondike Mountain Formation (50.4±1.7 Ma to 47.5±1.7 Ma) (Pearson and Obradovich, 1977) (see fig. 2 for Republic and Kettle grabens). The O'Brien Creek Formation is best exposed in the Keller graben (Atwater and others, 1984) and consists of terrigenous sedimentary rocks and crystal-lithic tuffs; the Sanpoil Volcanics is exposed in all three grabens where it consists of porphyritic lithoidal lava flows and minor porphyritic glassy dacitic lava flows; the Klondike Mountain Formation, exposed in the Toroda Creek and Republic grabens, consists of volcanic breccias and tuff, tuffaceous sedimentary rocks, and dacitic to quartz latitic lithoidal and glassy lava flows (Muessig, 1962; Pearson and Obradovich, 1977).



EXPLANATION

— — Boundary of structural feature—Dashed where approximately located

——— High-angle fault

▲—▲ Thrust fault—Sawteeth on upper plate

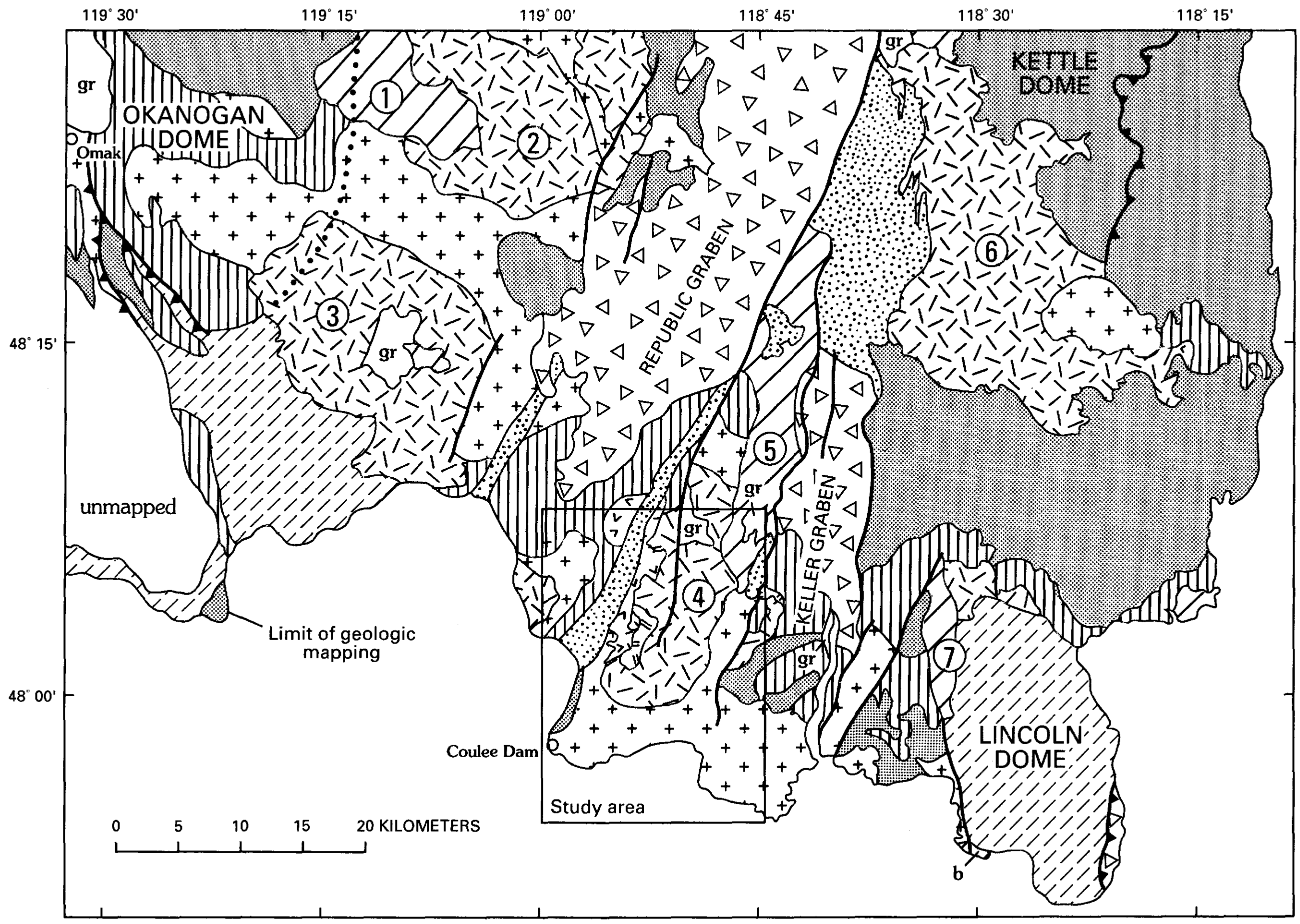
Figure 1. Northeastern Washington showing major structural features, Colville Indian Reservation (shaded), and study area. Modified from Rhodes and Cheney (1981) and Atwater and others (1984).

The older leucocratic suite, well exposed at the southern end of the Keller and Republic grabens, is elongate in outcrop parallel to the graben structures and has been involved in graben faulting. The suite dips northward under the cover of Eocene volcanic rocks exposed in the grabens (fig. 2) and to the south is uncomformably overlain by the Miocene Columbia River Basalt Group. It is cut by Eocene plutons and dikes (pl. 1) that are probably coeval with the volcanic rocks exposed in the grabens (Muessig, 1967; Moye, 1984). The dikes were feeders to the O'Brien Creek Formation and Sanpoil Volcanics and are localized along bounding faults in the grabens (Muessig, 1967). The volume of dike to country rocks requires at least 4 km of extension during injection of the dikes (Moye and others, 1982). The younger (Eocene) suite of intrusions also includes biotite-hornblende granitoids of the Devils Elbow, Swimptkin Creek, and Brody Creek plutons (Atwater and others, 1984) (fig. 2) and small silicic plutons that cut them. The Devils Elbow and Brody Creek plutons have a northerly trend and occupy the horsts on opposite sides of the Keller graben (fig. 2).

Columbia River basalts and granitic rocks of the Colville batholith are locally covered by thick accumulations of unconsolidated Quaternary deposits, including glacial outwash and till of late Wisconsin age and alluvial, lacustrine, eolian, and landslide debris (Atwater and others, 1984).

COULEE DAM INTRUSIVE SUITE

The here-named Coulee Dam Intrusive Suite consists of five mapped granitic units—Manila Creek Granodiorite, Swawilla Granodiorite, Keller Butte Granite, granite porphyry, and garnet-bearing granite—that belong to an older group of leucocratic plutons making up the Colville batholith. Granitic rocks belonging to the suite were first recognized by Utterback (1981), who noted the spatial and temporal relation between granitic phases associated with mineralization at the Mount Tolman molybdenum deposit just east of the map area. The suite is Eocene in age, based on K/Ar and U/Pb ages that average about 54 Ma (R.J. Fleck and D.L. Parkinson,



EXPLANATION

- Eocene volcanics—Includes O'Brien Creek Formation, Sanpoil Volcanics, and Klondike Mountain Formation
- Eocene hypabyssal dike swarm—Dacite and rhyodacite
- gr — Eocene granites—Intrude hornblende-biotite granitoids
- b — Hornblende-biotite granitoids—Includes Devils Elbow pluton
- Porphyritic granite—Includes Coyote Creek, Moses Mountain, Daisy Trail plutons, and Keller Butte Granite
- Garnet-bearing granite
- Granite porphyry
- Biotite granodiorite—Includes Swawilla Granodiorite and other correlative granitoids
- Porphyritic granodiorite and other megacrystic rocks
- Intrusive-metamorphic complexes, undivided
- Country rocks—Includes Covada Group low- and high-grade metasedimentary rocks

Plutons

1. Swimptkin Creek
2. Moses Mountain
3. Coyote Creek
4. Keller Butte Granite of Coulee Dam Intrusive Suite
5. Devils Elbow
6. Daisy Trail
7. Brody Creek

- Contact
- High-angle fault
- Thrust fault—Sawteeth on upper plate
- Approximate boundary of Okanogan dome

Figure 2. Generalized geologic map of Colville Indian Reservation (modified from Atwater and others, 1984; Utterback, written commun., 1984).

written commun., 1986). It trends north-northeast parallel to the trend of the Republic and Keller grabens (fig. 2) and is cut by the Sherman and Manila Pass faults (pl. 1). The type locality of the suite is here designated as a triangular area whose vertices are the town of Coulee Dam on the southwest, Buffalo Lake at the apex, and Manila Creek at the southeastern boundary of plate 1. Hypabyssal dike swarms, which have preferentially intruded along the graben faults, obscure relations between units of the suite, particularly along its western margin.

The five units that compose the Coulee Dam Intrusive Suite are distinguished by compositional (fig. 3) and textural differences and form a nearly concentric outcrop pattern (fig. 4); from the border inward they are the coarse-grained, megacryst-bearing Manila Creek Granodiorite; the medium-grained, locally porphyritic Swawilla Granodiorite; and the coarse-grained Keller Butte Granite and unnamed granite porphyry that is characterized by subhedral phenocrysts of quartz. The youngest unit is a garnet-bearing granite that is texturally aplitic or pegmatitic and locally contains abundant garnet and primary muscovite. Contact relations between the units, and relations with the slightly younger suite of associated intrusive rocks that cut the Coulee Dam Intrusive Suite, are shown schematically in figure 5.

Manila Creek Granodiorite

The porphyritic granodiorite that discontinuously forms the outermost unit of the Coulee Dam Intrusive Suite within the map area (pl. 1) and that crops out extensively elsewhere on the Reservation (Atwater and others, 1984), where it intrudes low- to medium-grade metasedimentary rocks of the Ordovician Covada Group, is here named the Manila Creek Granodiorite for the creek along which it is well exposed. K/Ar biotite ages of the granodiorite range from 61 to 48 Ma, and a U/Pb sphene age is 54±2 Ma (R.J. Fleck and D.L. Parkinson, written commun., 1986). Because the blocking temperature for sphene is about the same as that for hornblende, the sphene age probably reflects most closely the actual cooling age of the pluton. In the Nespelem quadrangle, the Manila Creek is gradational into, hence nearly contemporaneous with, the Swawilla Granodiorite, which has a K/Ar age of 53.5±0.03 Ma (R.J. Fleck, written commun., 1986). The type locality for the Manila Creek Granodiorite is here designated as the exposures along Manila Creek about 3 km east of the area shown on plate 1 in sec. 13, T. 29 N., R. 32 E. The locality is accessible from the old Manila Creek Road.

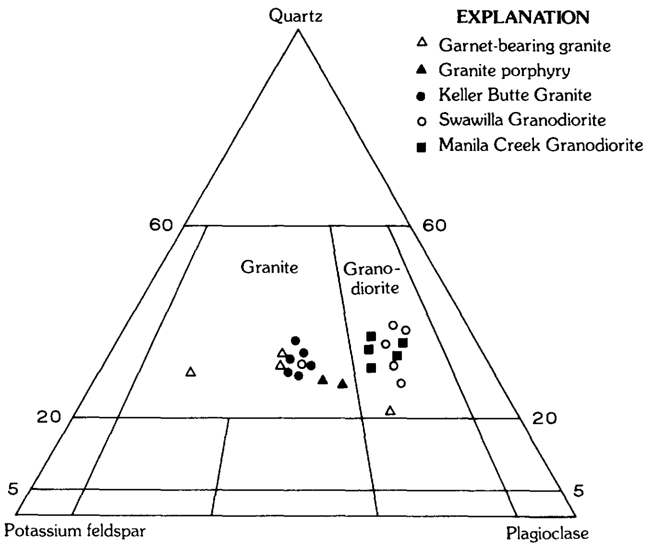


Figure 3. Modal composition of Coulee Dam Intrusive Suite (1,000 points counted on stained slabs 20 cm × 20 cm; classification fields from Streckeisen, 1976).

Along the southeastern margin of the map area near the type locality, the unit contains abundant aplite-pegmatite dikes that are offset as much as 1 m by steeply dipping faults. The dikes have shallow dips and are texturally similar to dikes associated with the younger units of the Coulee Dam Intrusive Suite.

Where the Manila Creek is exposed at higher elevations, such as at Mica Mountain, metasedimentary rocks of the Covada Group increase in abundance and appear to be roof pendants. The contact with the roof pendants is sharp and locally appears to be chilled. Andalusite porphyroblasts which overprint regional metamorphic assemblages are present locally, but for the most part contact metamorphic effects are minimal. Where weak foliation and (or) lineation is developed in the porphyritic granodiorite, it is usually oblique to the overall trend of the roof pendants.

The Manila Creek is distinguished from other units in the suite by its higher color index (8–19) and absence of groundmass potassium feldspar. At the type locality along Manila Creek, potassium feldspar occurs as pink subequant megacrysts that are typically subhedral and average 1.5 cm in length (fig. 6). The megacrysts are most abundant near pods and dikes of pegmatite (fig. 7) that are also pink.

The megacrysts are microperthitic microcline ($Or_{83}Ab_{17}$) that contain abundant inclusions of quartz, biotite, and euhedral plagioclase. Microcline boundaries are embayed and incorporate adjacent groundmass. Myrmekite is abundant near the grain boundaries, particularly in the presence of plagioclase feldspar. Plagioclase feldspar is subhedral and is concentrically zoned (An_{36}–An_{24}). Olive-green biotite is commonly altered to chlorite, magnetite, and muscovite. The biotite typically contains inclusions of subrounded zircon with halos of radiation damage. Sphene and apatite are the most abundant accessory minerals and occur in clusters associated with biotite.

Swawilla Granodiorite

The name Swawilla Granodiorite is here given to the medium-grained leucocratic granitic rocks that form a mostly continuous arcuate outcrop along the southern half of the map area (pl. 1) and crop out extensively east of the map area (fig. 2). Exposures are especially good along the margins of Swawilla Basin, for which the unit is named, in the southeastern part of the map area; exposures there, along the road east of Niles Canyon in sec. 3, T. 28 N., R. 32 E., are designated as the type locality. The best exposures, though less accessible, are along the north shore of Franklin D. Roosevelt Lake from the east abutment of the Grand Coulee Dam eastward toward Swawilla Basin. The area is accessible by the road that crosses the dam and by boat. The Swawilla Grandiorite has a biotite K/Ar age of 53.5±0.03 Ma (R.J. Fleck, written commun., 1986).

Contact relations between the Swawilla Granodiorite and the Manila Creek Granodiorite are obscured by dike swarms and faults; however, the contact with the Manila Creek Granodiorite along the western margin appears to be gradational over a distance of 500 m. The Swawilla is cut by the coarse-grained Keller Butte Granite; the contact with the granite dips steeply outward from the center of the suite. The contact zone contains abun-

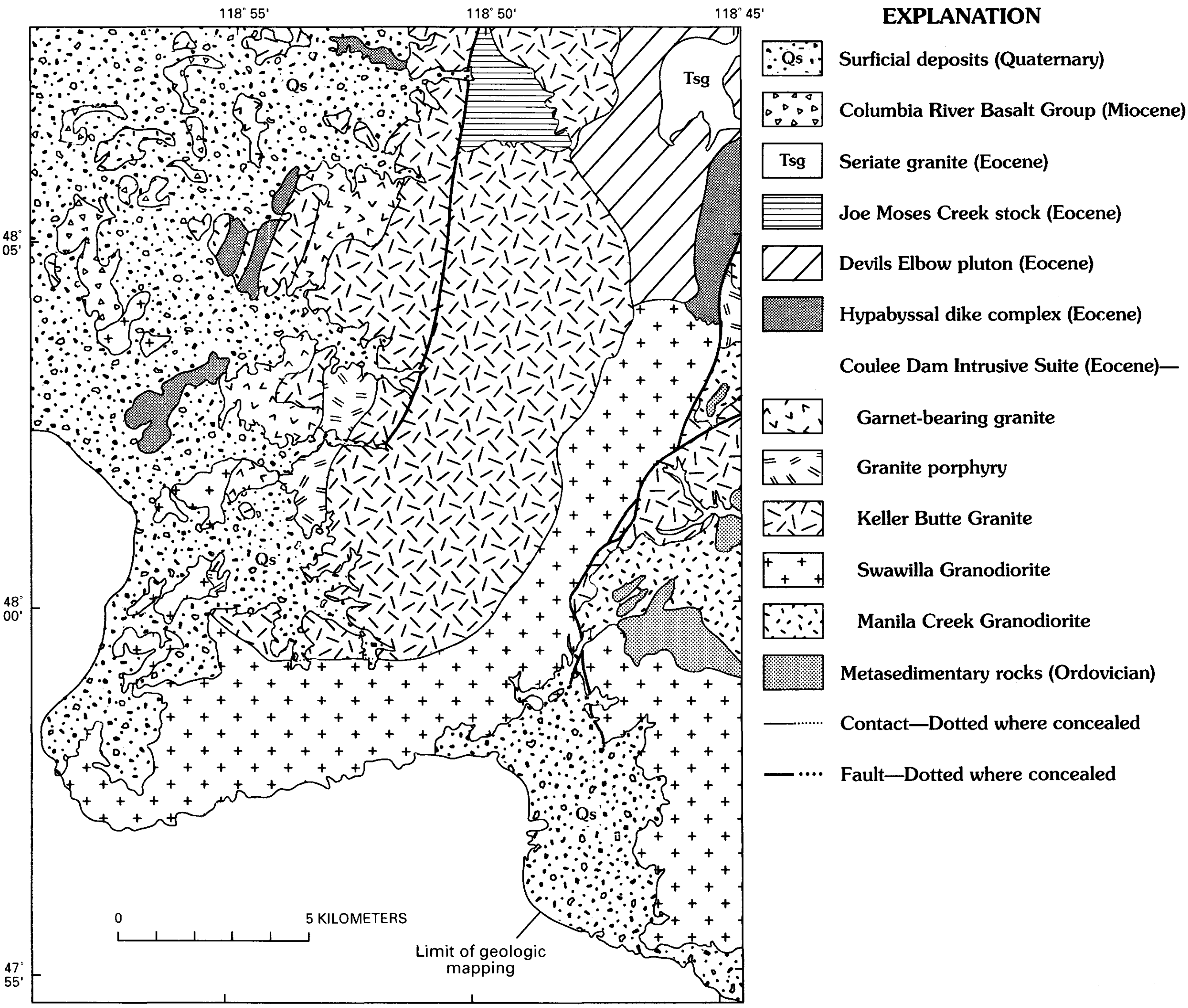
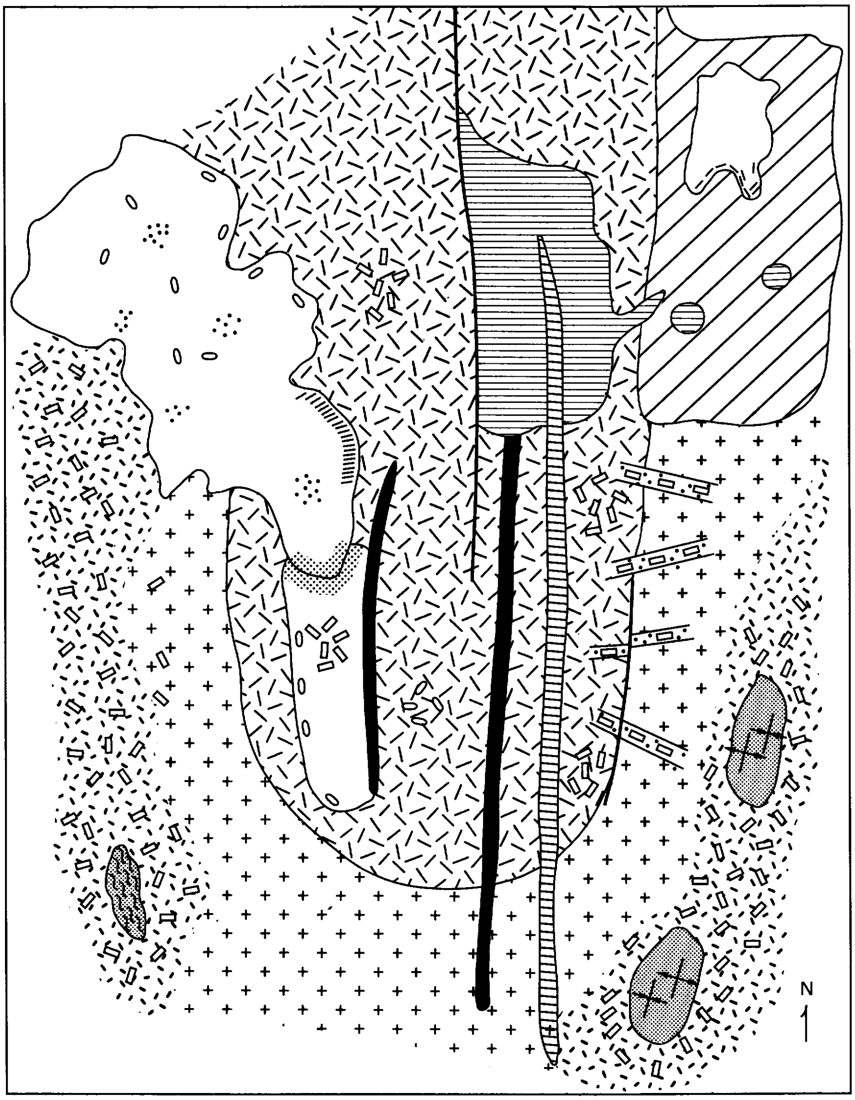


Figure 4. Generalized geologic map of Coulee Dam Intrusive Suite, associated intrusive rocks, and metamorphic rocks in study area.



EXPLANATION

Seriate granite (Eocene)—Intrudes Devils Elbow pluton; contact contaminated with xenocrystic hornblende (short dashes)

Joe Moses Creek stock (Eocene)—Small pods cut Devils Elbow pluton; nature of contact unknown; contact with the Keller Butte Granite abrupt

Devils Elbow pluton (Eocene)—Presumably cuts the Keller Butte Granite; exposed contacts are fault bounded or gradational into hypabyssal complex (plate 1)

Hypabyssal dikes (Eocene)—Rhyodacite (black) cuts all phases of the Keller Butte Granite; dacite (striped) cuts Joe Moses Creek stock

Coulee Dam Intrusive Suite (Eocene)—Consists of:

Aplite-pegmatite dikes—Contain potassium feldspar megacrysts as long as 11 cm in cores and aplite selvages

Garnet-bearing granite—Characterized by garnet-rich zones (stippled) and hypothermal quartz veins (dashes) and pods (ellipses); contact with granite porphyry is altered (shaded)

Granite porphyry—East contact bounded by rhyodacite dikes; may contain elongate quartz crystals (ellipses) near contacts; center contains large potassium feldspar megacrysts (rectangles). Contact with garnet-bearing granite is altered (shaded)

Keller Butte Granite—Locally contains potassium feldspar megacryst-rich zones (rectangles) and quartz crystals (ellipses) similar to granite porphyry; contact with the Swawilla Granodiorite is abrupt but not chilled; east contact is marked by zoned aplite and pegmatite dikes that contain potassium feldspar megacrysts

Swawilla Granodiorite—Contact with the Keller Butte Granite is locally faulted; contact with the Manila Creek Granodiorite is gradational where exposed

Manila Creek Granodiorite—Characterized by pink, equant potassium feldspar megacrysts (rectangles) and by phyllite and schist roof pendants or gneissic xenoliths; contact with country rocks is abrupt, may be discordant and chilled

Country rocks (Ordovician)—Roof pendants of the Covada Group metasedimentary rocks that contain postkinematic andalusite; outcrop near west border of suite contains gneiss xenoliths (wavy lines)

Contact

Fault

Anticline

Syncline

Figure 5. Schematic diagram of contact relations between units in Coulee Dam Intrusive Suite, associated intrusive rocks, and metamorphic rocks.

dant pegmatite dikes that locally contain small euhedral garnet or feldspar megacrysts as much as 5 cm in length. The megacrysts are identical to those in the interior part of the suite. The dikes are zoned and contain cores of quartz or coarse feldspar megacrysts; graphic intergrowths are common along the dike margins. The eastern contact of the Swawilla Granodiorite in the map area is a fault parallel to the north-northeast trend of the graben structures (pl. 1). Biotite-rich inclusions and schlieren (fig. 8) and high-grade metamorphic inclusions are common along the inner contact with the Keller Butte Granite. The metamorphic inclusions consist of veined gneisses and biotite-muscovite-sillimanite gneisses.

The Swawilla Granodiorite is typically medium grained and equigranular (fig. 9). Locally, it is porphyritic and contains megacrysts of microcline that range from 2 to 4 cm in length within a single outcrop. The color index is fairly low (3–5), and this distinguishes porphyritic varieties from the Manila Creek Granodiorite.

In thin section, the Swawilla Granodiorite appears similar to the Manila Creek Granodiorite, but the Swawilla contains less biotite, sparse muscovite, and groundmass potassium feldspar. In the porphyritic variety, microcline ($Or_{86}Ab_{14}$) with patchy zones of gridiron twinning is present in the groundmass and in the megacrysts. Plagioclase is weakly zoned (An_{22}–An_{17}) and slightly saussuritized. Accessory minerals include allanite and epidote in addition to sphene, apatite, and zircon. The epidote occurs as discrete euhedral blades or as reaction rims on allanite.

Keller Butte Granite

The coarse-grained, locally porphyritic granite that forms an elongated body in the center of the Coulee Dam Intrusive Suite is here named the Keller Butte Granite for Keller Butte, the highest point in the map area, where the unit is well exposed. The type locality is in the NW¼ sec. 33, T. 30 N., R. 32 E. and is accessible by the road to the Keller Butte fire tower. A sample of the Keller Butte Granite collected along the Peter Dan Creek Road has a K/Ar biotite age of 52.9±0.04 Ma (R.J. Fleck, written commun., 1986). The Keller Butte Granite cuts the Swawilla Granodiorite; their southern contact is sharp and dips steeply southward. Neither unit is chilled or altered, but quartz is slightly elongate in the granite. Pegmatite dikes are abundant along the contact, partic-

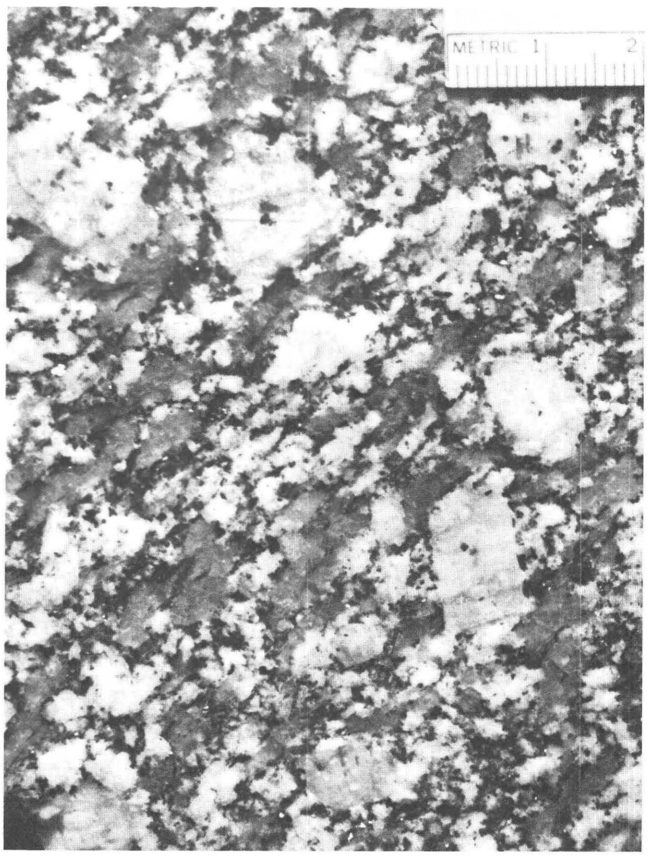


Figure 6. Subhedral and euhedral microcline megacrysts (light colored) and elongate quartz (medium gray) grains in Manila Creek Granodiorite. Scale is in centimeters.

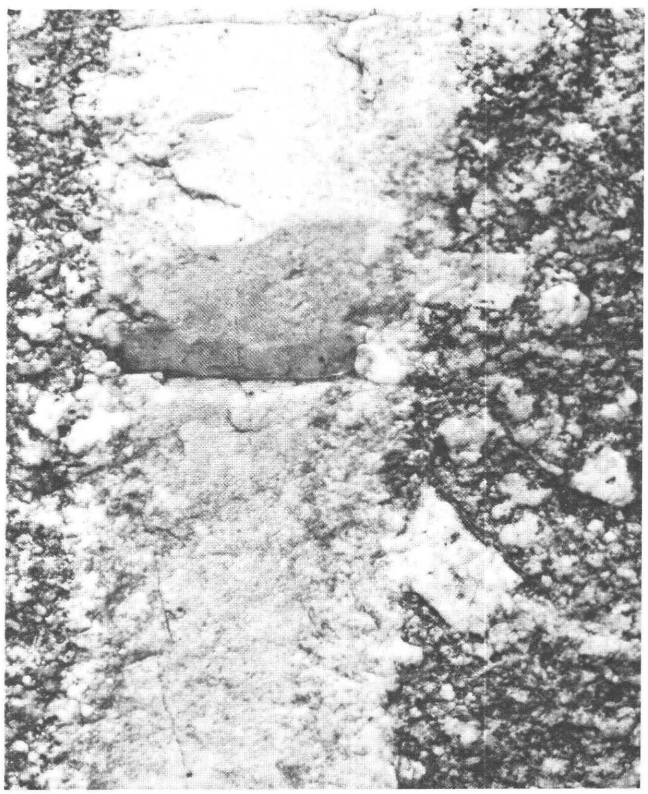


Figure 7. Relation of composite aplite-pegmatite dike and microcline megacrysts (light colored) in Manila Creek Granodiorite from north shore of Buffalo Lake. Dike is approximately 6.5 cm wide.

ularly along the eastern margin. Where the contact trends northeasterly, the granite is faulted against the granodiorite.

The granite is coarse grained, has a low color index (2–4) (fig. 10), and contains subequal amounts of microcline, plagioclase feldspar. At the Keller Butte type locality, the granite is porphyritic with megacrysts of euhedral microcline as much as 11 cm in length (fig. 11). The megacrysts have no preferred orientation and are confined to podlike zones.

Magnetite is common in the central part of the unit near Buffalo Lake where it is locally concentrated in subhorizontal layers as much as 1 m thick. The layers are overprinted by potassium feldspar megacrysts as much as 11 cm in length (fig. 12). The megacrysts are randomly oriented and differ from those in the Swawilla and Manila Creek units in being larger (as much as 11 cm in length) and euhedral (fig. 11), and they typically are zoned. Zoning in the megacrysts is defined by alignment of biotite, quartz, and euhedral plagioclase grains parallel to the outline of the megacryst. The megacrysts are microcline, whereas groundmass feldspar consists of both microcline and euhedral to subhedral plagioclase. Inward through the Coulee Dam Intrusive Suite, plagioclase becomes progressively more zoned and, based on microprobe data, shows an overall decrease in anorthite component from An_{36} to An_{16}. Zoning within individual plagioclase grains varies only a few percent. Groundmass microcline contains patchy mesoperthite, and plagioclase near the microcline has myrmekite embayments. Biotite is olive green and is slightly altered to chlorite, magnetite, and muscovite. Accessory minerals are much less abundant in the granite than in the Manila Creek and Swawilla Granodiorites and consist of zircon, needles and stubby prisms of apatite, euhedral prisms of epidote, and anhedral magnetite. The grains of magnetite in the magnetite bands near Buffalo Lake are either euhedral prisms or bleblike.

At the southwestern margin of the Keller Butte Granite (SE¼ SE¼ sec. 23, T. 29 N., R. 31 E.), a 100- by 200-m elliptical intrusive breccia pipe contains angular blocks of the granite (fig. 13). The blocks are subrounded and consist primarily of granite. The matrix of the breccia is fine grained and inequigranular and contains equal

Figure 8. Dark, biotite-rich inclusions in Swawilla Granodiorite that show varying degrees of assimilation. Lens cap is 5.5 cm across.

amounts of orthoclase, plagioclase, and quartz. The breccia probably formed by explosive near-surface venting of fluids similar to those found in other high-level intrusions associated with porphyry deposits.

Granite Porphyry

Granite porphyry forms an elongate body 5 by 1.5 km in dimension along the western margin of the Keller Butte Granite near McGinnis Lake (pl. 1). The unit is distinguished from the granite by the presence of quartz eyes (fig. 14) and a micr 0granular groundmass of euhedral plagioclase and microcline feldspar. Near the contact with the Keller Butte Granite, quartz eyes are locally elongate parallel to the contact. Contacts are fairly sharp and are not chilled. The northern contact may be a fault due to the abrupt termination of the porphyry under Buffalo Lake (pl. 1). North-trending contacts were preferentially intruded by dikes of rhyodacite. Although sections of the north-trending contact along the east side of the body are cut by dikes, the contact is fairly sharp and can be recognized by the absence of quartz eyes and microgranular feldspar groundmass in the adjacent Keller Butte Granite.

Granite porphyry also occurs as pods as much as 30 m in diameter enclosed within the Keller Butte Granite. Locally, quartz eyes or phenocrysts occur in the granite, which suggests that the two units are probably textural variants. The texture of the groundmass in the porphyry indicates crystallization under disequilibrium conditions probably due to near surface venting which resulted in rapid pressure fluctuations and the formation of quench textures (fig. 15).

In thin section, the quartz eyes are either composite grains separated by sutured grain boundaries (fig. 16) or discrete single crystals. Quartz in the groundmass is optically continuous around inclusions of plagioclase feldspar. Plagioclase typically is euhedral and shows pronounced oscillatory zoning (fig. 16) with preferentially saussuritized cores. The composition in a single zoned grain varies from An_{19} to An_{12}. Microcline is meso-

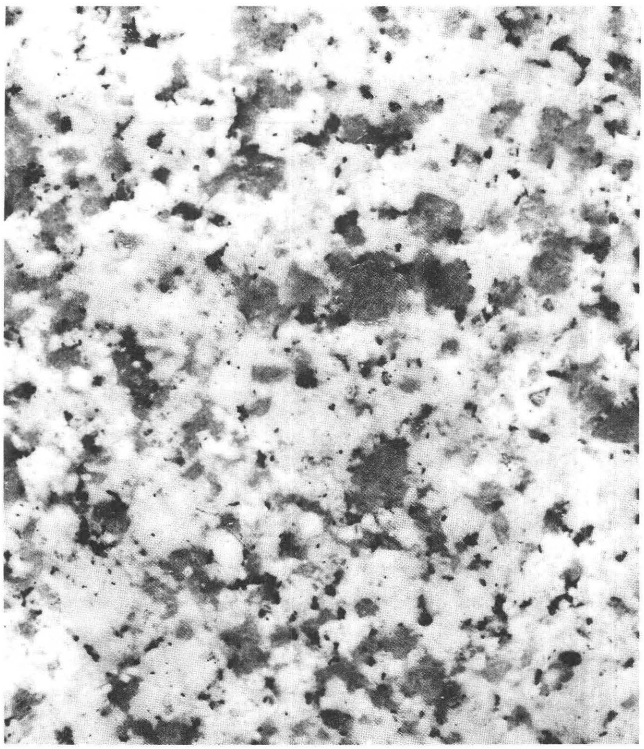


Figure 9. Medium-grained Swawilla Granodiorite from east abutment of Grand Coulee Dam that contains biotite (black), quartz (gray), and feldspars (white).

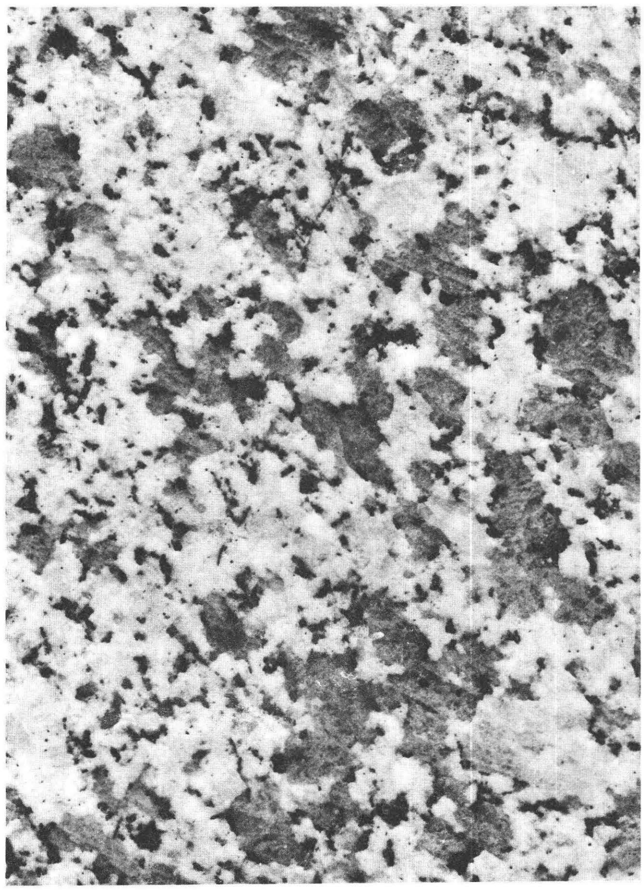


Figure 10. Equigranular phase of Keller Butte Granite from Peter Dan Creek.

perthitic and occurs as zoned megacrysts 4 to 6 cm long (fig. 17), similar to those in the Keller Butte Granite. Near McGinnis Lake the megacrysts occur in segregations 5 to 15 m in diameter that contain less than 5 percent interstitial quartz and feldspar.

The megacryst segregations and quench textures serve to differentiate the granite porphyry from other phases of the Coulee Dam Intrusive Suite. Compositionally, the granite porphyry is very similar to the Keller Butte Granite, but texturally the two units are quite distinct.

The granite porphyry is relatively devoid of accessory minerals except for a few stubby apatite prisms, magnetite anhedra, and epidote grains.

Garnet-Bearing Granite

Leucocratic granite containing garnet (fig. 18) intrudes all of the other units in the Coulee Dam Intrusive Suite. The contacts with the granite porphyry and Keller Butte Granite are sharp, not chilled, and locally contain abundant pods of milky quartz. At the contact with the granite porphyry, the porphyry contains a 20-cm-wide baked zone in which biotite is oxidized and feldspars are intensely altered to clay. As in the granite porphyry, quartz grains are elongate parallel to the contacts.

The granite is similar in composition to the garnet-bearing pegmatite dikes that cut the Swawilla Granodiorite and Keller Butte Granite. Texturally, the granite may vary within a single outcrop from aplite to alaskite to pegmatite. Biotite is present locally, but usually at the exclusion of garnet.

The garnet-bearing granite differs from the other units in the Coulee Dam Intrusive Suite in its xenomorphic texture, presence of spessartine and primary muscovite, and abundance of accessory minerals. Large grains of allanite are the most abundant accessory, followed by sphene, zircon, and apatite. Quartz is anhedral and turbid due to an abundance of fluid inclusions. Plagioclase is weakly zoned (An_{15}–An_{13}) and contains as much as 6 percent orthoclase in solid solution. Microcline ($Or_{89}Ab_{11}$) is anhedral and contains stringlet perthites; it typically contains inclusions of anhedral quartz and euhedral plagioclase.

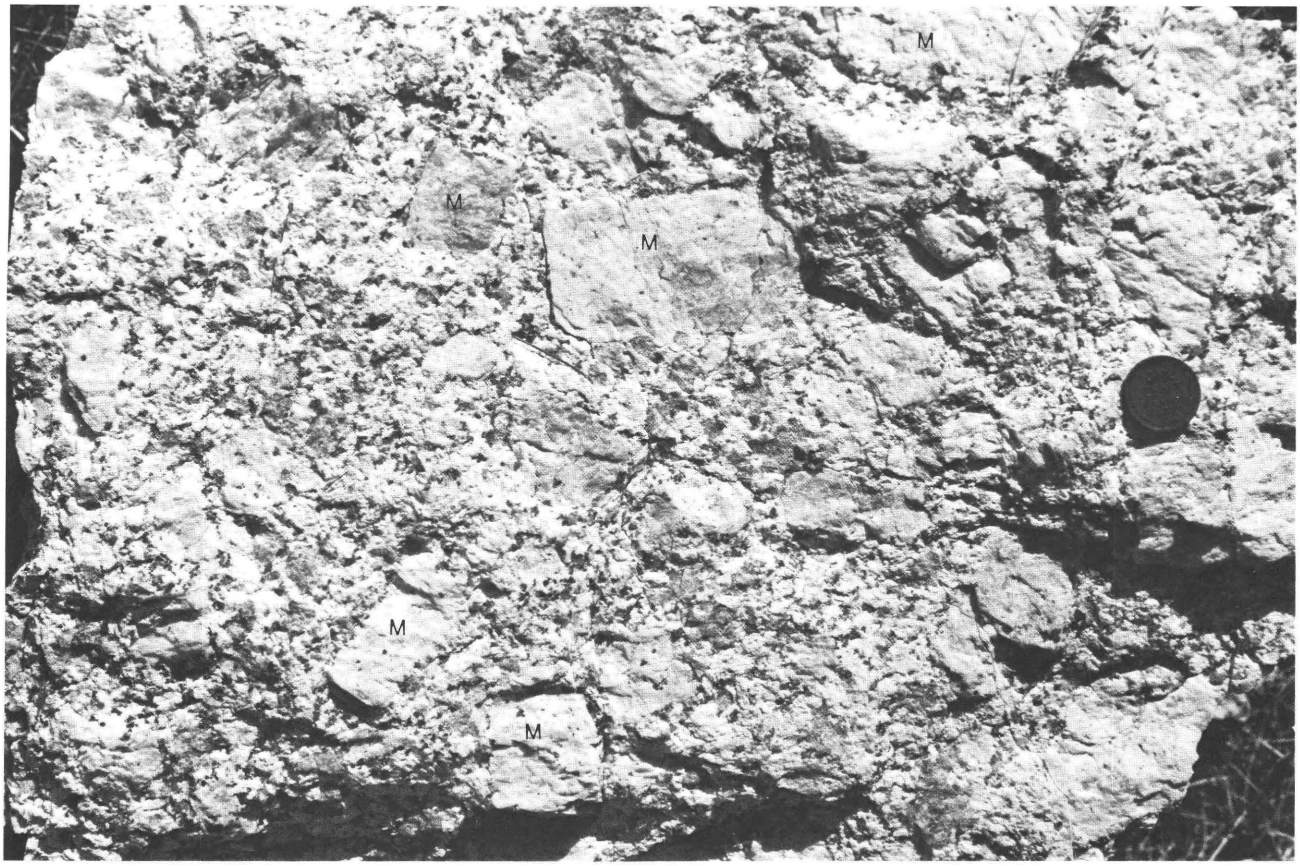


Figure 11. Microcline megacrysts (M) in Keller Butte Granite from podlike zone at Keller Butte. Coin is 1.9 cm across.

YOUNGER INTRUSIVE ROCKS

A suite of slightly younger intrusive rocks cuts the Coulee Dam Intrusive Suite in the map area and elsewhere on the Colville Reservation (Atwater and others, 1984). Within the map area, the intrusive suite consists of a hypabyssal dike complex, the southern extension of the quartz monzodiorite Devils Elbow pluton (Moye, 1984), and two pluglike intrusions—the Joe Moses Creek stock and the seriate granite.

The hypabyssal dike complex comprises an older (53 Ma) hornblende-free suite and a younger (49 Ma) suite of hornblende-bearing dikes. Emplacement of the dikes was structurally controlled by the Sherman and Manila Pass faults. Within the map area, the hornblende-free rhyodacite dikes form an intrusive complex within the southernmost extension of the Republic graben and are absent from the horst block between the Republic and Keller grabens. The younger hornblende dacite dikes are most abundant in the horst block near the Devils Elbow pluton (pl. 1). The hornblende-bearing dikes cut the Joe Moses Creek stock and small plugs of the latter intrude the quartz monzodiorite of the Devils Elbow pluton near Jack Creek. The seriate granite also cuts the Devils Elbow pluton and is the youngest granitic unit in the map area.

Hypabyssal Dike Rocks

The dike rocks are divided into two types based on mineralogy and chemistry (fig. 19): a hornblende-free variety that plots mainly in the rhyodacite field, and a younger hornblende-bearing suite that falls predominantly in the dacite field.

Hornblende-Free Rhyodacite

Rhyodacite dikes are the oldest dikes in the hypabyssal complex; they are most abundant at the southern end of the Republic graben, where they intrude all phases of the Coulee Dam Intrusive Suite. The overall trend of the dikes is parallel to the Republic graben, but in detail the dikes tend to bifurcate and terminate in en echelon segments (fig. 20). The dikes typically have chilled bor-

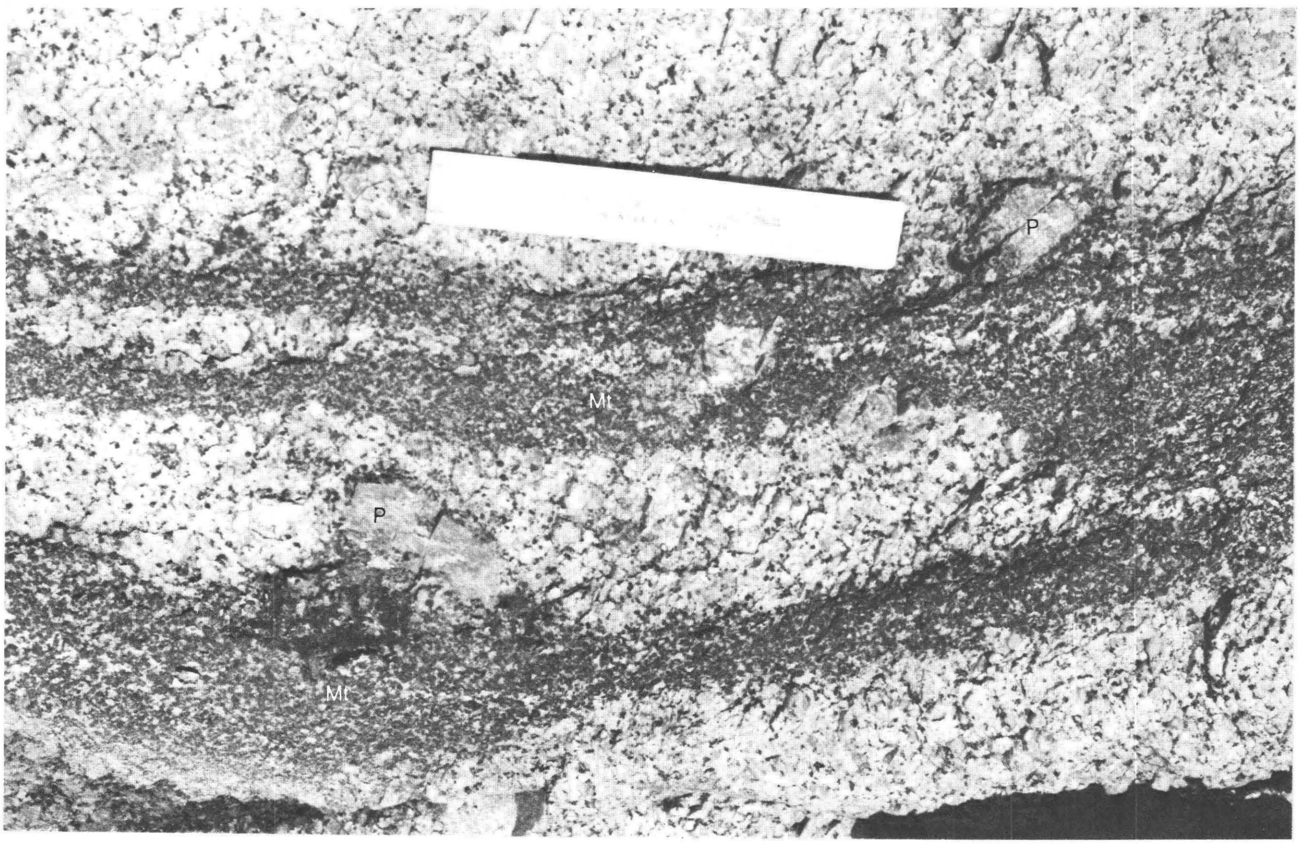


Figure 12. Magnetite-rich bands (Mt) and potassium feldspar megacrysts (P) in Keller Butte Granite from northeast shore of Buffalo Lake. Ruler is 15 cm long.

ders at their contacts with the granitic rocks and commonly display a flow foliation defined by alignment of biotite parallel to the dike margin (fig. 21). At outcrop scale, the contact is convoluted and contains xenoliths of the adjacent country rock (fig. 20).

Beyond the study area in the northern part of the Republic graben, Eocene volcanic rocks are abundant, and the rhyodacite dikes grade upward into light-colored lava flows and tuffs of the O'Brien Creek Formation (Moye, 1984). Based on chemical and petrographic similarities, Pearson and Obradovich (1977) postulated that the dikes may have been feeders to tuffs within the 53-Ma O'Brien Creek Formation.

The rhyodacite dikes typically contain 30 to 40 percent phenocrysts of andesine, quartz, and biotite set in a light-gray aphanitic groundmass. The groundmass contains cryptocrystalline to very fine grained quartz, potassium feldspar, and accessory amounts of biotite and magnetite. There is a direct correlation between width of the dikes and grain size of the groundmass; the wider dikes are coarser grained and have holocrystalline centers.

Plagioclase (An_{35}–An_{40}) is the most abundant phenocryst and is conspicuous as subequant altered grains that make up 30 to 40 percent of the rock. It occurs as single euhedral grains that may show normal or oscillatory zoning or as glomeroporphyritic clots. Quartz phenocrysts make up 1 to 2 percent of the rock and typically are bipyramidal. Biotite phenocrysts are less abundant than plagioclase and quartz, but where present occur either as anhedral chlorite pseudomorphs or as reddish-brown euhedral books.

Hornblende Dacite

In the map area, hornblende dacite dikes are confined mainly to the horst bounded by the Sherman and Manila Pass faults (pl. 1) and are most abundant along the margins of the Devils Elbow pluton. Along the eastern side of the pluton, swarms of dacite and younger rhyolite dikes form an intrusive complex that is gradational over 20 m into the quartz monzodiorite of the Devils Elbow pluton.

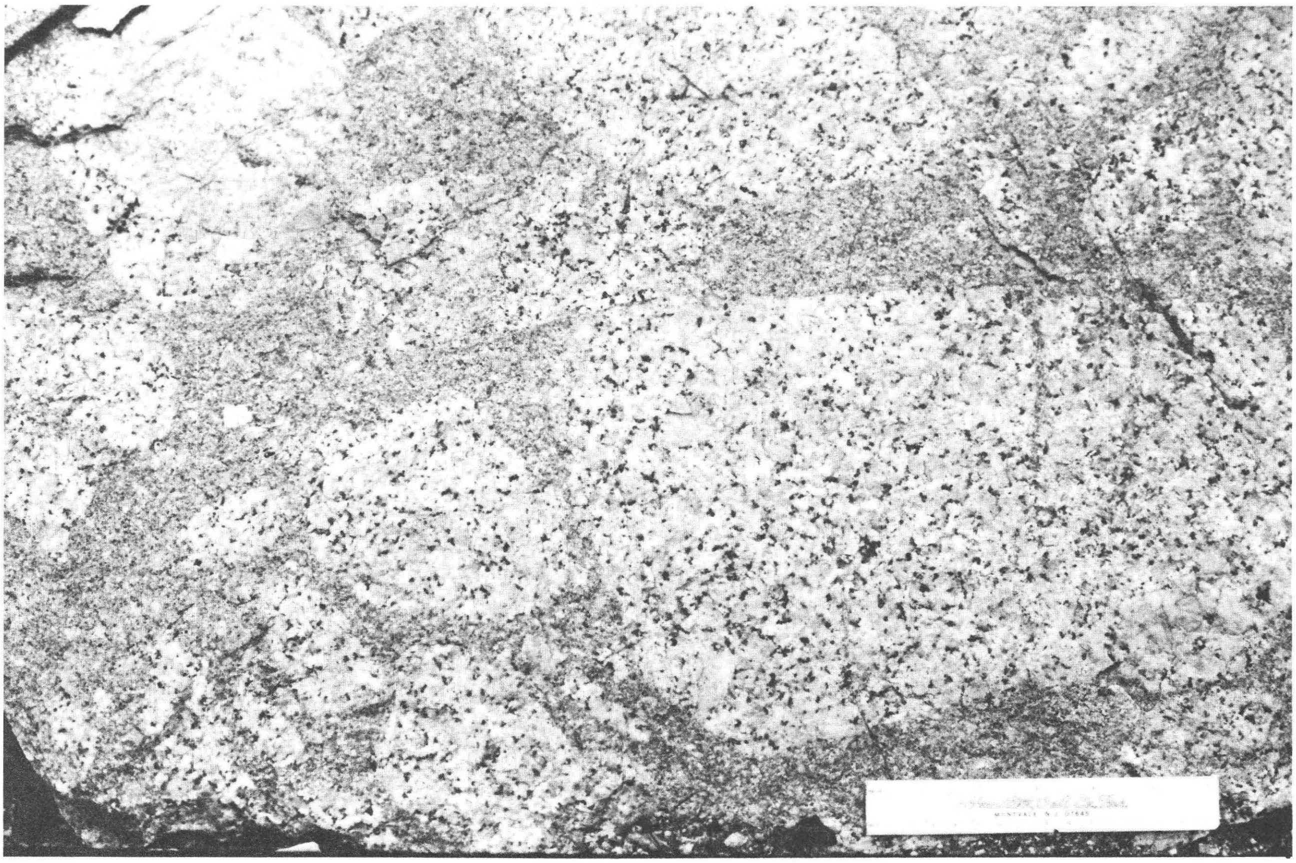


Figure 13. Blocks of Keller Butte Granite from intrusive breccia near Peter Dan Creek. Note variation in size and angularity of breccia blocks. Ruler is 15 cm long.

Beyond the study area, the volume of hornblende-bearing hypabyssal dikes increases northward along the Sherman fault. The dikes to the north have been named the Scatter Creek Rhyodacite (Muessig, 1967) and are probably correlative with those in the map area. At the Scatter Creek type locality, the hornblende rhyodacite dikes and pods intrude the 51 to 49 Ma Sanpoil Volcanics and are apparently feeders to some of the lava flows. The dikes yield a concordant K-Ar age of 51 to 50 Ma on hornblende and biotite (Pearson and Obradovich, 1977).

The dikes are medium to dark gray and contain 30 to 50 percent phenocrysts of hornblende, biotite, and plagioclase. Hornblende forms most of the phenocrysts and makes up 15 to 30 percent of the rock. It typically is twinned and occurs in rosettes (fig. 22) up to 2 cm across. Plagioclase forms subequant phenocrysts and laths in the groundmass; it ranges in composition from An_{44} to An_{66} and may show both oscillatory and concentric zoning, although unzoned crystals are more common. In general, the plagioclase laths in the fine-grained groundmass have a lower anorthite content (An_{44}–An_{50}) than the earlier-formed plagioclase phenocrysts (An_{50}–An_{66}). Biotite is reddish brown and occurs as subhedral to euhedral phenocrysts that compose less than 10 percent of the rock. Minor amounts (less than 5 percent) of augite occur as subhedral grains in mafic clots or as cores in hornblende phenocrysts. Quartz phenocrysts in the hornblende-bearing dike rocks are rare.

Devils Elbow Pluton

Quartz monzodiorite near Jack and Brush Creeks forms the southern extension of a 30-km-long body that was named the Devils Elbow batholith by Moye (1984). The Devils Elbow batholith is a north-northeast-trending pluton exposed in the horst between the Sherman and Manila Pass faults (pl. 1). The pluton has a K-Ar age of 49.2±1.5 Ma (Atwater and others, 1984). At Devils Elbow, a picturesque bend in the Sanpoil River north of

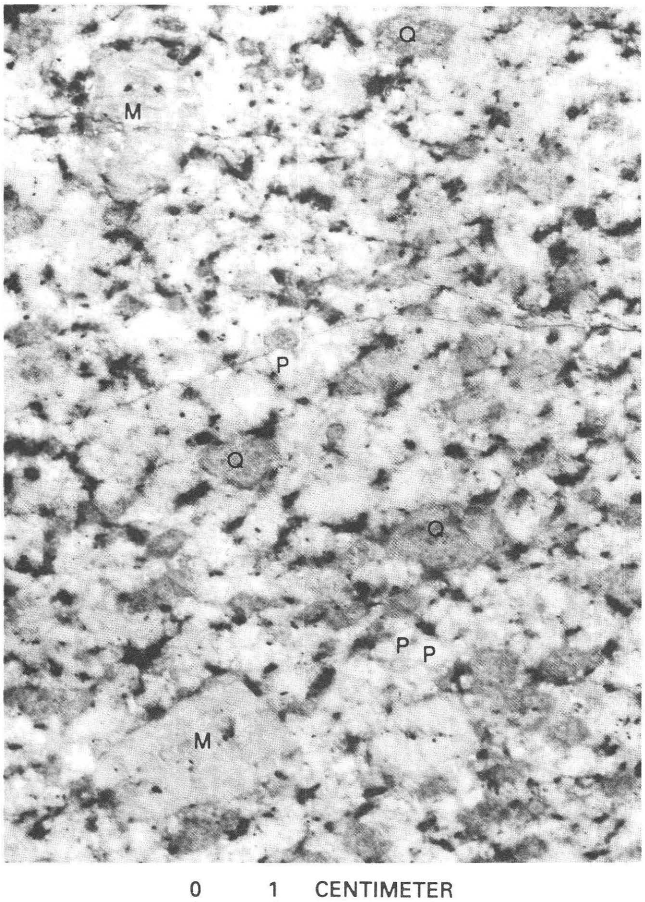


Figure 14. Granite porphyry containing microcline megacrysts (M) and oblate quartz eyes (Q). Small, equant crystals in groundmass are plagioclase feldspar (P).

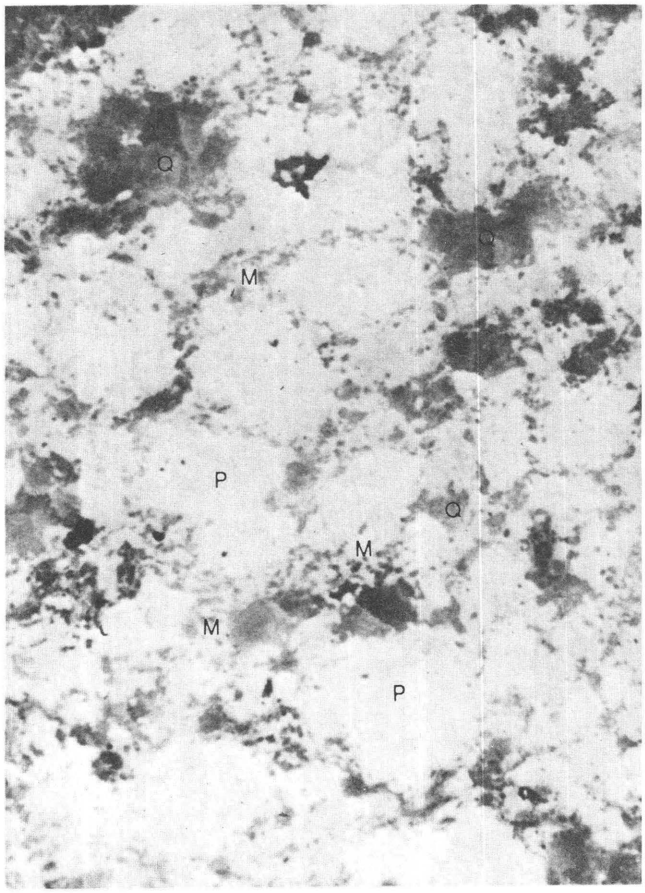


Figure 15. Quench texture in stained slab of granite porphyry. Subequant, coarser grains are plagioclase feldspar (P) enclosed by fine-grained, anhedral quartz (Q) and microcline (M). Field of view is 2.5 cm wide.

the study area, the pluton grades vertically upward from medium-grained subhedral-granular monzodiorite to subporphyritic rhyodacite; according to Moye (1984), these relations, in addition to chemical similarities, suggest that the Devils Elbow pluton was the source of Scatter Creek Rhyodacite dikes and certain lava flows within the Sanpoil Volcanics. Along the southern margin of the pluton, hornblende dacite dikes are spatially and probably temporally related to the body.

The contact with the Keller Butte Granite and Swawilla Granodiorite is poorly exposed along the southern part of the Devils Elbow pluton. The relatively straight southeast-trending western contact may be a fault. The northwestern contact of the pluton is bounded by Sherman fault north of the map area (Atwater and others, 1984). According to Moye (1984), the Devils Elbow pluton shows no evidence of faulting, such as slickensides or alteration, which suggests that the body may have used the fault as a conduit along which the magma intruded. In addition to the possibility of intrusion along related faults, the elongate or rectangular outline of the Devils Elbow body is characteristic of high-level plutons that intrude during cauldron subsidence or upheaval of the roof (Myers, 1975).

Crude compositional variation throughout the pluton is suggested by variation in the ratio of feldspars to quartz (fig. 23) and by variation in the percentage of mafic constituents. To the north at Devils Elbow, the pluton is predominantly quartz monzonite to granodiorite (fig. 24), and to the south the pluton grades into hornblende-rich monzodiorite that locally contains a crude layering (fig. 25) and consists largely of euhedral hornblende and interstitial plagioclase (fig. 26).

Most of the rocks in the southern part of the pluton plot in the quartz monzodiorite field, although there is a range in composition from diorite to granodiorite (fig. 23). The variation in composition is not mappable in the southern part of the pluton, where a crude gradation

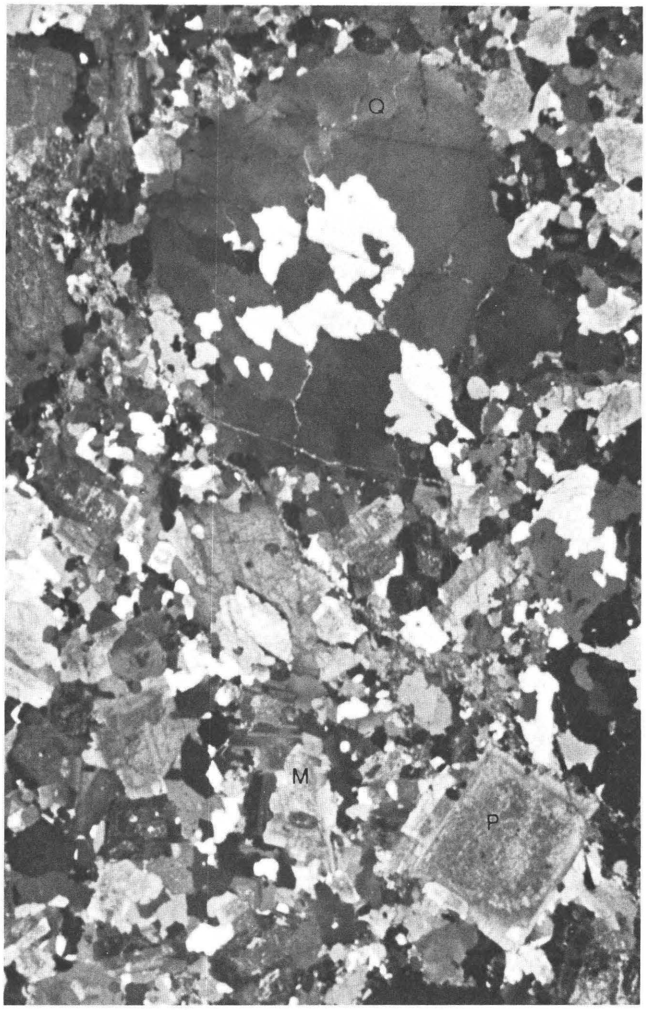


Figure 16. Photomicrograph of granite porphyry showing composite quartz phenocrysts (Q) and euhedral plagioclase feldspar (P). Quenched groundmass consists of quartz and microcline (M). Crossed nicols. Field of view is 1.5 cm wide.

Figure 17. Zoned microcline megacryst (left center) in granite porphyry south of Buffalo Lake.

from granodiorite to diorite is present that in part may be related to depth. The most mafic part of the pluton is exposed at lower elevations, particularly along the bed of Jack Creek. At outcrop scale, segregations of hornblende-rich diorite occur in the more leucocratic quartz monzodiorite and granodiorite.

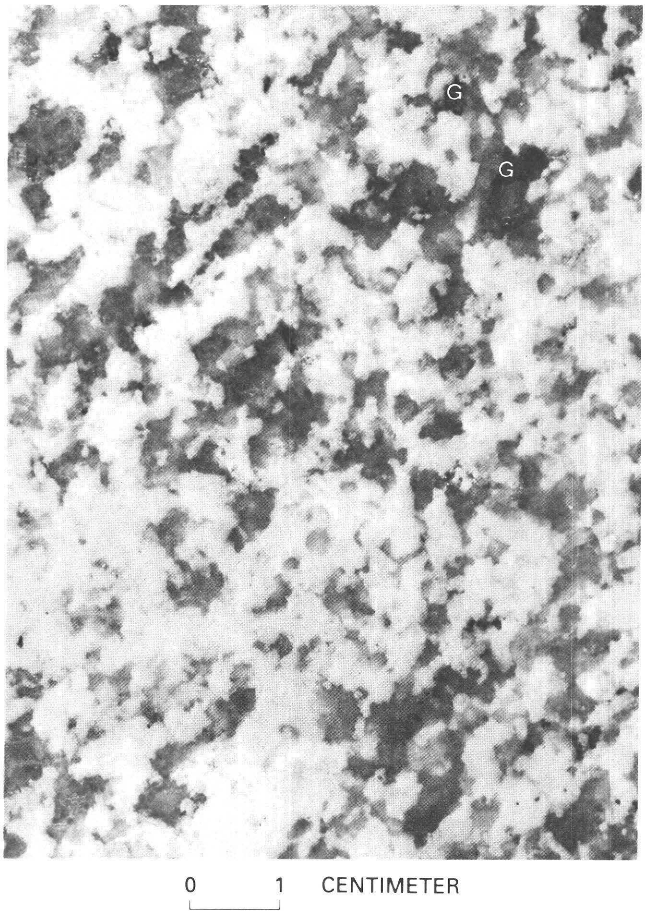


Figure 18. Xenomorphic-granular texture of garnet-bearing granite. Darker anhedral grains (G) in upper right corner of the photograph are spessartine garnet.

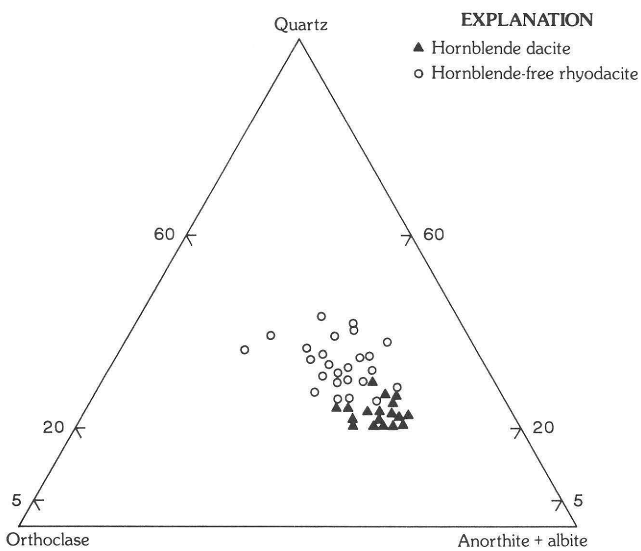


Figure 19. Normative composition of hornblende dacite and hornblende-free rhyodacite dikes.

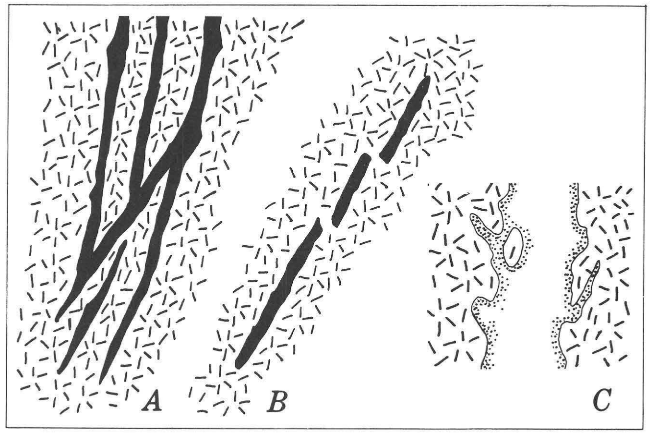


Figure 20. Sketches showing geometry of hypabyssal dikes. *A*, Hornblende-free rhyodacite dikes, showing bifurcation of dikes off main stem. *B*, En echelon dikes. *C*, Convolute nature of dike contacts.

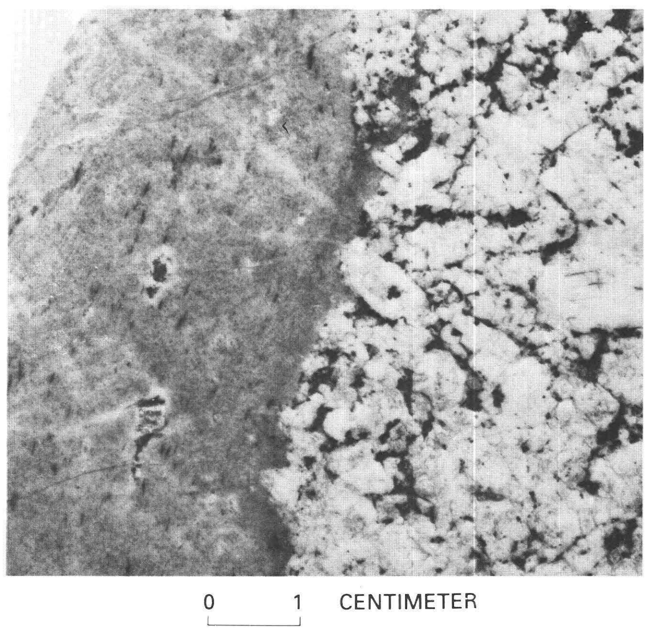


Figure 21. Contact between rhyodacite dike (left) and Keller Butte Granite (right). Dike contains biotite aligned parallel to margin. Contact of dike is chilled against granite.

Beyond the study area in the northern part of the Devils Elbow pluton, an upward gradation from equigranular monzodiorite to subporphyritic granodiorite is present (Moye, 1984). According to Moye (1984), the upper subporphyritic zone represents the chilled roof of the pluton. The close spatial association of hornblende dacite dikes, which cut the subporphyritic roof but not the more equigranular phase, suggests that the dikes may have emanated from the interior of the body. The textural and compositional changes at Devils Elbow could not be seen in the southern part of the pluton possibly owing to lack of relief. The eastern contact of the pluton does, however, grade into dacite porphyries similar to those at Devils Elbow between Brush and Jack Creeks, where a hypabyssal complex consisting of dacite and younger rhyolite dike swarms is parallel to the Manila Pass fault (pl. 1). The close proximity to the fault and the presence of porphyritic textures suggest that the dike swarms represent a near-surface vent of the monzodiorite magma.

The Devils Elbow pluton is not as well exposed in the study area as it is to the north at Devils Elbow. The hornblende-rich varieties are saprolitic whereas the less mafic compositions form low rounded exposures. Hornblende is conspicuous as rosettes similar to those in the hornblende dacite dikes (fig. 22); it is also conspicuous as single euhedral grains that may contain oxidized cores of pyroxene.

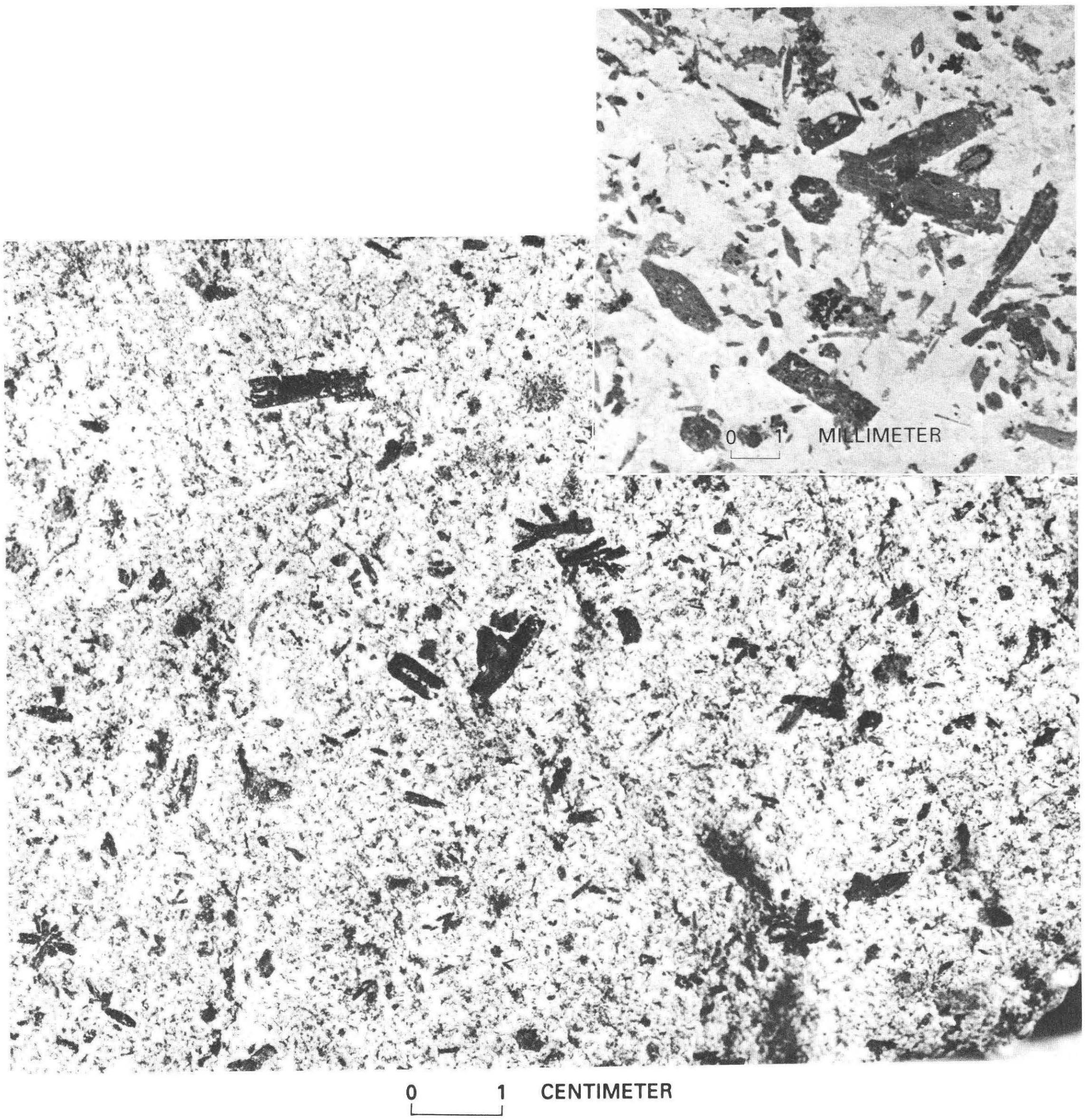


Figure 22. Hornblende rosettes in hornblende-bearing dacite dike. Photomicrograph (insert) shows detail of rosette in plane light.

In thin section, the hornblende-rich diorite and quartz monzodiorite contain up to 80 percent green hornblende euhedra (fig. 26); some of the hornblende contains cores of relict clinopyroxene. Plagioclase and minor amounts of anhedral quartz and orthoclase are interstitial to hornblende. Locally the interstitial plagioclase forms graphic intergrowths around the hornblende. Plagioclase is strongly zoned and ranges in composition from An_{41} in the core to An_{27} in the rim. The quartz monzodiorite to granodiorite parts of the pluton have a lower color index (15–45) than the diorite and contain euhedral phenocrysts of plagioclase in addition to hornblende. The plagioclase phenocrysts are moderately zoned (An_{26}–An_{36}), whereas interstital plagioclase ranges in composition from An_{31} to An_{24}. Biotite occurs as pseudohexagonal tablets and as reaction rims on hornblende. The porphyritic texture is not as apparent in the rocks that contain less than 45 percent hornblende. Coarse honey-colored sphene is the most abundant accessory mineral (less than 1 percent) followed by apatite, zircon, and magnetite.

Textural relations suggest that the clinopyroxene crystallized first, followed by hornblende and sphene, then plagioclase, biotite, orthoclase, and quartz.

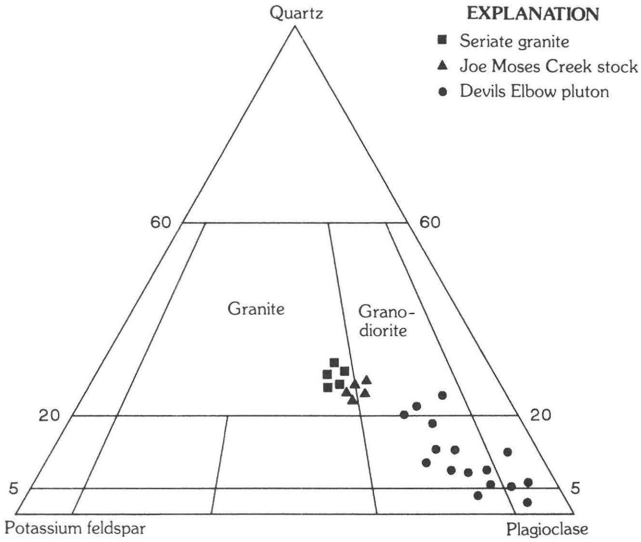


Figure 23. Modal composition of younger intrusive rocks (1,000 points counted on stained slabs approximately 15 cm by 15 cm; classification fields from Streckeisen, 1976).

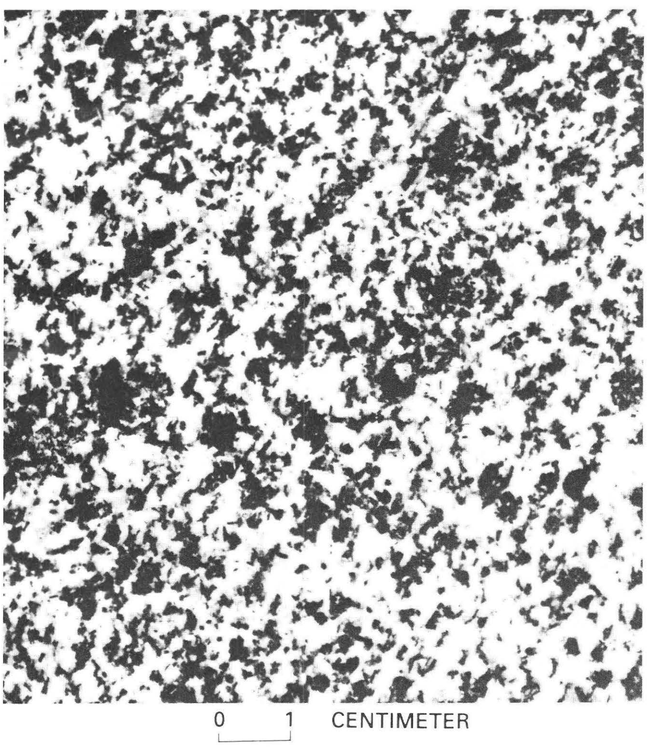


Figure 24. Biotite-hornblende granodiorite from Devils Elbow pluton at Devils Elbow north of study area.

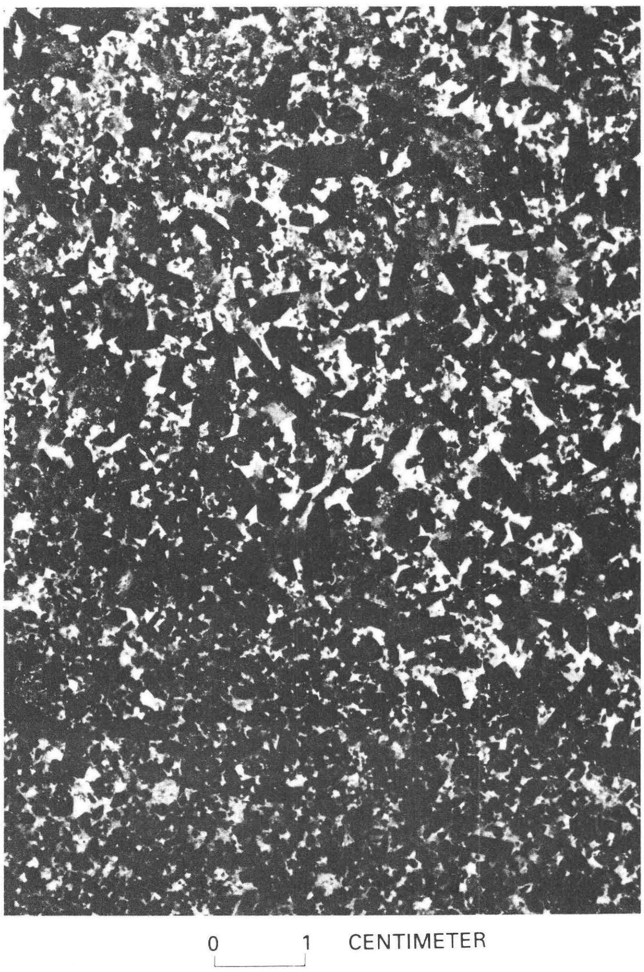


Figure 25. Hornblende-rich monzodiorite from southern part of Devils Elbow pluton at Jack Creek that consists largely of euhedral hornblende and interstitial plagioclase.

Joe Moses Creek Stock

The Joe Moses Creek stock is a hornblende-biotite granodiorite that intrudes the Keller Butte Granite of the Coulee Dam Intrusive Suite (pl. 1). Small pods of granodiorite intrusive into the Devils Elbow pluton are identical in composition to the granodiorite of the Joe Moses Creek stock. The stock is equant in plan view; it is bounded on the west by the Sherman fault and has intrusive contacts along the eastern and southern sides. The stock is situated on a broad, flat bench that may represent the configuration of its roof; the intrusive contacts dip outward at a shallow angle. The Joe Moses Creek stock does not show any effects of faulting though the western contact abuts the eastern boundary fault of the Republic graben. The Keller Butte Granite on the opposite side of the fault, on the other hand, contains microfractures, and the minerals have been altered. It thus seems likely that the intrusion of the Joe Moses Creek stock was structurally controlled and the existing Sherman fault served as a conduit along which the magma intruded. North of the study area, field relations along the western border of the Devils Elbow pluton where it abuts the fault also show no evidence of faulting (Moye, 1984).

The main body of the granodiorite is cut by hornblende-biotite dacite dikes that trend parallel to the Sherman fault (pl. 1). Outcrops of the granodiorite are flat and weathered into slabs. The granodiorite is light gray (fig. 27) and has a color index between 2 and 4. The presence of altered white plagioclase megacrysts and an occasional hornblende cross or rosette serves to distinguish the granodiorite of the Joe Moses Creek stock from the Swawilla Granodiorite in the Coulee Dam Intrusive Suite (table 1). The Joe Moses Creek is also more compositionally restricted (figs. 3, 23) and finer grained than the Swawilla. Locally, a groundmass consisting of quartz and plagioclase is present in the Joe Moses Creek stock.

Petrographically, xenomorphic-granular texture and plagioclase phenocrysts in the Joe Moses Creek stock distinguish it from the other granitic units. Plagioclase in the groundmass, is typically equant, and shows strong zoning (An_{38}–An_{19}) (fig. 28). Plagioclase phenocrysts are also equant, contain quartz inclusions, exhibit patchy zoning, and have sutured grain boundaries. Quartz has slightly undulose extinction and occurs as

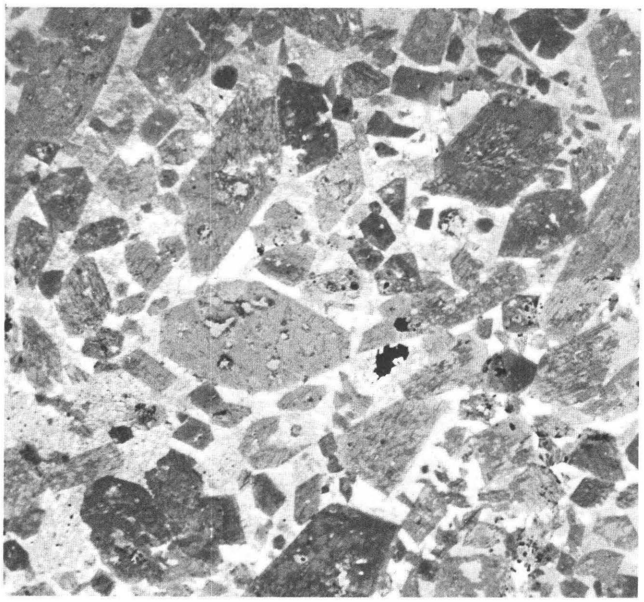


Figure 26. Photomicrograph of monzodiorite from Devils Elbow pluton showing euhedral hornblende grains in plane light.

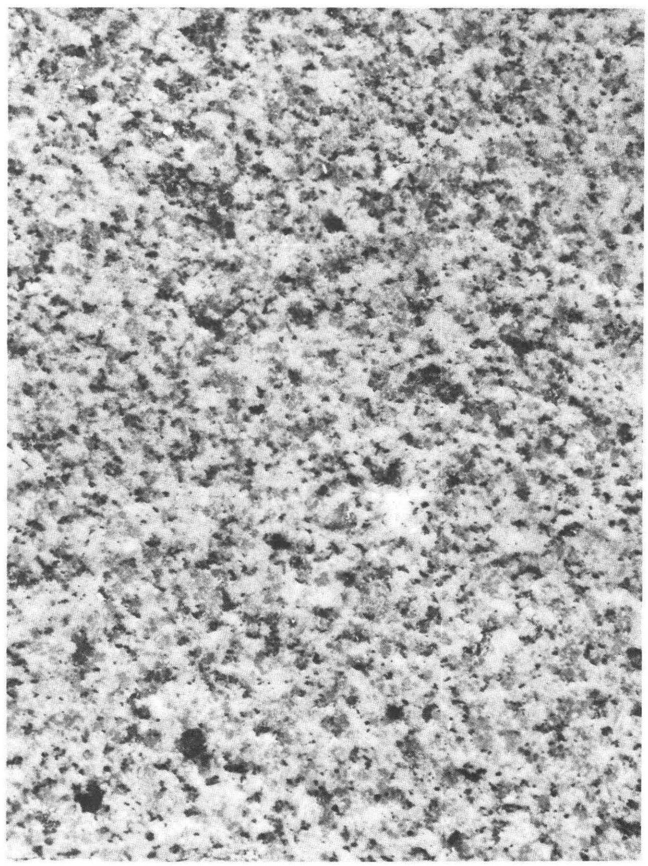


Figure 27. Hornblende-biotite granodiorite from Joe Moses Creek stock. Fine dark grains are biotite; coarser grains at lower left are hornblende.

Table 1. Summary of diagnostic features in granitic rocks northeast of Grand Coulee Dam

Rock Unit and age	Grain size	Megascopic features[1]	Texture		Diagnostic microscopic features
			Megascopic	Mircoscopic	
Manila Creek Granodiorite (61–48 Ma, K/Ar; 50 Ma, U/Pb)	Range 1–13 mm Average 8 mm Megacrysts 4–18 mm	Typically weathered forming dark-gray grussy exposures; where fresh, pink microcline megacrysts are conspicuous. Lack of Kf in groundmass and subhedral to anhedral megacrysts are diagnostic. Locally contains biotite foliation and quartz lineation	Porphyritic	Hypidiomorphic granular	Contains abundant sphene; generally occurs with biotite. Megacrysts are microcline showing Carlsbad and gridiron twins. Plagioclase is subhedral and only weakly zoned; quartz has undulose extinction
Swawilla Granodiorite 51.5±0.03 Ma (K/Ar)	Range 0.5–12 mm Average 8 mm	Medium to light gray, medium-grained granitoid containing 1–7 percent biotite; typically equigranular but locally may be porphyritic with Kf megacrysts that are more euhedral and elongate than those found in the Manila Creek Granodiorite	Equigranular to porphyritic	Hypidiomorphic granular	Similar to Manila Creek Granodiorite except for presence of allanite and epidote in addition to sphene and absence of subhedral megacrysts. Potassium feldspar megacrysts are typically euhedral and equant
Keller Butte Granite 52.9±0.04 Ma (K/Ar)	Range 0.5–18 mm Average 11 mm Megacrysts 2–11 mm	Light-gray to white, coarse-grained granitoid locally containing large (≤15 cm) Kf megacrysts that are euhedral and typically exhibit concentric zoning	Equigranular to porphyritic	Hypidiomorphic granular	Plagioclase exhibits strong normal zoning and has preferentially altered cores. Microcline is poikilitic
Granite porphyry	Range 2–13 mm Average 10 mm Megacrysts 3–6 cm	Light-gray granitoid characterized by round to oblate quartz "eyes" and zoned Kf megacrysts. Contact with Keller Butte Granite either sharp or gradational and is distinguished by the presence of quartz eyes in the porphyry. Quartz is generally flattened parallel to contact	Porphyritic (Kf and rounded qtz phenocrysts)	Quench texture	Aggregates or single crystals of round to oblate quartz phenocrysts and quench textures are diagnostic. Quench texture consists of cruciform microcline containing inclusions of optically continuous anhedral quartz and euhedral oscillatory zoned plagioclase
Garnet-bearing granite	Range 0.5–9 mm Average 4 mm	Light-gray granitoid characterized by variable grain size (aplite-alaskite-pegmatite), anhedral-granular texture and the presence of subhedral garnet. Locally, quartz and feldspar are flattened along and concordant with contact; contacts typically contain abundant hydrothermal quartz pods and dikes	Equigranular to "wormy"	Xenomorphic granular	Garnet, primary muscovite, and anhedral-granular texture are distinctive. Also contains abundant sphene, coarse allanite, epidote, and rounded zircon
Seriate granite	Range 2–22 mm Average 13 mm (includes megacrysts)	Characterized by salmon to buff color and by potassium feldspar megacrysts that vary in size (serial distribution). Locally contains aplite-pegmatite pods and is cut by aplite dikes. Contains xenocrystic hornblende near contact with monzodiorite of Devils Elbow pluton	Porphyritic or seriate	Hypidiomorphic granular	Diagnositc features are absence of perthite and myrmekite and presence of orthoclase and oscillatory zoned plagioclase; locally contains quench texture. Overall has a more subhedral to euhedral granular texture and is more altered than the other units
Granodiorite of Joe Moses Creek stock	Range 0.4–5 mm Average 3 mm	Light-gray, fine-grained granitoid which locally contains hornblende rosettes and euhedral plagioclase phenocrysts. Groundmass locally contains euhedral plagioclase	Equigranular to porphyritic	Hypidiomorphic to xenomorphic granular	Plagioclase occurs as euhedral, subequant crystals in the groundmass and as phenocrysts that have patchy or oscillatory zoning. Quartz is anhedral (bleblike) and locally forms aggregates; orthoclase is anhedral and appears to have crystallized late, along with quartz

[1]Kf, potassium feldspar.

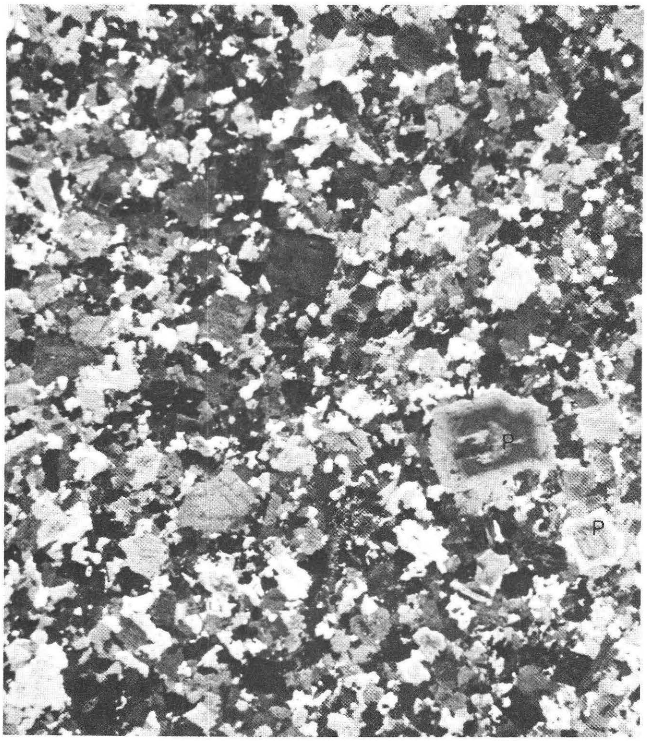
anhedral blebs or as composite grains. Orthoclase occurs as anhedral grains within the groundmass and as subhedral phenocrysts. Magnetite occurs in accessory amounts as inclusions in euhedral tablets of olive-green biotite. Other accessory minerals include minute apatite needles and zircon.

Seriate Granite

Seriate granite forms one of the youngest plutons in the map area and intrudes the Devils Elbow pluton near Brush Creek (pl. 1). The contact with the Devils Elbow pluton is abrupt, and the granite contains xenocrystic hornblende and xenoliths of monzodiorite near the contact. Lack of chilling and the mixed nature of the contact indicate that the monzodiorite had not fully crystallized before the seriate granite intruded. Similar contact relations were reported by Moye (1984, p. 140) for the granite of Deadhorse Creek, which intrudes the northern part of the Devils Elbow body. There, a 30-m-thick zone consisting of marble-cakelike, swirled layers of dark hornblende-biotite-rich rocks and light-colored rock separate the Deadhorse Creek granite from a roof of monzodiorite.

The seriate granite exposed near Brush Creek is characterized by buff to pink, weathered outcrops that vary texturally from aplite-pegmatite to inequigranular granite containing orthoclase phenocrysts that have a serial range in grain size (fig. 29*A*). The granite is cut by aplite dikes that contain less than 1 percent biotite. Although the dikes that cut the granite of Deadhorse Creek are miarolitic (Moye, 1984), the dikes near Brush Creek are not.

The seriate granite differs petrographically from units in the Coulee Dam Intrusive Suite because it lacks perthite and myrmekite, it has hypidiomorphic- to allotriomorphic-granular texture (fig. 29*B*) that contains orthoclase rather than microcline as the dominant potassium feldspar, and its plagioclase shows oscillatory zoning (table 1). These differences suggest that the seriate granite crystallized at slightly higher temperatures and possibly at shallower depths than the other granites in the map area. Locally in the groundmass, quench texture of fine-grained orthoclase and quartz indicates that the seriate granite crystallized under fluctuating pressure and temperature conditions.



0 2.5 MILLIMETERS

Figure 28. Photomicrograph of granodiorite from the Joe Moses Creek stock showing zoned, equant grains of plagioclase (P) and xenomorphic-granular groundmass. Crossed nicols.

A

Figure 29. Seriate granite in weathered outcrop along Brush Creek showing (*A*) serial range in grain size and (*B*) hypidiomorphic-granular texture of equigranular groundmass.

GEOCHEMISTRY

Analytical Procedures

Representative samples from the Coulee Dam Intrusive Suite and associated intrusive rocks were selected for analysis of major elements, trace elements, and rare-earth elements. Between 1.0 kg (dike rocks) and 5 kg (coarser granite) of each sample was crushed and ground using standard laboratory procedures; samples of coarse-grained phases were split, and duplicate samples were analyzed in order to ensure sample homogeneity and analytical precision.

Major element and trace elements Rb, Ba, Sr, and Zr were determined by X-ray fluorescence (XRF) using the Phillips PW 1410 manual spectrometer at the Basalt Research Laboratory, Washington State University. Samples were prepared following the procedure outlined in Hooper and Atkins (1969) and analyzed using U.S. Geological Survey standards G–2, AGV–1, GSP–1, BCR–1, and PCC–1.

Rare-earth elements and additional trace-element analyses were obtained by inductively coupled plasma (ICP) emission spectrometry at Kings College, London, England. The technique used for dissolving samples and separating rare-earth elements is that of Walsh and others (1981).

Microprobe analyses of feldspar were done on an automated Cameca Model Camebax electron microprobe at Washington State University, under the direction of S. Cornelius. X-rays were analyzed using wavelength spectrometry with a 12 nA beam current and a 10 second count time. Background-corrected intensity ratios were modified using a ZAF correction procedure.

Major-Element Variation

Coulee Dam Intrusive Suite

Major-element analyses indicate that the Coulee Dam Intrusive Suite is silica-rich, aluminous, and contains more K_2O than Na_2O (table 2). The SiO_2 content ranges from 69.07 percent in the Manila Creek Granodiorite to 77.35 percent in the garnet-bearing granite (table 2). The suite as a whole has an inferred calcic affinity (Peacock index, 65) and is peraluminous with the molecular ratio Al_2O_3:$Na_2O + K_2O + CaO$ greater than 1 and more than 5 percent normative corundum. Compared with the composition of an average granite (Nockolds, 1954; LeMaitre, 1976), the granite porphyry and Keller Butte Granite of the Coulee Dam Intrusive Suite are enriched in silicon and aluminum and depleted in potassium, iron, and magnesium (table 3). The garnet-bearing granite is highly silicic; it contains an average amount of alumina and considerably less iron and magnesium than the other units in the suite (table 2).

The Coulee Dam Intrusive Suite shows small but systematic variations in major-element chemistry (fig. 30). From the oldest unit in the suite (Manila Creek Granodiorite) to the youngest (garnet-bearing granite), FeO, MgO, CaO, TiO_2, and P_2O_5 decrease with increas-

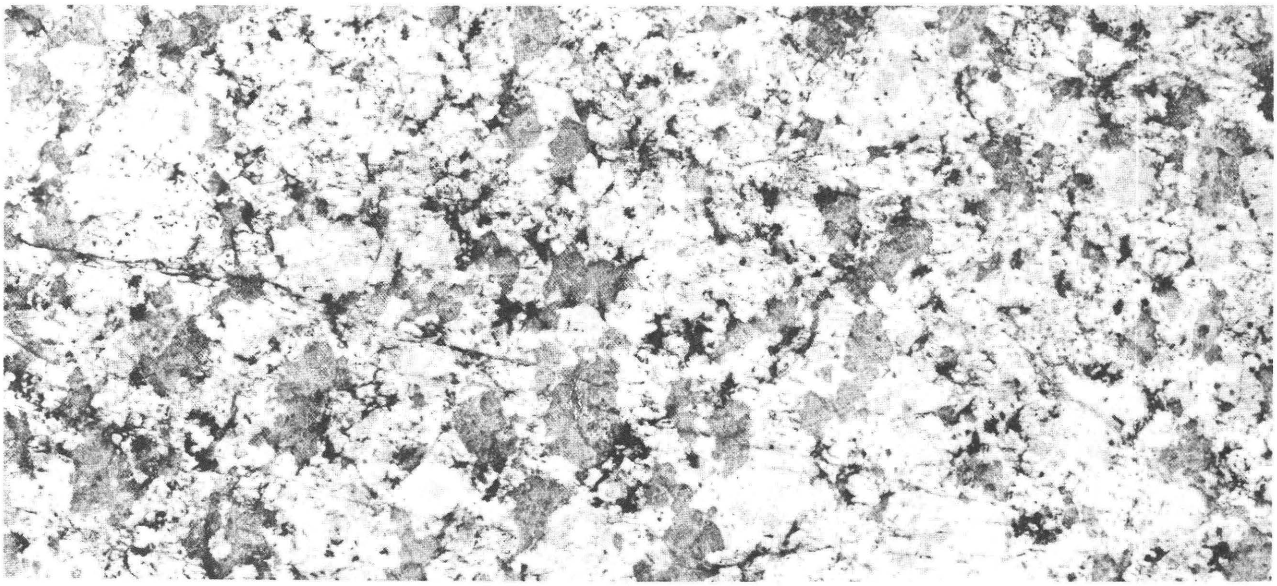


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Figure 29.—Continued.

Table 2. Whole-rock chemical analyses and CIPW norms for the Coulee Dam Intrusive Suite

[All iron reported as Fe_2O_3. DI, differentiation index (from Thornton and Tuttle, 1960); PI, peraluminous index]

Rock unit	Manila Creek Granodiorite		Swawilla Granodiorite							
Sample No.	81182A	81182B	81175	8132	8130E	M370	M379	M388	82110	82228
				Chemical analyses (in weight percent)						
SiO_2	69.07	66.96	72.89	71.54	69.01	69.81	70.88	70.88	73.39	73.65
Al_2O_3	15.20	16.38	15.64	15.49	15.26	14.95	15.81	14.83	14.85	13.83
Fe_2O_3	3.16	3.82	1.78	1.17	1.46	2.69	2.71	1.08	.85	1.14
MgO	1.17	1.11	.70	.39	.28	.60	.93	.21	.19	.20
CaO	2.84	3.26	2.13	2.18	2.06	2.48	2.94	1.89	1.85	1.22
Na_2O	2.31	2.98	2.44	3.44	3.35	2.71	3.11	2.49	3.39	2.58
K_2O	3.89	3.20	4.61	3.85	3.95	3.60	3.58	4.55	4.17	5.89
TiO_2	.68	.63	.29	.31	.30	.39	.50	.27	.22	.19
P_2O_5	.26	.24	.09	.11	.11	.21	.24	.08	.07	.07
MnO	.10	.09	.10	.02	.06	.06	.06	.03	.04	.04
Total	98.68	98.67	100.67	98.50	95.84	97.50	100.76	96.31	99.02	98.81
DI	77	75	83	85	85	81	79	86	88	91
PI	1.15	1.15	1.22	1.12	1.13	1.16	1.10	1.19	1.10	1.08
				CIPW norms						
Q	32.23	28.04	33.37	30.19	29.12	33.52	29.89	34.02	31.77	31.75
C	2.99	2.99	3.28	2.19	2.29	2.95	2.25	2.95	1.74	1.30
or	23.77	19.46	27.49	23.27	24.55	22.21	21.28	28.33	25.11	35.72
ab	21.45	27.54	22.11	31.60	31.65	25.41	28.09	23.56	31.02	23.78
an	12.81	15.03	10.07	10.33	10.00	11.42	13.10	9.33	8.89	5.74
hy	3.34	3.15	1.95	1.10	.81	1.73	2.58	.61	.53	.57
hm	2.28	2.74	1.25	.83	1.07	1.96	1.90	.79	.60	.82
il	.16	.15	.16	.03	.10	.10	.09	.05	.06	.06
ap	.56	.52	.19	.24	.24	.46	.50	.18	.15	.15
ru	.41	.38	.12	.20	.17	.23	.30	.17	.12	.10

ing SiO_2; K_2O and Na_2O behave in the opposite sense. Throughout the suite, K_2O increases at the expenses of CaO and to a lesser extent Na_2O (fig. 31). The Coulee Dam Intrusive Suite defines a typical calc-alkaline trend of alkali enrichment and depletion of total iron and magnesium (fig. 32).

The small but systematic variation in major-element chemistry throughout the suite is a function of the variation in the proportions of feldspars, quartz, biotite, and accessory minerals. Inward from the Manila Creek Granodiorite border to the granite porphyry, the ratio of plagioclase feldspar plus biotite to alkali feldspar diminishes; quartz remains nearly constant throughout the suite (fig. 3). The percentage of biotite differs most between the more mafic Manila Creek Granodiorite border and the Swawilla Granodiorite; the variation is also reflected in the decrease in total iron between the two units. The decline in the CaO/Na_2O ratio is due to the decrease in modal plagioclase and to the variation in anorthite content from An_{36} to An_{10} from the Manila Creek Grandodiorite inward to the garnet-bearing granite. The high Al_2O_3 values throughout the pluton are

Table 2. Whole-rock chemical analyses and CIPW norms for the Coulee Dam Intrusive Suite—Continued

Rock unit	Keller Butte Granite									
Sample No.	81192	8134B	81105A	81184	81187	81186	8135A	81191	81172A	88174
Chemical analyses (in weight percent)										
SiO_2	72.65	76.11	71.76	72.05	73.47	74.21	71.95	70.96	74.22	74.18
Al_2O_3	15.64	13.93	15.69	15.22	15.09	15.17	15.33	15.92	14.71	15.44
Fe_2O_3	.77	.37	.92	1.12	.60	.65	.58	1.15	0	.61
MgO	.21	.02	.30	.24	.21	.15	.22	.35	.12	.26
CaO	1.84	.45	1.77	2.02	1.54	1.30	1.86	2.00	1.58	1.64
Na_2	4.22	3.04	3.66	3.57	3.56	3.17	3.95	3.77	3.87	3.34
K2O	2.81	4.92	4.32	3.20	3.64	4.98	3.14	3.63	3.19	4.13
TiO_2	.22	.07	.23	.24	.23	.18	.22	.26	.24	.19
P_2O_5	.07	.04	.08	.08	.07	.06	.08	.08	.07	.07
MnO	.02	.05	.02	.05	.06	.03	.03	.03	.03	.02
Total	98.45	99.00	98.75	97.79	98.47	99.90	97.36	98.15	98.03	99.88
DI	87	95	88	86	88	90	87	86	90	88
PI	1.17	1.25	1.13	1.17	1.20	1.17	1.16	1.16	1.16	1.19
CIPW norms										
Q	31.42	36.66	28.19	33.04	33.57	31.68	31.39	29.97	34.33	32.95
C	2.76	3.21	2.18	2.71	2.97	2.58	2.52	2.62	2.45	2.93
or	16.92	29.71	25.96	19.51	22.01	29.71	19.13	21.95	19.33	24.63
ab	38.61	27.90	33.42	33.07	32.71	28.75	36.57	34.65	35.64	30.28
an	8.84	2.02	8.40	9.80	7.35	6.12	8.98	9.62	7.57	7.75
hy	.59	.06	.84	.68	.59	.42	.63	.99	.34	.72
hm	.55	.26	.65	.81	.43	.46	.42	.82	0	.43
il	.03	.08	.03	.08	.10	.05	.05	.05	.05	.03
ap	.15	.09	.17	.17	.15	.13	.17	.17	.15	.15
ru	.14	.01	.15	.13	.12	.10	.13	.16	.15	.12

difficult to explain in terms of mineralogy because alumina-rich phases (garnet and primary muscovite) are abundant only in the youngest garnet-bearing granite. It is also unusual that the percentage of Al_2O_3 is lower in the garnet-bearing granite despite the presence of garnet and muscovite. However, biotite is rare, or absent, in the garnet-rich varieties of the granite, which, together with the decrease in the abundance and anorthite content of plagioclase feldspar, may explain the diminished Al_2O_3.

Associated Intrusive Rocks

The younger suite of intrusive rocks, which includes the hypabyssal dikes, Devils Elbow pluton, seriate granite, and Joe Moses Creek stock, also define predictable major-element trends against silica (fig. 33). The percentage of SiO_2 ranges from 53.18 percent in the mafic part of the Devils Elbow pluton to 75.23 percent in the seriate granite (table 4). MgO, CaO, P_2O_5, TiO_2, FeO, and MnO decrease with increasing SiO_2 whereas Na_2O and K_2O behave in the opposite sense.

North of the study area, Moye (1984) divided this younger suite of rocks into three intrusive episodes based on relative age, spatial association, and chemical similarities (fig. 34). Her subdivisions consist of (1) an early silicic episode that has a restricted compositional range (69–72 percent SiO_2) and consists of the O'Brien Creek Formation and the older hornblende-free rhyodacite

Table 2. Whole-rock chemical analyses and CIPW norms for the Coulee Dam Intrusive Suite—Continued

Rock Unit	Granite porphyry				Garnet-bearing granite			
Sample No.	81185	8110A	8110B	8110C	8129	8152	8273A	8273B
	Chemical analyses (in weight percent)							
SiO_2	73.12	73.29	73.82	70.14	77.35	73.28	77.99	76.33
Al_2O_3	14.72	15.31	14.35	15.49	13.71	14.51	12.83	14.22
Fe_2O_3	.56	.22	.58	3.16	1.12	1.20	0	1.18
MgO	.08	.17	.19	.04	0	.28	0	0
CaO	1.50	1.24	1.58	1.45	.59	1.84	.75	.74
Na_2O	3.46	3.95	4.26	3.57	2.42	2.63	2.87	2.71
K2O	3.93	3.96	3.24	3.66	5.52	4.27	5.25	5.05
TiO_2	.21	.16	.20	.44	.02	.22	.07	.06
P_2O_5	.06	.04	.07	.12	.05	.05	.02	.04
MnO	.01	.10	.03	.06	.01	.04	.02	.02
Total	97.65	98.44	98.32	98.13	100.79	98.32	99.80	100.35
DI	89	91	90	86	93	86	92	95
PI	1.16	1.17	1.07	1.24	1.24	1.18	1.26	1.09
	CIPW norms							
Q	33.27	30.52	31.36	31.15	38.42	35.82	37.32	37.32
C	2.47	2.63	1.26	3.73	3.09	2.64	1.23	3.37
or	23.98	23.82	19.54	22.35	32.97	26.07	31.51	30.23
ab	32.08	36.11	39.04	33.13	21.97	24.41	26.18	24.65
an	7.28	6.00	7.54	6.63	2.63	9.10	3.65	3.46
hy	.23	.48	.54	.11	0	.80	0	0
hm	.40	.16	.41	2.28	.79	.86	0	.83
il	.02	.16	.05	.10	.02	.06	.03	.03
ap	.13	.09	.15	.26	.11	.11	.04	.08
ru	.14	.03	.12	.27	.01	.13	.03	.03

dikes, (2) an intermediate episode distinguished by a range in SiO_2 of 54 to 67 percent and by high K_2O, and consisting of the Devils Elbow pluton, hornblende dacite dikes, and the Sanpoil Volcanics, and (3) a late silicic episode that consists of rhyolite domes and the granitic rocks that cut the Devils Elbow Pluton. The intrusive rocks that cut the Coulee Dam Intrusive Suite can also be grouped into Moye's (1984) three episodes. The hornblende dacite dikes (table 9) and Devils Elbow pluton fit the intermediate episode, and the Devils Elbow pluton shows a gap between 57 and 62 percent SiO_2 (fig. 33). The hornblende-free rhyodacite dikes (table 10) and Joe Moses Creek stock fall within the early silicic episode of Moye (1984) but overlap the late silicic field (fig. 34). The seriate granite defines a separate field that contains slightly less K_2O than granite and rhyolite in the late silicic episode (fig. 34).

The associated intrusive rocks also define a smooth calc-alkaline trend toward enrichment of alkalis (fig. 35). The seriate granite and rhyodacite dikes show the greatest alkali enrichment followed by the Joe Moses Creek stock and dacite dikes. The associated intrusive rocks define a calc-alkaline trend that plots closer to the magnesium apex than the phases of the Coulee Dam

Table 3. Major-element composition of granites from Coulee Dam Intrusive Suite and average granite (Nockolds, 1954 and LeMaitre, 1976)

[n.a., not available. All iron reported as Fe_2O_3]

	Coulee Dam Intrusive Suite		Average granite compositions	
	Keller Butte Granite (average)	Granite porphyry (average)	Nockolds (1954)[1]	LeMaitre (1976)[2]
SiO_2	73.16	72.59	72.08	72.04
TiO_2	.21	.25	.37	.30
Al_2O_3	15.21	14.97	13.86	14.42
Fe_2O_3	.70	1.13	2.53	2.90
MnO	.03	.05	.06	n.a.
MgO	.21	.15	.52	.71
CaO	1.60	1.44	1.33	1.82
K_2O	3.80	3.77	5.46	4.12
Na_2O	3.62	3.81	3.08	3.69

[1]Average calc-alkaline granite.
[2]Average granite.

Intrusive Suite (figs. 32 and 35). This difference is a reflection of the higher MgO:FeO ratio in the hornblende dacite dikes than in the Manila Creek Granodiorite, the most mafic unit of the Coulee Dam Intrusive Suite (table 2).

The hornblende-free rhyodacite and hornblende dacite hypabyssal dikes are chemically distinctive. The rhyodacite dikes contain more SiO_2 and less TiO_2, Fe_2O_3, MnO, and Al_2O_3 than the hornblende dacite (table 5). Within each dike type, internal variation is limited to a fairly narrow range (tables 5, 9, and 10; fig. 33).

The Devils Elbow pluton shows considerable variation in SiO_2 (53–64 percent), MgO (3–10 percent), and CaO (5–9 percent) (fig. 33; table 4). These values correspond to the gradation from diorite containing more than 80 percent hornblende to granodiorite containing less than 20 percent biotite and hornblende. The most mafic diorites are chemically distinctive and plot in a field that is separate from the less mafic granodiorite. The less mafic compositions cluster with the hornblende dacite dikes and support Moye's (1984) interpretation that the dikes emanate from the granodiorite.

The seriate granite contains more MgO and K_2O but less CaO than the granite porphyry and garnet-bearing granite in the Coulee Dam Intrusive Suite (tables 2 and 4; fig. 33). The Joe Moses Creek stock is distinctive chemically in that it contains more Na_2O (3–4 percent) than the other younger intrusives (table 4). The high Na_2O corresponds with the abundance of plagioclase feldspar in the Joe Moses Creek stock.

Trace-Element Variation

The Coulee Dam Intrusive Suite shows random variation in trace element abundances (figs. 36 and 37). Strontium ranges between 67 and 747 ppm, rubidium between 112 and 195 ppm, and barium between 223 and 1,890 ppm (table 6). Rubidium/strontium and potassium/rubidium respectively vary from 0.167 to 2.627 and

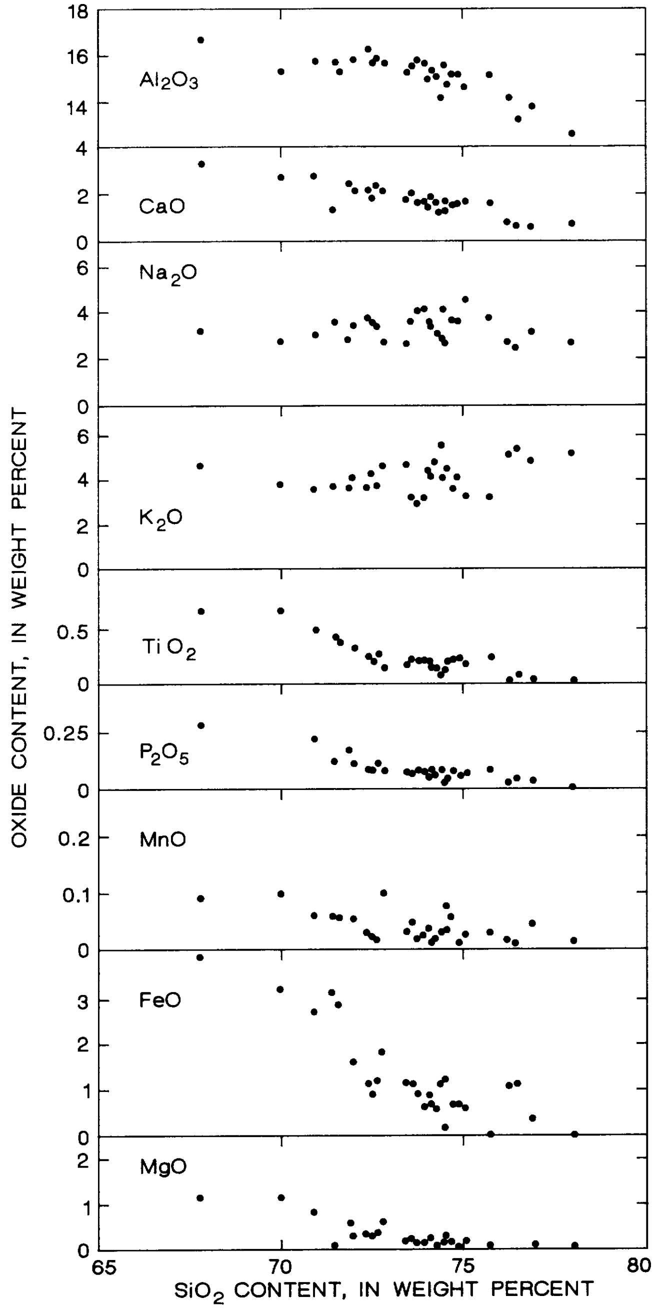

Figure 30. Harker variation diagram for Coulee Dam Intrusive Suite.

162 to 268 (table 6). The only systematic variation occurs in zirconium content, which diminishes inward toward the center of the suite (fig. 36). Based on limited data, there also appears to be no covariance between barium and rubidium and strontium and rubidium (fig. 37).

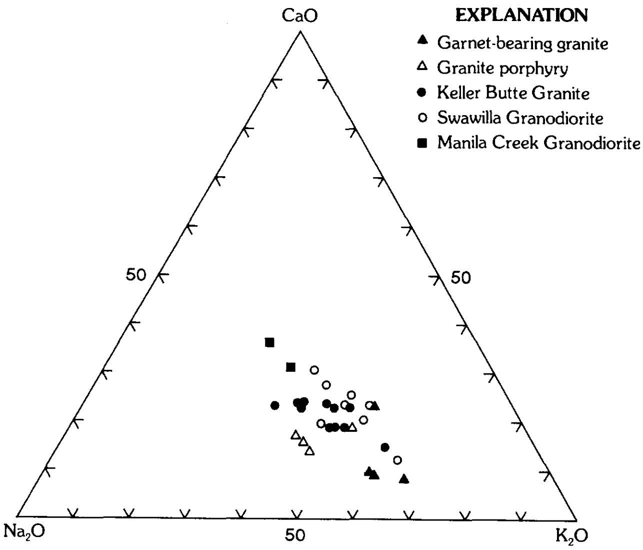

Figure 31. Na_2O, CaO, and K_2O contents of units in Coulee Dam Intrusive Suite. K_2O increases throughout suite; Na_2O and CaO decrease proportionately.

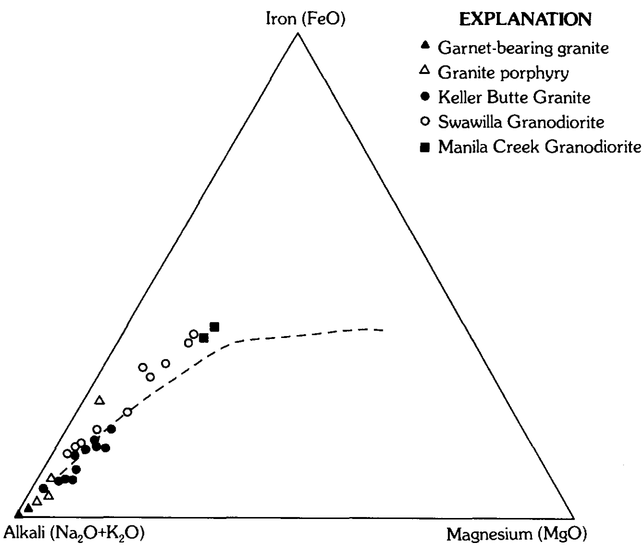

Figure 32. Alkali-iron-magnesium diagram showing alkali enrichment within Coulee Dam Intrusive Suite. Dashed line shows trend of associated intrusive rocks. Total iron shown as FeO.

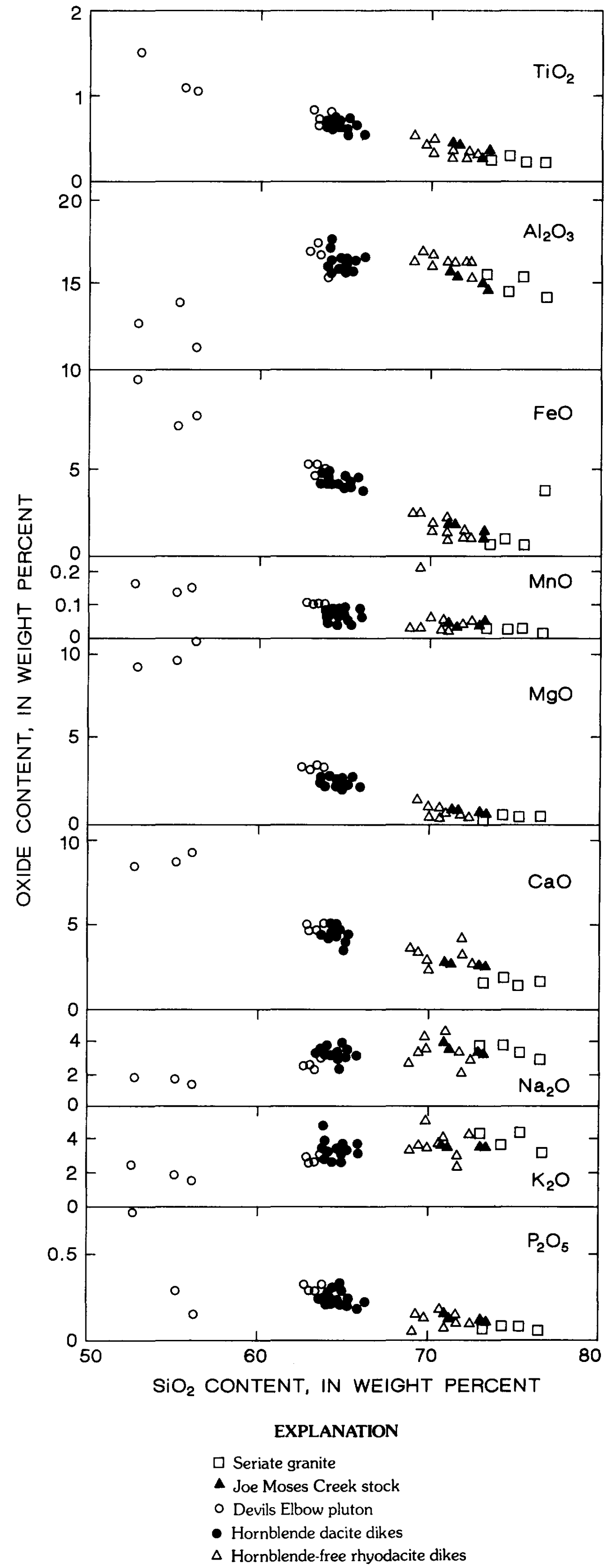

Figure 33. Harker variation diagram for associated intrusive rocks.

Table 4. Whole-rock chemical analyses and CIPW norms for the Devils Elbow pluton, seriate granite, and Joe Moses Creek stock

[n.d., not determined. All iron reported as Fe_2O_3. DI, differentiation index (from Thornton and Tuttle, 1960); PI, peraluminous index]

Rock unit	Devils Elbow pluton							Seriate granite				Joe Moses Creek stock			
Sample No.	83615	81176	8117	81179	81189	8116	82154	81180A	81180B	81178A	81178B	82134A	82134B	82150A	82150B
							Chemical analyses (weight percent)								
SiO_2	53.18	54.94	56.13	63.32	63.59	63.18	64.43	71.56	75.23	73.62	72.63	69.86	69.47	71.56	71.37
Al_2O_3	12.70	13.70	11.24	16.65	17.27	16.91	15.48	15.75	14.19	14.99	15.00	15.48	15.54	15.05	15.28
Fe_2O_3	8.61	7.50	8.09	5.15	4.91	5.25	4.46	1.97	.55	.88	2.10	2.74	2.76	2.30	2.32
MgO	9.10	8.65	10.06	3.02	2.94	2.95	2.93	.02	.40	.43	.20	.63	.65	.31	.33
CaO	8.39	8.63	9.03	4.82	4.98	5.08	5.09	1.55	1.65	1.52	1.87	2.48	2.55	2.30	2.33
Na_2O	1.93	2.18	1.89	2.80	3.08	3.03	3.02	3.38	3.19	2.63	3.42	3.42	3.45	3.39	3.33
K_2O	2.49	2.02	1.54	2.90	2.75	2.94	3.05	4.27	3.30	3.84	3.54	3.42	3.38	3.55	3.57
TiO_2	1.51	1.03	1.09	.73	.76	.86	.79	.22	.20	.21	.25	.40	.39	.30	.24
P_2O_5	.27	.30	.29	.30	.35	.33	.77	.09	.07	.05	.08	.13	.14	.11	.11
MnO	.13	.15	.09	.09	.09	.09	.06	.04	.02	.02	.03	.03	.03	.03	.03
Total	98.83	99.05	99.52	99.77	100.67	100.64	100.08	98.83	98.80	98.19	99.45	98.59	98.36	98.90	98.91
DI	38	39	36	63	63	63	65	87	88	86	86	81	81	84	83
PI	.60	.64	.53	1.01	1.01	.97	.88	1.21	1.20	1.33	1.17	1.12	1.11	1.11	1.13
							CIPW norms								
Q	8.25	9.03	12.22	22.33	21.31	20.47	22.52	31.55	39.27	38.52	33.70	30.58	30.04	32.72	32.64
C	0	0	0	1.70	1.81	.71	0	5.76	4.97	7.47	4.60	3.86	3.76	3.38	3.87
or	15.27	12.28	9.35	17.43	16.51	17.75	18.34	24.49	19.06	21.90	20.46	19.91	19.69	20.66	20.73
ab	16.96	18.99	16.43	24.11	26.49	26.20	26.01	27.76	26.40	21.48	29.30	28.52	28.79	28.26	27.70
an	19.35	22.27	18.12	22.41	23.12	23.42	20.03	6.89	7.56	6.96	8.56	11.29	11.57	10.54	10.66
hy	12.21	10.60	11.57	5.04	4.90	4.94	4.64	.03	.64	.68	.32	1.02	1.05	.50	.53
hm	8.96	7.74	8.33	5.26	5.00	5.38	4.55	1.92	.54	.85	2.06	2.71	2.73	2.27	2.29
il	.33	.29	.33	.20	.20	.20	.20	.04	.04	.04	.06	.06	.06	.06	.06
ap	1.76	.61	.68	.65	.67	.79	.74	.19	.15	.11	.17	.28	.30	.24	.24
ru	0	0	0	.64	.67	.78	0	.19	.17	.18	.21	.36	.35	.26	.20

Limited available data (table 7) suggest that the associated intrusive rocks differ in trace element content from the units in the Coulee Dam Intrusive Suite. The seriate granite contains less barium (577 ppm) than all phases of the suite except the garnet-bearing granite and is similar only to the granite porphyry in zirconium content (95 ppm). Compared to units in the suite, the Joe Moses Creek stock is characterized by moderately high contents of barium (1,426 ppm) and strontium (557 ppm). The Devils Elbow pluton contains less rubidium than the Coulee Dam Intrusive Suite and more zirconium than all but the Manila Creek and Swawilla plutons.

Rare-Earth-Element Variation

The Coulee Dam Intrusive Suite is unusual in that it shows a decrease in rare-earth elements (REE) from the oldest to the youngest unit (table 7; fig. 38). The abundance of REE decreases systematically from the Manila Creek Granodiorite (La/Lu ratio, 20; fig. 38*A*) to the garnet-bearing granite (La/Lu ratio, 13; fig. 38*B*). The nearly parallel slopes and the progressive decrease in REE throughout the suite suggest that mineral phases having distribution coefficients (K_D) greater than one were being removed in fairly constant proportions. Since the essential mineral constituents (feldspar, quartz, and biotite) have distribution coefficients (K_D) less than one for the REE (Hanson, 1980), accessory minerals must have had an important effect on the REE patterns depicted in figure 38*A*. The decrease in the light rare-earth elements (LREE) from the Manila Creek Granodiorite to the granite porphyry (La/Sm ratio is 4.4–1.7) is probably due to the occurrence of allanite, which has a very large K_D for the LREE (Brooks and others, 1981). Zircon, which is most abundant in the Manila Creek

Granodiorite, has an affinity for the heavy rare-earth elements (HREE) (K_D Lu=345) (Henderson, 1982) and could account for the slight decrease in HREE throughout the suite. The decrease in the middle REE (MREE) is probably a reflection of the presence of sphene and apatite, which also diminish in abundance from the older

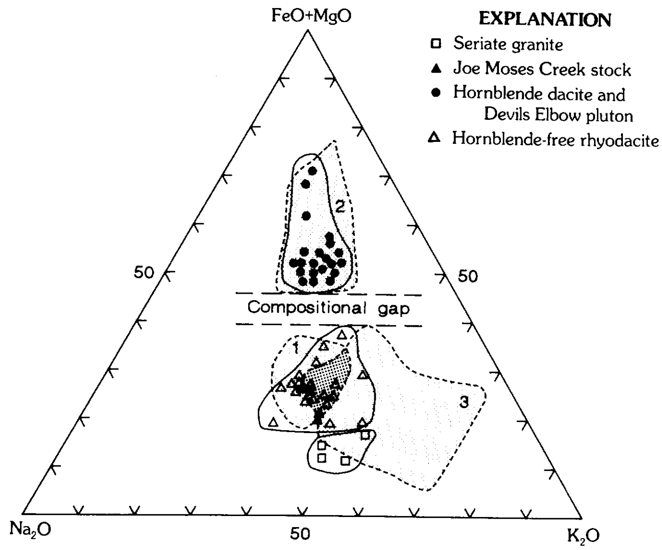

Figure 34. Plot of FeO + MgO, Na_2O, and K_2O for associated intrusive rocks. Early silicic (1), intermediate silicic (2), and late silicic (3) fields of Moye (1984) are shaded for comparison with fields defined in this study.

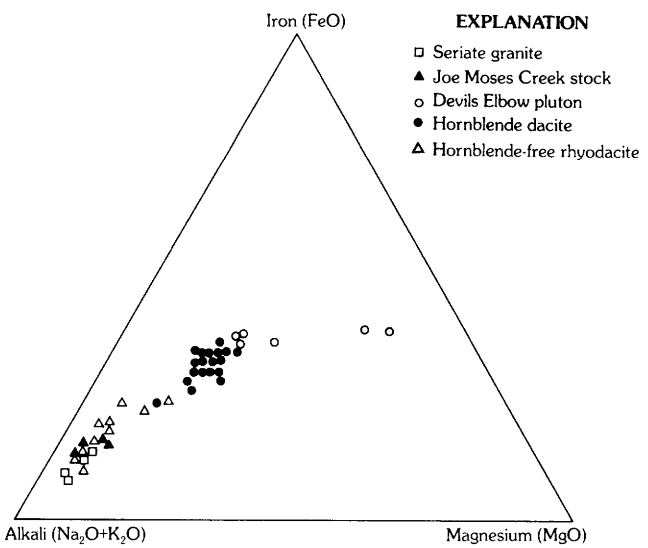

Figure 35. Alkali-iron-magnesium diagram showing alkali enrichment in associated intrusive rocks. Total iron shown as FeO.

Table 5. Average whole-rock chemical composition of hypabyssal dikes

[$\bar{x}$, mean; S, standard deviation. All iron reported as Fe_2O_3]

Species	Hornblende-free rhyodacite (11 analyses)		Hornblende dacite (19 analyses)	
	$\bar{x}$	S	$\bar{x}$	S
SiO_2	70.51	1.38	64.04	2.12
Al_2O_3	15.99	.41	16.01	.48
Fe_2O_3	1.89	.75	4.36	.55
MgO	.81	.41	2.48	.41
CaO	3.13	.57	4.61	.74
Na_2O	3.48	.76	3.28	.37
K_2O	3.62	.59	3.46	.57
TiO_2	.36	.05	.66	.08
P_2O_5	.14	.03	.25	.05
MnO	.07	.05	.08	.02

Manila Creek Granodiorite to the younger granite porphyry. In addition to the overall decrease in REE, Eu values also decrease steadily with age.

The garnet-bearing granite has an anomalous REE pattern compared to the other units in the Coulee Dam Intrusive Suite (fig. 38*B*). The ratio of LREE/MREE decreases relative to enrichment in heavy rare-earth elements (MREE/HREE). The garnet-bearing granite is characterized by a pronounced Eu anomaly that reflects the decrease from older units in modal plagioclase with respect to microcline and quartz. The anomalous REE signature in the granite is due to the low percentage of plagioclase and also to the presence of garnet, which has a high mineral/melt partition coefficient (K_D) for the HREE.

The associated intrusive rocks have more variable REE values (fig. 39) than the main phases of the Coulee Dam Intrusive Suite. The quartz monzodiorite from the Devils Elbow pluton has a La/Lu ratio of 6.0, which is lower than those of the Joe Moses Creek stock and the seriate granite (La/Lu ratio, 21.6–22.3). The Joe Moses Creek stock shows the strongest enrichment of LREE with a La/Sm ratio of 4.5. The seriate granite has the largest negative Eu anomaly.

Mineral Chemistry

Plagioclase and alkali feldspar from the Coulee Dam Intrusive Suite were analyzed by Carlson (1984, p. 127–139) to determine compositional ranges within individual zoned grains and systematic variations within the suite. The results of Carlson's (1984) 123 electron microprobe analyses of eight samples, representing the five units of the Coulee Dam Intrusive Suite and two units of the associated younger intrusions, are summarized in table 8 and, in part, on figure 40. Anorthite content varies considerably within individual zoned grains of plagioclase feldspar, particularly in the Manila Creek Granodiorite and garnet-bearing granite (table 8; fig. 40). The average anorthite content also decreases from andesine to albite toward the center of the suite. Within-sample variation is attributed to the stage at which the individual feldspar grain crystallized or last equilibrated. Average formulas calculated for plagioclase feldspar based on 8 oxygens (table 8) range from $Na_{0.71}\ Ca_{0.28}\ K_{0.01}\ Al_{1.32}\ Si_{2.69}\ O_8$ in the Manila Creek Granodiorite to $Na_{0.80}Ca_{0.15}K_{0.02}$-$Al_{1.19}Si_{2.82}O_8$ in the garnet-bearing granite.

Plagioclase feldspar in the Devils Elbow pluton is typically zoned and shows a decrease in anorthite content outward toward the rim from An_{41}(core) to An_{34}(int.) to An_{27}(rim) in the hornblende-rich varieties, and from An_{29}(core) to An_{23}(rim) in the less mafic varieties (table 8). Oscillatory zoning in plagioclase feldspar from the Joe Moses Creek stock varies from 19 to 42 percent anorthite.

MECHANISM OF INTRUSION OF THE COULEE DAM INTRUSIVE SUITE AND ASSOCIATED INTRUSIVE ROCKS

The Coulee Dam Intrusive Suite was emplaced approximately 54 m.y. ago during the initial stages of

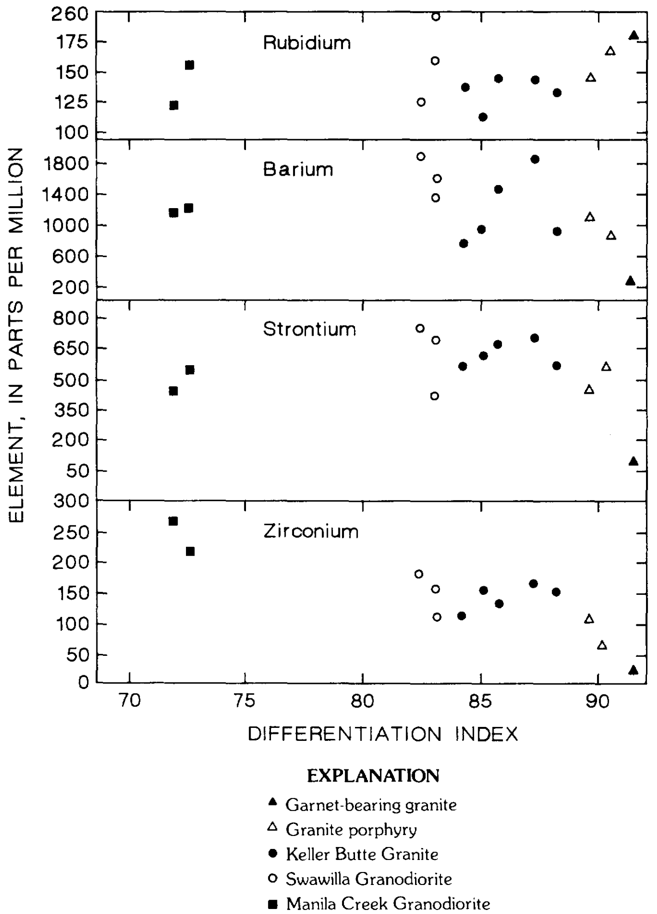

Figure 36. Comparison of zirconium, strontium, barium, and rubidium from Coulee Dam Intrusive Suite with the Thornton and Tuttle Differentiation Index (1960). (Differentiation index = normative quartz + albite + orthoclase + nepheline + kaliophilite + leucite.)

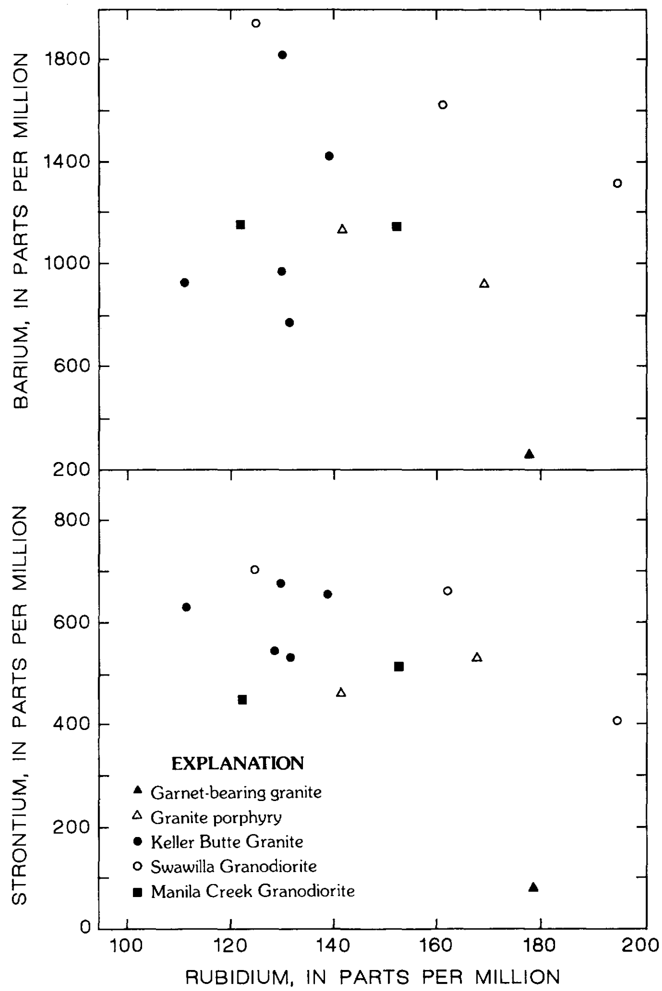

Figure 37. Comparison of rubidium with barium and strontium for the Coulee Dam Intrusive Suite.

Table 6. Major- and trace-element abundances for selected samples in the Coulee Dam Intrusive Suite

[All iron reported as Fe_2O_3. DI, differentiation index (Thornton and Tuttle, 1960); PI, peraluminous index. *, analysis by ICP; all others by XRF]

Rock unit	Manila Creek Granodiorite		Swawilla Ganodiorite			Keller Butte Granite				Granite porphyry			Garnet-bearing granite
Sample No.	81182B	81182A	8130E	8132	81175	81105A	81172A	81184	81192	81185	8110A	8110B	8273B
						Chemical analyses (weight percent)							
SiO_2	69.07	66.96	69.01	71.54	72.89	71.76	74.22	72.05	72.65	73.12	73.29	73.82	76.33
TiO_2	.68	.63	.30	.31	.29	.23	.24	.24	.22	.21	.16	.20	.06
Al_2O_3	15.20	16.38	15.26	15.9	15.64	15.69	14.71	15.22	15.64	14.72	15.31	14.35	14.22
Fe_2O_3	3.16	3.82	1.46	1.17	1.78	.92	.00	1.12	.77	.56	.22	.58	1.18
MnO	.10	.09	.06	.02	.10	.02	.03	.05	.02	.01	.10	.03	.02
McO	1.17	1.11	.28	.39	.70	.30	.12	.24	.21	.08	.17	.19	.00
CaO	2.84	3.26	2.06	2.18	2.13	1.77	1.58	2.02	1.84	1.50	1.24	1.58	.74
Na_2O	2.31	2.98	3.35	3.44	2.44	3.66	3.87	3.57	4.22	3.46	3.95	4.26	2.71
K_2O	3.89	3.20	3.95	3.85	4.61	4.32	3.19	3.20	2.81	3.93	3.96	3.24	5.05
P_2O_5	.26	.24	.11	.11	.09	.08	.07	.08	.07	.06	.04	.07	.04
Total	98.68	98.67	95.84	98.50	100.67	98.75	98.03	97.79	98.45	97.65	98.44	98.32	100.35
DI	73	72	83	82	83	86	88	84	85	87	89	90	92
						Trace elements (ppm)							
$K (\times 10^3)$	24	28	35	33	38	37	28	28	25	34	34	27	39
Rb	124*	153	162	125	195	138	130	132*	112	133	142*	167	176*
Ba	1,154*	1,159	1,601	1,890	1,306	1,415	996	784*	918	1,805	1,071*	903	223*
Sr	452*	518	665	747	406	654	542	533*	630	672	452*	532	67*
Zr	270*	216	152	187	118	133	153	132*	160	163	103*	63	35*
Rb/Sr	0.274	0.295	0.244	0.167	0.480	0.211	0.240	0.248	0.178	0.198	0.314	0.314	2.627
K/Rb	194	183	216	264	195	268	215	212	223	256	239	162	222

Eocene extension. A maximum of 2 m.y. was required for unroofing of the suite, based on the age of the O'Brien Creek Formation (53±1.5 Ma) (Pearson and Obradovich, 1977), which rests unconformably on eroded granitic rocks of the same age. The rapid unroofing of the pluton and evidence for near-surface venting of the pluton suggest that the roof was fairly thin (less than 5 km) or that roof rocks were being tectonically removed during Eocene extensional faulting. Rapid unroofing of the suite may also have resulted from doming of the roof during emplacement. Doming or upheaval of roof rocks is common for shallow intrusions, where plutons create space by dilating the crust in a vertical rather than horizontal direction (Myers, 1975).

The general lack of strain in the outermost unit, the Manila Creek Granodiorite, and its discordant, locally chilled contacts with the country rocks indicate that the Coulee Dam Intrusive Suite was passively emplaced at a fairly shallow depth. The abundance of xenoliths in the border zone of the Manila Creek Granodiorite suggests that stoping was an important mechanism of intrusion. In general, the Manila Creek Granodiorite contains lower grade metasedimentary xenoliths than the more interior unit, the Swawilla Granodiorite. The Swawilla Granodiorite contains biotite-muscovite-sillimanite gneisses that are confined to its inner contact with the Manila Creek Granodiorite. This association suggests that the higher grade rocks may have been brought up from greater depths as the Coulee Dam Intrusive Suite was emplaced, whereas lower-grade xenoliths represent stoped pieces of the roof.

Silicic magmas are generally mobile and volatile-rich at shallow levels (Hildreth, 1979). The volatile-rich character of the suite is indicated by intrusive breccias and quench textures in the younger units. Thus, it is probable that the suite vented either through pipes or, for the granite porphyry, along fissures marginal to the eastern bounding fault of the Republic graben. The granite porphyry forms a rectangular mass that is elongate parallel with the north-northeast-trending graben

Table 7. Major-element, trace-element, and rare-earth-element contents for representative units in the Coulee Dam Intrusive Suite and associated intrusive rocks

[n.d., not determined]

Rock unit	Manila Creek Granodiorite	Swawilla Granodiorite	Keller Butte Granite	Granite porphyry	Garnet bearing granite	Seriate granite stock	Joe Moses Creek	Devils Elbow pluton
Sample No.	81182B	8130E	81184	8110A	8273A	81180B	82150B	8117
Chemical analyses (weight percent)								
SiO_2	69.07	69.01	72.05	73.29	76.33	75.23	71.37	56.13
TiO_2	.68	.30	.24	.16	.06	.20	.24	1.09
Al_2O_3	15.20	15.26	15.22	15.31	14.22	14.19	15.28	11.24
Fe_2O_3	3.16	1.46	1.12	.22	1.18	.55	2.32	8.09
MnO	.10	.06	.05	.10	.02	.02	.03	.15
MgO	1.17	.28	.24	.17	0	.40	.33	10.06
CaO	2.84	2.06	2.02	1.24	.74	1.65	2.33	9.03
Na_2O	2.31	3.35	3.57	3.95	2.71	3.19	3.33	1.89
K_2O	3.89	3.95	3.20	3.96	5.05	3.30	3.57	1.54
P_2O_5	.26	.11	.08	.04	.04	.07	.11	.30
Total	98.68	95.84	97.79	98.44	100.35	98.80	98.91	99.52
Trace elements (ppm)								
Ba	1154	1890	784	1071	223	577	1426	376
Rb	124	125	132	142	176	139	n.d.	35
Sr	452	774	533	452	67	452	557	343
Zr	270	152	132	103	35	95	n.d.	147
Rare-earth elements (ppm)								
La	62.41	28.19	27.89	12.97	8.74	22.97	29.03	20.15
Ce	115.70	53.92	51.27	24.16	17.55	41.88	53.15	45.06
Pr	12.28	7.00	6.14	3.11	2.25	5.24	6.20	6.24
Nd	47.64	27.26	24.19	13.21	10.00	21.25	23.00	28.87
Sm	7.09	4.12	4.28	2.54	2.92	3.96	3.54	5.93
Eu	1.54	1.13	.77	.54	.34	.64	.78	1.53
Gd	4.93	2.65	3.05	1.92	3.04	2.88	2.64	5.12
Dy	3.43	1.68	2.14	1.55	5.52	2.07	1.92	4.31
Ho	.76	.53	.45	.32	1.52	.42	.52	.82
Er	1.96	.97	1.07	.87	6.37	10.1	1.14	2.36
Yb	1.61	.73	.80	.76	10.17	.80	.98	1.99
Lu	.24	.09	.08	.08	1.80	.09	.14	.29
Total REE	259.59	128.27	122.13	62.03	70.22	112.30	123.04	122.67

structures. Its apparent structural control suggests that the north-northeast-trending structures were active during the emplacement of at least the younger units in the suite.

The Devils Elbow pluton and Joe Moses Creek stock are clearly subvolcanic bodies. They have polygonal to rectangular outcrop patterns with flat roofs and steep, locally fault-bounded contacts. The Devils Elbow pluton

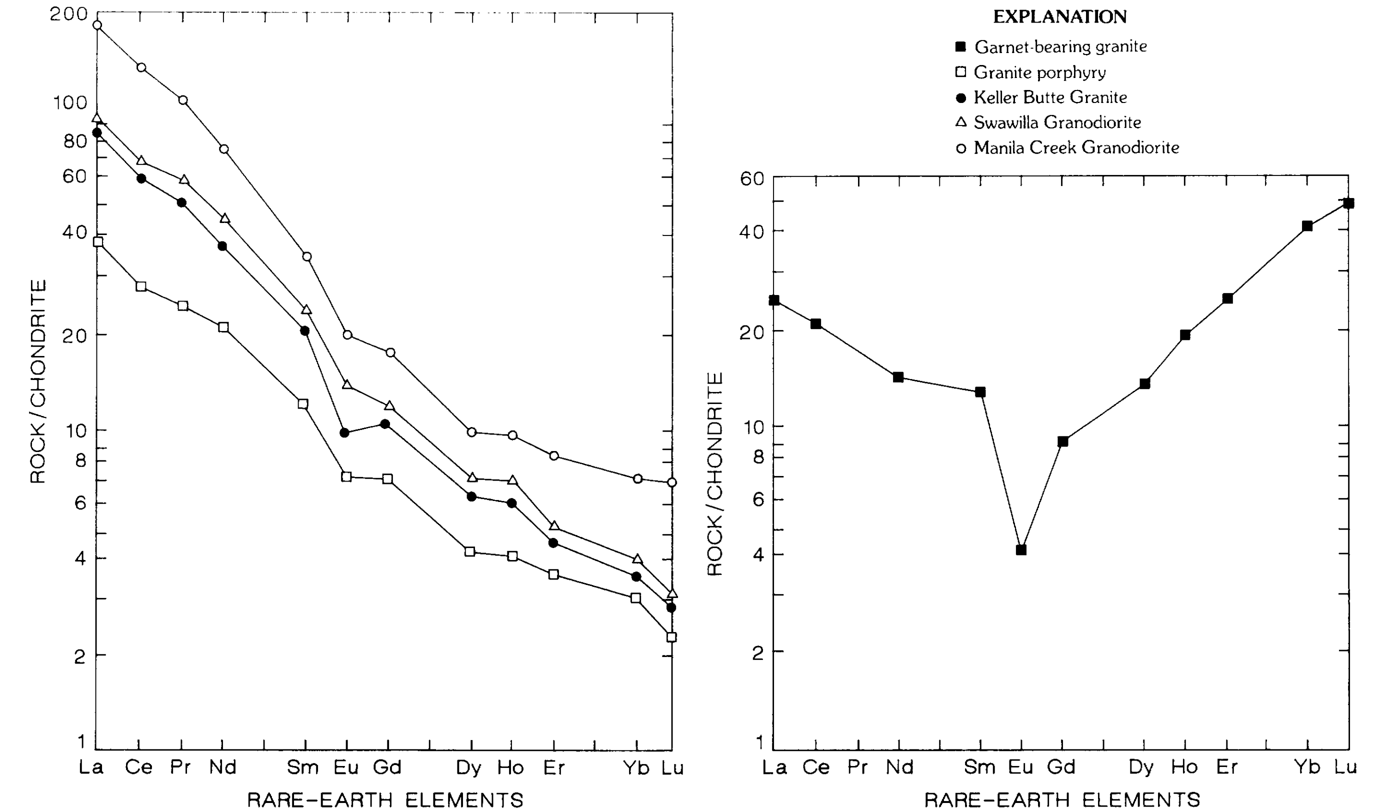

Figure 38. Chondrite-normalized rare-earth-element abundances in Coulee Dam Intrusive Suite.

grades texturally upward from equigranular to porphyritic granodiorite that is cut by hypabyssal dikes (hornblende dacite) (Moye, 1984). According to Moye (1984), the dacite dikes cut the upper porphyritic facies of the pluton but not the more equigranular interior phase. These relations indicate that the dikes emanated from the interior of the Devils Elbow body and intruded a subvolcanic roof. North of the study area, dikes of similar composition are also feeders to flows within the Sanpoil Volcanics (Muessig, 1962). The close spatial and textural relations between plutonic and volcanic rocks requires a roof probably less than 2 km thick in most places. Although the Devils Elbow pluton and Joe Moses Creek stock are confined to the horst between the Republic and Keller grabens, there is no evidence that the units were involved in the faulting. The western contact of the Joe Moses Creek stock that abuts the Sherman fault was not displaced or affected by cataclasis, whereas the Keller Butte Granite on the opposite side of the fault is brecciated and altered. Similar relations were described by Moye (1984) for the northern part of the Devils Elbow pluton. These relations indicate that the plutons were intruded after most movement on the Sherman fault and used the fault as a conduit for the intrusion of magma.

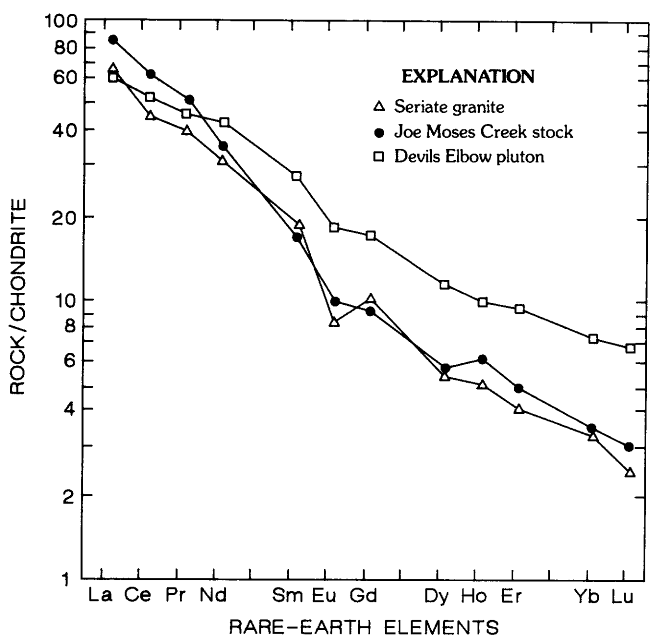

Figure 39. Chondrite-normalized rare-earth-element abundances for associated intrusive rocks.

Table 8. Microprobe analyses of feldspars from the Coulee Dam Intrusive Suite and associated younger intrusive rocks

[—, not applicable]

Rock unit	Average feldspar formula[1]		Range[2]			Number of analyses
	Plagioclase	Microcline-orthoclase	Core	Int	Rim	
Manila Creek Granodiorite	$Na_{0.71}K_{0.01}Ca_{0.28}Al_{1.32}Si_{2.69}O_8$	$K_{0.81}Na_{0.16}Al_{1.03}Si_{2.98}O_8$	An_{36-33}	—	An_{30-24}	20
Swawilla Granodiorite	$Na_{0.23}K_{0.01}Ca_{0.05}Al_{0.33}Si_{3.67}O_8$	$K_{0.87}Na_{0.10}Al_{1.05}Si_{2.97}O_8$	An_{24-22}	—	An_{22-17}	19
Keller Butte Granite	$Na_{0.82}K_{0.01}Ca_{0.16}Al_{1.20}Si_{2.82}O_8$	$K_{0.82}Na_{0.14}Al_{1.04}Si_{2.98}O_8$	An_{19}	An_{18}	An_{12}	11
Granite porphyry	$Na_{0.84}K_{0.01}Ca_{0.14}Al_{1.21}Si_{2.81}O_8$	$K_{0.82}Na_{0.14}Al_{1.04}Si_{2.98}O_8$	An_{17-14}	—	An_{15-12}	5
Garnet-bearing granite	$Na_{0.80}K_{0.02}Ca_{0.15}Al_{1.19}Si_{2.82}O_8$	$K_{0.85}Na_{0.11}Al_{1.04}Si_{2.98}O_8$	An_{14}	An_{14}	An_2	34
Devils Elbow pluton	$Na_{0.60}K_{0.02}Ca_{0.32}Al_{1.36}Si_{2.66}O_8$	—	An_{41}	An_{34}	An_{27}	21
			An_{38}	—	An_{32}	
Joe Moses Creek stock	$Na_{0.68}K_{0.03}Ca_{0.27}Al_{1.32}Si_{2.70}O_8$	$K_{0.12}Na_{0.03}Al_{0.19}Si_{0.66}O_8$	An_{42}	An_{35}	An_{19}	13

[1]Average of all analyses for unit; includes average of strongly zoned grains; formula calculated on basis of 8 oxygens.
[2]Range in anorthite content for zoned grains.

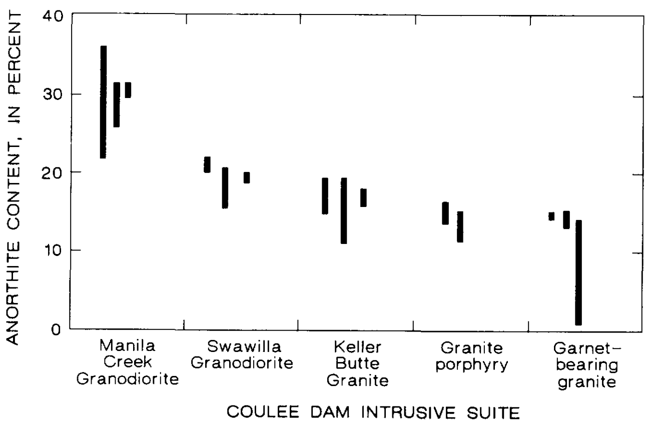

Figure 40. Range in anorthite content of plagioclase feldspar from the Coulee Dam Intrusive Suite. Each bar shows range in anorthite content within a single grain.

ORIGIN OF THE MAGMA

Major- and trace-element chemistry indicate that the Coulee Dam Intrusive Suite evolved from a magma that was rich in silica and alumina and somewhat depleted in REE. The suite is also enriched in strontium and barium and has a lower rubidium/strontium ratio than average calc-alkaline granite (Turekian and Wedepohl, 1961). The high strontium and low rubidum and REE values suggest that the magma was relatively unevolved with respect to those elements. The fact that rocks of intermediate composition in the suite and in the Colville batholith are not abundant may indicate that the magma evolved from a simple initial melt rather than as a differentiate. A similar line of reasoning was used by Hudson and others (1981) for the intrusive complexes associated with the Quartz Hill molybdenum deposit in Alaska. The Coulee Dam Intrusive Suite is similar in many respects to the intrusive rocks associated with the Quartz Hill deposit. Like the Coulee Dam Intrusive Suite, the Quartz Hill granitic rocks are also rich in SiO_2 and strontium but have low rubidium/strontium ratios and rubidium values. Based on the major- and trace-element signature and low $^{87}Sr/^{86}Sr$ ratios (0.705), Hudson and others (1981) concluded that the Quartz Hill rocks evolved from a simple initial melt generated from the mantle or lower crust from rapidly recycled mantle-derived material.

The Coulee Dam Intrusive Suite is characterized by intermediate initial $^{87}Sr/^{86}Sr$ ratios (0.707) (R.J. Fleck, written commun., 1985) and by a 1,700-Ma inherited lead component (D. L. Parkinson, written commun., 1986). These data, together with high strontium and low rubidium and REE values, suggest that the suite probably evolved from a simple initial melt generated from lower crustal rocks that were, in part, Precambrian in age. Intrusion of the suite was accommodated by Eocene crustal extension, which also resulted in graben formation and in detachment faulting on the Okanogan, Kettle, and Lincoln gneiss domes.

Table 9. Whole-rock chemical analyses and CIPW norms for hornblende dacite dikes from Mount Tolman

[n.d., not determined]

Sample No.	MT254845	MT254935	MT268173	MT276155	MT166172	MT172131	MT185119	MT251805	MT253435	MT253114
					Chemical analyses (weight percent)					
SiO_2	63.85	64.07	57.67	68.03	63.77	63.88	63.87	65.77	71.39	64.82
Al_2O_3	15.67	15.22	15.65	15.78	16.58	17.06	15.44	16.43	16.03	15.72
FeO	4.86	4.73	6.03	3.34	4.50	3.91	4.03	3.72	1.10	4.39
MgO	2.30	2.48	4.03	2.57	2.61	2.30	2.72	2.63	.51	2.62
CaO	4.79	5.23	7.30	3.40	5.06	4.97	4.43	4.40	2.60	4.29
Na_2O	3.53	3.05	3.35	2.43	3.41	3.60	3.33	3.04	4.68	3.16
K_2O	3.57	3.86	4.51	3.49	2.90	3.20	5.10	3.00	3.14	3.62
TiO_2	.76	.74	.78	.54	.64	.58	.60	.56	.32	.76
P_2O_5	.33	.31	.26	.18	.24	.20	.20	.20	.12	.31
MnO	.09	.08	.13	.08	.08	.10	.08	.08	.06	.08
Total	99.99	100.00	100.01	100.00	100.02	99.99	100.00	100.01	100.00	99.99
					CIPW norms					
Q	17.143	18.286	3.125	29.319	18.371	16.941	13.082	23.119	26.042	19.888
C	n.d.	n.d.	n.d.	2.254	n.d.	n.d.	n.d.	.661	.492	—
or	21.098	22.810	26.648	20.623	17.133	18.912	30.137	17.726	18.555	21.394
ab	29.873	25.808	28.344	20.562	28.849	30.465	28.178	25.721	39.601	26.742
an	16.370	16.439	14.344	15.691	21.364	20.942	12.120	20.520	12.115	18.020
wo	2.188	3.124	8.421	n.d.	.904	1.006	3.570	n.d.	n.d.	.518
en	5.729	6.176	10.036	6.401	6.499	5.729	6.774	6.549	1.270	6.526
fs	1.941	1.885	2.723	1.344	1.920	1.672	1.681	1.540	.257	1.635
mt	3.451	3.349	4.277	2.363	3.189	2.770	2.856	2.639	.783	3.118
il	1.444	1.405	1.481	1.026	1.215	1.102	1.140	1.063	.608	1.444
ap	.782	.734	.616	.426	.568	.474	.474	.474	.284	.734

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Table 9. Whole-rock chemical analyses and CIPW norms for hornblende dacite dikes from Mount Tolman—Continued

Sample No.	MT41485	MT41715	MT10915	MT17395	MT321325	MT47635	MT120215	MT831405	MT166715	MT254565
					Chemical analyses (weight percent)					
SiO_2	68.78	64.12	64.62	64.87	64.95	66.06	64.89	64.55	65.33	65.80
Al_2O_3	15.43	16.13	15.76	16.31	16.19	15.66	15.96	16.51	16.11	15.41
FeO	2.82	4.72	4.41	4.39	3.92	4.09	4.79	4.09	3.97	4.23
MgO	1.54	2.24	2.78	2.34	2.68	2.55	2.49	2.77	2.49	2.25
CaO	3.01	4.44	5.06	3.83	4.66	4.33	4.46	4.22	4.43	4.25
Na_2O	3.28	3.72	2.90	3.47	3.52	2.76	2.40	3.47	3.24	3.12
K_2O	4.28	3.23	3.26	3.45	3.00	3.43	3.81	3.23	3.33	3.79
TiO_2	.46	.79	.65	.72	.59	.62	.66	.64	.60	.63
P_2O_5	.19	.30	.25	.31	.22	.21	.21	.24	.22	.22
MnO	.06	.09	.09	.09	.08	.08	.10	.09	.08	.09
Total	99.99	100.01	100.00	100.00	100.00	99.99	100.00	100.01	99.99	100.00
					CIPW norms					
Q	24.608	17.787	20.827	19.880	19.370	23.631	22.724	18.752	20.623	21.107
C	.384	n.d.	n.d.	.646	n.d.	.037	.282	.208	n.d.	n.d.
or	25.294	19.085	19.264	20.387	17.728	20.271	22.514	19.085	19.680	22.396
ab	27.757	31.474	24.539	29.362	29.785	23.357	20.308	29.359	27.419	26.401
an	13.693	17.773	20.357	16.975	19.515	20.111	20.754	19.365	19.581	16.850
wo	n.d.	.957	1.299	n.d.	.904	n.d.	n.d.	n.d.	.401	1.168
en	3.836	5.578	6.924	5.828	6.675	6.351	6.201	6.898	6.202	5.604
fs	1.113	1.802	1.845	1.720	1.610	1.678	2.084	1.663	1.632	1.769
mt	2.001	3.349	3.132	3.117	2.784	2.900	3.393	2.900	2.813	3.001
il	.874	1.500	1.234	1.367	1.121	1.178	1.253	1.215	1.140	1.197
ap	.450	.711	.592	.734	.521	.497	.497	.568	.521	.521

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Table 10. Whole-rock chemical analyses and CIPW norms for hornblende-free rhyodacite dikes from Mount Tolman

[n.d., not determined]

Sample No.	MT148995	MT180525	MT91195	MT166125	MT52965	MT661865	MT671255	MT254795	MT275795	MT268875
				Chemical analyses (weight percent)						
SiO_2	72.32	71.78	68.79	70.78	69.84	65.08	69.40	70.08	71.73	70.82
Al_2O_3	15.46	16.27	16.34	15.30	16.54	16.04	15.91	16.16	16.38	16.26
FeO	1.12	1.48	2.51	2.23	2.89	3.77	2.26	1.59	1.36	1.00
MgO	.47	.49	1.52	.68	.61	2.12	1.24	.50	.65	.66
CaO	2.95	4.21	3.88	2.34	2.84	4.58	3.54	2.92	3.46	2.73
Na_2O	2.93	1.99	2.87	3.68	4.27	3.95	3.35	4.20	3.27	3.80
K_2O	4.25	3.04	3.32	4.32	3.38	3.45	3.57	3.81	2.55	4.14
TiO_2	.28	.31	.44	.34	.36	.56	.40	.35	.33	.34
P_2O_5	.10	.14	.16	.14	.13	.20	.16	.13	.13	.13
MnO	.07	.22	.06	.07	.05	.07	.05	.08	.07	.06
Total	100.01	100.00	100.01	99.99	100.00	100.01	99.99	99.99	100.00	99.99
				CIPW norms						
Q	32.101	38.838	28.832	26.774	25.128	16.986	26.883	24.047	34.740	26.330
C	.916	2.387	1.354	.651	1.005	n.d.	.482	.129	2.261	.875
or	25.112	17.964	19.617	25.531	19.973	20.385	21.098	22.517	15.069	24.467
ab	24.790	16.839	24.283	31.142	36.132	33.420	28.350	35.543	27.670	32.158
an	13.980	19.971	18.202	1.695	13.240	15.845	16.518	13.638	16.316	12.695
wo	n.d.	n.d.	n.d.	n.d.	n.d.	2.325	n.d.	n.d.	n.d.	n.d.
en	1.170	1.220	3.785	1.694	1.519	5.279	3.089	1.470	1.619	1.644
fs	.370	.827	.940	.964	.685	1.552	.856	.561	.427	.174
mt	.797	1.044	1.783	1.581	1.334	2.682	1.595	1.131	.971	.711
il	.532	.589	.836	.646	.684	1.063	.760	.665	.627	.646
ap	.237	.332	.379	.332	.308	.474	.379	.308	.308	.308

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