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GEOLOGIC MAP OF THE DOE MOUNTAIN 15' QUADRANGLE, OKANOGAN COUNTY, WASHINGTON

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DISCUSSION

INTRODUCTION

The Doe Mountain 15' quadrangle is located in north-central Washington in the eastern half of the Concrete 1° by 2° quadrangle (fig. 1; on map sheet). U.S. Geological Survey mapping in the eastern half of the Concrete quadrangle in 1981 and 1982 was part of a crustal transect across the northwestern United States. Previous work in the Doe Mountain quadrangle and adjacent areas dealt chiefly with the sedimentary rocks of the Methow basin, the southernmost part of the larger Methow-Pasayten trough (fig. 1) (Maurer, 1958; Dixon, 1959; Cole, 1973; Barksdale, 1975; Tennyson and Cole, 1978; Trexler, 1985). Major fault zones bound the Methow-Pasayten trough: on the west are the Hozameen, the North Creek, and the Twisp River-Foggy Dew faults; on the east is the Pasayten fault, which passes through the southwestern part of the map area. The Pasayten fault extends northwestward for at least 250 km, from about 5 km northeast of the town of Twisp, Washington (Lawrence, 1978), across north-central Washington, and into the interior of British Columbia (fig. 1). In the map area, the Pasayten fault separates two major crustal blocks. Plutonic rocks northeast of the Pasayten fault are within the western half of a Late Triassic to Late Cretaceous batholith, which is referred to informally in this report as the Okanogan Range batholith. This batholith underlies most of the rugged Okanogan Range, which is roughly bounded by the Chewack River-Eightmile Creek drainages on the west and the Sinlahekin Valley between Loomis and Concullony on the east (fig. 1) (Rinehart and Fox, 1972, 1976; Rinehart, 1981). The plutonic rocks are approximately equivalent to Barksdale's (1975) Okanogan batholithic complex and Hawkins' (1968) Chewack River Gneiss. Southwest of the Pasayten fault are exposures of Mesozoic marine and nonmarine sedimentary and volcanic rocks of the Methow basin (Barksdale, 1975; Tennyson and Cole, 1978). Rocks in the map area both northeast and southwest of the Pasayten fault are overlain locally by glacial drift and various postglacial deposits.

SEDIMENTARY AND VOLCANIC ROCKS

The Methow basin is the southern continuation of the informally named Methow-Pasayten trough (Tennyson and Cole, 1978), which extends from north-central Washington into southern British Columbia (fig. 1). The Mesozoic basin exposes a thick (15–20 km) sequence of unmetamorphosed to weakly metamorphosed Jurassic and Cretaceous sedimentary and volcanic rocks (Coates, 1974; Barksdale, 1975; Tennyson and Cole, 1978; O'Brien, 1986). 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. These rocks are unconformably overlain by beds of 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. Overlying these older rocks with local unconformity are marine chert-pebble conglomerate and mudstone, plant-bearing fluvial and deltaic plagioclase arkose, and andesitic flows and pyroclastic rocks of Albian and early Late Cretaceous age (Trexler, 1985; McGroder and others, 1990). These strata indicate that shoaling and emergence of the marine basin were accompanied by local volcanism (Tennyson and Cole, 1978).

The sedimentary and volcanic rocks exposed in the southwestern part of the map area consist of the following: interbedded volcanic- and chert-lithic sandstone, siltstone, shale, and conglomerate (flysch); andesitic tuff-breccia, conglomerate, and mafic volcanic flows; plagioclase arkose, mudstone, and granitoid-bearing conglomerate; and marine lithic sandstone, siltstone, and chert-pebble conglomerate. These rocks were originally assigned by Barksdale (1948, 1975) to his Jurassic Twisp Formation and

Cretaceous Buck Mountain, Goat Creek, and Virginian Ridge Formations. In this report, Barksdale's Twisp and Virginian Ridge Formations are retained, but sedimentary rocks in the Buck Mountain area are herein interpreted to be continuous with rocks of the Panther Creek and Harts Pass Formations, which are mapped in the Mazama 15' quadrangle to the west (fig. 1), and thus are referred to as such herein. The predominantly volcanic section west of Buck Lake was considered by Barksdale (1975) to be the basal part of his Buck Mountain Formation; however, in this report, an informal unit name—volcanic rocks, undivided—is used for all volcanic rocks in the southwestern part of the quadrangle. Sedimentary rocks within the study area that Barksdale (1975) assigned to his Goat Creek Formation could not be differentiated from his Harts Pass Formation, and therefore the name "Goat Creek Formation" is not used in this report.

Twisp Formation of Barksdale (1975)

The Twisp Formation of Barksdale (1975) was named for beds of thin-bedded black argillite and interbedded lithic sandstone that crop out north of the town of Twisp (fig. 1). The formation is exposed in the southwestern part of the map area west of the Chewack River in an apparently fault bounded block. The unit consists of thin-bedded (less than 30 cm) black shale; medium- to dark-gray, fine-grained sandstone and siltstone; and relatively massive coarse sandstone, which grades to grit and poorly sorted, tan-weathering pebble conglomerate in beds as much as several meters thick. Most lithologies contain broadly wavy laminations that vary in thickness from a few millimeters to a few centimeters. The thin bedding, the regular repetition of rock types, and the sedimentary structures, which include graded beds, ripple-drift cross-laminations, shale rip-up clasts in sandstone, and flame structures, all indicate deposition in a deep-marine basin by turbidity currents. Clasts in the sandstone and grit conglomerate, which vary from angular to subrounded, include abraded euhedral volcanic plagioclase and very fine grained porphyritic volcanic rocks, as well as chert and black shale. No monocrystalline quartz was seen. The rocks are variably altered to sericite, carbonate minerals, and clay minerals.

The Twisp Formation is complexly folded and faulted, probably in part because of its thin-bedded character. Bedding in the unit strikes north to northwest and dips steeply (generally greater than 70°). The profiles of large-scale tight folds can be seen on aerial photographs, and many undetected folds are undoubtedly present in the unit.

Although no age-diagnostic fossils have been found in the Twisp Formation, Barksdale (1975) considered the unit to be Jurassic in age on the basis of the following: (1) an unconformable relation between the Twisp Formation and the overlying Lower Cretaceous andesitic sedimentary breccia near Davis Lake, which is located 5 km south of the map area in the Twisp 15' quadrangle (fig. 1), and (2) lithologic correlation with the Lower and Middle Jurassic Ladner Group (Coates, 1970; Jeletzsky, 1972; O'Brien, 1986), which is exposed along regional strike to the northwest in southern British Columbia.

Volcanic rocks, undivided

Volcanic, volcaniclastic, and clastic rocks are mapped in the southwestern part of the map area in a narrow, north-northwest-trending wedge that is bounded on the west by unnamed faults and on the east by the Pasayten fault. The unit shows considerable variation in lithology, metamorphic grade, and deformation and probably comprises rocks of more than one age and depositional environment (Haugerud and others, 1993). Therefore, it is herein informally designated as the undivided volcanic rocks unit. The unit consists of interbedded volcanic breccia and tuff; mafic and silicic flows; mudstone; and sandstone, siltstone, and conglomerate composed largely of volcanic clasts. Clasts in the sandstone and conglomerate are poorly sorted, are subangular to subrounded, and consist of fine-grained porphyritic volcanic rocks, plagioclase crystals, pumice, and argillite. Chemical analysis of a mafic flow showed it to be basaltic andesite (52–53 percent SiO_2; V.R. Todd and S.E. Shaw, unpub. data, 1987). The rocks are variably metamorphosed to assemblages that include chlorite, epidote, albite, tremolite-actinolite, and carbonate minerals (Maurer, 1958; Barksdale, 1975). Bedding generally strikes north-northwest and dips steeply (more than 70°) to the east. The hinges of large-scale, tight isoclinal folds can be seen locally on aerial photographs.

Immediately west of Buck Lake, the unit consists chiefly of tuff-breccia, pumiceous tuff, lithic sandstone, and mudstone. Because of their proximity to the Pasayten fault, these rocks are intensely fractured, slickensided, silicified, and hydrothermally altered. The tuff-breccia is massive; primary layering was not observed in outcrop. Clasts in the tuff-breccia are dominantly porphyritic volcanic rocks, many of which are porphyro-aphanitic, and euhedral crystals and composite grains of plagioclase (glomeroporphyritic aggregates?). Clast shapes vary from subangular to irregular, subrounded, and flattened. The tuff-breccia west of Buck Lake closely resembles the volcanic subunit of Barksdale's (1975) Upper Cretaceous Midnight Peak Formation. A fault-bounded sliver of volcanic rocks is present on Isabella Ridge, which is located about 16 km north-northwest of Buck Lake in the Mazama quadrangle. The dominant lithologies within this sliver are massive subaerial tuffs, breccias, flows, and dikes of generally andesitic composition that were referred to as the Isabella andesite unit by Dixon (1959). The northward continuation of these rocks is the volcanics of Billy Goat Mountain (Staatz and others, 1971), described as a sequence of pyroclastic rocks that contains subordinate interbedded clastic rocks. Hornblende from the massive subaerial volcanic rocks on Isabella Ridge yielded a ^{40}Ar–^{39}Ar age of 87.0±0.4 Ma (Haugerud and others, 1993). Haugerud and others (1993) found that the Upper Cretaceous volcanic rocks locally overlie pre-Tithonian volcanic rocks unconformably.

The age of the volcanic rocks in the map area is not known. A sample from the basaltic andesite flow mentioned above yielded a K–Ar whole-rock age of 90.4±2.3 Ma (table 1, No. 1; on map sheet); however, this number is interpreted to be the age of widespread Late Cretaceous igneous and metamorphic activity in the region and not the time of eruption. About 2.5 km south of Twisp in the southern part of the Methow basin, undated volcanic rocks that also lie along the Pasayten fault and, therefore, may be lithologically equivalent to the undivided volcanic rocks unit are intruded by a pluton that has yielded a K–Ar hornblende age of 137.3±3.4 Ma (V.R. Todd, unpub. data, 1987; see also, Todd, 1987). About 6 km south of the map area near Davis Lake, a belemnite of Neocomian age was discovered in volcaniclastic rocks (Barksdale, 1975). Pending further investigation, the volcanic rocks of the map area are assigned a Jurassic and Cretaceous age; however, further study is needed to determine whether the slivers of volcanic rocks along the Pasayten fault in the Methow basin are indeed lithologically equivalent.

Panther Creek Formation of Barksdale (1975)

The Panther Creek Formation of Barksdale (1975) was named for black shale that contains beds of granitoid-bearing roundstone conglomerate and minor arkose in the Panther Creek drainage, which is located about 16 km northwest of Buck Mountain in the Mazama quadrangle (fig. 1). The formation is also present in the west-central part of the map area where it is bounded on the east by the Pasayten fault and by unnamed faults that separate it from the undivided volcanic rocks unit. On the south, the Panther Creek Formation is bounded by unnamed faults in and near the Little Cub Creek drainage.

In the Buck Mountain area, the Panther Creek Formation consists of the following: interbedded arkosic and subarkosic sandstone; black mudstone; laminated, dark-gray-weathering, fine-grained sandstone and siltstone; and well-indurated pebble and small-cobble conglomerate set in a dark, fine-sand matrix. Scarce beds of volcanic lithic sandstone containing minor quartz are also present in the section (see also Maurer, 1958; Cole, 1973; Barksdale, 1975). All of these lithologies repeat themselves in beds no more than a few meters thick. The conglomerate beds vary from discrete layers as much as several meters thick, in which aligned flat cobbles define bedding, to irregular pebbly lenses dispersed in sandstone. Clasts in the conglomerate are moderately well to very well rounded and matrix supported, consisting of porphyritic volcanic rocks, vein quartz, metasedimentary and sedimentary rocks, and a variety of foliated and unfoliated granitoid rocks. Thin-section views of sandstone and siltstone reveal sericitized plutonic plagioclase, plutonic quartz, biotite, and hornblende, as well as minor amounts of microcline, fine-grained porphyritic volcanic rocks, muscovite, epidote, and metamorphic and sedimentary clasts.

Sedimentary structures in sandstone of the Panther Creek Formation include graded bedding, mudstone rip-up clasts, wood fragments, and lamination in fine-grained sandstone. Locally, sandstone that is particularly rich in plagioclase forms white-weathering beds. In the Buck Mountain area, the proportion of arkosic sandstone in the Panther Creek Formation appears to increase westward (upsection) as the amount of conglomerate decreases and discrete conglomerate beds give way to pebbly lenses in sandstone. The contact with the overlying Harts Pass Formation is gradational.

The strike of bedding in the Panther Creek Formation varies from north-northwest to northwest; dips are variable to the east and west but are generally steeper than 80°, and beds are overturned locally. Opposed dips northwest of Buck Mountain may be due to either unrecognized unconformities, rotation of beds caused by faulting, or forceful emplacement of concordant or slightly discordant porphyritic sills and dikes. The sills and dikes, although not shown on the map sheet, locally make up from one-third to one-half of the stratigraphic section and are associated with baking and hydrothermal alteration of the Panther Creek rocks. Between Cub Creek and Buck Mountain, dips of bedding in the Panther Creek and the overlying Harts Pass Formation are predominantly steep to the northeast. Scarce facing indicators suggest that this part of the section is overturned (see also Maurer, 1958; Barksdale, 1975); this interpretation is in accord with structural relations seen to the west in the Mazama quadrangle in which the continuation of the two formations appears to lie in the overturned limb of a southwest-verging syncline that has the Harts Pass Formation in the core. Maurer (1958) attributed opposed dips in the Buck Mountain area to the presence of tight isoclinal folds, but the lack of data to support opposing tops, together with the essentially unmetamorphosed character of the unit, the massive arkose beds, and the absence of small-scale folds at the outcrop, appear to argue against isoclinal folding.

Fossils found in the type section of the Panther Creek Formation indicate an Aptian to Albian age (Barksdale, 1975); two of the species are suggestive of a late Hauterivian age. Additionally, black shale beds along strike in the Sweetgrass Butte-Cub Pass area, which is located 8 to 11 km southeast of the type area in the Mazama quadrangle (fig. 1), yielded a marine assemblage that indicates an Aptian to Albian age (J.W. Miller, written commun., 1984). Faunas collected near Buck Mountain represent a time interval from the middle or late Hauterivian to well into the Barremian (Barksdale, 1975, p. 25). McGroder and others (1990) noted that the presence of *Buchia piochii* from several beds within the type section of Barksdale's (1975) Buck Mountain Formation, which has been included as part of the Panther Creek Formation in this report, suggests that part of the unit may be as old as Late Jurassic. If this is true, then the age of the Panther Creek may increase along strike from northwest to southeast.

Harts Pass Formation of Barksdale (1975)

The Harts Pass Formation of Barksdale (1975) was named for a section of marine arkose and subordinate fossiliferous black shale exposed along the Cascade crest northeast and southwest of Harts Pass, which is located about 35 km west of Doe Mountain in the Slate Peak 7–1/2' quadrangle (fig. 1). Arkosic strata exposed in the west-central part of the map area are continuous with rocks that Barksdale (1975) mapped as the Harts Pass Formation in the Mazama quadrangle and are, therefore, herein referred to as the Harts Pass Formation. The unit consists of arkosic sandstone, subordinate siltstone and shale, and minor conglomerate in alternating beds that range in thickness from 3 to 30 m. Scarce internal structures in the thicker sandstone beds suggest that the beds comprise multiple sedimentation units (amalgamated beds). Thick-bedded sandstone and shale intervals are interbedded with, in graded sequences, minor thin-bedded sandstone, siltstone, shale, and pebbly sandstone and conglomerate.

Sandstone of the Harts Pass Formation is composed of, in order of abundance, intermediate-composition plagioclase, quartz, and lithic grains. Most sandstone is arkose, but some rocks approach lithic arkose. Potassium feldspar ranges from 0 to about 10 percent, but the mineral is generally scarce. Lithic grains include volcanic, sedimentary, plutonic, and metamorphic rock fragments, as well as biotite, muscovite, chlorite, hornblende, epidote, sphene, apatite, and chert.

Sandstone of the thick-bedded sequences is characteristically massive and homogeneous, medium to dark gray or greenish gray on fresh surfaces, and well indurated, fracturing 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 varies from fine to coarse, the sandstone is typically medium to coarse grained and granular and contains scattered 1- to 3-mm-wide biotite grains, small lithic pebbles, shale intraclasts, and pebbly sandstone lenses. Rip-up clasts as long as 30 cm of fissile shale in round or subangular shapes are common.

Shale is black and fissile and weathers to a chippy soil. The rock typically has silty laminae and carbonaceous films on bedding planes, and minor silty mudstone is present. Individual beds are thin (2–8 cm) and exhibit ripple-drift cross-lamination, planar and wispy laminations, and convoluted bedding. Contacts between sandstone beds and the underlying fine-grained rocks are usually sharp and locally show scour and fill or loading by sand layers. In some places, the shale grades to fine-grained, yellowish-brown-weathering sandstone that contains twigs, wood fragments, abraded ferns, and plant impressions.

Coarse-grained sandstone of the thick-bedded sequences grades to distinctive, matrix-supported pebbly sandstone, which is composed of single pebbles that are evenly distributed about 1 cm apart in coarse, structureless sand. The pebbly sandstone grades to minor lenticular beds of poorly sorted pebble conglomerate that is generally matrix supported but locally clast supported and has rough or no imbrication. The conglomerate beds range in thickness from 30 cm to 3.5 m, but most are less than a meter thick. Bedding may be defined by either discontinuous sandy lenses, aligned flattish clasts, or, in thin conglomerate beds, faint wavy lamination. Some conglomerate layers are chaotic. Clast size generally varies from small pebbles to pebbles, but occasional cobbles are present. The clasts include sedimentary, volcanic, plutonic, and metamorphic rocks, as well as quartz, shale intraclasts, and minor chert. Most clasts are subrounded or subangular but some are rounded. The matrix of the conglomerate consists of medium sand to grit and is identical to the interbedded arkosic sandstone.

The Harts Pass Formation is marine in origin on the basis of local occurrences of marine fossils.

Marine fossils collected at the type section of the unit at Harts Pass (fig. 1) collectively indicate an Aptian to Albian age for the Harts Pass Formation (Barksdale, 1975). Additionally, the Harts Pass section in the Mazama quadrangle has yielded two cephalopods of Early Cretaceous (Aptian to Albian) age (J.W. Miller, written commun., 1984).

Virginian Ridge Formation of Barksdale (1948, 1975)

The Virginian Ridge Formation of Barksdale (1948, 1975) was named for a section of marine lithic sandstone, siltstone, and chert-pebble conglomerate that crops out in Wolf Creek and on Virginian Ridge, about 8 km west of Winthrop (fig. 1). The formation has limited exposure in the southwestern part of the map area where it is in fault and unconformable(?) contact with the Harts Pass and Twisp Formations, respectively.

Trexler (1985) recognized both marine and nonmarine facies in the Virginian Ridge Formation and divided it into three members, which are, in approximate stratigraphic order, the Patterson Lake, Slate Peak, and Devil's Pass Members. The rocks in the map area were 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. Occasional interbeds of clean arkose are present in the upper part of the section (Barksdale, 1975; Trexler, 1985). 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 map area, one unit of McGroder and others (1990) that contains 10 to 40 percent conglomerate is approximately equivalent to Trexler's Slate Peak Member. McGroder and others (1990) also interpreted the rocks that make up the basal Patterson Lake Member as a separate formation, their informally named Patterson Lake conglomerate.

The Virginian Ridge Formation grades upward into the Winthrop Sandstone of Barksdale (1975) about 8 km northwest of Winthrop in the Mazama quadrangle (fig. 1). The Virginian Ridge Formation overlies the Harts Pass Formation with slight angular discordance in the Mazama quadrangle. About 0.5 km east of Patterson Lake in the Twisp 15' quadrangle (fig. 1), the Virginian Ridge overlies the Twisp Formation with marked angular discordance. Here, the clasts in the basal conglomerate consist mainly of black argillite, andesitic volcanic rocks, lithic sandstone, and chert, lithologies that match the underlying Twisp Formation closely (Barksdale, 1975). A small exposure of this unconformity is present in the southwestern part of the map area (Maurer, 1958; Barksdale, 1975).

The Virginian Ridge Formation has yielded a marine fauna that ranges in age from Albian to Cenomanian (Barksdale, 1975; Trexler, 1985). In addition, two Late Cretaceous (Turonian) marine gastropods were identified in shale collected about 600 m south-southeast of Slate Peak (fig. 1; J.W. Miller, written commun., 1984).

PLUTONIC ROCKS

Plutonic rocks in the map area include the Late Jurassic Button Creek stock, located west of the Pasayten fault, the Cretaceous Okanogan Range batholith, located east of the fault, and porphyritic dikes of presumed Late Cretaceous age, present on both sides of the fault. The Okanogan Range batholith is the probable southernmost continuation of a north-northwest-trending belt of Early Cretaceous volcanic and plutonic rocks in southern British Columbia and northern Washington, which includes the Mount Lytton Plutonic Complex of Monger (1985) and the informally named Eagle plutonic complex of Greig (1988, 1989) (fig. 1). The part of the Okanogan Range batholith that is exposed in the map area is chiefly trondhjemite, which by definition is a tonalite that has a color index less than 10 and contains andesine or oligoclase (Streckeisen, 1973). The batholith is zoned from hornblende-bearing trondhjemite (color index 9–10) on the west to biotite- and muscovite-bearing, leucocratic trondhjemite and granodiorite (color index 4–6) on the east. The hornblende-bearing trondhjemite contains several small bodies of gabbro and amphibolite (metagabbro). The easternmost unit, the gneissic trondhjemite of Tiffany Mountain (Rinehart, 1981), is part of a large, northwest-trending septum, or screen, that consists of highly assimilated and (or) incipiently melted wallrocks, which have been metamorphosed to amphibolite grade. These metamorphic rocks are interlayered with gneissic trondhjemite and quartz diorite. All the granitoid rocks of the Okanogan Range batholith in the map area have relatively high quartz, low potash, and low mafic mineral content (fig. 2; on map sheet). The western margin of the batholith underwent mylonitization probably during a late stage of batholithic development.

Uranium-lead isotopic dating of zircon and monazite from plutonic rocks in the map area has yielded minimum crystallization ages of 114–111 Ma (Early Cretaceous) for four major units of the Okanogan Range batholith (Hurlow and Nelson, 19?3). Additionally, K–Ar age determinations made in the present study on eight plutonic rocks from the Doe Mountain quadrangle range from about 106 to 95 Ma (table 1). Two samples from the massive Cathedral pluton, which is located 10 km north of the map area at Thirtymile Camp in the Coleman Peak 7–1/2' quadrangle (fig. 1), yielded K–Ar biotite ages of 96.7±2.8 and 100.1±2.9 Ma (samples 152 and 153, respectively, Engels and others, 1976; recalculated using current IUGS constants as given by Dalrymple, 1979). Rinehart (1981) suggested an approximate K–Ar age of 100±10 Ma for the gneissic trondhjemite of Tiffany Mountain. The most likely age for the plutonic rocks of the Okanogan Range batholith in the map area is Early Cretaceous.

Button Creek stock

The Button Creek stock (Barksdale, 1975) crops out in the western part of the map area, where it is bounded by the Pasayten and Ortell Creek faults, and also extends into the northeastern part of the Mazama quadrangle. The stock consists of medium- to coarse-grained, moderately foliated to relatively massive, subidiomorphic biotite-hornblende tonalite (color index 23) (fig. 2). Hornblende is prismatic, and biotite is present as large irregular grains. The rock is locally heterogeneous, owing to concentrations of mafic grains and to the presence of irregular fine-grained mafic inclusions as large as 25 cm (fig. 3; on map sheet). In the map area, the Button Creek stock consists of fine- to medium-grained gneissic 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 (strongly foliated tonalite) (V.R. Todd, unpub. data, 1987). Biotite from the older of the two samples was also dated at 145.9±3.6 Ma.

Gneissic trondhjemite of Tiffany Mountain

The gneissic trondhjemite of Tiffany Mountain was named by Rinehart (1981) for gneissic, leucocratic biotite quartz diorite, locally hornblende bearing and migmatitic, in the western part of the Tiffany Mountain 15' quadrangle (fig. 1). Mapping in the Doe Mountain quadrangle shows that these rocks form a large, generally north trending screen that separates the Early Cretaceous trondhjemite of Doe Mountain from several Cretaceous plutons to the east. In the map area, the Tiffany Mountain unit consists of migmatitic rocks that are heterogeneous in grain size and composition. The migmatite comprises interlayered trondhjemite (leucosome), quartz diorite (melanosome), and metamorphosed, partly assimilated wallrock inclusions. The leucosome (color index 4–6.5) is chiefly medium- to coarse-grained trondhjemite that contains widely and evenly spaced, 1–cm-wide aggregates of recrystallized biotite and lesser hornblende. Weak to moderate mineral foliation is oriented parallel to layering and to sparse biotitic inclusions that are flattened in the plane of foliation. Irregular leucocratic areas, scattered large (1–2 cm) plagioclase and (or) mafic grains, and areas of fine-grained tonalite may also be present in the leucosome. Some leucosome contains quartz grains as much as 1.5 cm across and subrectangular plagioclase grains as long as 5 cm. The melanosome (color index 23) is strongly foliated quartz diorite. In thin-section views, both leucosome and melanosome show igneous textures modified by strain and recrystallization. Biotite and hornblende grains are skeletal and are commonly pseudomorphed by chlorite, epidote, sphene, and muscovite.

In the Tiffany Mountain unit, trondhjemite and quartz diorite are interlayered in proportions that vary from centimeters to tens of meters. These rocks are further interlayered with variable amounts of upper amphibolite-facies metamorphic rocks that consist of biotite schist, feldspar-quartz-biotite schist, amphibolite, hornblende schist, and less abundant calc-silicate rocks and fine-grained mafic metavolcanic(?) rocks. Locally, amphibolite in the unit contains relict igneous plagioclase. These metamorphic rocks are lithologically similar to metasedimentary and metavolcanic rocks elsewhere in the Okanogan Range, for example, those described by Hawkins (1968) north of the map area, as well as rocks described by Rinehart (1981) east of the map area. Rinehart suggested that the protoliths of the metamorphic rocks east of the map area range in age from Late Permian to Late Triassic. The largest metamorphic inclusions are tabular, are tens of meters long in longest dimension, and are generally concordant with foliation and gneissic layering in the granitoid rocks. These inclusions reacted with the trondhjemite to form smaller mafic inclusions, schlieren, and wisps (fig. 4; on map sheet). The darker and more heterogeneous parts of the unit typically show complex swirling structures and isoclinal folds whose axial planes are oriented parallel to layering and mineral foliation. Thin leucocratic dikes that cut the unit commonly have been folded into the plane of layering and foliation and locally have been offset for distances of centimeters by healed synintrusive faults. Variable strikes of layering and foliation and several sharp flexures in the gneissic trondhjemite of Tiffany Mountain indicate that the unit was tightly folded on a regional scale before the intrusion of the trondhjemite of Doe Mountain.

Available modal data (fig. 2) suggest that the trondhjemitic leucosome is compositionally similar to the other trondhjemitic units of the Okanogan Range batholith; however, a single sample of quartz diorite (melanosome), which was taken from an outcrop of interlayered trondhjemite and quartz diorite, is markedly more mafic than the other samples and does not plot with the trondhjemitic rocks (fig. 2). The field relations are consistent with an origin of the unit either by anatectic melting of wallrocks to produce trondhjemite magma or by reaction of wallrocks with magma to produce migmatitic screens. In view of the generally inclusion free character of the other trondhjemitic units in the map area, the trondhjemitic migmatites of the Tiffany Mountain unit most likely were produced during an earlier (pre-Early Cretaceous?) magmatic episode.

The gneissic trondhjemite of Tiffany Mountain is considered by Rinehart (1981) to have a K–Ar age of 100±10 Ma. K–Ar age determinations made on two samples of the unit gave biotite ages of 95.1±2.4 Ma (leucosome) and 95.3±2.4 Ma (melanosome) (table 1, Nos. 2 and 3, respectively). These are considered to be minimum ages because of the following field relations. The gneissic trondhjemite of Tiffany Mountain has both concordant and discordant relations with the trondhjemite of Doe Mountain. The contact is broadly concordant in the southern part of the map area, but, in the northern part, the Doe Mountain unit not only truncates layering in the Tiffany Mountain unit but also carries inclusions of Tiffany Mountain rocks. In detail, the trondhjemite of Doe Mountain has intruded the Tiffany Mountain unit parallel to layering. The Tiffany Mountain unit appears to be a large screen that separates, on the west, the Early Cretaceous trondhjemite of Doe Mountain from, on the east, the Late Cretaceous(?) Old Baldy pluton (Rinehart, 1981), the Bottle Spring pluton of Rinehart (1981), which has a K–Ar biotite age of 89.2±2.2 Ma (V.R. Todd, unpub. data, 1987), and the Late Cretaceous(?) Cathedral pluton (Rinehart, 1981). The Doe Mountain, Bottle Spring, and Cathedral plutons are all relatively massive. Because of these relations, the Tiffany Mountain unit is considered to be at least as old as, and probably older than, the other gneissic trondhjemite units in the map area.

Gabbro

Small (less than 1 km) pods of deformed gabbro are found in the mylonitic border zone of the Okanogan Range batholith east of the Chewack River in the vicinity of Ramsey Creek. These pods are composed of foliated hornblende gabbro that is compositionally and texturally heterogeneous and locally displays coarse-grained pegmatitic texture. Thin-section views show igneous textures overprinted by high-temperature strain and recrystallization. Inclusions of amphibolite (probably metagabbro) too small to show at map scale are present in the mylonitic rocks in the vicinity of the gabbro pods. These gabbroic rocks have not been studied in detail, but they may be remnants of a mafic border phase of the batholith that was pulled apart during mylonitic deformation. Aside from similar small mafic bodies within the mylonitic border zone in the Twisp and Loup Loup 15' quadrangles to the south and southeast, respectively (J.R. Wilson, oral commun., 1983; Bunning, 1990), the only other exposure of gabbroic rocks in the region is the Cretaceous(?) Ashnola Gabbro of Daly (1912) (see also Hawkins, 1963, 1968; Stoffel and McGroder, 1989), which straddles the international boundary about 20 km east of the Pasayten fault. The age of the bodies of gabbro and metagabbro in the map area is unknown. On the basis of relict magmatic textures in these bodies and their close spatial association with the trondhjemite of Eightmile Creek, which is the most mafic of the Early Cretaceous units in the map area, the gabbro unit is tentatively considered to be essentially coeval with the granitoid units of the Okanogan Range batholith and, therefore, to be Early Cretaceous(?) in age.

Trondhjemite of Eightmile Creek

The trondhjemite of Eightmile Creek crops out in a narrow (1–2 km) zone along the western margin of the Okanogan Range batholith. The unit consists of medium- to coarse-grained, white-weathering trondhjemite (color index 9–10) (fig. 2) that has a strong foliation caused by the preferred alignment of recrystallized igneous grains. The rocks tend to break into slabs 15 to 20 cm thick that are produced by weathering along joints oriented subparallel to foliation. The trondhjemite contains plagioclase (andesine), quartz, biotite, hornblende, and traces of K-feldspar. Quartz appears as lenticular gray grains, and plagioclase is present as ovoid to prismatic, white-weathering grains as long as 2.5 cm. The most distinctive feature of the unit is the abundance of locally stout hornblende prisms that range in length from 0.5 to 2.5 cm (fig. 5; on map sheet). Some hornblende grains appear euhedral, but most have ragged recrystallized margins, and others occur in lenticular recrystallized aggregates. Scaly aggregates of biotite are about as abundant as hornblende.

In general, xenoliths are rare in the Eightmile Creek unit. The exceptions are isolated zones of fine-grained mafic inclusions that are flattened parallel to foliation, mafic and leucocratic schlieren, and thin biotitic sheets that probably represent residues of metapelite and other country-rock lithologies. In the southern part of the quadrangle, tabular inclusions of fine-grained amphibolite contain plagioclase that shows relict euhedral oscillatory zoning (magmatic plagioclase) and minor quartz. A relatively thick (8–10 m) amphibolite inclusion extends for at least several tens of meters along the strike of foliation.

These inclusions may represent mafic to intermediate-composition intrusions related to the small gabbro bodies in the mylonitic border zone. A sample from one such amphibolite yielded K–Ar apparent ages of 105.2±2.6 Ma for hornblende and 100.9±2.5 Ma for biotite (table 1, No. 4).

With the exception of a few large segregation masses of quartz and pink K-feldspar, thin aplite dikes, and pegmatite dikes containing coarse biotite, leucocratic dikes are relatively rare in the trondhjemite of Eightmile Creek. Where present, the dikes generally share the strong foliation of the host trondhjemite.

The texture of the unit is gneissic and commonly porphyroclastic, especially next to wallrock inclusions. Thin-section views show igneous textures modified by late- and (or) post-magmatic strain and recrystallization at high temperatures. Most hornblende prisms in the trondhjemite lie within, or very close to, the foliation plane, and most are aligned with their long axes parallel to a penetrative downdip mineral lineation. Locally, fractures are filled with pegmatitic material in which prismatic hornblende crystals have grown both parallel to and across the fractures. Thus, it appears that hornblende crystallized not only before(?) and during ductile deformation but afterwards as well, at which time residual melt was still present but the rock responded to stress by fracturing instead of flowing. Superimposed on the ductile fabric are brittle-shear zones and slickensided surfaces that are marked by chlorite and epidote. These low-temperature features are probably related to late movements on the Pasayten fault.

Both the east and west contacts of the trondhjemite of Eightmile Creek are marked by zones of intense ductile shear. Along the western 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 eastern margin, the trondhjemite of Eightmile Creek becomes progressively more recrystallized toward the trondhjemite of Lamb Butte. As the east contact is approached, the edges of large hornblende prisms appear ragged and are partly replaced by biotite. The prisms then give way to a mixture of scarce small hornblende relics and clots as long as 2.5 cm of biotite plus or minus hornblende that are oriented parallel to foliation. A narrow (100–400 m) transitional zone between the two units consists of strongly foliated rocks of the trondhjemite of Lamb Butte interlayered with rocks of the trondhjemite of Eightmile Creek. These rocks contain very sparse, small hornblende relics and biotite-chlorite-epidote-sphene-muscovite aggregates. The contact is drawn where hornblende relics are no longer visible in outcrop.

Hurlow and Nelson (1993) determined a U–Pb crystallization age of 110–112 Ma for the trondhjemite of Eightmile Creek. In the present study, a sample of the Eightmile Creek unit with large idiomorphic hornblende grains yielded concordant K–Ar ages of 104.8±2.6 and 105.7±2.6 Ma on hornblende and biotite, respectively (table 1, No. 5). These ages are considered to be cooling ages for the pluton.

Trondhjemite of Lamb Butte

The trondhjemite of Lamb Butte crops out in a narrow (1–4 km) zone between the trondhjemites of Eightmile Creek and Doe Mountain. The average rock is a medium-grained trondhjemite (color index 7–9) (fig. 2) that in rare cases has enough K-feldspar to make the rock a granodiorite. Plagioclase in the unit varies from andesine to oligoclase. The texture of the rock is strongly foliated to porphyroclastic. A penetrative downdip lineation is defined by aligned mineral grains and aggregates and, locally, by crenulation or ribbing. The trondhjemite of Lamb Butte weathers to light gray and locally displays slabby jointing that is subparallel to rock foliation. Characteristic of the unit are abundant 1- to 1.5-cm-long ribbon quartz grains, abundant 1- to 3-mm-long aggregates of recrystallized biotite, and sparse 2.5- to 10-cm-long lensoid biotitic clots, all of which are oriented parallel to foliation and locally impart a gneissic texture to the rock (fig. 6; on map sheet). Also characteristic of the Lamb Butte unit is locally extensive hydrothermal alteration that appears in outcrop chiefly as penetrative maroon (hematite?) and orange (iron oxides, hydroxides) staining, extreme hardness, and obliteration of gneissic texture. These alteration zones are also characterized by the presence of hairline shears that are surrounded by thin (2–4 cm) bleached haloes, slickensided surfaces, and larger (locally as wide as 100 m) brittle-shear zones.

Near its contact with the trondhjemite of Doe Mountain, the trondhjemite of Lamb Butte is cut by many pegmatite, aplite, and fine- to medium-grained granitic dikes (fig. 2), many of which contain pink K-feldspar, garnet, and schorl. The dikes, which range in thickness from 2.5 to 25 cm, are probably offshoots of the Doe Mountain unit. Many dikes are deformed, and their fabrics parallel the gneissic foliation of the Lamb Butte unit. Some pegmatite dikes appear wrinkled or crenulated. Poorly defined, irregular layers of a rock that resembles the trondhjemite of Doe Mountain also are found in the Lamb Butte unit near the contact between the two units. Near this contact, the Lamb Butte unit contains scattered inclusions of biotitic schist and smaller (2–8 cm) lensoid aggregates of biotite, the latter of which were apparently derived from the inclusions by reaction with magma. Also present are thin (1–3 cm) sheets of coarse black biotite that are peppered with large pink K-feldspar grains and are associated with pegmatite dikes that carry pink K-feldspar.

Hurlow and Nelson (1993) estimated the U–Pb crystallization age of the trondhjemite of Lamb Butte to be 111 Ma. This estimated age allows the possibility that the Lamb Butte and Eightmile Creek units are essentially coeval, as indicated by the gradational contact between them. In the present study, replicate analyses of biotite from a sample of the Lamb Butte unit yielded K–Ar ages of 102.5±2.6 and 99.8±2.5 Ma (table 1, No. 6). These numbers represent a minimum or cooling age for the Lamb Butte unit.

Trondhjemite of Doe Mountain

The trondhjemite of Doe Mountain consists of homogeneous trondhjemite and granodiorite (fig. 2) that form a north-northwest-elongate pluton in the map area. The rocks are distinctly more leucocratic (color index 4–6) than those of the other trondhjemite units and crop out as white-weathering cliffs above broad talus cones. Locally, outcrops are stained orange and brown by iron oxides. The rocks break along one flat-lying and at least two subvertical joint sets. The trondhjemite grades from fine and medium grain size near its western margin to medium and coarse grain size in the east and north. A diagnostic feature of the unit is abundant lenticular to equant gray quartz grains and granular aggregates (0.5–2 cm in largest dimension) (fig. 7; on map sheet). Rocks in which quartz grains are particularly large and abundant are nearly porphyritic. Scattered, large (1–2.5 cm), white, poikilitic K-feldspar grains are seen chiefly as flashing cleavage faces on weathered surfaces. The abundance of these grains increases eastward away from the contact with the trondhjemite of Lamb Butte. Locally, K-feldspar is present as subhedral grains as long as 2 cm, which may, in the Doe Mountain area, be pale pink. The unit also contains small (1 mm) scattered biotite grains and scaly aggregates. The grain size of biotite increases toward the interior of the pluton to discrete 2-mm-wide grains or aggregates. Locally, muscovite and pink garnet are visible in outcrop, but they are generally not abundant. Muscovite also forms thin (1–3 mm) sheets on joint surfaces.

The trondhjemite of Doe Mountain is weakly to moderately foliated in a zone that ranges in thickness from a few hundred meters to 0.5 km near its contact with the trondhjemite of Lamb Butte. Foliation is marked by aligned grains of platy biotite and lensoid quartz. Locally, a downdip lineation, which is marked by elongate quartz grains and biotite aggregates, is also present. Thin-section views indicate that foliation resulted from minor high-temperature submagmatic deformation and recrystallization. The orientation of foliation is difficult to measure because of the weak fabric and low color index of the rock, as well as the local presence of two foliations oriented at large angles to one another. The rocks of the eastern and northern parts of the pluton are very weakly foliated or structureless. Foliation in the interior of the pluton commonly lies at a relatively high angle to the northwest-striking foliation seen in the more strongly foliated units to the west, suggesting that a primary flow fabric was reoriented near the western margin of the pluton by shearing either against or with the older units.

Relatively little textural and compositional variation is exhibited in the trondhjemite of Doe Mountain, with the following exceptions: (1) coarse-grained rocks containing widely and evenly spaced mafic grains, and (2) rocks that are slightly more mafic than average. These two varieties show no regular distribution and appear to grade into the average rock of the Doe Mountain unit.

Inclusions are rare to absent in the trondhjemite of Doe Mountain; those present were seen chiefly near its east and west contacts. Scattered paper-thin sheets and lenses (2.5–7.5 cm long) composed of black biotitic rocks are present near the west contact of the Doe Mountain unit with the trondhjemite of Lamb Butte. Sparse biotitic schlieren, spots, and larger irregular aggregates of biotite schist and feldspar-quartz-biotite semischist are found in the Doe Mountain unit near its east contact with the Tiffany Mountain unit.

The contact of the trondhjemite of Doe Mountain with the Lamb Butte unit appears gradational in some places. Compositional and textural changes seen in the direction of the contact are subtle in both units. Dikes and irregular bodies of leucocratic granitic rocks that resemble the trondhjemite of Doe Mountain, as well as pegmatite dikes that locally contain abundant 5–cm-long white K-feldspar crystals, are common in the Lamb Butte unit near its contact with the trondhjemite of Doe Mountain. The leucocratic dikes increase in size and number toward the Doe Mountain unit. Chips of biotite schist and one or more thin screens of coarse-grained biotite at least 8 to 10 m long are oriented subparallel to foliation in the trondhjemite of Lamb Butte and thus are probably remnants of a wallrock screen that once separated the two units. The Doe Mountain rocks that are next to the Lamb Butte pluton tend to be finer grained and darker than the average rock in the interior of the pluton; however, thin-section views show that magmatic biotite and quartz grains in the marginal Doe

Mountain rocks were partly reduced by recrystallization flow to smaller, more uniformly disseminated grains, thereby giving the impression of a higher color index. The above relations suggest that the trondhjemite of Doe Mountain intruded into and chilled against the trondhjemite of Lamb Butte and (or) a wallrock screen that once lay between the two units. Residual leucocratic magma of the Doe Mountain pluton may have migrated to and ponded against this screen.

In the field, the trondhjemite of Lamb Butte is difficult to distinguish from the sheared trondhjemite in the marginal zone of the Doe Mountain unit, particularly in the southeastern part of the quadrangle where both units are thin. However, thin-section views show the marginal Doe Mountain rocks generally have relatively well preserved igneous textures, large subequant quartz grains, small interstitial grains and (or) scarce poikilitic grains of K-feldspar, scattered subhedral biotite grains that are partly recrystallized, and relatively abundant secondary and primary(?) muscovite. In contrast, the trondhjemite of Lamb Butte is characterized by strongly recrystallized textures, lenticular or ribbon quartz, little or no K-feldspar, fully recrystallized biotite in evenly distributed folia, and scarce secondary muscovite. In spite of these petrographic differences, some rocks in the contact zone could not be reliably assigned to one or the other unit, even in thin sections.

A zone of foliated trondhjemite in the southeastern part of the map area was initially mapped as a transitional gneissic unit between the Doe Mountain and Lamb Butte units (fig. 2). This transitional unit, which has since been abandoned, was thought to be similar to another unit of the Okanogan Range batholith mapped in the Loup Loup 15' quadrangle to the southeast (fig. 1). This unit, although it appears to die out northward (J.R. Wilson, oral commun., 1983), may extend into the Doe Mountain quadrangle and interfinger with the Doe Mountain and Lamb Butte units. Alternatively, these units may have been tectonically mixed by ductile shear along the contact; stained slabs of rocks from the contact zone locally reveal a gneissic banded rock in which the trondhjemites of Doe Mountain and Lamb Butte are interlayered on a scale of centimeters.

The contact of the Doe Mountain unit with the gneissic trondhjemite of Tiffany Mountain is described above. The westernmost outcrops of the Tiffany Mountain unit are cut by large concordant dikes that resemble the trondhjemite of Doe Mountain. Sparse inclusions of heterogeneous gneissic trondhjemitic and quartz dioritic rocks are present in the Doe Mountain pluton as far as 3.5 km from the contact with the gneissic trondhjemite of Tiffany Mountain. These relations suggest that the trondhjemite of Doe Mountain is younger than the Tiffany Mountain unit.

A minimum U–Pb crystallization age of 114 Ma was determined by Hurlow and Nelson (1993) for the trondhjemite of Doe Mountain. A sample of the Doe Mountain unit from a weakly foliated but essentially unrecrystallized part of the pluton yielded concordant K–Ar biotite and muscovite ages of 96.3±2.4 and 96.4±2.4 Ma, respectively (table 1, No. 7). This 96–Ma age represents a cooling age for the pluton. A fine-grained muscovite trondhjemite dike that cuts the trondhjemite of Doe Mountain also yielded concordant K–Ar biotite and muscovite ages of 95.7±2.4 and 96.1±2.4 Ma, respectively, (table 1, No. 8), which suggests that this and other similar dikes are genetically related to the Doe Mountain unit.

Mylonitic rocks

The trondhjemite of Eightmile Creek grades westward into a 1– to 2–km-wide zone of mylonitic rocks that are adjacent to the Pasayten fault. In the Eightmile Creek unit, grain size increases and the degree of recrystallization decreases away from the fault. Mylonitic rocks near the fault were originally described by Barksdale (1975) as cataclasite produced by movement on the Pasayten fault. Lawrence (1978) noted that the mylonitic fabric resulted from high-temperature ductile deformation and characterized the earliest movements on the fault as deep seated.

The rocks of the mylonitic border zone consist of biotite trondhjemite and granodiorite. The rocks are dark grayish brown weathering and medium to dark gray on fresh surfaces because of the comminution of biotite and quartz. Inhomogeneous shear locally produced irregular layers that vary from a few millimeters to a centimeter thick and consist of light-colored, less sheared rock and dark-colored, more sheared rock. Most samples contain at least a few relict magmatic plagioclase and quartz grains. The mylonitic rocks typically do not carry inclusions, although scarce 2.5– to 5–cm-wide flattened biotitic inclusions were seen in one place, and scarce amphibolite inclusions were seen near the small gabbro bodies in the Ramsey Creek area. The rocks have been stained orange and purple probably by fluids migrating along brittle fractures produced by late movements on the Pasayten fault. The unit underlies dark-brown, slabby-weathering, narrow strike ridges that have been produced by erosion along the prominent foliation.

Although the rocks of the mylonitic border zone grade into the trondhjemite of Eightmile Creek, only a few samples collected from the border zone contain hornblende relics, and many contain K-feldspar, suggesting that granodioritic magma was injected into the zone before or during mylonitization (see also Hurlow and Nelson, 1993). Many thin (2–5 cm), K-feldspar-rich, leucocratic granitic veins, as well as pegmatite and vein quartz dikes and segregations, are present in the mylonitic border zone. Although most are oriented parallel to foliation in the mylonitic rocks, some veins and dikes have been folded into concordance with the foliation, while others are only slightly deformed or undeformed. The local development of chlorite and epidote in mafic minerals and muscovite in feldspar indicates that mylonitization took place at a relatively late stage after the batholith was largely crystallized and temperatures had fallen, although the presence of variably deformed dikes suggests that some residual magma was still present.

A K–Ar biotite age of 101.4±2.5 Ma was obtained from a sample of mylonitic granodiorite from the border zone of the batholith (table 1, No. 9). This number probably represents a minimum age for the protolith of the mylonitic rocks, but it may also record the latest ductile movements in this part of the Pasayten fault zone.

Porphyritic sills and dikes

Porphyritic sills and dikes intrude both the sedimentary and the plutonic rocks exposed in the map area, although they are most abundant in the sedimentary rocks southwest of the Pasayten fault. In the densely forested northern part of the map area, the shapes of these bodies could not always be accurately determined; therefore, some of them could possibly be plugs. The sills and dikes are concordant with the foliation evident in the strongly foliated, westernmost units of the Okanogan Range batholith and are accompanied by hydrothermal alteration and brittle shear of both dikes and host rocks. The dikes weather to dark gray, brown, and ochre and contain randomly oriented, white-weathering plagioclase tablets and scarcer hornblende prisms, both of which are a few millimeters to 1 cm across, set in a finely crystalline or aphanitic groundmass. Many dikes are aphyric. Porphyritic sills, dikes, and plugs, most of which are coarser grained than those in the Doe Mountain quadrangle, are more abundant to the west and southwest in the Mazama and Buttermilk Butte 15' quadrangles (fig. 1). Modal and geochemical data indicate that most porphyritic sills and dikes in the region are andesitic and dacitic in composition (V.R. Todd and S.E. Shaw, unpub. data, 1987). Potassium-argon hornblende ages of porphyritic sills and dikes that are located in the Mazama and Buttermilk Butte quadrangles range from about 93 to 85 Ma (Todd, 1987), while a porphyritic andesite dike, which is located in the Coleman Peak 7–1/2' quadrangle to the north and cuts the trondhjemite of Doe Mountain, yielded a K–Ar hornblende age of 85.8±2.2 Ma (V.R. Todd, unpub. data, 1987). The ages and trace-element geochemistry of the sills and dikes are similar to those of Late Cretaceous stocks that intrude the Methow basin rocks to the west. However, two porphyro-aphanitic dikes that are located in the Mazama quadrangle yielded Eocene K–Ar ages (V.R. Todd, unpub. data, 1987), as did some dacite-andesite plugs, flows, and breccia that are mapped in the Tiffany Mountain 15' quadrangle to the east (Rinehart, 1981). Thus, most of the sills and dikes in the region are likely part of a Late Cretaceous magmatic episode, but some of them may be either offshoots of the Eocene Monument Peak and Lost Peak stocks (Tabor and others, 1968), which lie just north of the Mazama quadrangle, or feeders for now-eroded Eocene 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 surrounding mountains and left scattered deposits of till and outwash (Waitt, 1972). Many of the cobbles and boulders in this drift are exotic. Patches of till reach the highest peaks in the map area and also mantle bedrock terraces that lie between the mountain peaks and the modern valley floors. Stratified drift is present on these terraces, which were probably cut by ice-marginal streams, as well as on the sides of old high valleys that are ancestral to the present-day streams. Large (several meters across) glacial erratics, which are typically granitoid in composition, are scattered over the low hills that are underlain by the rocks of the Methow basin southwest of the Pasayten fault. As seen from a distance or on aerial photographs, these erratics appear as white specks against the dark-brown-weathering sedimentary and volcanic rocks.

Many of the glacial deposits are mantled by buff-gray-weathering colluvium that was formed when the once-blanketing drift was dissected and reworked downslope by streams, sheet floods, and mass wasting. Glacial drift grades downslope into postglacial older alluvium. In places where drift is less than a few meters thick, bedrock knobs are common. In these areas, the drift is not shown on the map, as only deposits whose exposed thicknesses are at least 6 m were mapped.

Older alluvium

Older alluvium consists of stratified deposits of sand, silt, and gravel that once filled modern stream valleys to depths of as much 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 have accumulated as slopewash and talus deposits. These deposits grade locally into the younger and older alluvium units and also into the glacial drift from which they are largely derived.

Younger alluvium

Younger alluvium consists of deposits 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 the lowest lying deposits of older alluvium.

STRUCTURE

The structure of the Doe Mountain quadrangle is discussed under the following subheadings: (1) predominantly ductile structures northeast of the Pasayten fault; (2) predominantly brittle structures southwest of the fault; (3) a description of the Pasayten fault zone itself; and (4) an inferred history of movement on the fault.

Structure northeast of the Pasayten fault

Ductile structures in the map area include steep, coplanar plutonic foliation and gneissic layering, a generally steep downdip mineral lineation that lies in the foliation plane, and tight isoclinal folds and swirled foliation that are found chiefly in the gneissic trondhjemite of Tiffany Mountain. Rarely, a subhorizontal lineation, which also lies in the plane of foliation, either joins the steep lineation or is the only lineation present. North-northwest-trending foliation in the strongly foliated units is locally broadly warped (wavelengths about 10 m) on subhorizontal axes. The intensity of deformation and recrystallization increases westward toward the Pasayten fault, culminating in a zone of locally retrograde mylonitic gneiss and schist next to the fault. In petrofabric studies of the Pasayten fault, Lawrence (1978) described it as having a regional strike of N. 30° W. and a steep dip; he also noted steeply dipping fluxion structures that strike N. 15° W. adjacent to the fault. In the map area, the fault trace is straight and strikes about N. 25° W. Mylonitic structures are oriented essentially parallel to the trace of the fault and dip steeply to the east and west.

The western margin of the trondhjemite of Doe Mountain bears a moderate to weak foliation caused by minor strain and recrystallization; this foliation resembles, but is much less intense than, that which is evident in the deformed plutonic rocks to the west. Toward the north and east, the Doe Mountain unit is weakly foliated to massive. The north- and, locally, northeast-trending strikes of foliation in the trondhjemite of Doe Mountain suggest the existence of an earlier magmatic flow fabric that was reoriented in a north-northwest direction during ductile shear related to movements on the Pasayten fault. If so, the minimum age of this shearing is either about the same or somewhat younger than the emplacement age of the Doe Mountain unit but older than uplift and cooling of the batholith.

The gneissic trondhjemite of Tiffany Mountain, which composes a large screen in the easternmost part of the Doe Mountain quadrangle and the westernmost part of the Tiffany Mountain quadrangle, contains ductile structures that predate the trondhjemite of Doe Mountain. This screen appears to have localized late- and (or) post-batholithic strain in the region. Several large sharp flexures in compositional layering and foliation of the unit are present in and near the map area. In the east-central part of the map area, an asymmetric (refolded?) antiform has a sinuous axial trace and an axial plane that dips steeply north. Both limbs of the fold appear to dip west; in the North Fork of Boulder Creek, the steeper western limb is tightly appressed and may have been sheared. Just outside the southeast boundary of the map area, a synform and antiform that have steep limbs plunge steeply to the west-southwest, and abrupt changes in the strike of layering east of Spur Peak suggest additional tight folds. The large folds are intruded by and, therefore, predate the trondhjemite of Doe Mountain.

Some large folds involving the Tiffany Mountain unit and Cretaceous plutons in the region probably formed during and (or) after intrusion. Just north of the map area, the contacts between the Tiffany Mountain unit and, on the west, the trondhjemite of Doe Mountain and, on the east, the Bottle Spring and Cathedral plutons appear to form a large, sinuous fold. In the southeastern part of the map area, the contact between the Doe Mountain and Tiffany Mountain units traces a large, open, west-facing synform that may have formed when Doe Mountain magma intruded a tighter synform already present in the Tiffany Mountain rocks.

The gneissic trondhjemite of Tiffany Mountain is cut by brittle faults that trend east, north, and possibly northeast. In the southeast corner of the map area, several east-trending faults are associated with small

(0.2–0.5 km) right- and left-lateral displacements, some of which are mapped east of the quadrangle boundary, of the contact between the Doe Mountain and Tiffany Mountain units. To the north, in the vicinity of Boulder Creek, two or more north-trending faults appear to offset the same contact right laterally from 1 to 4(?) km. In the drainage of the North Fork of Boulder Creek, a north- to north-northeast-trending fault or faults may have followed the trace of a ductile shear zone of batholithic age that possibly affected the western limb of the asymmetric antiform described above. Another apparent right-lateral offset in the same intrusive contact in the lower Twentymile Creek and Honeymoon Creek drainages suggests the possible existence of a similar northeast-trending fault or ductile shear zone in this area. Prominent northeast-trending lineaments and the straight northeast-trending course of Honeymoon Creek may mark the location of this hypothetical structure. However, because the intrusive contact here appears to dip gently to moderately to the east, the apparent right-lateral offset may be suspect.

Although dense forest and the ubiquitous glacial drift make it difficult to demonstrate the existence of faults and (or) ductile shear zones in the map area, ductile faults possibly formed late in the emplacement of the trondhjemite of Doe Mountain into the screen of Tiffany Mountain rocks and were later overprinted by brittle faults. The north- and northeast-trending foliation in the trondhjemite of Doe Mountain, mentioned above, may be related to such early ductile faults. Further evidence that deformation of the screen of Tiffany Mountain rocks was related to the emplacement of the Doe Mountain unit is that the northeast-trending faults do not extend westward into the older units of the batholith. A possible explanation is that the trondhjemite of Doe Mountain was not fully consolidated when faulting took place. Because of the inhomogeneous, highly layered structure of the Tiffany Mountain unit and its position as a screen between homogeneous plutons, the unit probably took up much of the late-batholithic regional strain. The gneissic trondhjemite of Tiffany Mountain, which continues to the south (J.R. Wilson, oral commun., 1983) and to the north (Staatz and others, 1971; Stoffel and McGroder, 1989), may provide an important marker for postbatholithic tectonism.

Aligned breccia zones and the linear east wall of the valley of the upper Chewack River mark the trace of the Chewack River fault, which extends for at least 4 km between Twentymile and Boulder Creeks. Contacts of units within the batholith are not offset by this fault. Presumably, minor dipslip movements on this fault occurred during a late brittle period of activity on the Pasayten fault or other faults in the region. The presence of additional minor faults in the area is suggested by several north- to northeast-trending bedrock lineaments mapped on both sides of the Chewack River. One of these is the straight course of upper Doe Creek, which appears to have been offset right laterally.

Structure southwest of the Pasayten fault

The chief structures in the Jurassic and Cretaceous sedimentary and volcanic rocks southwest of the Pasayten fault are large parallel folds that have wavelengths as long as 20 km whose axes are nearly parallel to the Pasayten and Hozameen faults (Barksdale, 1975; Tennyson and Cole, 1978). Smaller, tight folds having steeply inclined axial surfaces, which are present in the older sedimentary and volcanic rocks in the southwestern part of the map area, probably formed in a deeper, more ductile environment. Regional folding may have begun as early as the latest Albian, as indicated by the existence of an unconformity above presumed Albian strata in the Methow basin (Mohrig and Bourgeois, 1986; McGroder and Miller, 1989), and affected sedimentary units as young as Late Cretaceous. Deformation in the north-central part of the basin apparently had waned by 93 to 85 Ma, the age of slightly folded to undeformed stocks and porphyritic sills and dikes (Todd, 1987). However, significant deformation must have taken place in latest Cretaceous and early Tertiary time about 5 km south of the map area near the eastern margin of the basin, where the Pipestone Canyon Formation of Barksdale (1975) of presumed Paleocene age unconformably overlies, and is tightly folded with, Upper Jurassic and Lower Cretaceous strata (Bunning, 1990).

The sedimentary and volcanic rocks of the Methow basin are unmetamorphosed to weakly metamorphosed. Burial metamorphic minerals (zeolites, prehnite, and pumpellyite) are present locally (Tennyson and Cole, 1978). In the southern part of the basin, a predominantly volcanic sequence is metamorphosed to greenschist facies (Hopkins, 1987). Both the incipient metamorphism of the predominantly sedimentary section in the northern part of the basin and the lack of well-developed contact aureoles around late- to post-folding(?) stocks suggest that the sedimentary section was thickened during folding and intrusion but that uplift and unroofing occurred too rapidly to allow metamorphism.

A generally north trending high-angle fault extends for 8 to 10 km from the northern part of the Thompson Ridge 7–1/2' quadrangle (fig. 1) through the southeastern part of the Mazama quadrangle to the southwestern part of the Doe Mountain quadrangle, where it ends against a concealed fault in the Cub

Creek drainage. Only a small part of this fault can be seen in the map area (see sec. 32, T. 36 N., R. 21 E.). The southern part of the fault brought the Jurassic Twisp Formation up on the east against Cretaceous sedimentary and volcanic rocks on the west and probably has a minimum stratigraphic throw of about 1 km. Faults that have a similar trend cut the hinge area of one of the large parallel folds in the Methow basin rocks outside the map area and presumably formed during or shortly after folding. However, the fault that is exposed in the Doe Mountain quadrangle most likely had an earlier, pre-Late Cretaceous period of activity because it separates two apparently different stratigraphic sequences. West of the fault, the Albian and lower Upper Cretaceous Virginian Ridge Formation of Barksdale (1948, 1975) rests unconformably upon the Harts Pass Formation. East of the fault, the rocks that make up the basal part of the Virginian Ridge Formation (referred to informally as the Patterson Lake conglomerate by McGroder and others, 1990) contain clasts of the Twisp Formation, with which they are in both unconformable and fault contact; the Harts Pass Formation is missing entirely. For this reason, Barksdale (1975) suggested that the Patterson Lake rocks were originally deposited upon a Jurassic basement.

In the Buck Mountain area, a north-northwest-striking bedding-plane fault extends into the map area from the Mazama quadrangle to the west, where it has brought the Panther Creek Formation up on the east against the Harts Pass Formation, which lies in the trough of a syncline, on the west. In the map area (see sec. 20, T. 36 N., R. 21 E.), the fault is marked by a slight angular discordance between the Harts Pass and Panther Creek Formations. The fault cannot be traced to the southeast, where it either dies out or is obliterated by the train of porphyritic sills south of Buck Mountain. Apparently, this fault has been offset right laterally by several short transverse faults.

Pasayten fault

The Pasayten fault juxtaposes Mesozoic rocks of contrasting lithology, metamorphic grade, and structural style. Mylonitic structures, which parallel the fault in the rocks of the Okanogan Range batholith east of the fault, record an Early and mid-Cretaceous episode of ductile movement on an ancestral Pasayten fault. Subsequently, one or more episodes of brittle deformation in the ancestral Pasayten fault zone produced a narrow, linear fault trace that is well marked topographically. The linear trace of the fault in the map area suggests a steep dip. North of the map area, Lawrence (1978) measured dips of 55°, 65°, and 80°, all to the southwest. The fault is marked by, from north to south, a prominent notch at Billy Goat Pass, the linear valley of Eightmile Creek, and a prominent break in slope between the forested foothills of the Okanogan Range on the northeast and the low, dark, grassy hills of the Methow basin on the southwest. The fault does not have clear topographic expression beyond long 120°, where its trace becomes irregular (J.R. Wilson, oral commun., 1983).

In the map area, the style of deformation associated with the Pasayten fault differs markedly across the fault. As described above, the western part of the Okanogan Range batholith consists of amphibolite-grade gneissic plutonic rocks and mylonitic gneiss and schist. The intensity of ductile deformation dies out rapidly to the east away from the fault. Foliation and lineation in the mylonitic rocks resulted from high-temperature strain and recrystallization, suggesting that the batholith either intruded into or adjacent to a deep-seated shear zone or underwent postemplacement regional shearing when it was still deeply buried. In the map area, the west-to-east zonation of plutonic units from more mafic to less mafic compositions parallel to the Pasayten fault supports a hypothesis of syntectonic intrusion. Further support comes from the relations between foliation and leucocratic dikes, a small number of which are folded. Dikes in the Eightmile Creek and Lamb Butte units and in the mylonitic border zone apparently were emplaced before(?), during, and after the development of regional foliation (fig. 8; on map sheet). If the westernmost units of the batholith were emplaced during regional deformation, then movement on the Pasayten fault in the map area took place in late Early Cretaceous time.

The Pasayten fault juxtaposes high-grade batholithic rocks of Early Cretaceous age against unmetamorphosed and low-grade metamorphic sedimentary and volcanic rocks of Jurassic and Cretaceous age. Because brittle-shear structures are well developed, particularly in the sedimentary and volcanic rocks of the Methow basin, the post-Early Cretaceous movements likely occurred at relatively shallow depths. From east to west across the fault, ductile mylonite gives way to crushed and hydrothermally altered rocks. Just west of the fault, brecciated volcanic rocks are net veined by weathered leucocratic material, which suggests that igneous activity at depth may have supplied or mobilized fluids that caused the veining and hydrothermal alteration. The zone of crushed and altered rocks west of the fault is about 1 km wide. East of the fault in the Okanogan Range batholith, the mylonitic border rocks show pervasive discoloration by hydrothermal fluids. Both the mylonitic rocks and the trondhjemites of Eightmile Creek and Lamb Butte contain discrete, hydrothermally altered zones of brittle shear, particularly where they are adjacent to porphyritic sills. However, no broad breccia zone was seen in the batholithic rocks.

Late Cretaceous porphyritic sills and dikes of andesitic and dacitic composition are present on both sides of the Pasayten fault in the Doe Mountain and Mazama quadrangles. Thus, any large strike-slip movements probably had ceased in this area by Late Cretaceous time. The sills and dikes are associated with hydrothermal alteration and brittle shearing that affected both the dikes and their host rocks. The crustal extension, igneous activity, and faulting(?) represented by these dike swarms were possibly related to late, post-major strike-slip movements on the Pasayten fault. These movements continued in the Paleocene, the presumed age of the Pipestone Canyon Formation of Barksdale (1975), which is cut by the fault in the Twisp quadrangle (Barksdale, 1975), and ended by middle Eocene time, the age of the volcanics of Island Mountain (Staatz and others, 1971; White, 1986), which overlie and intrude the Pasayten fault.

History of movement on Pasayten fault

Microstructural analyses of mylonitic plutonic rocks adjacent to the Pasayten fault indicate a complex movement history for the fault. Lawrence (1978) postulated a mid-Cretaceous period of left-lateral strike-slip movement on the Pasayten fault at depths of 10(?) km and temperatures of 300 °C on the basis of petrofabric studies of plutonic rocks east of the fault; from the orientation of minor brittle structures, he inferred a later period of minor high-angle reverse motion, which was possibly related to folding of the Methow basin rocks, and, finally, normal faulting (graben formation). In recent studies, kinematic indicators in mylonitic rocks adjacent to the fault within the map area suggest an episode of ductile-to-brittle, southwest-directed reverse slip, whereas indicators north of the map area suggest left-lateral strike-slip motion (Hurlow, 1989). Although the timing relations between these two slip episodes are unknown (Hurlow, 1989), rare subhorizontal lineations in mylonitic rocks in the map area suggest that dip-slip movement may have obliterated structures that had formed during an earlier period of strike-slip movement. South of the map area, the Pasayten fault gives way to a system of west-directed reverse faults that carried high-grade metamorphic and plutonic rocks of the Okanogan Range batholith over greenschist- or lower-metamorphic-grade rocks of the Methow basin (Bunning, 1990; Gulick and Korosec, 1990). About 10 km southwest of Winthrop, the Pasayten fault passes southeast into the ductile Red Shirt thrust fault; kinematic indicators in mylonitic rocks record southwest-directed reverse movement on this fault (Frey and Anderson, 1987). The southern end of the Red Shirt thrust fault truncates the northern end of the northeast-striking Methow River fault, which experienced west-northwest-directed reverse movement (Frey and Anderson, 1987). Frey and Anderson (1987) did not preclude pre-Late Cretaceous left-lateral slip along the Pasayten fault-Red Shirt thrust fault trace.

The question of the magnitude of strike-slip movement on the Pasayten fault remains open. Although the rocks of the Methow basin and the Okanogan Range batholith are in part contemporaneous, they were not adjacent to one another when the batholith was emplaced, because the Methow basin rocks are not contact metamorphosed and no trondhjemite dikes have been recognized in them in the Doe Mountain and Twisp quadrangles. Additionally, the distinctive sedimentary and volcanic lithologies seen in the Methow basin rocks do not appear as metamorphosed inclusions in the batholith. Plagioclase-rich arkose and granitoid clasts in conglomerates of the Methow basin sequence were possibly derived from a proto-Okanogan Range batholithic terrane, which implies that the two fault blocks were adjacent by Early Cretaceous time and that a basement of trondhjemite floors the Methow basin. The presence along the Pasayten fault of fault-bounded slivers of Jurassic and Cretaceous volcanic rocks and, in the northeastern part of the Mazama quadrangle, Late Jurassic hornblende tonalite suggests that the Pasayten fault originated as a strike-slip fault. The fault slivers do not, however, indicate a unique direction or magnitude of displacement because rocks of similar lithology and age are present all along the west side of the fault from the international border to the southern part of the Methow basin.

The presence of a patch of presumed Paleocene continental rocks, the Pipestone Canyon Formation, which is mapped about 5 km south of the map area near the eastern margin of the basin, indicates that the rocks of the Methow basin were downdropped relative to the Okanogan Range in the late Paleocene(?) and Eocene. The Pipestone Canyon Formation contains clasts of most or all of the supracrustal units now exposed in the Methow basin, as well as granitoid and gneissic clasts (Barksdale, 1975).

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