AN ABSTRACT OF THE THESIS OF

Neil Elfrink for the degree of Master of Science in Geology presented on June 1, 1987.

Title: The Geology of the East Central Desolation Butte Quadrangle, Grant County, Oregon

Abstract approved: Redacted for privacy

Keith F. Oles

Pre-Tertiary metamorphic rocks, Jurassic granitic intrusions, and Eocene basalts are exposed along the North Fork of the John Day River at its confluence with Granite Creek. Geochemical and textural evidence suggest greenschist-metamorphosed, strongly sheared, volcanogenic rocks originated in an island-arc environment. These greenstones were apparently intruded during the Late Permian by a silicic pluton that is similarly metamorphosed and brecciated. South of this arc terrane, tectonically disrupted ophiolitic rocks are exposed. This east-west-trending belt of melange contains blocks of chert, metagabbro and metabasalt in a serpentinite matrix. Titanaugite indicates the original basalt may have been alkalic. Paleozoic or Triassic Elkhorn Ridge Argillite underlies much of the thesis area and consists mostly of contorted chert and argillite. Graywackes, greenstones and limestones are intercalated with Elkhorn Ridge Argillite. Regional metamorphism is lower greenschist facies.

Two relatively fresh granitic stocks may be satellites of the Upper Jurassic Bald Mountain batholith exposed nine kilometers to the east. An intrusive sequence ranging from mafic quartz diorite to granite comprises the larger stock, exposed along Granite Creek. This pluton contains mostly quartz diorite and tonalite. A 0.5 kilometer wide stock of porphyritic tonalite intrudes argillite on the north side of the North Fork, John Day River canyon. Mineral assemblages in the contact metamorphic aureoles around the two stocks are characteristic of hornblende hornfels facies.

Tertiary dark gray basalt overlies the Mesozoic and Paleozoic rocks at a profound unconformity. Geochemistry suggests the olivine-bearing, vesicular basalt is equivalent to the Clarno Formation exposed farther to the west.

THE GEOLOGY OF THE EAST CENTRAL
DESOLATION BUTTE QUADRANGLE,
GRANT COUNTY, OREGON

A THESIS

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THE GEOLOGY OF THE EAST CENTRAL DESOLATION BUTTE QUADRANGLE, GRANT COUNTY, OREGON

INTRODUCTION

Cenozoic continental volcanic rocks enclose exposures of pre-Tertiary rocks in the Blue Mountains of northeast Oregon. The pre-Tertiary rocks fit into the traditional eugeosynclinal model and probably represent a complex convergent margin system that was accreted to the North American continent. Pre-Tertiary exposures in Oregon are limited to relatively small areas. The thesis area is a significant "window" to the pre-Tertiary history of eastern Oregon. The delineation of previously unmapped pre-Tertiary units and the examination of younger Nevadan intrusives and Tertiary volcanics should contribute to the knowledge of the stratigraphy, structure, and geologic history of the Blue Mountains region.

Location and Accessibility

The thesis area lies within the Umatilla National Forest in the central part of the Blue Mountains of northeast Oregon. The area mapped in detail lies completely within the area defined as Township 8 South, Ranges 34 and 35 East, Willamette Meridian. The thesis area is in the eastern half of the Desolation Butte 15-minute quadrangle in northeastern Grant County and is centered around the 2,000 foot deep canyon of the North Fork of the John Day River. John Day, the largest town in Grant County, is 65 km to the southwest. Baker, Oregon is 55 km east of the study area and the hamlet of Granite is 7 km to the east.

Much of the study area is relatively inaccessible and cross-country hiking is required to reach many outcrops. Logging roads in the southeast corner of the map area can be reached from Granite via Forest Service road 1035. Forest Service Road 350 dead ends in the extreme southwest corner of the study area. The principal access to the northern half of the thesis area is from Silver Butte lookout and Silver Spring camp in section 6, T. 8 S., R. 35 E., immediately north of the map area. Well maintained foot trails cross the area and follow Granite Creek and the North Fork of the John Day River (Figure 6). Elevations range from a maximum of almost 6,300 feet on Rabbit Butte on the southern border of the map area to approximately 3,775 feet on the North Fork of the John Day River.

Climate, Flora and Fauna

The temperate climate is a continental type with large daily and yearly temperature ranges. Summers are warm but comfortable as the relative humidity is low. Precise weather data are not available but mean annual precipitation is probably around 30 inches. Summers are dry. Winters are rigorous and snow commonly covers the ground from November to April.

Flora and fauna are characteristic of the montane environment. Some slopes are covered with majestic stands of Ponderosa pine and Douglas fir. Some trees are over 400 years old. A mixed tamarack, lodgepole pine, and fir forest dominates. Mule deer, Rocky Mountain elk, badger, North American black bear, coyotes and numerous birds inhabit the forest. Hares are particularly common on Rabbit Butte.

Previous Work

Lindgren (1901) conducted the earliest geologic studies in the Blue Mountains but concentrated primarily on mineral deposits. Many geologic features of northeast Oregon were first described by Pardee and Hewett (1914). Taubeneck (1957) studied the Bald Mountain batholith and the Elkhorn Ridge Argillite. Two small-scale geologic maps include the thesis area: Geologic Map of the Canyon City Quadrangle, Northeastern Oregon (Brown and Thayer, 1966) and the Geologic Map of Oregon East of the 121st Meridian (Walker, 1977). Recent detailed work in the vicinity of the thesis area include a Master's thesis by David Matty (1980) on the North Fork Stock, located a few miles northwest of the thesis area, and a Master's thesis by Ellen Mullen (1978) on the Greenhorn Mountains, located a few miles south of the map area. The Oregon Department of Geology and Mineral Industries (DOGAMI) has recently published a series of geologic maps covering the traditional gold mining districts in the Blue Mountains. One of these maps, Geology and Gold Deposits Map of the Granite Quadrangle, Grant County, Oregon (Brooks et al., 1982), borders the east side of the thesis area. Many of the conventions used on the DOGAMI maps were applied to mapping in the thesis area. Part of the thesis area appears on the Mineral Resource Potential Map of the North Fork John Day River Roadless Area (Evans and Conyac, 1983).

General Geology

The Blue Mountains anticlinorium trends northeast to southwest from Idaho to central Oregon and has been a persistent structural feature since the Eocene (Robyn and Hoover, 1982). Pre-Tertiary igneous and sedimentary rocks exposed in erosional inliers of the Blue Mountains are separated from surrounding Cenozoic volcanics by a profound unconformity. The Paleozoic to Jurassic formations in northeast Oregon are complex and not fully understood. Various plate tectonic models have been proposed but problems remain. The consensus of recent workers is that the pre-Tertiary rocks represent fragments of oceanic and island arc crust that were accreted to the outer edge of North America during the Early Cretaceous.

The pre-Tertiary rocks exposed in northeastern Oregon, extreme southeastern Washington, and the Hells Canyon area of westernmost Idaho probably represent the dismembered components of a single island-arc complex - the Blue Mountains Island arc (Vallier and Brooks, 1986). Silberling and others (1984) divide the Blue Mountains island arc into five distinct tectonostratigraphic terranes: Grindstone, Izee, Olds Ferry, Baker, and Wallowa (Figure 2). The Grindstone and Baker terranes are subterranes of the dismembered oceanic terrane (Brooks and Vallier, 1978) also known as the central melange terrane (Dickinson, 1979) or the oceanic/melange terrane (Mullen and Sarewitz, 1983). The Izee terrane contains mainly Upper Triassic through Middle Jurassic flysch that overlies the Grindstone terrane (Blome et al., 1986). The Olds Ferry terrane includes the

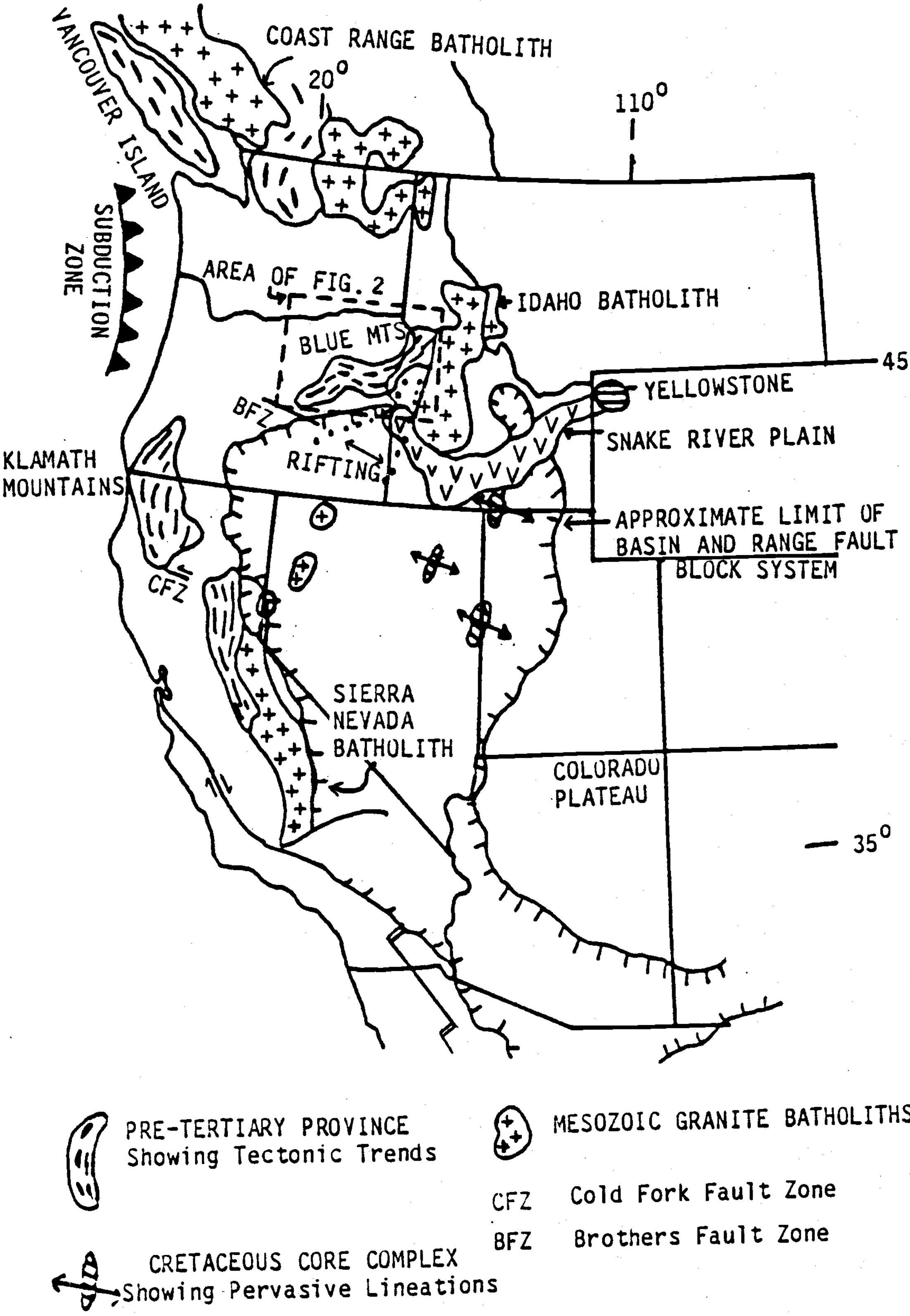


Figure 1. Tectonic and geographic setting of the Western Cordillera. Modified from Dickinson (1979).

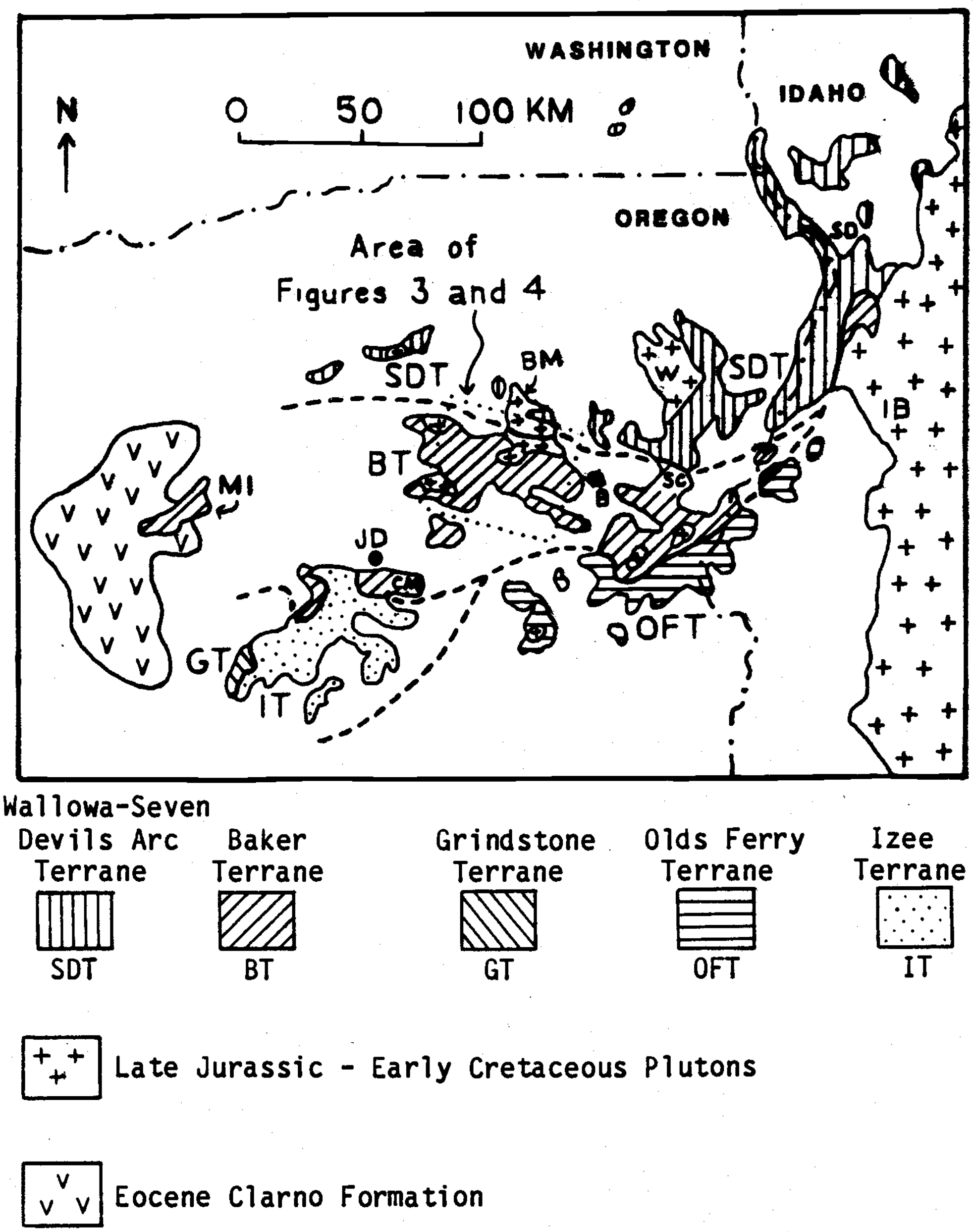


Figure 2. Distribution of pre-Tertiary terranes in the Blue Mountains province. Terrane contacts dashed where buried by Cenozoic cover (no pattern). Modified from Dickinson (1979). B, Baker, Oregon; JD, John Day, Oregon; MI, Mitchell Inlier; CM, Canyon Mountain Complex; BM, Bald Mountain Batholith; W, Wallowa Batholith; IB, Idaho Batholith; SD, Seven Devils Mountains; SC, Sparta Complex.

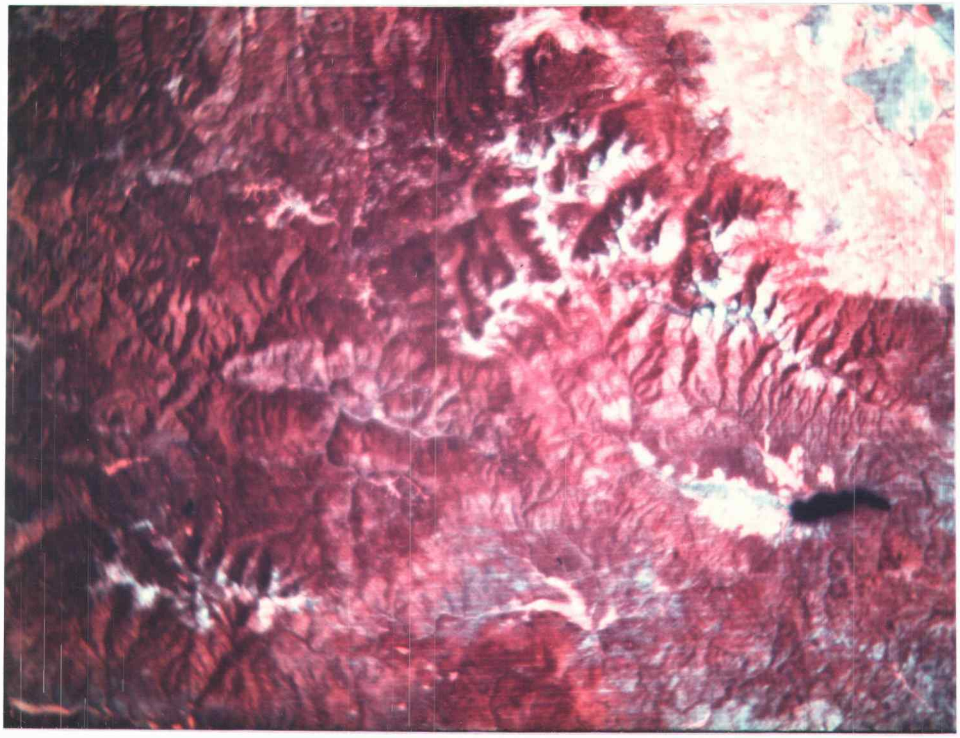
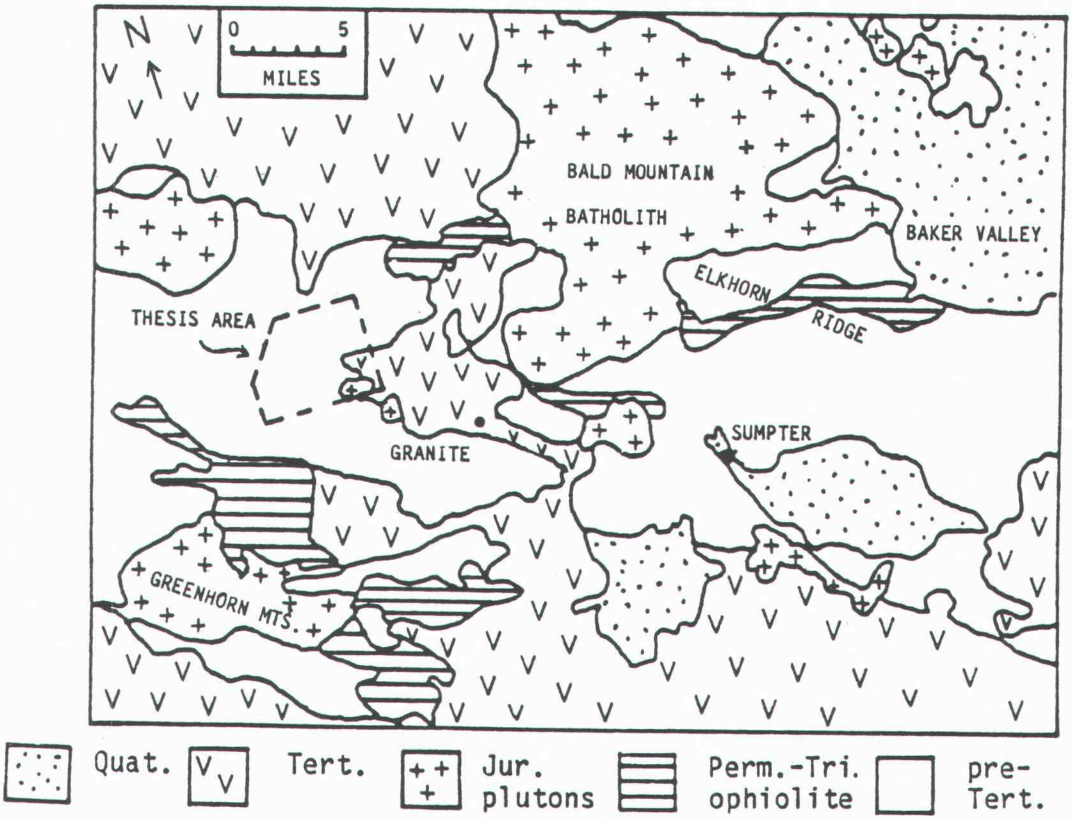


Figure 3. False-color Landsat image of central Blue Mtns.



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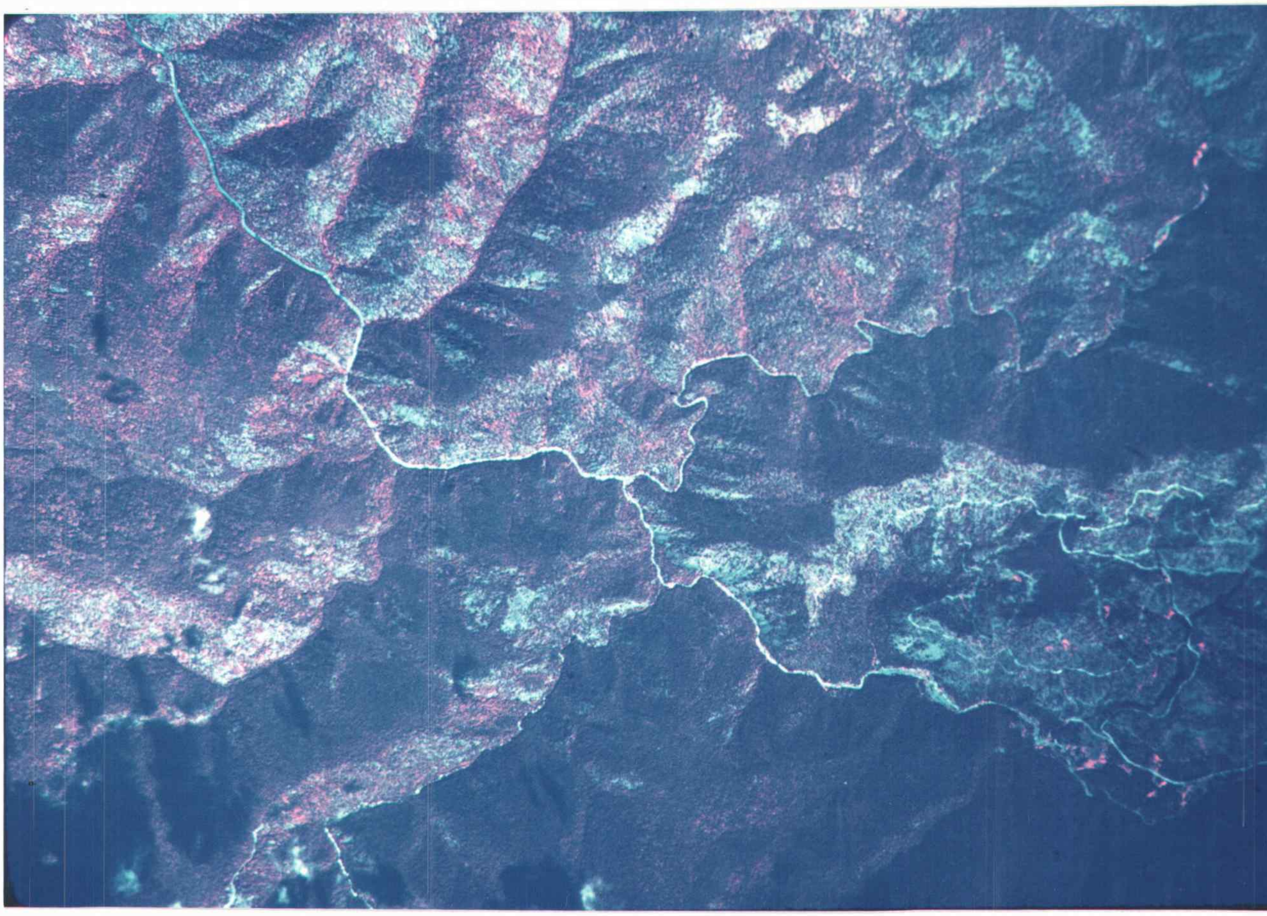


Figure 5. High-altitude, false-color, aerial photograph of the thesis area. E-W lineaments reflect structural trends.

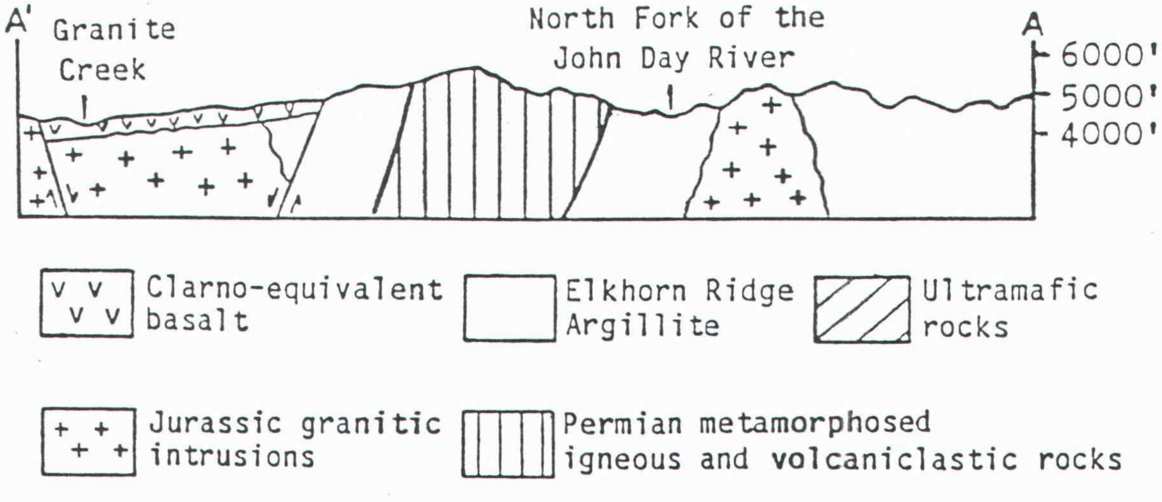


Figure 6. Schematic geologic cross section running N-S along the east side of the thesis area (line A-A' on Figure 7). No vertical exaggeration. Heavy lines are faults.

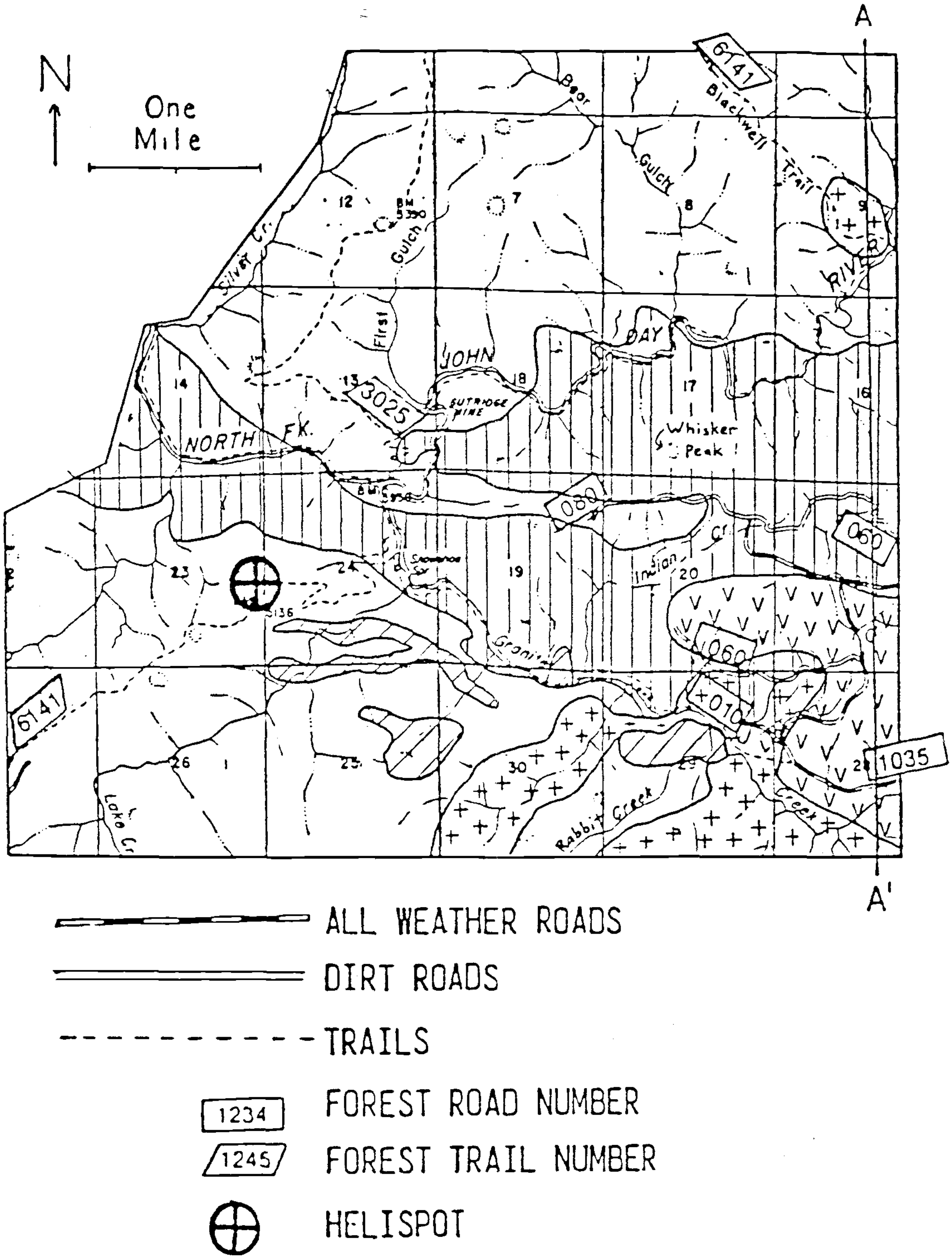


Figure 7. Simplified geologic map of the thesis area.

eastern parts of the Mesozoic clastic terrane (Dickinson, 1979) or forearc basin terrane (Brooks, 1979) and the Huntington arc. The Wallowa terrane is also known as the Wallowa Mountains - Seven Devils Mountains volcanic arc terrane (Brooks and Vallier, 1978) or the Seven Devils arc (Dickinson, 1979) - the term used in this report.

The Seven Devils and Huntington Arcs

Altered volcanic and volcaniclastic rocks of Early Permian and Middle and Late Triassic age are widely exposed in the Wallowa Mountains, Snake River Canyon, and the Seven Devils Mountains. Lithologies and chemistries within this thick sequence strongly resemble modern island arcs, hence the terrane is known as the Seven Devils arc. Plutonic rocks both underlie and intrude the volcanic rocks (Brooks, 1979). In the eastern part of the Seven Devils arc, Late Triassic and Early Jurassic sedimentary rocks were deposited on top of the paleovolcanics after volcanism had ceased.

South of the Seven Devils arc, Late Triassic volcanics and volcaniclastics of the Huntington arc are exposed. Early Jurassic sedimentary rocks also are present (Silberling, 1983). The Huntington arc was formed in a geologic setting similar to that envisioned for the Seven Devils arc but correlative sequences differ.

Paleomagnetic data indicate that the Seven Devils arc may have formed near the equator, far from North America (Hillhouse, 1980). The Seven Devils arc has been correlated with Wrangellia (Jones et al., 1977), a hypothetical exotic, dismembered, crustal block accreted to southern Alaska and Coastal British Columbia. However, arc-like volcanic and volcaniclastic rocks of the Seven Devils terrane differ from the contemporaneous tholeiitic basalts of Wrangellia (Sarewitz, 1982). The Seven Devils arc has been correlated with the similar Huntington arc (Brooks and Vallier, 1978). However, volcanism in the Huntington arc continued while only sedimentary rocks were being deposited in the Seven Devils arc (Silberling, 1983).

Volcanic-plutonic arc rocks extend across the thesis area, forming a greenstone belt. The oldest rock in the thesis area may be a brecciated and metamorphosed diorite informally named the Whisker Peak intrusive. These intermediate plutonic rocks underpin an assemblage of pyroclastic and volcanic rocks informally named the India greenstone. The Whisker Peak rocks may intrude the India greenstone but faulting has obscured relations. Alternatively, the intermediate plutonic rocks could be part of the basement upon which flow and sedimentary rocks were deposited. A sample of the Whisker Peak intrusive collected just east of the thesis area has been U-Pb dated at 243 m.y.B.P. (Brooks et al., 1982). Ages for similar plutonic rocks exposed in the Snake River Canyon and eastward into Idaho cluster around 248 m.y. Hence, arc-like rocks exposed in the thesis area greenstone belt probably formed in close association with the Seven Devils arc.

Baker Terrane

The Baker terrane consists mainly of ophiolitic rocks and an argillite-chert sequence with subordinate limestones and volcanic tuffs and flows. The thesis area contains all these lithologies and, like the Baker terrane throughout northeast Oregon, is dominated by fine argillite and chert of the Elkhorn Ridge Argillite. Dates for the Baker terrane range from Pennsylvanian to Early Jurassic, but most rocks are Permian or Triassic. Apparently, accumulation of the oceanic/melange terrane was more or less continuous for a long interval of time (Mullen and Sarewitz, 1983). Subduction beneath oceanic island arcs was active throughout much of this time (Avè Lallemant, 1983). Contacts between major rock units are generally faults. Structural deformation within the Baker terrane is consistent with formation in a subduction zone (Avè Lallemant et al., 1980).

Rock fragments of ophiolitic affinity occur throughout the Baker terrane of northeast Oregon but only two well-preserved ophiolitic complexes are exposed: the Sparta complex and the Canyon Mountain Complex (Figure 2). Both have had complex magmatic histories and were probably formed in immature island arc environments (Leeman et al., 1983, and Brooks, 1979). Radiometric ages for the Sparta complex (223 m.y. and 262 m.y.) are younger than ages for the Canyon Mountain complex (268 m.y. to 279 m.y.). Throughout the Blue Mountains, Triassic rocks generally lie in-board of Paleozoic assemblages.

An understanding of pre-Tertiary geology is further complicated by several factors: (1) a belt of blueschist exposures runs along the southern boundary of the Baker terrane, (2) both Tethyan and North

American faunas are found in limestone pods of the Baker terrane (Nestell, 1980); and (3) two penetrative deformations are recorded in the rocks of the central Blue Mountains. Late Triassic folds trend N-S and Late Jurassic folds trend E-W. The swing from E-W tectonic trends in the western Blue Mountains to N-S trends in the Seven Devils Mountains is an angular bend rather than a gradual change.

Simple eastward directed accretion cannot explain the regional structure. Transpressive tectonics, rotation, in situ generation, or some other complex model might be invoked to explain the complex regional geology of the Blue Mountains island arc. However, the overlap in radiometric ages from plutonic rocks throughout the older terranes suggests they all developed as parts of a single complex convergent margin system (Walker, 1983). This composite subduction complex is believed to have accreted to North America in the Early Cretaceous.

The pre-Tertiary rocks of the thesis area belong in the Baker terrane. However, their diverse character will become evident in the following discussion. The part of the Baker terrane exposed in the thesis area may represent a relatively coherent marginal basin assemblage genetically related to the Seven Devils arc. The laterally complex relations of lenticular carbonates and volcaniclastics suggest deposition in a setting of volcanoes and intra-arc basins.

Figure 8. Scenic view across the Granite Creek valley in section 19, T. 8 S., R. 35 E. Metavolcanics in the background have been uplifted along an E-W-trending fault. Low outcrops in the foreground are typical of the argillite unit.

METAMORPHIC ROCKS

Elkhorn Ridge Argillite

Gilluly (1937) gave the name Elkhorn Ridge Argillite to rocks exposed on Elkhorn Ridge, east of the thesis area. The Elkhorn Ridge Argillite and its more deformed correlative, the Burnt River Schist, extend from western Idaho to west of the study area (Brooks, 1979). The Elkhorn Ridge Argillite is a complex stratigraphic unit of diverse age; it consists mainly of argillite, siliceous argillite and chert with minor volcaniclastics, greenstones and limestone. Coward (1982) considered the unit to be an accretionary prism that included blocks of metavolcanics and metagabbro. The usage of the name Elkhorn Ridge Argillite is generally restricted to supracrustal rocks that form near the surface of the earth (Brooks, 1979). Similarities in lithology and structure support inclusion of thesis area metamorphic rocks in the Elkhorn Ridge Argillite. This correlation is lithologic and has little significance in a stratigraphic sense because of the questionable age of the structurally complex and widespread Elkhorn Ridge Argillite.

Fossils of Devonian, Pennsylvanian, Permian, Triassic, and Jurassic age have been found in the Elkhorn Ridge Argillite outside of the thesis area (Morris and Wardlaw, 1986). Many dates are based on fusulinid fauna from limestone pods. Both Tethyan and North American faunas have been reported but mixed faunas are unknown (Nestell, 1980; 1983). The carbonates may have formed in widely separated areas of the paleo-Pacific basin and been juxtaposed by later tectonism. However, Nestell (1980) has suggested local environmental control of adjacent faunas, rather than tectonic juxtaposition after geographic separation.

The major part of the Elkhorn Ridge Argillite is of Permian age, but Middle Pennsylvanian to Late Triassic fossils are common (Blome et al., 1986). Lower and Middle Triassic sedimentary rocks are apparently absent (Morris and Wardlaw, 1986). Radiolarians in the Elkhorn Ridge Argillite cherts yield mid-Permian to mid-Jurassic dates (Murchey et al., 1983). Late Triassic cherts are the dominant lithology in the Baker area (Blome et al., 1983). A Triassic to Early Jurassic age has been reported for cherts on Elkhorn Ridge near Sumpter (Coward, 1982). Elkhorn Ridge Argillite limestone pods enclosed within Mesozoic cherts can yield Paleozoic conodonts. James Evans has discovered Middle to Late Devonian conodonts from an Elkhorn Ridge Argillite limestone pod a few miles southwest of the thesis area (Morris and Wardlaw, 1986). The juxtaposition of various age lithologies suggests the Elkhorn Ridge Argillite formed in a forearc accretionary prism.

The fossil record indicates that deposition of the Elkhorn Ridge Argillite was a long and possibly continuous process. Younger rocks of the Baker terrane are generally found to the south and east with older rocks to the north (Blome et al., 1986). The location of the thesis area-in the northwest part of the Baker terrane-suggests a relatively older section of Elkhorn Ridge Argillite should be exposed.

Greenstones intercalated with chert and argillite in the thesis area have apparently been intruded by a silicic pluton. One km east of the thesis area, the pluton was U-Pb dated as 243 m.y. or Late Permian (Brooks et al., 1982). The supracrustal rocks it apparently intrudes are presumably older. Despite a search of chert outcrops and formic acid demineralization of four limestone samples, few fossils useful for dating were found in the thesis area. The author's discovery of what are probably fusulinids in a limestone pod, suggests an age older than Triassic. The Elkhorn Ridge Argillite exposed in the thesis area is tentatively assigned a Permian age although the presence of older or younger rocks cannot be excluded. Similar rocks in the Sumpter Quadrangle also have been dated as Permian (Taubeneck, 1955; Bostwick & Koch, 1962).

The Argillite Unit (TrPzs)

This section deals with the argillites, siliceous argillites and cherts that are the dominant rock types in the thesis area as well as in Elkhorn Ridge Argillite throughout the Blue Mountains. These rocks are referred to informally as "the argillite unit" and mapped TrPzs. The associated greenstones and coarser volcaniclastics (Pmv), although considered part of the Elkhorn Ridge Argillite, are discussed in a later section. Limestones from both the argillite unit and the greenstones are also discussed in a separate section. Similar deformational response and mineral assemblages in the argillite unit and the greenstones suggest that they were metamorphosed and deformed contemporaneously.

Distinctions between chert and argillite break down as the rocks grade into one another. Typically gray or buff chert grades into black, shaly argillite over small intervals. The argillite breaks into equidimensional fragments when struck with a hammer whereas the chert splinters into chips. Fresh surfaces of the argillite tend to be duller than the chert.

Chert is plentiful, but probably is disproportionately exposed in outcrop because of resistance to weathering. The chert is mostly gray to black, but light gray and greenish gray varieties are also present. Beds of chert up to two meters in thickness are common, but some are rhythmically bedded, with individual layers ranging from 1 to 10 cm in thickness.

Petrography

The argillites and cherty argillites are comprised of relict, detrital sodic plagioclase, quartz, and clays (illite?) with minor epidote, muscovite, calcite, and ferruginous minerals. Small amounts of sphene, zircon, and tourmaline (Figure 9) suggest a source from plutonic and metamorphic rocks exposed in deeply eroded parts of a volcanic arc. Cherts and argillites lacking secondary recrystallization are cryptocrystalline but some contain quartz and plagioclase fragments up to silt and sand in size. Silica has been mobilized during induration and metamorphism producing quartz

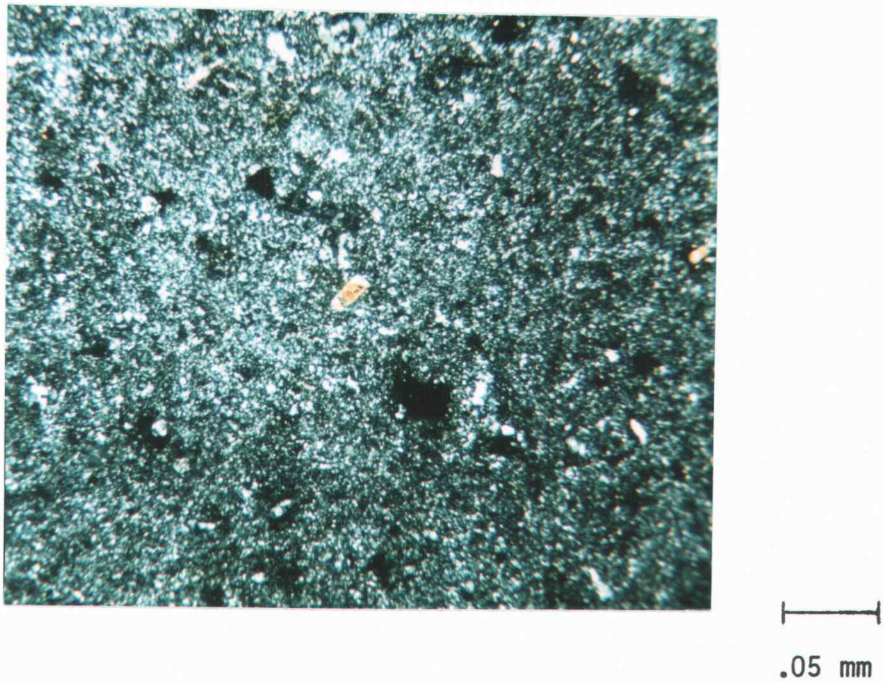


Fig. 9. Photomicrograph of relatively unaltered argillite (TrPzs)-sample #392 from NE1/4 SW1/4 Section 6, T. 8 S., R. 35 E. Rock is mostly extremely fine-grained quartz. A few euhedral plagioclase fragments may represent airfall ash. The elongate, birefringent grain in the center is tourmaline. Field of view is approximately 0.55 mm. (crossed nicols)

veinlets, some of which appear to be tightly folded. Fine flecks of carbonaceous material were noted, some with metallic luster. Graphite may have inhibited grain boundary growth during metamorphism, preventing recrystallization (Spry, 1969).

Prominent, murky, birefringent clay distinguishes the argillite from chert although cryptocrystalline impurities are locally common in cherts. At many places the cherts have been strongly fractured and healed by many criss-crossing quartz veinlets. Some thin sections are dominated by quartz recrystallization. Calcite veins, possibly replacing quartz, were noted. A micromosaic of anhedral quartz crystals is characteristic of chert. Ovoid structures in less recrystallized thin sections may be radiolarian relicts. Some argillite unit rocks contain abundant unabraded plagioclase microlites and grade into tuffs.

Argillite Unit Sandstones

Sandstone beds in the argillite unit (TrPzs) range from 1.0 cm to several meters in thickness. Locally the more competent graywacke beds are separated by distorted shaly interbeds. A faint parting parallel to the bedding is commonly visible.

The argillite unit sandstones are finer grained than the sandstones included in greenstones, which are described in the Pmv chapter. Grains range from silt (0.05 mm) to pebble (5 mm) in size. Sorting is poor and the fragments are angular to subangular. Abundant, unabraded plagioclase fragments in many sections suggest a pyroclastic origin. Graywackes apparently grade into lithic tuffs.

Rock fragments in the wackes are plentiful and include fine-grained altered mafic to intermediate volcanic rock and microcrystalline quartzite, probably metachert. No K-feldspar was seen, either in thin section or by etching and staining ground surfaces of rock specimens. Minor constituents include sphene, epidote, apatite, and chlorite. Scattered cubes of pyrite are probably authigenic.

The matrix of the sandstones is very fine-grained and individual constituents cannot be clearly resolved. In some sandstones the matrix is obviously recrystallized and wraps around the hazy boundaries of the larger grains. A characteristic feature of argillite unit sandstone is the calcareous composition. Calcareous siltstone and calcareous sandy siltstone also were noted.

The mineralogy of the argillite unit (TrPzs) sandstones is indicative of a volcanic source, possibly of intermediate composition, but the plentiful quartz content indicates contributions from a more silicic, possibly plutonic terrane. In contrast, the coarser grained wackes in the greenstone terrane were derived from volcanic rocks that were being erupted nearby, either subaerially or on the sea floor, during deposition of the sandstones.

Neptunian Dike

Distinctive sandstones occur in what is apparently a neptunian dike in the center of section 24, T. 8 S. R. 34 E. Neptunian dikes consist of sedimentary materials, generally sand, that are injected into undersea fissures in older sedimentary rock (Hsu, 1983). In exposures along the Lake Creek Trail and even in hand sample the rock resembles a light gray Tertiary volcanic. The dike is generally about 30 cm wide and extends over 0.5 km. Some brecciation of the host argillite is evident. The N-S-trending dike cuts perpendicularly across the E-W structural trend that dominates the thesis area.

In thin section, the dike rocks lack the shears so common in pre-Tertiary sandstones found elsewhere in the thesis area. The dike rocks are apparently less altered by metamorphism than other sandstones. Chlorite and epidote are relatively rare. Most clasts are 0.1 to 1 mm in diameter and are subangular to angular. The sand is poorly sorted. Most grains are plagioclase or quartz. Argillite and intermediate volcanic clasts were noted. Calcite is prevalent, occurring as both groundmass and 0.1 mm wide veinlets. Some plagioclase completely replaced by calcite retains polysynthetic twinning. Some plagioclase clasts are unabraded and may have been deposited by ash falls. The rock could be classified as a feldspathic calclithite or a tuffaceous lithic wacke. The sandstone may have been deposited contemporaneously with the surrounding argillite or earlier but its N-S trend suggests it was deposited in a fissure after the argillite had been deformed. Obviously more study is needed of this puzzling geologic feature.

Elkhorn Ridge Argillite Paleogeography

The fine-grained cherts and argillites are indicative of a relatively quiet, moderately deep depositional environment in a subsiding marine basin. Jenkyns and Winterer (1982) studied the worldwide paleoceanography of Mesozoic and Paleozoic ribbon radiolarites similar to the Elkhorn Ridge Argillite of the thesis area. They found that chert-argillite "couplets" are unique to Paleozoic and Mesozoic orogenic belts. In the Tertiary, diatoms replaced radiolarians as the main processors of dissolved silica. Jenkyns and Winterer (1982) suggested that these distinctive siliceous sediments were formed mainly in small arc-related or transform-dominated basins. In the thesis area, similar basin deposits, the argillite unit, were probably incorporated into a forearc or accretionary wedge.

Studies of modern trenches suggest an origin for the Baker terrane. Poorly consolidated sediments were scraped off the downgoing slab to form a sheared accretionary wedge - the Elkhorn Ridge Argillite. Some papers have interpreted the melange to be formed by submarine slumping, but seismic-reflection profiles across modern trench systems show olistostromes to be uncommon (Hamilton, 1985). Some early workers on Elkhorn Ridge Argillite envisioned coherent sections of argillite thousands of feet thick that were later intensely deformed. It is more likely that internal shearing and soft-sediment deformation accompanied the lateral and vertical growth of the accretionary wedge.

India Greenstone (Pmv)

Rocks informally designated in this report as the India greenstone occur in a broad east-west belt north of the ophiolitic rocks. This greenstone belt extends eastward two kilometers into the Granite Quadrangle (Brooks et al., 1982). The name is derived from a small tributary of Granite Creek shown on area maps as Indian Creek but known locally as India Creek (Figure 6). The India greenstone is composed mainly of metavolcanic rocks and related clastic rocks with minor interbedded cherts, argillites, limestones and metamorphosed intrusive rocks. The abundance of clastic rocks and geochemical evidence suggest the India greenstone formed in an island-arc environment (Garcia, 1975).

The India greenstone and the other greenstones of the Blue Mountains are similar in structural deformation and degree of metamorphism, but the paucity of fossils and extreme facies variations make correlations across the region difficult. Most of the greenstones are considered to be Triassic or older. The stratigraphic nomenclature of the various greenstones has become complex and confusing (Beaulieu, 1972). The India greenstone resembles Seven Devils arc rocks exposed in Hell's Canyon, such as the Permian Hunsaker Creek Formation (Vallier, 1977). The India greenstone is apparently more spilitic than most Blue Mountain greenstones (Mullen, 1983) and is similar to keratophyres Gilluly (1937) described in the Permian Clover Creek Greenstone east of Baker. Gilluly considered the sodium introduced to form the feldspars as having been derived from seawater. Albitization of these feldspars was postmagmatic but preceded formation of epidote and clinozoisite. Because the thesis area rocks are generally more sheared than most northeast Oregon rocks, the shearing may have aided albitization.

Bedding was not clearly recognized in the India greenstone in the field, but crude cleavages strike mainly east-west, analogous to the axial-plane foliation that dominates the Elkhorn Ridge Argillite. Quartz veins intrude both the greenstone and cherts. The metavolcanic rocks commonly are massive units, and presumably were flows. However, obvious pillow structures were not noted. In hand samples the rocks are greenish gray, finely crystalline to microscopic, and locally porphyritic. Shearing and metamorphism have left only the porphyries recognizable as of volcanic origin, but even these can be confused with sheared intrusive rocks in outcrop. In many cases it is impossible to distinguish aphanitic flow rocks from volcaniclastics or even tuffaceous cherts. The minerals and textures are generally visible only under the microscope.

The India greenstone exposures commonly show large lateral and vertical variations in lithology, although some presumed flow rocks are relatively continuous. Much of the heterogeneity is the result of deformation and the high fault density. Like the rest of the metamorphic exposures in the thesis area, much of the unit could almost be classed as a tectonic melange. It is possible, however, that the rocks were deposited on a varied topography with diverse environments, thus producing rapid facies changes. The presence of fine-grained sediments within the greenstone belt does not necessarily indicate large fault displacements. Discontinuous lenses of chert and argillite, compositionally similar to the deposits that dominated farther from the center of volcanism, could have been deposited in small basins.

Cherts within the India greenstone are less altered and recrystallized than cherts in the argillite unit. Abundant, unabraded plagioclase crystals were probably derived from ash falls. The thin section of sample #37 from SW1/4, NE1/4, Section 17, T. 8 S., R. 35 E. contains ovoid remnants of radiolarians and siliceous skeletal remains of possible algal fragments. A successful fossil search at this location may permit dating of the India greenstone.

Metavolcanic Petrography

Despite pervasive shearing, relict textures typical of greenstones are apparent in thin section. Original primary minerals are extremely rare, but the relative scarcity of mafic minerals or their replacements and the predominance of finely crystalline felty textures in most sections suggest andesitic compositions are more common than basaltic compositions. Low refractive indices indicate the plagioclase in most of the metavolcanics is highly sodic. The metavolcanics are commonly cut by narrow bands of microbreccia.

Metamorphism, retrograde metamorphism, alteration to clays, and tectonic deformation have produced many metabasites - completely recrystallized mafic rocks with little or no relict textures. The vague grain boundaries and amorphous nature of the minerals in many greenstones makes determination of modal composition impossible. Hand samples that appear to be fresh often are quite altered when viewed under the microscope.

The former flow rocks display the appropriate greenstone minerals: chlorite, albite, epidote, actinolite, carbonate, quartz, white mica, magnetite, and other opaques. Apatite, sphene, and leucoxene are common trace minerals. Brown biotite was noted in some metavolcanic and volcaniclastic sections but hornblende was not. The biotite probably denotes contact metamorphism.

Relict porphyritic, intergranular, and pilotaxitic textures have been preserved. Rare, small circular concentrations of albite, quartz, actinolite, epidote, and chlorite probably represent relict vesicles.

Plagioclase in the metavolcanics generally occurs as small (~ .25 mm), randomly oriented laths in the groundmass. Large phenocrysts are not common. The plagioclase is hazy and saussuritized with alteration products, yet original zoning and lamellar twinning is observed in some specimens. The plagioclase has been altered to finely crystalline calcite, albite, epidote, and chlorite. The low refractive indices indicate that the recrystallized plagioclase, in most rocks recognizable as having originally been volcanic, is highly sodic (An_5). Although albite dominates, the plagioclase is sodic oligoclase(An_{15}) in some more metamorphosed specimens.

Some of the greenstones contain small amounts of pyroxene occurring between the plagioclase laths and also as small phenocrysts. Calcite is common as veinlets and as grains, indicating that CO_2 was abundant in the fluid phase during metamorphism. Sphene has been partly altered to leucoxene. Black opaques occur as blobs and skeletal masses, presumably magnetite, locally accompanied by leucoxene.

Relict mineralogy is seldom preserved. Primary pyroxene was observed in a few thin sections. Pyroxene phenocrysts have most commonly been altered to epidote or actinolite, usually in combination with chlorite. Similarly, hornblende has been altered to mixtures of actinolite, epidote, chlorite or opaque minerals. Plagioclase phenocrysts contain abundant inclusions of chlorite. Much of the plagioclase has been saussuritized to an aggregate of zoisite or epidote and carbonate. Saussurite is particularly common in the cores of some plagioclase phenocrysts and probably represents primary normal zoning.

The groundmass minerals of many of the flow rocks have been altered to an amorphous mass. Individual minerals in the matrix can be recognized only with difficulty.

Greenstone Geochemistry

Major element geochemistry of two India greenstone samples was performed by Professor Peter Hooper at Washington State University (Table 1). Two other analyses of greenstones from the thesis area were discussed by Mullen (1983b). Major element geochemistry has been published for four Pmv greenstones located less than one mile east of the thesis area (Brooks et al., 1982). The continuity of outcrops justifies plotting all this data together (Figures 10 to 12).

TABLE 1. MAJOR ELEMENT ANALYSES OF INDIA GREENSTONES (Pmv)

Sample	76	138
SiO_2	50.89	55.15
Al_2O_3	17.10	17.36
TiO_2	1.00	1.12
CaO	10.56	10.50
Na_2O	3.13	4.54
K_2O	.03	.18
Fe*O	9.61	4.62
MgO	6.92	5.18
MnO	.15	.24
P_2O_5	.13	.16
TOTAL	99.52	99.15

76 Metabasalt (Pmv)
SE1/4, NW1/4, Section 20, T. 8 S., R. 35 E.

138 Metavolcanic (Pmv)
SW1/4, SE1/4, Section 16, T. 8 S., R. 35 E.

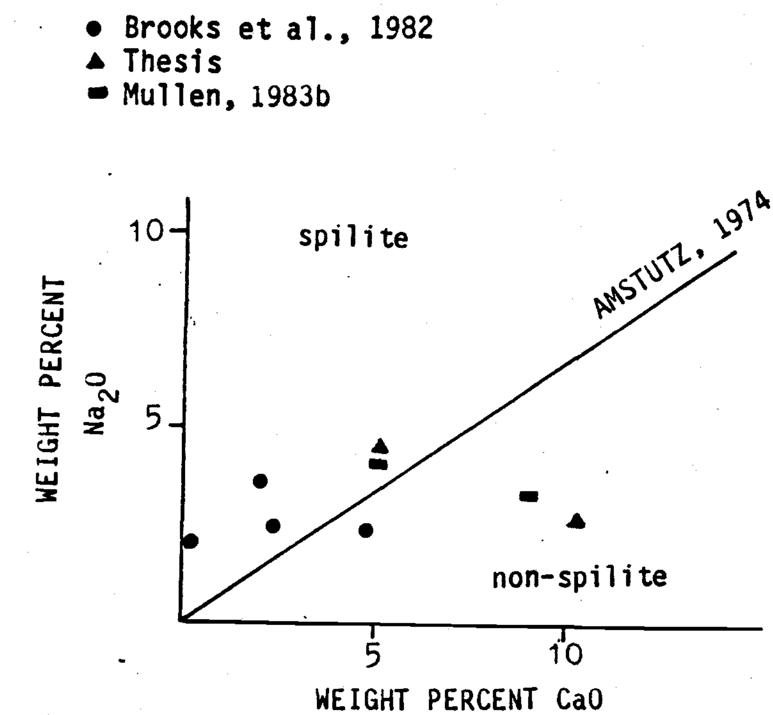


Figure 10. Na_2O/CaO plot of India greenstones indicates some samples are slightly spilitic.

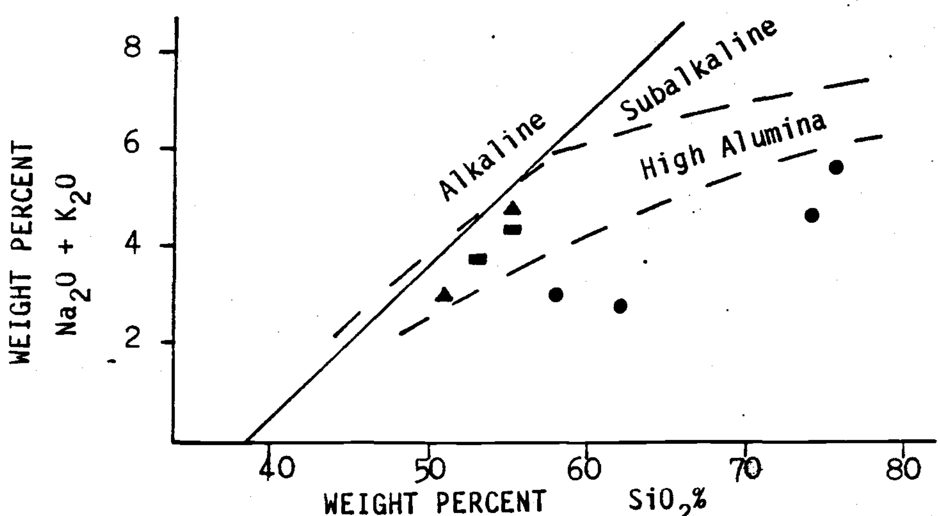


Figure 11. $Na_2O + K_2O$ versus SiO_2 plot for India greenstones. Mobilization of major oxides during metamorphism may limit the value of these plots.

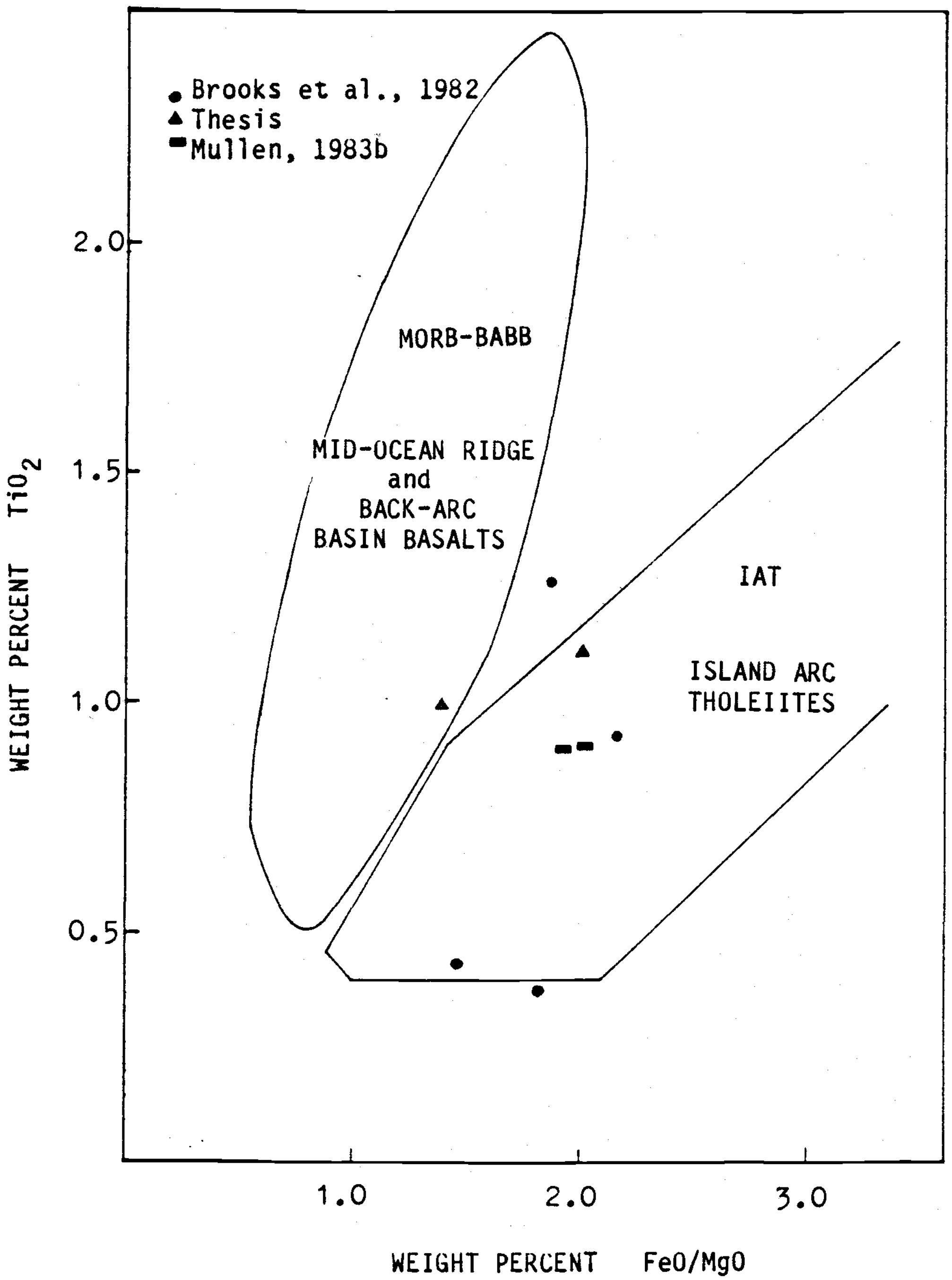


Figure 12. TiO_2-FeO/MgO plot for India greenstones. Relatively low TiO_2 concentrations resembles island arc tholeiited (IAT) more than mid-ocean ridge or back-arc basin basalts (Garcia, 1978).

However, any inferences drawn from the geochemistry of these altered rocks must be considered highly speculative. Major element abundances are very susceptible to modification during low-grade metamorphism. The Na_2O/CaO plot (Figure 9) puts some samples into the spilite field, indicating at least some mobilization of the major oxides.

Although the major oxide abundance may not be useful for classification, the bulk-rock geochemistry is similar to island arc rocks. The low TiO_2 concentrations resemble island arc rocks (Jakes & White, 1972). The greenstones are high in Al_2O_3 and P_2O_5 compared to oceanic rocks (Mullen, 1983a).

Five samples of India greenstone were sent to Specomp Services for semiquantitative spectrographic analysis. (See Table 7 in the Economic Geology section of this report.) The likelihood of alteration and mineralization of the greenstones combine with the questionable accuracy of the results to make these data of limited value for determining magmatic affinities. Nevertheless, the trace element abundances are more compatible with island arc rocks than ocean floor rocks. Concentrations of Ba and Pb are relatively high compared to ocean floor rocks. Low concentrations of Ni, Zr and Cr resemble island arc rocks.

Fragmental Greenstones

Many pre-Tertiary rocks that appear to be flow rocks in the field are actually volcaniclastics when viewed in thin section. Other volcaniclastic beds are readily distinguished from flow rocks by obvious grain size and sorting variations. Differing shades of green and gray with some red and bluish tinges are also characteristic of some volcaniclastics. These pale colors are the result of clay alteration of the groundmass. Rare, normally graded beds are visible in outcrop and in thin section. Other sedimentary structure were not observed. Most specimens are volcanic wackes in which quartz grains and chert fragments are subordinate to plagioclase and volcanic fragments.

Volcaniclastic breccias are common in the greenstone belt. Many of these poorly sorted breccias show little evidence of having undergone any sedimentary processes. Some are composed chiefly of volcanic clasts and may be autoclastic flow breccias. Others display distinct bedding and contain clasts of chert.

Most volcaniclastics in the study area display clast rounding and diversity. Sorting and graded bedding were noted. These features suggest the sediments formed from weathering products of pre-existing rocks and are therefore considered epiclastic. A few volcaniclastics compositionally similar to the epiclastics contain a high percentage of individual plagioclase crystals and a low diversity of rock fragments. These are considered pyroclastic although altered glass shards and pumice are not recognizable in thin section. Such chemically unstable constituents probably were not preserved. A few monolithologic fragmental rocks may be autoclastic breccias formed in place by crushing and shearing during dynamic metamorphism.

The sandstones of the India greenstone (Pmv) are volcanic wackes composed of significant quantities of plagioclase and rock fragments in a matrix of chlorite, sericite, quartz, feldspar, and iron oxides. All of the wackes are poorly sorted and are dominated by subangular to angular clasts. Euhedral plagioclase grains may be pyroclasts derived from volcanoes erupting during deposition of the sedimentary rocks. The compositions of most volcanic fragments apparently range from basaltic to andesitic. Most volcanic fragments are microlitic and contain subhedral to euhedral feldspar prisms with pilotaxitic or felty textures. More mafic volcanic clasts contain plagioclase laths in intergranular and intersertal textures; felsitic grains are subordinate. Both composition and texture suggest the wackes probably were derived from contemporary volcanic rocks that were being erupted nearby, either subaerially or on the sea floor. The preservation of labile mineral and rock clasts suggests rapid uplift, deposition, and burial in a eugeosynclinal environment.

Quartz is common in some sandstones as grains up to 0.5 mm in diameter. The quartz fragments tend to be angular but some smaller grains are subround. The size, inclusions, and strain features of the quartz fragments imply they were derived from a volcanic, plutonic or high grade metamorphic source. Albite is abundant in the volcaniclastics; however, most of the plagioclase has altered to sericite or has been saussuritized.

The relatively high alkali content (Table 2), the high Na_2/K_2O element ratio, and the high Al_2O_3 content, may reflect a volcanic

TABLE 2. MAJOR ELEMENT ANALYSES OF PRE-TERTIARY SANDSTONES (Pmv)

Sample	24	422
SiO_2	50.62	74.04
Al_2O_3	17.27	12.88
TiO_2	.90	.46
CaO	5.61	1.55
Na_2O	4.84	3.93
K_2O	1.57	2.49
Fe*O	6.24	2.97
MgO	2.38	1.33
MnO	0.13	0.13
P_2O_5	0.23	0.08
TOTAL	99.69	99.86

24 Volcanic Wacke (Pmv)
NW1/4, NE1/4, Section 21, T. 8 S., R. 35 E.

422 Tuffaceous, Volcanic Wacke (Pmv)
NE1/4, SE1/4, Section 17, T. 8 S., R. 35 E.

source of andesitic composition (Condie & Snansieng, 1971). However, later alteration may have enriched the rocks in Al and Na. The high silica content may reflect the dilution of volcanic source rocks by reworked older seds or silicification during alteration.

Limestones (ls)

Lenticular bodies of limestone, ranging from a few meters to as much as 70 m wide and 150 m long, occur within the argillite unit and the India greenstone. On Rabbit Butte a few discontinuous limestone bodies form an E-W belt more or less on strike. The limestones are dense and impure. They are commonly crystalline and weather light gray.

The limstone pods are composed almost entirely of calcite with minor dolomite, plagioclase and quartz. Most are highly recrystallized, especially in the argillite unit where most of the large outcrops occur. The isolated pods and lenses of limestones may have once been more continuous beds that have been stretched and intensely folded (Pardee & Hewett, 1914; Gilluly, 1937).

Limestone conglomerate is common in a limestone pod exposed near the mouth of Backout Creek. The clasts are mostly pebble size and subangular. These clasts may have originated by disruption of newly deposited and partially indurated carbonate mud by high energy storm waves. The fragments could also have been formed in a turbidity current. Another possibility is the production of a limestone conglomerate by subaerial erosion but the lumps are apparently incorporated within the sedimentary unit from which they were derived.

The presence of a piece of oolitic limestone float from a limestone pod exposed on the Silver Hill Trail in Section 14 suggests shallow water deposition in this area. This pod is surrounded by cherty argillite and if the pod is not an olistolith or was not emplaced by faulting, then a shallow water environment of deposition is indicated for some of the cherty argillite.

Limestones within the greenstones (Pmv) appear to be less altered and more fossilliferous than limestone pods in the argillite unit. Only two sizable Pmv limestones were found. Sample 473 was taken in the NW1/4 Section 23, T. 8 S., R. 34 E. This carbonaceous micritic limestone is fractured and partially recrystallized. Kaolinite is concentrated along stylolites. The thin section contains crinoid ossicles (Figure 13) and an elongate algal structure.

A 3 m by 1 m limestone pod (#307), partially recrystallized, in the NE1/4, NE1/4 Section 24 yielded a small conodont fragment from a 1000 gm sample. Unfortunately, the fragment is too small for identification. The small conodont fragment is black with a color alteration index of five, yielding a maximum temperature range of 300-400°C (Epstein et al., 1977).

Obviously any further study would benefit from a more thorough fossil search at both these locations.

High fluid pressures are inferred from intense brecciation along with multiple phases of silica and carbonate veining. Some rocks display signs of being replaced by silica. Sample #452 from a limestone pod is a cherty rock shot full of diagenetic carbonate occurring in veins and as felty random masses (Figure 14). Accompanying or closely following the crystallization of

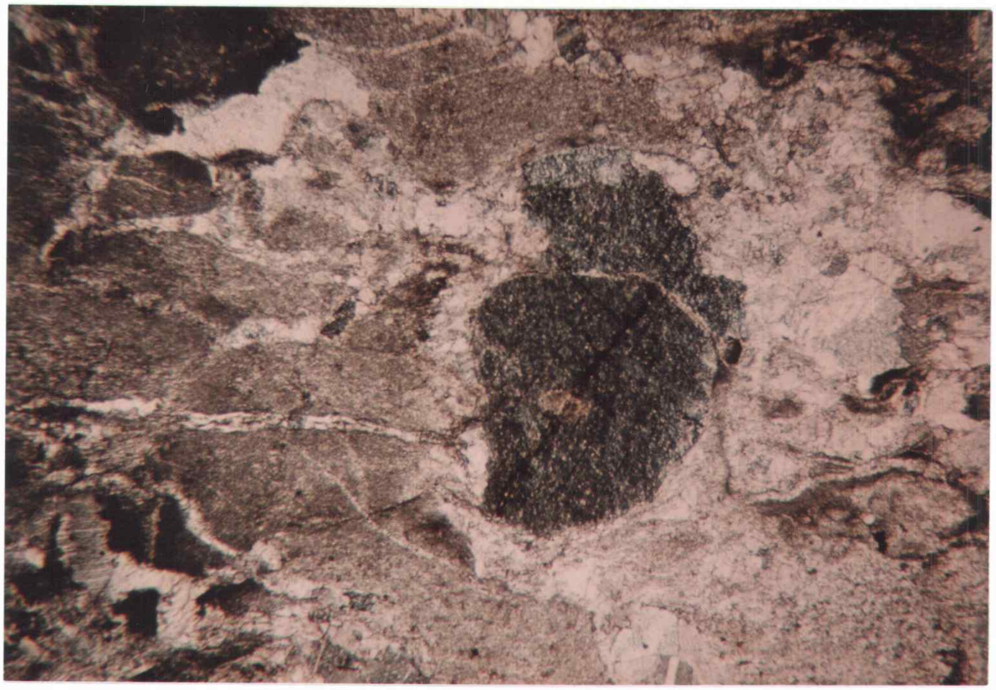


Figure 13. Photomicrograph of fossiliferous limestone sample #473 from the India greenstone (Pmv), SW1/4 SW1/4 Section 14, T. 8 S., N. 34 E. Deformed crinoid ossicle surrounded by a sparry calcite overgrowth. Part of the overgrowth is in optical continuity with the crinoid fragment. Note calcite veinlets cutting unrecrystallized limestone. Field of view is approximately 7.5 mm. (crossed nicols)

1 mm

Fig. 14. Photomicrograph of calcareous chert (#452), possibly of replacement origin, from a limestone pod in argillite NW1/4 NW1/4 Section 25, T. 8 S., R. 34 E. Carbonate veinlet on right appears to have been partially replaced by subhedral quartz grains. Field of view is approximately 7.5 mm. (Crossed nicols)

this marmoraceous carbonate was the formation of small, euhedral quartz polygons within the carbonate. These disseminated quartz grains and crystals in a matrix of recrystallized calcite resemble the early stages of replacement of limestone by jasperoid (Lovering, 1972).

Whisker Peak Intrusive (Pi)

An elongate body of metamorphosed plutonic rock mapped as Pi occurs in the northeastern part of the India greenstone belt on the south side of the North Fork, John Day River. The intrusion forms a prominent ridge in the center of section 17, T. 8 S., R. 35 E, which locally is known as Whisker Peak (Figure 15). The informal name Whisker Peak intrusive is used here for this 3 km long exposure of metamorphosed quartz diorite and less silicic plutonic rocks. The unit also contains finely crystalline metavolcanics indistinguishable from rocks of the India greenstone (Pmv).

The contact relations of the plutonic rocks with the surrounding metamorphosed India greenstones are unknown because of poor exposures and difficulty in distinguishing rock types on outcrop. However, the abundance of biotite in the supracrustal rocks around the Whisker Peak intrusive suggests the presence of contact metamorphic effects. Plutonic clasts were not noted in the nearby volcaniclastic sandstones, indicating that the Whisker Peak intrusive probably did not form a basement upon which the volcaniclastic and flow rocks were deposited, a suggestion made by Evans and Conyac (1983). On the other hand, the pluton may have been faulted against the volcanic and

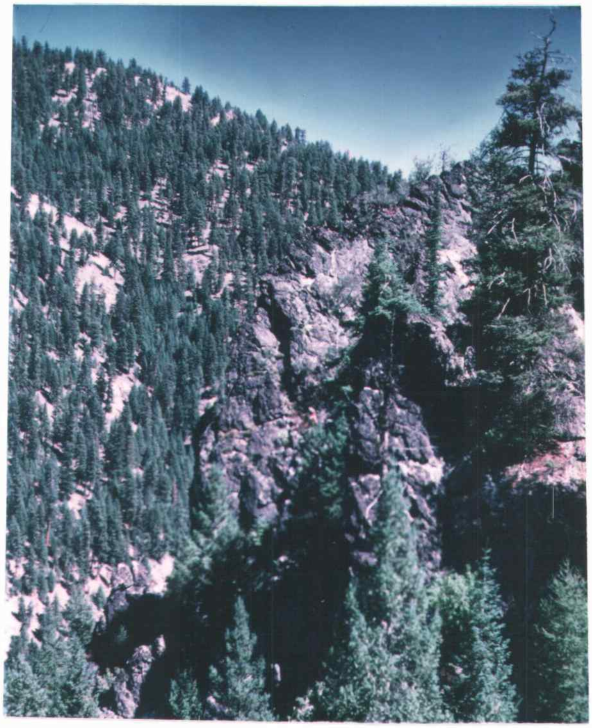


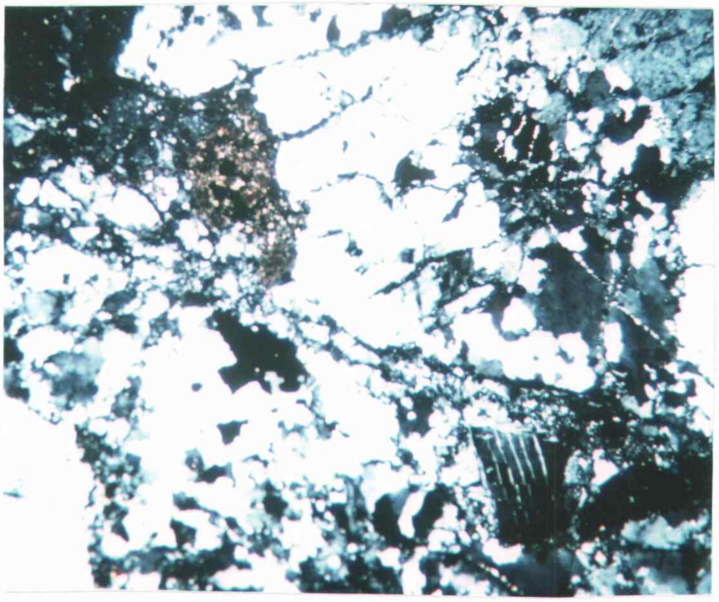
Figure 15. Scenic view of Whisker Peak (in foreground), center of Section 17, T. 8 S., R. 35 E. Metamorphosed siliceous intrusive rocks exposed in this area are informally named after this geographic feature. A meta-quartz diorite in SE1/4, Section 16, T. 8 S., R. 35 E. in the adjacent Granite Quadrangle yielded a Permian date (Brooks et al., 1982). Relationships between the Whisker Peak intrusive and surrounding India greenstones are unclear.

volcaniclastic rocks. The metamorphosed plutonic rocks continue eastward for over one km into the adjacent Granite Quadrangle where they appear to intrude the metavolcanic and related related sedimentary rocks (Brooks et al., 1982). Major element abundances for a sample of Pi from the Granite Quadrangle are very similar to Pmv geochemistry, suggesting a common magma source. A Late Permian age (243 m.y.b.p.) for the Pi unit was obtained on zircon from a quartz diorite exposed adjacent to the thesis area (Brooks et al., 1982).

The weathered surfaces of the Whisker Peak intrusive are dominantly reddish brown to a dull yellowish orange in color. Megascopically, these altered granitoid rocks are composed of greenish gray, equigranular feldspars and quartz crystals in a dull grayish green matrix. Fresh surfaces are pale yellowish green and commonly appear fine-grained. Differentiation between metamorphosed intrusives and metavolcanics is easier on weathered surfaces where visible grains of quartz and feldspar up to 1 cm in diameter distinguish the plutonic rocks. Shearing and brecciation are ubiquitous.

Petrography

All of the Whisker Peak thin sections examined have a cataclastic texture. Fractures and seams of microbreccia crisscross the slides (Figure 16). The twinning lamallae of plagioclase crystals are commonly bent and microscopically faulted. The quartz is strained and recrystallized.



1 mm

Figure 16. Photomicrograph of metamorphosed quartz diorite (Pi), Whisker Peak intrusive sample #249 from NW1/4, SW1/4, Section 17, T. 8. S, R. 35 E. A shear zone with recrystallized quartz cuts across the view. A deformed plagioclase crystal in the lower right contains offset twin lamellae. Although some epidote is visible, mafic minerals are apparently scarce in this rock. Field of view is approximately 7.5 mm. (crossed nicols).

The subhedral albitic plagioclase crystals are embayed and enclosed by quartz. The plagioclase is commonly saussuritized, having been partially replaced by epidote and flecks of sericite. Epidote also occurs as coarsely crystalline interstitial material, probably replacing the original mafic constituents. Chlorite is also present. The accessory minerals are sphene, zircon, and opaque minerals, mainly secondary iron oxides.

The modal composition of the rock is difficult to determine but it is estimated that quartz ranges from 12-30%, plagioclase 60-70%, and mafics 10%. Potassium feldspar was not noted in thin section. According to the mineral composition, many of the rocks are altered quartz diorite; the scarcity of mafic minerals suggests some may have been trondhjemitic.

Metagabbro (Pgb)

Bodies of mafic intrusive rock are found mostly within the India greenstone belt. Metagabbro found in the serpentinite melange (mt) is discussed elsewhere. More work would be necessary to determine the relations between the metagabbros and surrounding metavolcanics (Pmv) as well as the associated siliceous intrusives (Pi). Plutonic rock assemblages in Hell's Canyon contain sheared gabbros and are associated with and possibly intruded by diorites. These complex rocks may be part of the basement for the Seven Devils arc (Vallier, 1977). Although commonly sheared, metagabbros can at places be recognized in the field by the granular texture. The fresh surfaces are very pale green and mottled, whereas the rocks weather dusky yellowish brown.

Altered plagioclase and pyroxene pseudomorphs form equigranular and interlocking crystals about 0.5 to one mm in diameter. The primary pyroxene has been largely altered to bluish green actinolite. Carbonate has replaced some of the plagioclase crystals. Clinozoisite, comminuted plagioclase, and minor quartz are concentrated in fluxion structures.

The metamorphic grade in the metagabbros may approach the epidote-amphibolite facies once known as the greenschist-amphibolite transition facies (Turner, 1960). Chlorite is scarce while plagioclase compositions tend to be more calcic than the albite that dominates the metavolcanics. Sample 262 contains zoned amphiboles, the outer rims composed of darker more birefringent brownish green hornblende. Zoning shows that only partial equilibrium was reached during metamorphism. The smaller surface area of grains in the coarsely crystalline rocks may have inhibited intergranular diffusion of fluids and mineral reactions (Spry, 1969).

Ultramafic Rocks

One of the more interesting geologic features of the thesis area is a tectonically disrupted belt of ophiolitic rocks that extends over 3 km in an E-W direction, parallel to the regional structural trend. This pre-Tertiary serpentinite-matrix melange is one of the most northerly reported ultramafic bodies in Oregon. Ophiolitic rocks of the Blue Mountains probably have diverse origins. Most are relatively siliceous and probably related to island arcs rather than oceanic crust (Mullen, 1983b). The age, origin and significance of these complex rocks are difficult questions. Isotopic age data for ophiolitic and melange complexes throughout northeastern Oregon and west-central Idaho seem to be synchronous with arc volcanism (Walker, 1983). This overlap in age between the varied tectonic elements suggests they all formed together and now make up a "single but complex convergent margin system that was accreted to North America" (Walker, 1983).

Metavolcanic rocks (mt) from the ophiolitic belt in the southern part of the thesis area differ signifcantly from the India greenstones (Pmv) exposed a short distance to the north. Intense shearing in the thesis area may indicate juxtaposition of different tectonic environments at a subduction zone. It is certainly possible that the meta-igneous rocks in the mixed terrane (mt) are exotic; originating at a spreading center or isolated seamount far from the island arc environment of the India greenstones (Pmv). Alternatively, a simpler hypothesis would have the ophiolitic rocks forming in a marginal basin by Permian or Triassic back arc rifting, and thus being genetically related to the India greenstones. The ophiolitic rocks could also be arc basement (Thayer, 1978).

Poor exposures obscure relations of the ophiolitic rocks in the thesis area. Outcrops lack lithologic coherence and are thus considered a melange. Areas dominated by serpentinite were mapped as sp whereas areas mapped as mixed terrane (mt) are characterized by blocks of mafic greenstones in a pervasively sheared matrix. Further investigation of these rocks might resolve some of the problems but better models of sea floor hydrothermal metamorphism and diapiric intrusions are also needed. Unfortunately, the processes of ophiolite formation are poorly understood because of technical difficulties in sampling sea floor fracture zones and spreading systems (Moody, 1979).

Serpentinites (sp)

According to plate tectonic theory, ultramafic igneous rocks and the hydrously altered equivalents (serpentinites) represent mantle material brought to the surface at accreting margins. Ultramafics form the basal zone of the typical ophiolite suite, overlain by sequences of cumulates, pillow basalts, possible massive sulfides, and a capping of deep sea sediments including chert.

Most of the serpentinite (sp) unit is highly sheared and completely serpentinized. The serpentine forms grayish green outcrops that weather to a dusky yellow. Serpentine terranes that have escaped Jurassic contact metamorphism are smooth with low relief. Varying degrees of the characteristic shiny, smooth surface are seen in hand sample. Thin veins of asbestos were noted. There is no layering or other evidence that a magmatic stage ever existed at the present site. The lack of contact metamorphism in the surrounding rocks and the deformed foliations of the serpentinite suggest diapiric emplacement in a semisolid or solid state.

The serpentinites not affected by Jurassic contact metamorphism are composed of antigorite, chrysotile, magnetite and chromite, with carbonate identifiable in some thin sections. Primary minerals and relict textures are rare but the serpentinites were probably once peridotites. The serpentine typically shows cell structures cut by antigorite veinlets. Mesh textures are not outstanding but present in some areas. Rounded, mesh textured balls may have been olivine. The fibrous antigorite formed approximately perpendicular to initial olivine boundaries, radiating from the center of the pseudomorphes. Fibrous antigorite is also found arranged along the cleavages of completely replaced orthorhombic pyroxenes to form bastite (Figure 21). Relict pyroxene cleavages are also delineated by magnetite concentrations in stripes.

Antigorite veinlets traversing the thin sections may be related to a volume increase involved in the serpentinization of olivine-rich rocks. When olivine alters to serpentine, cracks develop in the olivine and surrounding minerals. These cracks are filled with antigorite.

Opaque minerals are irregularly scattered throughout the ultramafics as small blebs and interstitial concentrations. Cubic chromite crystals display reddish centers.

Mixed Terrane (mt)

Tectonic melanges are interpreted as forming at a subduction margin, perhaps as part of an accretionary prism (Moore, 1979).

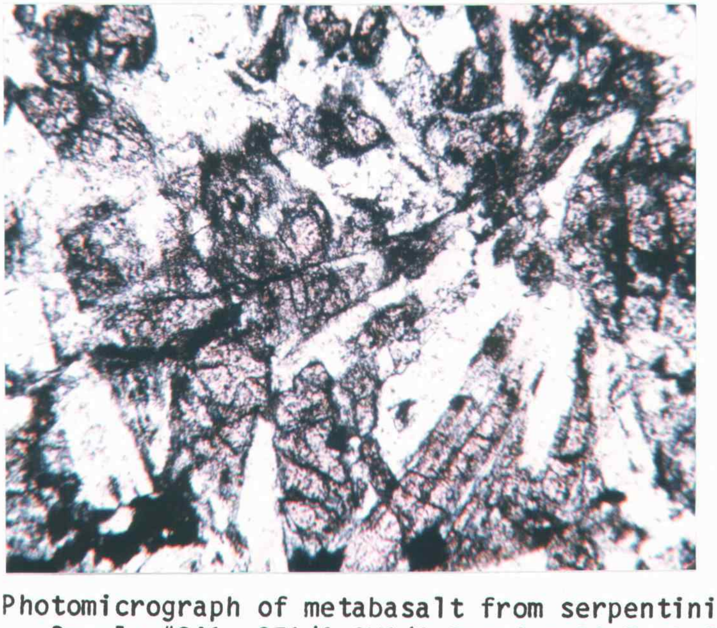
Saleeby (1977) proposed an origin of melanges along transform faults. The thesis area melange may represent a suture zone between island arc rocks to the north and more oceanic rocks to the south. Regardless of the origin of the melange, its presence implies that the emplacement of the ophiolitic rocks was by some kind of plate boundary process. Meta-igneous rocks in the mixed terrane may have been scraped off the descending plate and accreted to the forearc (Vallier, 1983). The relationships of the ultramafics and mixed terrane metagabbros may be gradational but could not be determined with certainty in the thesis area.

In thin section the mixed terrane metagabbros (Figure 17) are highly altered. Original plagioclase crystals have been replaced by epidote, clinozoisite, albite, and carbonate. Primary pyroxene has been replaced by chlorite and a fibrous amphibole.

The mineralogy in one metavolcanic rock from the mixed terrane indicates the original basalt may have been alkalic (Figure 18). Similar greenstones at the east and west extremities of the oceanic/melange terrane may represent accreted seamount volcanics or extensional tectonics (Mullen, 1983). The titanaugite in sample 341 has a small 2V and pink to brown pleochoism. The titanium concentration (Table 7A) is higher than most India greenstones except for sample 205 which is also closely associated with ultramafics even though it is mapped as Pmv. Unfortunately, relict pyroxenes were not noted in 205. Pyroxene composition data from electron microprobe analysis might help determine the original igneous association.

1 mm

Fig. 17. Photomicrograph of metagrabbro cumulate from mixed terrane (mt). Sample #342, SE1/4 SW1/4 Section 24 T. 8 S., R. 34 E. Plagioclase veinlet cutting across center of picture has a mosaic texture from recrystallization. Highly birefringent mineral is amphibole-pseudomorphous after clinopyroxene. Field of view is approximately 7.5 mm. (Crossed nicols)



.25 mm

Figure 18. Photomicrograph of metabasalt from serpentinite-matrix melange (mt). Sample #341, SE1/4 SW1/4 Section 24 T. 8 S., R. 34 E. Lath-shaped plagioclase crystals are partially included in titanaugite crystals forming an ophitic texture. Similar alkalic basalts are common in back arc basins (Batiza, 1977). Field of view is approximately 2 mm. (Plane light)

The ophitic texture of sample 341 suggests that pyroxene crystallized early along with plagioclase. This sequence of crystallization is typical of ocean ridge and intraplate basalts. In contrast, the intergranular texture common in the India greenstones is characteristic of island arcs. Another metabasalt from the mixed terrane (#332) displays a relict felty texture - similar to the India greenstones. Both 332 and 341 contain abundant epidote, clinozoisite and chlorite.

GRANITIC INTRUSIVES

Mesozonal granitic intrusives are exposed in about ten percent of the thesis area. Most of the exposures occur along Granite Creek in the southeast corner of the map area and for purposes of this study will be referred to informally as the Granite Creek stock. A granitic boss about 0.5 km in diameter was discovered 3.5 km north of the Granite Creek stock. This smaller pluton is here informally named the Blackwell stock. The Granite Creek and Blackwell stocks are parts of a northeast-trending belt of Upper Jurassic quartz diorite-granodiorite intrusions in the Blue Mountains.

The Granite Creek and Blackwell stocks resemble the composite intrusive of the Bald Mountain Batholith (Taubeneck, 1957) in texture and composition. The Monumental salient of the Bald Mountain Batholith intrudes pre-Tertiary country rock 9 km east of the thesis area. The first mention of the Bald Mountain Batholith was by Lindgren (1901). He called it granodiorite and named the pluton after Bald Mountain. Bald Mountain has since been renamed Mount Ireland. Granitic stocks in the study area are probably satellites, closely related in age and origin to the Bald Mountain Batholith.

The regional tectonic phenomena responsible for emplacement of the Jurassic and Cretaceous plutonic rocks of northeastern Oregon are poorly understood. Taubeneck (1957) reported a calc-alkaline differentiation trend for the Bald Mountain Batholith. Calc-alkaline magma is most prevalent in island and continental arcs (Miyashiro, 1974).

Taubeneck (op cit.) found eight phases in the Bald Mountain Batholith from norite to quartz monzonite with tonalite predominant. Field and petrographic observations indicate that at least three plutonic rock types are associated with the granitic rocks in the study area. The major rock types are quartz diorite and tonalite, but compositions range from mafic quartz diorite to granite. The granitic rock is equigranular, medium-grained, and nonfoliated. Xenoliths and schlieren are abundant near the contacts with the country rocks. Contacts with the country rock are sharp except where forcible intrusion brecciated the wall rocks. Contacts appear to be vertical. Mineralogy, texture, contact metamorphism, peripheral dikes, and the abundance of xenoliths indicate emplacement of the plutons as a magma.

The granitic intrusions truncate all pre-Tertiary units. Clarno-equivalent basalt flows overlie the Granite Creek stock. Spheroidal weathering and weak, north-south, vertical joint systems are common.

Large, rounded, granitic boulders up to four meters in diameter are common near the contact with the Tertiary basalt. Some of the boulders appear entirely separated from the bedrock. These rocks may be core-stones formed during intense weathering by penetration of acidic ground water along joint systems before deposition of the basalt. The climate during Clarno deposition (Eocene-Oligocene) was subtropical to tropical (Baldwin, 1981). A thick layer of gruss overlies the granitic rocks in some areas near the contact with the basalt, and may represent an Eocene paleosol. A granitic dike that intrudes the country rock and is exposed along Forest Service road 060, just below the basalt contact, has apparently been baked by the lava.

Field and petrographic data suggest at least three units are exposed in the Granite Creek stock. The informal units apparently form a mafic-to-felsic sequence: 1) mafic quartz diorite, 2) quartz diorite-tonalite, and 3) granite. Poor exposure prevented the mapping of each individual unit. Contacts between the different phases of the intrusive sequence are generally sharp, suggesting the older units were already cooled when the younger phases were emplaced. Younger intrusive units have brecciated preceding phases within the pluton. The mafic to felsic emplacement sequence observed in the Granite Creek stock is typical of Mesozoic composite batholiths throughout the Western Cordillera (Carmichael et al., 1974).

Age of Granitic Intrusives

Plutons similar to the Granite Creek stock in northeastern Oregon and extreme western Idaho have been radiometrically dated and most yield ages in the 145 to 161 million year old range. These include the Bald Mountain Batholith and Wallowa Batholith in Oregon and the Peck Mountain Complex and the Deep Creek stock in Idaho (Armstrong et al., 1977). However, younger dates have been reported; for example, 120 ± 6 million years for similar rocks in the Ironside Mountain Quadrangle southeast of the thesis area (Thayer and Brown, 1964). The age of the Granite Creek stock and Blackwell stock is tentatively dated Late Jurassic.

Mafic Quartz Diorite of the Granite Creek Stock

Field relations indicate that the earliest intrusive phase associated with the Granite Creek stock is a mafic quartz diorite, which is exposed along the western margins of the pluton. In hand sample, the mafic quartz diorite is darker than the quartz diorite and tonalite that surround it. Dark xenoliths in the quartz diorite and tonalite close to the contact were probably derived from the mafic quartz diorite.

In thin section, this early phase is a hypidiomorphic-granular, medium-grained, hornblende and biotite-bearing, mafic quartz diorite. Major minerals include plagioclase (An_{60-37}), hornblende, biotite and enough interstitial quartz to make the rock a quartz diorite instead of a diorite. Accessory minerals are apatite, sphene, zircon, and opaques. Plagioclase crystals very commonly display a blotchy extinction pattern. A mode of a mafic quartz diorite, sample #133, appears in Table 3.

Quartz Diorite-Tonalite Unit of the Granite Creek Stock

Quartz diorite and tonalite form the bulk of the Granite Creek stock. Dark bands of hornblende and biotite, resembling gneissic layers, are observed locally in the field and are probably flow structures.

The rocks of the quartz diorite - tonalite series contain plagioclase (An_{51-21}), quartz, biotite, and hornblende as primary minerals. Potassium feldspar and chlorite may or may not be present. Common accessory minerals include zircon, sphene, apatite, and iron oxides. Modes for the series are presented in Table 3B.

In thin section, plagioclase is generally subhedral and commonly displays distinctive oscillatory zoning. Cores are more calcic (up to An_{51}), and altered in some samples to clay, but the rims are fresh. Thin jackets of untwinned oligoclase (as sodic as An_{21}) were noted surrounding plagioclase crystals in some sections. Fractures in the plagioclase locally contain oligoclase stringers in continuity with the oligoclase mantle. Chlorite and sericite also occur in crosscutting fractures within the plagioclase crystals.

Potassium feldspar commonly fills the interstices between the other minerals, but generally accounts for less than two percent of the rock by volume.

Biotite occurs as subhedral laths and shows crystalline boundaries against later crystallized minerals: quartz, potassium feldspar, and some plagioclase. These biotite books are commonly strained or altered to chlorite. Biotite also occurs as a later mineral, forming fresh shreds and stringers interstitial to other minerals. Biotite commonly contains euhedral quartz, apatite, and zircon inclusions (see Figure 20).

Hornblende is usually green with a 2V of about 75-80. Amphibole began to crystallize after formation of the calcic plagioclase cores,

TABLE 3A. JURASSIC INTRUSIVE SAMPLE NAMES AND LOCATIONS FOR MODES OF JURASSIC INTRUSIVES.

9	Granite	NW1/4	NW1/4	Sec.	28	T.8S	R.35E
57A	Granodiorite	Sw1/4	NW1/4	Sec.	28	T.8S	R.35E
67	Tonalite	SW1/4	SE1/4	Sec.	29	T.8S	R.35E
131	Tonalite	SE1/4	NW1/4	Sec.	29	T.8S	R.35E
58	Quartz Diorite	NW1/4	SW1/4	Sec.	28	T.8S	R.35E
59	Quartz Diorite	SW1/4	SW1/4	Sec.	28	T.8S	R.35E
99	Quartz Diorite	Center		Sec.	29	T.8S	R.35E
133	Mafic Quartz Diroite	SE1/4	NE1/4	Sec.	30	T.8S	R.35E
118	Tonalite-Blackwell Stock	SE1/4	NW1/4	Sec.	9	T.8S	R.35E
385	Tonalite-Blackwell Stock	NW1/4	SE1/4	Sec.	9	T.8S	R.35E

TABLE 3B. MODES OF JURASSIC INTRUSIVES

Sample no.	133	58	59	99	67	131	9	57A	118	385
Plagioclase	50.0	55.7	60.9	54.3	47.5	50.5	33.4	45.8	45.3	41.8
Quartz	6.4	12.8	13.6	12.1	27.1	30.2	37.1	23.8	23.0	26.4
Orthoclase	---	1.2	1.1	0.3	1.8	0.2	22.6	20.2	---	---
Biotite	7.0	8.7	14.6	14.6	12.7	11.8	5.7	8.0	15.5	12.3
Hornblende	31.4	19.9	8.1	11.7	9.9	3.9	---	---	12.7	18.0
Apatite	0.1	0.2	0.4	0.5	tr	0.3	0.1	tr	---	---
Zircon	0.1	0.1	tr	tr	---	---	0.1	0.1	tr	---
Opaques	1.2	0.3	0.2	2.2	tr	1.3	---	tr	1.2	0.6
Clays	1.0	0.1	0.7	0.9	0.6	0.8	0.9	1.0	1.3	0.7
Chlorite	2.7	0.1	0.1	2.3	0.2	---	0.1	1.1	0.2	tr
Other Accessories*	---	0.7	0.1	0.2	---	0.6	---	---	0.5	---
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Modes based on at least 1,000 points.

*Other accessories include zeolite, epidote, calcite, and tourmaline.

133	Mafic Quartz Diorite unit of the Granite Creek Stock
58,59,99 67,131	Quartz Diorite-Tonalite unit of the Granite Creek Stock
9,57A	Granite unit of the Granite Creek Stock
118,385	Tonalites from the Blackwell Stock

but shows euhedral crystal boundaries with later plagioclase. Some hornblende crystals were probably partially resorbed after crystallization because they are embayed by later quartz and potassium feldspar.

Quartz is generally an interstitial mineral and commonly maintains a constant crystallographic orientation throughout small sections of a slide. That is, seemingly isolated 'islands' of quartz will go extinct at the same time. This optical continuity indicates a late stage silicic liquid crystallized after most of the magma had solidified. Potassium feldspar crystallization generally preceded formation of quartz.

Zircon forms short, clear to faint brown prisms associated with biotite or iron ores (Figure 20). Apatite occurs as swarms of tiny (.01-.03 mm), elongate, euhedral prisms within quartz or plagioclase. Small, grayish blue, prismatic crystals of tourmaline were noted in two sections, partly clumped into aggregates. Iron ores are the most common accessory and commonly follow the cleavage traces of the mafic minerals they replace.

Granite Unit of the Granite Creek Stock

The youngest intrusive phase of the Granite Creek Stock consists of granite and granodiorite and is informally named the granite unit. In the field, granite unit rocks are lighter colored than the quartz diorite and tonalite they intrude. In

Figure 19. Metabasite xenoliths in quartz diorite of the Granite Creek stock.

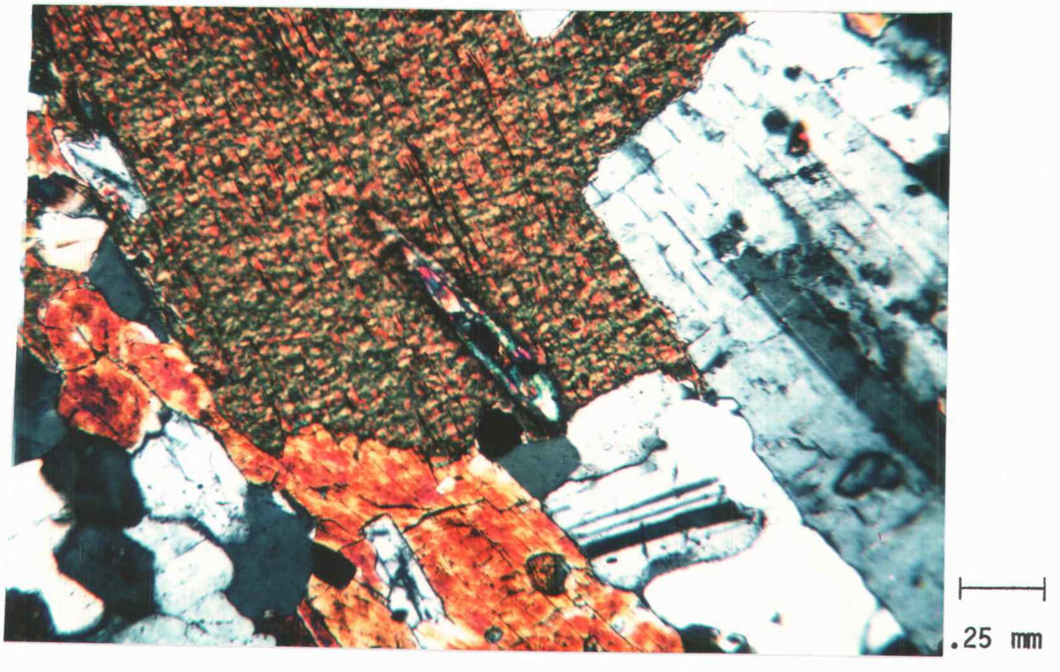


Figure 20. Large, elongate, radiogenic zircon subparallel to the 100 cleavage of a biotite in quartz diorite of the Granite Creek stock (Ji); sample #58, NW1/4 SW1/4 Section 28, T. 8 S., R. 35 E. Plagioclase, quartz, and hornblende are also present. Field of view is approximately 2 mm (crossed nichols).

thin section, granite unit rocks lack the hornblende so common in the earlier phases. Abundant potassium feldspar also distinguishes granite unit rocks from the more mafic phases.

Modes for two granite unit rocks appear in Table 3B. Plagioclase (An_{35-22}) can be surrounded by orthoclase. Some replacement of plagioclase by potassium feldspar is evident, forming antiperthite. Unmixing structures were noted but are not common. String-type perthitic lamellae and micro-perthite are present in the K-feldspars. Myrmekite is found along some of the boundaries of the potassium feldspar with plagioclase and quartz.

Plagioclase contains more clays than the generally less altered orthoclase. Biotite altered to chlorite is commonly associated with orthoclase.

Accessary minerals include small apatite needles. Zircon was also noted.

Blackwell Stock

The Blackwell stock is a small intrusive mass exposed north of the North Fork of the John Day River, immediately west of McCarty Gulch. The intrusion is informally named for the Blackwell Trail which is shown on the 1953 Desolation Butte Quadrangle as traversing the Blackwell stock. This part of the Blackwell Trail could not be located, but Forest Service trail 6141 passes west of the intrusion. The relationship of the Blackwell stock to the Granite Creek stock is not known. In the field, the rock appears finer grained than the

Granite Creek stock, has white plagioclase phenocrysts, and could be called a porphyritic tonalite. The contact of the intrusion with the surrounding argillite is not well exposed but contact metamorphism appears slight.

In thin section, the main intrusive rock of the Blackwell stock is a fine- to medium-grained, porphyritic, hornblende-biotite tonalite. The major mineral phases are plagioclase (An_{42-29}), bleached hornblende, biotite, and quartz. Accessory phases include sphene and euhedral magnetite octahedrons. Alteration is indicated by the replacement of biotite by chlorite. The replacement of hornblende by biotite was probably a magmatic reaction. Clays are common in the plagioclase crystals and zeolite and epidote also were noted. Modes for samples #118 and #385 (Table 3B) are from the Blackwell stock. Major oxide analysis for #385 appears in Table 4.

Rounded plagioclase glomerocrysts, up to 5 mm in diameter, are set in a groundmass of quartz, plagioclase, biotite, and hornblende crystals that are generally 0.5 to 1 mm in diameter. Plagioclase displays intricate oscillatory zonation from An_{42} to An_{29}. Patchy zoning in the plagioclase glomerocrysts may crosscut earlier truncated zoning indicating multiple episodes of resorption and re-equilibration in the magma.

Hornblende in the Blackwell stock is commonly twinned and is generally more altered than that in the Granite Creek stock. In places hornblende is almost completely replaced by chlorite, biotite, calcite, and iron oxide - commonly rimmed by sphene.

TABLE 4. CHEMICAL ANALYSES OF JURASSIC INTRUSIVES

Samples	57A	67	385
SiO_2	73.17	64.68	65.49
Al_2O_3	14.25	16.12	15.09
TiO_2	0.27	0.68	0.58
CaO	1.68	4.84	5.57
Fe*O	2.58	5.53	5.32
Na_2O	3.62	3.59	3.00
K_2O	3.72	2.33	1.56
MgO	0.58	1.97	3.17
MnO	0.05	0.11	0.09
P_2O_5	0.08	0.14	0.13
Sum	100.00	99.99	100.00

57A Granodiorite from Granite Creek stock.
SW1/4 NW1/4, Section 28, T. 8 S., R. 35 E.

67 Biotite-hornblende tonalite from Granite Creek stock.
SW1/4 SE1/4, Section 29, T. 8 S., R. 35 E.

385 Hornblende-biotite tonalite from Blackwell stock.
NW1/4 SE1/4, Section 9, T. 8 S., R. 35 E.

Titanium may have been released from the hornblende by chloritization and then nucleated on the magnetite.

Contact Metamorphism

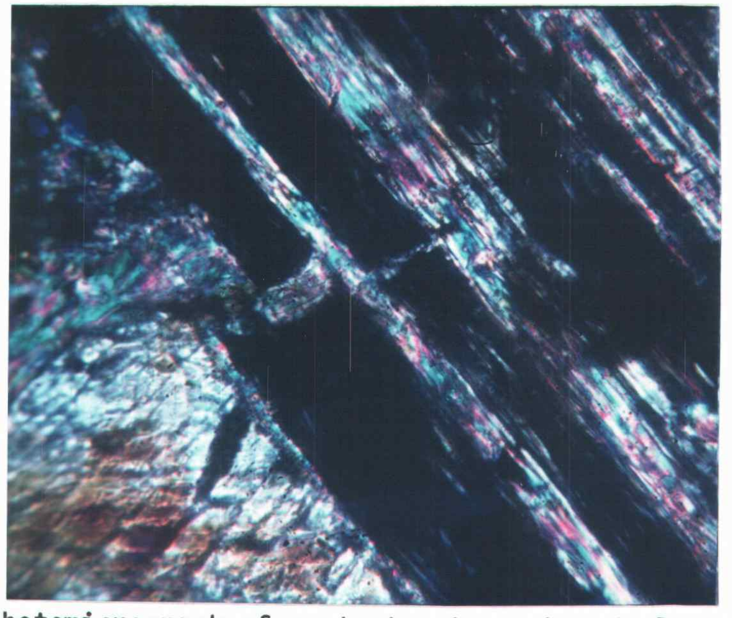
Intrusion of the Jurassic granitic plutons has affected the country rocks up to two kilometers from the contact. A contact metamorphic aureole of hornblende-hornfels facies is superimposed upon the greenschist facies of regional metamorphism.

The amphibolites found close to the contact probably were once volcanic or volcaniclastic rocks that have since been completely recrystallized. They display no relict textures. Quartz poikiloblasts enclose andesine, hornblende, biotite, clinopyroxene and iron oxides. Quartz and plagioclase are intermixed in granoblastic textures. Only one section contains abundant clinopyroxene (diopside) - a gneissic rock a few meters from the contact. One section taken from the contact lacks orthopyroxene so it is possible that pyroxene hornfels conditions were ever attained.

The argillite unit rocks have been less affected by contact metamorphism than the greenstones. Cherty rocks show coarser recrystallization as the contact with the granitic rocks is approached. The matrix has apparently altered to muscovite and chlorite. Granoblastic textures and granophyric intergrowths of quartz and plagioclase near the contact indicate recrystallization.

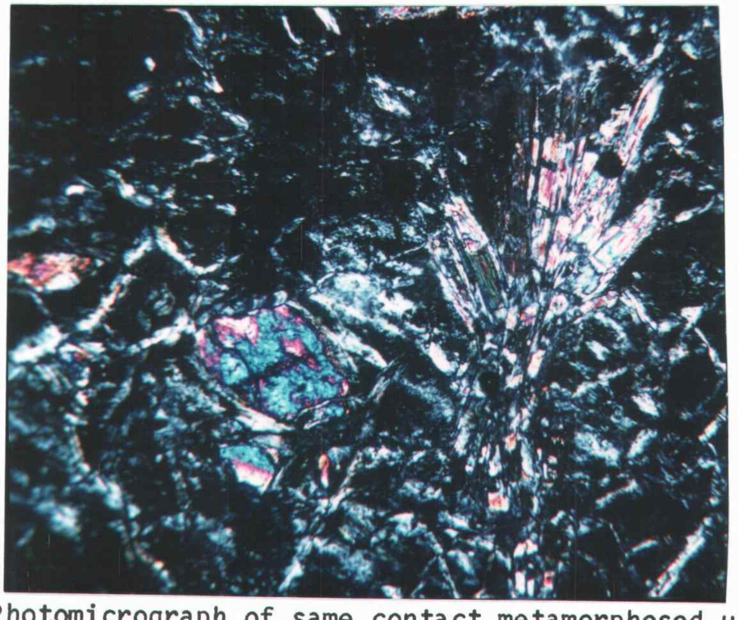
Farther from the contact biotite crystals are smaller and lighter colored. The outer zones of the contact aureole contain cummingtonite and lack the epidote so common in the regional terrane. The scarcity of biotite and metamorphic hornblende in areas not affected by plutonism suggests a low-temperature greenschist facies of regional metamorphism.

Contact assemblages (Figures 21 and 22) in ultramafic rocks suggest metamorphic intensities of the hornblende-hornfels facies.



.05 mm

Figure 21. Photomicrograph of contact metamorphosed ultramafic rock from serpentinite (sp) unit, sample #94, center of section 29, T. 8 S., R. 35 E. Magnesio-cummingtonite in lower left shows faint amphibole cleavage. Bastite that predominates in center of photo may be pseudomorphous after pyroxene. Antigorite and talc are also present. Field of view is approximately 0.5 mm. (crossed nicols)



.25 mm

Figure 22. Photomicrograph of same contact metamorphosed ultramafic rock shown above, sample #94. Relict olivine crystal in left center is fairly clear and clean. Radiating tremolite and olivine are surrounded by chrysotile and antigorite. Field of view is approximately 2 mm. (crossed nicols)

TERTIARY VOLCANICS (Tb)

Dark gray, olivine-bearing, vesicular basalt mapped as Tb crops out in the study area only in the southeast corner. Similar basalts are present in the center of section 5, T. 8 S., R. 35 E., just north of the map area. The fine-grained, porphyritic basalt weathers to grayish orange or dark reddish brown. Zeolite filled amygdules are clearly visible. Prominent outcrops are absent but the basalt is well exposed in the road cuts of Forest Service road 1035. The area mapped as Tb is characterized by subrounded basalt cobbles and boulders on reddish soils. Semi-consolidated, tuffaceous gravels were noted in the float but were not seen in outcrop. Some larger fragments of this light-colored, angular conglomerate can be found along the dead-end Forest Service road 060 in the southwest part of section 21, T. 8 S., R. 35 E.

Tertiary basalts buried an irregular pre-Tertiary erosion surface. The thickness of the basalt is approximately 35 meters. Exposure is on a dip slope so thickness does not have to be great in order to account for the extent of the exposure. The basalt unconformably overlies rocks of the Granite Creek stock and metamorphic rocks of the pre-Tertiary. Similar basalts are associated with volcaniclastics, silicic flows and tuff in the Granite Quadrangle just east of the map area (Brooks et al., 1982) and overlie mudflows, tuffs and ignimbrites in the Greenhorn Mountains to the south (Mullen, 1978).

Tertiary volcanics in the area were mapped as Clarno Formation on the Geologic Map of the Canyon City Quadrangle (Brown and Thayer, 1966). Work done in this study supports Brown and Thayer's interpretation that the flows are Eocene in age. An abundance of secondary carbonate and the relatively high degree of alteration present in the basalts of the study area indicate they are not members of the Columbia River Basalt Group. Two major element chemical analyses were obtained on basalts from the map area and are presented in Table 5 along with typical Columbia River Basalt and John Day basalt chemistry. Details are discussed in a later section but the analyses indicate basalts in the study area differ from basalts of the John Day Formation, which is exposed west of the map area. Mafic flows from the Oligocene to Miocene John Day Formation are all low silica, silica-undersaturated alkali-olivine basalts with high titania (Robinson and Brem, 1981). Olivine basalts in the study area are low in iron, P_2O_5, and TiO_2 relative to mafic lava flows of the John Day Formation. Similarities in the major element chemistry of the Clarno Formation and basalts in the study area can be seen on the Harker diagrams in Figure 23.

The Eocene Clarno Formation is the lowermost Tertiary rock unit of north-central Oregon. The Clarno Formation crops out over a large area in central Oregon and the western Blue Mountains. The Clarno Formation is predominantly volcanogenic and stratigraphic relationships are complex. Oles and Enlows (1971) elevated the Clarno rocks near Mitchell to group status, with two dissimilar rock

TABLE 5. CHEMICAL ANALYSES OF TERTIARY VOLCANICS (Tb)

Sample	71	73	Picture Gorge*	John Day**
SiO_2	51.75	49.38	50.47	46.05
Al_2O_3	13.56	17.57	15.00	15.72
TiO_2	1.26	1.35	1.72	4.02
CaO	8.96	10.18	9.59	7.32
Na_2O	2.98	2.94	3.03	3.80
K_2O	0.89	0.31	0.76	1.65
Fe*O	9.44	9.98	12.23	16.88
MgO	10.64	7.95	5.54	3.73
MnO	0.14	0.15	0.22	0.15
P_2O_5	0.38	0.21	0.26	0.68
Total	100.00	100.02	100.14	100.00

71 Olivine Basalt, Clarno-equivalent.
NE1/4 SE1/4, Section 28, T. 8 S., R. 35 E.

73 Basalt, Clarno-equivalent.
NE1/4 SW1/4, Section 28, T. 8 S., R. 35 E.

* Average Picture Gorge, Columbia River Basalt Group.
See McDougal, 1976.

** Average of two analyses in Lower Member, eastern facies John Day Formation. See Robinson and Brem, 1981.

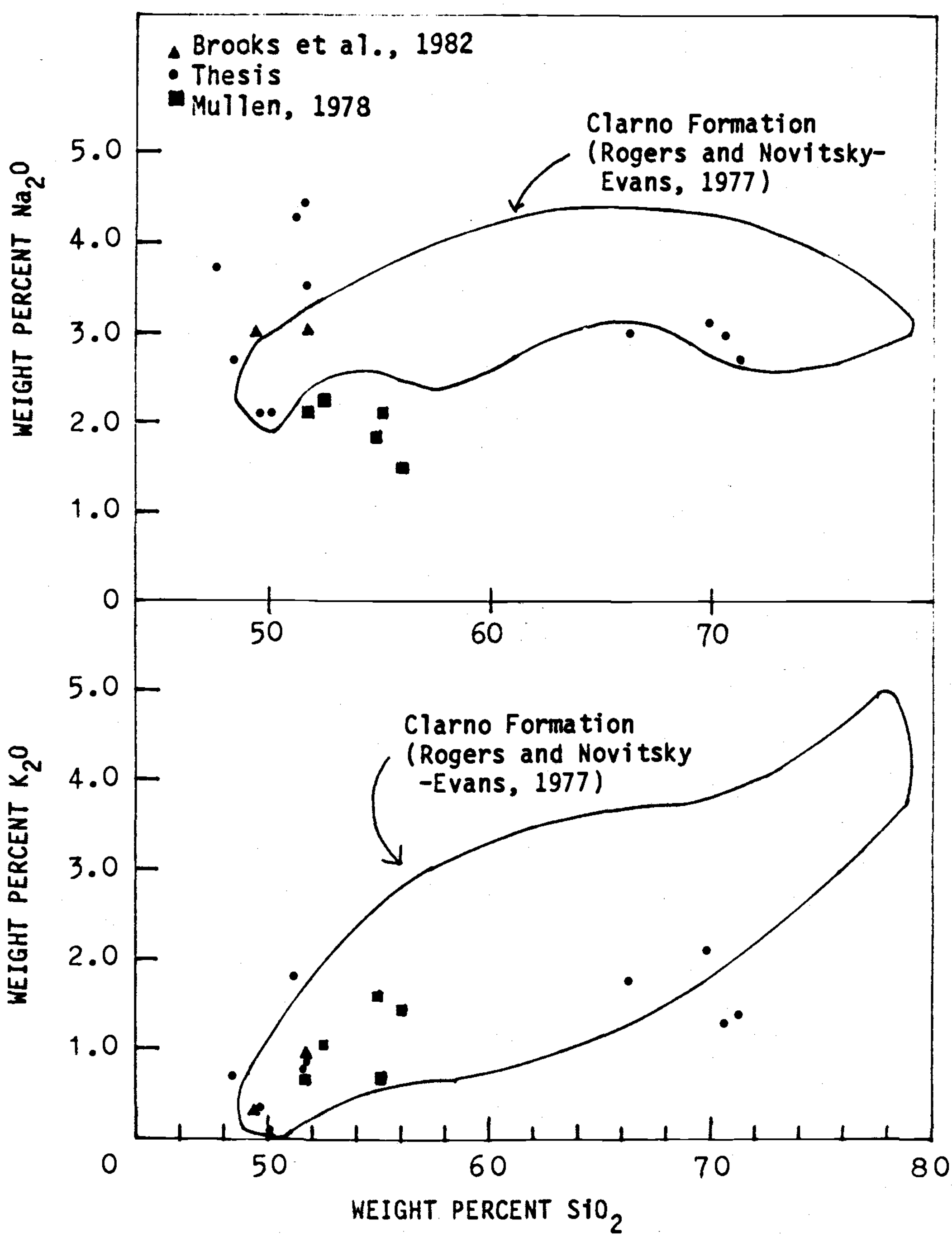


Figure 23a. Harker diagrams of Na_2O and K_2O in Clarno-equivalent volcanics (Tb) from the thesis area, Greenhorn Mountains and the Granite Quadrangle. Distribution of Clarno Formation is outlined (Rogers and Novitsky-Evans, 1977).

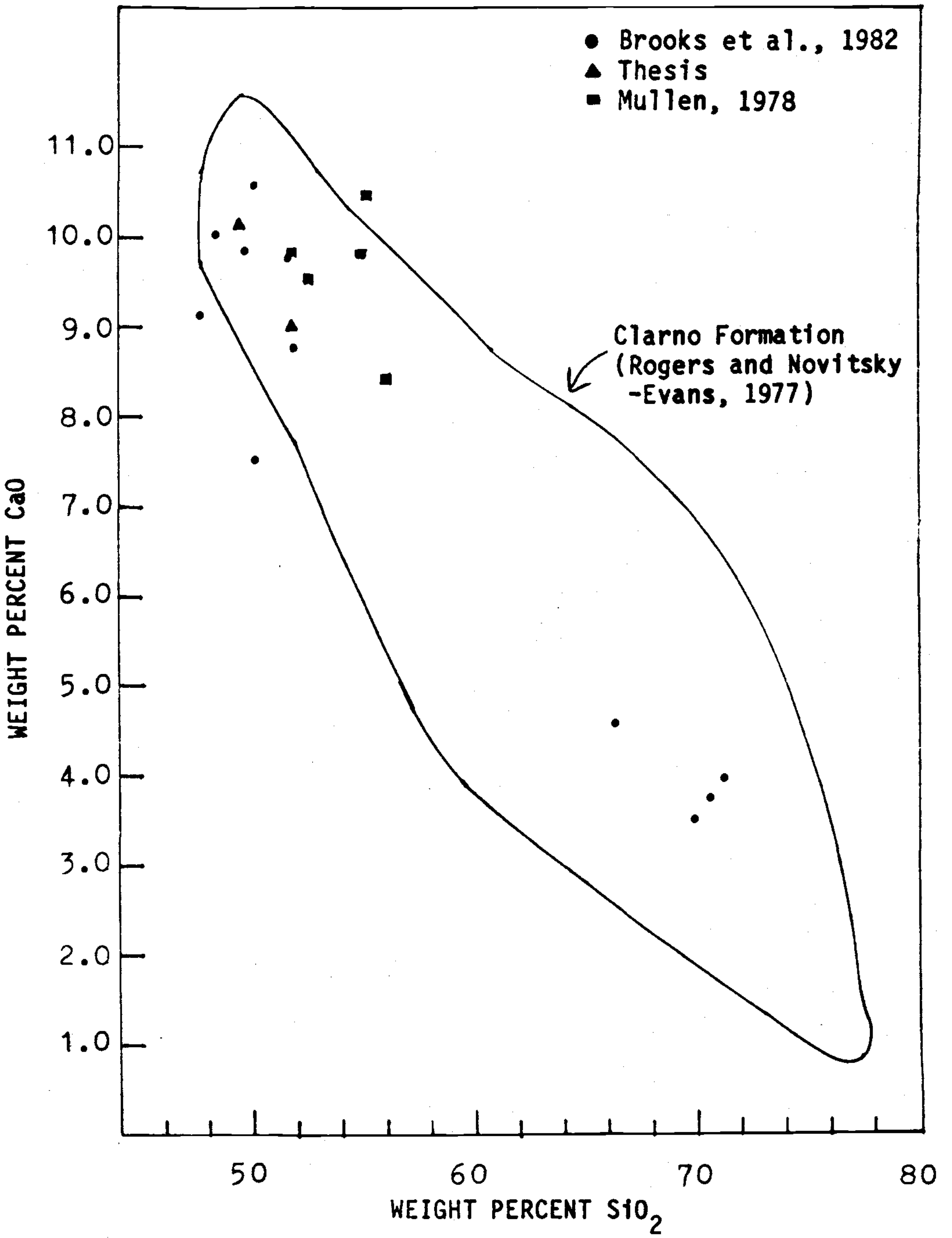


Figure 23b. Harker diagram of CaO in Tertiary volcanics (Tb) from the thesis area, Greenhorn Mountains, and the Granite Quadrangle.

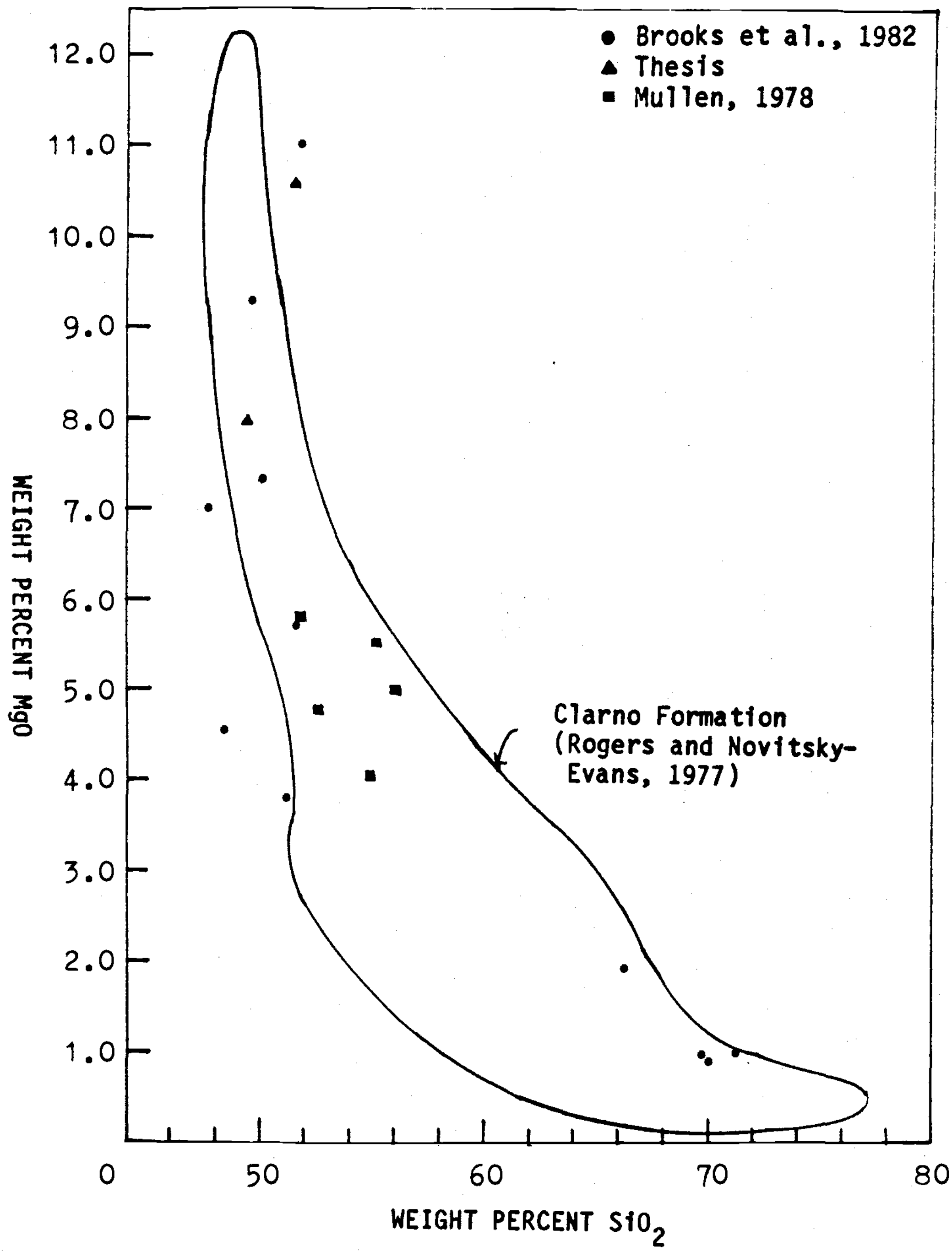


Figure 23c. Harker diagram of MgO in Tertiary volcanics from this thesis and nearby areas.

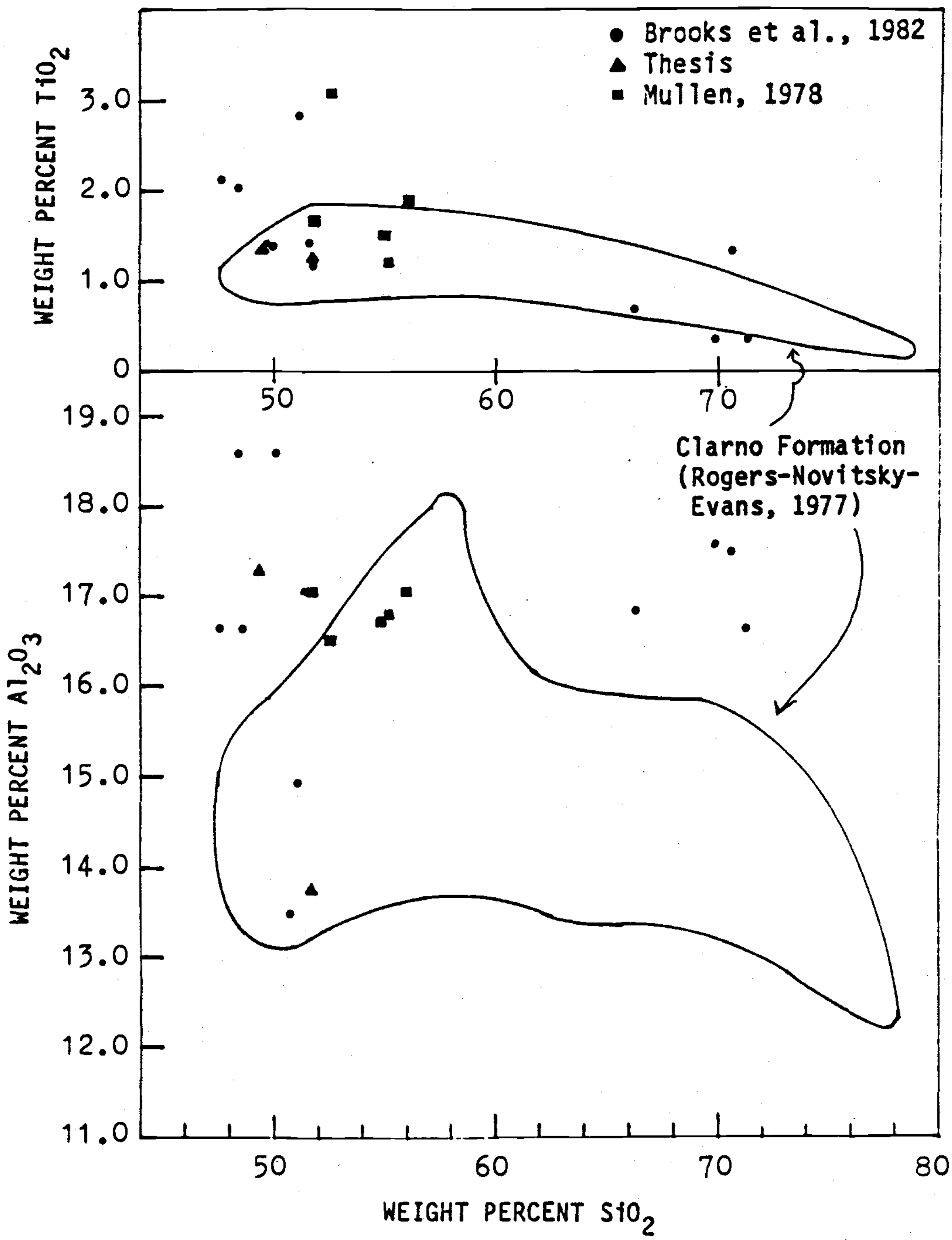


Figure 23d. Harker diagrams of Al_2O_3 and TiO_2 in Clarno-equivalent volcanics. Distribution of Clarno Formation is outlined (Rogers and Novitsky-Evans, 1977).

sequences separated by an angular unconformity. Outside the Mitchell area, mappable subdivisions are not formally defined so the entire Clarno is referred to as a formation in this paper. Clarno rocks throughout north-central Oregon are dominantly andesites, although mafic to silicic members are common. Rogers and Novitsky-Evans (1977) concluded that the Clarno Formation was formed on thin continental crust from magmas derived about 120 km deep above a subduction zone dipping to the east.

Petrography

Clarno-equivalent basalts are pilotaxitic to intergranular. The angular interstices between plagioclase microlites are occupied by clinopyroxene and iron-titanium oxides. Good ophitic textures are common. Alteration products in the basalt include smectites, chlorite, calcite, zeolites, prehnite, and iron oxides. Modes for two Clarno-equivalent basalts are presented in Table 6.

Olivine is present as phenocrysts ranging from 1-3 mm in diameter. The olivine is optically positive with a large 2V of about 85^{o}. The olivine is extensively altered to bowlingite, iddingsite, and iron oxides. In sample 71 the olivine has been completely pseudomorphed by alteration products. Groundmass olivine is not common. Orthopyroxene was not noted. A few small, embayed augite and diopsidic augite phenocrysts are present.

Plagioclase phenocrysts and groundmass are euhedral to subhedral. Plagioclase composition ranges from labradorite to

TABLE 6. MODES OF CLARNO-EQUIVALENT BASALTS (Tb)

Sample number	73	74
Plagioclase	62.2	59.3
Olivine	0.2	5.0
Clinopyroxene	25.6	23.1
Opaque	1.6	3.3
Apatite	---	0.2
Glass	---	0.1
$CaCO_3$	1.2	0.7
Alteration products*	9.2	8.3
Sum	100.0	100.0

Sample 73 NE1/4 SW1/4, Section 28, T. 8 S., R. 35 E.

Sample 74 SW1/4 NW1/4, Section 28, T. 8 S., R. 35 E.

* Alteration products include iddingsite, bowlingite, smectites, chlorite, calcite, zeolites, prehnite, and iron oxides.

.25 mm

Figure 24. Photomicrograph of Clarno-equivalent olivine basalt, (Tb) sample #74 from SW1/4 NW1/4, Section 28, T. 8 S., R. 35 E. Phenocryst on the right is olivine altering to iddingsite. On the left, plagioclase microlites are partly enclosed by clinopyroxene to form a subophitic texture. The green material is a clay mineral. Field of view is approximately 2 mm. (Plane light).

andesine, with An_{51} as an average. Plagioclase phenocrysts display a faint normal zoning. Most phenocrysts are elongate and range in size from 2-5 mm long. Plagioclase microlites are generally less than 1 mm long.

Chemistry

The major element chemistry of basalts in the thesis area was compared with analyses of Clarno-equivalent dikes and flow rocks from the Greenhorn Mountains (Mullen, 1978) and analyses of Tertiary volcanic rocks from the adjacent Granite Quadrangle (Brooks et al., 1982). On the basis of leaf fossils, Tertiary volcanics from the Granite Quadrangle are considered to be Clarno-equivalent or slightly older, that is early Oligocene to early middle Eocene (Brooks et al., 1982). Six of the seven analyses from the Granite Quadrangle are from within eight km of the study area. All data plotted are from samples within twenty-five km of each other. Correlation of these samples is not positive and there may exist significant age differences among them. Rock types plotted include basalt, olivine basalt, porphyritic dacites, basaltic andesites, and hornblende rhyodacites. Chemical variation among even the mafic rocks is considerable.

Major element chemistries of the Tertiary volcanics from the Granite Quadrangle, the Greenhorn Mountains, and especially the thesis area are similar to those of the Clarno Formation (Figure 23). However, the rocks generally are higher in alumina than the Clarno

Formation. About half the mafic samples, including number 73 from the thesis area, would be considered high-alumina basalts according to Kuno (1960). High Al_2O_3, 16 to 19%, in mafic to intermediate rocks is a feature of island arc and continental margin igneous rock series (Green, 1980). Total alkali content of the samples plotted is extremely variable. Most of the mafic rocks fall into the mildly alkaline series (Schwarzer and Rogers, 1974). However, silicic rocks from the Granite Quadrangle fall into the subalkaline field. Three basalts from the Granite Quadrangle could be considered strongly alkaline and have high Na_2O contents relative to the Clarno Formation. The Clarno-equivalent rocks from the Greenhorns east of the Granite Quadrangle have low Na_2O contents compared to the Clarno Formation.

The chemical differences and variable frequency distribution of elements found among Tertiary volcanics in the thesis area and nearby volcanics to the south and east suggest the mixing of separate suites. However, if a single suite is represented by the data plotted, that suite would resemble the Clarno Formation in being dominantly calc-alkaline but with some patterns transitional between calc-alkaline and tholeiitic (Rogers and Novitsky-Evans, 1977). Most data points fall below the critical iron enrichment line (Kuno, 1968) on the AFM diagram (Figure 25) and so the suite would match the classical notion of the calc-alkali rock series. However, even the less alkaline samples span the line that separates tholeiitic and calc-alkaline compositions, according to Irvine and Baragar (1971). The moderate K_2O-SiO_2 slope (Figure 23a) is intermediate between

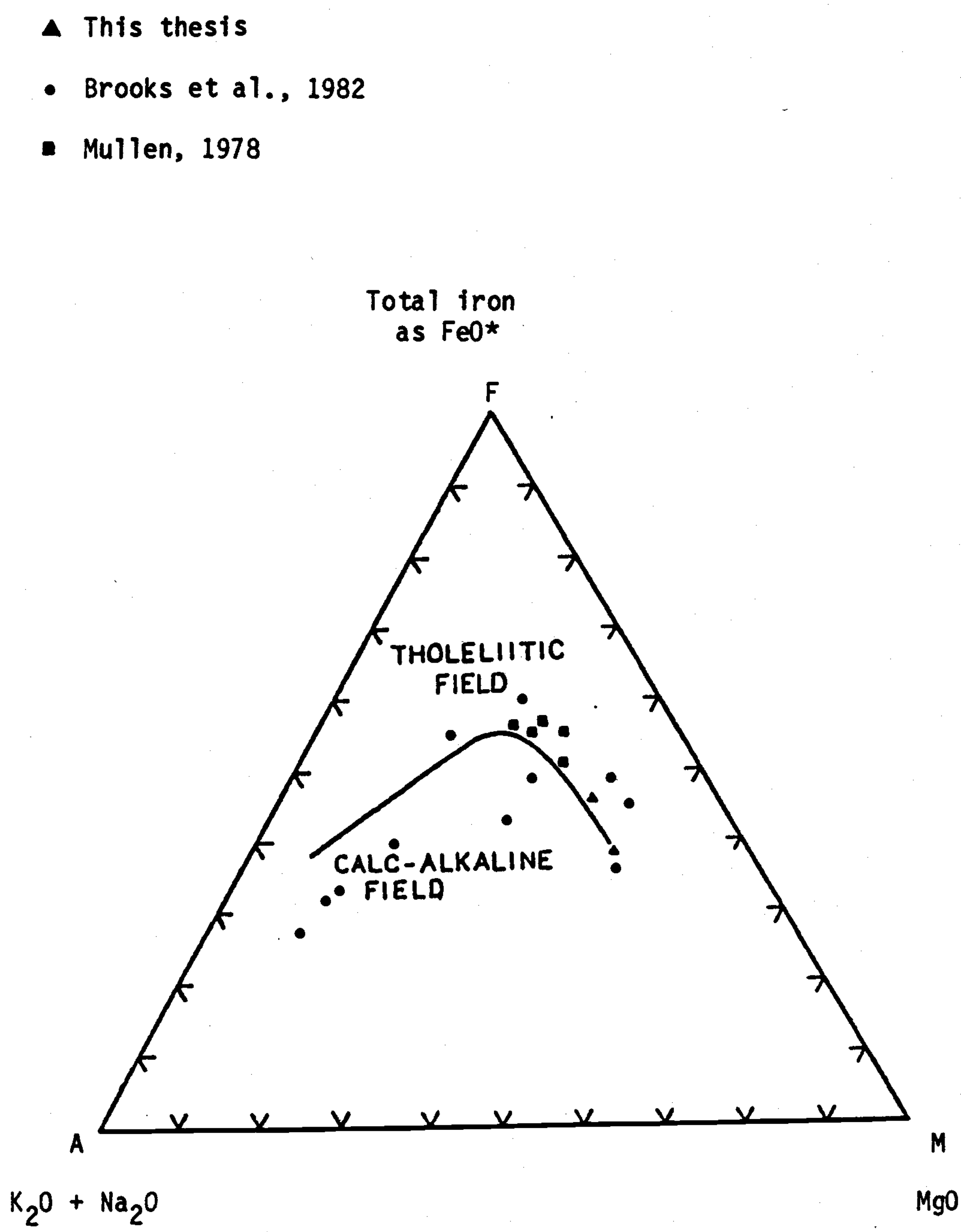


Figure 25. AFM diagram of Clarno-equivalent volcanic rocks from the thesis area and vicinity. F = FeO + 0.9 Fe_2O_3. Line on AFM diagram is from Irvine and Baragar, 1971.

calc-alkaline and island arc tholeiitic trends (Gill, 1970). On the SiO_2-FeO^*/MgO diagram (Figure 26), the mafic samples straddle the line used by Miyashiro (1974) to separate calc-alkalic and tholeiitic fields while the silicic samples fall into the calc-alkaline field. This transitional appearance may represent the mixing of separate calc-alkaline and tholeiitic rocks rather than the intermediate character of a single suite.

Tertiary volcanics in the vicinity of the thesis area display a bimodal distribution of mafic and silicic rocks, generally basalts and dacites. Rocks of intermediate composition appear to be sparse or lacking. Hamilton (1965) called such assemblages bimodal. Similar igneous fields that occur in the western U.S. and other regions of the world are characterized by tectonic extension (Christiansen and Lipman, 1972). Bimodal volcanism was accompanied by normal faulting in the adjacent Granite Quadrangle (Brooks et al., 1982) suggesting an extension took place in this part of the Blue Mountains during the late Eocene. West-to-northwest-trending lineaments visible on aerial photos border the Tb unit on both the north and south and extend into the Granite Quadrangle. If these lineaments are normal faults, then Clarno-equivalent basalts in the thesis area are confined to a graben.

Based on hot-spot data, a decrease in the absolute velocity of the North American upper plate took place about 60 to 30 m.y. ago (Morgan, 1981, Engerbretson et al., 1982). A drop in upper plate velocity can lead to steepened subduction (Cross and Pilger, 1982).

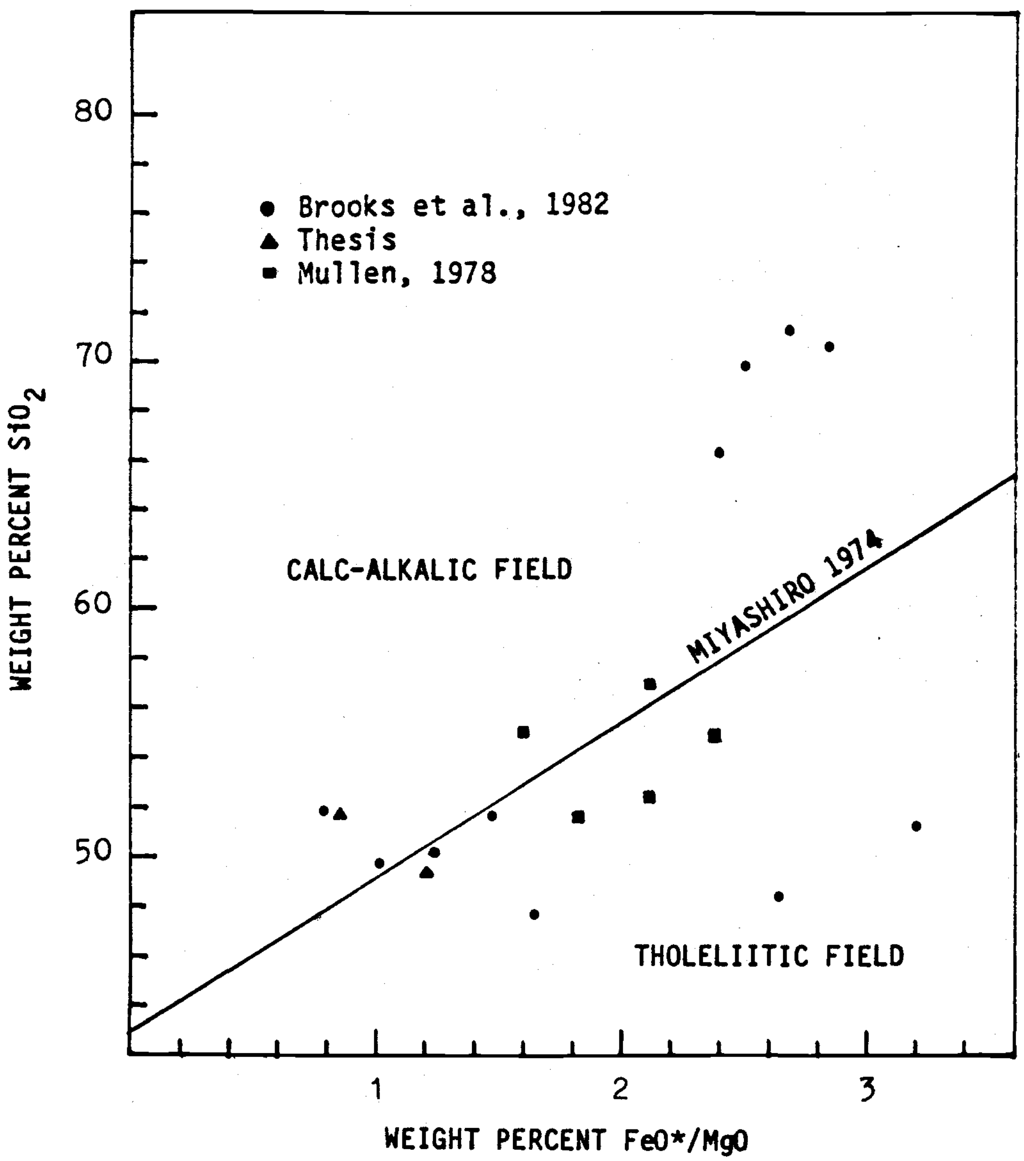


Figure 26. SiO_2FeO*/MgO Diagram for Clarno-equivalent volcanic rock from the thesis area and vicinity.

Heating caused by induced convection from steepened subduction caused volcanism and extension in the northern Great Basin. This back-arc extension began some 40 to 50 m.y. ago. Plate steepening may have introduced hotter mantle material to the lithosphere below the thesis area (Figure 27). The bimodal distribution of the Tertiary volcanics, the ambiguous geochemical features, and normal faulting can be explained by back-arc crustal extension. It is thus conceivable that Eocene extension and volcanism in the thesis area was triggered by steepening of the downgoing Pacific plate.

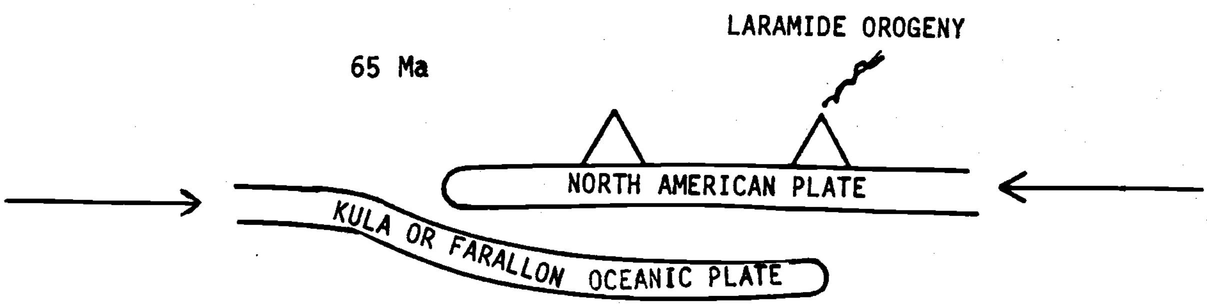


Figure 27a. Rapid convergence rate triggers mountain building as far east as Montana and Wyoming (Engebretson, Cox, and Gordon, 1985).

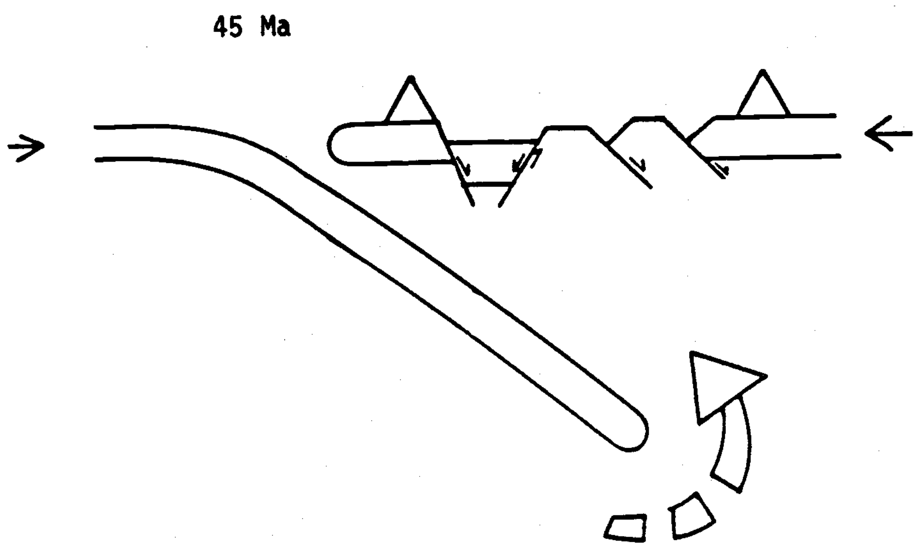


Figure 27b. Convergence rate slows. Subducting plate dives steeply and arc volcanism retreats westward. Hot asthenosphere flows into region above the downgoing slab, possibly causing crustal extension and a short-lived, widespread volcanic episode (Tb).

QUATERNARY DEPOSITS

Surficial Deposits

Thin, poorly sorted stream deposits, extensive enough to be mapped, are restricted to the narrow valley floors of Granite Creek and the North Fork, John Day River. Some small placer gold operations work these unconsolidated silts, sands, and gravels. The gold is fine-grained and apparently concentrated in certain layers. Most of this placer gold was probably derived upstream from the Granite mining district. Streams flowing into Granite Creek and the North Fork, John Day have cut narrow gorges and have deposited only small amounts of alluvium.

Powdery white volcanic ash forms thin layers and lenses as much as 4 m thick. The deposits are exposed mainly in stream valleys, where erosion has concentrated the ash. Notably thick deposits are seen in Bear Gulch, Center of Section 8, T. 8 S., R. 35 E. The thesis area lies along the northeast axis of ash fallout from the explosion of Mount Mazama which formed Crater Lake (Borchart & Norgen, 1973). Borchart and Norgen date ash deposits from the Elkhorn Mountains as 9,460 b.p. and 6,600 b.p. The younger ash is more abundant and correlates with the Mt. Mazama eruption.

A landslide along Granite just east of the study area has developed in the Tertiary basalt. The floor of Granite Creek in Section 28, T. 8 S., R. 35 E. appears to be littered with landslide deposits (Qls). Another landslide was noted along Lake Creek in Sections 25 and 26.

Glacial moraines are common in the Elkhorn and Greenhorn Mountains but glacial deposits were not noted in the thesis area.

ECONOMIC GEOLOGY

Although no lode mineral deposits have been discovered in the field area, the existence of small gold, silver, or copper deposits cannot be ruled out. Mineral production in the thesis area has been restricted to small placer gold claims that are still being mined along Granite Creek and the North Fork of the John Day River. The fine-grained nature of this placer gold suggests that most of it was derived from veins in the Granite mining district to the east. The Granite mining district encompasses the headwaters of Granite Creek and the North Fork, John Day (Koch, 1959). Placers in the region have been worked since 1863 (Lindgren, 1901).

Sixteen hand specimens of metamorphic rock were selected for semiquantitative spectrographic analysis and sent to Specomp Services, Boise Laboratory (Tables 7A,B,C). Most of the samples were cherts or greenstones displaying various degrees of alteration and iron staining. Some of the data on relatively immobile trace elements are discussed elsewhere. In this section, the concentrations of indicator elements that might suggest the presence of a mineral deposit are compared with data in the literature for similar rocks (Rose et al., 1979). On the basis of this simple procedure, some of the rocks apparently are slightly enriched in chalcophile elements and one sample contains anomalous molybdenum (Table 8). Although these patterns could be significant and may be worth further study, conclusions based on this reconnaissance survey should be regarded as preliminary and tentative.

TABLE 7A. SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSIS

Element in %		Fe	Mg	Ca	Ti	Na	K	Si	Al	P
Reference	Rhyolite Porphry	1.5	0.05	0.1	0.3	1.5	5.0	30	7.0	0.1
172	Sheared Greenstone	1.5	0.2	L	0.2	N	1.0	30	5.0	N
205	Metavolcanic Greenstone	10.0	2.0	3.0	G1.0	5.0	1.0	30	7.0	0.2
255	Metavolcanic Greenstone	1.0	0.2	0.07	0.1	L	2.0	30	5.0	N
377	Greenstone	5.0	1.0	3.0	1.0	2.0	1.0	30	7.0	0.2
422	Volcaniclastic Greenstone	2.0	0.5	1.0	0.3	3.0	1.0	G	5.0	0.1
155	Chert	1.5	0.5	0.2	0.2	2.0	1.0	G	7.0	N
318	Chert	1.5	0.3	0.05	0.2	N	0.5	G	2.0	N
355	Brecciated Chert	7.0	0.02	L	0.15	N	N	30	1.0	N
356	Cherty Argillite	1.0	0.07	L	0.03	N	N	G30	N	N
396	Cherty Argillite	1.0	0.03	0.07	0.03	3.0	0.5	g	7.0	N
307B	Metagabbro	1.5	5.0	2.0	0.07	5.0	N	30	3.0	N
338	Serpentinite	2.0	10.0	L	0.001	N	N	25	N	N
341	Metavolcanic	5.0	2.0	5.0	1.0	N	N	25	N	N
342	Metagabbro	3.0	3.0	2.0	0.15	3.0	1.0	30	5.0	N
Lower Detection Limit		0.05	0.02	0.05	0.001	0.2	0.5	1	0.5	0.1

N-Not Detected L-Detected, but below limit of determination G-Greater than value shown
Instrument: Wadsworth mounted, Jarrel-ash 1.5 meter DC Arc Emission Spectrograph.
Analysis by Specomp Services, Boise Laboratory.

TABLE 7B. SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSIS

Element in PPM		Au	Ag	Cu	Pb	Zn	Mo	Ni	Co	Cr	Mn	V	Sn
Reference	Tertiary	N	2	50	100	200	N	50	10	100	700	100	N
172	Pmv	N	0.2	70	15	N	5	5	N	N	500	100	N
205	Pmv	N	5	150	70	200	N	70	50	N	1000	200	N
255	Pmv	N	N	50	50	200	L	10	N	L	1500	50	N
377	Pmv	N	N	50	10	N	5	100	30	150	1500	200	N
422	Pmv	N	N	100	15	N	N	10	10	20	1500	150	N
155	Pmv	N	N	10	20	N	N	10	N	L	500	30	N
294	TrPer	N	N	300	15	L	10	50	10	L	200	20	N
318	TrPer	N	N	50	10	N	7	20	N	30	700	200	N
355	TrPer	N	N	200	15	N	500	10	N	20	100	500	10
356	TrPer	N	N	15	N	N	N	20	N	100	30	10	N
396	TrPer	N	N	15	10	N	5	20	N	30	150	10	L
307B	Pgb	N	N	300	10	N	N	N	20	20	700	150	N
338	sp	N	N	15	N	N	N	1500	70	1500	700	20	N
341	mt	N	N	50	10	L	N	50	30	30	1000	300	N
342	mt	N	N	15	10	N	N	30	30	30	1000	150	N
Lower Detection Limit		10	0.5	5	10	200	5	5	10	20	10	10	2
Average Igneous Rock		0.004	0.07	55	13	70	1.5		25	100		135	2

N-Not Detected L-Detected, but below limit of determination
Analysis by Specomp Services, Boise Laboratory

TABLE 7C. SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSIS

Element in PPM						Zr	B	Ba	Be	Nb	Sc	Sr	Y
Reference						100	N	1500	3	L	N	200	N
172	NW1/4	SW1/4	Sec.20	T.8.S	R.35.E	100	20	500	5	N	5	N	10
205	SE	SE	19		35	150	N	30	1	N	30	200	30
255	SW	SW	17		35	50	N	1000	15	N	N	L	N
377	Center		14		34	100	10	500	1	15	30	300	30
422	NE1/4	SE1/4	17		35	100	15	500	1	10	10	N	20
155	SE	NW	16		35	70	N	300	20	N	10	N	30
294	SW	NE	20		35	10	10	100	3	N	N	N	N
318	NW	SE	13		34	50	30	700	7	N	10	N	15
355	NE	NE	13		34	30	20	70	3	N	N	N	10
356	NE	NE	13		34	20	N	20	N	N	N	N	N
396	NE	SW	8		35	70	15	1000	5	10	N	100	15
307B	NW	NW	24		34	N	N	500	N	N	20	150	N
338	SE	SE	24		34	N	70	N	N	N	N	N	N
341	SE	SW	24		34	50	N	30	N	N	20	100	20
342	SE	SW	24		34	N	50	1500	N	N	30	150	N
Lower Detection Limit						10	10	10	1	10	5	100	25
Average Igneous Rock (Rose et al. 1979)							10	425	2.8	20		100	25

N-Not Detected L-Detected, but below limit of determination
Au, Cd, As, Sb, Bi, and La were not detected
Analysis by Specomp Services, Boise Laboratory

Many metal deposits in northeastern Oregon probably formed during subaqueous volcanic activity. An example is the Irondyke Mine in Hell's Canyon. Elsewhere, metals from enriched sediments and volcanics were assimilated into the rising magmas of the Jurassic intrusives and concentrated into veins. Such are apparently the origin of lode deposits in the Granite mining district (Young, 1979). Whether the slight mineralization noted in the thesis area (Table 8) is syngenetic or epigenetic could not be established, but the relatively high molybdenum values were probably superimposed on the pre-existing country rocks. Molybdenum is associated more with porphyry-type and vein deposits than with massive sulfide deposits. At porphyry-moly deposits, molybdenum anomalies can extend well beyond the ore zone (Woodcock and Carter, 1976). The mineralized rocks in the thesis area may have been affected by convecting ground water set in motion by the heat from Jurassic plutons. It seems likely that at least some of the metals were magma derived.

Small quartz veins are common throughout the thesis area but few show much mineralization. A broad zone of bleached argillite runs east-west across the northern part of the thesis area from the northern third of Section 13, T.8.S., R.34.E to the center of Section 8, T.8.S., R.35.E. This zone appears to contain more iron staining and mineralized quartz veins than the argillites found elsewhere in the area. Samples 355, 356, and 396 are from this one km. wide bleached zone.

TABLE 8. ELEMENTS FOUND IN RELATIVELY HIGH CONCENTRATIONS

Sample	Mo	Ag	Cu	Pb	Sn	Zn	V
172	X	X					
294	X		X				
318	X						
355	X		X		X		X
396	X						
377	X						
205		X	X	X		X	
307B			X				
255				X		X	

X indicates element exceeds normal concentrations expected in similar sedimentary and igneous rocks (Rose et al., 1979).

The greenstones in the area offer the greatest ore potential. However, the highly sheared nature of these rocks would probably frustrate any attempt to mine a deposit even if metals were discovered. The lack of much surface expression of mineralization at the Irondyke deposit in Hell's Canyon and other deposits elsewhere in northeastern Oregon (Lindgren, 1901) means that commercial mineral deposits might also be a possibility within the thesis area. A local miner, Steve Brown, reported finding small particles of gold from stream sediments in India Creek in SE1/4 Section 19, T. 8. S., R. 35. E. This gold must have been derived from within the thesis area, probably from the India greenstone.

STRUCTURAL GEOLOGY

At least one pre-Tertiary orogenic event has isoclinally folded the argillite unit and intensely sheared the greenstones and ultramafics. The geometric features of the folds in the study area could not be determined with certainty. Large-scale folds are not exposed to view. Mesoscopic folds with wave lengths of about one meter are locally visible within the argillite unit. These rare, small-scale folds are of two types. The first type is tight to isoclinal with upright axial planes running generally parallel to foliation (Figure 28). The second type gently folds vertical foliation or bedding and has a horizontal axial plane.

Orientation of foliations within the field area is variable. However, a pronounced E-W regional foliation is present (Figure 30). This foliation generally dips steeply to the south and will be referred to as S_1. The contoured pi diagram of foliations in the argillite unit (Figure 32) indicates the highest concentration of foliations is around N 78^{o}W, 59^{o}S. Most foliations strike between NNE and NNW. This dominant foliation may be an axial plane feature that formed during folding or may be shear induced. The interpretation of the pi diagram as representing tightfolding rather than homoclinal structures is consistent with regional structural observations (Taubeneck, 1957). Each layer within the dominant planar fabric tends to be homogeneous, that is, composed of one lithology. This suggests that original bedding is generally parallel to the plane of

Figure 28. Isoclinally folded chert exposed in the stream bed of Silver Creek, NE1/4 NE1/4, Section 14, T. 8 S., R. 34 E.

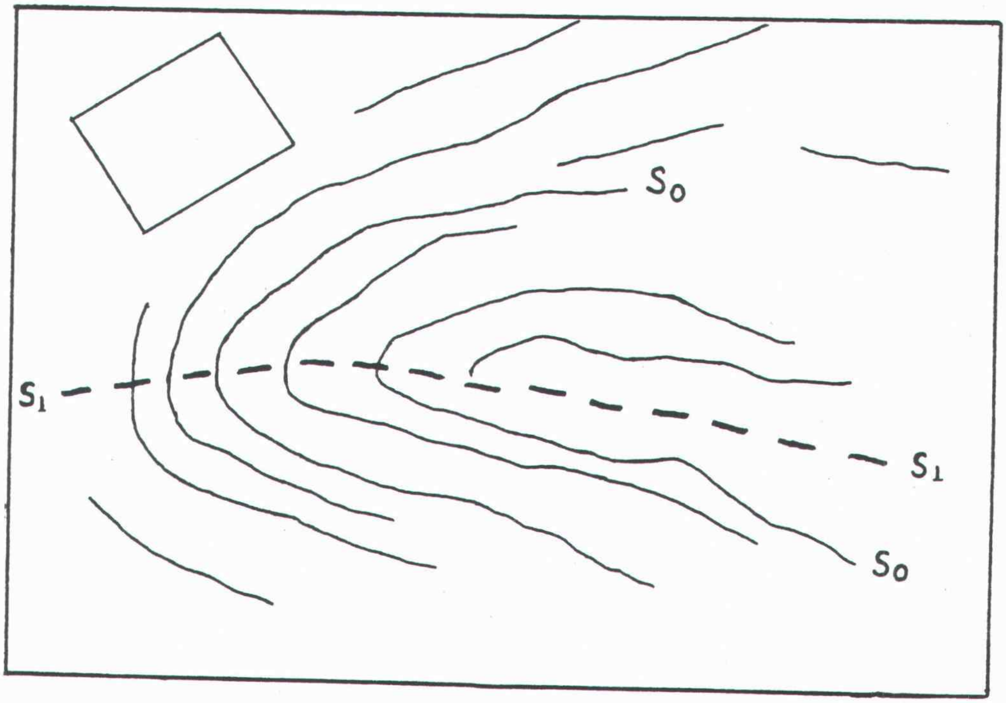
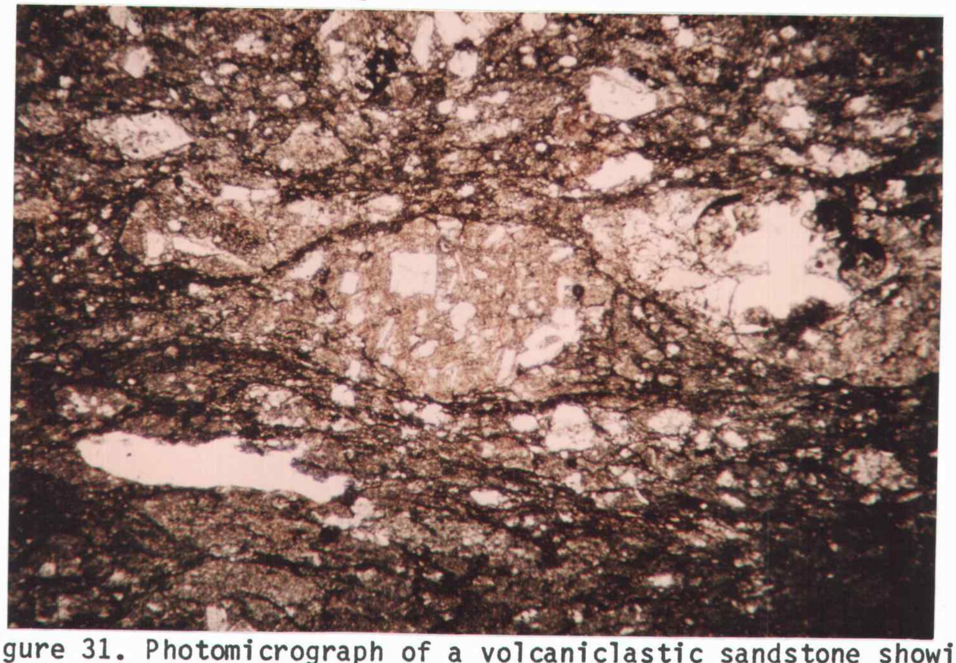


Figure 29. The axial plane of the fold nose pictured in Figure 28 runs parallel to the dominant regional foliation, S_1, present in the thesis area. S_0 represents original bedding.

Figure 30. Foliation, S_1, developed in argillite.



.05 mm

Figure 31. Photomicrograph of a volcaniclastic sandstone showing (Pmv) sample #175 from SE1/4 SW1/4 Section 17, T. 8 S., R. 35 E., rough S_1 cleavage. Nearly continuous cleavage seams anastomose between the larger volcanic clasts. Quartz and feldspar may have been removed by dissolution from seams that are now dominated by metamorphic chlorite. Field of view is approximately 7.5 mm. (Plane light).

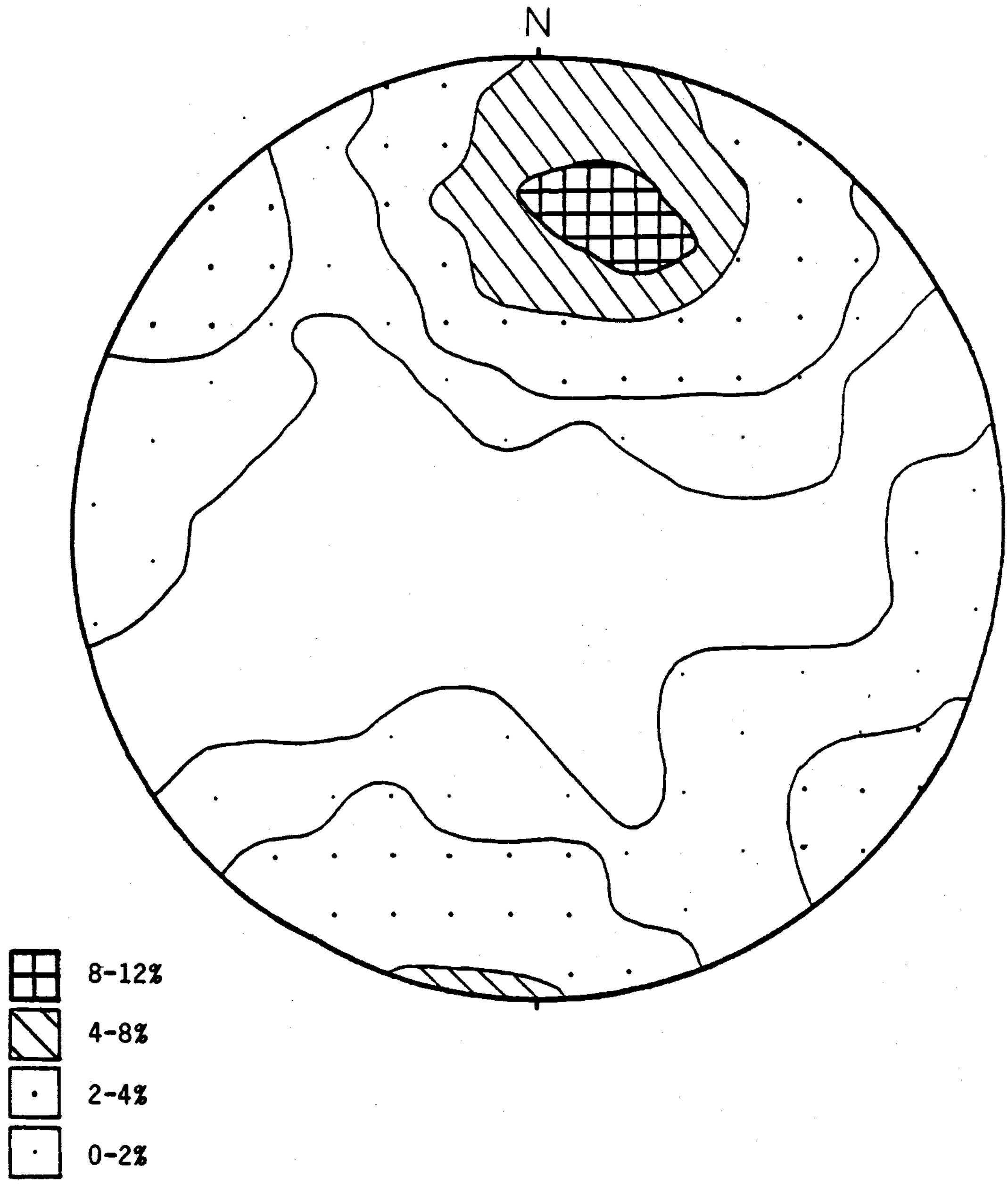


Figure 32. Contoured pi diagram of perpendiculars to foliation planes of the argillite unit in the thesis area.

flattening. When the chert and argillite beds were folded, most of the slip probably occurred along micaceous and carbonaceous layers. The folds may have formed in one generation or later deformation may have flattened early, more open folds to make them look isoclinal.

Rocks in the thesis area locally show evidence of multiple deformation. In addition to the dominant E-W, S_1 foliation, other planar structures also are present. These less prominent foliations may have formed before or after the S_1 foliation. The most prominent one is represented by the smaller maximum on the contoured pi diagram (Figure 32) and is referred to as S_2. S_2 is generally vertical with an average strike of about N36^{o}E. This discontinuous foliation does not greatly disrupt the E-W trend expressed by the apparently older, bedding-parallel S_1 foliation.

Dynamic Metamorphism

Shear fabrics are well displayed in pre-Tertiary rocks throughout the study area and are important in the formation of cleavage. Fragments in the volcaniclastic rocks commonly are flattened and elongated. Shear foliations and mylonitization zones characterize many thin sections. Many rocks that appear to be fine-grained flow rocks or cherts in hand sample are found to be mylonites when viewed under the microscope. Shear foliations in the mylonites are usually zones of fine-grained, polycrystalline, strained quartz. Minerals in these cataclastic foliations commonly exhibit serrate or lobate grain boundaries. Cataclastic structures in the cherts and argillites can be defined by stringers of opaque materials. Bands of aligned chlorite and mica in randomly oriented matrix may be the result of shear. Porphyroclasts of plagioclase, quartz, rock fragments, and opaques commonly deflect rudimentary cleavage surfaces around them (Figure 31). These, weak, deflected cleavage surfaces either merge with other similar surfaces or completely attenuate. Elongate lenses of iron oxides between grains indicate possible former fluid channels.

Relict plagioclase crystals commonly exhibit deformation twinning, undulating extinction and rupturing. Deformation can result in feldspar mylonitization along fracture zones. Recrystallization commonly accompanies this fragmentation and develops an interlocking mosaic of granular plagioclase. Recrystallization in cataclastic foliations is aided by frictional heating, bond breakage, introduction of strain, increased surface area caused by grinding and breaking, and an increased volume of fluids moving through. In gabbroic rocks, deformed, relict plagioclases may form "augen" structures in the mass of crushed rock.

The development of shear textures is governed by rock type and proximity to faults. In general, flow rocks and intrusives show less evidence of shearing than volcaniclastics. The internal structure of the igneous rocks is relatively isotropic and more resistant to shear. Shear textures are also common in isolated outcrops of limestone. Ductile deformation has formed closely spaced fracture cleavage visible in outcrop. In thin section, shear foliation is manifested by alternating bands of coarse- and fine-grained calcite.

Dynamic metamorphism has produced pseudoconglomerates or intra-formational breccias from some of the cherts and cherty argillites (Figure 33). The lenticular "clasts" are really microlithons of less deformed material separated by a groundmass of anastomosing cleavages. Thin section analysis suggests the microlithons and the groundmass had similar original compositions. The groundmass formed a rock powder during deformation and in some cases was subsequently stained by percolating fluids (Figure 34).

Tectonic Setting

Two separate orogenic events have been postulated to explain the penetrative deformation in the pre-Tertiary rocks of the Blue Mountain region (Avè Lallement et al., 1980). The first orogeny may have occurred at some distance from the continent and culminated during Late Triassic to earliest Jurassic time. This orogeny is related to the formation of north- to northeast-trending folds and faults and the fragmentation of the central melange terrane. A weak northeast-trending cleavage, S_2, is present in the thesis area but the time of formation is unclear. The second orogeny could be related to the accretion of the terrane to the North American continent about Late Jurassic or to the collision of the Seven Devils arc with the Huntington arc and the intervening Elkhorn Ridge Argillite (Coward, 1982). East-trending thrust faults and folds in the western Blue Mountains Province may have resulted from this collision. The dominant E-W structural trend found in the thesis area agrees with the

Figure 33. Boudins elongated parallel to S_1 form a pseudoconglomerate in cherty argillite NW1/4 NW1/4, Section 20, T. 8 S., R. 35 E.

.05 mm

Figure 34. Photomicrograph of boudinage in pseudoconglomerate, (TrPer) sample #291 from NW1/4 NW1/4, Section 20, T. 8 S., R. 35 E. Iron oxides have formed in the pressure shadow of chert "clast." Field of view is approximately 7.5 mm. (Crossed nicols)

Late Jurassic fold trend reported for this part of the Blue Mountains by Avé Lallement and others (1980). The second orogeny stopped before the terranes were intruded by granitic plutons 160 to 95 m.y. ago (Armstrong et al., 1977).

Poor exposure and the possibility of gravitative downslope movement at many locations limited the amount of reliable structural data that could be obtained in the map area. Correlation of structures in the field area with either of the postulated orogenic events is uncertain. Penetrative deformation of pre-Tertiary rocks may have been almost continuous throughout formation of the subduction complex and the collision of the terrane with North America.

Some small-scale distributive faults can be seen near the intrusive margins of the Granite Creek stock. Taubeneck (1957) considered similar faulting associated with the Bald Mountain Batholith to be evidence for forceful emplacement. Within the granitic intrusive rocks, both horizontal and vertical joints occur. The Mesozoic intrusive rocks do not show evidence of mineral cataclasis or recrystallization characteristic of crystallization in an active tectonic environment.

The pre-Tertiary terranes in the Blue Mountains may have undergone a clockwise rotation of $60^{o} \pm 29^{o}$ relative to the stable craton (Wilson & Cox, 1980). Most of the clockwise rotation is presumed to have occurred between 130 - 50 m.y. ago (Hillhouse et al., 1982), after emplacement of the granitic plutons. This rotation may be related to a Cretaceous, heat-driven, continental extension localized in the northern Great Basin. Cretaceous core complexes exposed in the northeast Great Basin (Armstrong, 1982) shown on Figure 1 may have formed during an episode of heat-driven extension. This backarc extension may have displaced the Klamath Mountains westward over 100 km. Cretaceous backarc extension could explain the curvature in tectonic trends and foliation directions from the Sierras through the Klamaths and into the Blue Mountains (Figure 1).

Tertiary volcanism and blockfaulting in the thesis area may be related to a second episode of heat-driven extension. This subject is discussed in the chapter on Tertiary volcanics.

The timing of faulting in the thesis area could not be determined. Complex folding and faulting continued in the Blue Mountain region throughout the late Cenozoic (Thayer, 1957). The orientation of faults in the thesis area, particularly the east-trending fault forming the north contact of the Tertiary basalt, could reflect the effect of pre-Tertiary structures on Cenozoic faulting. Hooper and Camp (1981) found pre-Cenozoic basement structures of the southern Columbia Plateau could affect strain patterns generated in younger rocks. Robyn and Hoover (1982) postulate the existence of a relatively thick and rigid microplate under the Blue Mountains. Northwestward-moving lithospheric blocks south of the Blue Mountains may be wedged against this microplate causing compression throughout central Oregon. Thinner crust south of the Blue Mountains may have been made more susceptible to Basin and

Range extension by an earlier crustal thinning episode during the Cretaceous.

Paleogeographic Setting

The contact between the argillite and the greenstones is a fault contact in many places. The high fault density in the thesis area has allowed few planes to escape shearing. The planar contacts are generally parallel to the dominant E-W foliation direction. The three dimensional orientation of the fault planes could not be determined but it is likely that some of the faults are thrusts. Reverse and thrust faulting would not be inconsistent with the isoclinal style of folding the rocks underwent in the pre-Tertiary or the compression they experienced in the Cenozoic (Robyn & Hoover, 1982). The movement along these faults was probably not very great.

Intensity of deformation in the greenstone belt varies but is generally less intense than deformation in the surrounding argillite. The metavolcanics and meta-intrusives would be expected to be more competent than the sedimentary rocks. Steeply dipping foliations in the greenstone body have the same general E-W strike as structures in the enclosing argillite. This consistency suggests that the greenstones and the argillite were already juxtaposed when deformation occurred.

Contacts between volcaniclastics of the metavolcanic unit and the argillite unit appear to be gradational in some areas. The paleovolcanics and volcaniclastics are part of a volcanic constructional pile that is intercalated with the argillite unit.

Flow rocks, volcaniclastic sandstones, and tuffs are common in the transition zone between the greenstone and argillite units. Metamorphosed mafic to silicic plutonic rocks are common in the central parts of the greenstone belt. These rocks probably intruded the volcanic pile and represent the roots of the volcanic center. The different lithologies have been folded together, faulted and sheared.

The structural relationships between the different metamorphic rock units are complex. The pre-Tertiary rocks have been strongly folded and faulted. Gradational lithologies from adjacent depositional environments have been juxtaposed during deformation. Dickinson and Thayer (1978) applied the term melange to the entire pre-Tertiary terrane between the Seven Devils arc and forearc basin terranes. Within the thesis area, the serpentinite matrix unit mapped as mt or "mixed terrane" is a tectonic melange. Some limestone pods and small bodies of sheared argillite with inclusions of sandstone fragments are probably sedimentary melanges. However, most of the pre-Tertiary exposures in the thesis area are not chaotic enough to warrant the term melange.

Although parts of the Baker terrane in northeastern Oregon probably do represent a deep oceanic environment (Brooks and Vallier, 1978), the rocks in the thesis area probably did not form in an abyssal environment. The silicic nature of many igneous rocks in the greenstone belt and the abundance of coarse volcaniclastics throughout the thesis area suggest the pre-Tertiary rocks are not real oceanic crust. Some of the limestone pods apparently formed in shallow marine environments. Infolding of younger shallow-water limestones into a deep ocean assemblage has been proposed (Wheeler, 1976). However, Wheeler's other explanation of limestone origin as reefs on former structural highs seems more applicable in the case of the thesis area. Gravity sliding could have deposited the limestone into deeper environments.

Pre-Tertiary rocks in the thesis area probably represent a complex basinal environment rather than an oceanic environment. Chert and argillite sedimentation predominated in this environment except where volcano-sedimentary piles were built. Metamorphosed igneous and coarse sedimentary rocks in the thesis area resemble rocks in the Seven Devils arc. However, the abundant argillite in the thesis area is characteristic of the Baker terrane. Boundaries between the terranes in northeast Oregon are not precisely defined because relations between the different terranes are complex, and pre-Tertiary exposure is discontinuous. Pre-Tertiary rocks in the thesis area represent a transition zone between predominantly arc and more basinal environments. This relationship supports Walker's (1983) assertion that the tectonic elements of the Blue Mountains island arc were formed in close association to each other.

Serpentinite-matrix melanges similar to the mt (mixed terrane) and sp (serpentinite) units mapped in the thesis area are exposed throughout the western part of the Baker terrane (Ferns & Brooks, 1983). Ultramafic rocks in northeastern Oregon have been correlated with the Canyon Mountain Complex (Brooks & Vallier, 1978) but metagabbros from the Greenhorn Mountains are generally more tholeiitic than the Canyon Mountain Complex (Mullen, 1983). Ophiolitic rocks throughout the Blue Mountains may be too silicic for normal oceanic crust and were more likely associated with an arc (Thayer, 1978). A titaniferous, subophitic metabasalt found in the mt (mixed terrane) unit of the thesis area and two similar metavolcanics found elsewhere in the Melange terrane (Mullen, 1985) may represent ocean-island or seamount alkalic basalts. The southern boundary of the Baker terrane is marked by discontinuous exposures of serpentinite-matrix melange containing rocks metamorphosed at high pressure (Mullen, 1978). The blueschist at Mitchell has been dated at 223 m.y. and linked to a Triassic subduction zone (Holtz et al., 1977).

The geology of convergent plate margins is complex and diverse. Hamilton (1969) described how through time seafloor spreading could sweep slices of crust against the margin of a continent. In addition to accretion of oceanic plate and trench materials, tectonic erosion and subduction of the overriding plate are also possible (Schweller et al., 1981). Growth of a subduction complex or accretionary wedge is inferred to occur dominantly by offscraping of oceanic and trench materials (Karig & Sharman, 1975). Kulm and others (1981) have developed a convergent plate boundary model in which uplifted basaltic ridges on the oceanic plate may be emplaced into the subduction complex forming a sediment-basalt melange (Figure 35). Such basaltic slabs incorporated within the trench axis may be the forerunners of ophiolitic slivers in ancient subduction complexes.

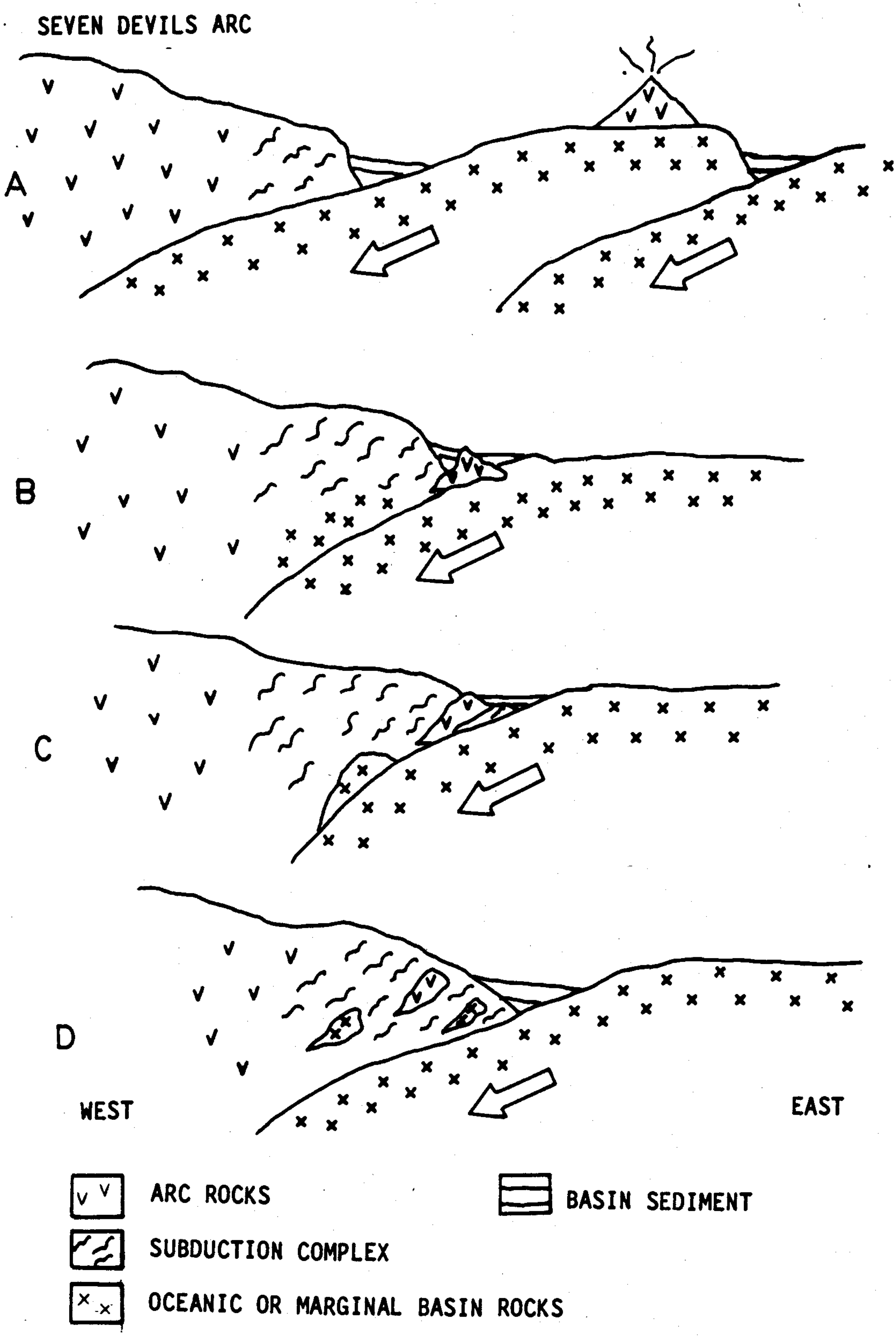


Figure 35. Proposed model for assembly of thesis area rocks in a Permian-Triassic forearc. Modified from Kulm et al., 1981. Timing, location and direction of subduction is highly speculative.

Meta-igneous rocks and serpentinites have been dredged from Atlantic ridges and fracture zones (Aumento et al., 1971 and Rosendahl, 1976). Deep fractures probably allowed fluids to invade the lower crust and alter rocks which then ascended diapirically to the present position on the ocean floor. The serpentinite-matrix melanges in the Blue Mountains may have had a similar origin in the tensional environment of a slow spreading ridge in a marginal basin. Slow spreading ridges are characterized by deeply penetrating faults (Rosendahl, 1976). Rates calculated for backarc basin spreading in the western Pacific (Weissel, 1981) are relatively slow, with half rates on the order of 1.0 cm/a to 3.0 cm/a. These altered rocks may have subsequently accreted to the subduction complex in the manner suggested by Kulm and others (1981). The disruption of the serpentine layers in the map area suggests serpentinization of the ophiolitic material took place before tectonic emplacement.

Before being accreted to the subduction complex, the pre-Tertiary rocks of the thesis area were probably formed in a complex basinal setting. Seamounts and ophiolitic melange material may have floored this basin. Chert and argillite were deposited in this environment except where volcano-sedimentary complexes were built. The presence of intermediate volcanic and quartz clasts in the abundant sandstones suggest slope and trench deposits were derived from a volcanic arc source region.

Lithologies and deformation in the forearc terrane of the Mariana island-arc system resemble those of the pre-Tertiary rocks in the thesis area (Bloomer & Hawkins, 1983). Mullen (1985) has suggested that the diverse meta-igneous and meta-sedimentary rocks of the Melange terrane represented a forearc related to the Seven Devils Island arc. Reconstruction of a paleotectonic setting is highly speculative, but a Permian and Triassic forearc terrane currently provides the simplest working hypothesis for explaining the complex rocks of the thesis area.

SUMMARY OF GEOLOGIC HISTORY

Early Permian and Middle and Late Triassic intra-oceanic, arc volcanism formed the Seven Devils terrane. Paleomagnetic data indicate that the Seven Devils volcanic arc assemblage originated 18^{o} ($\pm 4^{o}$) north or south of the Triassic paleoequator (Hillhouse, 1982). Tectonically disrupted rocks known as the Baker terrane, lie south of the Seven Devils arc volcanics. Metamorphosed pre-Jurassic rocks in the thesis area are located on the northern edge of the Baker terrane and may represent a forearc associated with the Seven Devils island arc (Mullen, 1985). Intense deformation accompanied the formation of the forearc and juxtaposed various lithologies that had originally formed in a complex setting of marine basin sedimentation with interspersed centers of volcanism and plutonism.

The sequence of tectonic and metamorphic events responsible for the accretionary orogen that dominates the thesis area is poorly understood. A pervasive east-west foliation, isoclinal folding, and tectonic emplacement of serpentinite bodies may be the products of continuing deformation within a single orogenic episode. Subduction mixed the various sedimentary, volcanic, and plutonic rocks. Most of the pre-Jurassic rocks in the thesis area could have formed in a marginal basin, not far from the Seven Devils arc, or at some remote location. The wide age range of fossils from the Baker terrane - some are as old as Devonian - suggests some far-traveled blocks of the paleo-Pacific ocean basin were incorporated into the accretionary wedge. Middle to Late Devonian conodonts from a few miles south of the thesis area have been reported (Morris et al., 1986).

The major part of the Elkhorn Ridge Argillite, which underlies most of the thesis area and much of the Baker terrane, is inferred to be of Permian age. However, fossils ranging in age from Middle Pennsylvanian to Late Triassic are fairly common (Blome et al., 1986). Elkhorn Ridge Argillite exposed in the thesis area consists mostly of a thick sequence of chert and argillite with isolated lenses of graywacke and carbonate. Carbonate pods are elongated parallel to the deformation of the enclosing sedimentary rocks.

An arc-related assemblage of metavolcanic and lower greenschist-facies sedimentary rock forms a one-to-three kilometer wide greenstone belt across the center of the thesis area. Although highly sheared, the greenstones appear to be intercalated with the surrounding Elkhorn Ridge Argillite. A conodont fragment recovered from a small limestone pod within the greenstone yields a color-alteration index indicating metamorphism at 300°-$400^{\circ}C$.

A brecciated and metamorphosed, intermediate pluton apparently intrudes the greenstone and may represent the intrusive phase of a volcanic arc. A Late Permian radiometric date for this intrusion was obtained adjacent to the thesis area (Brooks et al., 1982). Metagabbro is also associated with the metavolcanics but relationships are unclear.

A melange-related assemblage is exposed in an east-west-trending belt south of the arc-related assemblage. Metabasalt in the serpentinite-matrix melange contains titanaugite in an ophitic texture and differs distinctly from the felty textured metavolcanics of the arc-related assemblage. The original basalt may have been alkalic, suggesting an origin in an oceanic island or extensional environment. The melange also contains blocks of chert and metagabbro. A similar melange southwest of John Day, Oregon is overlain unconformably by Upper Triassic Vester Formation (Dickinson, 1979). Melange formation may have been coeval with Middle Triassic volcanism in the Seven Devils terrane.

The Blue Mountains island arc appears to have gradually moved northward and subsided during Late Triassic, Early Jurassic, and Middle Jurassic times (Pessagno et al., 1986). Flysch-like sediments exposed south of the Baker terrane were deposited during this time. Regional uplift of the Blue Mountains island arc during the Late Jurassic has been correlated with Late Jurassic plutonism (Brooks et al., 1986). Two granitic plutons exposed in the thesis area are probably Late Jurassic in age. They resemble Bald Mountain Batholith rocks exposed nine kilometers to the east. The plutons are significantly less deformed and altered than the surrounding metamorphic host rock.

The larger of the two post-amalgamation plutons in the thesis area consists of at least three phases, ranging in composition from quartz diorite to granite. Tonalite predominates. The smaller pluton is mainly fine-grained, porphyritic tonalite. The slight enrichment of the country rock in chalcophile metals is probably a hydrothermal effect of the Late Jurassic plutonism. Semiquantitative spectrographic analysis of one sample of iron-stained metamorphic rock revealed an anomalous concentration of molybdenum.

The Blue Mountain Island Arc accreted to the North American continent after the Jurassic plutonism; probably during the Early Cretaceous.

Tertiary basalt overlies the Mesozoic and Paleozoic rocks above an angular unconformity. The basalt is probably equivalent to the Eocene-Oligocene Clarno Formation exposed in the western Blue Mountains. Bimodal volcanism and normal faulting in the vicinity of the thesis area may be related to an Eocene episode of heat-driven extension. Slowing of the rapid plate convergence that had triggered the widespread Laramide orogeny, may have caused the subducting plate beneath the Blue Mountains to dive steeply. Hot asthenosphere flowed into the region above the downgoing slab and caused crustal extension and a short-lived, widespread volcanic episode in this part of the Blue Mountains.

The explosion of Mount Mazama (Crater Lake) ±6,600 years ago blanketed the thesis area in volcanic ash. This ash is now concentrated in some stream beds.

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