U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

GEOLOGY OF PART OF THE MAZAMA QUADRANGLE, OKANOGAN COUNTY, WASHINGTON

by

VICTORIA R. TODD[1]

Open-File Report 95-523

1995

[1]U.S. Geological Survey, Department of Earth Sciences, University of California, Riverside, California 92521

GEOLOGY OF PART OF THE MAZAMA QUADRANGLE,

OKANOGAN COUNTY, WASHINGTON

by

V.R. Todd

1995

Geology of part of the Mazama quadrangle, Okanogan County, Washington

INTRODUCTION

The Mazama 15-minute quadrangle is located in north-central Washington in the east half of the Concrete 1° by 2° quadrangle (fig. 1). U.S. Geological Survey mapping in the east half of the Concrete sheet in 1982 and 1983 was part of a crustal transect across the northwestern United States. Previous work in the Mazama quadrangle dealt chiefly with the sedimentary and volcanic rocks of the Mesozoic Methow basin (Dixon, 1959; Cole, 1973; Barksdale, 1975; Trexler, 1984, 1985; Rau, 1987). The present distribution of supracrustal rocks in the region does not represent the basin's original shape and extent because it was truncated by regional faults (fig. 1). The Hozameen and Twisp River-Foggy Dew faults form the west boundary of the present structural basin, separating it from Paleozoic through Mesozoic terranes that comprise the North Cascades core. The Pasayten fault, which passes through the northeast corner of the Mazama quadrangle, separates rocks of the Mesozoic Okanogan Range batholith on the east from the Methow basin on the west.

The Methow basin exposes a thick (15-20 km) sequence of unmetamorphosed to weakly metamorphosed Jurassic and Cretaceous sedimentary and volcanic rocks (Barksdale, 1975). In general, the older rocks are exposed on the flanks and in the southern part of the basin. The sequence is dominantly marine, although the Cretaceous part includes both marine and nonmarine rocks. The Jurassic and lower Lower Cretaceous part of the section consists of volcanic, volcaniclastic, and clastic strata that were deposited in and adjacent to a marine basin (Tennyson and Cole, 1978). These rocks are unconformably overlain by plagioclase arkose, shale, and granitoid-bearing conglomerate, all of which are Hauterivian through Albian in age (Barksdale, 1975; McGroder and others 1990), that were deposited in similar marine and nearshore environments. Albian and lower Upper Cretaceous strata, at least locally unconformable on the older rocks, consist of interbedded marine chert-pebble conglomerate and mudstone that interfinger with plant-bearing, fluvial and deltaic plagioclase arkose and also with andesitic flows and pyroclastic rocks. These strata indicate shoaling and partial emergence of the marine basin with local volcanism (Tennyson and Cole, 1978; Trexler, 1985; McGroder and others, 1990). At about the same time, the basin underwent broad regional folding, faulting, and intrusion of Late Cretaceous stocks. Intrusion of Late Cretaceous sills and dikes and Eocene plutons and dikes largely postdated compression and, at least locally, accompanied extension and normal faulting along the eastern margin.

PLUTONIC ROCKS

Button Creek stock

The Button Creek stock (Barksdale, 1975) crops out in the northeastern part of the Mazama quadrangle in the west wall of Eightmile Creek. The stock is bounded on the east by the Pasayten fault, on the south by faults in Ortell Creek, and on the west by the Isabella Ridge fault. To the north, it is overlain depositionally and (or) in low-angle fault contact by the Panther Creek Formation of Barksdale (1975) and intruded probable Jurassic metavolcanic rocks (Haugerud and others, 1993; R.A. Haugerud, oral commun., 1993). Basement equivalent to the Button Creek stock may continue north of the study area beneath the volcanics of Billy Goat Mountain (Staatz, and others, 1971) to the Island Mountain area (fig. 2), where no source was found by White (1986) for monolithologic boulder-conglomerate composed of hornblende tonalite.

The Button Creek stock consists of medium- to coarse-grained, moderately foliated to relatively massive subidiomorphic biotite-hornblende tonalite (Streckeisen, 1973)(fig. 2). Hornblende is prismatic, and biotite is present as large irregular grains (color index 23). The rock is locally heterogeneous due to concentrations of mafic grains and abundant, irregular fine-grained mafic inclusions as large as 25 cm. The outcrops in lower Ortell Creek consist of fine- to medium-grained mylonitic tonalite. Two samples of the stock yielded K-Ar hornblende ages of 153.2±3.8 Ma (massive tonalite) and 150.2±3.8 Ma (mylonitic tonalite) (table 1, Nos. 1 and 2, respectively). Biotite from the older of the two samples was also dated at 145.9±3.6 Ma (table 1, No. 1).

Okanogan Range batholith

A small part of the Okanogan Range batholith is exposed east of the Pasayten fault in the northeast corner of the Mazama quadrangle. The plutons present in the Mazama quadrangle are the trondhjemites of Eightmile Creek and Lamb Butte (Todd, 1995).

Trondhjemite of Eightmile Creek—The trondhjemite of Eightmile Creek crops out in a narrow (1-2 km) zone along the west margin of the Okanogan Range batholith. The rock is medium to coarse grained and white-weathering, with a strong foliation caused by the preferred alignment of recrystallized igneous grains. The unit consists of plagioclase (andesine), quartz, biotite, hornblende, and traces of K-feldspar and has a color index of 9 to 10. Quartz occurs as lenticular gray grains and plagioclase as ovoid to prismatic white- weathering grains as long as 2.5 cm. The unit's most distinctive feature is the presence of abundant, locally stout hornblende prisms that range in length from 0.5 to 2.5 cm. Some hornblende grains appear euhedral, but most have ragged, recrystallized margins, and others are present in lenticular recrystallized aggregates. Biotite in scaly aggregates is about as abundant as hornblende. Locally, the unit carries mafic inclusions that are flattened parallel to foliation, but in general inclusions are rare. Both the east and west contacts of the trondhjemite of Eightmile Creek are marked by zones of ductile shear. Along the west margin of the unit, the trondhjemite becomes progressively mylonitic toward the Pasayten fault until the original igneous grains are no longer visible in hand specimen. Along the east margin, the trondhjemite of Eightmile Creek becomes progressively more recrystallized toward the trondhjemite of Lamb Butte. There is a narrow (100-400 m) transitional zone between the two units consisting of trondhjemite that contains sparse hornblende relics and biotite-chlorite-epidote-sphene aggregates. The contact is drawn where hornblende relics are no longer present.

Hurlow and Nelson (1993) determined a U-Pb crystallization age of 110-112 Ma for the trondhjemite of Eightmile Creek. A sample of trondhjemite with large idiomorphic hornblendes from the Doe Mountain quadrangle to the east yielded concordant K-Ar ages of 104.8±2.6 and 105.7±2.6 Ma on hornblende and biotite, respectively (Todd, 1995). These ages are considered to be cooling ages of the pluton.

Trondhjemite of Lamb Butte—The trondhjemite of Lamb Butte consists of light-gray-weathering medium-grained trondhjemite and rare granodiorite with a color index of 7 to 9. The rock's texture is strongly foliated to porphyroclastic. Characteristic of the unit are abundant 1- to 1.5-cm-long ribbon quartz grains, 1- to 3-mm aggregates of recrystallized biotite, and sparse lensoid biotitic clots from 2.5 to 10 cm long, all oriented parallel to foliation and imparting a gneissic texture to the rock. A penetrative down-dip lineation is defined by aligned mineral grains and aggregates and locally by crenulation or ribbing.

The trondhjemite of Lamb Butte grades westward into the trondhjemite of Eightmile Creek, as described above. Hurlow and Nelson (1993) estimated the U-Pb crystallization age of the trondhjemite of Lamb Butte to be 111 Ma. Replicate analyses of biotite from a sample of the Lamb

Butte unit from the Doe Mountain quadrangle yielded K-Ar ages of 102.5±2.6 and 99.8±2.5 Ma (Todd, 1995). These ages may represent the age of ductile deformation of the Lamb Butte unit.

Fawn Peak stock

The Fawn Peak stock (Barksdale, 1975) is a northwest-elongate body in the central part of the Mazama quadrangle that intruded the Winthrop Sandstone of Barksdale (1948, 1975) and the Midnight Peak Formation. The stock's south contact with these units is a fault and its southwest contact is covered by alluvium in the Methow Valley. Its shape is inferred to be partly sill-like from the near concordance of the stock's north and northeast boundaries with bedding in the Winthrop Sandstone and Midnight Peak Formation (see cross section *B-B'*). The stock may have been emplaced initially as a large sill that intruded across the surrounding units as it grew.

The Fawn Peak stock is composite and consists mainly of diorite with lesser monzodiorite and quartz diorite (fig. 2). As described by Riedell (1979), the informally named Fawn Peak intrusive complex consists of a main fine- to medium-grained diorite phase, subordinate coarse-grained diorite phase, and several late quartz diorite phases distributed more or less peripherally around the stock. Fawn Peak itself is underlain by a large sill, or sill complex, composed of quartz diorite porphyry (Riedell, 1979). In the western part of the stock, between Goat Peak and Flagg Mountain, a complex series of alteration and mineralization events associated with the younger, quartz-bearing intrusive phases culminated in a low-grade porphyry copper-molybdenum system (Riedell, 1979).

The Fawn Peak stock has a chilled, porphyro-aphanitic margin as wide as 1 km along much of its north and south boundaries. Part of the south margin of the stock was mapped by Barksdale (1975) as andesite belonging to the Midnight Peak Formation. However, these rocks are modally and chemically indistinguishable from, and grade into, fine- and medium-grained diorite in the inner part of the stock. The fresh marginal rock is dark gray or black, massive, with 1- to 2-mm plagioclase and mafic phenocrysts set in an aphanitic groundmass. Thin-section views show euhedral plagioclase laths and tablets and stubby euhedral pyroxene phenocrysts set in a fine-grained groundmass of plagioclase, pyroxene, and black opaque altered to chlorite, sericite, and calcite. Some groundmass may have been glassy, particularly next to epidotized sedimentary inclusions. Less chilled marginal rocks contain no fine-grained groundmass but consist of a felty intergrowth of subhedral plagioclase laths and prisms containing smaller subhedral and anhedral grains of hypersthene and augite. The marginal rock is closely jointed and weathers to angular orange, brown, and greenish-gray blocks. Fractures are filled by white quartz and calcite, and hairline cracks are locally filled by hornblende.

The marginal facies carries scattered 1- to 2-cm, fine-grained mafic inclusions and rounded epidotized fragments 2 to 15 cm across of the Midnight Peak Formation. The epidotized fragments are surrounded by reaction haloes in the diorite. Tabular inclusions of hornfelsed sandstone and siltstone (probably the Winthrop Sandstone) 20 to 40 meters long are oriented parallel to the contacts of the stock. Commonly, faults have developed along the margins of these inclusions. Pegmatitic plagioclase-hornblende veins are fairly common in the marginal facies. Fine- and coarse-grained diorite alternate over distances of 2 to 3 meters near the margins of the Fawn Peak stock in some places. Complex dike patterns among these phases suggest repeated surges of Fawn Peak magma into a partly crystallized margin.

The marginal facies gives way toward the center of the Fawn Peak stock to medium-gray, fine- to medium-grained equigranular diorite that carries 1- to 4-mm subhedral plagioclase and hornblende grains. Scattered larger hornblende prisms give some rocks a subporphyritic texture. Coarse-grained diorite present chiefly in the northern part of the stock weathers lighter gray in color and carries subhedral plagioclase and mafic grains typically 1 to 2-cm long. Locally, mafic minerals are interstitial to abundant 1- to 2-cm plagioclase grains. Much diorite is weakly foliated because of the alignment of both mafic grains and plagioclase crystals. In the Fawn Creek drainage, foliation dips steeply to the northeast. North of Fawn Creek, it appears to follow the outlines of the elliptical body of coarse-grained diorite mapped by Riedell (1979), which may represent late upwelling of magma in the center of the stock.

Modal minerals of the diorite are plagioclase, hornblende, pyroxene, biotite, and minor quartz and K-feldspar. Thin-section views show that most rocks have undergone hydrothermal alteration. Plagioclase is present as euhedral laths, tablets, and radiating clusters of grains that exhibit delicate oscillatory zoning and polysynthetic twinning. Plagioclase is zoned from labradorite cores to andesine rims. Hornblende is the chief mafic mineral in quartz-bearing diorite. The mineral occurs as euhedral prisms, acicular grains, and in multigrain aggregates. Where least altered, hornblende is medium brown to olive brown, but altered varieties are pale olive to yellowish tan or have pale reddish-tan cores and pale-green rims. In some rocks, large hornblende oikocrysts enclose single small irregular pyroxene relics as well as 3 to 6 subhedral early plagioclase grains. The oikocrysts are surrounded by felty intergrowths of plagioclase laths. Pyroxene, generally more abundant than hornblende in quartz-free rocks, is mainly subhedral augite in single grains and aggregates, commonly partly altered or pseudomorphed by actinolite, biotite, and black opaque minerals. Biotite is present as coarse dark-brown oikocrysts surrounding small relict grains of brown hornblende and augite, and as smaller, pale-reddish-brown to straw- colored irregular grains and aggregates replacing pyroxene. Textures locally suggest that the reaction of early pyroxene with magma to form hornblende and, later, biotite was followed closely by hydrothermal alteration. Quartz ranges from 0 to 5 percent and occurs as small interstitial grains. K-feldspar may be present as thin films and pockets interstitial to, and in part replacing, plagioclase. Stained slabs show that K-feldspar is distributed evenly throughout the rock. Although it is difficult to determine whether the mineral was magmatic or secondary, some K-feldspar is found with magmatic biotite and, thus, could be a primary phase. K-feldspar-rich veins suggest late introduction of potassic fluids in some rocks. Accessory minerals of the diorite include a black opaque mineral and apatite. Alteration minerals are actinolite, chlorite, biotite, sericite, epidote, calcite, and phyllosilicates.

Swarms of porphyritic sills and dikes are associated with the margins of the Fawn Peak stock. They cut the stock and extend for distances of 1 km or more into the surrounding country rocks. The sills are associated with hydrothermal alteration and brittle shearing of the stock and inliers of country rocks. Some sills are probably a quenched facies of the diorite, but others are identical to ubiquitous Late Cretaceous porphyritic sills and dikes (discussed below). These regionally extensive sills and dikes may be related to Riedell's (1979) late quartz-bearing plugs and dikes.

Magmatic biotite and finer grained secondary biotite from fine- to medium-grained diorite gave K-Ar ages of 87.9±3.5 Ma, respectively (Livingstone and Wolfhard, 1976), while magmatic biotite from dacite porphyry yielded a K-Ar age of 87.6±3.3 Ma (Riedell, 1979). In the present study, hornblende was found to be too intergrown with other mafic minerals for concentration, but magmatic biotite from monzodiorite gave a K-Ar age of 86.9±2.2 Ma (table 1, No. 3). These ages are consistent with the Early and Late Cretaceous ages of the host rocks of the stock--the Winthrop Sandstone (Albian through Cenomanian) and the underlying Virginian Ridge Formation of Barksdale (1948) (Albian through Turonian; see section on Virginian Ridge Formation for discussion of problems of its age).

In the area between Fawn Peak and Rendezvous Mountain, the contact between the Fawn Peak stock and the underlying Winthrop Sandstone dips steeply to the southwest concordant with bedding in the sandstone. Farther to the north, both the contact and bedding in the Winthrop Sandstone are overturned toward the southwest. North of Goat Creek, Barksdale's (1975) Ventura Member of his Midnight Peak Formation thins abruptly southward toward the stock and overturned northeast-dipping bedding in the Winthrop Sandstone and Ventura Member are juxtaposed against upright southwest-dipping bedding in the volcanic member of the Midnight Peak Formation. These relations suggest that the contact between the Winthrop unit and the stock is probably a fault. Apparently, the stock was largely emplaced into, and cuts out, the weakly resistant Ventura Member. Although no well-developed contact aureole is present, the Winthrop Sandstone is altered to hornfels locally against marginal dikes of the stock and much of the sandstone near the stock is extremely hard.

The Fawn Peak stock is spatially associated with the Midnight Peak Formation in the axis of the Goat Peak syncline. The stock underlies and interfingers with the volcanic (upper) member of the Midnight Peak Formation with a relatively flat contact north of Goat Creek. Here, the contact is marked by numerous porphyritic dikes, brittle shears, and associated hydrothermal alteration. South of Goat Creek, the Midnight Peak Formation is missing except at Grizzly Mountain where it is downfaulted, along with the Winthrop Sandstone, against the stock.

Contact relations, and similarities in the range of compositions and ages of the units suggest that the Fawn Peak stock is the hypabyssal equivalent of the volcanic rocks of the Midnight Peak Formation, as suggested originally by Barksdale (1975) and Riedell (1979). Fragments of diorite are incorporated in breccia of the Midnight Peak Formation. In a narrow zone near the contact between the Midnight Peak Formation and the stock, the Midnight Peak unit contains poorly exposed areas of fine-grained igneous rocks with no breccia fragments, and the stock consists of highly fractured, very fine-grained igneous rocks. Outcrops of these fine-grained rocks in both units consist of as much as 50 percent porphyritic dikes. Whether they are flow rocks in the Midnight Peak Formation or chilled diorite, or both, the fine-grained rocks appear to represent a gradation between the two units. The contact was drawn in the middle of this gradational zone.

Porphyritic sills and dikes

Porphyritic sills and dikes are markedly abundant in the study area. Although they are generally concordant with bedding in the sedimentary rocks, in detail some bodies are discordant. The sills and dikes are exposed along strike for as much as 2 km, and are associated with broad zones of hydrothermal alteration and brittle shearing (slickensides, calcite veins) in host rocks and dikes. Most dikes are medium to dark gray on fresh surfaces, weather greenish gray, and contain randomly oriented, white-weathering plagioclase tablets and scarcer hornblende prisms, both a few millimeters to 1 cm across, set in a finely crystalline or aphanitic groundmass. Some thin, presumably rapidly cooled, dikes are porphyroaphanitic with white-weathering plagioclase euhedra as long as 2 cm set in a dark-gray to black groundmass. Minor mafic dikes weather dark green. Some dikes show weak flow structure. Angular xenoliths composed entirely of amphibole and small, baked sedimentary inclusions are seen rarely. The dikes intrude all pre-Quaternary units in the area, and locally cut one another. They have chilled margins against the host rocks and in some places have baked the country rocks over a distance of about 15 cm. Locally, porphyritic dikes display embayed margins against the Winthrop Sandstone, which in turn, shows soft-sediment deformation features, suggesting that the sandstone may have been relatively unconsolidated and still wet at the time of intrusion.

Preliminary modal and geochemical data indicate that porphyritic sills and dikes in the region are composed of diorite, quartz diorite, quartz monzonite, and quartz monzodiorite (V.R. Todd and S.E. Shaw, unpublished data, 1987)(fig. 2). K-Ar hornblende ages of porphyritic sills and dikes in the Mazama and Buttermilk Butte 15-minute quadrangles (fig. 1) range from about 93 to 85 Ma (Todd, 1987) (table 1, Nos. 4-6). The trace-element geochemistry of the sills and dikes is similar to that of the Late Cretaceous stocks, including the Fawn Peak stock, that intrude the Methow basin, and it is likely that most of the sills and dikes are part of the same magmatic episode.

Two porphyro-aphanitic dikes in the Mazama quadrangle yielded Eocene K-Ar ages (table 1, Nos. 7 and 8). One is a basaltic dike that cuts the Midnight Peak Formation (table 1, No. 7). The second body is one of a large number of light-green-weathering sills that intruded the Midnight Peak Formation in the northwest part of the quadrangle (table 1, No. 8). These sills are from 10 cm to 2 to 4 m thick and consist of scattered hornblende and plagioclase phenocrysts in an aphanitic groundmass. The high-level Eocene Monument Peak stock (Tabor and others, 1968) extends into the northwest corner of the Mazama quadrangle. Yellow- and orange-weathering silicic dikes that cut across bedding in the east wall of Lost River Gorge (not shown on the geologic map) are most probably offshoots of the Monument Peak stock. These dikes consist mainly of quartz in both euhedral and anhedral grains (the latter with resorbed margins), and subhedral feldspar set in a sugary matrix. They strike about N. 25 E., are near vertical, and are as much as 15 m thick.

SEDIMENTARY AND VOLCANIC ROCKS

Twisp Formation

The Twisp Formation was named by Barksdale (1975) for thin-bedded black argillite and interbedded lithic sandstone just north of the town of Twisp, Washington (fig. 1). The formation crops out in the extreme southeast corner of the Mazama quadrangle in a fault-bounded block. The Twisp Formation has been uplifted against Cretaceous formations to the west along a north-trending high-angle fault. The unit consists of thin-bedded (typically less than 30 cm but as much as one meter) black shale, medium- to dark-gray fine-grained sandstone and siltstone, and relatively massive coarse sandstone grading to grit and poorly sorted, tan-weathering pebble conglomerate in beds as thick as 2 to 4 meters. The shale is commonly contorted and weathers to a chippy dark-brown soil. Most lithologies of the unit contain broadly wavy laminations ranging from a few millimeters to a few centimeters in thickness. The thin bedding, regular repetition of rock types, and sedimentary structures such as graded beds, ripple-drift cross-laminations, shale rip-up clasts in sandstone, and flame structures indicate deposition by turbidity currents, probably in a deep marine basin. Bouma sequences were observed locally. Clasts in the sandstone and grit-conglomerate range from angular to subrounded and include abraded euhedral volcanic plagioclase, very fine-grained porphyritic volcanic rocks, chert, and black shale. No quartz was seen. The rocks are variably altered to sericite, a carbonate mineral or minerals, and clay minerals. The Twisp Formation is complexly folded and faulted.

Although no diagnostic fossils have been found in the Twisp Formation, Barksdale (1975) considered it to be Jurassic in age on the basis of an unconformable relation between the unit and overlying fossiliferous Lower Cretaceous andesitic sedimentary breccia in the Davis Lake area about 12 km southeast of the Mazama quadrangle (fig. 1).

Volcanic rocks of Isabella Ridge

Massive subaerial tuffs, breccias, flows, and dikes of generally andesitic composition are exposed in a narrow, north-northwest-trending fault-bounded block in the northeastern corner of the Mazama quadrangle. The rocks are highly resistant and form a series of rugged peaks called Isabella Ridge. The volcanic rocks are separated from Lower Cretaceous units, which Tennyson and Cole (1978) informally called the Harts Pass group, on the west by a major fault that extends northward from upper Ortell Creek for a minimum of 9 km, as shown by Dixon (1959). The volcanic rocks are probably truncated to the south by faults in Ortell Creek. The rocks rest depositionally(?) upon the Late Jurassic Button Creek stock and probable Jurassic (pre-Tithonian) low-grade metavolcanic rocks intruded by the stock (Haugerud and others, 1993; R.A. Haugerud, oral commun., 1993). The contact dips gently to the west, is complicated by steep east-west faults, and is partly obscured by colluvium and landslides. North of the Mazama quadrangle, the volcanic rocks are juxtaposed against the Early Cretaceous western Okanogan Range batholith by the Pasayten fault.

The volcanic rocks of Isabella Ridge are continuous to the north with the volcanics of Billy Goat Mountain (Staatz and others, 1971). The latter rocks lie only a few km to the south (separated by faults and Eocene volcanic rocks) of a belt of volcanic rocks described by Smith and Calkins (1904) and extending northward to the international border. These rocks were described as resting upon granite at their east margin. The continuation of these volcanic rocks at the Canadian border is basal member A of Daly's (1912) Pasayten Series, which is described as consisting of volcanic agglomerate resting nonconformably on the Remmel batholith.

The volcanic rocks of Isabella Ridge consist of a series of thick, homogeneous massive layers on the order of tens of meters thick that strike generally north-northwest and dip about 30° to 40° to the west. Layering is not always visible in outcrop, but can generally be seen from a distance. The rocks are cut by numerous steep joints. Tuff-breccia weathers dark gray, brown, green, and purplish red depending upon the color of volcanic rock fragments and the local extent of hydrothermal alteration. The fresh rock is dark gray or black and is composed mainly of subangular and subrounded fragments, or clasts, of a variety of porphyritic volcanic rocks set in a matrix consisting of broken euhedral plagioclase crystals in a range of diminishing sizes, subrounded or subhedral pyroxene and hornblende grains, and dark opaque material partly replaced by chlorite. Clast size ranges from 2 to 25 cm, but larger blocks were seen locally. Flows are dark gray to black with small phenocrysts of plagioclase and mafic minerals set in an aphanitic groundmass. Many rocks have undergone at least some degree of alteration of groundmass to chlorite, epidote, sericite, albite, calcite, and actinolite. Rocks with extensive alteration are greenstones. Some, perhaps much, of the hydrothermal alteration, silicification, and brittle shearing is related to movements on the Pasayten and antithetic faults.

The volcanic rocks of Isabella Ridge were not studied in detail, but descriptions can be found in Dixon (1959) and Staatz and others (1971). Dixon (1959) suggested that the rocks represent subaerial pyroclastic deposits. Staatz and others (1971) reported compositions in the Pasayten Wilderness that are dominantly andesitic but range from basalt to dacite. Porphyritic textures are common. These authors described water-laid tuffs, mudflows, and thin lenticular beds of clastic sedimentary rocks interbedded with the pyroclastic rocks. The lithology of the volcanic rocks of Isabella Ridge most closely resembles the volcanic subunit of Barksdale's (1975) Upper Cretaceous Midnight Peak Formation, which is interpreted as representing continental pyroclastic deposits and lahars.

Hornblende from massive subaerial volcanic rocks on Isabella Ridge yielded a ^{40}Ar-^{39}Ar age of 87.0±0.4 Ma (Haugerud and others, 1993). These Upper Cretaceous volcanic rocks locally overlie pre-Tithonian metavolcanic rocks unconformably. North of the study area, workers have recorded dips as high as 70° to 90° in the northward continuation of the volcanic rocks of Isabella Ridge (Staatz and others, 1971), suggesting that the contact between the volcanic section and the inferred underlying Jurassic basement is a fault. Pending further study, the volcanic rocks of Isabella Ridge are assigned a Jurassic and Cretaceous age.

Early Cretaceous units

The name "Harts Pass group" was used by Tennyson and Cole (1978) as an informal stratigraphic designation for the Lower Cretaceous Goat Creek, Panther Creek, and Harts Pass

Formations of Barksdale (1975). These three formations, which consist of variable proportions of arkosic sandstone, siltstone, shale, and granitoid-bearing conglomerate, are lithologically similar and gradational. It is not certain that the same stratigraphy is present in all the rocks of the Harts Pass group throughout the basin. Tennyson (1974) was unable to differentiate rocks of Goat Creek type as a separate formation in most places in the west-central part of the basin. She also found that the Panther Creek Formation was lenticular and present at several horizons in the section. In the present study, only two formations, the Harts Pass and Panther Creek Formations, have been mapped. Arkosic rocks mapped by Barksdale (1975) as the Goat Creek Formation are virtually lithologically identical to those in the overlying Harts Pass Formation. In the drainages of the Fifth and Sixth Creek tributaries of Cub Creek, Barksdale's Goat Creek and Harts Pass Formations merge just south of the area where the Panther Creek Formation lenses out. The only difference between the Goat Creek and Harts Pass Formations here may be that the underlying Goat Creek section contains more fine-grained sandstone and siltstone, and therefore crops out less boldly, than the Harts Pass Formation. The Harts Pass group is correlated with the Jackass Mountain Group of Hauterivian to Albian age in the Manning Park area of southern British Columbia (Coates, 1970; Jeletzky, 1972).

Panther Creek Formation—The Panther Creek Formation was named by Barksdale (1975) for a section of black shale containing beds of granitoid, roundstone conglomerate and minor arkosic sandstone that crops out in the Panther Creek drainage in the Mazama quadrangle. Barksdale estimated that shale forms 90 percent and conglomerate 6 percent of the Panther Creek Formation at the type section. He found less conglomerate and more arkose interbedded with black shale in the section south of the Ortell Creek fault. The formation crops out in the northeastern part of the quadrangle in what appears to be a faulted series of north-northwest-trending folds involving the Panther Creek and Harts Pass Formations. The western band of outcrop of the Panther Creek Formation may include, from west to east, the faulted western limb of a west-verging anticline and a faulted syncline (see cross section *B-B'*). This band thins and pinches out to the south where it grades to lenses of pebble conglomerate in the enclosing Harts Pass Formation suggesting that the Panther Creek comprises lenticular sheets in the Harts Pass Formation. The eastern outcrop band of the Panther Creek Formation lies in the eastern limb of the Sweetgrass Ridge syncline.

South of the Ortell Creek fault, thin-bedded black shale with minor graded beds of siltstone and fine-grained sandstone is present in intervals as thick as 30 m. The shale is fossiliferous and in the Sweetgrass Ridge-Cub Pass area contains abraded bark, twigs, and plants. The thick shale intervals grade downward to relatively nonresistant, poorly exposed, dark-gray or greenish-gray fine- to medium-grained arkosic sandstone containing scattered lithic pebbles and shale rip-ups. The sandstone is massive with no obvious bedding except parallel alignment of platy grains and pebbly layers. Sorting is fair to good and grains are subangular, subrounded, and angular.

The fine- to medium-grained arkosic sandstone and black shale of the Panther Creek Formation are interbedded with poorly sorted, coarse pebbly sandstone and conglomerate. Bed thickness of conglomerate generally ranges from 0.5 m to 4 m, but some beds are 30 to 50 m thick and continue along strike for more than 1 km. Much of the conglomerate is well indurated, breaking across clasts and matrix, but locally it weathers to earthy disaggregated pebbles and cobbles. Clast size ranges from pebbles to boulders, with pebbles and small cobbles making up the thinner beds, and cobbles and small boulders (as large as 0.6 m) the thicker beds. Clasts consist of a great variety of plutonic rocks ranging from aplitic dike rocks and leucogranite to tonalite, diorite, and gabbroic rocks. Both foliated and unfoliated varieties are present. Volcanic clasts include dark-red, green, and gray porphyritic rocks including felsic to mafic compositons. Metamorphic clasts consist of quartzite, slate-phyllite, and amphibolite. Sedimentary clasts are sandstone, siltstone, and argillite. Vein quartz and minor chert were seen in some rocks. Cobbles and boulders are well rounded to subrounded, while smaller clasts are subrounded to subangular. Matrix consists of abundant, gray- and buff-weathering, coarse-grained arkosic sandstone and grit lithologically identical to the interbedded arkosic sandstone. Clasts touch locally but the conglomerate is largely matrix supported. Indistinct bedding is suggested by the alignment of ovoid cobbles and by lateral gradation to gritty sandstone containing sparse cobbles and faint dark planar laminae and crossbeds.

The poorly exposed northern part of the eastern band of outcrop of the Panther Creek Formation was mapped by Barksdale (1975) as the Panther Creek Formation. These rocks continue southward into the Buck Mountain area (Doe Mountain 15-minute quadrangle, fig. 1), where Barksdale (1975) mapped the Buck Mountain Formation as a separate formation on the basis of interbedding of volcanic rocks in the section. However, the arkosic sandstone, siltstone, shale, and conglomerate beds in the Buck Mountain area are (1) virtually lithologically identical to the Panther Creek Formation in the western belt of outcrops, (2) continuous with the Panther Creek Formation to the north, and (3) overlain conformably by the Harts Pass Formation. The section near Buck Mountain also contains interbedded volcanic sandstone, breccia, and flows, and small amounts of volcanic sandstone were found in Panther Creek strata of the western outcrop band.

The contacts between the Panther Creek and Harts Pass Formations are marked by the disappearance of abundant cobble conglomerate beds and the appearance of thick massive arkosic sandstone beds. Conglomerate beds in the Harts Pass Formation immediately above and below the Panther Creek Formation tend to be lenticular, thin, fine-grained, with clasts that are subrounded or subangular. These beds contain mainly lithic (sedimentary and volcanic rocks) pebbles with minor granitic rocks, quartz, and chert.

Marine fossils of Aptian to Albian age were collected 400 m above the base of the Panther Creek Formation in its type area (Barksdale, 1975). In the present study, gastropods, pelecypods, and a cephalopod fragment were collected from black shale beds in the Sweetgrass Ridge-Cub Pass area (table 2, Nos. 1-3). These collections also indicate an Aptian to Albian age for the Panther Creek Formation (J.W. Miller, written commun., 1984) (table 2). McGroder and others (1990) summarized unpublished biostratigraphic data for the United States part of the Methow basin. According to McGroder and others, the age of the Panther Creek Formation is constrained to the late Hauterivian to early Albian. Lithologically identical conglomerates in the Manning Park area of Canada are early early Albian in age (Coates, 1974). The probable depositional environment and source of the Panther Creek Formation are discussed below.

Harts Pass Formation—The Harts Pass Formation was named by Barksdale (1975) for a section of marine arkose and subordinate fossiliferous black shale exposed along the Cascade crest northeast and southwest of Harts Pass (fig. 1). Rocks that Barksdale considered to be the Harts Pass Formation are exposed in the northern part of the Mazama quadrangle. Barksdale noted that, in the northwestern part of the quadrangle, north of the Ortell Creek fault, the formation is mainly thick-bedded arkose, while on Sweetgrass Butte, south of the fault, the arkose is not as thickly bedded and contains more shale than basal sections of the formation elsewhere in the Methow basin.

On Sweetgrass Butte and Isabella Ridge, the Harts Pass Formation consists of arkosic sandstone and subordinate siltstone and shale in alternating beds from 3 to 30 m thick. These thick, laterally extensive beds give rise to prominent light and dark striping on strike ridges. Scarce internal structures in the thicker sandstone beds suggest that they consist of multiple sedimentation units (amalgamated beds). The thick-bedded sandstone and shale are interbedded with graded sequences of less common thin-bedded sandstone, siltstone, and shale.

Thick-bedded sandstone is characteristically massive and homogeneous with bedding suggested only by alignment of platy grains. The rock is medium to dark gray or greenish gray on fresh surfaces, well indurated, and fractures to angular blocks less than 0.5 m across.

Characteristic yellowish-white, buff, and brown weathered surfaces are peppered with large white-weathering plagioclase grains. Although grain size ranges from fine to coarse, the sandstone is typically medium- to coarse- grained and granular. Sorting is good to fair except for coarse-grained rock that contains scattered 1- to 3-mm biotite grains, small lithic pebbles, and shale intraclasts. Bedding in the massive sandstone is locally marked by isolated, indistinct dark laminae, two or three of which may be spaced less than 1 m apart in the vicinity of thin (5 to 30 cm) shale interbeds. Faint grading, both normal and inverse; vague crossbeds in 2- to 5-cm sets, defined by silt or fine-sand laminae; and lenses of pebbly sandstone were seen locally. Rip-up clasts of fissile shale in round or subangular shapes as long as 30 cm are common. Rectangular or platy shale clasts may be oriented parallel to bedding.

Coarse-grained thick-bedded sandstone grades vertically and laterally to distinctive pebbly sandstone containing isolated, evenly distributed pebbles set about 1 cm apart in coarse structureless sandstone. In some places, this rock grades to poorly sorted pebble conglomerate in lenticular beds from 30 cm to 3.5 m thick. The conglomerate in the Harts Pass Formation is similar to that in the Panther Creek Formation, except that conglomerate beds are less numerous, thinner, finer grained, and contain fewer granitic clasts in the Harts Pass Formation. Most conglomerate beds are less than 1 m thick, matrix supported (locally in part clast supported), with crude or no imbrication. Bedding may be defined by discontinuous sandy lenses, aligned flat clasts, and in thin conglomerate beds, faint wavy dark lamination. Some conglomerate layers are chaotic. Clasts are small-pebble to pebble size, with occasional cobbles. They consist of sedimentary, volcanic, plutonic, and metamorphic rocks, as well as quartz, shale intraclasts, and minor chert. The clasts are subrounded and subangular, with some rounded shapes. The matrix of the conglomerate, medium sand to grit, is lithologically identical to the interbedded arkosic sandstone.

Shale in beds as thick as 12 m is interbedded with the massive sandstone. The rock is black, fissile, and weathers to a dark chippy soil. The shale typically has silty laminae and carbonaceous films on bedding planes. Minor silty mudstone is present. Interbedded black shale and gray- to black-weathering siltstone also form 1- to 4-m-thick beds in thick-bedded sandstone. Individual beds are thin (2-8 cm) and exhibit ripple-drift cross-lamination, planar and wispy laminations, and convoluted bedding. In the upper Deer Creek and Fifth Creek Pass areas, fine-grained yellowish-brown-weathering sandstone of the Harts Pass Formation locally contains twigs, wood fragments, abraded ferns, and plant impressions. The contact between sandstone and underlying fine-grained beds is usually sharp and locally shows scour and fill or loading by sand layers.

Sandstone of the Harts Pass Formation is composed of intermediate plagioclase, quartz, and lithic grains, in order of abundance. The composition and texture of sandstone in the Harts Pass unit are identical to those of sandstone in the Panther Creek unit. Most sandstone is arkose, but some rock compositions approach lithic arkose. Most plagioclase has undergone some degree of sericitization, with alteration outlining normal euhedral zones, but fresh grains were also observed. A substantial number show slightly abraded euhedral or subhedral shapes. Polysynthetic and Carlsbad twins were seen locally. K-feldspar grains range from 0 to about 10 percent, but the mineral is generally scarce. Quartz is present in monocrystalline and polycrystalline varieties. Single grains are clear, show trains of vacuoles, and are unstrained or weakly to strongly undulose. Polycrystalline quartz consists of plutonic, metamorphic, and hydrothermal varieties. Lithic grains include volcanic, sedimentary, plutonic, and metamorphic rock fragments, and chert. Clear chert grains similar to those in the overlying Virginian Ridge Formation are rare to absent. Volcanic rock fragments are mainly hypabyssal porphyries and porphyro-aphanitic rocks, some containing quartz phenocrysts. The most common plutonic rock fragments are quartz-plagioclase aggregates, including myrmekite, with both oriented and nonoriented fabrics. Tonalite and granodiorite fragments were also seen. Metamorphic rock fragments consist of metaquartzite, quartzite-mylonite, mylonitic granitic rocks, mica schist, metasiltstone, and rare calcsilicate rocks. Sedimentary rock fragments are mainly siltstone, argillite, and very fine-grained sandstone. Grains of biotite, muscovite, chlorite, hornblende, epidote, sphene, and apatite form minor but ubiquitous clasts. Biotite is kinked and locally altered to chlorite or phyllosilicate minerals. Gray-green hornblende, including abraded euhedral grains, makes up a few percent of some rocks.

The above framework grains are subangular, subrounded, and angular; no well-rounded grains were seen. Most sandstone contains scarce matrix (fine sand, silt) and virtually no mud or clay. Cement consists of phyllosilicate minerals that fill pores and replace biotite, and volcanic and sedimentary clasts. Chlorite and sericite replace lithic grains. Pseudomatrix is composed of squashed biotite, volcanic fragments, and hornblende. Locally, brown iron oxide is present as grain coatings. Calcite replacement ranges from scarce to none. Barksdale (1975) reported occurrences of prehnite in arkosic sandstone of the Harts Pass Formation, and prehnite and pumpellyite in the Panther Creek Formation.

The Harts Pass Formation underlies a unit composed of undivided rocks of the Virginian Ridge Formation and Winthrop Sandstone with slight angular unconformity on the northeast limb of the Goat Peak syncline. The unconformity is marked by a mapped discordance of about 15° to 20° between contacts and bedding in the Harts Pass group and those in the overlying undivided Virginian Ridge Formation and Winthrop Sandstone and younger units. Scattered facing indicators show that bedding in both the Harts Pass Formation and the undivided Virginian Ridge Formation and Winthrop Sandstone is steeply overturned to the southwest. A few km to the east, an apparently upright section of the Harts Pass Formation is repeated in the center of a narrow syncline on Sweetgrass Butte. The overlying undivided Virginian Ridge Formation and Winthrop Sandstone is not present in this area. These relations suggest that an intervening west-verging anticline was broken by a reverse fault with the Harts Pass group in the hanging wall (see cross sections *A-A'* and *B-B'*).

An alternative possibility and one favored by Barksdale (1975) is that folding, uplift, and erosion of the Harts Pass group preceded deposition of the Virginian Ridge Formation and Winthrop Sandstone and that these events were followed by development of the Goat Peak syncline. In this scenario, if the strata in the northeast limb of the syncline are restored to horizontality, the underlying Harts Pass group would form a series of large nearly recumbent folds. Such a sequence of folding, uplift, and erosion signifies a major tectonic episode that should result in a profound regional unconformity. Yet, elsewhere in the basin, the Harts Pass group and Virginian Ridge Formation appear conformable. It is possible that a fault, or faults, developed in shale beds within the western outcrop band of the Panther Creek Formation in the hinge area of a westward-overturned anticline. Continuing northeast-southwest-directed compression may then have caused the east block to ride over the west block, resulting in juxtaposition of older, deeper lying Harts Pass strata against younger strata in the Goat Peak syncline. A third possibility is that the entire Cretaceous section, including the Harts Pass group, is homoclinal and overturned to the southwest.

Marine fossils collected at the type section of the Harts Pass Formation collectively indicate an Aptian to Albian age (Barksdale, 1975). A visit to this area in this study yielded two cephalopods of Early Cretaceous (Aptian to Albian) age (J.W. Miller, written commun., 1984) (table 2, No. 4). McGroder and others (1990) considered a late Aptian to middle Albian age to be most likely for the Harts Pass Formation.

Depositional setting and source of the Harts Pass and Panther Creek Formations—Much, if not all, of the Harts Pass group is marine in origin based upon occurrences of marine fossils. In the west-central part of the Methow basin, sedimentary structures such as graded beds, parallel lamination, scour and fill, and sole markings suggest deposition by turbidity currents on submarine fans (Tennyson, 1974; Tennyson and Cole, 1978). Paleocurrent data together with westward decrease in the average thickness of sandstone beds, sandstone to shale ratios, and maximum clast size further suggest westward transport of sediment (Cole, 1973; Tennyson and Cole, 1978). In the

Mazama quadrangle, in the eastern part of the Methow basin, sandstone of the Harts Pass group is marked by exceptionally coarse grain size, thick beds, and relatively poor development of grading and sole marks. This change indicates that the eastern exposures represent proximal parts, and the western exposures distal parts, of the submarine-fan complex. The ubiquitous abraded plant material in the eastern exposures suggests a nearby landmass. The amalgamated sandstone beds in the Mazama quadrangle probably represent deposition in valleys on submarine fans, while the finer grained graded sequences were deposited in interchannel areas (Cole, 1973). The thick conglomerate layers are interpreted as channel fillings.

The source terrane for the Harts Pass and Panther Creek Formations consisted largely of plutonic rocks, metamorphic rocks of high and low grade, and minor epiclastic rocks. This assemblage is consistent with derivation from a partly unroofed magmatic arc. Batholithic rocks presently exposed in the Okanogan Range (fig. 1) east of the Pasayten fault include plutons of Late Triassic through Paleogene age and metamorphosed supracrustal rocks of Late Permian through Late Triassic age (Rinehart and Fox, 1972, 1976; Rinehart, 1981). The Okanogan Range batholith is a likely source because the plutons are trondhjemitic (Menzer, 1983; Rinehart, 1981; Todd, 1995) and therefore rich in intermediate plagioclase and poor in K-feldspar and have yielded Early Cretaceous (110 to 114 Ma) uranium-lead zircon emplacement ages (Hurlow and Nelson, 1993). The locally abundant hornblende in sandstone of the Harts Pass group may have been derived from the Late Jurassic Button Creek stock or related plutons. The freshness, angularity, and local euhedral shapes of much of the plagioclase and hornblende in these rocks suggest that the detritus did not travel far and was quickly buried.

The clast assemblage in conglomerate of the Harts Pass group gives evidence for two different sources, one supracrustal and producing angular small-pebble- and pebble-sized clasts, and the other plutonic and producing larger, rounded farther-travelled(?) clasts. A few pebbles of gray chert commonly are seen in conglomerates of both the Harts Pass and Panther Creek Formations, suggesting that a source of chert (Twisp Formation?) was available in Aptian to Albian time. The volume of chert pebbles increases dramatically in the overlying Virginian Ridge Formation, which is generally considered to mark the emergence of a western oceanic terrane.

Early to Late Cretaceous units

The Virginian Ridge Formation of Barksdale (1948, 1975), Winthrop Sandstone of Barksdale (1948, 1975), and Midnight Peak Formation of Barksdale (1975) are closely related Early to Late Cretaceous units that represent a transition from marine deposition to continental sedimentation and intrabasinal volcanic activity. They are laterally equivalent to the Pasayten Group (Pasayten Series of Daly, 1912; Rice, 1947; Coates, 1970, 1974; Jeletzky, 1972) of the Manning Park area in southern British Columbia. The Virginian Ridge Formation overlies the Harts Pass group of Tennyson and Cole (1978) with slight angular unconformity in the study area, but elsewhere appears essentially conformable with it. The three formations locally grade vertically into, and interfinger laterally with, one another with local omission of strata, suggesting that they are in part facies-equivalents (Tennyson, 1974; Barksdale, 1975; Tennyson and Cole, 1978; Trexler, 1984). During this period of deposition, at least two source regions contributed detritus to the basin.

Virginian Ridge Formation—Barksdale (1948, 1975) assigned the name "Virginian Ridge Formation" to a steeply dipping section of marine lithic sandstone, siltstone, and chert-pebble conglomerate that crops out in Wolf Creek and on neighboring Virginian Ridge, about 8 km west of Winthrop (fig. 1). The main exposure of the formation in the Mazama quadrangle is in the west limb of the Goat Peak syncline. Trexler (1984, 1985) recognized both marine and nonmarine facies in the Virginian Ridge Formation and divided it into three members. In approximate stratigraphic order, these are the Patterson Lake, Slate Peak, and Devil's Pass Members. The rocks in the

Mazama quadrangle were all assigned by Trexler to the Slate Peak Member, which consists of thin-bedded lithic sandstone, siltstone, and mudstone that contain isolated sheetlike beds of chert-pebble conglomerate. These rocks can be recognized in the field by ledges of resistant conglomerate that continue for hundreds of meters across hillsides. McGroder and others (1990) subdivided the Virginian Ridge Formation into three map units on the basis of the percentage of chert-rich conglomerate in local sections. In the study area, Trexler's Slate Peak Member is approximately equivalent to a unit of McGroder and others that contains 10 to 40 percent conglomerate. These authors also interpreted the Patterson Lake Member as a separate formation, the informally named Patterson Lake conglomerate.

In limited exposures in the southeast part of the Mazama quadrangle and southwest part of the Doe Mountain quadrangle, dark-gray to brown lithic sandstone, siltstone, mudstone, and conglomerate appear to overlie the Twisp Formation in angular unconformity (Maurer, 1958; Barksdale, 1975; Todd, 1995). These rocks, which are rich in volcanic and sedimentary rock fragments derived from the underlying Twisp Formation, comprise the northernmost exposure of the Patterson Lake conglomerate of McGroder and others (1990) (Bunning, 1990).

Sandstone of the Virginian Ridge Formation in the study area is predominantly dark-gray, thin-bedded (15-50 cm) fine- to medium-grained litharenite. Occasional interbeds of clean arkose are present in the upper part of the section (Pitard, 1958; Barksdale, 1975; Trexler, 1984). North of the Methow River, arkosic interbeds lithologically similar to the overlying Winthrop Sandstone are generally present throughout the Virginian Ridge Formation. In the present study, these rocks have been mapped as the undivided Virginian Ridge Formation and Winthrop Sandstone. Sedimentary structures in sandstone of the Slate Peak Member include planar lamination, graded beds, mudstone rip-up clasts, and rare crossbeds. Lenses of coarse-grained pebbly sandstone are present locally. Sandstone is interbedded with, and grades upward into, thin-bedded black siltstone and mudstone. Locally, sandstone and mudstone layers are in sharp contact, and the sandstone exhibits scour-and-fill relations with the underlying mudstone. Some mudstone layers contain silty laminae, while others are massive. The fine-grained rocks show graded beds, ripple-drift cross-lamination, and convolute bedding. Wood fragments and leaves are concentrated locally along bedding planes. Some predominantly siltstone-mudstone sequences are as much as 6 to 20 m thick.

Interbedded with, and gradational into, the fine-grained rocks of the Virginian Ridge Formation are more or less regularly spaced tabular beds of dark-gray- and dark-brown-weathering pebbly sandstone and chert-pebble conglomerate. Locally, lenticular bodies of conglomerate channel or load into the underlying fine-grained sediments. Bed thickness ranges from 1 to 6 m, and is locally greater. The conglomerate ranges from easily disaggregated to extremely hard, the latter cemented by silica and fracturing across clasts and matrix. Pebbles of white, black, and gray chert, some veined by dark- or light-colored silica and others mottled, are characteristic of the conglomerate. A distinctive pebble type consists of gray chert with a narrow white rim. Chert clasts rarely exceed 3 cm in diameter. The remaining clasts mainly consist of sedimentary and volcanic rock fragments and quartz. Sedimentary rock fragments include dark-gray and black-weathering fine-grained sandstone, siltstone, and mudstone, and minor greenish-gray siltstone. Many of these clasts are similar to the Slate Peak lithologies and are probably intraclasts. The volcanic clasts consist mainly of dark-gray- and greenish- gray-weathering finely porphyritic volcanic rocks. Quartz is present as both polycrystalline (metaquartzite, vein quartz) and monocrystalline clasts. Scarce low-grade metasedimentary and granitic pebbles are seen locally. Pebbles and scarce small cobbles are set in a sand-silt matrix. Clasts range from subangular to subrounded, with local rounded and angular shapes.

Bedding in the conglomerate ranges from chaotic to poorly developed. Some layers are poorly sorted, clast poor, and matrix supported, with no grading, imbrication, or alignment of planar clasts. Others are moderately sorted and clast supported, and show rough grading, imbrication, alignment of tabular clasts, and scarce crossbeds. Both types of conglomerate grade vertically and laterally into coarse-grained sandstone that contains isolated "floating" pebbles, or strings of pebbles. Alternation of these two conglomerate end-members suggests repeated "dumping" of coarse material, perhaps followed by distribution by turbidity currents.

Thin-section views of sandstone of the Virginian Ridge Formation reveal moderately sorted to well-sorted, subrounded and subangular grains of chert, plagioclase, quartz, and volcanic and sedimentary rock fragments in widely varying proportions. Chert, which forms from 0 to about 40 percent of the framework grains, is present in clear homogeneous grains and in grains that are partly recrystallized and (or) veined by silica. Remains of radiolarians have been identified in chert clasts (Trexler, 1984). Plagioclase grains range from unaltered to variably sericitized. Quartz is present as single unstrained grains (volcanic quartz?) and as less abundant polycrystalline grains (metaquartzite and hydrothermal quartz). Volcanic rock fragments are composed chiefly of finely porphyritic intermediate lithologies. Cole (1973) reported both andesitic and basaltic compositions, with andesitic fragments outnumbering basaltic fragments. Trexler (1984) noted a preponderance of felsic volcanic compositions. Sedimentary rock fragments include fine-grained sandstone, siltstone, and argillite. Biotite, muscovite, and chlorite are minor constituents of the sandstone, whereas metamorphic and plutonic rock fragments are present in trace amounts. Epidote and amphibole grains are scarce constituents. All of these framework grains are set in a generally sparse detrital matrix that has been cemented or replaced by sericite, silica, calcite, and phyllosilicates. Calcite and dolomite replace clasts in some rocks. Laumontite and prehnite are recognized locally (Cole, 1973), suggesting local hydrothermal alteration, incipient burial metamorphism, or contact metamorphic effects.

The Virginian Ridge Formation grades upward into the Winthrop Sandstone (Cole, 1973; Tennyson, 1974; Barksdale, 1975; Trexler, 1984). The units are generally interbedded at the contact and are characterized by rapid changes in thickness and local pinching out of the characteristic lithologies (Barksdale, 1975; Trexler, 1984; Rau, 1987). Trexler noted arkosic interbeds with plant debris in the upper part of the Virginian Ridge Formation in the eastern part of the Methow basin. He interpreted these beds as deposits of a prograding delta-lobe system related to, and preceding, deposition of the Winthrop Sandstone. In the Mazama quadrangle, the contact between the two formations is gradational but relatively distinct south of the Methow River. In the type locality of the Virginian Ridge Formation, in Wolf Creek and on the south end of neighboring Virginian Ridge, Barksdale (1975) measured about 150 to 200 m of interstratified black siltstone and arkosic sandstone near the top of the section. In the present study, the contact south of the river was placed approximately at the base of the first of the massive arkose beds.

The contact between the Virginian Ridge Formation and the Winthrop Sandstone is more ambiguous north of the Methow River. Trexler (1984) found his Slate Peak Member to be anomalously thin in this area (100 m in the vicinity of McLeod Mountain). The formations are considered to be gradational over 350 m at the type section of the Winthrop Sandstone, east of Boesel Canyon (Rau, 1987). The 350-m-thick transitional zone, which has characteristics of both the Virginian Ridge Formation (chert-pebble conglomerate, black shale) and the Winthrop Sandstone (cross-bedded arkosic sandstone), was included by Rau in the basal part of his Winthrop Sandstone. The present study has determined that the Virginian Ridge Formation probably thins and in part gives way north of the river to relatively thin beds of black sandstone and siltstone and minor chert-bearing pebble conglomerate interbedded with Winthrop-type arkose. These rocks, mapped in this report as the undivided Virginian Ridge Formation and Winthrop Sandstone, are described in the following section.

The Virginian Ridge Formation has yielded a marine fauna that ranges in age from Albian to Cenomanian (Barksdale, 1975; Trexler, 1984). In this study, a Late Cretaceous (Turonian) marine gastropod was identified in shale collected about 600 m south-southeast of Slate Peak in the Slate Peak quadrangle (fig. 1; table 2, No. 5) (J.W. Miller, U.S. Geological Survey, written commun., 1984). A problem recognized by many workers is that the age of the overlying Winthrop Sandstone is generally accepted as late Albian (McGroder and others, 1990). These authors reported the occurrence of an Aptian to Cenomanian fossil assemblage in the Virginian Ridge Formation, but because this assemblage stratigraphically overlies the Patterson Lake Member, which contains fossils of middle to late Albian age, and underlies the Winthrop Sandstone, they considered the Virginian Ridge to be no younger than late Albian. Trexler (1984, p. 108) suggested that the Virginian Ridge Formation is time transgressive with respect to the Winthrop Sandstone, which he inferred to represent a single large deltaic system. He cited as evidence an apparent down-section shift of Winthrop-type arkosic strata from a position atop the Virginian Ridge Formation in the southeast part of the middle Methow basin (including the study area), to a position near the lower part of the formation, below the most abundant chert-pebble beds, in the northern middle basin (including the fossil localities). In the latter case, the Winthrop Sandstone is missing and the Midnight Peak Formation overlies the Virginian Ridge conformably, as shown by Barksdale (1975). In Trexler's view, the Albian to Cenomanian (or Turonian) fossil faunas may represent a higher, younger part of the Virginian Ridge section. Supporting evidence for this view is the local interbedding of Midnight Peak-type volcanic strata in both the Virginian Ridge Formation and Winthrop Sandstone (Tennyson, 1974; Barksdale, 1975; Trexler, 1984; McGroder and others, 1990; V.R. Todd, unpublished mapping, 1984). If the Midnight Peak Formation is genetically related to the 88-Ma Fawn Peak stock, then it seems likely that these volcanic precursors and the enveloping Virginian Ridge and Winthrop strata are Cenomanian to Turonian in age. If, on the other hand, both the Virginian Ridge Formation and Winthrop Sandstone are entirely Albian in age, then a separate, pre-Fawn Peak magmatic episode must be invoked. Resolution of this age problem awaits future stratigraphic and (or) radiometric dating studies.

Depositional setting and source of the Virginian Ridge Formation—Trexler (1984) interpreted the depositional setting of the Virginian Ridge Formation as a fan-delta system that prograded eastward into a shallow-marine basin. According to Trexler, the Devil's Pass Member in the western part of the basin grades upward from marine beds of the Slate Peak Member, through deltaic and fluvial beds, to an alluvial fan complex. The fan-delta system is characterized as short, steep, and fluvially dominated. The Slate Peak Member, present mainly in the central and eastern parts of the basin, represents deposition in a shallow-marine basin into which thin sheets of coarse delta-platform sediments built eastward intermittently (Trexler, 1984). The two members thus interfinger laterally. The thin, laterally persistent coarse sand and gravel beds of the Slate Peak Member represent distal lobes of the prograding fan-delta system. Additionally, debris flows and conglomeratic turbidites were derived by submarine slumping and sliding from the toes of the delta lobes (Trexler, 1984). At some time during Slate Peak deposition, the Winthrop fan-delta system (discussed below) began to be active along the east shore of the basin. In the Mazama quadrangle, the Slate Peak Member thins rapidly and appears to pinch out to the northeast, where it intertongues with the Winthrop Sandstone (undivided Virginian Ridge Formation and Winthrop Sandstone).

Average bed thickness, clast size, and sandstone to shale ratios in the Virginian Ridge Formation increase markedly to the west (Cole, 1973). Paleocurrent data indicate transport of sediment eastward across the basin and northward along the axis of the basin (Cole, 1973; Trexler, 1984). These trends suggest a western source for much of the Virginian Ridge detritus. Variable but commonly significant volumes of quartzofeldspathic material in the Slate Peak Member were probably derived from basement highs somewhere to the east (Trexler, 1984). The most likely source for the abundant chert and volcanic clasts in the Virginian Ridge Formation are upper Paleozoic and lower Mesozoic marine sedimentary and volcanic rocks presently exposed on the east flanks of the North Cascades (Tennyson and Cole, 1978). The closest outcrop of such rocks is the Hozameen Group (Cairnes, 1944), which is separated from the Methow basin on the northwest by the Hozameen-Jack Mountain fault system. The Hozameen Group of consists of greenstone containing minor radiolarian chert, marble, and phyllitic argillite (Staatz and others, 1971). Hozameen cherts have yielded Permian, Middle and Late Triassic, and Middle Jurassic radiolarians (Tennyson and others, 1982; Haugerud, 1985). Radiolarians recovered from chert pebbles in the Slate Peak Member were tentatively identified as Triassic or Early Jurassic in age (Trexler, 1984).

Virginian Ridge Formation and Winthrop Sandstone, undivided—North of the Methow River, the Virginian Ridge Formation of Barksdale (1948, 1975) is interbedded with arkosic sandstone that is identical to the overlying Winthrop Sandstone of Barksdale (1948, 1975) through about 750 m to 1 km of section. Although the characteristic Virginian Ridge lithologies are present in this area, the chert-pebble conglomerate layers are less numerous, thinner, more lenticular, and finer grained than those south of the river. In addition, there appear to be more intraclasts and fewer chert pebbles in the northern conglomerates. North of Slate Peak, McGroder and others (1990) mapped a similar undivided Virginian Ridge and Winthrop unit that consists of mixed Virginian Ridge and Winthrop lithologies and is overlain by the Winthrop Sandstone.

In the study area, black mudstone and siltstone, fine- to medium-grained sandstone, and pebble conglomerate are interbedded in beds from 10 to 30 m thick with planar-laminated, crossbedded biotite arkose in the Cub Creek and Goat Creek drainages. Minor light-green-weathering, fine-grained micaceous sandstone and siltstone are interbedded with these lithologies. Mudstone and siltstone with minor interbedded sandstone form intervals as thick as 8 m. These intervals grade vertically into well-sorted, fine- to medium-grained dark-gray sandstone that contains mudstone rip-up clasts and lensoid accumulations of woody material. This sandstone generally appears more lithic in outcrop than the interlayered Winthrop Sandstone. Thin-section views suggest compositions similar to those of Virginian Ridge sandstones elsewhere in the Methow basin, except that chert is less abundant, and plutonic and metamorphic grains more abundant, in sandstone of the undivided Virginian Ridge Formation and Winthrop Sandstone. The actual volume of chert detritus at a given locality is difficult to determine because chert may not be present in the same abundance in all size fractions. The fine- to medium-grained sandstone grades into coarse-grained sandstone, pebbly sandstone, and pebble conglomerate in lenticular beds from 0.5 to 3 m thick. Crude bedding is defined by alternating, predominantly sandy or pebbly layers, or by a slight tendency for alignment of tabular clasts. Clasts in the conglomerate consist of chert, fine-grained sedimentary rocks, porphyritic volcanic rocks, and minor quartz and granitic rocks. The clasts are subrounded, subangular, and angular, and are mostly supported by a coarse sand matrix.

East of Boesel Canyon in the type locality of the Winthrop Sandstone, black fine-grained sandstone, siltstone, and silty mudstone in 30-cm-thick layers are interbedded with thinly laminated Winthrop-type arkosic sandstone in the lower part of the section (through about 1 km). These rocks are mapped as undivided Virginian Ridge Formation and Winthrop Sandstone in this report. The black interbeds contain fine, planar varvelike laminae that continue laterally for several meters in outcrop, indistinct crossbeds, and isolated small pebbles and pebble beds. Pebbles consist mainly of black mudstone and siltstone, and chert. In thin section, the black sandstone has abundant chert and volcanic rock fragments. Locally, mudstone is carbonaceous and contains abundant plant material, including tree branches. Soft-sediment deformation, burrows(?), and replacive pyrite were seen locally. Rare clastic dikes that superficially resemble intraclast-rich conglomerate cut across bedding. They consist of coarse sand crowded with 1-cm angular and rounded black mudstone clasts.

The contact between the undivided Virginian Ridge Formation and Winthrop Sandstone and the overlying Winthrop Sandstone is gradational. In the Cub Creek and Goat Creek drainages, going down section, the contact is drawn where black mudstone and siltstone and chert-bearing pebble-conglomerate intervals first appear in abundance. Locally, angular clasts of green or black siltstone were seen in the basal part of the Winthrop Sandstone. In the type locality of the Winthrop Sandstone, Pitard (1958) and Barksdale (1975) drew the contact between the Winthrop Sandstone and the Virginian Ridge Formation where beds of chert-pebble conglomerate are no longer laterally continuous but are found as lenses in the Winthrop. Rau (1987) apparently placed the contact in the same location but, as mentioned above, recognized a 350-m-thick transitional zone within the basal part of the Winthrop Sandstone. In the present study, these transitional rocks are mapped as the undivided Virginian Ridge Formation and Winthrop Sandstone, and the contact is therefore located higher in the section.

The undivided Virginian Ridge Formation and Winthrop Sandstone is characterized by coarsening-upward sequences (Trexler, 1984; Rau, 1987) that indicate up-section shoaling. The section probably consists of nearshore marine, shoreline, and fluvial facies deposited in a part of the Methow basin where shallow-marine sediments interfingered with, and were gradually overwhelmed by, a fan-delta system building westward from basement uplifts on the east. A fossil leaf collected from a fine-grained cherty sandstone-shale interval at Banker Pass was identified as "a perfectly actinodromous dicotyledonous leaf, a type of foliar morphology unknown prior to the middle Albian" (J.A. Wolfe, U.S. Geological Survey, written commun., 1985)(table 2, No. 6).

Winthrop Sandstone—Russell (1900; see also, Barksdale, 1948, 1975) gave the name Winthrop Sandstone to light-colored arkosic sandstone that crops out in the north wall of the Methow Valley, about 10 km northwest of the town of Winthrop (fig. 1). As mentioned above, the basal part of this section has been mapped as undivided Virginian Ridge Formation and Winthrop Sandstone in this report. In the Mazama quadrangle, the Winthrop Sandstone is exposed in the steeply dipping limbs of the Goat Peak syncline (Barksdale, 1975), where as much as 1,700 m may be present in the north limb (Rau, 1987). A much thinner section is exposed about 8 km to the south in the Midnight Peak syncline (Barksdale, 1975).

The Winthrop Sandstone consists of well-indurated to locally friable, light-gray, greenish-gray, and buff-weathering arkose that underlies prominent peaks and strike ridges. Lithic arkose is common in the lower part of the section (Barksdale, 1975). Sandstone makes up approximately 93 percent of the unit, with 5 percent finer grained rocks, and 2 percent conglomerate (Rau, 1987). The sandstone is typically medium- to coarse-grained, locally granular, with abundant reddish-weathering biotite grains as much as 0.5 cm across. Thin, planar, dark carbonaceous laminae and large trough crossbeds in sets as thick as 1.5 m are characteristic. Locally, the sandstone is massive or forms crude beds up to 5 m thick. Graded beds and lenticular bodies of coarser grained sand are scarce. Wood fragments and shale rip-up clasts are concentrated locally in the plane of lamination. Dark mottling is common near concentrations of organic material.

The Winthrop Sandstone contains interbeds of dark-gray fine-grained sandstone, siltstone, and black shale ranging from a 2 cm to 2 m thick. Cross-lamination, convolute bedding, flame and load structures, and rip-up clasts are common in these fine-grained rocks. Less common black mudstone weathers to subrounded blocks as much as 25 cm across. Rarely, massive mudstone beds are crossed by fine irregular fractures suggesting periods of dessication.

Coarse granular sandstone with isolated shale intraclasts and small pebbles is interbedded with thin (less than 1-m-thick) beds of gray- and brown-weathering matrix supported pebble conglomerate. Angular and subangular clasts in the conglomerate consist of light- and dark-gray chert, granitic and mafic plutonic rocks, dark-gray- and green-weathering porphyritic volcanic rocks, and shale (intraclasts). Small boulder-size angular blocks of mudstone were seen locally. Pebble lag deposits are present in sandstone at the base of large crossbeds.

Plant fossils, including (1) fronds of ferns, (2) leaves, twigs, and bark of conifers, (3) reeds(?), (4) broad-leaf plants, and (5) aspen(?) are common in fine-grained sandstone, siltstone, and shale.

Branches and tree trunks as long as 3 to 4 m and 25 cm in diameter are seen in coarse sandstone of the unit.

Sandstone compositions in the Winthrop Sandstone range from litharenite to arkose, with plagioclase arkose the most common lithology (Rau, 1987). Thin-section views show that plagioclase, quartz, and biotite, generally in that order, are the dominant clasts. Clast shapes range from angular to subrounded but most are angular or subangular. Sorting is typically moderate to poor with an overall range from good to poor. Polysynthetic twinning and euhedral normal zoning are commonly preserved in plagioclase, even though grains are slightly sericitized and locally altered to fine-grained epidote. At least a few clasts composed of plutonic plagioclase and quartz, including myrmekite, were seen in each thin section. Quartz clasts, some with trains of vacuoles, range from unstrained to strongly undulose. Scarce polycrystalline clasts are composed of lenticular or irregular subgrains with sutured boundaries (recrystallized plutonic quartz?). Variably chloritized biotite grains as much as 1 to 2 mm in diameter are common constituents. Minor clasts include mylonitic quartzite, metaquartzite, metasiltstone, microcline, epidote-clinozoisite, sphene, and brown-weathering porphyro-aphanitic volcanic rocks. Phenocrysts in the volcanic clasts are plagioclase laths and microlites, locally flow banded, or set in a groundmass of devitrified glass. Chert, zircon, chlorite, green amphibole, and argillite are scarce clast types in sandstone. In some thin sections, faint bedding is marked by parallel alignment of platy grains.

Matrix, consisting of silt, chlorite, calcite, clay minerals, and modified clasts, constitutes less than 5 percent of the Winthrop Sandstone. Modified clasts including altered biotite, volcanic rock fragments, and plagioclase, have been molded against and between the more resistant quartz and feldspar grains. Biotite is commonly kinked. Locally, both framework grains and matrix have been replaced by calcite and epidote. The flattening of lithic clasts, kinking of mica, and local planar contacts between feldspar and quartz grains probably occurred during burial and diagenesis. Scattered occurrences of prehnite and laumontite are reported (Cole, 1973; Tennyson, 1974; Rau, 1987).

The basal contact of the Winthrop Sandstone with the underlying Virginian Ridge Formation is a transitional zone of interbedded arkosic and chert- bearing sediments representing the upward transition from marine to continental deposition (see preceding section). Although the upper contact of the Winthrop Sandstone with the Ventura Member of the Midnight Peak Formation is gradational throughout much of the study area (see also Pitard, 1958; Barksdale, 1975; Rau, 1987), local unconformities are reported. The Ventura Member overlies the Winthrop Sandstone with angular discordance locally at Lucky Jim Bluff, the type section of the Ventura Member (M.F. McGroder, written commun., 1987), and more prominently on the south slopes of Last Chance Point, about 5 km west of the Mazama quadrangle (fig. 1), where boulders of arkose are incorporated within the Ventura Member (D.C. Mohrig, personal commun. *in* Rau, 1987, p. 46). The two units are juxtaposed by faults in and near Boesel Canyon. There, the upper part of the Winthrop Sandstone contains tuff beds lithologically similar to the overlying Midnight Peak Formation (this study), as well as intercalated redbeds (Rau, 1987).

The contact between the Winthrop Sandstone and the Ventura Member of the Midnight Peak Formation in the eastern part of the Methow basin is marked in many places by a transitional, or mixed, zone. This zone consists of massive dark-greenish-gray sandstone composed of subequal arkosic and volcanic-chert-lithic grains. The transitional sandstone is fine- to coarse-grained with common dark mottling, poorly to moderately sorted, and well indurated. Sandstone containing isolated pebbles and small cobbles contains interbeds of conglomerate composed of red- and green-weathering volcanic rocks, chert, and argillite. Large mudstone intraclasts and clumps of large wood fragments are seen locally. Lamination in the transitional sandstone ranges from well-defined and planar to crude; large crossbeds are seen locally, but these are not as well developed as those in the Winthrop Sandstone. Dark finely laminated siltstone and mudstone beds make up a minor part of the transitional zone. In this study, the contact was drawn arbitrarily where redbeds become more numerous than arkosic or transitional beds. Pierson (1972), Cole (1973), and Barksdale (1975) also noted an upward increase in volcanic detritus in the Winthrop Sandstone, suggesting that Midnight Peak volcanism began during deposition of the Winthrop Sandstone.

Leaf fossils collected from the Winthrop Sandstone by Barksdale and earlier workers were assigned a Late Cretaceous age (Barksdale, 1975). Lithologically similar arkosic sandstone in the lower part of the Pasayten Group of Manning Park, British Columbia has been assigned an Albian age (Daly, 1912; Rice, 1947; Coates, 1970, 1974; Jeletzky, 1972) on the basis of the similarity of its plant fossils to the Albian Blairmore flora of Alberta. Fossil leaves collected from the Winthrop Sandstone by Rau (1987) and identified by D. Crabtree (Rau, 1987, p. 97; Crabtree, 1987) confirm the similarity with the Blairmore flora. In this report, an Albian to (possibly) Cenomanian age is adopted for the Winthrop Sandstone. Some evidence indicates that the Winthrop Sandstone might locally be younger, as it overlies the Virginian Ridge Formation, which contains possible Turonian fossils. Barksdale (1975, p. 44-45) suggested that the Winthrop-like arkosic sandstones are time transgressive, being Albian in age in Manning Park and younger in the Methow Valley.

Depositional setting and source of the Winthrop Sandstone—Rau (1987) interpreted the Winthrop Sandstone as the intertonguing deposits of a marine basin and a prograding shoreline that graded upward into a fluvial system. According to Rau, the fluvial system was characterized by streams with mobile channels and low sinuosity. Tennyson and Cole (1978) considered the Winthrop Sandstone to represent the deposits of a fluvial-deltaic system. Trexler (1984) suggested that eastward-derived, coarsening-upward sandstone cycles in the upper part of the Virginian Ridge Formation and lower part of the Winthrop Sandstone represent advancing prodelta lobes.

Paleocurrent data indicate overall westward transport of sediment (Cole, 1973; Rau, 1987). These data and the westward decrease in average grain size and sand to shale ratios of the Winthrop Sandstone (Rau, 1987) indicate an eastern source for the detritus. Modal compositions of the Winthrop Sandstone suggest that its source was a basement uplift and (or) magmatic arc complex. Rau noted a westward decrease in the proportion of volcanic clasts, which would suggest an eastern source for volcanic debris, possibly the volcanic carapace of a magmatic arc complex. The most likely source for the Winthrop Sandstone is the Okanogan Range batholith east of the Pasayten fault.

Midnight Peak Formation—The Midnight Peak Formation was named by Barksdale (1948, 1975) for a non-marine sequence of andesitic breccia, flows, and volcaniclastic rocks at Midnight Peak (Midnight Mountain on modern maps) about 24 km west-northwest of the town of Twisp (fig. 1). The formation, which is the youngest Mesozoic deposit in the Methow basin, crops out in the troughs of several large synclines. It consists of a lower redbed unit and a volcanic upper part referred to by Barksdale (1975) as the Ventura Member and the volcanic (upper) member, respectively. The top of the Midnight Peak Formation is not exposed.

Ventura Member—The Ventura Member of the Midnight Peak Formation in the study area overlies the Winthrop Sandstone in most part conformably in the limbs of the Goat Peak syncline. However, as mentioned above, this contact is an unconformity in most places in the western part of the Methow basin (McGroder and others, 1990). The unit was originally named the Ventura Formation by Russell (1900), and its rocks were later included by Barksdale (1975) in his Midnight Peak Formation. Barksdale's Ventura type section is located on Lucky Jim Bluff on the south side of the Methow Valley, about 14 km from Winthrop. In general, the Ventura Member consists of alternating dark-red shale and siltstone, sandstone, and conglomerate mostly in beds less than 1 m thick. Lenticular interbeds of these lithologies form fining-upward sequences. The shale weathers maroon and brown, is commonly silty, and contains poorly bedded mudstone that weathers to rounded surfaces. Some shale beds contain vertical round or oval bodies of buff-colored fine sand (burrow fillings?). Minor green mudstone, siltstone, and fine-grained sandstone are interbedded locally with the redbeds. Andesitic breccia makes up 10 percent of the type section (Barksdale, 1975).

Sandstone of the Ventura Member is very fine grained to coarse grained and friable. Its weathered color ranges from gray to green to dark red or pink depending in part upon the proportions of arkosic and lithic grains. Dark-red-brown iron oxide cement is present in fine-grained sandstone and siltstone, but the red color of the coarser grained sandstone is due in part to abundant red chert, volcanic, and sedimentary grains. The red color of the volcanic grains is apparently due to alteration of the source rocks, while the sedimentary grains are probably intraclasts of Ventura rocks. Scarce intermittent beds of light-gray laminated sandstone are present in the section. Beds of sandstone are typically less than 60 cm thick and no more than 1 m thick and contain lenses of small pebbles. Sedimentary structures include fine, even dark laminae, small low-angle crossbeds, ripple-drift in fine-grained sandstone, and crude grading. Coarse sandstone loads into, or scours, fine- grained beds with sharp contacts. The bases of the sandstone beds locally contain mud balls, rip-up clasts, and flame structures.

Coarse-grained sandstone grades downward and laterally to poorly indurated pebble and cobble conglomerate in beds as thick as 2 m whose bases are generally sharp. The conglomerate is varicolored (dark-purplish red, pink, gray, and ochre) reflecting variable compositions of clasts and cement. The rock is poorly sorted and is both clast and matrix supported. Clasts in some beds were "dumped" with little or no sorting (fanglomerate). Crude bedding is defined mainly by irregular, dark silt-sand laminae or a slight tendency for alignment of flat clasts. Imbrication was seen in a few places. Large crossbeds are present locally in coarse sandstone, grit, and conglomerate. The largest clasts are generally small cobbles but isolated, well rounded small boulders are seen locally. Smaller pebbles tend to be angular and subangular, while larger ones show a greater number of rounded and subrounded forms. Overall, pebbles are subrounded to subangular and cobbles are subrounded and rounded. Clast lithologies include (1) white, green, red, black, and light-gray chert, (2) finely porphyritic volcanic rocks that weather to dark shades of red, green, and gray, and also to black, and (3) minor sedimentary rocks, quartz, metasedimentary rocks, and volcanic breccia. The largest pebbles are generally composed of volcanic rocks. Sedimentary rock clasts include sandstone and siltstone, some reddish in color, dark-red argillite, dark-gray lithic sandstone, and chert-pebble conglomerate. Barksdale (1975) reported occasional clasts of arkose and chert-pebble conglomerate, and rare granitoid clasts. Clasts are set in a matrix of silt, sand, and grit. Volcanic breccia of the unit weathers greenish gray or green and consists of subangular clasts of finely porphyritic volcanic rocks set in a tuffaceous matrix.

Sandstone of the Ventura Member is poorly to moderately sorted and has a highly variable composition. Thin-section views show that most rocks are mixtures of volcanic rock fragments, quartz, and feldspar with subordinate but locally abundant chert, metamorphic rock fragments, and epidote. Cole (1973) reported an average sandstone composition of 20 percent quartzose grains, 40 percent feldspar grains, and 40 percent lithic grains. Volcanic rock fragments include a variety of very fine-grained porphyritic rocks including flows and hypabyssal rocks. Quartz occurs as slightly undulose single grains with trains of vacuoles (plutonic quartz) and as large, clear unstrained grains (volcanic quartz?). Plutonic quartz aggregates were also seen. Feldspar is mainly plagioclase, although a few samples contain a few percent and one sample contains as much as 20 percent K-feldspar. Slightly sericitized plagioclase is present in euhedral and subhedral grains that locally are abraded. Chert, metamorphic rock fragments, and epidote are absent or scarce to relatively abundant. Chert grains of Virginian Ridge-type are subangular and locally stained pink. Most metamorphic rock fragments are of high-grade metasedimentary rocks and most epidote appears to be detrital. Scarce sedimentary rock fragments include dark-red-brown siltstone and argillite (intraclasts?), and arkose. Some rocks contain detrital calcite or calcite replacing plagioclase. Traces of sphene, chlorite, and clinozoisite are present. Basal sandstone transitional to the underlying Winthrop Sandstone contains locally abundant green hornblende, pyroxene, biotite, and coarse muscovite. Grains in sandstone of the Ventura Member are uniformly angular and subangular. Little true matrix was observed, but deformed volcanic clasts fill interstices between grains. Fine-grained sandstone and siltstone contain abundant dark-red-brown cement, probably hematite derived from oxidation of mafic grains, while coarser grained sandstone has phyllosilicate minerals filling pores. Minor replacement minerals are calcite, chlorite, and epidote-clinozoisite.

The Ventura Member has a generally sharp conformable, though locally gradational. contact with the overlying upper part of the Midnight Peak Formation. Cole (1973) reported that volcanic rocks locally occupy channels in the underlying Ventura Member. The Ventura Member of the Midnight Peak Formation has not been dated. Because it overlies the Winthrop Sandstone of late Albian or younger age and is intruded by the 88-Ma Fawn Peak stock, the most probable age for the Ventura Member is Cenomanian to Turonian.

Depositional setting and source of the Ventura Member of the Midnight Peak Formation—The oxidized nature of the Ventura Member together with poor sorting, lenticular bedding, channelling, and other features suggest that the unit was deposited on an alluvial fan or fan complex (Cole, 1973). The intense red color of the fine-grained sediments probably resulted from oxidation of iron-bearing detrital grains in a subaerial environment. The alluvial fan complex was presumably located adjacent to volcanic highlands, precursors of Midnight Peak volcanoes, and the source for the abundant volcanic clasts and minor layers of volcanic breccia in the Ventura Member.

The source area for, and direction of sediment transport on, the alluvial fan complex are unknown. The clast assemblage of the Ventura Member, probably the most varied in the basin, reflects a complex source or sources (Cole, 1973; Tennyson, 1974). Tennyson and Cole (1978) postulated uplifts on the east side of the Methow basin as the most likely source for plutonic and metamorphic debris in the Ventura Member. The abundant quartz and feldspar sand and minor pebbles of arkose and chert-pebble conglomerate suggested to Tennyson (1974) that a part of the Ventura detritus was reworked from local uplifts of recently deposited sediment (probably the Virginian Ridge Formation and the Winthrop Sandstone). The occurrrence of intraclasts of Ventura-type supports this idea. However, quartz and chert grains in the Ventura Member are angular and subangular and therefore do not appear to have been recycled. It is possible that Virginian Ridge and Winthrop strata were essentially unconsolidated at the time of local uplift and erosion, and that redeposition on Ventura fans was so rapid that little additional abrasion took place. The abundant volcanic clasts and some of the plagioclase(?) in the Ventura Member may have come from penecontemporaneous volcanic centers.

Mohrig and Bourgeois (1986) interpreted the Ventura Member as an alluvial fan system that prograded eastward through time. They considered the clast assemblage to represent reactivation of a western supracrustal source (chert) and the inception of a new western source (granitic rocks, sandstone, and rare fossiliferous limestone containing Valanginian *Buchia*).

Volcanic (upper) member—In the study area, the main outcrop of the volcanic (upper) member of the Midnight Peak Formation is located north of the Methow River in the trough of the Goat Peak syncline. In addition, two small knobs of breccia overlie the Ventura Member in the southwest wall of the Methow Valley. The unit consists of andesitic lapilli-tuff and tuff-breccia, tuff, and flows. Much of the breccia and tuff was reworked by water into massive lahars, water-laid tuffs and volcanic sandstone (Tennyson and Whetten, 1974; Mohrig and Bourgeois, 1986).

Breccia is well indurated, massive, and weathers gray, buff, brown, and green. Clasts and matrix have been replaced to varying degrees by epidote and chlorite. Epidote is also found in veins and as joint coatings. Numerous joints have produced blocky outcrops that weather to rounded lumpy surfaces. It is generally impossible to see bedding at the outcrop except for scarce indistinct layers as thick as 2 to 4 m and local crude grading in tuffaceous rocks. From a distance, crude layers on the order of tens of meters thick can be seen to dip toward the axis of the syncline. Freshly broken rock is dark gray, purplish gray, or black. Finely porphyritic gray, red, and green volcanic rock fragments are set in a dark-gray tuffaceous matrix. Rock fragments include (1) flow rocks, some glassy, (2) porphyries, (3) volcanic sandstone, and (4) rare clasts of diorite and crossbedded sandstone. Most clasts are subangular or angular and measure 2.5 to 10 cm across; rarely, blocks as much as 30 cm or 0.5 m across were observed. Some clasts are subrounded and a few are squashed (welded?) or show blurred, embayed edges, as if partly melted. Breccia is typically chaotic but locally clasts are weakly aligned.

Tuffs and flows are dark gray to black, massive, and aphanitic and contain tiny phenocrysts of plagioclase and pyroxene. Staatz and others (1971) reported flow compositions ranging from dacite to pyroxene andesite in the Robinson Mountain area (fig. 1). In the present study, silica content of five tuffs indicate compositions ranging from basalt to andesite (S.E. Shaw, written commun., 1987).

Thin-section views indicate that the larger fragments, or clasts, in lapilli-tuff and tuff-breccia of the volcanic (upper) member of the Midnight Peak Formation include (1) a variety of plagioclase-phenocrystic, porphyro-aphanitic volcanic rocks with variable crystallinity of groundmass, including glassy types, and with or without flow banding, (2) tuff and lapilli-tuff, (3) recrystallized pumice, (4) felsite, and (5) volcanic sandstone. Most of the smaller clasts are single euhedral plagioclase crystals, many of which are broken and subangular (abraded?) and partly replaced by ragged epidote. Rare clasts of quartz and epidote were also seen. Overall, clasts are subangular to subrounded. Indistinct layering produced by slight alignment of the flat dimensions of ovoid clasts was observed in some thin sections. Fine-grained tuff and the tuffaceous matrix of lapilli-tuff and tuff-breccia consist of euhedral plagioclase crystals in a range of sizes. These fine-grained rocks are variably replaced by sericite, chlorite, calcite, iron oxide(?), and phyllosilicate minerals.

No fossils have been found in the Midnight Peak Formation. Its age is closely bracketed by the Early and Late Cretaceous (Albian through Turonian) overall age of the underlying Winthrop Sandstone and Virginian Ridge Formation, both of which locally interfinger with volcanic rocks, and the 87- to 88-Ma Fawn Peak stock, which intrudes the Midnight Peak Formation. If Midnight Peak volcanism and Fawn Peak intrusion are genetically related, as seems likely, then the Midnight Peak Formation is probably only slightly older than the Fawn Peak stock. The most probable age range for the Midnight Peak Formation is Cenomanian to Coniacian. The spatial association of the volcanic rocks with the Fawn Peak stock has led most workers to speculate that the stock was the feeder for the overlying volcanic rocks.

SURFICIAL DEPOSITS

Glacial Drift

During the last glaciation (Fraser glaciation of Armstrong and others, 1965), the Cordilleran ice sheet covered the Methow Valley and adjoining mountains and left scattered deposits of till and outwash (Waitt, 1972). Many of the cobbles and boulders in these deposits are exotic. Patches of till mantle parts of bedrock terraces that lie between the mountain peaks and the floor of the Methow Valley. These terraces were probably cut by ice- marginal streams. Stratified drift is found on these terraces, as well as on the slopes of stream valleys. Valley glaciers eroded the spectacular U-shaped valleys of the Methow River and Eightmile Creek, and Alpine-type glaciers produced impressive cirques on the east side of the ridge that joins McLeod Mountain and Sunrise Peak in the north-central part of the Mazama quadrangle as well as several small cirques in the east wall of Isabella Ridge. Glacial striations are preserved on Goat Peak and locally on Isabella Ridge (Dixon, 1959).

Many of the glacial deposits are mantled by buff-gray-weathering colluvium, and some are mixtures of drift and slopewash formed when the once- blanketing drift was dissected and reworked downslope by streams, sheet floods, and mass wasting. Reworking is indicated by the freshly broken character of many faceted cobbles and boulders. Drift grades downslope into post-glacial older alluvium. In places where drift is less than 2 to 3 m thick, bedrock knobs are common, and these deposits are not shown on the map.

Older alluvium

The older alluvium consists of stratified deposits of sand, silt, and gravel that once filled stream valleys to depths at least as great as 100 m. These deposits consist almost totally of reworked Pleistocene glacial drift. Modern streams have dissected the older alluvium leaving patchy remnants along the sides of valleys.

Colluvium

Colluvium consists of mixtures of sand, silt, and gravel that accumulated as slopewash and talus deposits. These deposits grade locally into younger and older alluvium units and into the glacial drift from which they are largely derived.

Younger alluvium

Younger alluvium consists of sand, silt, and gravel that occupy modern stream beds and form alluvial cones at the mouths of tributary streams. Much of this alluvium was derived from Pleistocene glacial drift. In some places, younger alluvium grades into older alluvium.

STRUCTURE

Folds

The chief structures in the Methow basin are large (wavelengths as large as 20 km), northwest-trending, generally south-plunging parallel folds whose axes are nearly parallel to the bounding Pasayten and Hozameen faults (Barksdale, 1975; Tennyson and Cole, 1978). The folds are characterized by complexly faulted hinges and longitudinal bedding-plane faults. No satellitic folds were seen at the outcrop.

The most prominent structure in the study area is the Goat Peak syncline, which involves all of the Cretaceous section. This fold is part of a regional downwarp or synclinorium that includes smaller synclines to the north at Robinson Mountain, Last Chance Point, and Scramble Point (Barksdale, 1975; Stoffel and McGroder, 1990)(fig. 1). The Goat Peak syncline is doubly plunging and its northwest and southeast terminations are complicated by north- and east-striking faults. The fold is asymmetrical, in part overturned, toward the southwest. South of Fawn Peak, the northeast limb is upright, but it is near-vertical or overturned north of Fawn Peak. The southwest limb of the fold is upright. The Late Cretaceous Fawn Peak stock intruded, and underlies, the Midnight Peak Formation in the core of the fold. A similar relation exists in other synclines in the basin where Late Cretaceous stock-dikes or sills intrude Midnight Peak Formation in or near the troughs of the folds. These Late Cretaceous intrusions form a northwest-trending linear array close to the axis of the synclinorium (Stoffel and McGroder, 1990).

The Goat Peak syncline may be flanked on the northeast by one or more north-northwest-trending folds in the Harts Pass group of Tennyson and Cole (1978). The best-exposed fold is the syncline on Sweetgrass Ridge, which extends for a minimum distance along strike of 15 km. The northeast limb of this fold is oversteepened toward the west in the vicinity of Deer and Cabin Creeks. The fold has been offset left-laterallly by the Ortell Creek fault and uplifted against the volcanic rocks of Isabella Ridge by the Isabella Ridge fault. North of the Ortell Creek fault, the syncline is obscured by minor faults and possibly by tilting or rotation of bedding.

Scattered indications of opposed facings in the rocks of the Harts Pass group require a southwest-overturned anticline between the Goat Peak and Sweetgrass Ridge synclines. This fold apparently broke along one or more weak shale(?) horizons in the Panther Creek Formation to form a west-verging bedding-plane fault. Rocks of the Harts Pass group on the east were juxtaposed by this fault against the Harts Pass group and overlying younger rocks in the northeast limb of the Goat Peak syncline (cross sections *A-A'* and *B-B'*). An alternative explanation for the relations in the Sweetgrass Ridge area is that the facing indicators that suggest the presence of upright Harts Pass Formation are anomalous and that the entire stratigraphic section in the Sweetgrass Ridge area faces to the southwest. Further biostratigraphic and sedimentologic studies are needed to resolve this problem.

The onset of folding in the basin is constrained by the age of the youngest affected unit, the Midnight Peak Formation (Cenomanian to Coniacian?) and the age of the sills and dikes that cut the Goat Peak and other synclines (93-85 Ma). The Fawn Peak stock (88-87 Ma), which is probably cogenetic with the volcanic rocks of the Midnight Peak Formation, apparently was emplaced at a late stage in folding. The northeast plunge of a breccia pipe in the stock on Flagg Mountain led Riedell (1979) to suggest 45° of tilting down to the west-southwest in this area.

Faults

Pasayten fault—The Pasayten fault is a major regional structure that extends southward for a minimum distance of 200 km from the Fraser-Yalakom fault zone in British Columbia (Kleinspehn, 1982) to 120° W. longitude, about 10 km northeast of Twisp, Washington, where its trace becomes irregular and disappears (J.R. Wilson, written commun., 1983). The fault separates deep-seated batholithic rocks of the Okanogan Range on the east from sedimentary and volcanic rocks intruded by high-level plutons in the Methow basin on the west. Its movement history is not completely understood, but is thought to include both strike-slip and dip-slip movements (Lawrence, 1978). Lawrence postulated a mid-Cretaceous period of left-lateral strike-slip on the Payayten fault at depths of 10(?) km and temperatures of 300° and 400°C, on the basis of petrofabric studies of plutonic rocks east of the fault. Todd (1995) found that the western plutons of the Early Cretaceous Okanogan Range batholith apparently were intruded during movement on the Pasayten fault, culminating in the formation of a mylonitic border zone. The presence west of the fault of Late Jurassic basement (the Button Creek stock) that differs lithologically from the trondhjemitic Okanogan Range batholith suggests significant strike slip. From the orientation of minor brittle structures in the fault zone Lawrence (1978) inferred a late period of high-angle reverse motion, possibly related to folding in the Methow basin. Late Cretaceous brittle deformation in the fault zone produced a narrow linear fault trace that is well marked topographically by the valley of Eightmile Creek. Brittle shearing resulted in a zone of brecciated and altered rocks about 1 km wide west of the fault.

Late Cretaceous porphyritic sills and dikes of similar lithology are present on both sides of the Pasayten fault in the Mazama and Doe Mountain quadrangles (this report; and Todd, 1995). If these intrusions are genetically related, then large strike-slip movement probably had ceased in this area by Late Cretaceous time. The sills and dikes are associated with brittle shearing and hydrothermal alteration in both dikes and host rocks. It is likely that crustal extension, rise of magma, and minor faulting(?) were associated with late movements on the Pasayten fault. A patch of Paleocene(?) continental rocks, the Pipestone Canyon Formation of Barksdale (1975), located immediately northeast of Twisp on the west side of the fault indicates that the rocks of the basin were down-dropped relative to the Okanogan Range batholith in early Tertiary time. These movements continued into the Eocene and ended by about 47 Ma (White, 1986). About 15 km north of the study area, the Eocene volcanics of Island Mountain of Staatz and others (1971) are cut by and intrude the Pasayten fault (White, 1986).

Isabella Ridge fault—A steep north-northwest-striking fault on Isabella Ridge separates Jurassic and Cretaceous volcanic rocks overlying the Late Jurassic Button Creek stock on the east from the Harts Pass group on the west over a minimum distance of 18 km. This fault is parallel to, and lies 3 to 4 km west of, the Pasayten fault. The Isabella Ridge and Pasayten faults are joined by a series of complex transverse faults in the Button and Ortell Creek drainages. These generally east-striking, left-lateral faults probably formed at about the same time as the Isabella Ridge fault, for they locally offset it or are truncated by it. The block that lies between the Isabella Ridge and Pasayten faults must have undergone significant uplift and erosion between intrusion of the Late Jurassic Button Creek stock and deposition of the uppermost, Late Cretaceous volcanic sequence on Isabella Ridge. Earlier strike slip on the Isabella Ridge fault is not ruled out, but the latest movement on the fault was down-dropping of the block against rocks of the Harts Pass group on the west (cross section *A-A'*). The above relations suggest that the Isabella Ridge fault is a subsidiary strand of the Pasayten fault. Similar relations may be found in the western part of the Doe Mountain quadrangle where Jurassic and Cretaceous volcanic rocks are present in what appear to be fault-bounded slivers west of the Pasayten fault (Todd, 1995).

Fault west of Lewis Butte—A major north-trending fault extends for 8 to 10 km from the northeastern part of the Buttermilk Butte quadrangle to the southwestern part of the Doe Mountain quadrangle, where it ends against a fault or faults in Cub Creek (Todd, 1995). Part of this fault is exposed in the southeast corner of the map area. The fault has brought the Jurassic Twisp Formation up on the east against Cretaceous formations as young as the Winthrop Sandstone on the west and probably has a stratigraphic throw of more than a kilometer. This fault is one of a complex group of north- and east-trending high-angle faults that cut the southeast nose of the Goat Peak syncline and that presumably formed during or shortly after folding. However, the Lewis Butte fault most likely had an earlier, pre-Late Cretaceous period of activity, because it separates two apparently different stratigraphic sequences. West of the fault, the Lower and Upper Cretaceous Virginian Ridge Formation of Barksdale (1948, 1975) rests upon the Harts Pass Formation. East of the fault, the Harts Pass Formation is missing or is in fault contact with the Virginian Ridge and Twisp Formations and the Virginian Ridge rests upon the Twisp Formation.

Boesel Canyon fault—The Boesel Canyon fault consists of a series of short, north-northeast-trending high-angle faults that extends for a minimum of 14 km from the vicinity of Cub Creek on the north to Wolf Creek on the south. The fault has brought the Virginian Ridge Formation, the undivided Virginian Ridge Formation and Winthrop Sandstone, and the Winthrop Sandstone up on the east against these same units overlain by the Midnight Peak Formation on the west. The fault is marked by the juxtaposition of north- northeast-striking, west-dipping beds in the east block against northwest-striking, northeast-dipping beds in the west block. The Boesel Canyon fault and transverse faults with apparent small right-lateral offsets are probably accommodation faults in the hinge area of the Goat Peak syncline. The stratigraphic separation across the fault south of the Methow River may be as large as 3 km, based upon estimated thicknesses of the missing Midnight Peak Formation and Winthrop Sandstone on the east side of the fault.

Ortell and Button Creek faults—Apparently, Ortell Creek was eroded along a series of short faults that connect the Isabella Ridge and Pasayten faults. The net result of faulting in Ortell Creek and in Button Creek to the north was apparently down-dropping of the Late Jurassic Button Creek stock and overlying volcanic strata on the north and east against the Panther Creek Formation on the south and west (cross section *B-B'*). The Ortell Creek fault continues westward at least to the drainage divide between Goat Creek and Lost River. Contacts in the Harts Pass group in this area show apparent left-lateral offsets ranging from 150 to 500 m. Geologic relations in Eightmile Creek suggest that either the trace of the Pasayten fault is broadly curvilinear, or that it was offset right-laterally less than 1 km by the Ortell and Button Creek faults (this study; and Todd, 1995). The Button Creek fault is truncated to the west by the Isabella Ridge fault.

Bedding-plane faults—A bedding-plane fault is inferred to have developed in a southwest-verging anticline in the Harts Pass group, as discussed above (cross sections *A-A'* and *B-B'*). The hanging wall, or northeast side, of this fault is up relative to the foot wall, or southwest side. The chief evidence for a bedding plane fault in the Panther Creek Formation in the Goat Creek drainage consists of opposed facing indicators that suggest the presence of a tight syncline in the Panther Creek and Harts Pass Formations on the east side of the fault. From north to south, the fault may be expressed by north-northwest-trending lineaments in Panther Creek and aligned features to the south such as a linear reach of Goat Creek, a bench in the east wall of Goat Creek, a notch in Sweetgrass Ridge, and fractured, slickensided, calcite-veined rocks in the area between Cub Pass and Fourth Creek. The fault must be covered by alluvium in Cub Creek, where it juxtaposes the undivided Virginian Ridge Formation and Winthrop Sandstone, with tops to the southwest, on the west against the Harts Pass group, with tops to the northeast, on the east (cross section *C-C'*). Porphyritic sills and dikes are especially abundant in the Panther Creek Formation in this area, suggesting that heat and fluids from these intrusions may have facilitated faulting in weakly resistant shale beds.

A second bedding-plane fault apparently formed near the contact between the Panther Creek and Harts Pass Formations on the east side of Sweetgrass Ridge. The chief evidence is that the east limb of the Sweetgrass Ridge syncline is cut off by this contact. The fault is expressed by several benches in the west wall of Ortell Creek. It is not clear whether the poorly exposed eastern contact between the Panther Creek and Harts Pass Formations south of Cabin Creek is a fault or a depositional contact; dips in both formations are near-vertical in this area.

The existence of a minor bedding-plane fault near the contact between the Winthrop Sandstone and the overlying Ventura Member of the Midnight Peak Formation in the northeast limb of the

Goat Peak syncline is suggested by thinning of the Ventura Member and opposed dips in the Winthrop Sandstone and the volcanic (upper) member of the Midnight Peak Formation in the area northeast of Goat Peak. Heat and fluids introduced by the Fawn Peak stock may have facilitated a breakaway along this horizon.

ACKNOWLEDGMENTS

I wish to thank personnel of the Winthrop and Twisp Ranger Districts of the Okanogan National Forest for their assistance during the field study. Peggy Wang provided able assistance and good company during the 1982 field season. Ralph Haugerud and Alan Bartow reviewed the map and text and made suggestions for improvement.

REFERENCES CITED

Armstrong, J.E., Crandell, D.R., Easterbrook, D.J., and Noble, J.B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bulletin, v. 76, no. 3, p. 321-329.

Barksdale, J.D., 1948, Stratigraphy in the Methow quadrangle, Washington: Northwest Science, v. 22, p. 164-176.

——— 1975, Geology of the Methow Valley, Okanogan County, Washington: Washington Division of Geology and Earth Resources Bulletin 68, 72 p., 1 pl.

Bunning, B.B., 1990, Geologic map of the east half of the Twisp 1:100,000-scale quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-9, 51 p., scale 1:100,000.

Cairnes, C.E., 1944, Hope Sheet, British Columbia: Geological Survey Canada Map 737A.

Coates, J.A., 1970, Stratigraphy and structure of Manning Park area, Cascade Mountains, British Columbia, *in* Structure of the southern Canadian Cordillera: Geological Association of Canada Special Paper 6, p. 149- 154.

——— 1974, Geology of the Manning Park area, British Columbia: Geological Survey of Canada Bulletin 238, 177 p.

Cole, M.R., 1973, Petrology and dispersal patterns of Jurassic and Cretaceous sedimentary rocks in the Methow River area, North Cascades, Washington: Seattle, University of Washington, Ph.D. dissertation, 110 p.

Crabtree, David, 1987, Late Cretaceous angiosperms of the Northern Rockies: Annals of the Missouri Botanical Gardens, v. 74, p. 707-747.

Daly, R.A., 1912, Geology of the North American Cordillera at the forty-ninth parallel: Geological Survey of Canada Memoir No. 38, 3 parts, 857 p., 17 map sheets.

Dixon, R.W., 1959, Geology of the Isabella-Sweetgrass area, Okanogan County, Washington: Seattle, University of Washington, M.S. thesis, 63 p.

Haugerud, R.A., 1985, Geology of the Hozameen Group and the Ross Lake shear zone, Maselpanik area, North Cascades, southwest British Columbia, Seattle, University of Washington, Ph.D. dissertation, 263 p.

Haugerud, R.A., Tabor, R.W., Snee, L.W., and Hurlow, H.A., 1993, Mid-Cretaceous unconformity in the Methow basin, north-central Washington: Geological Society of America Abstracts with Programs, v. 25, no. 5, p. 49.

Hurlow, H.A., and Nelson, B.K., 1993, U-Pb zircon and monazite ages for the Okanogan Range batholith, Washington: implications for the magmatic and tectonic evolution of the southern Canadian and northern United States Cordillera: Geological Society of America Bulletin, v. 105, no. 2, p. 231-240.

Jeletzky, J.A., 1972, Jurassic and Cretaceous rocks along Hope-Princeton Highway and Lookout Road, Manning Park, British Columbia (supplement to section 10 of 24th International Geological Congress Guidebook A03- C03): Geological Survey of Canada, 38 p., 1 pl.

Kleinspehn, K.L., 1982, Sedimentation and tectonics, Tyaughton-Methow basin, southeastern British Columbia: Princeton, New Jersey, Princeton University, Ph.D. dissertation, 106 p.

Lawrence, R.D., 1978, Tectonic significance of petrofabric studies along the Chewack-Pasayten Fault, north-central Washington: Geological Society of America Bulletin, v. 89, no. 5, p. 731-743.

Livingstone, K.W., and Wolfhard, M.R., 1976, Porphyry copper deposit at Goat Creek, Methow Valley, Washington: Preprint AIME Regional Meeting, Coeur d'Alene, Idaho, April 1976.

Maurer, D.L., 1958, Biostratigraphy of the Buck Mountain member and adjacent units in the Winthrop area, Washington: Seattle, University of Washington, M.S. thesis, 111 p.

McGroder, M.F., and Miller, R.B., 1989, Geology of the eastern North Cascades, *in* Joseph, N.L., and others, eds., Geologic guidebook for Washington and adjacent areas: Washington Division of Geology and Earth Resources Information Circular 86, p. 97-118.

McGroder, M.F., Garver, J.I., and Mallory, V.S., 1990, Bedrock geologic map, biostratigraphy, and structure sections of the Methow Basin, Washington and British Columbia: Washington Division of Geology and Earth Resources, Open-File Report 90-19, 32 p.

Menzer, F.J., Jr., 1983, Metamorphism and plutonism in the central part of the Okanogan Range, Washington: Geological Society of America Bulletin, v. 94, no. 4, p. 471-498.

Mohrig, D.C., and Bourgeois, Joanne, 1986, A new source terrane for Methow Basin (WA) sediments: Evidence from the Cenomanian(?) Ventura Member, Midnight Peak Formation, southern Canadian Cordillera (abs.): Geological Society of America Abstracts with Programs, v. 18, no. 2, p. 159.

Palmer, A.R., 1983, The Decade of North American Geology 1983 geologic time scale: Geology, v. 11, p. 503-504.

Pierson, T.C., 1972, Petrologic and tectonic relationships of Cretaceous sandstones in the Harts Pass area, North Cascade Mountains, Washington: Seattle, University of Washington, M.S. thesis, 37 p.

Pitard, A.M., 1958, Geology of Mazama area, Methow Valley, Washington: Seattle, University of Washington, M.S. thesis, map scale 1:62,500, 61 p.

Rau, R.L., 1987, Sedimentology of the upper Cretaceous Winthrop Sandstone, northeastern Cascade Range, Washington: Cheney, Eastern Washington University, M.S. thesis, 197 p.

Rice, H.M.A., 1947, Geology and mineral deposits of the Princeton map area, British Columbia: Geological Survey of Canada Memoir 243, 136 p.

Riedell, K.B., 1979, Geology and porphyry copper mineralization of the Fawn Peak intrusive complex, Methow Valley, Washington: Seattle, University of Washington, M.S. thesis, 52 p.

Rinehart, C.D., 1981, Reconnaissance geochemical survey of gully and stream sediments, and geologic summary, in part of the Okanogan Range, Okanogan County, Washington: Washington Division of Geology and Earth Resources Bulletin 74, 24 p., 3 pl.

Rinehart, C.D., and Fox, K.F., Jr., 1972, Geology and mineral deposits of the Loomis quadrangle, Okanogan County, Washington: Washington Division of Mines and Geology Bulletin no. 64, 124 p., scale 1:62,500.

——— 1976, Bedrock geology of the Conconully quadrangle, Okanogan County, Washingtron: U.S. Geological Survey Bulletin 1402, 58 p., scale 1:62,500.

Russell, I.C., 1900, A preliminary paper on the geology of the Cascade Mountains in northern Washington: U.S. Geological Survey, Annual Report 20, pt. 2, p. 83-210.

Smith, G.O., and Calkins, F.C., 1904, Geologic reconnaissance of the Cascade Range near the 49th parallel: U.S. Geological Survey Bulletin 235, 103 p.

Staatz, M.H., Weis, P.L., and Tabor, R.W., 1971, Mineral resources of the Pasayten Wilderness Area, Washington: U.S. Geological Survey Bulletin 1325, 225 p.

Stoffel, K.L., and McGroder, M.F., 1990, Geologic map of the Robinson Mountain 1:100,000-scale quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 90-5, 39 p., scale 1:100,000.

Stoffel, K.L., Joseph, N.L., Waggoner, S.Z., Gulick, C.W., Korosec, M.A., and Bunning, B.B., 1991, Geologic map of Washington-northeast quadrant: Washington Division of Geology and Earth Resources, Geologic Map GM-39, 1:250,000.

Streckeisen, A.L., 1973, Plutonic rocks classification and nomenclature recommended by the IUGS subcommission on the systematics of igneous rocks: Geotimes, v. 18, no. 10, p. 26-30.

Tabor, R.W., Engels, J.C., and Staatz, M.H., 1968, Quartz diorite-quartz monzonite and granite plutons of the Pasayten River area, Washington-- petrology, age, and emplacement: U.S. Geological Survey Professional Paper 600-C, p. C45-C52.

Tennyson, M.E., 1974, Stratigraphy, structure and tectonic setting of Jurassic and Cretaceous sedimentary rocks in the west-central Methow-Pasayten area, northeastern Cascade Range, Washington and British Columbia: Seattle, University of Washington, Ph.D. dissertation, 3 plates, 112 p.

Tennyson, M.E., and Cole, M.R., 1978, Tectonic significance of upper Mesozoic Methow-Pasayten sequence, northeastern Cascade Range, Washington and British Columbia: Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium 2, p. 499-508.

Tennyson, M.E., and Whetten, J.T., 1974, Late Cretaceous volcanism in the Harts Pass area, Methow-Pasayten graben, North Cascade Range, Washington (abs.): Geological Society of America Abstracts with Programs, v. 6, no. 3, 266-267.

Tennyson, M.E., Jones, D.L., and Murchey, B.L., 1982, Age and nature of chert and mafic rocks of the Hozameen Group, North Cascade Range, Washington, Geological Society of America Abstracts with Programs, v. 14, no. 4, p. 239-240.

Todd, V.R., 1987, Jurassic and Cretaceous plutonism in and near the Methow basin, north-central Washington: Preliminary K-Ar data (abs.): Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 458.

Todd, V.R., 1995, Geologic map of the Doe Mountain quadrangle, Okanogan County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2306, scale 1:62,500.

Trexler, J.H., Jr., 1984, Stratigraphy, sedimentology and tectonic significance of the upper Cretaceous Virginian Ridge Formation, Methow Basin, Washington--Implications for tectonic history of the north Cascades: Seattle, University of Washington, Ph.D. dissertation, 172 p.

——— 1985, Sedimentology and stratigraphy of the Cretaceous Virginian Ridge Formation, Methow basin, Washington: Canadian Journal of Earth Sciences, v. 22, p. 1274-1285.

Waitt, R.B., Jr., 1972, Geomorphology and glacial geology of the Methow drainage basin, eastern North Cascade Range, Washington: Seattle, University of Washington, Ph.D. dissertation, 154 p.

White, P.J., 1986, Geology of the Island Mountain area, Okanogan County, Washington: Seattle, University of Washington, M.S. thesis, 80 p.

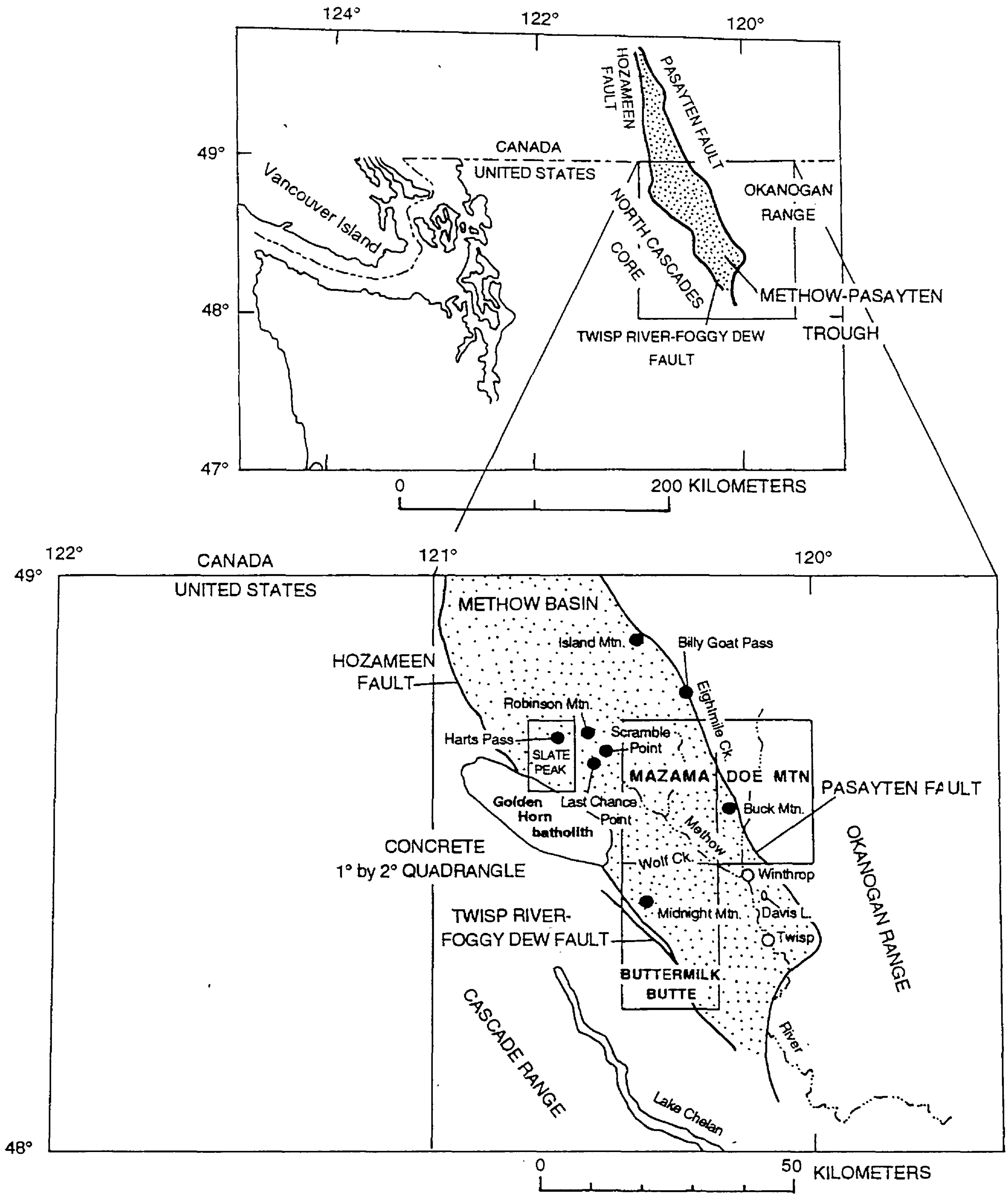

Figure 1. Regional geologic setting of Mazama quadrangle (modified from Stoffel and others, 1991; McGroder and Miller, 1989) and index map of geographic features and quadrangles mentioned in text.

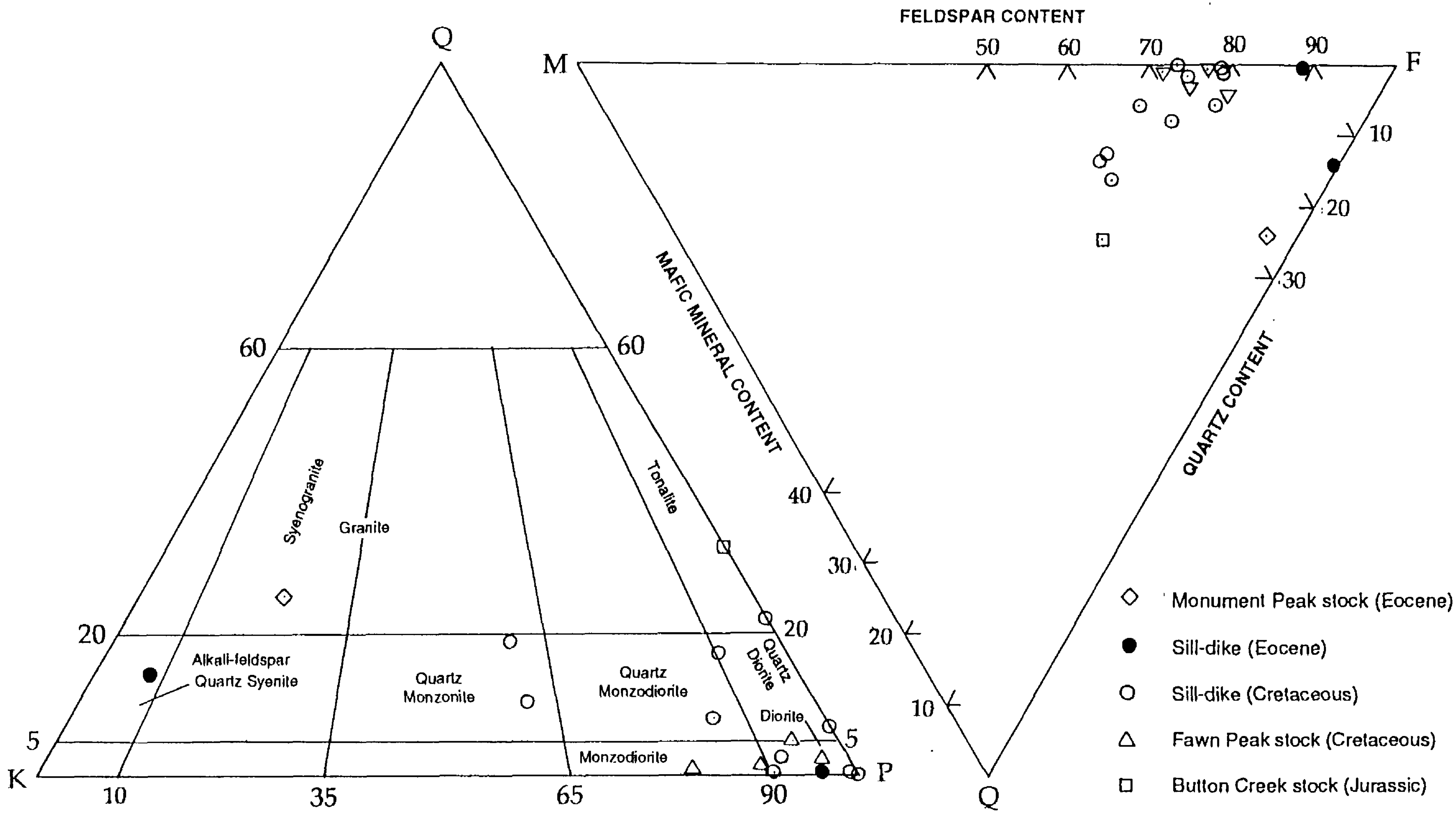

Figure 2. Modal data for plutonic rocks from Mazama, Doe Mountain, and Buttermilk Butte 15-minute quadrangles. **QKP**, modal quartz-potassium feldspar-plagioclase. **QFM**, modal quartz-feldspar-mafic minerals. Modes determined by point-counting stained rock slabs. Classification from Streckeisen (1973).

Table 1. Potassium-argon ages from the Mazama quadrangle (bio, biotite; hbl, hornblende; w.r., whole rock)

Map No.	Unit or rock type	Latitude Longitude	Material dated	Apparent age (Ma)	Sample No.
1	Button Creek stock	48°42'34" 120°17'31"	hbl bio	153.2±3.8 145.9±3.6	M-85
2	Button Creek stock	48°40'01" 120°15'26"	hbl	150.2±3.8	M-22
3	Fawn Peak stock	48°35'41" 120°22'10"	bio	86.9±2.2	M-10
4	Porphyritic sill (quartz monzodiorite)	48°31'51" 120°16'26"	hbl	81.7±2.5 86.9±2.6	PM-17
5	Porphyritic sill (diorite)	48°37'56" 120°21'33"	hbl	93.2±2.3	M-16
6	Porphyritic sill (quartz diorite)	48°39'57" 120°18'40"	hbl	87.8±2.2 84.0±2.1	PM-2[illegible]A
7	Porphyro-aphanitic dike (basalt)	48°39'20" 120°24'44"	w.r.	47.3±1.2	PM-25B
8	Porphyro-aphanitic dike (basaltic andesite)	48°37'48" 120°26'04"	w.r.	47.8±1.2 49.2±1.2	M-49A

Table 2. Fossil data from the Mazama and Slate Peak quadrangles

Map No.	Field No.	Unit	Latitude Longitude	Fossils	Age	Identified by
1	PM-9	Panther Creek Formation	48°38'12" 120°17'38"	Gastropod: ANCHURA BIANGULATA Anderson Pelecypod: GONIOMYA sp. appears to be GONIOMYA VESPERA Anderson	Early Cretaceous (Aptian to Albian)	J.W. Miller
2	PM-29A	Panther Creek Formation	48°39'34" 120°18'22"	Cephalopod: Fragment that appears to be BREWERICERAS sp. Pelecypod: AUCELLINA sp. NUCULANA sp.	Probably Early Cretaceous (Albian)	J.W. Miller
3	PM-34	Panther Creek Formation	48°38'24" 120°17'45"	Gastropod: ANCHURA BIANGULATA Anderson ATRESIUS sp. Pelecypod: MERETRIX? sp.	Early Cretaceous (Aptian to Albian)	J.W. Miller
4	PM-44[1]	Harts Pass Formation	48°43'24" 120°39'48"	Cephalopod: MELCHIORITES? sp. HAMITES sp.	Early Cretaceous (Aptian to Albian)	J.W. Miller
5	PM-45B[2]	Virginian Ridge Formation	48°44'12" 120°40'38"	Gastropod: ACTEONELLA PACKARDI Anderson	Late Cretaceous (Turonian)	J.W. Miller
6	M-29	Virginian Ridge Formation and Winthrop Sandstone, undivided	48°38'15" 120°19'30"	Leaf: Actinodromous dicotyledonous leaf	Unknown prior to middle Albian	J.A. Wolfe

1. Type section of Harts Pass Formation in Slate Peak quadrangle.
2. Collected 600 m south-southeast of Slate Peak in Slate Peak quadrangle.