AN ABSTRACT OF THE THESIS OF

Ellen Domaratius Mullen for the degree of Master of Science

in Geology presented on June 8, 1978

Title: GEOLOGY OF THE GREENHORN MOUNTAINS, NORTH-EASTERN OREGON

Abstract approved: Redacted for privacy

(William H. Taubeneck)

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(Robert D. Lawrence)

The Greenhorn Mountains contain a tectonically disrupted ophiolite and both arc-derived and pelagic sediments. Age of major sedimentary units within and bordering the thesis area is Early Permian, based upon dates of conodonts and fusulinids from contemporaneous but allocthanous limestones. Sediments near the south boundary of the thesis area previously considered Triassic to Jurassic are re-assigned to the upper-Early Permian. Metamorphic grade varies in metasediments from prehnite-pumpellyite in the southern, proximal arc sediments to incipient (disequilibrium) upper greenschist facies in the pelagic series. Pillow lavas associated with Elkhorn Ridge Argillite of the thesis area are only partly spilitized and have original alkalic affinities, probably representing a seamount.

High pressure, incipient blueschist metamorphism which retrograded with time to lower greenschist facies is recognized at Bennett Creek, and is correlated with the Mine Ridge Schist. Microprobe

analyses of amphiboles and other phases from Bennett Creek, Mine Ridge Schist near Hereford, Oregon, and the lawsonite blueschist of Mitchell, Oregon indicate that in all units pressure decreased and temperature increased with time. Bennett Creek and Mine Ridge Schist metamorphism may be associated with tectonic overpressures followed by burial and increased temperatures with approach of the North American plate, or may be related to subduction. The Mitchell blueschist appears to be a product of subduction.

Metagabbro and alpine peridotites of the ophiolite are structurally and lithologically equivalent to the Canyon Mountain Complex, and were tectonically emplaced during Late Triassic time. Late Jurassic intrusives similar to the Bald Mountain batholith range from norite to two-mica granodiorite. Seven discrete intrusions were recognized.

Eocene olivine basalt and basaltic andesite exposed in the thesis area are alkalic in affinity and are equivalents of the Clarno Formation. Overlying andesites and dacites are probably Oligocene and may represent the equivalent of John Day volcanism. The Columbia River group consists of two Picture Gorge flows in the western-most portions of the thesis area.

Extensive alpine glaciation during the Pleistocene incised deep, U-shaped valleys in the western thesis area. Morainal deposits are common at lower elevations in the area. Deposits of Mazama ash up to six feet in thickness occur along streams of the area.

Geology of the Greenhorn Mountains,
Northeastern Oregon

by

Ellen Domaratius Mullen

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GEOLOGY OF THE GREENHORN MOUNTAINS, NORTHEASTERN OREGON

INTRODUCTION

The Greenhorn Mountains are a subdivision of the Blue Mountain geomorphic province of northeast Oregon (Walker, 1977). They contain exposures of pre-Tertiary metasediments, and ophiolitic and granitic rocks common to the Blue Mountain region. Tertiary volcanics cover approximately half of the area mapped, and range from alkaline dacites and rhyolitic tuffs to tholeiitic basalts of the Columbia River Group. Study of the Greenhorn Mountains should provide some insight to the regional geology and geologic history of the Blue Mountains.

Purpose

The primary purpose of this thesis is to investigate the petrology, environment of origin, and tectonic history of the Triassic and older metasediments, greenstones, and intrusives in order to: 1) determine whether they represent an ophiolitic sequenc; 2) correlate ultramafics and metagabbros of the Greenhorns with the Canyon Mountain Complex 30 miles to the south; 3) date and identify the depositional and tectonic environment of Permo-Triassic argillites and greenstones using field, petrographic, and geochemical parameters, and correlate with regional geology; 4) determine the effects of thermal metamorphism from granitic intrusions; 5) identify any regional metamorphic grade and determine whether any systematic change in regional grade occurs, and finally 6) to relate this information to the petro-tectonic history of the Blue Mountain region in general.

In addition, this thesis seeks to describe the Late Jurassic intrusive rocks of the Greenhorn Mountains, and from field, petrographic, and limited chemical data, distinguish discrete intrusive units and determine whether they represent independent batches of melt from different sources or are separate pulses from a single fractionation source. Furthermore, this thesis includes petrographic and limited geochemical studies and description of the Tertiary volcanic sequence in the Greenhorns. Particular attention is given to the Tertiary basaltic rocks to determine from field, petrographic and chemical data whether they represent alkalic or tholeiitic volcanism, and whether they are related to the Columbia River group.

Area of Investigation

The area mapped and considered in detail for this thesis comprises approximately 98 square miles in the Greenhorn Mountains of northeast Oregon. The rectangular area extends seven miles (11.6 km) in a north-south direction and 14 miles (23.2 km) east-west. It is approximately bisected by 118°30'E longitude, and is bordered on the north by 44°47'30"N latitude. It is divided almost equally between the Desolation Butte, Bates, Greenhorn, and Granite U.S. Geological Survey topographic quadrangles, and lies in T. 9 and 10 S., R. 34, 35, and 35 1/2 E. Nearly 75 square miles adjacent to the area mapped in detail were covered in reconnaissance.

The Greenhorn Mountains are a small and topographically subdued range which is a subdivision of the better-known Blue Mountain geomorphic province (Walker, 1977). The Greenhorns comprise a little less than 150 square miles in Grant, Baker, and Umatilla counties and are bordered on the north by the North Fork of the John Day River and on the south by the Middle Fork of the John Day River (see Figure 1). Elevations range from a high of 8131 feet (2478 m) at the summit of Vinegar Hill to a low of 4750 feet (1148 m) along Olive Creek. Total relief is about 3400 feet (1036 m). Elevations above 7000 feet are restricted to the west half of the thesis area where steep-sided glacial valleys are incised into a largely pre-Tertiary terrane. Cirque walls form 400-500 foot near-vertical cliffs in the granitic rocks of Ben Harrison Peak and Sunrise Butte. South-facing slopes of the west part of the thesis area are commonly more gentle, with relatively moderate, even inclines of five to 15 degrees.

Pleistocene alpine glaciation had little direct effect on the region

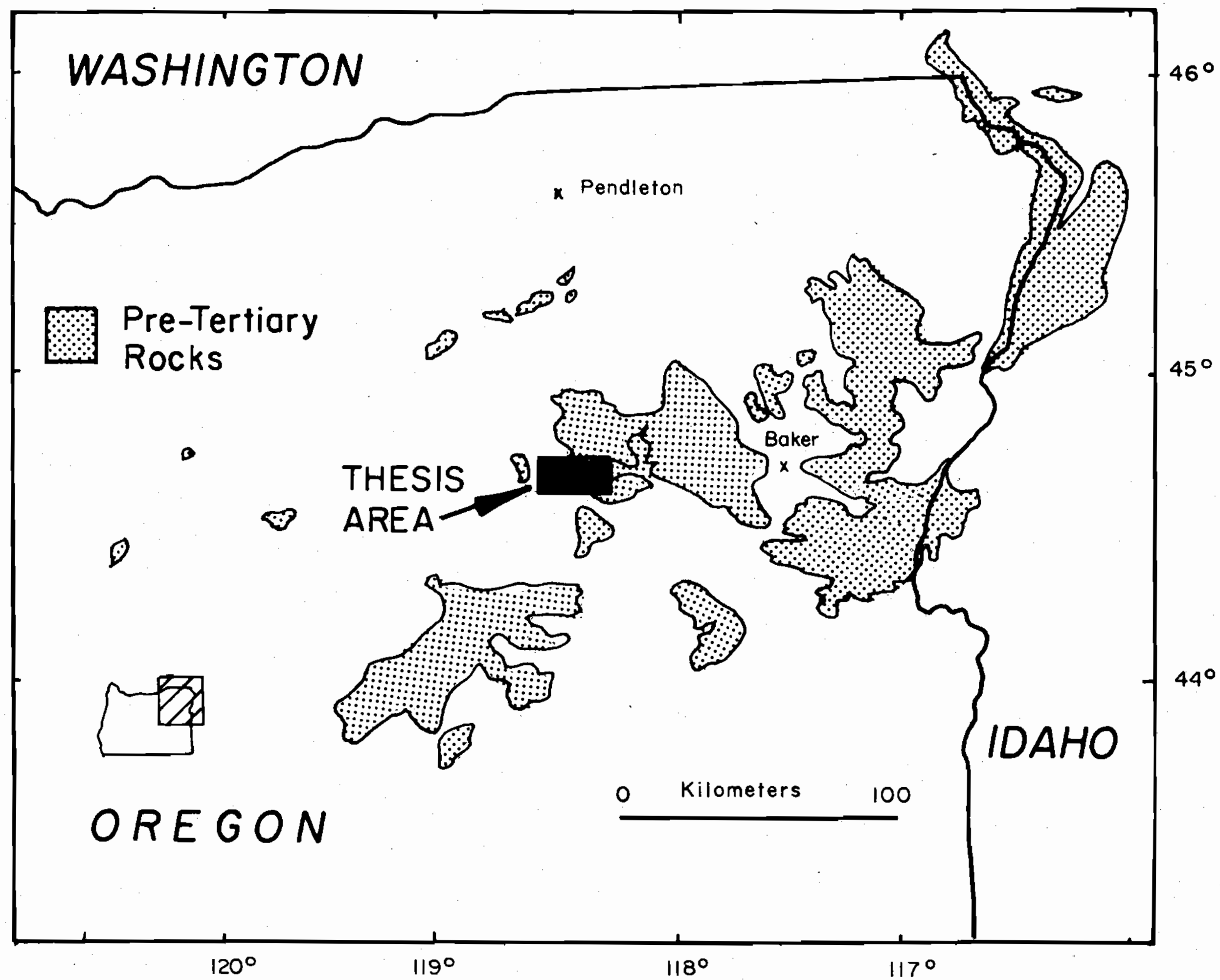


Figure I. Location Map of the Thesis Area (after Vallier, 1977) east of 118°30'E longitude. Elevations in the east part of the thesis area range from about 6500 feet (1981 m) at the town of Greenhorn, to a low of about 4750 feet (1448 m) along Olive Creek. In the east part of the area, precipitous slopes occur only in the west-facing volcanic cliffs on Olive Butte.

Vegetation varies with elevation, exposure, and outcrop. The relatively dry, south-facing slopes of elevations above 6500 feet support sagebrush (Artemisia L.) as the principal flora, with buckwheat (Eriogonum flavum), paintbrush (Castilleja sp.), and arrowleaf balsamroot (Balsamorhiza sagittata) as common wildflowers. Gnarled lodgepole pine (Pinus contorta) and stunted white fir (Abies concolor) occupy exposed ridge-tops at elevations of 8000 feet (2438 m) to 7400 feet (2255 m). At slightly lower elevations on north, east, and west-facing slopes, mixed spruce (Picea engelmannii) and tamarack (Larix occidentalis) or spruce, fir, and tamarack forests persist, with increasing admixtures of lodgepole pine with decreasing elevation from 7000 to 6500 feet.

Mixed tamarack, lodgepole pine, and fir forest occurs throughout the thesis area below 6500 feet. Nearly pure stands of lodgepole pine cover northern parts of the thesis area mapped as Tertiary volcanic. Trees in these stands seldom exceed five inches (12.6 cm) in diameter, and may be spaced less than three feet (0.9 m) apart, and thus present considerable challenge in mapping and traversing the area. Large ponderosa pine (Pinus ponderosa) are confined to south-facing slopes below 6200 feet (1890 m).

Fauna common to the Greenhorn Mountains include Rocky Mountain elk, mule deer, North American black bear, coyotes, badger and numerous species of birds, including redtailed, sharp-shinned, and goshawk, as well as great horned owl and long-eared owl. Ruffed grouse are common, particularly in recently logged clearings; blue grouse was noted at higher elevations. A nesting pair of sandhill crane was noted at Olive Lake in 1977. Of the smaller birds, most noteworthy were the mountain bluebird (Sialia currucoides) which was found in open areas above 7000 feet (2134 m), and the water ouzel, or dipper (Cinclus mexicanus) which provided many hours of bemused companionship along Granite Boulder Creek.

Flora and fauna of the Greenhorn Mountains are characteristic of alpine to sub-alpine topography with moderate precipitation, rigorous winters, and warm, dry summers. Snow may remain in sheltered, north-facing locations into July; in the unusual summer of 1976, nearly two inches of fresh snowfall accumulated on Ben Harrison Peak in mid-August. Precise climatic data for the Greenhorns are not available, but an estimate of annual precipitation from U.S. Department of Commerce records at Ukiah (40 miles/67.6 km) to the northwest, and at Desolation Butte lookout indicate that average annual precipitation slightly exceeds 28 inches (70 cm) at higher elevations.

Winter snowfall at the town of Greenhorn commonly exceeds six feet (183 cm) according to local residents.

Access to the thesis area is available along several improved U.S. Forest Service roads. Similar roads also provide some access to the south portions of the area; logging roads are common east of 118°30'E longitude. Approximately 35 square miles (96 km^2) of the high country (above 6800 feet) in the west portion of the area is designated as a U.S. Forest Service Scenic area from which all vehicular traffic is banned.

Methods of Investigation

Field investigations in the Greenhorn Mountains occupied a total of 22 weeks during the two summers. Sixty square miles (160 km^2) were mapped in detail in 14 weeks, June through September, 1976. An additional 38 square miles (100 km^2) were mapped in detail during eight weeks, June through August, 1977. Reconnaissance mapping and investigation included approximately 75 square miles (206 km^2) adjacent to the thesis area during two field seasons. In addition, a brief study was made of approximately one square mile near Hereford, Oregon (see Plate 3, regional sample locations) for purposes of sampling Mine Ridge Schist (Lowry, 1968).

Mapping was done on a scale of 1:24,000 on U.S. Geological Survey topographic base maps. Desolation Butte and Bates 15' quadrangle sheets were enlarged to the appropriate scale prior to mapping. U.S. Forest Service black and white aerial photographs were examined prior to, during, and after field work, but generally proved of minimal value due to dense forest in the thesis area.

Laboratory work included examination of 405 standard petrographic thin sections for determination of mineralogy, alteration, and deformation of specimens. Of these, 218 were rocks from the pre-Tertiary ophiolitic suite, 107 were Jurassic granitic rocks, and 79 were Tertiary volcanics. Modal analysis by point-counting after the method of Chayes (1947, 1956) was employed for 85 slides. For coarse specimens, 2300 to 3000 points were tallied (granitic rocks and some porphyritic volcanics); for finer-grained material (basalts, volcanic greenstones) 1800-2500 points were counted. Staining techniques were used to identify orthoclase feldspar in eight slides of granitic rocks and in five slides from metasediments. Point-counting in subdued light proved an equally satisfactory method of identifying potassium-feldspar in fresh granitic samples, however, and was used for most of the granitic rocks. Determination of plagioclase composition was by Michele-Levy rotation.

Thirty specimens were selected for chemical analysis based upon field location, freshness, and petrography. Selected rocks were carefully powdered, prepared, and analyzed for major oxides (SiO_2, Al_2O_3, TiO_2, CaO, K_2O, Fe*O, P_2O_5) and trace elements

(Ba, Zr, Ni, Sr, and, for six separate samples, S and Co) by X-ray fluorescence techniques on a Norelco single channel fluorescence unit. Fused glass discs of $LiBO_4$, LaO, and sample powder were utilized for major oxides. Powder pellets of chromatographic cellulose and sample powder were used for determination of P_2O_5, low-abundance K_2O checks, TiO_2 checks, and trace element analysis. Atomic absorption spectrometry on a Perkins and Elmer 403 photospectrometer with deuterium arc was used in analysis for Na and Mg. (See detailed discussion of X-ray fluorescence analytical techniques, Appendix 3.)

X-ray diffraction analysis of whole-rock sample powders was undertaken on a Phillips-Norelco X-ray diffraction unit for the determination of amphibole, garnet, and plagioclase compositions in schists, olivine composition in serpentinized peridotites, and serpentinite mineralogy. X-ray diffraction methods with whole rock powders were also utilized for confirmation of pumpellyite in some greenstones, determination of pelitic content of some cherts, and a check for An content of plagioclase in greenstones.

Electron microprobe analyses of selected mineral grains were made on a Materials Analysis Corporation electron microanalyzer, model 5-SA3 and PDP 8/L compiler at the California Institute of Technology, Division of Geology and Planetary Sciences. One-inch diameter round polished microprobe sections were prepared to permit analysis of white mica, garnet, blue amphibole, chlorite, and plagioclase in Bennett Creek and Mine Ridge Schists, and relict pyroxenes, feldspar, opaques, garnets, and amphiboles in greenstones. (See Appendix 3 for more detailed discussion of microprobe analysis.)

Separation of white mica from Bennett Creek schists for potassium argon dating and $O^{16/18}$ determination was done by a sequence of crushing in jaw-crusher, sieving to segregate grains by size, then separation of light minerals from heavy by settling in bromoform, and finally multiple runs through a Franz Isodynamic magnetic separator (Model L-1).

Previous Work

The pioneer study of geology in northeast Oregon was made by Lindgren (1901) who focused on the gold mines of the Baker area, and whose field season extended from August to December, 1899.

Actual work in the Greenhorn Mountains was first done by Westgate (1921) who produced a generalized map and description of localized chromite bodies in eastern Oregon, including two in close proximity to the thesis area. Gilluly (1933) also investigated the area's mining districts briefly, and noted that pre-Tertiary structures dominate the geology. A later report by Gilluly (1937) on the Baker quadrangle carefully described units which are also common to the Greenhorns, namely the Elkhorn Ridge Argillite and Clover

Creek Greenstone. Gilluly recognized that each of these units might be further subdivided.

Pardee et al. (1941) mapped the east portion of the thesis area as part of the Sumpter, Oregon 30' quadrangle, and delineated five distinctive units: 1) an argillitic metasedimentary formation correlative to Gilluly's Elkhorn Ridge Argillite which contained interbedded shales, sandstones, limestone lenses, and cherts, 2) serpentinite, peridotite, and metagabbro, 3) granodiorite, 4) andesite flows and tuff breccias, and 5) "younger, basic lavas."

Allen (1948) mapped the Morning Mine region and recognized the same five units.

More recently Taubeneck (1957) mapped extensive areas of the Sumpter quadrangle as part of work on the Bald Mountain batholith, and determined a Permian age for the Elkhorn Ridge Argillite (1955). The thesis area is included on the geologic map of the Canyon City quadrangle (Brown and Thayer, 1966), and on the Geologic Map of Oregon East of 121° (Walker, 1977).

Two recent theses include portions of the thesis area; Perkins (1976) mapped and described the geology of the Greenhorn quadrangle--an overlap of 21 square miles (56 km^2) discussed in this thesis. Wheeler has worked (1971, in progress) in the north portion of the Bates quadrangle as part of a Ph. D. thesis at the University of Washington. Approximately 20 square miles of this writer's thesis overlap that of Wheeler.

Stratigraphic Nomenclature

Unit names proposed and utilized in this thesis are intended informal designations for the purposes of discussion herein only.

REGIONAL GEOLOGY OF PRE-TERTIARY UNITS

The Blue Mountain region of northeast Oregon, which includes the Greenhorn Mountains, contains substantial exposures of pre-Tertiary rocks considered almost without exception Pennsylvanian or later in age (Brown and Thayer, 1966; Vallier et al., 1977). The assemblage is structurally complex and lithologically diverse.

Remnants of tectonically disrupted ophiolite, Triassic arc, and Paleozoic arc, oceanic, and shelf terranes are present in the northern and eastern Blue Mountains; late Triassic and Jurassic arc sediments and keratophyres are exposed in southern and western portions of the region. Late Jurassic to Cretaceous calc-alkaline intrusives, from minor norite to granodiorite are exposed throughout the Blue Mountains. They record the transition from oceanic crust in the western region to continental basement near the Idaho-Oregon border in their $^{87}Sr/^{86}Sr$ ratios. This thesis is most directly concerned with Paleozoic greenstones and sediments, ophiolitic rocks tectonically emplaced in Triassic time, and the Late Jurassic igneous intrusives.

The Paleozoic oceanic assemblage of northeast Oregon is dominated by the Elkhorn Ridge Argillite (Gilluly, 1937)--contorted ribbon cherts and siliceous argillites, with minor shale and conglomerate and intercalated greenstones and keratophyre tuffs. This formation extends at least from Cuddy Mountain in west Idaho west to the Greenhorn Mountains. It is generally considered Permian (Taubeneck, 1955), although limestones of Late Pennsylvanian and Late Triassic age (Bostwick and Koch, 1962) are also associated with the Elkhorn Ridge Argillite. The formation varies in metamorphic grade from lower to upper greenschist facies. Higher metamorphic intensity may be represented by the phyllites of the Burnt River Schist exposed in the eastern portions of the Blue Mountains (Ashley, 1967).

Paleozoic and Triassic arc-derived greenstones, keratophyres, and associated sediments were mapped north of Baker, Oregon by Gilluly (1937) as the Clover Creek Greenstone. Similar rocks are dominant in the Snake River Canyon and west Idaho where they have been included in the Seven Devils Group (Vallier, 1967; 1974). Triassic arc-derived rocks decrease in abundance westward from the Snake River Canyon; Permian arc-derived rocks of the Seven Devils Group and Clover Creek Greenstone appear to increase relative to the Triassic assemblage in a westward direction (Vallier, 1977). Rocks of Triassic age have been considered unconformable with the underlying Permian assemblage (Vallier, 1967; Prostka, 1962) in the Snake River Canyon; Permian and Triassic rocks appear conformable in the southeastern Wallow Mountains (Wetherell, 1960). Metamorphism varies from prehnite-pumpellyite facies to amphibolite facies (Vallier, 1977); greenschist facies metamorphism is the most common.

The ophiolitic intrusive rocks of the Blue Mountains consist of extensive metagabbro, minor alpine peridotite, and sheared serpentinite which serves as a melange matrix. Emplacement of this assemblage into both the oceanic and the arc-derived formations was tectonic, and commonly severely disrupted stratigraphy. Juxtaposition of contrasting lithologies is common. Permian ophiolitic rocks are best exposed in the Canyon Mountain Complex (Ave Lallemant, 1976) to the south of the thesis area, where they have been considered of probable oceanic affinity by Vallier (1977) and of possible arc origin by Ave Lallemant (1976). Arc-derived rocks of similar nature occur in the Sparta quadrangle to the east of Baker (Prostka, 1962). Ophiolitic igneous assemblages are metamorphosed in greenschist to amphibolite facies. Gabbros and peridotites show characteristics of both high and low temperature deformation; localized transformation of gabbros to mylonitic amphibolites is common in the Canyon Mountain Complex (Ave Lallemant, 1976).

The calc-alkaline Jurassic to Cretaceous intrusives of the Blue Mountains are predominantly granitic, with minor norite and gabbros. The rocks of the Bald Mountain batholith represent numerous, separate magmatic pulses (Taubeneck, 1957) rather than a single intrusion. Ages of related intrusions vary from 95 to 160 million years, with a maximum age suggested as 155-160 million years (Armstrong _et al._, 1977). Age of the Bald Mountain batholith has been reported as 147±17 million years (Armstrong _et al._, 1977).

PRE-JURASSIC UNITS OF THE GREENHORN MOUNTAINS

The pre-Jurassic basement of the thesis area is part of a regional tectonic melange which incorporates nearly coherent blocks of Permian island arc and oceanic material in a serpentinite matrix. Units of arc and oceanic terranes are closely juxtaposed tectonically in the Greenhorn Mountains, and can be interpreted systematically. Informal geographic names have been given to the various units for convenience in discussion.

Island arc rocks include a proximal unit of coarse conglomerates, sandy turbidites, allochthonous limestones and spilitized volcanic greenstones metamorphosed in lower greenschist facies named the Badger Creek Beds, and possibly also a granite-andesite boulder conglomerate called the Snow Creek Conglomerate. Distal arc-derived rocks of the Vinegar Hill Beds include siliceous argillite, shale, volcanoclastics, minor conglomerates and keratophyre tuffs. The distal arc units are the most severely disrupted by serpentinite. Metamorphism of individual blocks varies from lower greenschist to prehnite-pumpellyte facies. Relict near-blueschist facies metamorphism occurs in one large block, called the Bennett Creek Schist.

The oceanic terrane consists of contorted radiolarian ribbon cherts named the Alamo Argillite, and intercalated alkalic pillow

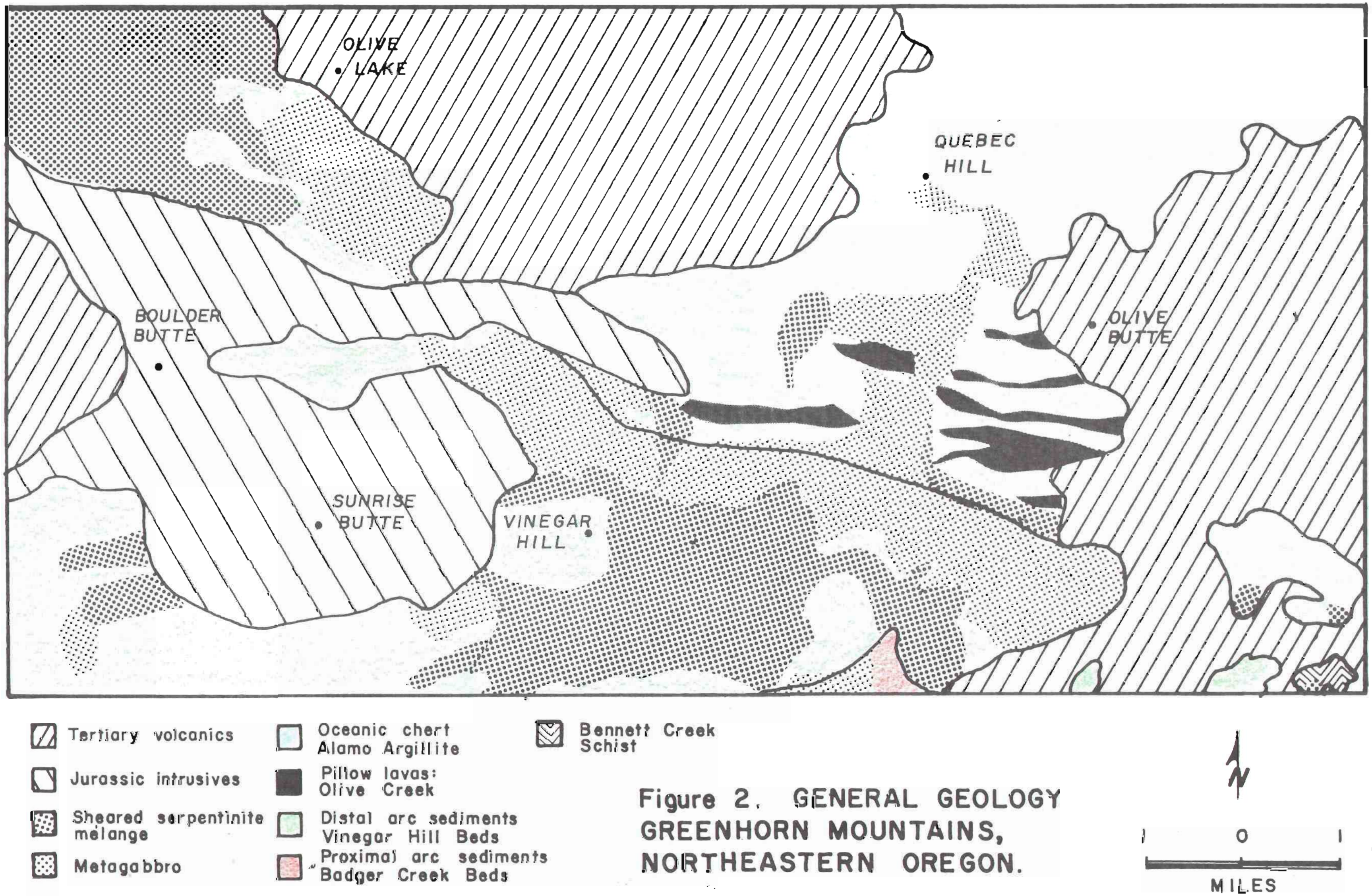


Figure 2. GENERAL GEOLOGY GREENHORN MOUNTAINS, NORTHEASTERN OREGON.

lavas in disequilibrium upper greenschist facies. The oceanic units are correlative to the Elkhorn Ridge Argillite (Gilluly, 1937).

Metagabbro and serpentinized alpine peridotites are tectonically mixed with sediments and greenstones. Metagabbro and serpentinite extend across the thesis area in a broad band from northwest to southeast, and appear to separate the oceanic and arc terranes. A regional northeast-striking cleavage penetrates nearly all units of the melange, so that the northwest trend may be partly a function of exposure rather than tectonics.

Badger Creek Beds

A sequence of proximal, arc-derived tuffaceous sandstone, chaotic angular conglomerate and minor chert is included in a metagabbro-serpentinite terrane in section 16 of the southern portion of the thesis area near the Roberts Mine. The sediments appear to be tectonically intruded by and emplaced with serpentinite and metagabbro. The metasediments are similar to much coarser rocks mapped by Wheeler (1976) south of this thesis area, and named for exposures at a type location along Badger Creek in section 13, T. 10 S., R. 33 E., approximately three miles southwest of the area considered in detail for this thesis (see Plate 3). For the sake of future consistency the name Badger Creek Beds is retained in this thesis as an informal designation.

At the type location and in section 16 bedding strikes northwest and dips steeply northeast, in marked contrast to the northeast to easterly regional strike of most pre-Tertiary units in the thesis area and through the Blue Mountains (Vallier et al., 1977). The divergence of Badger Creek Beds from regional trends is localized, and probably related to intrusion by and inclusion in the metagabbro-serpentinite melange, rather than to any major unconformity as suggested by Wheeler (1976) and Brown and Thayer (1966).

Tuffaceous sandstone is the most prevalent lithology at the section 16 locality. It is olive brown and contains thin beds of greywacke one to two centimeters thick. Graded bedding is indistinct. Conglomerates are grey to grey-brown with angular to subangular clasts of chert, felsic volcanics, and mafic volcanics. Bedding is not evident in the conglomerates. Chert is light brown to off-white and slightly argillaceous.

Cherts form steep slopes and unvegetated cliffs in section 22 near Lemon Cabins and Blackeye Creek, and are probably a large clast of oceanic sediments tectonically emplaced within the proximal arc material. They are grey to black in outcrop, and usually dark grey on a fresh surface. No radiolarians were noted at the section 22 location. The sediments are typical ribbon cherts, rhythmically layered in the alternating two to four inch (five to 13 cm) chert and one to five mm siltstone sequence common to the Elkhorn Ridge Argillite.

Contorted folds, about four feet (1.3 m) in width occur across the entire outcrop.

Exposures of Badger Creek Beds south of the thesis area reveal a similar series of proximal turbidites, fine sandstones, siltstones and conglomerates, with the addition of (pillowed?) volcanic greenstones.

Volcanic greenstone include both keratophyres and spilites. Flows are intercalated with sediments, and are usually deeply weathered. Keratophyres are light grey-green and disintegrate easily. Rounded forms in some outcrops--notably V-219--suggest that some greenstones may represent pillow lavas. The flow rocks noted in outcrop are not more than 150 feet (45 m) thick.

Petrography

Sample Badger Creek Bed greenstones, including V-252 and V-219 are diabasic to subophitic in texture. Small laths of plagioclase (now albite) 0.2-0.7 mm are partly replaced by chlorite and sericite. The groundmass is a felted intergrowth of chlorite and actinolite with albite and small equant epidote. Occasional secondary segregations of granoblastic quartz and albite one to four millimeters in diameter which contain vermicular chlorite are dispersed throughout the rock and may represent vesicle fillings. Granular sphene altering to leucoxene is common. Pseudomorphs after mafic phenocrysts are not evident in thin section.

The keratophyres of the Badger Creek sequence consist of a felsic groundmass of quartz and feldspar with plagioclase phenocrysts altering to chlorite and calcite.

Siltstones and fine wackes generally surround the greenstone and keratophyre units. These siltstones are olive-brown and commonly display graded bedding in three to six inch layers typical of turbidites. Bedding varies in attitude, from N. 60°E. to N. 40°W. with generally steep dips. Cleavage trends generally northwest and is near vertical. The inconsistent "up" directions of the graded beds and the near vertical nature of the cleavage suggest that folding in the Badger Creek Beds is isoclinal and slightly overturned. The siltstones of the Badger Creek Beds exposed to the south of the thesis area are similar to the rocks described from section 16 within the thesis area.

The conglomerates are varied with respect to clast size, size distribution, angularity, and lithology and are intercalated with finer sediments in lenses of 50 to 150 feet thick. Pebble conglomerates similar to those of the Vinegar Hill Beds occur. Coarse conglomerates are more common than fine ones. A quarry in sections 32 and 29 along Granite Boulder Creek (see Plate 3, A-217) provides excellent examples of the coarse conglomerates associated with the Badger Creek Beds. The rock is grey to buff-brown and contains angular to subround clasts from less than one inch to over one foot (two-35 cm) in diameter. Lithologies of felsic volcanics, possible chert, and mafic volcanics are identifiable in outcrop. "Chert" and mafic volcanic clasts are generally largest, and most angular. Several elongate, rounded inclusions of basalt were noted which approached two feet in length, and which disintegrated readily upon sampling. The streamlined shapes of the mafic clasts suggest that some are volcanic bombs which were either washed into source sediments from a nearby (submarine?) volcano or possibly are direct air-fall contributions. Seismic activity associated with volcanic eruptions might explain the generation and periodic deposition of coarse conglomerates as well as the apparent restriction of volcanic bombs and lapilli to such units.

In thin section, the conglomerates display a quartz-lithic fragment matrix with granoblastic quartz and albite enclosing angular lithic fragments of mafic volcanics and recrystallized felsic volcanics and chert. Poorly crystalline chlorite is disseminated throughout the matrix and fills occasional cavities. Actinolite is strikingly developed as radiating sheaves in A-263, but was noted only as occasional acicular crystals usually associated with mafic clasts in V-217, a difference probably due to the apparent higher iron and calcium content and greater effect of the granitic thermal aureole on A-263.

Associated Limestones

Limestone pods are common in the Badger Creek Beds (as noted also by Wheeler), and vary from about one foot (33 cm) in diameter to dimensions which might be considered biohermal, on the order of 40 feet (14 m) in width, extending parallel to bedding for a considerable distance. In all exposures they are deformed, with extension parallel to axial plane cleavage. This extension is apparent both from the ellipsoidal shape of the smaller pods and the parallel strain ellipsoids produced from formerly round corals and crinoids.

The limestone is dark pinkish grey on fresh surfaces and usually contains an appreciable component of silts and clays which have commonly altered to chlorite. A small 2V was noted in some highly strained carbonate.

The limestones associated with Badger Creek Beds are usually highly fossiliferous. Fusulinids, crinoids, bryozoa, brachiopods, corals, and possible pelecypods were identified at L-202, an only moderately deformed locality. The fauna seemed intact, rather than disaggregated and broken as would be true if transported as debris rather than in a biohermal mass, and was generally segregated with respect to larger genera.

Age

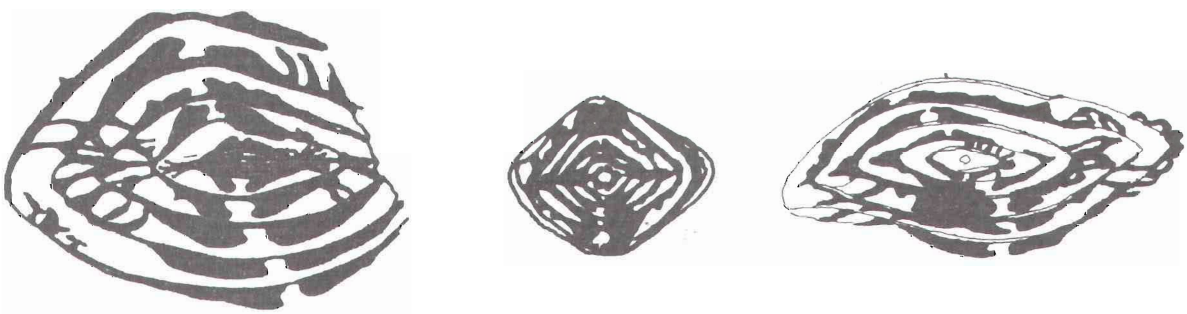
Limestone from four localities within the Badger Creek Beds were collected for age determination. Two samples (L-203, L-204) contained highly deformed corals and crinoids as well as a conodont bar fragment and fish debris. Bar fragments from L-203 yielded a Color Alteration Index (C. A. I.) (Epstein et al., 1977) of 5, indicating host rock metamorphic temperatures of 300-400°C.

Sample L-202, the locality described above, yielded identifiable conodonts: Negondolella cf. N. idahoensis and Neostreptognathodus pequopensis Behnken, as well as the usual fragments, fish debris, and sponge spicules. The conodonts indicate a Leonardian (upper Early Permian) age (Wardlaw, pers. comm., 1978).

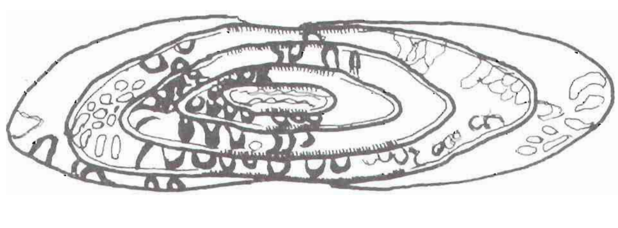
Fusulinids were also recovered from L-202. The fusulines in L-202 were identified as Pseudofusulinella and probable Schwagerina, or allied genus of middle to late Wolfcampian age (Bostwick, pers. comm., 1978). Highly fluted septa in Schwagerina(?) suggest a middle to probable upper Wolfcampian age (Bostwick, pers. comm., 1978). Because the Wolfcampian-Leonardian boundary is not well defined, the conodonts and fusulines may possibly be considered of equivalent age.

A small, frilled brachiopod was recovered from a limestone block two feet in diameter in the Badger Creek Beds of section 16

Permian fusulines, L-202
Limestone pod in the Badger Creek Beds.



Pseudofusulinella



Schwagerina?

Figure 3. Permian fusulines, L-202.

within the thesis area. No conodonts were reported from this sample (L-5), but Dr. J. G. Johnson identified the brachiopod as Cleiothridina(?) sp. and assigned an age of Late Mississippian to Permian based upon the highly frilled structure of the shell. He also recovered fragments of an ambocoelid species of longer age range.

Origin and Significance

The depositional environment of the Badger Creek Beds limestone pods was, by all lines of evidence, shallow and reef associated. Abundant growth of corals indicates that development of the limestones occurred well within the photic zone (Ginsburg and Lowenstam, 1958). The limestones included within the Badger Creek Beds are considered to have originated from a shallow reef which probably fringed the arc from which the sediments were derived. The extremely coarse nature of some sediments and their probable small continuous lateral extent suggest that they were not transported too far from their source region, and that much movement of sediment occurred as turbidite flows. Moussa (1977) demonstrated that gravity sliding of shallow water reefal banks can result in their emplacement as undisturbed fragments in deep-water sediments. Ginsburg (1978, AAPG Disting. Lect.) also observed the emplacement of shallow-water reefal limestone on the Bahama banks into deeper environments by the "calving" of overhanging reef edges and subsequent sliding into deeper water.

A similar mechanism is suggested for the origin of limestones within the Badger Creek Beds, and for limestone fragments found enclosed within Elkhorn Ridge Argillite and Vinegar Hill Beds an assemblage of chert, tuffs, greenstones, and conglomerates mapped across the central thesis area. Lack of breccias and the Permian age seems to preclude down-faulting from the Triassic Martin Bridge Formation as an origin (Prostka, 1962). The absence of tectonic breccias and mylonitic texture in surrounding sediment indicates that the limestone was not faulted into place after consolidation of the sediments. The overall uniformity on a local basis of limestone lithology and fossil content, and the absence of inclusions of rock type other than reefal limestones strongly suggests that the carbonates are contemporaneous with the enclosing sediments, and do not represent inclusions of an older terrane as suggested by Jones et al. (1977).

Previous workers (Brown and Thayer, 1968; Wheeler, 1976; Walker, 1977) considered the Badger Creek Beds to be Triassic to Jurassic in age, based upon lithologic similarity to the Rastus Formation of the Ironside quadrangle (Lowry, 1968) and the Hurwal Formation near Baker (Brooks, 1977; Prostka, 1962). However, the presence of Early Permian fossils from at least one and probably two localities in the limestones associated with Badger Creek Beds indicates that the units should undoubtedly be reassigned to Permian age, and are contemporaneous with the oceanic Elknorn Ridge Argillite, and the distal arc derived Vinegar Hill Beds. The coarseness in the sediments, and the association of spilitic lavas suggests that the Badger Creek Beds represent a proximal arc facies.

Total thickness of the Badger Creek Beds cannot accurately be estimated due to probable isoclinal folding. An estimate of 1500 to 3000 feet (440-900 m) seems reasonable.

Conditions of Metamorphism

Metamorphic grade in Badger Creek Beds did not reach temperatures or probably pressures as high as the oceanic or distal arc assembledge. Conodont coloration index indicates temperatures of 300° to 400°C for Badger Creek Beds, while Vinegar Hill Beds temperatures by the same criteria varied between 400° and 500°C (and were probably near the lower temperature). Metamorphic grade reached by oceanic Alamo Argillite pillow lavas appears to be even higher, into upper greenschist facies with the onset of green biotite. This lower P/T metamorphism is in part responsible for the relatively undeformed appearance of the Badger Creek Beds.

The 300-400°C range is within conditions of lower greenschist facies metamorphism. Chlorite is common in the few sections of Badger Creek Beds examined, but epidote is rare and where present is small and granular. At high fO_2 the stability field of epidote expands to about 220°C at one to six kb, and 300°C at seven kb (Liou, 1973), into the upper zeolite and prehnite-pumpellyite facies. It is likely that the high carbonate content of the Badger Creek Beds sediments may have buffered the system with respect to fO_2, so that initiation of epidote crystallization under conditions of one to six kb may have approached 300°C. The fine and dispersed nature of the epidote suggests that nucleation had commenced but growth had not proceeded. Wheeler (1976) reported the presence of pumpellyite in X-ray diffraction patterns from Badger Creek Beds. This writer, however, did not identify any in the limited number of Badger Creek Beds thin sections examined, and therefore, assigns the Badger Creek Beds to the threshold of lower greenschist facies rather than to the prehnite-pumpellyite facies.

Snow Creek Conglomerate

A coarse possibly arc, but probably continentally derived conglomerate containing well rounded clasts of bedded sediments, andesitic volcanics, and granitic rocks up to two feet (61 cm) in diameter is exposed in two small isolated areas on south-facing slopes above Snow and Slab Creeks in section 15, T. 10 S., R. 35 E.

The conglomerates are tectonically intruded and surrounded by serpentinite melange and tectonite metagabbro. The contact between the gabbro and conglomerate is sharp and slickensided, with no evidence of thermal effects. The boulder conglomerate is massive, with no discernible bedding. The matrix is light-brownish green; cobbles and boulders range from greenish-yellow grey for granitic clasts to dark pinkish grey for volcanics. Evenly spaced northwest trending joints, two to six inches apart, penetrate the outcrop, cutting both the matrix and clasts. No displacement was noted along the joints. Cobbles and boulders are elongated in a N. 40°W. direction parallel to the joint strike. Clast size decreases toward the west. The coarse portion of the conglomerate extends across an outcrop area no greater than 200 feet (61 m). Finer grained, related clastic rocks continue for about 800 feet (250 m) of discontinuous exposure.

Andesitic clasts are the most common type, comprising 51 percent of a 100 clast count. They range in size from less than one inch to 13 inches in maximum diameter and are usually phaneritic, although some are extremely fine grained. Plagioclase phenocrysts, usually about one mm in length can be distinguished in most volcanics.

Petrography

In thin section, andesite clasts are trachytic to pilotaxitic, with flow texture delineated by relict microlites. Plagioclase phenocrysts are rectangular to equant, and euhedral to slightly corroded in outline. Zoning is absent, and was possibly destroyed by re-equilibration during metamorphism. Relict zones are outlined by alteration products, most commonly chlorite and calcite, but occasionally epidote. Carlsbad and albite twins are well developed in most relict phenocrysts; pericline twinning is rare. Anorthite content of plagioclase determined from the albite and carlsbad-albite twins varies from An_{70-63} in more mafic clasts to An_{52-43} in more leucocratic volcanics. (Range in An content given above is the variation in determination of An in a single slide for all crystals measures, and does not refer to zonation within single crystals.) Quartz phenocrysts occur in Cg-4, a possibly dacitic clast which had less well developed pilotaxitic texture than other clasts examined in thin section, and contained less than five percent mafic constituents. The quartz was slightly corroded, clouded by chlorite and sphene, and had slightly wavy extinction.

Relict mafic phenocrysts in the andesitic clasts are apparently limited to dark green hornblende. The amphibole is extensively altered to colorless to light green plumose chlorite, light blue-green uralitic actinolite, and yellow to light-yellow green granular and poikiloblastic epidote. Simple twinning of relict hornblende is common.

The matrix of volcanic clasts consists of plagioclase microlites largely altered to calcite and chlorite, and a felted mat of chlorite, actinolite, and dispersed granular sphene altered to leucoxene.

Small nucleii of green biotite are scattered throughout the groundmass chlorite, and suggest that conditions of upper greenschist facies metamorphism were reached, but equilibrium was not attained.

Coarse to medium-grained granitic clasts are less abundant than the andesites (39 percent) but are slightly larger, reaching a maximum diameter of 2.1 feet (64 cm). In thin section granitic rocks range from biotite granodiorite to hornblende quartz diorite. Plagioclase is subhedral, and varies from An_{62} to An_{40}. It is unzoned but commonly twinned on albite and carlsbad laws, and pervasively replaced along relict zones and in cores by calcite, chlorite, and epidote in a manner similar to that observed in the andesite. Quartz and orthoclase feldspar are interstitial to the plagioclase, and are both extensively altered and replaced by calcite, chlorite, and fine white mica. Orthoclase was distinguished by staining methods in two slides, and was found to form patchy, probably secondary replacements in the interiors of plagioclase. Potassium feldspar comprises up to 12 percent of one granitic rock but is also virtually absent in other sections examined.

Mafic constituents of granitic rocks include relict biotite and hornblende. Biotite is replaced by light green chlorite and granular epidote. Hornblende is light to dark green, and ubiquitously replaced by chlorite, epidote, and actinolite. Irregular aggregates of sphene are partly altered to leucoxene. Accessory minerals--apatite and zircon--are present, and relatively unaltered. Zircon is embayed and cuspate in outline whereas apatite occurs in its characteristic habit of stubby prisms.

Bedded sediments are a rare constituent of the Snow Creek Conglomerate, and are present as small, rounded pebble to cobble sized clasts, less than one to three inches in diameter. Their small size suggests that they were either transported from a greater distance than the granites and andesites or that the (probable) cleaved and bedded nature of the source rock resulted in rapid reduction to small clast size. In outcrop, the bedded sediments are apparently quartzites, with alternating thin red-brown ferrigenous layers one to five mm thick and purer white bands, five -20 cm thick. In thin section, the alternating bands consist of granoblastic quartz with varying amounts of chlorite and hematite. Small, acicular blue-green actinolite occasionally transects the granoblastic fabric.

The matrix of the Snow Creek Conglomerate contains lithic clasts of annealed microcrystalline cherts or quartzite, recrystallized silicic turfs, and andesite volcanics and plagioclase, quartz, and rare potassium feldspar as mineral grains. One cupsate zircon fragment was noted in Cg-3. The metamorphic constituents of the matrix are poikiloblastic and granular epidote, occasionally developed in tabular poikilitic crystals, aggregates of chlorite and actinolite, albite usually in granoblastic segregations rimmed by chlorite and hydrous iron oxides, and fine green biotite within chlorite aggregates.

Age

The age of the Snow Creek Conglomerate is difficult to determine from field evidence. It is intruded tectonically by metagabbro and included in the serpentinite melange, but contains no fragments from that suite, so must be older than Late Triassic (Thayer and Brown, 1964). The pervasive jointing and tectonic elongation of clasts, as well as the incipient upper greenschist facies metamorphism suggest that the conglomerate was subjected to prolonged burial and strain, though not to excessively high pressures. This, coupled with the absence of any known Triassic assemblage of northeast Oregon containing similar lithologies, and the association of the unit with sedimentary terranes which, with the exception of local erosional products (Greenhorn Conglomerate) is entirely Permian, indicate that the Snow Creek Conglomerate is probably at least Early Permian in age.

Two other occurrences of conglomerates of similar form and lithologies have been noted in northeast Oregon. Wetherell (1960) mapped and described a discontinuous conglomerate which contained well-rounded pebble to boulder sized clasts of aphanitic to porphyritic volcanic (andesitic) and one granitic cobble in the Permian Trinity

Formation. Taubeneck (1969) reported granitic clasts of the Pennsylvanian Spotted Ridge formation of central Oregon up to 11 inches (28 cm) in length including granodiorite, quartz diorite, and quartz monazite. The clasts have undergone low grade metamorphism, and contain acicular actinolite.

Rocks of accepted age older than Devonian are unknown in northeast Oregon (Baldwin, 1964). Hence the age of the Snow Creek Conglomerate can be stated to lie between Middle Devonian and Late Triassic. However, based upon the close spatial association and similar metamorphic facies to the Early Permian section of the Greenhorn Mountains, the similarity of the Permian andesite boulder conglomerate of Wetherell (1960), and the possible affinity with the granitic clasts of the Pennsylvanian Spotted Ridge formation, the Snow Creek Conglomerate is tentatively assigned an Early Permian or Late Pennsylvanian age.

Origin and Significance

Rocks similar to clasts within the Snow Creek Conglomerate are not exposed in the Greenhorn Mountains, nor are they common within the Blue Mountain region. Pre-Jurassic granitic rocks are generally confined to the east parts of the Blue Mountain anticlinorium adjacent to the Snake River canyon, and have been noted in western Idaho by Hamilton (1963) and Hietanen (1963), where they are considered to represent the leading edge of Paleozoic continental crust. Volcanic rocks which may be the equivalent of the Snow Creek andesitic clasts have not been described in the literature to the writer's knowledge. However, pervasive greenschist metamorphism and spilitization of equivalent units might obscure textures and mineralogy sufficiently to confound attempts at comparison. Equivalent, more highly altered flows might be associated with the Seven Devils group of west Idaho or with the Permian section of the Snake River Canyon.

Coarse conglomerates of the type represented by the Snow Creek Conglomerate have been considered unshakable evidence of deposition in shallow water, with probably restriction to near-shore shelf facies. However, recent results of Deep Sea Drilling Project Legs 56 and 57 drilling and dredge hauls have disclosed the presence of a coarse, at least cobble-size conglomerate containing granitic and volcanic clasts at a depth of 2500 meters in the Japan trench (Curray, White, pers. comm., 1978). It may be assumed that the conglomerate was transported by a turbidity current from shallow water, but according to these Deep Sea Drilling Project results, presence of a coarse conglomerate along cannot be regarded as firm evidence for shallow water deposition.

Two depositional environments may be proposed for the origin of the Snow Creek Conglomerate:

First, the combination of granitic and andesitic clasts may signify an Aleutian type island arc where granitic rocks were eroded along with volcanics. Granitic exposures are common in the eastern Aleutians and topography is sufficiently youthful to engender coarse conglomerates. Formation of the conglomerates along an arc similar to the modern Aleutians might explain the bimodal andesitic and granitic character of the conglomerate.

This interpretation, however, rests upon the uncertain correlation of three widely scattered and heretofore uncorrelated formations. It is an interesting possibility which might bear further investigation. The association of bedded, quartz-rich sediments in the conglomerate is difficult but not impossible to consign to an arc origin. A second, and more plausible explanation for the Snow Creek Conglomerate is an origin from a shelf or continental fragment of westward-advancing North American continent with an Andean-type margin, and inclusion in the Greenhorn ophiolitic assemblage by tectonic transport within a serpentinite melange. Shelf facies have been noted by Vallier et al. (1977) to extend in a broad, east-west belt across southern portions of the Blue Mountains, and are included in serpentinite melange in central Oregon exposures. Transport of the Snow Creek Conglomerate as an exotic block within the melange is not unlikely and is adopted here as the probable origin of the unit.

Vinegar Hill Beds

The siliceous and volcanoclastic sediments along the axis of Vinegar Hill extend roughly east-west through the southern portion of the thesis area. These rocks are distinct in appearance and metamorphic grade from Elkhorn Ridge Argillite. For purposes of discussion they have been subdivided into four units: chert, tuffs and volcanoclastics, conglomerates and shales, and volcanic flows.

Cherts

Red to red-brown chert and highly siliceous argillites occur at the summit of Vinegar Hill and form resistant ridge crests through the central portion of the thesis area. Although degree and style of deformation varies between outcrops, the unit is usually penetrated by a well developed axial plane cleavage parallel to bedding. True ribbon cherts are rare in the Vinegar Hill Beds. Instead, siliceous layers one to two inches (four to six centimeters) in width alternate with equal bands of grey argillite. The contorted small scale folds characteristic of the Elkhorn Ridge Argillite are absent from these red Vinegar Hill Beds.

Intraformational conglomerates with elongate clasts of grey argillite in a red matrix are found on Vinegar Hill. The clasts are three to six inches (eight to 15 centimeters) long, disoriented, and brittly deformed with closely spaced, en echelon shears. There is no consistency to left or right lateral direction, although left lateral offsets were tabulated in a majority of 20 fractured clasts. The chaotic nature of the conglomerates, and the exclusive inclusion of siliceous argillite wihtin the chert suggest that they resulted from soft sediment deformation. Recently Keene (1976) showed that the apparent brittle deformation of clasts within chert deposits may be a consequence of silica migration and subsequent strain during diagenesis. The brittle deformation of the chert clasts occurred after initial disruption of bedding but prior to final sediment consolidation.

Sediments on Rosey Finch Ridge (section 19, north of Squaw Rock) are deformed in a great variety of fold styles, ranging from tight chevron folds to broad, gentle undulations. Folding is discontinuous and apparently disharmonic. Bedding is disrupted at the base and apex of many tight folds. The irregularity of folding and disturbed nature of the sediments are highly suggestive of soft sediment deformation. Schweikart et al. (1977) described similar chaotic features from the Calaveras Complex of the western Sierra Nevada, which he has categorized as "type II diamictite." The Calaveras rocks range from highly siliceous argillite to cherts, and grade abruptly from continuously layered sections into "closely packed slabs of once continuous chert beds" and intraformational conglomerates of "subparallel chert slabs in a dark, argillaceous matrix" (p. 326).

Figure 4a. Intra-formational breccia, Vinegar Hill Cherts. Note brittle deformation of clast on the far left.

Figure 4b. Rhythmically bedded chert and argillite of Vinegar Hill chert, Rosey Finch Ridge.

Schweikart et al. (1977) attributed the chaotic disrupted nature of the Calaveras to submarine sliding. Cox and Pratt (1975) also noted similar intraformational conglomerates in the Klamaths, and suggested the association of these features with submarine slides. Similar disruption of bedding has been noted in Deep Sea Drilling Project (DSDP) cores from Sunda Arc subduction zone slides surveyed by reflection profiling (Moore et al., 1976; Moore, 1978, pers. comm.). Field evidence, then, suggests that soft sediment deformation and submarine sliding were important processes to the development of the Vinegar Hill Bed assembledge.

Thin sections of cherts are a mixture of cryptocrystalline and microcrystalline quartz with chlorite and albite. Albite is not readily determinable in thin section, but is evident on whole rock X-ray diffraction patterns. Red-brown layers contain a higher percentage of iron oxide (hematite). In cherts exposed to contact metamorphism by granitic intrusions, granoblastic textures are developed in the quartz-albite matrix, and porphyroblasts of slightly poikilitic red-brown biotite reach diameters of about one millimeter. In sections with no thermal metamorphic effects, but sufficient Fe and Al, pumpellyite and/or stilpnomelane are developed. Pumpellyite occurs as small, rectangular prisms, 0.05 mm in length, faintly pleochroic, yellow to clear. It commonly displays lamellar twinning on (100), and has an extinction angle of about 28°. Stilpnomelane in all samples has retrograded to chlorite, and is restricted to iron-rich bands within the cherts, where it is characteristically a bright yellow to dark reddish-brown on α-B. It is too fine in thin section to obtain a reliable figure, but was confirmed in A-12 by X-ray diffraction.

Conglomerates and Shales

A lens of black shale and intercalated pebble conglomerate extends along the northeast side of Vinegar Hill. The unit contains equal amounts of shale and conglomerate; sandstone or wacke is rare. Shale is dark blue-grey to black and usually fissile, although it does not approach the extreme fissility of a pencil shale. An east-west slaty cleavage is well developed in some exposures, notably south of the Morris Mine where very fine sandy lenses two to four mm thick are interbedded with shale. Bedding is parallel to cleavage.

The light reddish-brown conglomerates contain rounded to subround chert and volcanic pebbles usually less than an inch (2.54 cm) in diameter. Pebbles in some exposures have been tectonically elongated parallel to regional strike, about N. 80 E. This elongation was probably initiated by the emplacement of the gabbro-serpentinite series, and in some outcrops near Ben Harrison Peak appears enhanced by forceful granitic intrusion. The apparent strike of pebble elongation west of Upper Olive Lake is N. 65-70 W. in contrast to the almost uniform northeast strike through the Greenhorns and the region. Elongation of clasts at Upper Olive Lake was controlled by intrusion of the adjacent serpentinized peridotite among northwest-southeast trends.

The conglomerate matrix consists of clays altered to chlorite, quartz, and albite, with rare granular aggregates of epidote. Clasts are fine-grained felsites, volcanics, and microcrystalline quartz (chert?). Wavy stringers of iron encompass many clasts. Fine iron oxides are disseminated through the groundmass. Neither pumpellyite nor stilpnomelane were noted in thin section. Green biotite is absent, and actinolite and blue-green hornblende occur as effects of thermal metamorphism.

From the close spatial association of the conglomerates with chert on Vinegar Hill, the conformable contact at that location, the low-greenschist metamorphism, and the large percent of andesite and felsite clasts included in the conglomerate, the shale-conglomerate units are assigned to the Vinegar Hill Beds. However, the units are also similar in appearance and lithology to sediments which have been correlated with the Elkhorn Ridge Argillite by previous workers, including Gilluly (1937) and Prostka (1962). This association should not be overlooked. Conglomerates of similar but often more mafic lithology are sporadically distributed through the Elkhorn Ridge Argillite, and the Alamo Argillite, the equivalent unit in the thesis area. The shales and conglomerates may represent a facies which is transitional from the arc-derived sequence to a more pelagic sediment.

Volcanoclastics

Tuffaceous, fine to medium-grained volcanoclastics comprise up to 50 percent of the Vinegar Hill Beds. In outcrop they range from a light to dark yellow green with thin veins of albite and quartz common. Cleavage is closely spaced and near vertical.

Thin sections contain a matrix of quartz, albite, and disseminated chlorite, with extremely fine volcanic rock fragments. Clasts of volcanic rock are sub-angular to sub-round, 0.1-0.9 mm in diameter, and finely crystalline basalt to andesite. Strings of dark green chlorite and iron oxide cut through the rock and rim clasts. Quartz, chlorite, albite, actinolite, and epidote + clinozoisite are usual constituents of the volcanoclastics. Sphene is an abundant accessory.

Volcanoclastic rocks of the Vinegar Hill Beds contain pumpellyite in exposures closely associated with the serpentinite melange. In V-80 from the North Fork of the Burnt River, sections 12 and 13, pumpellyite occurs as light yellow-green to clear slightly corroded crystals twinned on (100). The pumpellyite is deformed and alters to chlorite + calcite. Actinolite is faint green and occurs both as subidiomorphic crystals and as fine aggregates of acicular crystals rimmed by chlorite. Epidote is granular, idiomorphic, faint yellow,

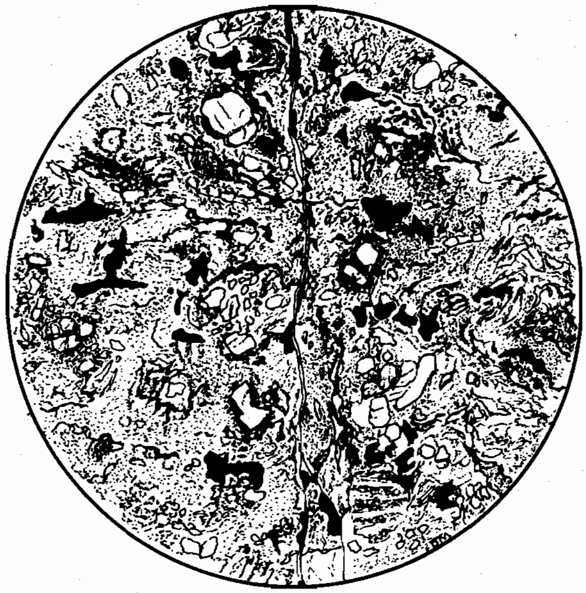


Figure 5. V-80. Pumpellyite greenstone, Vinegar Hill beds. Corroded and deformed pumpellyite (clear) in chlorite + albite + sphene + quartz matrix. X 40.

and does not show the deformation characteristic of pumpellyite and actinolite. Relict clinopyroxene is altered to chlorite, and can be distinguished only by the slightly higher relief in plane light. Pervasive alteration causes it to "disappear" when nicols are crossed. Extinction angles of the pyroxene appear to be 35°-38°; pyroxene cleavage is also evident in some relicts. Carbonate is found in segregations of quartz-albite and as replacement-alteration patches around epidote. This rock probably represents a mafic volcanoclastic with a fairly large amount of tuffaceous material.

V-22, from section 8 on the east side of Vinegar Hill contains more mafic clasts than V-80. Iron enriched areas of V-22 contain actinolite + chlorite + epidote + albite + pumpellyite + quartz + prehnite. In clasts low in original iron content, clinozoisite has developed instead of epidote. Idioblastic pumpellyite is deformed and usually rimmed by a light red-brown to green brown amphibole, which also forms stout acicular crystals. Optical properties suggest kaersutite. Prehnite occurs in radiating, bow-tie clusters in the more siliceous and calcic areas of the slide. The original texture of the rock has been obliterated by deformation, leaving the quartz-albite matrix in wavy bands and allowing the idioblastic growth of pumpellyite. A second episode of deformation was followed by the growth of epidote and amphiboles at slightly elevated temperature.

Tuffs

Tuffaceous rocks are usually light grey to brown and are commonly found in close spatial association with flow rocks and volcanoclastics. They are usually massive and siliceous, with an uneven fracture and porcellaneous texture. Precise thickness and lateral extent of each tuffaceous unit cannot be accurately determined due to limited exposure or tectonic disruption by intruding serpentinite. A thickness of less than about 100 feet (30 m) per unit seems reasonable.

Thin sections display feathery intergrowths of quarts and albite with iron oxides evenly distributed as small blobs and rare octahedra. Idioblastic pumpellyite, 0.10 to 0.30 mm, light green to light yellow-green with occasional lamellar twinning parallel to (100) is developed in A-6 as slightly corroded, tabular porphyroblasts. Chlorite and sphene are common in all sections.

Volcanic Greenstones

Volcanic greenstones associated with the arc-origin sediments are light to medium green, aphanitic, and highly chloritic. Closely spaced cleavage, combined with inherent softness due to high chlorite content results in low topographic expression and poor exposure. Relatively fresh samples, however, were collected from a U.S.

Forest Service quarry in section 16 near the Banner Mine. The greenstone may be more closely related to the proximal arc Badger Creek Beds than to the Vinegar Hill distal arc sediments, and may be tectonically mixed in the melange with the distal arc sequence.

In thin section the volcanic greenstone (V-252) is extremely fine-grained with small plagioclase phenocrysts, 0.10 mm in length. The rock has a diabasic or sub-ophitic texture. Plagioclase is albite, replaced by chlorite and some calcite. Chlorite is the predominant constituent of the rock, and fills much of the matrix. Small granular epidote is distributed randomly through the rock. Actinolite is rare, and where present forms tiny felted aggregates on the borders of plagioclase laths. Iron ore is interstitial, filling gaps between plagioclase. Evidence for the occurrence of mafic phenocrysts is lacking; no pseudomorphs of relict phenocrysts were noted in thin section. Small, relicts of groundmass pyroxene are present in the slide, however. No pumpellyite or stilpnomelane were identified in mafic greenstones.

Chemistry

One sample from volcanic greenstone associated with the arc sediments was chemically analyzed (V-252). Results are compatible with analyses of other spilitic greenstones of northeast Oregon (Vallier and Batiza, 1976), spilites from the Semail ophiolite (Coleman, 1977) and analyses reported by Amstutz (1968). The rock is enriched in SiO_2 and Na_2O, and depleted in MgO and Al_2O_3 with respect to both average basalt analyses and the alkalic Olive Creek pillow lavas of the oceanic terrane. V-252 is also depleted in Sr and Zr with respect to the Olive Creek pillow sequence. This variaton is compatible with the greater degree of spilitization observed in the Vinegar Hill Beds greenstones. The two series of greenstone are probably separate and genetically unrelated, and the processes and environment responsible for spilitization were not as strongly imposed upon the Olive Creek pillow lava series as upon the Vinegar Hill Bed greenstones. Vallance (1969) noted that spilitization occurs at pH of seven to ten in hydrous, low redox, low P and T conditions. P_{CO_2} is not critical to the process. Cann (1969) suggested that spilites form in environments of low shear stress. If these relations are true, they indicate that spilitization of V-252 accompanied low stress greenschist metamorphism and preceded deformation. The variation in degree of spilitization between V-252 and the Olive Creek series may be related to the original chemistry of the rocks, redox conditions, availability to hydrothermal alteration, and probably higher stress and metamorphic grade imposed upon the Olive Creek series.

Age

A large limestone pod associated with volcanoclastic sediment of the Vinegar Hill Beds yielded brachiopods, crinoids, bryozoa, and a conodont bar fragment, none of which were sufficiently well preserved for dating. The conodont fragment, however, places an upper age limit of Triassic on the associated sediments.

Arc-derived greenstones and volcanoclastics of the Clover Creek Group (Gilluly, 1937) have been assigned to Permian and Triassic ages (Gilluly, 1937; Prostka, 1962; Bostwick and Koch, 1962). Both Prostka (1962) and Bostwick and Koch (1962), noted that the Permian of the Clover Creek Group increase westward across the Blue Mountains. The Vinegar Hill Beds are assigned a Permian age based upon their close association with Permian sediments to the north and south in the Greenhorn Mountains, and their location near the west extremity of the region considered by Bostwick and Koch (1962).

Origin and Metamorphism

Abundance of volcanic detritus with a comparatively low percentage of mafic phenocrysts and mafic components, the intercalation of keratophyre tuffs with volcanoclastic sediments, and the presence of fine conglomerates containing volcanic clasts suggest that the Vinegar Hill Beds originated near an island arc. Siliceous sediments and oozes are common in cores from Deep Sea Drilling Project sites near arcs. Features of soft sediment deformation noted in the

Vinegar Hill cherts may have been caused by slumping due to submarine erosion seismic activity (Berger, 1977).

The Vinegar Hill cherts might also represent pelagic and arc-derived sediments which were deposited and deformed in a fore-arc accretionary wedge (Karig and Sharman, 1976). The presence of such wedges has been demonstrated by seismic reflection profiling along several major trenches (Japan, Sunda, Aleutian), and the presence of a substantial arc-derived component in the wedge sediments has been observed in results from Leg 57 of the Deep Sea Drilling Project (Curray, pers. comm., 1978).

The Vinegar Hill Beds are extensively intruded and disrupted by sheared serpentinite. Large "pods" of chert, tuff, volcanoclastics, and greenstone up to several hundred feet in length are enclosed in a serpentinite matrix and form an irregular topography along the crest and southern slopes of Vinegar Hill.

Metamorphic grade varies across the Vinegar Hill Beds. Regional metamorphism is over-printed by thermal metamorphism in western regions of the thesis area around Rosey Finch Ridge. Regional grade is prehnite-pumpellyite in some eastern exposures and especially in those rocks included in the serpentinite melange. The relatively clear color of the pumpellyite in these units suggests metamorphism at pressures above about five kb (Seiki, 1963).

Rocks of the Vinegar Hill Beds not obviously enclosed in serpentinite are metamorphosed in lower greenschist facies. Temperatures of metamorphism determined from conodonts in a limestone pod in section 16 near the Parkerville Mine suggests metamorphic temperature maximum of 400-500°C (Wardlaw, 1978, pers. comm.). Absence of any biotite from the associated volcanoclastic sediments indicates that temperatures were near the low end of this range.

Thus, two metamorphic facies--prehnite-pumpellyite and lower greenschist are represented in the Vinegar Hill Beds. Restriction of the higher pressure pumpellyite assembledge to clasts included in serpentinite suggests that the higher P conditions may be related to emplacement with the serpentinite, or that these clasts may represent sediment metamorphosed at relatively shallow depths in a subduction zone and emplaced by tectonic transport within rising sheared serpentinite.

Elkhorn Ridge Argillite

A thick and pervasively deformed series of pelagic cherts, siliceous argillites, fine greywackes, both sheared and rounded pebble conglomerates, discontinuous lenticular limestones, tuffaceous sediments, and intercalated greenstones and pillow lavas comprises the pre-Tertiary oceanic terrane of the Greenhorn Mountains. The appearance and relative overall abundance of the units are similar to the Elkhorn Ridge Argillite described previously by many workers such as Gilluly (1937), Taubeneck (1955), and Prostka (1962) from adjacent area.

From field appearance and petrography, units of the Greenhorns equivalent to the Elkhorn Ridge Argillite have been subdivided into two members, the Alamo Argillite which consists predominantly of radiolarian ribbon cherts with some fine greywackes and argillite and intercalated Olive Creek pillow lavas.

The name "Alamo Argillite" is used throughout this thesis in reference to exposures of chert and siliceous argillite within the thesis area which are equivalent to the regional Elkhorn Ridge Argillite to avoid confusion between local and regional references in discussions. The name "Alamo Argillite" is not proposed as a formal designation.

Alamo Argillite

Chert and siliceous sediments mapped as Alamo Argillite form steep slopes and small cliffs in the northeast portions of the thesis area. Grey to black argillaceous ribbon cherts consisting of highly siliceous layers two to four inches (five to ten cm) thick alternating with thin laminae (two to five mm) of easily parted, fissile black clays are the most common rock type, comprising 80 percent of noted exposures. Many cherts contain small, round siliceous blobs which may represent recrystallized radiolarians, or may be diagenetic in origin. Red chert was noted in only one location associated with Alamo Argillite, and appeared to be higher in clay content than other, black to light grey cherts which are more characteristic. Bedding of Alamo ribbon cherts varies from highly contorted, usually concentric folds which range from chevron to open in style, to evenly layered, unfolded, flat strata. Soft sediment deformation may in part be responsible for the variation in deformational styles, but the regional subalignment of fold axes (see structure), and strong development of axial plane cleavage suggests that most folding is of tectonic origin.

No clear-cut distinction between chert and siliceous argillite is possible. The rock types are gradational, and each outcrop contains rocks which vary considerably in clay content. Many units high in tuff and/or clays appear to be light grey on fresh surfaces, whereas cherts frequently are black due possibly higher graphite content. However, this generalization cannot be universally applied.

Siliceous argillite is non-fissile, and commonly displays nearly concoidal fractures characteristic of cherts. Rhythmic, two to four inch (five to ten cm) bedding is also common to many siliceous argillites. Tuffaceous members of Alamo Argillite are infrequently exposed, and are intercalated between layers of more siliceous, resistant beds. They are unusually light green, thin but non-fissile, and probably silicified by migration of silica from adjacent beds.

Greywacke, noted only in one road cut along Olive Creek, is very finely bedded, with slight expression of grading, and did not exceed ten feet (three meters) in thickness. Similar greywackes may be intercalated elsewhere with more siliceous argillite, but due to their less resistant nature are limited in exposure.

Sheared conglomerates which contain lenticular clasts of chert and altered volcanic rocks, 0.4 cm to two cm in length, bounded by stringers of chlorite and graphite occur sporadically in the Alamo Argillite. Like greywacke, conglomerates are exposed only in roadcuts due to their less resistant nature.

The durable quality of chert and siliceous argillite result in their preferential availability for examination, and there is a tendency to disregard the potential abundance and importance of tuffs, wackes, and conglomerates. In the area mapped as Alamo Argillite, the more resistant rock predominates (60 to 70 percent of exposure). The remaining unexposed rock probably consists of tuffs and wackes, but the approximate percentage of each cannot be determined. However, overall abundances of chert, cherty argillite, tuff, and tuffaceous argillite probably agree closely with the estimate of Gilluly (1937) for the Elkhorn Ridge Argillite as a whole.

Petrography. Cherts and siliceous argillites consist of varying proportions of microcrystalline quartz, with fine chlorite and occasional graphite aligned along cleavage planes at an acute angle to bedding. Small rhombs of calcite are secondary in origin, and commonly seem to crosscut the lamination developed as S_2 parallel to cleavage. Iron ore and possibly rare sphene are disseminated through the matrix.

The tuffaceous argillite contains occasional small plagioclase phenocrysts, of probably intermediate (andesine?) composition, and an extremely fine-grained matrix consisting of quartz plus penninite (chlorite).

Wackes contain sub-round quartz and plagioclase grains, with small segregations of chlorite which may represent altered volcanic clasts. Quartz is the dominant constituent, comprising in excess of 80 percent of the rock. Hence the fine wackes associated with the Alamo Argillite might best be classified as lithic arenites (Pettijohn, 1975).

The sheared conglomerates contain clasts of pink, grey, or black chert which display no distinctive qualities in thin section. Chert and siliceous argillite clasts are microcrystalline to cryptocrystalline and sub-angular where shearing has not obliterated original shape. Volcanic fragments contain fine plagioclase laths in a matrix largely replaced by chlorite and iron oxides. Occasional pyroxene(?) pseudomorphs are small, indistinct, and entirely replaced by aggregate chlorite. The volcanics are generally diabasic, with randomly oriented plagioclase, but due to alteration, distinction cannot be made between original diabasic versus intergranular or intersertal textures. Although one to five mm clasts of limestone have been noted in conglomerates of Elkhorn Ridge Argillite (Gilluly, 1937), none were observed in Alamo Argillite conglomerates. Fine stringers of chlorite and graphite(?), with occasional blobs of iron ore rim the clasts and extend through the section. The matrix material is chlorite and cataclastized and sutured quartz, with minor albite. Staining techniques and X-ray diffraction patterns revealed a substantial component of orthoclase dispersed throughout the slide forming replacements of quartz and, rarely, plagioclase phenocrysts in the volcanic fragments. The origin of most potassium feldspar is undoubtedly secondary, and may result from potassium metasomatism coincident with emplacement of nearby granitic rocks. Some orthoclase, however, may be an original feature of the sediments. High potassium content has been noted in many near-arc sediments of similar lithology (Hawkins, 1977, pers. comm.; Moore *et al.*, 1972).

Age. The Elkhorn Ridge Argillite, which is correlative to the Alamo Argillite has been dated as Permian by previous workers (Taubeneck, 1955; Bostwick and Koch, 1962) on the basis of both fusulinids from included limestone lenses and the intrusive relation of upper Triassic gabbros. Other workers have dated portions of the Elkhorn Ridge Argillite as Triassic (Bostwick, 1976, pers. comm.) from Pentacrinis in limestone pods. Both Permian and Triassic dates have been obtained from limestones which may be allochthonous, and hence may be somewhat older than the cherts of the Elkhorn Ridge Argillite. Jones et al. (1976) identified Jurassic radiolaria from cherts of the Canyon Mountain Complex, previously considered to be Paleozoic to early Triassic. However, Jones (1977, pers. comm.) and Vallier et al. (1977) now consider the radiolaria from the Canyon Mountain Complex to be of probable Triassic age. However, due to erosion, transport, and mixing of pelagic sediments, identification of a single radiolarian may be no more reliable means of dating the rock than yielded by allochthonous limestones (Berger, 1977; Riedel, 1978, pers. comm.).

Dates for Elkhorn Ridge Argillite, then, range from early Permian to mid-Triassic. Despite a thorough search, no identifiable radiolarians were recovered from the Alamo Argillite, nor were any identifiable fossils found in associated small limestone pods. The argillite is tectonically intruded by Triassic gabbro, so can be no younger than Middle Triassic. It is tentatively assigned a Permian age on the basis of similarity and proximity to parts of the Elkhorn Ridge Argillite in the Sumpter quadrangle dated by Taubeneck (1955) and Bostwick and Koch (1962) as Early Permian.

Thickness. Complex folding on both large and small scale make determination of the thickness of Alamo Argillite problematical. Previous workers have estimated the total thickness of the Elkhorn Ridge Argillite from 3,000 feet (Pardee and Hewitt, 1914) to in excess of 5,000 feet (Gilluly, 1937). Although Alamo Argillite represents only a portion of the Greenhorn sequence correlative to Elkhorn Ridge Argillite, no repetition of section was found, despite the presence of several units or unit sequences which were unique enough to serve as marker beds. A thickness of at least 5,000 feet is appropriate for the Alamo Argillite.

Origin. Many features of the Alamo Argillite are strongly suggestive of deep-water, marine origin. The generally fine and mature nature of the sediments associated with cherts indicate long transport from their source region. The fine and slightly graded nature of the wacke/lithic arenite is characteristic of distal turbidites, and again is indicative of deep-water deposition. Fine grained tuffaceous sediments are common in Deep Sea Drilling Project cores from abyssal sites (Moore et al., 1972), and are usually intercalated with siliceous and chalk-rich oozes which form cherts upon diagenesis (Keene, 1976; Keene and Kastner, 1974).

Radiolarians are common criteria for assigning a deepwater, marine environment of origin to siliceous sediments and cherts. Indeed, in post-Cretaceous formations which were deposited after the development of diatoms and their evident restriction to shallow coastal waters, such a designation is virtually unquestionable. However, the Elkhorn Ridge Argillite and Alamo Argillites are both of Permian age, and hence were deposited prior to the influx of diatoms and their sole association with shallow coastal waters. Prior to Cretaceous time, radiolarians may have occupied shallow as well as deep water ecological niches, and hence may not alone be a completely valid criteria for deep water deposition (Kastner, 1978, pers. comm.). However, from the fine nature of Alamo Argillite sediments, and the similarity between them and Deep Sea Drilling Project abyssal cores, as well as the presence of radiolaria, the Alamo Argillite is considered to have been deposited in deep marine water.

Olive Creek Pillow Lavas

Mafic greenstones which commonly exhibit rounded to ellipsoidal relict pillow structures, extend in a band approximately 3/4 mile in width in an east-west direction along regional strike near the south limit of the Alamo Argillite. The rock varies from a dense, dark green amphibolite where hornfelsed by the thermal aureole of the Tone Spring tonalite to a soft yellow-green greenstone speckled with dark clots of chlorite and epidote and a slightly more resistant uniform pinkish grey rock with elongate small white amygdaloidal fillings of calcite. The sequence of pillow lavas is underlain by a highly vesicular tuff and pillow breccia which contains brown spindle-shaped lapilli and elongate vesicular clasts in a greenstone matrix. Pillows ranging from three inches to two feet in diameter (eight to 61 cm) are readily discernible in outcrop as ellipsoidal to irregularly rounded segregations of slightly more resistant greenstone. They display concentric structure, and are somewhat lighter in color toward the edges. Dark chlorite bands which surround them may be remnants of original glassy rims; whitish rim material is a later growth of finely crystalline calcite + chlorite. Radiating vesicles enlarge and increase in abundance near the pillow rim. The marked vesicular nature of the pillow lavas and their association with vesicular bombs and fragments suggests that either the original magma contained abundant volatiles, or that it was extruded at fairly shallow depths (J. Moore, 1971). However, abundant vesicles have been reported in pillow lavas from 2-2.5 km depth (Hawkins, 1978, pers. comm.). The interior of pillows in yellow-green greenstone is riddled with small cavities, less than one centimeter in length. In contrast to vesicles, the internal holes show no radiating pattern although they are commonly elongated along the same axis as the pillow. The cavities are frequently coated by a thin rim of dark chlorite, similar in appearance though not quite as thick as chlorite rims on pillow exteriors. Calcite or, less commonly, calcite-albite-quartz fills some pillow interiors. The fine rims of chlorite around the larger interior cavities suggest that these cavities were a primary feature of the pillow, rimmed by glass in early cooling stages.

Material from interstices between pillows is friable and easily eroded except where the greenstone has been thermally metamorphosed. In the hornblende-hornfels aureole of the Tone Spring tonalite, interstitial areas are dense amphibolites with veins of calcite and quartz. Elsewhere, interstitial material apparently is chlorite, calcite, and sinuous veins of iron oxide and quartz.

Although pillows can be distinguished easily, they do not display obvious top and bottom relations. Foreset beds are not apparent. However, from the imbrication of individual pillows, particularly along Olive Creek and the Mann Placer Ditch, "top" seems to lie at the south side of exposures. Elongated pillows dip near-vertically, so that direction of flow is not readily determinable. Thickness of the pillowed sequence is estimated at 700 feet from the Olive Creek section.

Petrography. The pillow lavas are generally diabasic to sub-ophitic where original texture can be seen. Laths of plagioclase, in various stages of alteration and replacement, are frequently bent and aligned sub-parallel to the rim along pillow edges. In section V-212 albitized plagioclase laths one to two mm in maximum length are clustered in a few glomeroporphyritic groups. Unclustered plagioclase has a vaguely pilotaxitic texture in this slide.

Relict minerals are scarce. Interstitial clinopyroxene occurs in V-27 as 0.1-0.6 mm patches altering to chlorite and actinolite. Optically this clinopyroxene is brown to light purple, a titanaugite. 2V could not be clearly distinguished, but appeared to be in the

Figure 6a. Vesicular tuff breccia, Olive Creek volcanics, Alamo argillite series.

Figure 6b. Pillow lavas, Alamo argillite series. "Top" is to the left.

TABLE 1. MODES OF VOLCANIC GREENSTONES

	V27	V207	V215	V212	V217	V217a	V210	V88	V252	V280	V21	V218
Clinopyroxene	31.5	--	--	--	--	--	--	--	14.3	tr	--	--
Plagioclase	36.7	47.3	18.5	42.0	56.3	46.1	63.1	0.9	59.5	35.3	35.3	62.7
Quartz	tr	--	2.1	--	--	tr	--	--	tr	2.6	0.8	tr
Actinolite	4.2	tr	1.1	tr	tr	--	--	tr	tr	tr	0.5	10.2
Chlorite	14.3	29.3	54.0	35.7	39.1	10.3	21.4	4.1	20.7	48.1	58.2	tr
Clinozoisite	2.1	--	--	0.5	--	--	--	--	--	--	--	--
Epidote	--	1.2	22.7	--	--	--	--	--	--	--	--	--
Sphene	1.8	0.4	1.3	tr	1.2	2.7	2.9	--	2.8	4.9	4.1	5.1
Opaque	0.1	5.4	0.2	2.6	2.1	9.6	3.8	23.4	0.3	0.4	--	--
Calcite	1.4	14.6	0.2	18.7	14.1	31.2	8.0	20.8	54	0.4	--	--
Pumpellyite	--	--	--	--	--	--	--	--	--	7.2	--	--
Stilpnomelane	--	--	--	--	--	--	--	--	0.2	tr	tr	--
Brown biotite	--	--	--	--	--	--	--	--	--	--	tr	13.0
Green biotite	tr	tr	tr	0.3	tr	tr	0.4	tr	--	--	--	--
Sericite	tr	tr	tr	0.1	--	tr	--	51.7	--	--	0.7	--
SUM	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

normal 50° range for augites. Rare lamellar twinning was noted in two crystals. Titanaugite has important implications for the original character of the associated pillow lavas, suggesting an alkalic affinity.

Pseudomorphs of clinopyroxene and possibly olivine phenocrysts are present in nearly all slides of the pillow lavas examined. The original mineral is replaced commonly by a felted mat of chlorite which often contains granular epidote and/or acicular to aggregate light green actinolite. Occasional tabular clinozoisite occurs in V-27 and V-213. Granular calcite forms fine patches intimately associated with faintly yellow epidote. Dusty to globular iron oxides and sphene cluster along the edges of mafic pseudomorphs. Sphene is common in pseudomorphs as dispersed particles altering to leucoxene.

Plagioclase is partly altered to albite, and replaced by an aggregate of calcite, chlorite, sericite, and in areas adjacent to the tonalite intrusion, by occasional patches of prehnite. Replacement and alteration by these minerals generally follow albite or carlsbad twin planes.

One unusual example of pervasive alteration and calcification of the pillow lavas was observed in V-88. In outcrop, the rock varies little in appearance from other rocks of the sequence; it is dense, and light pinkish grey, with discrete pillows up to two feet in diameter. Plagioclase is replaced by a fine mat of calcite and white mica. Groundmass minerals consist exclusively of chlorite, calcite, sphene, and disseminated magnetite. Fine quartz-albite veins crosscut the section along cleavages. The most striking feature of the slide is strained calcite which fills vesicles. Calcite cleavage traces and twin lamellae are bent, indicating strain. The calcite has a slight 2-V of about 10° (less than aragonite) which is also evidence of strain.

There are two possibilities for the unusual alteration in V-88:

1. Replacement may have occurred as a result of Ca-metasomatism from nearby granitic intrusions. However, if metasomatism is the mechanism, it is difficult to explain the intense, post replacement strain of the calcite, unless major stress post-dated the intrusion. Alternatively, if calc-metasomatism preceded granitic intrusion, then the pluton itself could have imposed the requisite stress on the adjacent greenstones. Strain and elongation of sedimentary features near granitic contacts was noted both elsewhere in the Greenhorns (this report) and by Taubeneck (1957a). But if stress was imposed by a granitic intrusion immediately adjacent to the greenstone, then annealing and re-equilibration of the strained carbonate would be expected, and more pronounced thermal metamorphism should be developed. Furthermore, there is no clear evidence

of granitic rocks in close proximity to the greenstone, nor do similar greenstones adjacent to mapped granitic bodies show this pervasive alteration.

2. Replacement may be due to early regional greenschist metamorphism and re-equilibration of calcium within an extremely calcic rock, or to localized calcium metasomatism. Strain would then be subsequent to initial metamorphism. This seems a more plausible explanation than metasomatism related to granitic intrusion.

In more conventional pillow lavas, the groundmass consists of poorly crystalline chlorite with fine, irregular masses of quartz and albite, which encloses tabular to granular yellow pleochroic epidote, or in some slides, colorless clinozoisite. Epidote minerals in tabular form are usually slightly embayed. Actinolite, pale yellow green to light blue-green is usually acicular but does occur in felted aggregates of elongate laths within the groundmass. It also occasionally appears as fasicular sheaves. Green biotite is rare, and is found only as small nuclei widely dispersed through chlorite. It is pleochroic, yellow-green to dark-yellow-green, and exhibits typical micaceous "bird's eye" extinction. Vesicles are filled with chlorite + calcite + albite. Chlorite in vesicles and veins develops a fine, vermicular texture of inward wormy extensions with acicular actinolite. Sphene is granular, widely dispersed and pervasively altered to leucoxene. Apatite was noted in only two slides, as elongate prisms. Highly irregular, cuspate forms filled by clear chlorite, and rimmed by sphene and magnetite represent replacements of interstitial glass.

One thin section of material between pillows revealed fine, cuspate to semi-circular glass replaced by chlorite and calcite, in a matrix of chlorite, lath-like actinolite, and granoblastic albite + quartz.

The highly vesicular breccia contains volcanic fragments more pilotaxitic than generally found in pillow lavas, but the overall mineralogy and metamorphic textures are equivalent.

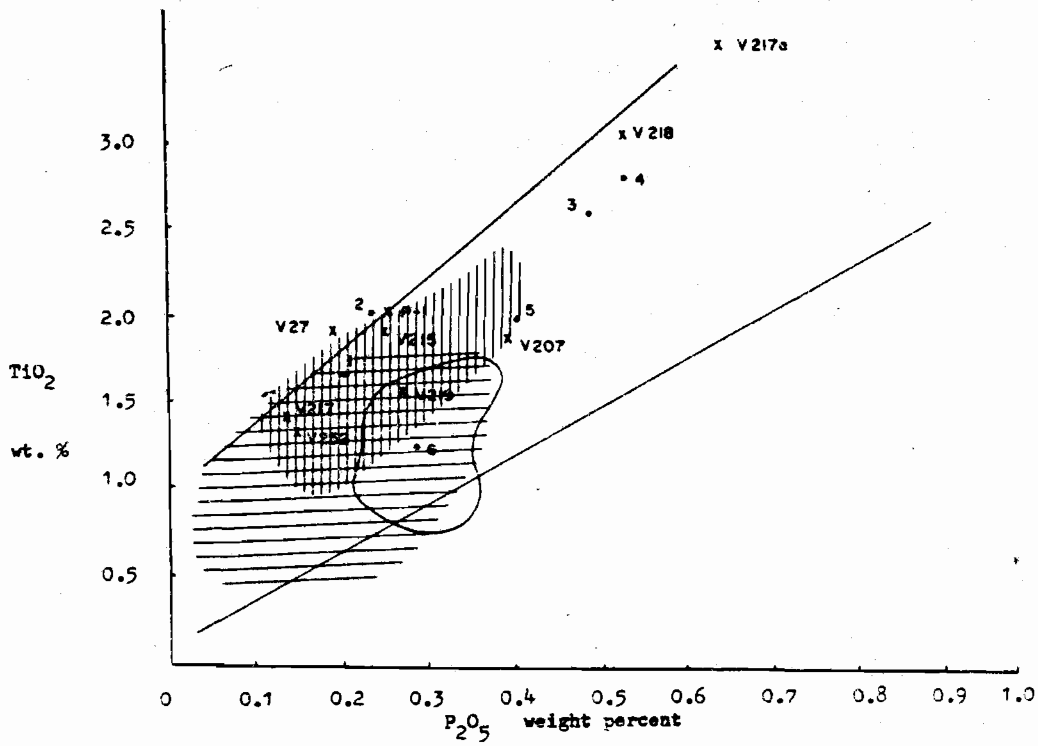
Chemistry. Analyses of whole rock samples from the Alamo Argillite pillow lava series (V-27, V-207, V-215, V-217, V-217a) indicate that the major oxide concentrations are in most cases comfortably within the range for basalt. SiO_2 varies between 46 and 50 percent, Al_2O_3 is 15-17 percent, Fe*O is 10-12 percent, CaO is six to eight percent, slightly low. Na_2O is depleted, 1.6 to about two percent whereas MgO varies from the six to seven percent usually found in basaltic rocks, to extreme enrichment, 18.5 percent in V-217. K_2O varies between 0.2-0.6 percent. The low content of Na is not surprising because of the low degree of spilitization observed in thin sections and the common replacement of plagioclase by calcite, and chlorite. Similar low values of Na in pillow lavas are reported from

TABLE 2. CHEMICAL ANALYSES OF VOLCANIC GREENSTONES*

	Olive Creek Pillow Lavas					Arc-Derived		Bennett Creek Schist	
	V-27	V-207	V-215	V-217	V-217a	V-252	V-80	V-89**	V-90**
SiO_2	50.64	50.00	51.46	45.91	49.70	50.60	56.70	69.07	48.41
Al_2O_3	17.33	16.80	15.52	15.19	17.35	18.24	12.80	14.17	16.73
TiO_2	1.92	1.80	1.80	1.30	2.72	1.25	0.55	0.72	0.67
CaO	9.03	5.96	7.12	8.84	5.90	5.92	9.83	1.50	9.12
Na_2O	1.01	3.14	2.10	0.92	1.12	4.60	1.27	4.90	2.80
K_2O	0.32	0.19	0.10	0.32	1.94	0.08	0.18	1.25	0.25
Fe*O	12.82	10.61	12.06	9.76	12.58	12.08	13.68	6.55	14.96
MgO	7.14	10.18	8.15	18.50	7.30	6.13	3.28	0.60	5.20
P_2O_5	0.18	0.40	0.25	0.14	0.61	0.16	0.12	0.13	0.11
SUM	99.94	99.08	98.56	100.12	99.22	99.05	98.41	99.00	98.27
TRACE ELEMENTS: ppm									
Ba	134	--	--	--	--	33	--	--	--
Ni	172	234	91	228	124	265	30	--	--
Sr	307	262	214	357	365	110	612	245	162
Zr	84	152	127	79	160	10	368	100	65

*See Appendix 2 for sample descriptions.

**V-89 and V-90 are Bennett Creek schists. V-89 was pelitic protolith, V-90 from volcanic.



1 Average oceanic tholeiite
2 Average tholeiite
3 Average tholeiitic andesite
4 Average alkalic andesite
5 Average Yakima basalt
6 Average andesite
7 Average Picture Gorge basalt

x Greenhorn greenstones

Snake River Canyon greenstones, Triassic

Snake River Canyon greenstones, Permian

Arc andesite field

Figure 7.

TiO_2-P_2O_5 relations,

Greenhorn and Snake River Canyon greenstones.

Data base, Vallier and Batiza, 1976.

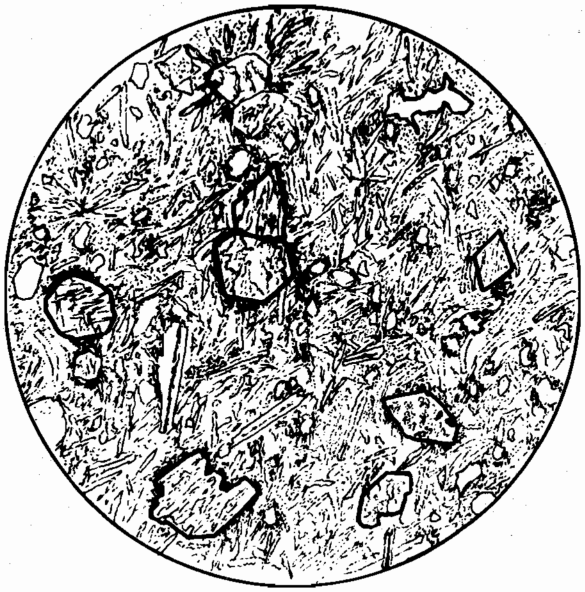
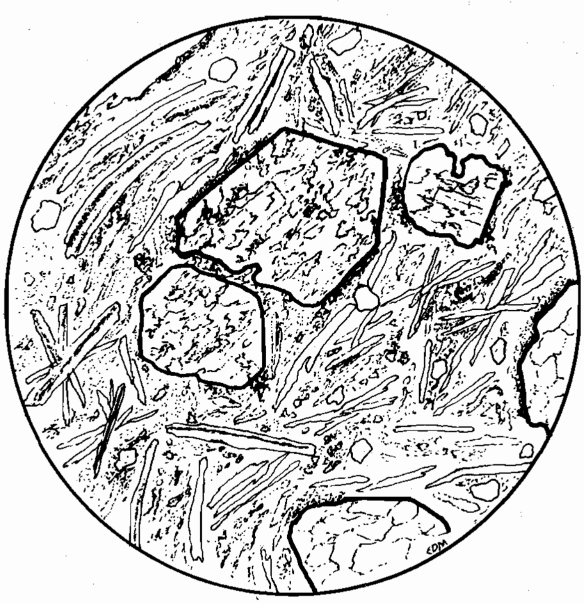


Figure 8. Olive Creek pillowed greenstones. V-212. Pyroxenes pseudomorphed by chlorite + calcite + sphene. Slightly glomoporphyritic pilotaxitic texture. N te bent but unbroken plagioclase laths. X 25 and X 40.



the Troodos ophiolite (Moores and Vine, 1971; Miyashiro, 1973; Coleman, 1977), and are also attributed to low degree of spilitization and low initial abundance of Na in basaltic lavas. However, low abundance of Na_2O in Olive Creek (Alamo) pillow lavas is in marked contrast to overall enrichment in Na_2O in spilitic Permian pillow lavas and related greenstones from the Snake River Canyon (Vallier, 1967; Vallier and Batiza, 1976). This contrast in values for sodium is probably a function of the degree of spilitization, which, as noted by Amstutz (1968) increases SiO_2 and Na_2O abundances yet decreases Fe*O, MgO, and CaO. Spilitization and albitization, in fact, seem to generally increase eastward from the Greenhorns to the area of the Snake River Canyon. The overall abundances of K_2O are low in Olive Creek pillow lavas, and are in accordance with the low K_2O abundances noted in Permian volcanics by Vallier and Batiza (1976). K_2O does not appear affected by the trend of increasing spilitization.

CaO contents of the pillow lavas may reflect low initial abundances in the lavas, or may be a function of removal of CaO during metamorphism and associated <u>slight</u> spilitization. Extensive alteration to calcite in some greenstones (V-88, for example), indicates that calcium was very mobile during metamorphism prior to late stages of deformation. Hence the depletion in calcium is probably related to ionic migration during some stage of metamorphism. The slight depletion in CaO is correlative to the trend for Permian rocks of the Snake River Canyon (Vallier and Batiza, 1976), and some ophiolitic pillow lavas, notably spilitic pillow lavas from Oman (Coleman, 1977), and Point Sal (Hopson et al., 1975). CaO in Olive Creek lavas is generally lower than reported for oceanic tholeiites or mid-ocean ridge basalts (ten-13 percent, Engel and Engel, 1964; Carmichael et al., 1975; Batiza et al., 1977) and for marginal basin basalts (Hawkins, 1976). However, CaO contents are equivalent to the analyses for some basalts of the Line Islands and Samoans (Natland, 1975), basalts and hawaiites from Hawaii and the Emperor seamounts (Clague, 1974), alkalic basalts of seamounts reported by Batiza (1977), and to other oceanic islands (Engel and Engel, 1964). It must also be noted that the six to eight percent range for CaO in Olive Creek pillow lavas is also lower by two or three percent than some analyses in the reportes cited above.

The extreme enrichment of MgO in V-217 is also probably related to metamorphic processes and ionic migration. Mid-Ocean Ridge basalt abundances generally range between nine and 11 percent (Carmichael et al., 1975; Batiza, 1977). Slight to strong low temperature alteration of oceanic tholeiites may result in one to two percent depletion of MgO (Hawkins, 1977). Enrichment of one to two percent in MgO by uptake of MgO by mid-ocean ridge basalt from percolating sea water during submarine greenschist facies metamorphism has been reported by some workers and may in part be responsible for the excessive MgO of V-217. However, contents of as much as 16.20 percent MgO have been reported from alkalic basalts of oceanic islands by Natland (1975). The high percent of magnesium in the sample is probably a primary feature of the basalt, enhanced by metasomatism during hydrothermal alteration.

Permian spilites of the Snake River Canyon are depleted in MgO, which may be a reflection again of more intense spilitization of rocks to the east, and may reflect water/rock ratio during alteration.

The field appearance of V-217 is noteworthy. In outcrop it is a light pinkish grey, in marked contrast to pillow lavas of similar grade elsewhere which are yellow-green. V-217a, collected approximately six feet (two meters) from V-217 (from an adjacent flow ?), conforms to the usual, yellow-green characteristics of most pillow lavas. Analysis of V-217a does not show the marked enrichment in MgO of V-217, and is correspondingly higher in SiO_2, Al_2O_3, Fe*O, TiO_2, and Na_2O, although depleted relative to CaO. This abrupt contrast in chemistry suggests that the difference is primary, reflecting the presence of two adjacent flows of vastly different (but generally alkalic) chemistry. Alternatively, metamorphic conditions may have allowed the concentration of ionic constituents in restricted locations with sharp or steep concentration gradients. Close proximity between basalts of radically different chemistry has been noted during dredging operations (A. E. Engel, 1978, pers. comm.), but of course, the precise location of each type and intervening distance was not well documented. The slight depletion of most pillow lavas in MgO suggests that ionic migration might play a role in V-217 enrichment, as does the progressive depletion of submarine basalts in MgO with increased alteration (Hawkins, 1976). However, textures of V-217 are not suggestive of appreciable replacement, and it is suggested that much of the high MgO is primary, possibly enhanced by metasomatism.

Iron contents (Fe*O) as noted, are within the ranges of normal basaltic rocks. Olive Creek pillow lavas do not exhibit the iron-enrichment noted by Cann (1969) for spilites; Fe*O is equivalent to slightly higher than in rocks of similar silica content in the Permian volcanic rocks of the Snake River Canyon (Vallier and Batiza, 1976).

Whole rock analyses for major oxides, then, indicated a probable low spilitization and substantial ionic conservation in the Olive Creek lavas. K_2O is low, and fits the trend noted by Vallier and Batiza for Snake River Canyon greenstones, but other chemical data are dissimilar to their findings. In particular, Na_2O and MgO differ from abundances found in Snake River Canyon. There is some correlation between whole rock chemistry of Olive Creek rocks and CaO, MgO and FeO from oceanic island lavas, but little correspondence between whole rock analyses and modern mid-ocean ridge basalt.

Alteration may in part account for variation in composition among greenstones.

Recent work (Cann, 1969; Pearce and Cann, 1973) has suggested that P_2O_5, Zr, and TiO_2 are immobile during greenschist facies metamorphism, and may be utilized to discriminate between original petrotectonic provinces of different basalt types. Vail (1977) utilized Zr/Ti plots to characterize the origin of ophiolitic greenstones and cumulates in the Oregon Mountain area of southwest Oregon; Ridley et al., used P_2O_5/TiO_2 to distinguish basalt types. Vallier and Batiza have applied a plot of P_2O_5/TiO_2 to rocks of the Snake River Canyon, and have thus shown that the Snake River Canyon rocks are similar to oceanic basalts, although they did not distinguish between oceanic, seamount, and arc related lavas. The analyses of Olive Creek lavas, plotted on a P_2O_5/TiO_2 diagram give similar results. Pillowed greenstones with the exception of V-217 plot within the range expected for basalts. Some workers (Hart, 1970; Hawkins, 1976, 1977 pers. comm.), however, have noted high probability of P_2O_5 mobility during sea-floor alteration, especially of seamount materials, which requires judicious consideration of this plot and its application on only a generalized basis.

On a Zr/Ti diagram, pillow lavas plot within or near the field of Hawaiian tholeiites, although there is some small overlap with the field of ocean floor basalts.

Mineral Analyses. In order to obtain more diagnostic data for the original character of the pillow lavas along Olive Creek, relict groundmass clinopyroxene (titanaugite) in sample V-27 (the only sample which contained relict clinopyroxene) was analyzed by electron microprobe. Feldspar and chlorite were also analyzed.

Clinopyroxene. Clinopyroxene composition has long been recognized as a reflection of chemical characteristics of the parent magma or rock type. Wilkinson (1956) noted that augites of alkalic rocks were significantly enriched with respect to calcium. Hess (1941) and Brown (1957) defined trends characteristic of tholeiitic magmas on ternary Mg-Ca-Fe plots. Kushiro (1960) noted that pyroxenes from silica-saturated, tholeiitic magmas have more silicon and less aluminum in tetrahedral sites, whereas pyroxenes from alkalic magmas are low in silicon and high in aluminum. Increase of titanium in pyroxenes of under-saturated volcanic rocks was attributed by Kushiro (1960) to the entrance of Ti, Al, and Fe^{+++} in the octahedral position due to an excessive negative charge from the increased amount of Al instead of Si in the tetrahedral position.

Recently, Garcia (1975) applied Mg-Ca-Fe differentiation trends of clinopyroxene composition and TiO_2/Al_2O_3 to determine the original character of altered volcanic suites. Work by Nisbet and Pearce (1977) expanded upon previous study, utilizing clinopyroxene Na_2O and MnO as well as discriminant functions for the classification of altered lavas into different tectonic settings.

Four relict titanaugites in sample V-27 were analyzed. Probe analyses vary within one or two percent due to either slight alteration of pyroxenes or partial analysis of small (0.1 μm) inclusions. The average of the three analyses is SiO_2 44 percent; Al_2O_3 seven percent; TiO_2 3.2 percent; CaO 19.6 percent; Na_2O 0.7 percent; MgO 9.5 percent; Fe*O 12 percent; MnO 0.21 percent; $En_{34}Wo_{42}Fs_{24}$. This analysis compares closely with that of typical titanaugite (Deer et al., 1965), but is significantly different than analyses of relict clinopyroxene from the arc-derived metavolcanics of the Snake River Canyon analyzed by Vallier and Batiza (1976) (see Table 5). The low silica content and high Al_2O_3 and TiO_2 suggest that the original character of the Olive Creek pillow lavas was alkalic, and undersaturated with respect to SiO_2. In contrast, SiO_2 is higher, and $Al_2O_3 + TiO_2$ lower in pyroxenes from the Snake River Canyon, suggesting that those lavas were less alkalic and closer to silica saturation.

Five relict clinopyroxenes from basaltic pods (now amphibolites) included in the Alpine Ultramafic rocks of the Greenhorns were also analyzed (P-1), and have compositions significantly different from pyroxenes of the pillow lavas. Results and interpretations are discussed under the separate section on amphibolite pods in discussion of the metagabbro.

Composition of analyzed V-27 clinopyroxenes were plotted on compositional diagrams to facilitate determination of original lave type and possible tectonic setting (Figures 9-13).

On a Mg-Ca-Fe ternary diagram, the Olive Creek (V-27) clinopyroxenes plot in a highly calcic position, well above the tholeiitic trend, and within the alkali-olivine basalt field defined by Wilkinson (1956). On plots of Al versus Si atomic proportions, V-27 clinopyroxene falls within the field of alkalic basalts also. Nisbet and Pearce (1977) have utilized a similar plot to discriminate between ocean floor basalts, within-plate tholeiites, and within plate alkali basalts. On this diagram, V-27 falls exclusively within the peralkaline, within plate alkali basalt plot. Nisbet and Pearce utilized two additional diagrams to distinguish between clinopyroxenes of major tectonic settings: SiO_2/TiO_2 weight percent, and a ternary MnO-TiO_2-Na_2O plot. On these diagrams V-27 clinopyroxenes plot the compositional ranges of within plate alkalic basalts.

According to available criteria, the clinopyroxenes from Olive Creek pillow basalts are relicts of an alkalic basalt extruded within a plate rather than at a plate margin. This strongly suggests the original, genetic association of the pillow lavas with a seamount, the most likely location of within plate submarine alkalic volcanism.

Feldspar. Probe analyses of feldspars revealed incomplete spilitization in V-27. Feldspar compositions range from An_{17-18} (oligoclase) in plagioclase which seemed secondary, to An_{69},

TABLE 3. FELDSPAR MICROPROBE ANALYSIS

	V-27		P-1*			
SiO_2	53.93	66.12	43.67	43.38	44.25	43.37
Al_2O_3	21.47	22.24	34.95	21.75	25.65	35.90
Na_2O	6.67	9.50	0.72	1.08	1.02	0.34
K_2O	2.50	0.07	0.07	0.24	0.67	0.01
CaO	3.17	3.88	18.75	15.73	15.29	20.05
TiO_2	0.14	0.04	0.02	0.34	0.29	0.00
MgO	3.48	0.03	0.00	3.79	2.97	0.00
Fe*O	4.41	0.31	0.14	9.75	9.65	0.53
BaO	0.04	0.06	0.02	0.00	0.00	0.29
SUM	95.82	98.25	98.35	96.07	99.79	99.99
An	66/17/16	81/18/1	6/93/1	10/89/1	10/85/4	3/97/0

*See Appendix 2 for sample descriptions.

labradorite. The spot size required for analysis of alkali-rich minerals included some chlorite rich alteration in one analysis (3.5 percent MgO, 0.4 percent Fe*O) which might otherwise have been more calcic.

Chlorite. Chlorites from V-27 are high in silica, and low in Al_2O_4 and MgO compared to ripidolites from chlorite-albite-epidote schists (Deer et al., 1965). Compositionally they are closest to penninite, though slightly higher in Fe*O.

Summary: Pillow Lava Affinity. Petrographic, whole-rock chemical, and microprobe data have been presented for the Alamo Argillite related Olive Creek pillow lavas which suggest the original alkalic nature of the rocks. The presence of titanaugite in V-27, and the whole-rock abundances of CaO, and MgO are indicative, but not compelling evidence for the alkalic affinities of the greenstone protolith. High concentration of TiO_2 and P_2O_5 in some pillowed greenstones is characteristic of alkalic magmas. The consistent association of V-27 relict clinopyroxene compositional parameters with those for pyroxenes of alkalic, within plate basalts is good indication that the pillow lavas were, indeed, alkalic. The pillowed nature of the greenstone, and its intimate association with deep-water, possibly abyssal, sediments requires its extrusion at depth in a sub-aqueous environment. Furthermore, exposures of the greenstone associated with the argillite are comparatively rare,

TABLE 4. RELICT CLINOPYROXENE PROBE ANALYSES

	V-27*			P-1*				
	101	102	103	101	102	103	201	202
SiO_2	46.58	44.01	41.05	47.70	46.46	49.37	51.24	48.80
Al_2O_3	6.28	6.93	7.56	5.11	7.24	3.96	2.02	5.06
TiO_2	3.34	2.74	3.62	0.33	0.42	0.31	0.16	0.34
CaO	20.06	19.67	19.07	16.57	14.87	16.37	21.39	15.72
Na_2O	0.84	0.55	0.63	0.681	0.97	0.61	0.34	0.68
MgO	8.80	9.11	10.43	10.59	9.19	11.48	11.33	11.15
Fe*O	11.37	12.29	12.13	15.32	15.78	14.74	13.10	15.69
MnO	0.24	0.22	0.14	0.23	0.25	0.29	0.38	0.30
Cr_2O_3	0.09	0.02	0.09	0.02	0.000	0.04	0.03	0.00
SUM	97.60	95.00	95.20	96.55	95.20	97.17	99.99	97.72
En/Wo/Fs	32/45/23	33/42/25	36/39/25	35/35/30	35/32/34	38/35/27	34/41/23	38/33/30
Ti/Cr+Al+Ti	0.252	0.201	0.233	0.039			0.047	

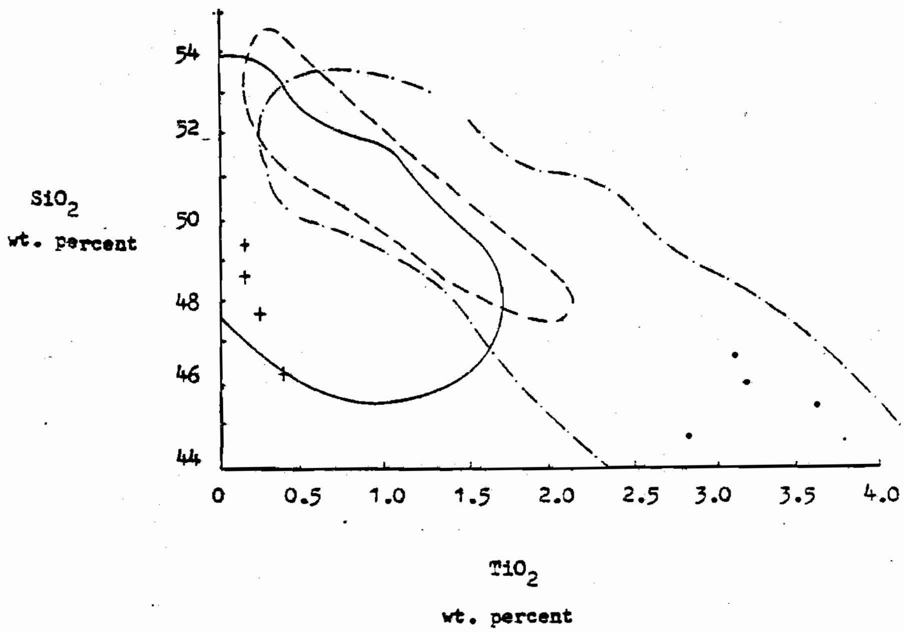
*See Appendix 2 for sample description.

TABLE 5. COMPARATIVE RELICT CLINOPYROXENE CHEMISTRY

	V-27 Average	P-1 Average	SRC Average**
SiO_2	43.88	48.71	30.4
Al_2O_3	6.92	4.68	4.3
TiO_2	3.23	0.31	0.47
CaO	19.60	16.98	18.48
Na_2O	0.67	0.66	0.27
K_2O	--	--	0.04
MgO	9.45	10.75	14.90
Fe*O	11.93	14.93	11.19
MnO	0.20	0.29	0.32
Cr_2O_3	0.06	0.01	--
TOTAL	96.94	97.32	99.85

*See Appendix 2 for sample description.

**Average from Permian greenstones of the Snake River Canyon. (Vallier and Batiza, 1976, Table 5).



• V-27 Pillow basalt, Olive Creek

+ P-1 Amphibolite in ultramafic

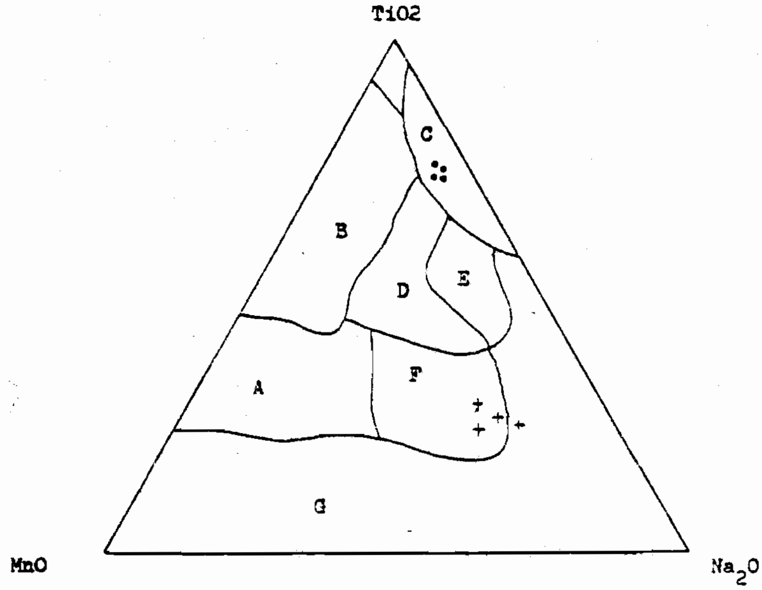
- - - Ocean floor basalt field

—·— Within plate alkali basalt field

—— Volcanic arc basalt field

Figure 9. SiO_2 - TiO_2 relations in clinopyroxenes from basalts of major plate tectonic provinces.

Data base from Nesbit and Pearce, 1977.



• V-27 Pillow lava, Olive Creek

\+ P-1 Amphibolite in ultramafic

A Volcanic arc basalts

B Ocean floor basalts

C Within-plate alkali basalts

D All basalts

E VAB + WPA + Within plate Tholeiites

F VAB + WPA

G Within plate tholeiites

Figure 10. $TiO_2/MnO/Na_2O$ compositions of clinopyroxenes from basalts of major plate-tectonic provinces.

Data base from Nesbit and Pearce, 1977.

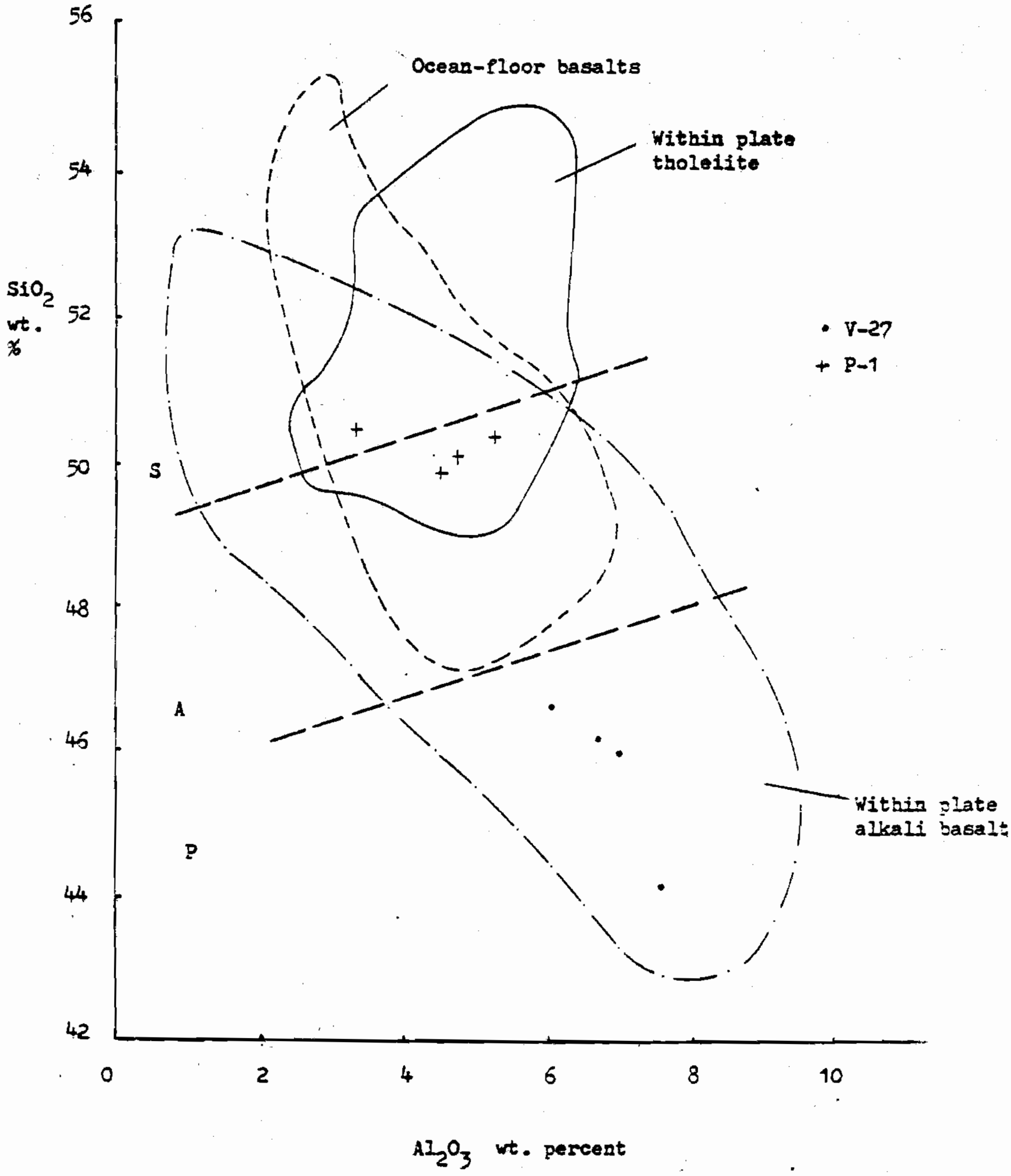
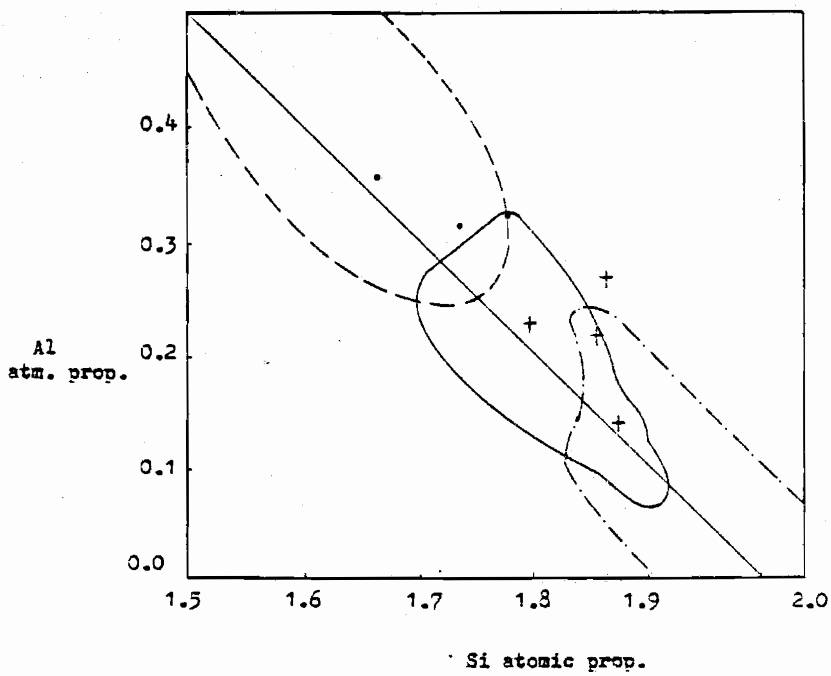


Figure 11. SiO_2 - Al_2O_3 relations in clinopyroxenes from basalts of major plate tectonic provinces.

S subalkaline
A alkaline
P peralkaline

Data base from Nesbit and Pearce, 1977.



• V-27 Pillow lavas, Olive Creek

+ P-1 Amphibolite in ultramafic

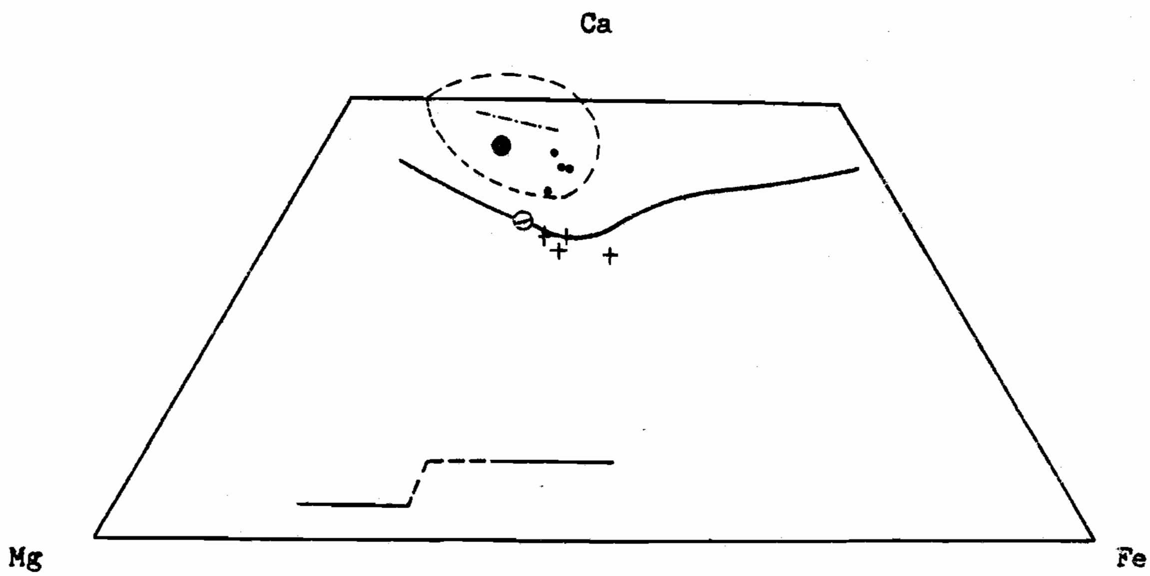
-·- Tholeiites

— Feldspathoid-bearing alkalic basalts

--- Alkalic basalts.

Figure 12. Si-Al Relations in clinopyroxenes from basaltic lavas

Data base from Kushiro (1960)



•	V-27	Pillow lavas, Olive Creek
+	P-1	Amphibolite in ultramafic
●		Pillow lava, Snake River Canyon (Vallier and Batiza, 1977)
⊖		East Pacific Rise tholeiite (Batiza, 1976)
——		Skaergaard trend
—·—·—		Garbh Eilean alkalic sill (Wilkinson, 1956)
----		Alkali-olivine basalt field (Wilkinson, 1956)

Figure 13

Primary clinopyroxene compositions

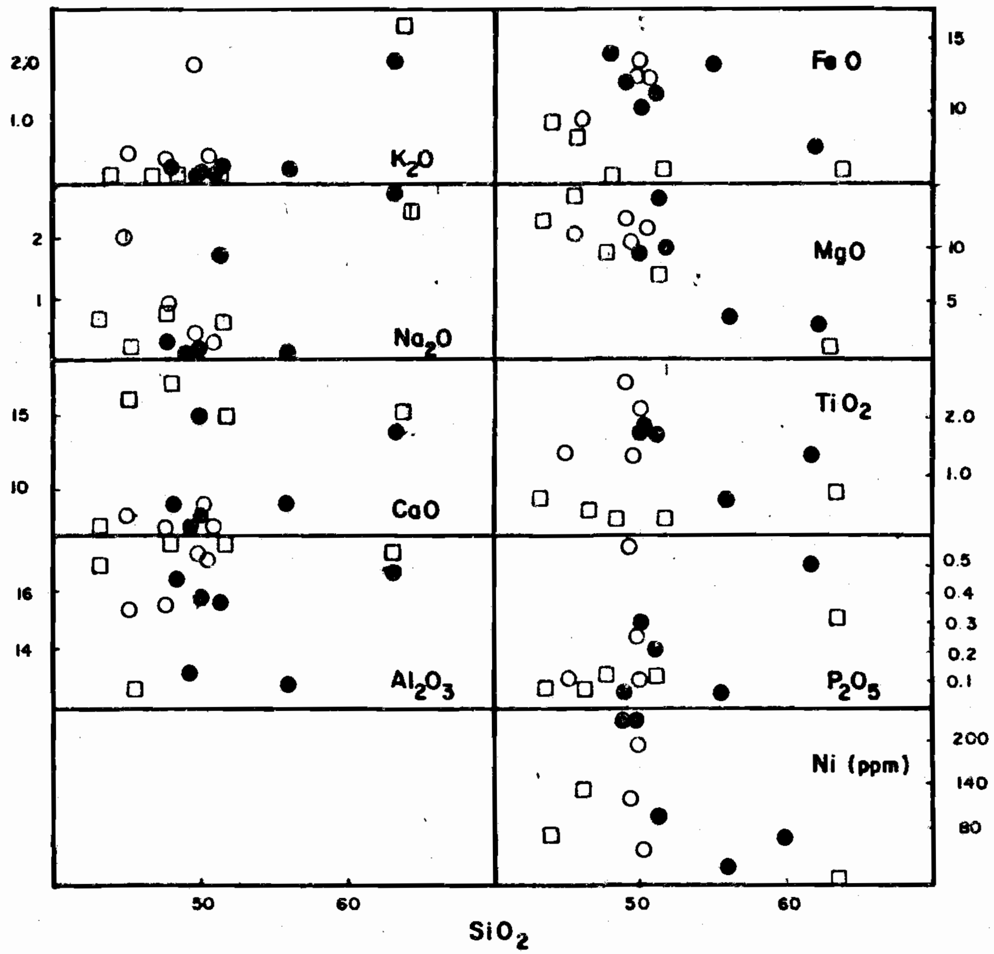


Figure 14:

Major and Trace Element Variation in Greenstone & Gabbro

● Pev Olive Creek pillow lavas
○ Pvv Vinegar Hill series
□ Trgbc cumulate metagabbro

suggesting that perhaps a sporadic, singular, and not too prolific point source was involved in magma extrusion rather than a mid-ocean ridge environment which would produce voluminous greenstones. The source best fitting these geochemical, tectonic, and distributional criteria is a seamount, and such an origin is suggested for the pillow lavas of Olive Creek.

Bennett Creek Schists

Pelitic and mafic schists are exposed beneath Clarno lahars in an area of about 0.5 square miles (1.4 km^2) at the head of Bennett Creek in section 15, T. 10 S., R. 35 1/2 E. Two lithic types were distinguished in outcrop: a finely crystalline muscovite schist which is highly foliated, friable, and commonly has a slightly blue sheen on fresh surfaces, and a more massive, only slightly foliated, soft, blue-green greenstone which disintegrates easily. Greenstone comprises about 20 percent of the Bennett Creek outcrops. Porphyroblasts of elongate rectangular amphiboles are oriented in sub-parallel alignment on some cleavage planes in the mica schist. Porphyroblasts are not distinguishable in the greenstone, but lenticular patches and wavy, folded veins of calcite and some pistachio-green segregations of epidote occur. Both deformed and straight quartz veins crosscut the Bennett Creek rocks.

The pre-Tertiary schists are intruded by a 100-foot (30 m) wide body of highly sheared, green-to-black serpentinite. Contact between schists and serpentinite is not exposed, but the intrusion is inferred to be tectonic as are the other serpentinites in the Greenhorns.

At least two deformations were distinguished in outcrop. Major foliation of the schists trends generally northeast, but wide variations are common between outcrops, and there is no single consistent direction. Small isoclinal folds usually less than two feet in width, and generally on the scale of inches, represent a second deformation. F_2 axial planes strike northwest. This structural pattern is in accord with the pre-Tertiary structure of the Greenhorns and common to the Blue Mountains.

Petrography

Mafic and pelitic units are distinct with only a slight gradation in modal mineralogy within each rock type. The mica schist is characterized by segregation bands of granoblastic clear quartz and clouded, untwinned albite (0.1 mm or less), annealed and strained, with secondary mortar texture, alternating with crystalline layers of white mica interleaved with varying amounts of pale green pennin-ite (30 to 60 percent of micas). The micaceous bands include fine stringers and veins of red or yellow brown iron oxides and thin discontinuous layers of graphite. The alternating quartz-mica bands define S_1, and are folded into tight isoclinal folds, analogous to F_2, about 10 mm in maximum width. Pre-tectonic garnet and sphene are broken and stretched along F_2 axial plane directions. Garnet is small, 0.05 to 0.04 mm in reconstructed diameter, and is restricted to quartz-albite layers. It is faintly red-brown, only slightly pleochroic, and is optically analogous to the pyralspite series. Syntectonic, deformed garnets are corroded and embayed by quartz, and often jacketed by a very fine rim of chlorite. Sphene is restricted to micaceous layers, and like garnet, occurs as deformed, pretectonic porphyroblasts of small dimensions which are strung out along F_2 axial plane foliation. Epidote is uncommon in the mica schists, forming only about 0.5 percent of the one thin section in which it was noted (V-91). Where present it is associated with micaceous bands as small equant and faintly yellow porphyroblasts. Blue amphibole is also a rare component of the mica schists, present in V-91 as deformed, feathery laths in micaceous layers.

Sample V-91 is a slight compositional gradation between the mica schist and the foliated greenstone. Its field location is intermediate in position between the two end members, but despite a slightly gradational mineralogy, its appearance is distinctly that of a foliated mica schist. Calcite and other calcium-rich phases are generally absent from micaceous rocks of Bennett Creek, with the notable exception of V-91. The development of Ca-rich components in V-91 may be due to ionic migration from adjacent Ca-rich greenstone during both phases of metamorphism, rather than to an original composition slightly enriched in Ca.

In thin section, the mafic greenstones consist predominantly of chlorite, quartz, albite, and epidote, with about ten to 15 percent blue amphibole, and accessory sphene, white mica, and apatite. Foliation is subtle, and best seen in parallel orientation of recrystallized quartz. Although evident occasionally in slightly parallel alignment of amphiboles, compositional banding is not present in the rock, but is developed in small relict lithic clasts within the greenstone.

Chlorite occurs both as radiating sheafs of crystalline light green penninite and as large irregular areas of fine aggregate dispersed throughout the rock. Epidote, as clear to light yellow, pleochroic, 0.05-0.2 mm granular crystaloblasts is widely distributed throughout the sections, and may cluster around amphiboles. Clear albite prophyroblasts attain lengths of 0.4 mm and are commonly nearly square in shape. They are strained, with bending and offset of twin lamellae and wavy extinction in untwinned, unbroken crystals. In contrast to porphyroblasts, groundmass albite is usually slightly cloudy.

Blue amphibole is a distinctive and important feature in the mafic greenstones of the Bennett Creek Schists. The amphibole occurs both as prismatic basal sections perpendicular to (011) which are light, straw-yellow to purplish blue, α-γ, and in rectangular sections parallel to (001) which are light greenish yellow to light greenish blue on α-β. Cleavage is usually readily apparent on sections perpendicular to (011) or (001), and averages 56 degrees. Amphiboles which were observed in basal (001, 011) sections rarely showed much alteration. Many sections on (010) or (100), however, were feathery and altered extensively to chlorite. Optical zonation was not apparent nor was twinning observed in the amphiboles. Evidence of strain, however, is widespread. Slight offsets of basal sections occur in several slides, and the rectangular prisms are bent and broken, then mantled by chlorite. Rotation of broken amphiboles approaches a maximum of 35 degrees.

Sphene is a common accessory, and is pre-tectonic in mafic greenstone as well as in mica schists. Rhomboidal fragments which exhibit simultaneous extinction are separated by a chlorite-epidote matrix.

Apatite is included as clear, unzoned clusters of elongate prisms within albite porphyroblasts, and was not observed elsewhere in thin section. Veins and stringy patches of calcite and chlorite cut irregularly through the rock, and are cross-cut by fine quartz veins. Magnetite occurs as fine, globular inclusions in the sutured quartz-albite matrix. White mica is found as rare single crystals, 0.1 mm or less, generally associated with epidote.

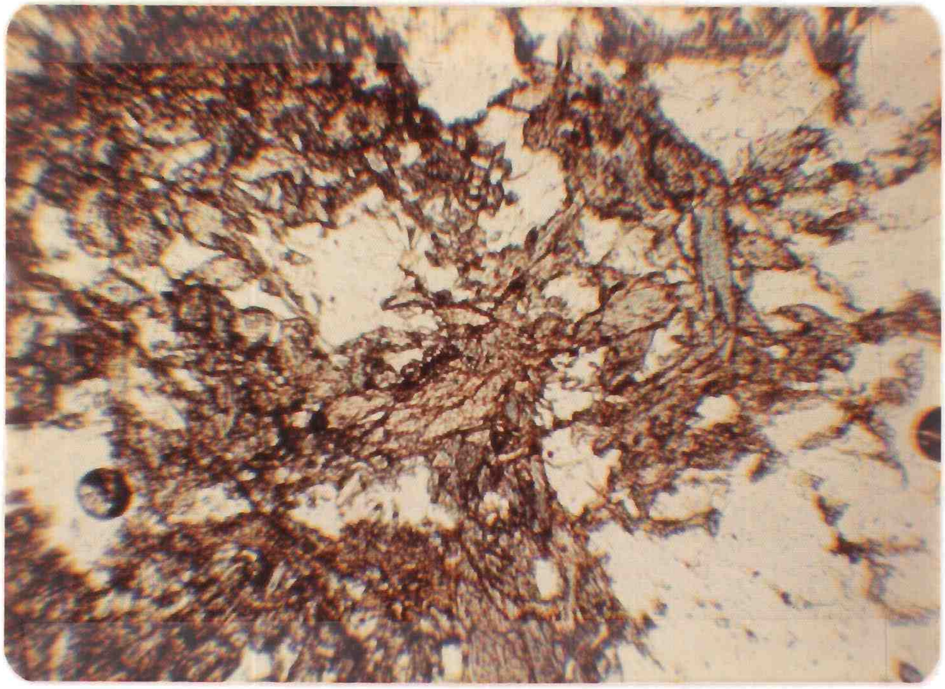


Figure 15. V-90, plane light. Amphiboles and chlorite in quartz-albite matrix. Note blue color on α, straw-yellow on β.

Compositional and mineralogical segregation occurs only in remnant lithic clasts in the mafic greenstones. They are generally small (0.5-one mm), angular, and not visible in hand specimen. In thin section, the clasts consist of bands of alternating blue amphibole altering to chlorite, epidote, and quartz-albite. The original affinity and mineralogy of the clasts cannot be readily determined from the examples observed in Bennett Creek rocks, but the high Ca and Fe contents of their replacement constituents suggests that they may have been basaltic or andesitic.

Petrography confirms the bimodal nature of the Bennett Creek Schists. The preponderance of aluminous and alkali-rich phases in the mica schists with only minor incidence of phases with significant Fe or Ca (garnet, sphene) suggest a pelitic sediment similar to the cherts of the Alamo Argillite or siliceous sediments of the Vinegar Hill Beds as a protolith. The greenstone, with its inclusions of angular mafic lithic clasts, and preponderance of calcic and iron rich phases, probably represents a basaltic to andesitic volcanoclastic tuff conglomerate, rather than an igneous flow rock. Lack of foliation may reflect either its original lack of bedding, or a composition lower in alkalis and silica and hence less susceptible to ionic migration and segregation, or both. A heterogeneous, but well-mixed sediment such as a volcanic tuff breccia might not develop sharp concentration gradients. The migration of constituents along gradients during metamorphism would be less pronounced than in a bedded sediment which alternated silicic and argillaceous components. That some ionic migration occurred in the greenstone is evident from the banded lithic clasts in the greenstone and the minor development of amphiboles and epidote in adjacent mica schists.

Chemistry

Major element chemical analyses of two Bennett Creek rocks, V-89 and V-90 (Table 7) show large and distinct differences in elemental abundances between the pelitic mica schists (V-89) and the blue-amphibole-bearing mafic greenstones. Pelitic schists are high in silica (69 percent) and contain significant amounts of Al_2O_3 (14 percent), Na_2O (five percent), and FeO (seven percent) which indicate that a large component of ferrigenous clay was included with the original sediment. The high content of Na compared to that in shales, oceanic clays, and certainly cherts suggests addition of some Na by metasomatic processes.

Analysis of the greenstone reveals a low content of silica (48 percent) which is in accord with its basaltic-tuff breccia affinity. The overall analysis shows little deviation from that expected in a basaltic rock, with about 17 percent Al_2O_3, nine percent CaO, and 15 percent Fe*O. Again, the figure for Na is somewhat higher than typical basalts, and suggests metasomatic addition of Na during alteration or metamorphism.

TABLE 6. MODES OF BENNETT CREEK ROCKS IN VOLUME PERCENT*

	V-90 Greenstone	V-89 Mica Schist
Quartz	19.2	59.2
Albite	17.6	12.1
Chlorite	30.6	19.9
Epidote	21.8	--
Blue amphibole	9.7	--
White mica	tr.	18.7
Garnet	--	tr.
Sphene	1.1	0.2
Graphite	--	tr.
Iron ore	tr.	--
Total	100.0	100.1

*See Appendix 2 for sample descriptions

Major element analyses of Bennett Creek rocks are similar to analyses of blueschists from tectonic blocks in the California Coast Ranges of similar lithology and mineralogy (Ernst et al., 1970), to glaucophane schists of Taiwan (Liou et al., 1975), and to rocks from zones I (glaucophane schist) through III (epidote-amphibolite) of the Sanbagawa terrane, Japan (Ernst et al., 1970; Toriumi, 1975).

Trace element analyses were performed for Sr and Zr. Abundances of Sr are not in accord with petrographic observation and major element results, and general Sr systematics, which are consistent with enrichment of Sr in rocks of more mafic affinities, rather than higher contents of Sr in a pelitic sediment. However, precise data on Sr in oceanic sediments is not commonly available, and final conclusions on the abundance of Sr in V-89 must await better correlative data. Abundance of Sr in V-90 is within the range reported in sub-alkalic basalts of the Lau Basin and mid-ocean ridge basalt (Engel et al., 1965; Kay et al., 1970; Carmichael et al., 1974) but is generally lower than basalts of oceanic islands (Batiza, 1977; Clague, 1974; Natland, 1975; Engel et al., 1965; Kay et al., 1970), as well as most arc-derived basaltic to andesitic volcanics (Carmichael et al., 1974). Data on Sr in volcanoclastics is not available. Several possible explanations for the seemingly non-systematic abundances in Sr noted in the Bennett Creek rocks:

1. Contamination of the basaltic componente of V-90 by sediment or possibly with low Sr volcanic ash or silicic components might easily account for the 162 ppm abundance of Sr. Such contamination might be expected in sedimentary volcanic tuff-breccia, and again supports the probable sedimentary basaltic tuff origin of the greenstone unit.

2. Another plausible explanation for V-90 is that the original basaltic and tuffaceous components of the greenstone were of uniformly low (+ 100 ppm) Sr abundances such as those noted

TABLE 7. CHEMICAL ANALYSES OF BENNETT CREEK ROCKS

	V-90 Greenstone	Mica Schist
SiO_2	48.4	69.1
Al_2O_3	16.7	14.2
TiO_2	0.7	0.7
CaO	9.1	1.5
Na_2O	2.8	4.9
K_2O	0.2	1.3
Fe*O	15.0	6.6
MgO	5.2	0.6
P_2O_5	0.1	0.1
TOTAL	98.2	99.0
Trace elements, ppm		
Sr	162	245
Zr	64	100

by Hawkins (1975) from the Lau Basin, and by others (Engel et al., 1965; Kay et al., 1970) for mid-ocean ridge basalt. Textural evidence indicates the greenstone is fragmental, and probably tuffaceous. Such a lithology is not common in mid-ocean ridge basalts.

3. Transfer of Sr from the V-90 greenstone to the V-89 pelitic sediment is possible, and quite likely during conditions of prolonged and multiple metamorphism at P_{H_2O}. Under such conditions, however, equilibration of Sr would be expected unless it could find adequate new sites in Ca-silicates generated as a consequence of metamorphism. Calc-silicates are not a significant component in the muscovite schists.

4. Although Sr analyses are within reasonable confidence limits (±30 ppm) experimental error cannot be completely disregarded. If analysis of V-90 is in the low error range, and that of V-89 in the high side, then Sr content of the two samples could be within 20 ppm, and represent equilibration of Sr between the two rocks.

Zr abundances are similar to the fairly low amounts (100 ppm) in basaltic rocks associated with island arcs (Kay, 1977), and also at the low end of abundances reported for some mid-ocean ridge basalts (Kay et al, 1970). A plot of Zr versus Ti in ppm from V-90 (Pearce and Cann, 1975) falls within the range of overlap of both

Japanese arc tholeiites and ocean ridge basalts, and is inconclusive regarding the origin of the basaltic component of V-90. It may be argued that Zr-Ti data from a sediment is not necessarily representative of the igneous rock from which the flow rock sediment constituent was derived. Generally, this argument is valid. However, because the angularity of fragments suggests minor transportation, and because the overall major element chemistry of V-90 is distinctly basaltic, some consideration should be given to this data.

Whole Rock X-ray Diffraction Studies

X-ray diffraction analysis of whole rock powders were undertaken to determine composition of amphiboles, plagioclase, and chlorite in V-90, and check for the presence of lawsonite. Patterns were run on mineral separates from BC-1 (equivalent in mineralogy to V-89) in order to determine whether an appreciable spessartine component was present. X-ray diffraction results were as follows:

1. Albite composition, determined by the method of Wright (1968), is An_2.
2. Chlorite present in both V-90 and BC-1 is penninite, with peaks at 7.11 Å, 4.73 Å, and 3.54 Å.
3. No lawsonite was observed in V-90.
4. The garnet peak at 1.55 Å is shifted toward spessartine, but overall garnet composition is that of almandine.

5. Amphibole peaks were not specifically characteristic of any end-member composition, but most closely fit patterns of magnesioriebeckite and hornblende, indicating a possible intermediate composition.

TABLE 8. AMPHIBOLE X-RAY DIFFRACTION RESULTS

	(110)	(310)	(151, 331)
V-90 amphibole	8.50 Å	3.12 Å	2.84 Å
magnesioriebeckite	8.45	3.12	2.89
riebeckite	8.40	3.12	2.73
glaucophane	8.26	3.06	2.69
actinolite	8.42	3.11	2.71
hornblende	8.43	3.13	2.71

Mineral Analyses

Chemical compositions of selected mineral grains from V-90 and V-89 were analyzed to determine the phases and deduce the pressure and temperature of metamorphism in the Bennett Creek Schists. Methods and instrumental operating conditions are described in the appendix. Amphibole, epidote, and feldspar were analyzed in V-90; garnet and white mica were analyzed in V-89.

Amphiboles. Composition of blue amphiboles in V-90 is intermediate between hornblende, actinolite, and the sodic amphiboles of the glaucophane-magnesioriebeckite series. Results from multiple analyses of a single crystal suggest that the amphiboles are zoned from sodic cores to more calcic rims.

For thesis purposes, definitions of Binns (1967) are adopted for barroisite as Na=Ca in X sites, and Ernst (1977) for actinolite as Al less than 0.5 in Y sites (Al^{IV}).

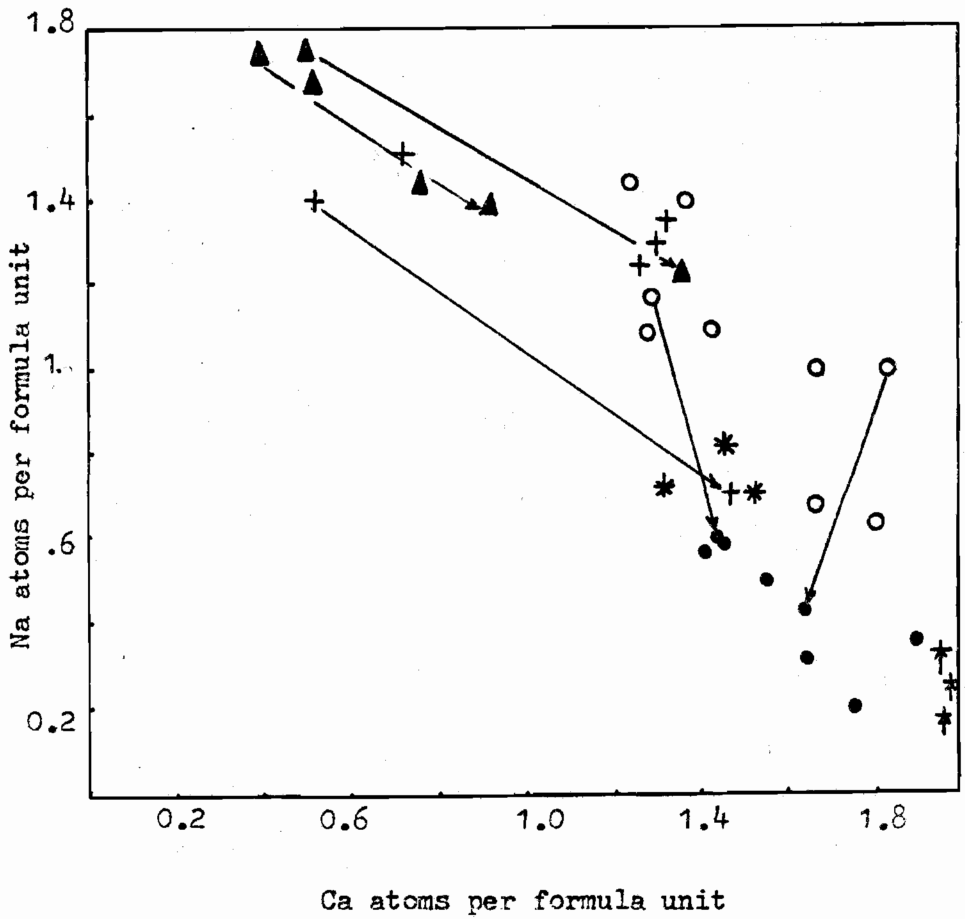
The average amphibole analysis is 52 percent SiO_2, five percent Al_2O_3, 16 percent Fe*O, 12.5 percent MgO, 3.5 percent Na_2O, and eight percent CaO, on a weight percent basis. The formula is: $[NaCa(Fe_2Mg_2Al)(Si_7Al)O_{22}]$. This composition is too high in Al and Na to properly be considered actinolite, too high in Ca for sodic amphibole, and too low in Ca for a true hornblende. The average amphibole in the Bennett Creek rocks is best characterized as barroisite, similar in composition to barroisites from the Sanbagawa IIb terrane by Toriumi, and to calcic amphiboles from the Ligurian Alps by Ernst (1976).

Extremes in composition were found at the core and rim of Bennett Creek amphiboles. The core composition investigated was highly sodic: 4.7 weight percent Na_2O. The formula is: $[Na_{1.4}Ca_{0.5}(Fe_2\ Mg_{2.2}Al_{0.8})(Si_{7.8}Al_{0.2})]$. The analysis is best correlated with magnesioarfvedsonite composition but probably represents an intermediate solid solution of the glaucophane-hornblende amphibole series. Rim composition is much less enriched in sodium: 1.6 percent Na_2O, $[Na_{0.4}Ca_{1.6}(Fe_{1.6}Mg_{e.5})(Si_{7.8}Al_{0.2})]$, and represents a true actinolite.

Mg/Fe ratios in the average amphiboles are in the range 1.3 to 1.4. In the 102/101 analyses, rim composition (Mg/Fe=2.28) is enriched by nearly a factor of two with respect to the core (Mg/Fe = 1.35). Titanium is low in overall abundance, from slightly more than 0.1 percent to below detectable limits (0.001 weight percent TiO_2). Error in determination of an oxide with such small abundance may be significant, but overall abundance relations are probably correct for minerals analyzed from the same rock during the same run. TiO_2 is present as 0.1 weight percent in the rim, and absent in the core.

The distribution of aluminum between four-fold (Y) and six-fold (Z) coordination sites also varies from amphibole to amphibole. In average analyses, Al^{IV} is 0.15 to 0.28, and Al^{VI} is 0.85 to 0.77 of total aluminum. The Al^{IV}/Al^{VI} ratio is in the range of 0.25 to 0.40. For 102/101, the core contains no Al^{IV}, and $Al^{VI} = 0.688$. The rim of the same amphibole has an Al^{IV}/Al^{VI} of 0.38, with $Al^{IV} = 0.111$ and $Al^{VI} = 0.291$.

In all amphibole analyses, MnO, K_2O, F, and Cl abundances were small.



\+ V-90 Bennett Creek Schist

MRS-1 Mine Ridge Schist

* MRS-2 Mine Ridge Schist

▲ MC-1 Meyers Canyon Blueschist

○ Barroisite, Ligurian Alps (Ernst, 1976)

● Aluminous actinolite, Ligurian Alps (Ernst, 1976)

Note: Tie-lines indicate core to rim relations in single crystal.

Figure 16

Na/Ca content of hornblendes from blueschist terranes

Relation of Composition to Pressure and Temperature of Metamorphism

A number of compositional parameters in amphiboles have been related to metamorphic conditions by previous workers. Some suggestions based on such analyses conflict and are discussed below.

A miscibility gap at high pressures or low temperatures and high P/T was noted in calcic and sodic amphiboles by Klein (1969), Brown (1974) and Green and Spiller (1977). From studies of two-amphibole assemblages of the Franciscan and Sanbagawa terranes, Klein (1967) concluded that miscibility gaps occur between actinolite and hornblende at temperatures below the epidote-amphibolite facies and for the pair glaucophane-actinolite at temperatures below about 400°C, the upper limit of blueschist facies conditions. Brown (1974) and Katagas (1974) independently noted that with increasing T/P, the miscibility gap between sodic and calcic amphiboles diminishes, and at threshold conditions to blueschist facies, 300-400°C, five to ten kb pressure, the field of two amphiboles becomes significant. Both Brown (1974) and Green and Spiller (1977) recognized that pressure plays an important, but to date unquantified, role in the miscibility relations in amphibole assemblages. Bennett Creek amphiboles represent a solid solution of calcic, aluminous, and sodic amphibole components, and therefore formed under final conditions which would allow amphibole miscibility. Results from the reports cited suggest

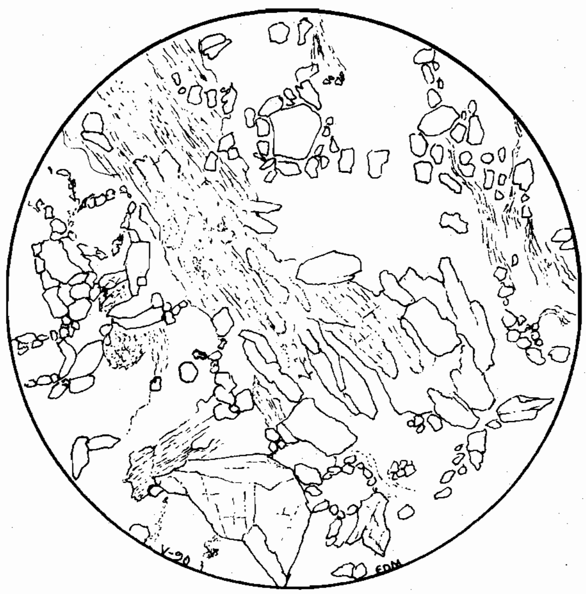


Figure 17. V-90 amphibole altering to chlorite. Equant, clear epidote. Quartz-albite matrix is blank. X 25.

final metamorphic conditions of 300+°C and slightly less than five kb pressure (total). However, the presence of strong zonation in the amphibole indicates that conditions which allowed miscibility may have changed through the metamorphic history of the rock, or have developed only late in the metamorphic history.

Coleman and Papkie (1968) noted that with increasing grade of metamorphism, the Ca content of glaucophane increases. More recently Brown (1977) has noted that Ca amphiboles from high pressure areas contain significantly more Na in X (M_4) sites than amphiboles from low pressure terranes. Where greenschist temperatures (300-400°C) are developed, and there is no miscibility gap between amphiboles (where the buffering assemblage albite + iron oxide + chlorite occurs), there should be a fixed content of Na in the amphibole at any given P and T, and Na content of amphibole should increase with increase in P. Hence, at pressure ranges just below those of the blueschist facies, where sodic and calcic amphiboles are miscible, the Na/Ca content of amphiboles may be fixed by pressure.

The Bennett Creek greenstones contain the buffering assemblage required for determination of P by the method of Brown (1977). Na (M_4) contents for Bennett Creek rocks are generally about 1.0 for average amphiboles, and range from 1.4 in the core to 0.4 at the rim.

Ernst (1968), Liou et al. (1975) and Brown (1977) observed that Al^{IV} increases in amphiboles with temperature due to increased substitution of tschermakite and edenite components. This reaction is also apparently buffered by the same reactions as the Na substitution in M_4 (Brown, 1977), and hence provides a possible relative geothermometer.

Brown (1977) has developed a tentative plot of calcic amphibole Na M_4 versus Al^{IV} as a tool for deduction of possible metamorphic P-T. Plots of Bennett Creek amphiboles on this diagram suggests that metamorphism of the schists occurred initially at a preseure between six and seven kb, at relatively low temperature, and with time progressed to pressures of four to five kb at slightly increased temperature.

A plot of other calcic amphiboles which contained similar buffering assemblages and for which approximate P/T conditions had been deduced (Engel and Engel, 1962; Ernst, 1970) agree well with Brown's predictions.

The TiO_2 content of calcic amphiboles increases with increase in temperature of metamorphism (Ernst, 1968; Leake, 1965). TiO_2 contents of the Bennett Creek amphiboles vary widely, but the absence of Ti in the core and its presence as 0.10 weight percent in the rim is noteworthy, and also indicates increasing temperature through time during metamorphism.

The chemistry of the Bennett Creek amphiboles suggests relatively high pressure origin, with decreasing pressure through time. Temperatures, suggested primarily by the Ti contents of the amphiboles, increased with time. Initial pressures may have been as high as 6.5 kb, with initial temperature of about 300°C, the threshold of blueschist metamorphism.

Plagioclase. The plagioclase of V-89 and V-90 is extremely albitic, with only 0.04 weight percent CaO présent (An_1). Low iron content is indicative of the minor degree of clouding, as the large spot size would have revealed a higher iron content if a notable quantity of iron oxides were present.

Epidote. Epidote, $Ca_2Al_{2.3}Fe_{0.7}Si_3O_{12}(OH)$, is slightly enriched in Al (Clinozoisite component). This enrichment has been attributed to substitution of Al for Fe with increasing metamorphic grade in the Otago (Brown, 1967) and Franciscan (Ernst, 1970) terranes. Liou (1973) noted that the compositional range of epidote increases with increased fO_2, and Miyashiro and Seki (1958) attributed the rise in Al component in epidote to a combination of decreased oxygen fugacity and increase in temperature. Banno (1964) considered differences in Al in epidote due to whole rock compositional variation.

Petrographic observations bear on the origin and stability of Al enrichment in V-90 epidote: 1. Proximity to graphite-containing assemblages of the mica schists may have slightly buffered O_2, resulting in a low fO_2 in V-90 greenstones. The extent of this probable effect is dependent upon factors which allowed exchange between the systems, but some exchange between greenstones and schists is supported by transitional mineralogy in the schists. Epidote co-exists with graphite in V-91, and probably formed in an environment of low fO_2. Although this relation cannot be directly extrapolated to the V-90 epidote (distance between samples was approximately 15 meters), the high Al content of the V-90 epidote probably is related to development at low oxygen fugacity.

The temperature-pressure range for stability of epidote given by Liou (1973) suggests an upper limit of epidote stability of 650°C at two kb. Conversion of the greenschist facies assemblage epidote + chlorite + albite = + quartz to oliglocalse + Tschermakite amphibole occurs at 475°C, two kb (Liou, 1973). The low temperature/pressure limit, at high oxygen fugacity is near 300°C, seven kb. Consideration of the probable formation of epidote at fairly low to moderate fO_2 suggests that the lower temperature limit of formation was somewhat above 300°C. The range of probable temperatures for the formation of epidote (which post-dated growth of amphibole) is then in the range of about 350°-450°C, at pressures between two and six kb.

Compositional zoning has been documented in epidotes of the Sanbagawa terrane by Toriumi (1972, 1975), and Ernst et al. (1970).

TABLE 9. AMPHIBOLE MICROPROBE ANALYSES. BENNETT CREEK SCHIST V-90**

Grain number	101	102	103	104 rim	104 core	105	106	Average V-90 Amphibole
OX	0.000	1.006	1.772	1.667	1.360	8.927	5.010	4.1
SiO_2	52.321	52.248	50.667	54.549	55.035	55.101	51.231	52.0
Al_2O_3	5.564	5.719	5.585	2.360	4.546	4.449	5.055	5.0
TiO_2	0.112*	0.092*	0.073*	0.016*	0.021*	0.005*	0.062	0.0
CaO	8.043	8.182	7.586	10.295	4.415	1.633	8.039	8.0
Na_2O	3.528	3.476	3.697	1.587	4.735	3.695	2.069	3.2
K_2O	0.148*	0.153*	0.987	0.083	0.082*	0.053*	0.137*	0.1
Fe*O	16.690	16.357	16.377	12.825	17.420	14.865	15.159	16.0
MgO	12.322	12.542	12.850	16.371	11.995	11.018	12.930	12.0
MnO	0.257*	0.200*	0.258*	0.246*	0.299*	0.197*	0.242*	0.2
Cr_2O_3	0.002*	0.000	0.000	0.000	0.054*	0.000	0.059*	0.0
F	0.082*	0.034*	0.244*	0.000	0.065*	0.097*	0.000	--
Cl	0.009*	0.007*	0.007*	0.001*	0.000	0.000	0.010*	--
SUM		98.994	98.228	98.333	98.640	91.073	94.990	100.4
Al^{IV}	0.164	0.192	0.285	0.111	0.000	0.000	0.163	
Al^{VI}	0.819	0.815	0.717	0.291	0.821	0.863	0.748	
Mg/Mg+Fe	0.568	0.577	0.583	0.695	0.551	0.569	0.603	
Mg/Mg+Fe+Mn	0.564	0.577	0.579	0.691	0.547	0.566	0.599	
Na+k	1.053	1.037	1.283	0.460	1.423	1.191	0.641	

*Standard deviation exceeds 5.0.

**See Appendix 2 for sample descriptions.

Enrichment in aluminum increases with increasing grade of metamorphism. Investigation of the zonal composition of Bennett Creek epidotes was not undertaken in this study, but would be useful to confirm trends in the amphibole and garnets of the terrane.

Garnet. Analyses of two fractured and slightly strung out garnets from sample V-89 are given in Table 10. An attempt was made to analyze the rim-core sequence in each, but because the minerals were substantially deformed it must be cautioned that probe locations are probably as noted for rim, intermediate, and core positions, but not positively in that sequence in the original, reconstructed, and undeformed grain.

Garnet compositions are characteristic of almandine, but are slightly enriched in the spessartine (MnO) component. Garnets contain an insignificant pyrope (MgO) component. Both garnets are compositionally zoned with respect to MnO, Fe*O, and MgO, with content of MnO increasing and Fe*O + MgO concomitantly decreasing from rim to core. Overall composition and intensity of zoning in the Bennett Creek garnets is similar to minerals from the Goat Mountain area of the California Coast Ranges and zones I and II of the Shirataki district, Sanbagawa terrane, Japan (Ernst et al., 1970).

Miyashiro (1957) and Banno (1965) first noted the general tendency for garnets of blueschist terranes to exhibit progressive enrichment in MnO from rim to core. This enrichment has most

TABLE 10. GARNET ELECTRON MICROPROBE ANALYSES

	Garnets V-89				
	101 Rim	101 Core	102 Rim	Intermediate	102 Core
SiO_2	38.38	38.50	38.77	37.81	38.31
Al_2O_3	21.67	21.84	22.12	21.69	21.36
TiO_2	0.04*	0.08*	0.04*	0.05*	0.07*
CaO	9.19	10.13	11.02	11.69	11.75
Fe*O	25.43	22.42	23.01	22.50	21.06
MgO	0.73	0.61	0.80	0.69	0.59
MnO	4.12	6.99	4.76	5.71	7.27
Cr_2O_3	0.00**	0.00**	0.01*	0.01*	0.00**
SUM	99.56	100.56	100.52	100.14	100.14
Al^{IV}	0.00	0.00	0.00	0.02	0.00
Al^{VI}	2.05	2.01	2.05	2.00	1.98
Fe^{++}	1.71	1.51	1.57	1.55	1.44
Fe^{+++}	0.00	0.00	0.00	0.00	0.00

*Near detectable limits.

**Below detectable limits.

commonly been attributed to the increase in metamorphic intensity with time. Decrease in Mn garnets of Kurata (1972) and Black (1973), and attributed to the temperature dependent partitioning of Mn and Fe between garnet and chlorite.

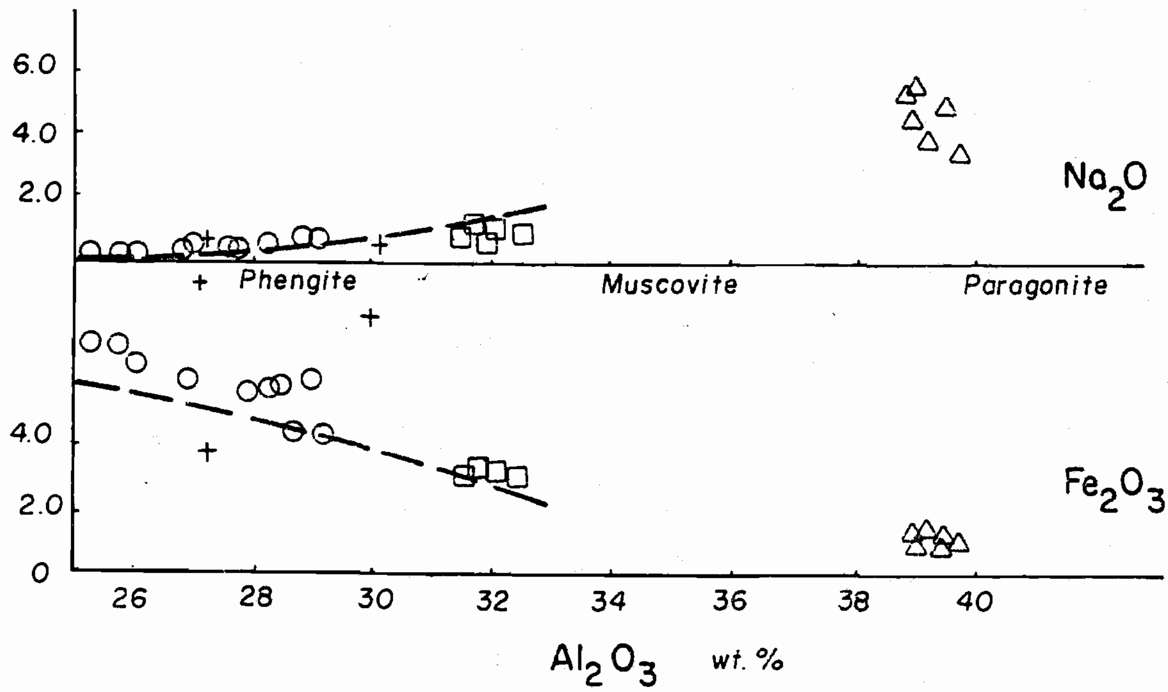
Hollister (1966), however, attributed the common zonation of Mn in garnet to a Rayleigh fractionation. Concentration of Mn in garnet relative to other minerals causes early concentration of Mn in garnet nucleii, and leaves the surrounding matrix depleted in Mn, so that subsequent growth of garnet will incorporate material depleted in Mn by initial preferential incorporation of Mn in garnet nucleii.

Hence, some caution must be utilized in the interpretation of MnO gradients within garnets as representative of changing temperature conditions. The writer is not aware of any instances where MnO concentration in garnet decreases from rim to core, although there are many documented examples of decrease in metamorphic intensity (e.g. Franciscan assemblages from the Cadezaro, California region, Coleman and Papike, 1968; Coleman, 1977, pers. comm.). However, from the zonation of amphibole and the probable tendency for re-equilibration within a single crystal if constant P/T conditions are maintained through time, it is tentatively concluded that the zonation of garnet reflects increase of temperature with time in the Bennett Creek Schists.

White Mica. White micas from sample V-89 contain appreciable amounts of Fe (three to seven percent) and Mg (0.3-0.5 percent). They are slightly enriched in Si and depleted in Al with respect to muscovite. Compositionally, they are phengites.

Several workers observed that phengitic white micas are most commonly associated with rocks of the glaucophane schist and lower greenschist facies (Miyashirio, 1962; Ernst, 1963; Velde, 1965, 1967; Brown, 1967; Ernst et al., 1970). The assemblage phengite + chlorite, common to V-89 and other mica schists of Bennett Creek, is stable at high P_{H_2O} and low (300°C) temperatures (Velde, 1967). Bocquet (1974) suggested that the reaction illite + chlorite = phengite may occur at temperatures as low as 240°C, and that the reaction glauconite + quartz → phengite may take place in metasediments at temperatures of 370-380°C. Ernst et al. (1970) showed that with increasing temperature of metamorphism, the Na_2O content of the phengite increases, although relations are not quantitative. The Na_2O content of Bennett Creek phengites is extremely low: on the order of 0.06 percent, and from the relationship suggested by Ernst et al. (1970), temperature of formation of the white mica may be near the minimum for phengite. Velde (1967) suggested that the Si contents of white micas might be used to calibrate P/T conditions of metamorphism.

The micas of Bennett Creek are similar in composition to phengites reported by Ernst et al. (1970) and Toriumi (1975) for the



○ Glaucophane schists

□ Garnet - epidote amphibolite

△ Epidote amphibolite

\+ V - 89 (Bennet Creek)

— — Shirakiaki trend

Figure 18 -

White mica compositions - after Ernst (1972)

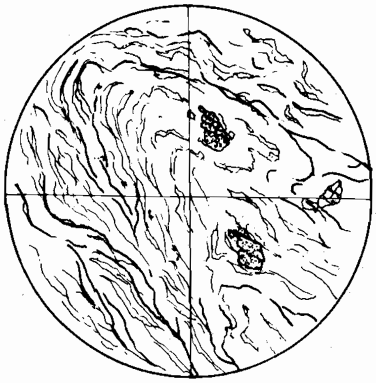
Sanbagawa zone II terrane, and by Liou from glaucophane schists of Taiwan. Their composition is probably indicative of formation at temperatures not much in excess of 350°C, and fairly high pressure.

Age

Although no fossils were found in direct association with the Bennett Creek Schists, conodonts from a large limestone pod in the lithological equivalent mafic tuffaceous breccia of Vinegar Hill Beds within 0.5 miles of the Bennett Creek locality were dated as Middle Permian (Leonardian) by Bruce Wardlaw of the U.S. Geological Survey, Denver. (Temperature of metamorphism indicated by conodonts was 300-400°C.) An equivalent age of origin is suggested for the Bennett Creek Schists, but age of the predominant metamorphism is inferred to be Triassic, contemporaneous with or slightly prior to intrusion of the serpentinite and emplacement of the ophiolite.

Origin and Metamorphism

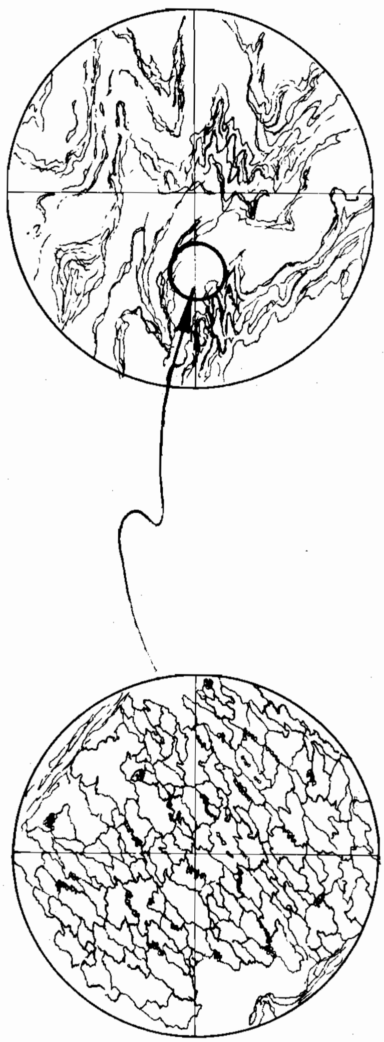
Petrographic, mineralogical, and chemical characteristics lead to the conclusion that the Bennett Creek Schists represent both pelitic, highly siliceous and mafic tuff breccia protoliths which were equivalent in lithology to Vinegar Hill cherts and arc-derived mafic series, but which were subjected across a small area to different,



BC-1

Open microfold. S_1 defined by compositional layering, S_2 by axial plane foliation. Note garnets extended along S_2.

X 2.5



V-89

Complex microfolds. Crumpling of micas along S_2.

X 2.5

V-89

Sutured recrystalixation of quartz along S_2. Secondary mortar texture developed subsequent ot S_2.

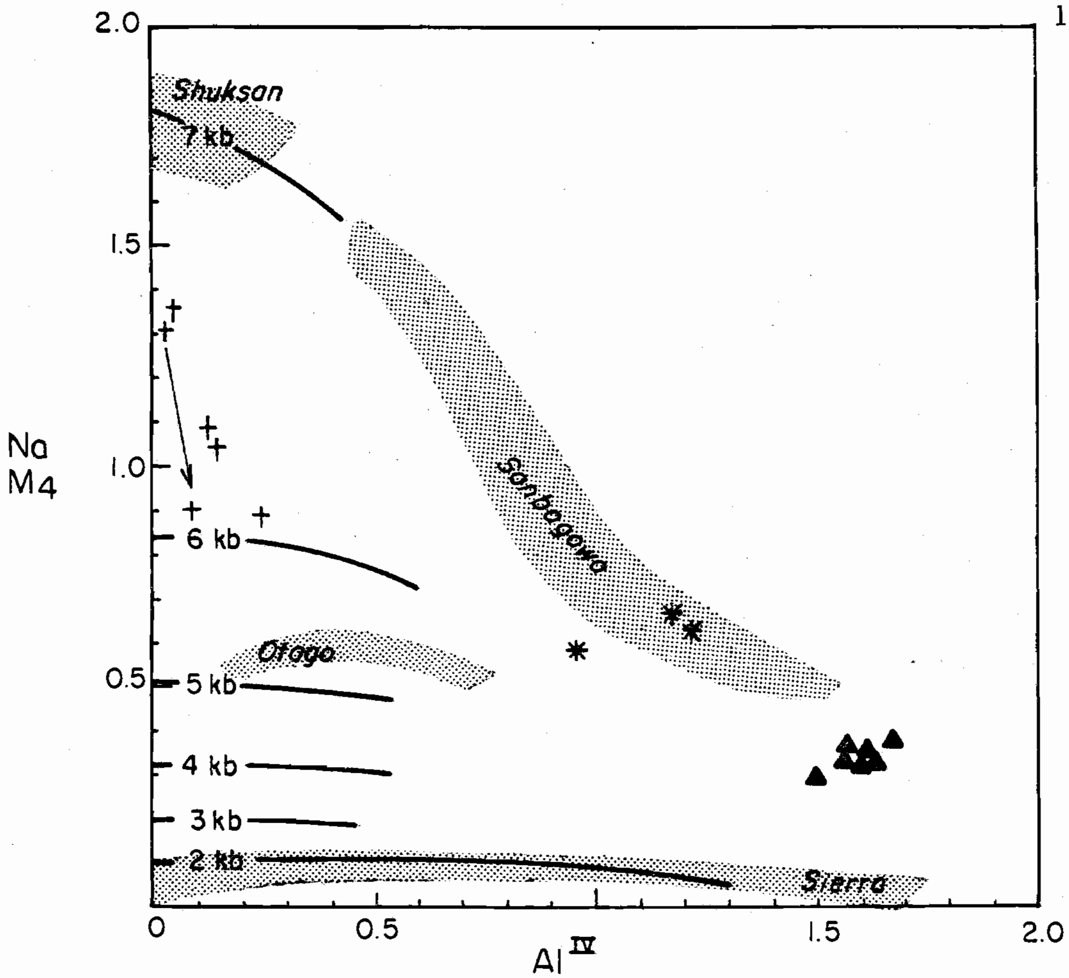
X 10

Figure 19. Bennett Creek Schist Petrography

high pressure conditions of metamorphism.

Textural evidence indicates that the rocks underwent two periods of metamorphism and deformation. The initial metamorphic episode was responsible for the growth and development of blue, calc-sodic amphiboles in the mafic tuffs and of Mn-enriched garnet in the pelitic sediments. From analysis of amphibole core composition, initial metamorphic conditions approached 6.5 kb at 350+°C. With time, temperature increased, pressure decreased, and refolding (F_2) commenced. This period of deformation resulted in the strain of pre-F_2 amphibole, sphene, mica and garnet. Development of epidote and continued crystallization of phengitic mica post-dated the F_2 phase. Increasing temperature and decreasing pressure are reflected in the composition of amphiboles, and growth of epidote, and probably reached conditions of mid epidote-amphibolite facies (400-450°C, three to five kb). It is possible that a phase such as lawsonite which may have developed during the first, lower temperature, high pressure phase of metamorphism reacted to form an epidote mineral at temperatures of about 375-400°C at five to six kilobars (Crawford and Fyfe, 1965). (Data for the system CaO-FeO-Al_2O_3-SiO_2-H_2O and the probable reaction lawsonite + iron ore + quartz → epidote are not available.)

This metamorphic regime of decreasing pressure and increasing pressure with time is similar to conditions of metamorphism in



+	V-90	Bennet Creek, Greenhorn Mts.
✳	MRS-2	Mine Ridge Schist, Hereford, Ore.
▲		Blue-green hornblende, regional metamorphism at approx. 2.5 kb. (Engel & Engel, 1962)

Figure 20. Na M4/Al^{IV} of calcic amphiboles and relation to pressure of metamorphism. After Brown (1977).

the North Cascades (Lawrence, pers. comm., 1978); the Alps (Bearth, 1959; Bocquet, 1974; Ernst, 1976) and in the Sanbagawa terrane (Ernst *et al.*, 1970; Toriumi, 1975), but is reverse to trends noted in the Franciscan of California (Ernst, 1965; Ernst *et al.*, 1970; Coleman, 1967; Coleman, 1977, pers. comm.).

Similar Metamorphic Rocks of the Blue Mountains

Two areas of schistose metamorphic rocks in northeast and north-central Oregon were briefly investigated to determine any possible lithologic or petrologic relation to the schists of Bennett Creek.

Mine Ridge Schist

The Mine Ridge Schist is a lithologically diverse assemblage of quartz, quartz-mica (pelitic) and amphibole-rich foliated rocks which is best exposed through an extensive cover of Tertiary volcanics in the Ironside, Oregon quadrangle. The rocks were mapped, described, and named by Lowry (1968) who recognized the diverse lithologic nature, and assigned a pre-Devonian age, based upon the intense metamorphism. Lowry obtained an age of 142-150 m.y. by whole rock K-Ar radiometric techniques, but ascribed this late age to contact metamorphic effect from the intrusion of granitic plutons.

Two localities of Mine Ridge Schist mapped by Lowry (1968)

TABLE 11. EPIDOTE MICROPROBE ANALYSES, BENNETT CREEK AND MINE RIDGE SCHIST

Sample	V 90 101/401	V 90 103/201	MRS 2 101/301
OX	1.552	2.504	0.000
MgO	0.088*	0.054*	0.051*
Al_2O_3	23.608	23.009	24.276
SiO_2	38.874	37.495	38.824
CaO	23.847	23.207	23.641
TiO_2	0.052*	0.009*	0.147*
MnO	0.088	0.171*	0.014*
Fe*O	11.806	13.386	11.937
Ce_2O_3	0.083*	0.102*	0.000
F	0.001*	0.000	0.000
Y_2O_3	0.000	0.000	0.000
La_2O_3	0.000	0.000	0.000
Nd_2O_3	00.000	0.000	0.000
SUM	98.448	97.496	99.007

TABLE 11a. AMPHIBOLE MICROPROBE ANALYSES OF MRS-2.

SAMPLE	1/101	1/201	2/202	2/204
OX	1.144	1.061	5.622	1.124
Na_2O	2.310	2.707	1.342	2.640
MgO	12.510	12.108	11.833	11.761
Al_2O_3	9.425	12.493	11.045	10.640
SiO_2	47.825	45.529	47.029	47.297
K_2O	0.563	0.703	0.609	0.556
CaO	10.545	10.102	7.89	10.002
TiO_2	0.334	0.601	0.201*	0.331
Cr_2O_3	0.048*	0.013*	0.016*	0.000
MnO	0.272*	0.225*	0.219*	0.183*
FeO	15.021	14.405	14.153	15.352
F	0.000	0.084*	0.072*	0.168*
Cl	0.006*	0.005*	0.000	0.020*
SUM	98.856	98.939	94.378	98.876
Al IV	0.965	1.294	0.826	0.831
Al VI	0.670	0.876	1.160	
Mg/Mg+Fe	0.597	0.600	0.598	0.577
Mg/Mg+Fe+Mn	0.593	0.596	0.595	0.574
Na+K	0.795	0.905	0.515	0.596

*Standard deviation exceeds 5.0

were investigated by the writer. Examination of the type locality, Mine Ridge, in section 11, T. 14 S., R. 36 E. revealed close contact with a granitic (tonalite?) intrusive, and only one sample of schist was collected. Exposures of Mine Ridge Schist in section 14, T. 13 S., R. 38 E. (five miles south of Hereford, Oregon) were not in apparent close contact with granitic rocks (although granitic rocks could have been concealed beneath Tertiary cover), and samples of differing lithologies were taken for petrographic and electron microprobe analysis.

Good exposures of micaceous or mafic members of Mine Ridge Schist are rare, as also noted by Lowry (1968); the rock weathers quickly to a terrane of low or uniform topography. In section 14, however, a highly siliceous member of the Mine Ridge Schist forms a narrow, high-standing ridge, with near-vertical relief of 400 feet. The siliceous rock (sample MRS-4) is similar in appearance to the contorted ribbon cherts common to Elkhorn Ridge Argillite (Gilluly, 1937) and to the cherts and siliceous sediments on Vinegar Hill. It is light brown to tan on weathered surfaces, and light grey on fresh surfaces, rhythmically bedded as two-to-three inch thick siliceous (chert) layers alternating with pelitic layers less than a half inch in thickness. Bedding is intensely deformed into chevron folds of one to several feet in width with axial planes striking generally northwest.

Three other lithologies were sampled from the exposures in section 14: a finely crystalline quartz-mica schist, brown to light bluish grey on cleavage surfaces (MRS-1); a coarse blue-green amphibole along foliation and lenticular or fine, wavy inclusions of calcite, and a rock of probable intermediate composition (MRS-3 and MRS-5), which was coarsely schistose and contained discrete siliceous layers about four millimeters in thickness. Schists in section 14 are intruded by a highly sheared dark to chartreuse-green serpentinite, approximately 125 feet (38 m) in irregular diameter. Contact between the serpentinite and Mine Ridge Schist is not exposed, but is assumed to be tectonic.

Petrography. The siliceous member of the Mine Ridge Schist has a granoblastic matrix of quartz and occasional, untwinned albite clouded by fine, dusty inclusions (iron ore?). Slight mortar texture is evident. Relict porphyroblasts of epidote are present as poikiloblastic, and highly embayed relicts in quartz-rich matrix. Blue-green hornblende is deformed, embayed, and replaced by light blue to green actinolite, with thin overgrowths of chlorite. Fresh, poikiloblastic red-brown biotite is idioblastic to subidioblastic in form, and of later generation than the other mafic minersls.

Mica schists of Mine Ridge Schist (MRS-1) contain alternating bands of slightly granoblastic, quartz-albite with slight development of mortar texture, and lenticular laths of white mica with aggregate and sometimes finely crystalline chlorite cut by fine strings of graphite. Albite porphyroblasts 0.05-0.2 mm are usually twinned, only slightly clouded, and deformed, with twin lamellae bent or broken. Subidioblastic blue to light blue-green actinolites (2V 70-75, γ-z 12-15°) also commonly bent or fractured, and are rimmed by feathery, retrograde chlorite. Epidote is idioblastic, and usually restricted to mafic-rich bands. Small, patchy, aggregate growths of green biotite (0.05 mm or less) are common to the chlorite matrix, and are the last metamorphic mineral developed. Lowry (1968) reported both idiorphic, deformed garnet crystals, 0.9 mm in diameter and rutile from section 22, T. 13 S., R. 38 E.

The more mafic variety of Mine Ridge Schist (MRS-2) consists of coarse, 0.5-2.0 mm, amphibole blue to blue green$_{\alpha\beta}$, and blue to straw yellow$_{\alpha\gamma}$, 2V about 40° as sub-parallel idioblasts with poikiolitic inclusions of clear to light yellow epidote, 0.05 mm or less. Actinolite forms discrete reaction rims on some blue-green amphiboles, and is partly altered to a mat of light green chlorite. Amphibole deformation is much less pronounced in amphibolites than in more heterogeneous units, probably as a consequence of greater competence than the quartz-rich unit. White mica is rare, and where developed occurs as isolated, fibrous crystals 0.1 mm in length. Some lenticular segregations of granoblastic, slightly clouded quartz contain very fine inwardly radiating acicular and finely prismatic crystals of apatite. Magnetite occurs as finely disseminated globules and as occasional clusters along barroisite-actinolite boundaries.

Small idioblastic red-brown biotite is restricted in occurrence to quartz-rich veins which crosscut the mafic Mine Ridge Schist. Biotite commonly contains poikiloblastic quartz and rare albite inclusions. Green biotite occurs as small birefrigent patches within areas of chlorite interstitial to amphiboles. Both biotites apparently crystallized late.

Petrographic examination reveals striking similarities between both the pelitic and mafic members of the Mine Ridge Schist and the schists of Bennett Creek. These include similarities in mineral paragenesis, in degree and sequence of deformation, and in sequence of mineral growth. From field and petrographic correspondence, the Bennett Creek Schists are considered equivalent to the Mine Ridge Schist in lithology and genesis.

Mineral Analyses. Analysis of selected amphibole, feldspar, and epidote from MRS-1 (mica schist) and MRS-2 (amphibolite) were undertaken to facilitate comparison of metamorphic conditions imposed upon Bennett Creek and Mine Ridge Schists. Results confirmed the presence of barroisitic hornblende and actinolite in Mine Ridge Schist and are elaborated below:

Amphiboles from both the pelitic (MRS-1) and mafic (MRS-2) members of the Mine Ridge Schist (section 14) were analyzed, and were found to be distinct in composition. The amphiboles, unfortunately, were not checked for compositional zoning.

Results from MRS-1 (mica schist) indicate that amphiboles from pelitic rocks are intermediate in composition between actinolite and hornblende, but are best characterized as actinolite because of generally low Al and substantial component of Na. They contain no Al in six-fold co-ordination. Their average composition by weight percent is 52 percent SiO_2, three percent Al_2O_3, one percent Na_2O, 14.5 percent CaO, 14 percent Fe*O, and 15 percent MgO; the formula is: $[Na_{0.3}Ca_{1.7}(Mg_{2.7}Fe_{1.8}Al_{0.5})Si_8O_{22}]$.

The substantial component of Na indicates possible formation under fairly high pressure. Plots of the MRS-1 actinolites on Brown's (1977) Al^{IV}/Na_{M4} diagram places them in the four to five kilobar pressure range. However, absence of the complete buffering assemblage (no magnetite in MRS-1), indicates that formation at higher pressure is possible (Brown, 1977).

Amphiboles from MRS-2 are much more sodic than amphiboles from MRS-1, and probably reflect compositional differences between protoliths. Average composition by weight percent of five analyzed amphiboles is: SiO_2 46 percent, Al_2O_3 11 percent, Na_2O 2.5 percent, CaO ten percent, Fe*O 15 percent, MgO 12 percent. The formula is: $[Na_{0.7}Ca_{1.3}(Mg_{2.7}Fe_{1.8}Al_{0.5})Si_7Al_1O_{22}]$. Aluminum is present in six-fold co-ordination in all analyses. Compositions of MRS-2 amphibole are closest to barroisitic hornblende (barroisite) reported from the Sanbagawa III terrane by Toriumi (1975) and Ernst et al. (1970). On a diagram of Al^{IV} versus Na_{M_4} (Brown, 1977), MRS-2 amphiboles plot in the same field as Sanbagawa barroisites, suggesting a pressure range of five to six kilobars. The buffering assemblage of albite + magnetite + chlorite is present in the MRS-2 sample; therefore this pressure may represent a maximum.

Two plagioclases were analyzed in MRS-1, and one in MRS-2. Results from the first analysis of MRS-1 indicated a composition of An_{10} (albite). Spot size for this analysis, however, was small (ten to 15 μm). Spot size was adjusted to about 25 and the sample run again, with a result of An_1 (albite), which is probably a more accurate compositional determination. Analysis of MRS-2 plagioclase utilizing a large spot size also gave An_1 as feldspar composition. Clouding of feldspar by iron oxide particles is evident from the 0.1 to 0.3 weight percent Fe*O component present in all three analyses.

Epidote, $Ca_2Al_{2.5}Fe_{0.5}Si_3O_{12}(OH)$, is strongly enriched in aluminum, a characteristic indicative of increased temperatures of metamorphism (Brown, 1967; Ernst et al., 1970).

Conditions of Metamorphism, Mine Ridge Schist. Petrography and mineral chemistry suggest that conditions and sequence of metamorphism of the Mine Ridge Schist were similar to those of Bennett Creek rocks.

The high contents of Na and Al in Mine Ridge Schist amphiboles suggests that growth of the idioblastic amphiboles began under P-T conditions above the amphibole miscibility gap (Klein, 1967; Brown, 1974). Presence of up to 2.5 weight percent of Na in the calcic amphiboles of Mine Ridge Schist also suggests that the initial pressure of metamorphism was fairly high, up to five to six kilobars, according to estimates from Brown's (1977) figrues. A possible alternate mechanism for addition of Na to amphiboles is temperature increase across a regional thermal gradient (Engel and Engel, 1962). This relationship may not be effective in regimes at elevated pressure (Engel, 1977, pers. comm.) where pressure effects are more dominant. Lower Na contents of Mine Ridge Schist amphiboles compared to those of Bennett Creek may indicate initial metamorphism of the two assemblages under conditions of similar temperature (same mineral assemblages), but slightly lower pressure at the site in section 14 of Mine Ridge Schist. However, such factors as whole rock compositional differences or Na influx during metamorphism cannot be conclusively rejected until more detailed study is made. Compositional differences apparently governed the development of actinolite and barroisite in adjacent Mine Ridge Schist units.

As in schists of Bennett Creek, deformation of amphiboles and garnets preceded growth of epidote. The temperatures of this second metamorphic phase probably increased relative to the regime responsible for the development of amphibole and garnet. The final phases of "regional" metamorphism may also have involved temperatures higher than those of Bennett Creek, as indicated by the higher Al content of epidote and the very limited generation of green biotite within chlorites, indicating the onset of upper greenschist facies grade. Although the higher Al content of epidote could also be a compositional variation, formation of green biotite which is absent in the Bennett Creek rocks, suggests a higher concluding metamorphic temperature in Mine Ridge Schist.

Effects of contact metamorphism are not entirely absent in Mine Ridge Schist from section 14. Thermal metamorphism apparently reached lower albite-epidote hornfels. Late development of chlorite and actinolitic rims on barroisite, and presence of red-brown oxy-biotite in siliceous rocks are indicative of albite-epidote hornfels thermal metamorphism, probably related to the widespread intrusion of Jurassic granitic rocks. Temperatures of thermal metamorphism were probably not above 300°C, the temperature cited by Vernon (1975) for the production of biotite in rocks of low Al, and thus might not greatly affect compositions of pre-existing phases formed at somewhat higher temperatures.

Age. Lowry (1968) assigned a pre-Devonian, and possibly Precambrian age to the Mine Ridge Schist, based upon possible similarity to rocks northwest of Bald Mountain considered Archean by Lindgren (1901), and to the greater deformation of Mine Ridge Schist in comparison to surrounding Mesozoic metasediments.

However, Taubeneck (1978, pers. comm.) has recovered fossils of probable Triassic age from some limestones associated with Mine Ridge Schist, and the striking similarity of MRS-4 to cherts of the Elkhorn Ridge Argillite is compelling evidence for the reassignment of Mine Ridge Schist to a probable Permian to Triassic age.

Lawsonite Blueschist of Meyers Canyon

Lawsonite blueschists of Meyers Canyon near Mitchell in north-central Oregon were mapped and described by Swanson (1969). However, no microprobe data regarding the compositions of individual phases within the blueschists has been compiled previously. In light of the zonation of Bennett Creek amphiboles from sodic cores to calcic rims, and the probable equivalent trend from higher P/moderate T toward decreased pressure and/or increased temperature in Mine Ridge and Bennett Creek Schists probe analyses of three amphiboles from Meyers Canyon were undertaken to determine whether any zonation existed in the central Oregon blueschists.

Exposures of pre-Tertiary rocks in Meyers Canyon include crystalline limestone, quartzite, chert, and mafic metavolcanics. Swanson (1969) noted exposures of serpentinite at a nearby (Tony Butte) blueschist locality.

Petrography. In thin section, the Meyers Canyon blueschist (MC-1) contains feathery to idioblastic blue amphibole 0.05-0.1 mm in length, light yellow to pale blue on α-γ, and light purple to pale blue on α-β, with a small 2V where determinable. Swanson (1969) classified the amphiboles as crocidolite and crossite with composition close to glaucophane. Very fine, slightly corroded prismatic lawsonite is dispersed throughout the rock, and in fine aggregates. White mica forms aggregates and occasional lenticular crystals. Folds and crenulations are defined by alignment and fine banding of amphiboles and quartz. Chlorite forms a fine felty aggregate around amphibole and micas. Quartz and albite are groundmass constituents. An occasional small relict plagioclase may be partly replaced by micas and lawsonite.

Mineral Analyses. Three rather large idioblastic amphiboles (0.4 mm) were selected for core and rim analysis. The results show that amphiboles from MC-1 are zoned from sodic cores to more calcic rims.

Analyses of three cores gave consistent results for two amphiboles (102 and 201), and somewhat higher Ca content for the third. The formula is $[Na_{1.7}Ca_{0.4}(Fe_{2.0}Mg_{1.8}Al_{1.2})Si_8O_{22}]$.

Rim analyses vary widely in the amount of CaO present from 4.5 percent to 8.6 percent, which may be a function of precise site analyzed. The formula is $[Na_{1.3}Ca_{1.6}(Fe_{1.5}Mg_{1.7}Al_{0.7})Si_8O_{22}]$.

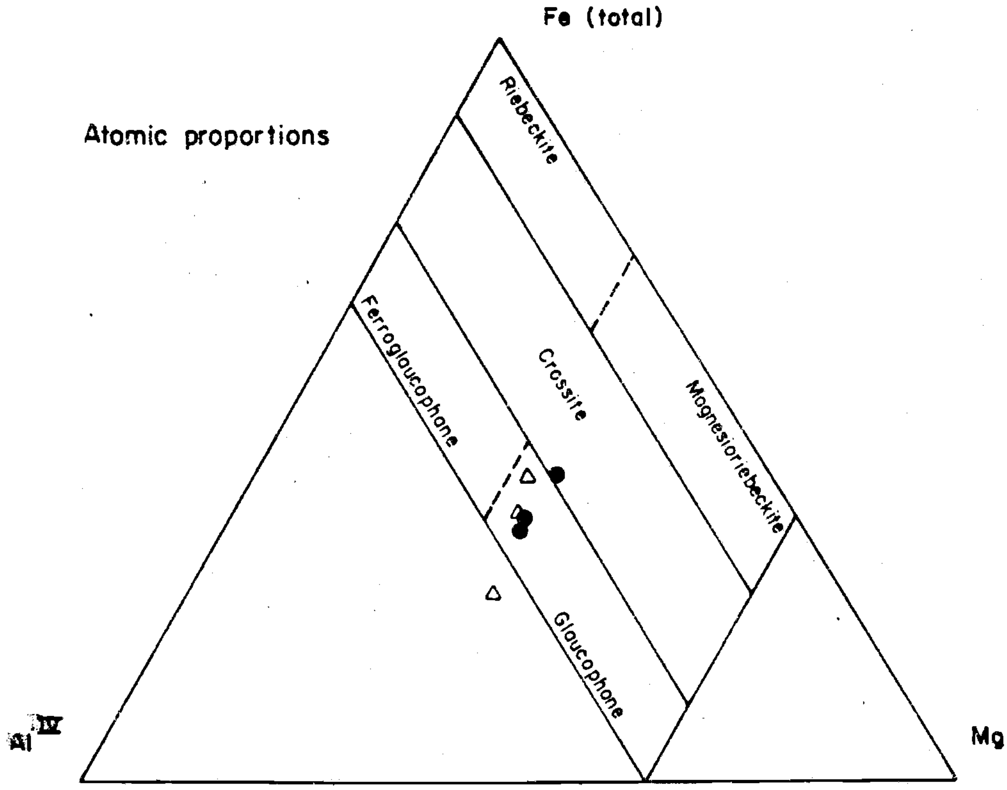


Figure 21

Sodic Amphibole Composition: Meyers Canyon Locotion

△ Rim
● Core

Diagram after Ernst (1977).

TABLE 12. AMPHIBOLE MICROPROBE ANALYSES, MC-1. *

Sample	101		102		201		Average	
	Rim	Core	Rim	Core	Rim	Core	Rim	Core
SiO_2	54.82	53.66	55.57	56.69	53.17	55.26	54.0	56.0
Al_2O_3	9.86	10.27	7.23	7.60	11.40	9.93	8.5	8.0
TiO_2	0.05	0.06	0.02	0.02	0.04	0.06	0.4	0.1
CaO	7.37	5.64	4.47	3.54	8.55	3.50	6.5	4.0
K_2O	0.06	0.06	0.06	0.07	0.03	0.05	0.3	0.1
Na_2O	4.43	4.93	53.7	5.81	4.01	5.93	4.7	5.9
MgO	9.13	9.30	9.47	9.50	7.74	9.04	9.0	9.3
Fe*O	13.40	14.41	14.99	15.04	11.58	14.65	12.0	15.0
MnO	0.18	0.19	0.13	0.16	0.13	0.11	0.2	0.2
Cr_2O_3	0.00	0.04	0.08	0.07	0.05	0.00		
F	0.00	0.00	0.00	0.00	0.00	0.00		
Cl	0.00	0.00	0.00	0.00	0.00	0.00		
H_2O	0.00	1.05	2.40	1.50	3.34	1.22	2.10	1.23
SUM	99.30	99.61	99.79	100.00	100.04	99.75		
Al^{IV}	0.00	0.00	0.00	0.00	0.00	0.00		
Al^{VI}	1.755	1.854	1.333	1.395	2.070	1.816		

*Meyers Canyon Blueschist. See appendix for sample description.

Two cores of the amphiboles are high calcium glaucophanes which plot in the glaucophane field on composition diagram defined by Al^{VI}-MgO-FeO relations. One core plots in the crossite field (see Figure 21). Rim analyses are intermediate between actinolite and hornblende, and might best be characterized as barroisite. The transition from comparatively low Ca content (but high for a sodic amphibole) of cores to increased Ca content of rims suggests increasing miscibility of Ca-Na amphibole with time, and a probable increase in T and decrease in P. Plots of the amphibole composition on a Na_{M4}-Al^{IV} diagram after Brown (1977) indicate that pressures of metamorphism for both rim and core compositions exceeded seven kilobars, and were well within blueschist parameters. The restriction of aluminum to six-fold coordination sites suggests that temperatures of metamorphism were low, but quantitative estimates cannot be made from the discussion of Ernst (1968).

One microprobe analysis of a small, prismatic phase initially thought to be lawsonite produced an analysis characteristic of pumpellyite from the Goat Mountain area of the Franciscan (Ernst _et al._, 1970).

Swanson (1969) tentatively identified pumpellyite in thin section in Meyers Canyon rocks. Pumpellyite is fairly common in rocks of the glaucophane schist facies, at localities such as Goat Mountain, California, and the metavolcanics of the Oboke district, Sanbagawa, Japan, and even in rocks of the lower greenschist facies in the Oboke district (Ernst _et al._, 1970).

TABLE 13. PUMPELLYITE MICROPROBE ANALYSES

	MC-1	GM*	GM*	GM*
SiO_2	37.00	37.00	37.13	38.24
Al_2O_3	29.03	23.73	24.22	25.55
TiO_2	0.16	0.23	1.31	0.13
CaO	21.73	22.33	22.47	21.38
Na_2O	0.12	0.40	0.21	0.05
K_2O	0.01	0.04	0.03	0.00
MgO	1.45	2.84	2.44	3.32
Fe^*O	2.57	4.46	4.90	3.71
Anhydrous Sum	92.08	91.03	92.71	92.97

*GM; Goat Mountain (Ernst _et al._, 1970).

Conditions of Metamorphism. Sweeping conclusions regarding the metamorphic history of the Meyers Canyon blueschists are not justified from just three amphibole and one pumpellyite analyses. However, consistent zonation of the three amphiboles examined suggests that increasing temperature and/or decreasing pressure were imposed upon the Meyers Canyon rocks with time. The slightly calcic glaucophanitic core composition indicates initial metamorphism at pressures in excess of seven kilobars, and low temperatures. Increasing Ca content of the amphibole with time probably reflects increased miscibility of Ca and Na amphiboles, with decreased pressures, and possibly little temperature increase. Final metamorphic pressures, suggested by rim compositions, may have been on the order of six to seven kilobars.

Age. Fusulinids of early to middle Permian age have been recovered from the metasediments associated with Meyers Canyon blueschists (Bostwick, pers. comm., 1978). Swanson (1978, pers. comm.) obtained a K-Ar radiometric date of 220 m.y. (Triassic) from mica separates of the Meyers Canyon blueschists. Hence the sediments are probably Permian and were subjected to metamorphism during the Triassic.

Possible Interrelationships and Metamorphic History

From the preceding data and discussion it may be concluded that: 1. Schists of Bennett Creek, Mine Ridge and Meyers Canyon have a similar metamorphic hisotry. Petrographic and mineralogical criteria strongly suggest initial metamorphism at high (but varying) pressure, and decrease of pressure with probable increase of temperature through time. This trend is generally opposite to the metamorphic history of the Franciscan. 2. There is a systematic increase in pressure and decrease in temperature for the metamorphic regimes from east to west through the Blue Mountains. 3. The

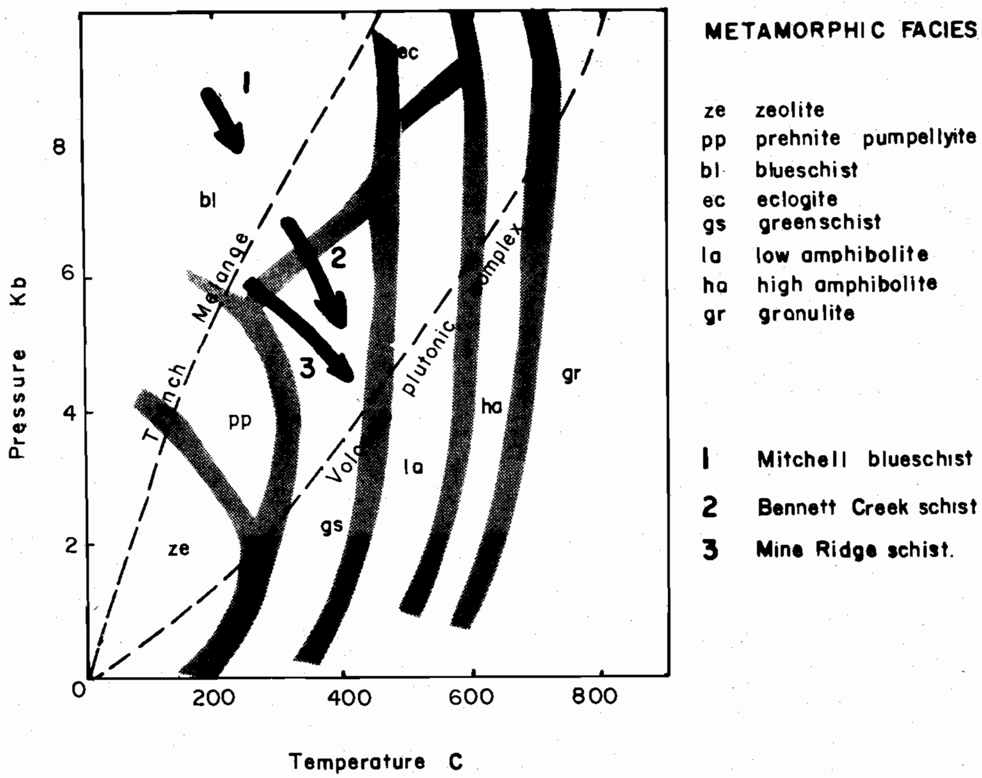
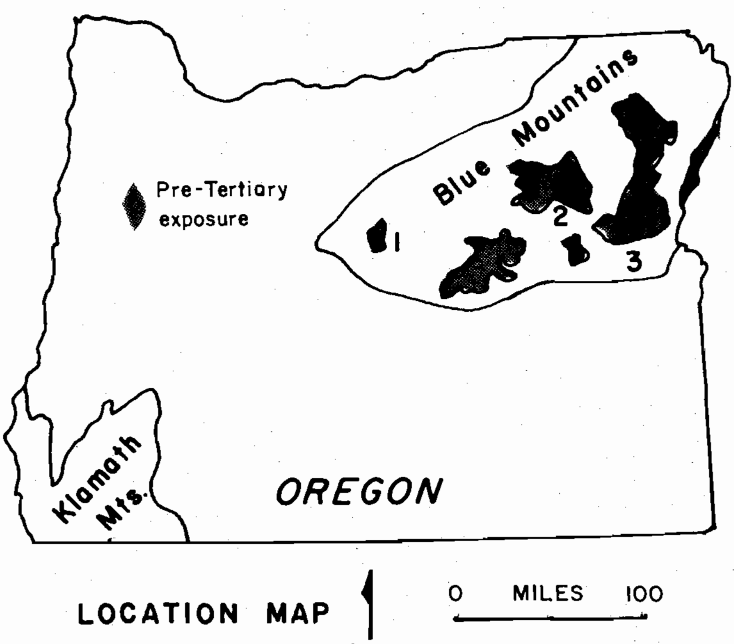


Fig. 22. Metamorphic petrogenetic conditions, N.E. Oregon schists. Based upon microprobe data. After Ernst, (1973).



LOCATION MAP

schists investigated apparently are approximately equivalent in age. Radiometric dating of the Bennett Creek rocks may change this conclusion.

Two possible mechanisms have been proposed for development of blueschist facies metamorphism. The most common is subduction of sediment as well as oceanic lithosphere to depths of up to 35 km (13 kb along the lowered geothermal gradient associated with the subduction zone (Ernst, 1963). This model easily accounts for the hydrous, low T, high P conditions associated with blueschist facies by adiabatic rise of blueschists through the crust (Ernst, 1977). However, it is not clear that adiabatic rise through crustal material occurs (Ernst, 1977, pers. comm.), and there has also been much disagreement concerning whether subduction of low density sediments is feasible.

A second mechanism, suggested by Coleman (1967), is production of schists at low temperaturs and near surface conditions by tectonic overpressures. There are two possible schemes which the high pressure schists of northeast Oregon's Blue Mountains might be related:

1. All units investigated in this thesis could have originated in a fore-arc accretionary wedge (Karig and Sharman, 1975) or on an oceanic plate. Blueschist or near-blueschist metamorphism resulted from subduction of sediment dragged down with oceanic lithosphere.

Higher grades of metamorphism developed due to subsequent adiabatic rise through the crust. If subduction zone metamorphism was responsible for the Mine Ridge Schist and Bennett Creek Schist, increasing pressure of metamorphism might be expected from west to east along the trend of progressively deeper burial. In fact, the opposite trend is observed. However, more prolonged retrograde metamorphism at higher temperatures with adiabatic rise from deeper burial might have altered the original sodic character of the amphiboles, or the original subduction zone may have trended obliquely. Tectonic displacement due to incorporation of sediments in serpentinite melange might also explain the discrepancy.

2. The Meyers Canyon blueschist may represent the product of an eastward-dipping subduction zone west of a Permian island arc. The slightly higher grade Bennett Creek and Mine Ridge Schists (and Burnt River Schist (Ashley, 1967)) may be the products of a mechanism similar to tectonic overpressure produced by westward thrusting of distal arc and marginal basin sediments as a result of marginal basis closure.

Evidence has been presented which suggests some pre-Tertiary sediments of the Greenhorn Mountains originated in a fore-arc accretionary wedge. High pressure metamorphism in a subduction zone is the simplest and most likely origin for the Mine Ridge and Bennett Creek Schists. However, because back-arc deposition cannot be ruled out, metamorphism by a mechanism similar to tectonic overpressure, although discounted by Brace et al. (1970) might be considered as an alternative.

Metagabbro

Units collectively termed "metagabbro" are a texturally diverse and structurally complex assemblage of mafic rocks which occupy approximately 13 square miles (35 km^2), or nearly 15 percent of the thesis area. Investigation of the unit(s) requires more rigorous study than is possible in this thesis.

From appearance in outcrop, the metagabbro can be readily subdivided into four end-members: cumulative metagabbro, tectonite metagabbro, amphibolite gneiss, and leucocratic differentiates (hornblende metagabbro). Each type is discussed separately.

Cumulate Metagabbro

Coarse to finely crystalline, relatively untectonized gabbroic rocks occur as pockets in an overall tectonite matrix. The units defined [in outcrop and in thin section] as cumulates are completely phaneritic. They display only limited amounts of cataclysis confined to discrete, usually cross-cutting zones in which slight stretching, but no mylonization of crystals occurs.

Such rocks are dark to light grey-green and vary widely in

TABLE 14. MODES OF METAGABBROS*

	Cumulates				Tectonites			
	M-208	M-213	M-240	M-46	M-232	M-234	M-23	M-223
Plagioclase	45.5	--	44.9	49.7	52.8	--	38.5	20.8
Clinopyroxene	32.1	7.4	12.5	15.1	0.5	--	--	--
Hornblende	18.1**	31.0	39.1	30.2	--	--	--	48.2
Actinolite	tr	tr	1.2	1.9	3.7	tr	19.3	tr
Epidote	--	3.7	--	--	3.4	0.7	0.6	22.0
Clinozoisite	--	--	--	--	9.7	28.5	3.3	--
Chlorite	1.2	6.7	tr	2.8	18.1	39.0	28.2	4.3
Calcite	tr	1.0	0.7	--	7.2	24.6	1.8	1.3
Prehnite	--	--	--	--	--	--	--	--
Quartz	--	--	--	tr	1.6	2.1	5.2	1.2
Wollastonite	--	47.7	--	--	--	--	--	--
Sphene	--	2.5	0.7	tr	1.9	3.7	3.1	2.1
Apatite	--	--	tr	0.3	tr	--	--	--
Opaque	2.1	tr	0.9	tr	1.1	tr	0.2	tr
SUM	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*See Appendix 2 for sample description. **pargasite in M-208 grain size and overall texture. Dense, fine-grained varieties occur as linear or tabular segregations within a lighter, usually coarse matrix. Boundaries are sharp between these two subtypes of cumulate gabbro. Layered gabbros are exposed on ridges west of Upper Olive Lake. Series of alternating mafic and leucocratic bands, one to four inches (two to nine cm) in width are interspersed with more homogeneous, coarse hornblende gabbro.

Although outcrop differences are not readily apparent, a distinct change occurs in secondary mineralogy between cumulate gabbros of the west and east halves of the thesis area. In gabbros from the west, relict clinopyroxenes are rimmed by uralitic blue-green hornblende or actinolite. Where clinopyroxene is interstitial to mesocumulate plagioclase (M-46), decussate blue-green amphibole may obliterate the original pyroxene. Where relict clinopyroxene is evident, epidote and some actinolite occur along (100) cleavages. Plagioclase (An_{92-61}) is cracked and veined by chlorite, epidote, and albite, but twin lamellae are rarely offset. Plagioclase contains inclusions of sericite, acicular actinolite, quartz, and small clinozoisite. Where plagioclase is interstitial to pyroxene (orthocumulate textures), pyroxenes are rimmed by feathery and decussate blue-green hornblende, and contain inclusions of chlorite. Prochlorite occasionally forms jackets around clinopyroxene inside amphibole. Plagioclase is largely replaced and veined by albite; relict composition is An_{68-55}). Clinozoisite and acicular actinolite are commonly included in interstitial plagioclase. Apatite is uncommon and forms elongate prisms. M-213, a finely layered rock shows secondary, tectonically enhanced layering. Leucocratic bands are composed of plumose prochlorite, with quartz and albite, whereas mafic clinopyroxene bands appear to alter to tremolite + prehnite.

Cataclasis is more evident where plagioclase is interstitial. In M-240, clinopyroxene cleavages are slightly bent. Plagioclase is somewhat granulated and more commonly altered to chlorite.

In cumulate rocks from the east half of the thesis area, alteration of clinopyroxene to blue-green hornblende is absent. Rounded orthocumulate augite (?) in M-232 displays exsolution of orthopyroxene along lamellae parallel to (100), and alteration to clear chlorite, granular sphene, and clinozoisite. Plagioclase is interstitial and alters to albite, sericite, sphene, calcite, and prehnite. In a more iron-rich, finer-grained sample from the same outcrop, (M-232b) similar primary mineralogy occurs, but alteration products include yellow epidote and green chlorite developed around clinopyroxene and within plagioclase, and veins of calcite, albite and quartz. Plagioclase twinning is infrequent and poorly developed in the cumulate metagabbro from the east half of the thesis area, and is commonly deformed.

Variation in crystal size within cumulate metagabbro appears random, and cannot be mapped. Fine and coarse phanerites merge gradationally except in melanocratic amphibolite pods. Cumulate texture of those segregations and close spatial association with thinly layered gabbros of similar orientation strongly suggests that the fine, massive amphibolites originated as thick beds in a layered sequence.

Tectonite Metagabbro

Variation among tectonite metagabbros is extreme. Cumulates grade into tectonites; progressive cataclasis of cumulates can be traced across outcrops west of Upper Olive Lake and along the east side of Clear Creek. Phaneritic cumulates are increasingly disrupted by mylonitic zones with increasing development of phanentic lenticles in a mylonitic network. Ultimately, cataclasis is complete.

The most prevalent type of tectonite metagabbro is dark green. Some are vaguely phaneritic, but an irregularly laminated fabric is common to all tectonites.

Tectonite metagabbro consists of both coarse and fine-grained types, with gradations in between and seemingly random distribution. Some textures within fine grained units are suggestive of volcanic rocks in outcrop and in thin section. Volcanic greenstones may be included within the tectonite metagabbro assemblage. Some thoroughly cataclastized "volcanics" contain brownish segregations of seemingly vesicular and porphyritic material which might represent relicts of noncataclastized basaltic lavas. A very distinctive tectonite is a metagabbro breccia which contains large angular fragments of cumulate and hornblende metagabbros, as well as some slightly porphyritic clasts, in a highly cataclastic matrix. This breccia is probably related to gabbro emplacement, but because it occurs as a glacial erratic in Upper Olive Lake, its precise nature is difficult to determine.

Cataclasis and mylonization of some rocks is extreme. In M-17, fine epidote, granulated clinopyroxene actinolite and albite occur as prophyroblasts or as fine fragments in a mylonitic matrix. Clots with centers of epidote and albite rimmed by concentric rings of albite + actinolite + chlorite suggest syntectonic rotation of some components. Sphene altered to leucoxene is disseminated throughout many rocks and the pervasive presence of leucoxene commonly gives a "fuzzy" appearance to the section. Segregation into compositional bands occurs in the most completely mylonized rocks.

Veins of calcite, chlorite, quartz, prehnite, and albite crosscut the rock. Particularly in the eastern thesis area, large tabular clinozoisite extends from vein boundaries toward vein centers. A few veins of cataclastized clinozoisite occur in M-26, suggesting that clinozoisite was both pre and post tectonic.

Tectonite metagabbros from the west portion of the thesis area resemble those of the east, but contain much more blue-green hornblende. At least one dark-green blastomylonite (M-206) contains relict volcanic textures. Green-brown hornblende, quartz, albite, epidote, and sphene are incorporated in the granulated, slightly differentiated matrix. Relict phenocrysts of corroded plagioclase, An_{55}, 0.5 mm long exhibit bent twin lamellae where intact. Plagioclase has inclusions of apatite and chlorite. Relict clinopyroxene in western tectonites is usually cataclastic, indicating formation before final stages of deformation.

Banded Amphibolite

Thinly banded and tightly folded amphibolites occur on the east banks of Upper Olive Lake. The rocks contain alternating leucocratic and melanocratic layers from less than an inch to about five inches in width. Mineral lineation parallels layering. More restricted banded amphibolites also occur in the half of the thesis area near Greenhorn in section ten, T. 10 S., R. 35 E. Banded amphibolite near Greenhorn is gradational to tectonite metagabbro (which is gradational to cumulate metagabbro...).

All banded amphibolites contain alternating layers of blue-green hornblende/actinolite + epidote + epidote ± quartz and albite and albite + quartz ± epidote ± sphene.

Various mechanisms have been suggested for generation of banded, gneissose amphibolites from sediments and mafic protoliths by metamorphic differentiation. Ramberg (1952) proposed that differentiated stress during metamorphism produces ionic migration along chemical potential gradients. Constituents with the highest concentration or largest molar volume would undergo the greatest change in chemical potential and hence would migrate first (Vernon, 1975). The incipient development of amphibolite in localized occurrences of tectonite metagabbro indicates that differential stress as proposed by Ramberg (1952) is the probable mechanism for the development of the banded amphibolites.

Hornblende Metagabbro

A leucocratic metagabbro occurs locally on the south side of Black Butte. Poor exposure prevented confident determination of the relation of this unit to other metagabbro, but similarity in alteration and deformation suggests that the rock is a more leucocratic associate of the metagabbro units.

On a weathered surface, the rock is dark grey with small black flecks of hornblende in a directionless fabric. Fresh exposures are slightly pinkish grey. Cleavage faces of plagioclase and some small porphyroblasts of quartz (one mm ±) are visible in addition to dark rectangular hornblende.

Texture of hornblende metagabbro approaches hypidiomorphic, with considerable cataclasis of the groundmass.

Relict plagioclase occurs as two or three mm equant, corroded crystals showing faint remnants of carlsbad twins. Plagioclase is so extensively replaced by calcite, epidote, sericite, and chlorite that original outlines of crystals are obscure. Deformation frequently offsets relict twins and results in albite-filled fractures. The best determinations of composition indicated that the relict plagioclase varies from andesine to oligoclase.

Relict hornblende is green-brown to deep green one-three mm in length, euhedral to subhedral, and rimmed and replaced by green chlorite. Laths are broken and cut by chlorite-filled transverse fractures and rare poikilolitic inclusions of epidote occur.

Quartz porphyroblasts appear to be secondary and post-tectonic. They are clear and prismatic with even extinction and show no evidence of deformation. Small aggregates of green-brown to red-brown biotite are nucleated both in the groundmass and in areas of green chlorite. They indicate that metamorphism of the hornblende gabbro reached at least lower greenschist facies. Due to the relatively high Al, Fe, and K content of the hornblende gabbro (M-250) biotite may form at lower T/P conditions than in more mafic rocks such as the Olive Creek pillow lavas (McNamara, 1966).

Figure 23a. Cumulate metagabbro (dipping right, parallel to knife) cut by F_{3b} mylonitic amphibolite.

Figure 23b. Serpentinite melange, east of Vinegar Hill. Serpentinite matrix contains clasts of tuffaceous argillite and metagabbro. Large pinacle in left center is the "green horn," for which mountains were named.

Chemistry

Four cumulate metagabbros from the west part of the thesis area were analyzed for major oxides to determine affinity to other rocks of ophiolitic suites and to provide general information regarding interrelations. Results are given in the table below.

Analyses are similar to results given for mafic cumulates of ophiolites (Coleman, 1977), which vary widely.

Modal abundances are reflected in the chemical analyses. M-46, the only rock containing orthocumulate plagioclase with interstitial clinopyroxene is understandably higher in SiO and Al_2O_3 than associated mafic cumulates which contain interstitial plagioclase.

Several chemical trends in the mafic cumulate series duplicate trends common to mafic cumulates of ophiolites. $CaO/Al_2O_3/MgO$ for known ophiolites follows a trend generally of $CaO = Al_2O_3$ and $MgO = 1/2\ Al_2O_3 + CaO$ (approximately). This trend is similar to the Skaergaard, but the magma is depleted in equal amounts of Ca and Al at an earlier stage (Coleman, 1977).

It is also possible that the variation between documented Skaergaard differentiation trends and those of mafic cumulates from ophiolites may be a function of metasomatic alteration of initial abundances in the ophiolite suite.

Low overall Na_2O, and K_2O are compatible with ophiolite trends.

TABLE 15. CHEMICAL ANALYSES OF METAGABBRO AND P-1

	Cumulate Metagabbro				Hornblende Metagabbro	Amphibolite Pod.
	M-46	M-208	M-213	M-240	M-250	P-1
SiO_2	51.55	45.87	48.19	43.64	58.85	50.18
Al_2O_3	19.90	12.53	20.13	17.63	13.41	16.24
TiO_2	0.21	0.32	0.22	0.46	0.81	11.05
CaO	15.10	15.95	17.35	15.80	14.56	5.24
Na_2O	0.58	0.21	0.61	0.41	2.10	1.73
K_2O	0.11	0.06	0.05	0.05	2.67	0.27
Fe*O	5.97	8.54	5.32	9.00	6.06	15.10
MgO	6.40	14.40	7.90	12.72	1.50	0.23
P_2O_5	0.16	0.19	0.23	0.18	0.37	0.13
SUM	99.98	98.07	100.00	99.89	100.33	100.35

However, Ti and P_2O_5 are slightly enriched, above the concentration in the usual cumulate suite. As both elements are considered relatively immobile during hydrous metamorphism and alteration, the increased abundance of TiO_2 and P_2O_5 is probably a primary feature of the Greenhorn gabbros.

On plots of major oxides versus SiO_2, a crude differentiation is apparent for metagabbro with respect to P_2O_5, K_2O, MgO, and CaO. FeO appears to have a nearly reversed trend, and little significant variation is present in TiO_2 and Al_2O_3 plots.

Metagabbro Structure

At least four episodes of deformation are evident from examination of cumulate and tectonic metagabbros:

1. F_1 - Stretching and elongation of cumulate crystals parallel to layering.
2. F_2 - Formation of broad, northwest trending folds in cumulate layers.
3. F_3 - Mylonitic shear zones, generally sub-vertical, which cut the F_2 folds in stretched cumulate layers. Two sets of mylonites occur: a northwest trending set generally displaying left-lateral offset, and a northeast trending set evenly divided between left and right lateral offsets. Mylonites commonly cut tectonite metagabbros as well as cumulates.

4. North-South shear zones, usually subvertical, with slight right lateral movement. These fractures also affect the peridotites.

Structural elements listed above are similar in intensity, sequence, and direction to deformation in the Canyon Mountain Complex (Ave Lallemant, 1976). Two elements apparently missing from the Greenhorns are present in the Canyon Mountain Complex:

1. Ave Lallemant (1976) observed an F_{3a} which consists of subhorizontal mylonites. This element may have been overlooked in the Greenhorns, and considered as shear along places of foliation and layering. Certainly there is considerable shear parallel to tectonized layering in thin section.

2. Ave Lallemant (1976) reports a "large, north-west trending anticline, overturned to the south" as F_4 and sub-vertical faulting as F_5. Folding occurs in the Greenhorns, and trends generally northwest where cumulates are sufficiently well layered to determine a strike, so elements of F_4 may be common to the Greenhorns. However, the terrane in the thesis area is greatly disrupted, and sequence of units is not a reliable guide to "top." Graded cumulate layers are not well developed, so until more extension investigation of the area is undertaken, or critical new outcrops are located, the <u>unequivocal</u> presence of an F_4 correlative to the Canyon Mountain Complex F_4 remains uncertain.

Similarity in rock type, appearance, and deformational sequence and directions indicate that the metagabbros of the Greenhorns are the equivalents of the Canyon Mountain Complex, and demonstrates that no significant rotation of the Greenhorns with respect to the Canyon Mountain Complex has occurred since emplacement.

Age

Metagabbros of the Greenhorns are considered the same age as the Canyon Mountain Complex due to structural and lithologic equivalency. Both intrude sediments of Early to Middle Permian age. The Canyon Mountain Complex has been considered pre-Late Triassic (Brown and Thayer, 1969). Recently Lanphere determined radiometric ages of 240 to 250 my for hornblende-rich dikes which cut the gabbro, and dates from 184 to 236 my for amphibolite blocks in melange and for other intrusions which post-date the Canyon Mountain Complex (Vallier *et al.*, 1977). Therefore, the age determined radiometrically for the Canyon Mountain Complex, and hence for the Greenhorn gabbro-peridotite-serpentinite sequence is probably Middle to Late Permian. Emplacement occurred during the Triassic.

Alpine Ultramafics

Alpine-type peridotites, in varying stages of serpentinization, form a small but distinctive component of the pre-Tertiary ophiolitic sequence of the Greenhorns. Four strongly similar peridotite bodies were distinguished. The mile-long Ben Harrison body, in sections 34 and 35 north of Ben Harrison Peak affords excellent exposures due to dissection and erosion by alpine glaciation, and is the basis of most observations and discussion. However, other pertinent locations of relatively un-serpentinized and unsheared peridotites are the outcrops at the head of Wray Creek, section seven and 18, T. 10 S., R. 34 E., small body northwest of Vinegar Hill in section 12, T. 10 S., R. 34 E., and serpentinized peridotite on Rosey Finch Ridge, section 19, T. 9 S., R. 34 E. Most exposures grade into sheared serpentinite, and none show pristine mineralogy.

Units mapped and discussed as serpentinized peridotite are light red-brown to yellow brown on weathered surfaces and dark greenish grey to olive-brown on fresh surfaces. Rocks with harzburgite and dunite protoliths can be distinguished by surface texture. Dunites exhibit a smooth surface, and often small black spinels are visible in the usually yellow-brown peridotite. Peridotite with a harzburgite protolith generally has a knobby surface, with shiny relict or pseudomorphed pyroxene giving a rough appearance. Spinels are seldom visible on the surface of the harzburgite. Narrow serpentinized wehrlite and pyroxenite dikes crosscut the peridotites, and are more common in "harzburgite."

The ultramafic rocks have developed a crude and indistinct layering which is largely secondary in origin. There is no discernible regularity to the distribution of harzburgite and dunites, but tectonic and metasomatic layering and boudining can be observed in the Ben Harrison and Rosey Finch Ridge bodies.

Petrography

In thin section, serpentine and talc rarely occupy more than 90 percent or less than 40 percent of the total volume of the peridotite. Olivine is usually altered to a combination of talc, chlorophaeite, and serpentine. Relict olivine is plastically deformed and elongated. Clinopyroxene is well preserved and commonly is strained slightly, with some wavy extinction. More brittle deformation and kink banding, however, are not apparent in clinopyroxenes of alpine peridotite bodies. Extensively deformed and kink-banded pyroxenes occur in one pyroxenite knocker (not in place) in serpentinite associated with layered ultramafics near Spring Creek in section 3, T. 10 S., R. 35 E. Similar knockers show few strain features.

Clinopyroxene is frequently rimmed by fibrous tremolite. Occasional acicular or prismatic cummingtonite occurs with orthopryoxene, and is characteristically twinned on (100). Both pyroxenes alter to colorless chlorite, as well as talc. In addition, some clinopyroxene is partly altered to carbonate.

The matrix of the serpentinized ultramafics consists of serpentine, talc, brucite, colorless chlorite, and veins of carbonate, prehnite, and occasional quartz. Lizardite with minor chrysolite is found in both mesh and aggregate textures. Mesh structure with antigorite is more common in rocks which are distant from granitic intrusions, indicating that recrystallization of the serpentinite matrix accompanied thermal metamorphism. Radiating talc sheaves are common in all locations sampled.

Contact effects of granitic intrusions are pronounced for a short distance. Samples of peridotite within three feet of the contact with tonalite at Ben Harrison Peak at an elevation of 7670 feet (2324 m) show extensive recrystallization of olivine in small (0.2-0.6 mm) clear porphyroblasts. The magnetite + antigorite matrix is very fine grained and matted. Large, radiating clusters of clear, optically positive, magnesian anthophyllite, one to four millimeters in length are visible on fresh surfaces and impart an appearance similar to, but much finer than the true metamorphic spinifex texture noted adjacent to amphibolite pods. Limited development of small, equant hydrogrossular is found in harzburgite near the contact, and probably is derived in part from calc-metasomatism during intrusion of the granitic rocks (Deer _et al._, 1966). Very small poikiloblastic almandine is developed in along veins and associated with harzburgite at one location approximately 400 feet from the nearest granitic contact. Almandine probably represents the alteration of amphibolitic material

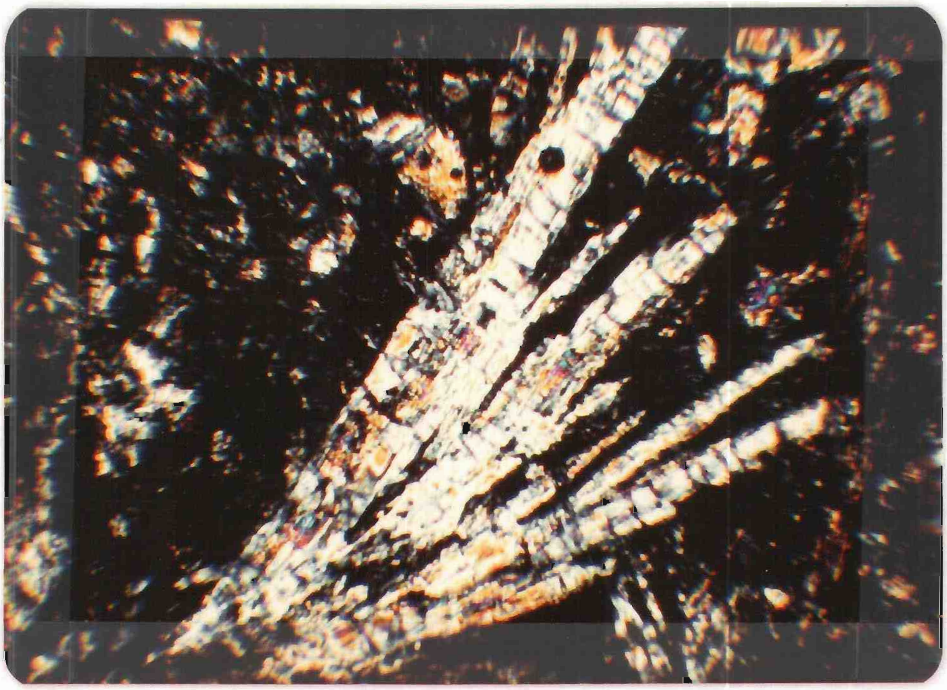


Figure 24. Radiating anthophyllite, thermally metamorphosed peridotite, Ben Harrison Peak. Sample from within three feet of contact between tonalite and ultramafic. Crossed nichols, X100.

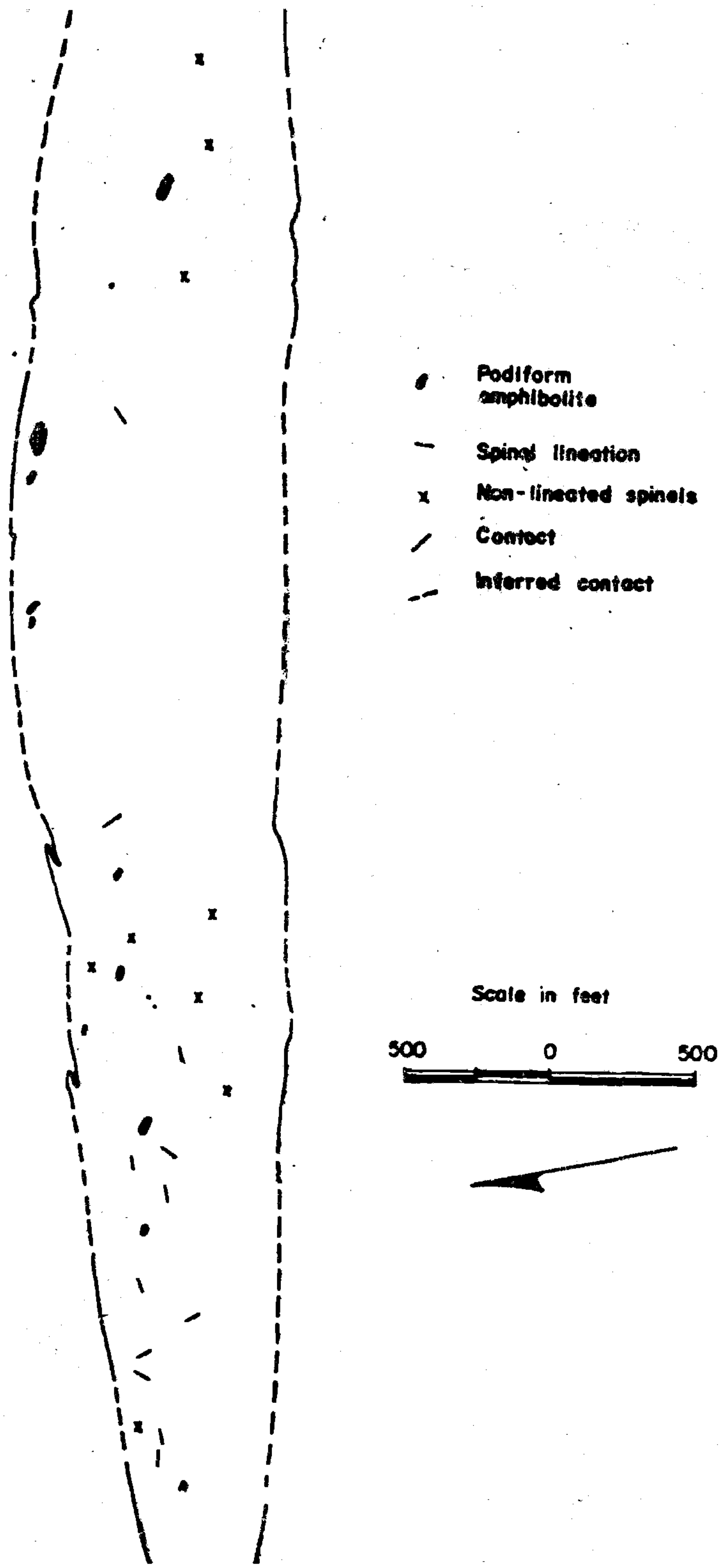


Figure 25

PODIFORM AMPHIBOLITES AND SPINELS

BEN HARRISON ULTRAMAFIC BODY

Figure 26a. Metamorphic spinifex texture, M-222.

Figure 26b. Metasomatic dunite "dike," Ben Harrison ultramafic.

included in the peridotite. At distances more than 500 feet from the contact, thermal metamorphism is responsible for enlargement of tremolite rims around clinopyroxene, and growth of some acicular tremolite.

Metasomatic Dunite

Possible metasomatic recrystallization of dunites occurs in two locations of the Ben Harrison ultramafic body. Metasomatically recrystallized rock crosscuts and appears to intrude peridotite of harzburgite type. The surface of the metasomatized rock is not entirely smooth, but shows a slight knobby texture, suggesting that it also formed from the harzburgite. In thin section, small, clear, granular olivine is enclosed by a felted talc-serpentine-magnetite matrix. Relicts of clinopyroxene are rimmed by extremely uralitic tremolite.

Occurrence of hydrogrossular near the contact with tonalite indicates that metasomatic processes were active during granitic intrusion. Dungan and Ave Lallemant (1976) noted the presence of similar features in the Canyon Mountain Complex 35 miles (58 km) to the south. In Canyon Mountain Complex dunite bodies, the orientation of groundmass spinels is not changed in the transition from harzburgite to "dike" and back to harzburgite, so metasomatic transformation of the harzburgite to dunite was inferred. Dungan and

Ave Lallemant (1976) proposed that high pH aqueous solutions or vapors removed Si and Ca locally and resulted in growth of olivine from unstable pyroxene. In the Ben Harrison body, the olivine seldom occurs with the triple point junctions reported for the Canyon Mountain Complex, and elevated temperatures in the thermal aureole of the adjacent pluton possibly were partly responsible for dehydration of the serpentinite and reaction of unstable pyroxenes. The localized presence of quartz and carbonate veins supports the possibility of fairly high pH fluids circulating within the Ben Harrison ultramafic.

Metamorphic Spinifex Texture

Small, randomly oriented bladed recrystallized olivines (Fo_{88-90}) in a talc matrix occur in two locations of serpentinized peridotites. Textures and mineralogy are similar to rocks described as metamorphic spinifex texture (Hietanen, 1977) or jackstraw texture (Snoke and Calk, 1978) from the northern Sierra Nevada. Field relations, petrography, whole rock and mineral chemistry suggest this texture resulted from thermal metamorphism and consequent dehydration of ultramafic rocks. See Appendix 1 for analyses and detailed discussion.

Structure

The Ben Harrison and other peridotite bodies are crudely layered. Close examination of layering discloses that it is composed of bands which alternate in the degree of serpentinization and to some extent in mineral content. The bands are boudined and then folded in both tight and relatively open folds, suggesting initial elongation in a probably northeast-southwest direction followed by east-west compression. This pattern is generally consistent in the four peridotite bodies mapped.

Although pyroxenes from the crudely layered rocks are only slightly deformed, olivine has deformed plasticly, probably by syntectonic recrystallization, although at present stage of study this is conjecture only. Ave Lallemant (1975) noted that the mechanism of syntectonic recrystallization is plausible for olivine maxima from the Canyon Mountain Complex. Deformation and evident preferred orientation of olivine may have partly resulted from solid state flow in the upper mantle prior to obduction and emplacement (Nicolas, 1976).

To help resolve the pattern and sequence of folding in the Ben Harrison body, spinel orientations were plotted on a map of the peridotite. According to Nicolas and Boudier (1975) and Boudier (1976, pers. comm.), spinel orientations are good indicators of fold directions in alpine-type peridotites. Although the sparse occurrence of well oriented spinels allows a smaller data-base than desirable, spinel orientations suggest that the last major deformation of the peridotite was east-west compression.

Amphibolite Pods

Elongate pods of dense, uniformly fine-grained black amphibolite occur in the serpentinized peridotites of Ben Harrison Peak, Rosey

Finch Ridge, and Saddle Camp. They also are present as fine-grained, laminar segregations within cumulate metagabbros of the Upper Olive Lake region, but it is not certain that the mafic amphibolite segregations of the metagabbro are equivalent to those in the serpentinite.

Amphibolites in the cumulate metagabbros have sharp and usually regular contacts with the adjacent gabbro, although the amphibolites are not of great axial extent and extend for distances of about 100 feet (30 m). Width of darker bands varies from a few feet or less (less than one m) to about ten feet (three m). Field appearance and close relations to the cumulate metagabbro as well as petrography suggest that the fine-grained, uniform amphibolites of the metagabbro represent a mafic cumulate layer.

Pods associated with the alpine ultramafic rocks are criss-crossed by a network of siliceous and chloritic veins, and range in size from less than one foot (30 cm) in diameter, to elongate elliptical forms with a maximum axis of 60 feet (18 cm) and a width of 30 feet (nine m). Except in extremely small pods, which might represent only partial exposure of larger amphibolites, the long axis was almost uniformly twice the length of the pod width.

The elongate amphibolites occur in en echelon segments along the length of the Ben Harrison and Rosey Finch Ridge ultramafics. They were not sufficiently common in the remaining exposures to determine a valid geometric relations. The pods are displaced generally in a right-stepped en echelon pattern where individual pods of small dimensions show immediate and closely spaced breaks.

However, the broad, overall pattern of offset between widely separated pods is left-stepped.

Contacts between the peridotite and the amphibolite pods are sheared where exposed. Where the contact is not apparent, it is usually covered by vegetation or deeply eroded due to the softer nature of the sheared material. Poorly displayed contacts can be inferred as tectonic also.

The tectonic nature, general uniformity in size, shape and appearance, and regularity of en echelon offsets, suggest that the amphibolite pods of the ultramafic bodies represent a single or several cumulate layers. Occasional diabasic texture suggests some are dikes which intruded the peridotites at an early stage in emplacement history, perhaps prior to extensive hydration and serpentinization, and underwent simultaneous extension and deformation with the host peridotite. The uniform dimensions of the fully exposed amphibolite pods suggest that with extension and elongation of the peridotite, perhaps during ductile flow in the upper mantle, the more competent amphibolite layers boudined, developed "eaded structure," and finally broke into discrete, equidimensional "pods" which were further extended with continued upper mantle flow. Compression and folding during emplacement caused the major, generally left-stepped pattern of the pods. Left-lateral offset occurs on only a small scale of several feet and is generally parallel to small Jurassic dikes which intrude the Ben Harrison body. The minor left-lateral offsets are probably related to stress associated with granitic intrusions.

Petrography

Textures of amphibolite pods ranged from slightly cataclastized, fine-grained relict diabasic to coarse, relict idiomorphic to heteradcumulate. Medium to fine-grained (gabbroic) heteradcumulate, textures prevail. The mineralogy of all is similar: relict clinopyroxene may be present, and is surrounded and/or replaced by massive blue-green to green or yellow-brown to green hornblende. The hornblende is twinned on (100). Deformation of hornblende is common; sections parallel to (100) are frequently bent or kinked. Relict clinopyroxene is altered to calcite + magnetite + actinolite in hornblende interiors. Poikilolitic inclusions of plagioclase, epidote, and sphene are present in massive hornblende. A fine rim of uralitic actinolite often surrounds the hornblende, altering to chlorite. (See Fig. 50, p. 346.)

Interstitial areas between mafic minerals are occupied by plagioclase. Relief of the plagioclase is considerably higher than balsam, and determination of An by Michel-Levy methods gave a range of An_{82-78}. No zoning occurs in the plagioclase, but albite twinning is common and well developed where cataclastic textures are not pervasive. Plagioclase is not extensively clouded, but contains a large number of inclusions. Boundaries between plagioclase are irregular. Decussate blue-green actinolite which rims the more massive hornblende extends into the plagioclase. Epidote and acicular needles of actinolite are randomly distributed through the rock, forming up to 50 percent of the interstitial areas in more melanocratic slides. Plagioclase is not highly altered in most rocks, but where alteration is present, calcite, chlorite, and epidote form granular aggregates. Thin veins of calcite and quartz-albite crosscut both cataclastic zones and relatively undeformed (but strained) sections of the podiform amphibolites.

Sphene and apatite are common accessories. Sphene is usually granular and commonly rims magnetite. Symplectic intergrowths of sphene and opaque iron ore were noted in one slide (P-1). Apatite occurs in plagioclase as elongate, clear, and unzoned prisms, 0.5 to one mm in length. Almandine was noted in hand specimen and microscopically in one amphibolite pod from Rosey Finch Ridge (P-202). This sample was collected near a granitic intrusion. The texture is granoblastic and red-brown biotite is developed. Garnet apparently is a porphyroblast generated by thermal metamorphism.

Chemical Analysis

One amphibolite from the Ben Harrison body (P-1) was analyzed for major oxides as well as Ni and Zr. The results are given in Table 14. P-1 also contains 49 ppm Ni and 36 ppm Zr.

The analysis of P-1 generally conforms to the overall abundances of SiO_2, Al_2O_3, and Fe*O and MgO in sheeted dikes, pillow flows, and mafic (gabbroic) cumulate suites from ophiolites (Coleman, 1977). However, several critical differences are apparent between the typical ophiolitic suite and P-1. CaO is greatly enriched in P-1. Enrichment in CaO may result from circumvention of spilitization and consequent depletion in CaO by inclusion in the peridotite. However, even in unaltered basalt analyses, enrichment of P-1 in CaO approaches an excess of four to five percent (comparative data from Engel and Engel, 1963; Natland, 1975; Hawkins, 1977). The extremely high calcium content is explained by microprobe data for plagioclase. Plagioclase is anorthitic, about An_{95}.

The abundance of TiO_2 (1.7 percent) is slightly higher than the one percent or less which might be expected for spilites, and considerably higher than associated with most cumulate rocks of the lower gabbro series (Coleman, 1977).

P-1 is depleted in Na_2O and K_2O relative to spilites, most oceanic and all alkalic basalts, and in K_2O relative to mafic cumulate series of ophiolites. This extreme depletion indicates that P-1 was not subjected to spilitization, and strongly suggests its origin from a partly differentiated peridotite (or lower gabbro) melt.

The extremely low abundance of Ni in P-1 is somewhat puzzling at first, in light of the implications of data from CaO, alkalis, and TiO_2. However, both petrographic and X-ray diffraction scrutiny of P-1 indicate that although clinopyroxene is abundant, olivine is absent in the rock. Olivine is (or was before serpentinization) abundant in the peridotite as a whole. Analysis of a serpentinized dunite from the Ben Harrison body gave 1860 ppm Ni; analysis of a peridotite (wehrlite?) containing about 50 percent clinopyroxene showed 586 ppm Ni. The distribution coefficient (K_D) for the partitioning of Ni between co-existing clinopyroxene and olivine is:

K_D Cpx/01 = 0.2 (Gast, 1968)

K_D Plag/01 = 0.0 (assumed)

K_D liq/01 = 1.0 (Gast, 1968)

For a liquid (or solid at incipient melting) with approximately 200 ppm Ni (assumed from the 1860 ppm analysis of dunite) clinopyroxene crystallizing from that liquid should contain about 400 ppm Ni. Clinopyroxene plus hornblende which developed as a secondary or late, hydrated reaction of primary clinopyroxene constitutes approximately 20 percent by volume of P-1. Thus the expected content of Ni in P-1 is about 80 ppm, or close to the 49 ppm recorded.

Low abundance of Zr (36 ppm) is within the range for cumulates from early partial melts of peridotites (Coleman, 1977; Gast, 1968).

Mineral Analyses

Relict clinopyroxene, plagioclase, and amphibole were analyzed in sample P-1 to: possibly determine the petro-tectonic type of the magma, to confirm optical determination of high An content of the plagioclase, and to utilize the chemistry of the amphibole, specifically Na_{M_4} on a Brown type plot to determine possible pressure or P/T conditions of peridotite hydration.

Results from four clinopyroxenes are plotted on Si/Al, Si/TiO_2, MnO-TiO_2-Na_2O, and the traditional Mg-Ca-Fe ternary diagram together with analyses of clinopyroxenes from the Olive Creek pillow lavas (see pages 85-89 for plots). All schemes for classification of clinopyroxenes after Nisbet and Pearce (1977), Kushiro (1960) and Wilkinson (1956) demonstrate that the pillow lava clinopyroxene is distinctly alkalic whereas the clinopyroxene of P-1 plots in the field for volcanic arc basalts in most diagrams, and lies near the Skaergaard tholeiitic trend rather than in the alkali basalt field.

Plagioclase varies from An_{93} to An_{85}. No attempt was made to delineate zoning. The high content of iron and magnesium in the plagioclase analyses represent possible inclusion of some acicular amphibole and/or epidote in the probe beam. However, to analyze for Na, a large size beam was essential (see Appendix 3). The percentage of Na is lower in the plagioclase analyses which include some impurities.

The massive green to blue-green amphibole which rims clinopyroxene is a high Al hornblende to low Al, low Ca actinolite (definition of Binns, 1967; Deer et al., 1966). The formula is $[Ca_{1.7}Na_{0.3}(Fe_{2.4}Mg_{2.1}Al_{0.5})Si_{6.7}Al_{1.3}O_{22}]$. A plot of Na_{M_4}/Al^{IV} indicates rather high temperatures, with pressures in the range of three to four kb. Thermal metamorphism from adjacent granitic intrusions may be responsible for the environmental indication of the blue-green amphibole. Pressures of "regional" metamorphism and clinopyroxene hydration may have been higher and temperatures lower.

Conclusion: Origin of Amphibolite Pods

The usual cumulate texture of the amphibolite pods, combined with major element data and Ni and Zr trace element composition indicate that the pods represent a differentiate or possibly a partial melt of the Ben Harrison ultramafic body. Textures and field relations suggest that the amphibolite--originally an anorthositic gabbro--accumulated as a layer in the peridotite which was deformed in at least two stages by initial east-west elongation followed by compression during emplacement. Analyses of relict clinopyroxene from P-1 indicates that the melt which formed the podiform amphibolites is distinct from and not related to alkalic magmas of the Olive Creek pillow lavas (V-27). In addition, the clinopyroxene may have volcanic arc (arc tholeiite?) rather than oceanic affinities.

From data presented the writer suggests that the alpine peridoties of the Greenhorn Mountains may have originated as the base of an island arc system, and perhaps represent true cumulates at the bottom of a magma chamber beneath an arc. They might also represent a fragment of marginal basin which was close to and intimately associated with the arc. Further investigation of relict clinopyroxenes and primary olivine from the peridotites and metagabbros is necessary to reach a valid conclusion.

Irish Gulch Layered Series

A very distinctive layered serpentinized peridotite occurs in section three, T. 10 S., R. 35 E. near the Royal White Mine at the head of Irish Gulch. The outcrop area is small, encompassing only two slabs of peridotite, both highly serpentinized, which have a total area of about 350 square feet (32 square meters). The outcrops are easily accessible from the forest service road which leads to the mine.

The entire sequence of sheared serpentinite nearby in Irish Gulch is finely layered in two to seven centimeters bands of alternating serpentinized olivines (dunite), harzburgite, wehrlite and white serpentinite. Knockers of coarse clinopyroxenite, more resistant to serpentinization and shearing than dunite and harzburgite are linearly distributed in the sheared serpentinite matrix parallel to the direction of layering. These knockers contain websterite veins and have clinopyroxene crystals up to five centimeters in length. The clinopyroxene exhibits varying deformation which increases in intensity westward through the unit. In knockers from the vicinity of the Meyer's Mine, clinopyroxene deformation is limited to slightly wavy extinction and small offsets of plagioclase twin lamellae. In knockers collected from the Spring Creek area westward along the same trend, kink bands are ubiquitous and wavy extinction and bent cleavages effect pyroxene and plagioclase.

Where peridotite is not sheared and layering is well preserved, cumulative olivine is mostly replaced by serpentine. Intercumulate clinopyroxene is not as pervasively altered as the olivine. Fibrous tremolite forms about two percent of thin sections from dunitic layers. White layers which appear to be plagioclase cumulates in outcrop instead are white serpentinite, brucite and chlorite which appear to embay relict clinopyroxene and pseudomorph olivine.

The layered complex was emplaced adjacent to Alama Argillite by low temperature shearing. To the west it appears to grade into a coarse, dark cumulate metagabbro, but critical areas for the determination of exact gabbro/peridotite relations are buried beneath Cenozoic basalts.

Origin of Irish Gulch Layered Series

Cumulate textures and the apparent (but not proven) gradational relations between peridotite and melanocratic cumulate metagabbro suggest that the Irish Gulch layered series represents the basal parts of a differentiating magma chamber in which rapid fluctuations in pressure (P_T; P_{H_2O}) and possible influx of new melt led to the rapid and cyclic deposition of cumulates. Possibly, metamorphic differentiation during shearing, as described by Dick (1977) enhanced the initial cumulate layering.

Age and Origin of Alpine Ultramafics

Alpine ultramafic rocks in the Greenhorns are structurally analogous to peridotites of the Canyon Mountain Complex and show probable syntectonic deformation of olivines which may be related to upper mantle flow. They include pods of cumulate anorthositic gabbros, which have both sheared tectonic and gradational contacts with the host peridotite. Hence the alpine peridotites of the Greenhorns are representative of somewhat undepleted, upper portions of the usual ophiolite peridotite sequence (Coleman, 1977).

Compositions of clinopyroxenes in amphibolite pods suggest that the rocks may be arc-related.

The alpine peridotites tectonically intrude Permian sediments, and are cut by zones of sheared serpentinite which accompanied final stages of melange emplacement. They are also intruded by Late Jurassic plutons, and consequently were emplaced in Middle Permian to Middle Jurassic time, probably in Late Triassic. Vallier et al. (1977) reported dates of 184 to 234 m.y. for amphibolized blocks in the Canyon Mountain Complex serpentinite melange, and indicated that the initial age of the peridotite is "early Permian or older." Emplacement and metamorphism of the Canyon Mountain Complex occurred during late Permian to Triassic time. This information correlates well with the above deduction of similar ages for the peridotites of the Greenhorns.

Sheared Serpentinite

Sheared serpentinites of the Greenhorn Mountains intrude and enclose representatives of virtually all other pre-Jurassic units, but most severely affect distal arc units of the Vinegar Hill Beds. Vinegar Hill cherts and volcanoclastics are tectonically mixed with fragments of tectonite metagabbro and Alamo Argillite along the summit of Vinegar Hill in a serpentinite melange. Clasts vary from several feet to several hundred feet in length and rise steeply above the less resistant serpentinite terrane. Bennett Creek Schist and Snow Creek Conglomerate are intruded by diapiric serpentinite, and are included in a melange terrane hidden beneath the pervasive cover of Tertiary volcanics. Small, irregularly shaped exposures of serpentinite are dispersed through the cumulate and tectonite metagabbro terrane near Greenhorn, and are commonly fringed by a breccia of serpentinite and metagabbro. Foliation of some metagabbro wraps around the serpentinite as though forceful intrusion of diapiric serpentinite disrupted the normal alignment of gabbroic minerals. At the contact between serpentinite and slightly tectonized cumulate metagabbros at the head of Greenhorn Creek, serpentinite is highly oxidized and a distinctive red, but changes to a more normal green within ten feet of the contact.

Nearly vertical broad bands of sheared serpentinite, up to about a hundred feet in width both crosscut and parallel the dominant east-west pre-Jurassic trend of the thesis area. Serpentinite in these zones is mostly deep green to light green in color, but occasionally black varieties occur, as on the east "col" of Vinegar Hill. These extensive, linear exposures of serpentinite have been considered shear zones by previous workers (Allen, 1948; Wheeler, 1976). Although distance and direction of offset cannot be determined accurately, units on opposite sides of these zones are juxtaposed, and cannot be traced from one side of the zone to the other.

In the east part of the thesis area, however, serpentinite intrusion is not linear, but more closely approaches ameoboid and irregular injections of serpentinite into zones of weakness.

Petrography

Serpentinites vary from rocks composed entirely of serpentine minerals, to rocks with up to 15 percent relict pyroxenes. No obvious distinction between end members can be made in outcrop; both fully serpentinized and relict bearing serpentinites are sheared, both are found in a wide range of colors, and both occur with irregular distribution in the same exposure. Where relict minerals are absent, mesh structure is highly developed, with iron ores distributed through the matrix as small particles and some regular octahedrons and concentrated along lizardite mesh "edges." Fibrous crysotile is found only as cross-fibers within the mesh structure. Talc is virtually absent from sheared serpentinites. Carbonate occurs as secondary aggregates in these rocks, and with brucite, rare prehnite, and secondary quartz in veins which crosscut serpentinite. Pseudomorphs after olivine and pyroxenes are filled by aggregate lizardite or crysotile with relict cleavages delineated by concentrations of fine magnetite. Where relict minerals occur, they are inevitably partially serpentinized and highly strained. Bent and parted cleavages along (100) characterize clinopyroxenes; olivines occur rarely. Talc replaces enstatite.

Distinction between bladed lizardite and antigorite was difficult in thin section. Antigorite appeared to be present in about 30 percent of the slides. X-ray diffraction studies were undertaken to determine the distribution of the three characteristic serpentinite minerals in the Greenhorn sheared serpentinites. According to Coleman (1969, 1971, 1977), the stability fields of serpentinite minerals are dependent upon Fe and Al concentration, oxygen fugacity, and activity of H_2O. Lizardite and crysotile are stable at temperatures below 350°C, whereas antigorite is a higher temperature polymorph that is stable below temperatures slightly in excess of 500°C (Coleman, 1971, 1977). The occurrence and distribution of antigorite is of particular interest because it is indicative of higher temperatures of metamorphism. The distribution of antigorite then, has important implications for the thermal and emplacement history of the Greenhorn serpentinites.

Antigorite is identifiable in X-ray diffraction patterns from serpentinites near to granitic intrusions, but commonly shows no obvious effects of thermal metamorphism in thin section, such as M-219. It is apparently absent from Vinegar Hill (M-226, a, b, c, and M-225) near the "green horn," where sheared serpentinite is voluminous. Possible antigorite was identified in samples M-7 and M-10 from small pods of serpentinite isolated in the metagabbro, and from M-5 in the north branch of Greenhorn gulch where serpentinite extensively intrudes metagabbro and displays evidence of oxidation along the contact.

Conditions of Emplacement

Study of a traverse across sheared serpentinite from a granitic contact toward lower temperature environments could not be made because of the absence of essential exposure. The presence of antigorite, which evidently recrystallized as a replacement of lizardite (Coleman, 1977) in sheared serpentinites within about 1800 feet (545 m) of a granitic intrusion, and also adjacent to a metagabbro is inconclusive evidence for emplacement of serpentinite at elevated temperatures, because thermal effects of the granitic rocks may have extended far enough to cause low temperature recrystallization of lizardite during a prolonged period. However, the seeming absence of antigorite in zones of serpentinite where contacts with adjacent formations are distant, and where sheared serpentinite is voluminous, indicates that the probable emplacement temperature of the serpentinite was low, and conditions did not favor development of antigorite.

The probable generation of small amounts of antigorite in sheared serpentinite adjacent to metagabbro may indicate that the gabbro was at elevated temperatures during serpentinite intrusion, or that frictional heating was substantial. Two additional observations support these contentions: 1. Where some diapiric serpentinites intrude metagabbro, foliation is distorted and wrapped around the serpentinite, without an apparent increase in cataclasis. 2. At locations intruding serpentinite is highly oxidized along borders with metagabbro, suggesting migration of oxygen from the metagabbro into the lower fO_2 environment of the serpentinite with subsequent oxidation of the serpentinites iron oxides. Contacts between serpentinite and metagabbro are neither brecciated nor slickensided at these locations.

However, other evidence, such as the presence of slickensided and brecciated contacts between metagabbro and serpentinite in other small dispiric intrusions indicate that conditions responsible for local generation of antigorite were not present uniformly throughout the metagabbro. The presence of antigorite in Greenhorn serpentinites is a consequence of localized variations in temperature, pressure and other geochemical parameters, and not the result of higher grade metamorphism.

The Greenhorn Ophiolite: Implications of Investigation

The concept of ophiolite as a suite of related rock types was proposed by Steinmann (1927) who considered noteworthy the common association of serpentinized peridotite, mafic metavolcanics and overlying deep water sediments such as cherts. This association was mostly ignored by American geologists until recognition that oceanic lithosphere and upper mantle fragments were frequently thrust onto continental margins.(Thayer, 1967; Coleman, 1971;

TABLE 16. METAMORPHIC MINERALS OF MAPPED UNITS.

Unit / Mineral	Badger Creek Beds (Proximal Arc)	Vinegar Hill Beds (Distal Arc)	Olive Creek Pillow Lavas (Oceanic) Mafic	Olive Creek Pillow Lavas (Oceanic) Pelitic	Bennett Creek Schist Mafic	Bennett Creek Schist Pelitic	Mine Ridge Schist Mafic	Mine Ridge Schist Pelitic	Metagabbro
Quartz	— — — — —	————	— —	————	— —	————	— —	————	- - - - - - - -
Albite	— — — — —	— — — — —	— —	————	— —	————	— —	————	— — — —
Chlorite	————	————	————	— — -	————	— — —	————	— — —	— — — —
Stilpnomelane		- - - - - - - - - -							
Prehnite		- - - - - - - - -	+ +						+ + + +
Pumpellyite									
Barroisite					— —	- - - - -	————		
Actinolite	— — — —	— — — —	- - - - -						
Hornblende									— — — — —
Phengite					- - - -	— — —			
Green biotite			- - - - -						
Brown biotite	+ + + +	+ + + +		+ + +				+ + +	
Clinozoisite		- - - - - - - - - - - -							— — — — —
Epidote	- - - - - - - - - - - -	- - - - - - - - - - - -	— — —		— — —	- - - - - -	— — —	- - - -	— — — —
Spersartine						- - - - -		?	
Andradite			+ + +						
Sphene	- - - - - - - - - -	- - - - - - - - - - -	— —	- - - - - - - -	— —	- - - - - -	— —	- - - - -	— — - - - - -
Magnetite	- - - - - - - - - -	- - - - - - - - - - - -	- - - - -		- - - - -		- - - - -	- - - - -	- - - - - - - - - - -
Carbonate	— — — —	— — — —	— - - -	- - - - -	- - - -	- - - - -	- - - - -	- - - - -	- - - - - — — —

———— Major 25%+   — — — — Minor 5-25%   - - - - - trace< 5%   + + + + + + + contact metamorphism

Dewey and Bird, 1971; Moores and Vine, 1971). The term "ophiolite" presently applies to a distinctive assemblage of rocks which are considered to be equivalent to oceanic lithosphere, including a basal serpentinized peridotite and layered ultramafic complex overlain by a sequence of cumulate gabbros, and pyroxenites, a sheeted dike complex, and a submarine, generally pillowed and commonly spilitized mafic volcanic series. Pelagic sediments usually cherts, commonly occur with the igneous rocks (Anonymous, 1972).

Assemblages of rocks currently considered as ophiolites generally conform to the above criteria, although thickness of units and individual chemistry vary widely. In general, all are equivalent in part to present concepts of oceanic lithosphere, and most, by virtue of the required presence of a sheeted dike complex, are regarded as forming at an oceanic spreading center prior to obduction. A singular exception to the spreading center origin is Miyashiro's (1972) argument, based upon sediment associations and chemistry that the rocks of Troodos originated in an island arc.

Except for the sheeted dike complex, the Permo-Triassic igneous units of the Greenhorns include all the lithologies characteristic of classical ophiolites. The intrusive units are analogous to the Canyon Mountain Complex which contains a small sheeted dike complex (Thayer, Himmelberg, 1965; Ave Lallement, 1976), so lack of dikes exposed in the Greenhorns should not preclude consideration as an ophiolite.

However, some significant deviations from "normal" ophiolite should be cited. The pillow lavas associated with the Alamo Argillite have original alkalic affinities, and are probably the product of a seamount rather than a tholeiitic midocean ridge. The alpine peridotite contains cumulate pods of gabbroic affinities which may represent an original cumulate layer, so the truely basal, depleted ultramafic assemblage may be absent. Clinopyroxenes from these pods have compositions suggestive of arc or arc-tholeiite associations. Cumulate metagabbros are similar in overall chemistry to "normal" ophiolites, but also have a higher CaO/Al_2O_3 ratio and higher TiO_2 content. This variation may in part be the result of alteration, but may also (especially for TiO_2) represent a primary difference.

Moreover, sediments associated with the mafic-ultramafic suite are not strictly pelagic, but can be divided into three depositional provinces: 1. Arc derived, coarse proximal sediments, conglomerates, and greenstones which contain numerous reefal limestone pods and are less intensely deformed than other Greenhorn metasediments (Badger Creek Beds); 2. Distal arc derived sediments which consist of volcanoclastics, fine conglomerates and shales, tuffs, and siliceous argillite (Vinegar Hill Beds), and finally 3. Pelagic cherts and siliceous argillites which contain (in the Greenhorns) only very small allocthonous limestones and have alkalic pillow lavas presumably near the top of the section (Alamo Argillite). All metasedimentary units are tectonically intruded by the igneous series of the ophiolite.

The regular progression of sediments from coarse, proximal arc derived units in the south, thru distal arc rocks to pelagic cherts in the north strongly suggests that this is an original sequence more closely juxtaposed by tectonism. Serpentinite melange intrudes a large part of the central, distal arc (Vinegar Hill) units. The thermal grade of metamorphism increases regularly from proximal arc derivatives (low prehnite-pumpellyite) to distal arc derivatives (prehnite-pumpellyite to low greenschist), to pelagic assemblage (incipient upper greenschist). Higher metamorphic grades, to epidote-amphibolite, are in the gabbro complex. Pressure of metamorphism is apparently highest in the central sediment belt (distal arc or Vinegar Hill Beds).

From overall similarity between the tectonically disrupted units of the Greenhorn Mountains and the assemblage of rocks generally considered to represent an ophiolite, the Permo-Triassic series of the Greenhorns may be considered an ophiolite or at the very least, "ophiolitic."

Presence of voluminous arc derived sediments in the Greenhorn Mountains suggests that the ophiolite is spacially, if not petrologically related to an island arc system. Relict pyroxenes in cumulate amphibolite pods within the alpine peridotite may have island arc rather than oceanic affinities, but evidence is not conclusive and further investigation is required.

Sedimentary and igneous components of the Greenhorn ophiolite suite may have originated in a fore-arc accretionary wedge-oceanic plate environment or in a back-arc, marginal basin environment.

Three models for development of the Greenhorn ophiolitic sequence might be proposed based upon relations previously discussed (see Figure 27).

1. Sediments may have accumulated in a fore-arc accretionary wedge above an eastward dipping subduction zone to the west of an island arc and marginal basin bordering west of an island arc and marginal basin bordering westward moving North America. Subduction may have been impeded by seamounts and entry of thickened oceanic lithosphere into the subduction zone. Sediments might also have accumulated in a back-arc environment with seamounts in the original basin.

   Progressive flattening of the Benioff zone with time and outward migration of the accretionary wedge may have induced migration of the Permain island arc toward the continent in Triassic time. Closure of the marginal basin and obduction of the ophiolite occurred in Late Triassic due to collision with North America.

2. A west-dipping subduction zone may have operated in the Permian with an island arc developed above the down-going

North American plate. Again, a seamount chain may have impeded subduction, and a new subduction zone may have been generated to the east in Early Triassic. Encroachment by westward moving North America halted subduction and resulted in obduction of arc and oceanic crust.

3. Model three is similar to model two, but calls for the reversal in direction of subduction from westward to eastward in Triassic time in response to clogging the Permian subduction zone. Westward movement of North America initiated the obduction of oceanic crust.

Model one allows for the deposition of pelagic and arc-derived sediments in a fore-arc accretionary wedge or a marginal basin, back-arc environment, and their later tectonic disruption at the time of marginal basin closure. It explains high pressure metamorphism of the Bennett Creek and Mine Ridge Schists as a result of subduction and emplacement with serpentinite melange marginal basin closure, or possibly by tectonic overpressure. It also suggests that east-to-west thrusting occurred in Late Triassic, but evidence for movement is not obvious in the Greenhorn Mountains. In this model the Permian-Triassic arc transition should be gradational, and possibly conformable. Arc-derived volcanics in the Snake River Canyon area, however, show an angular unconformity between Permian and Triassic rocks (Vallier, 1967; Vallier _et al._, 1977). This unconformity might

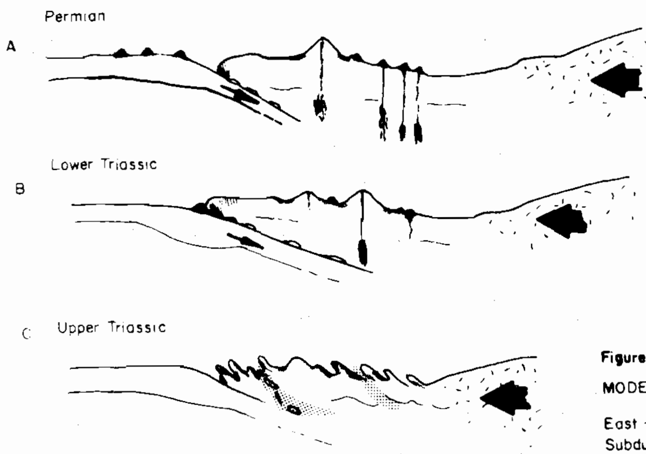


Figure 27a.
MODEL 1 :
East - dipping
Subduction zone

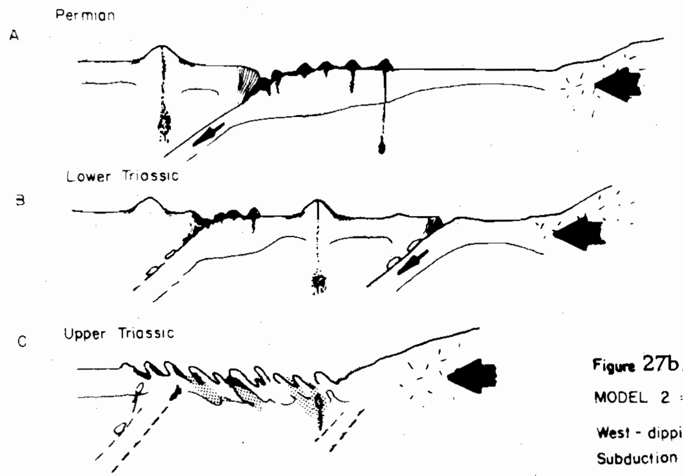


Figure 27b.
MODEL 2 :
West - dipping
Subduction zone

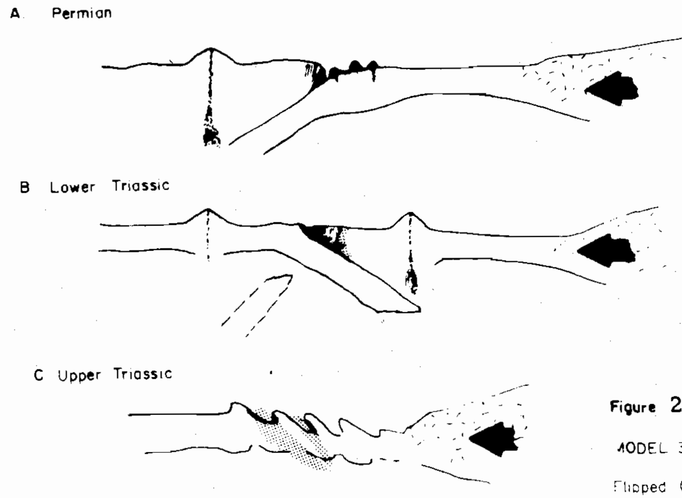


Figure 27c.
MODEL 3
Flipped (reversed)
Subduction zones

KEY :

Seamount
Accretionary sediments
Continental crust
Serpentinite melange

be explained by a hiatus in arc activity during west to east migration, by late tectonic juxtaposition of the units, or possibly by the presence of an exotic allochthonous arc component rafted in on the Pacific plate (Nur, pers. comm., 1978).

Development in a fore-arc region, places a major site of sediment accumulation in an accretionary wedge (Karig and Sharman, 1975), and would allow generation of the ophiolitic igneous rocks from either an arc or oceanic source. Metamorphism of Meyers Canyon Blueschist, and high pressure metamorphism of both Mine Ridge and Bennett Creek Schists would have occurred in a subduction zone, with Mine Ridge and Bennett Creek Schists possibly representing arc-derived, accretionary wedge sediments dragged down the subduction zone, and emplaced in serpentinite melange during or prior to ophiolite obduction. Soft sediment deformation and the evident intercalation of deep-water chert with arc derived sediments observed in the Vinegar Hill Beds are characteristic of an accretionary wedge environment (Karig and Sharman, 1975). However, this model does not satisfactorily explain the progression from high to lower pressure metamorphism in an eastward direction across the Blue Mountains unless this sequence has been displaced from an initially different orientation.

Model two, multiple west-dipping subduction zones, accounts for observed differences in Permian and Triassic arcs (Vallier,

1967) and for the eastward increase in Triassic rocks. It explains the progression from high-pressure, low-temperature blueschist metamorphism in Central Oregon to higher pressure, lower temperature grades eastward through the Blue Mountains. However, this model cannot be resolved with the observed eastward dip of subduction zones along western North America (Kulm and Fowler, 1974) or with the thin and probable oceanic crust which underlies northeast Oregon (Kulm and Fowler, 1974; Armstrong et al., 1977).

Model three is complex. It explains the unconformity between Permian and Triassic arcs, the occurrence of blueschists near Mitchell, Oregon, and decreasing pressure eastward. Subduction zone reversals are poorly understood, however, and should not be adopted for the thesis area until better documented.

From the decrease in metamorphic pressure, and increase in temperature eastward observed in Meyers Canyon, Bennett Creek, and Mine Ridge Schists, model 1, fore-arc accretionary wedge origin is tentatively adopted for the ophiolitic suite of the Greenhorn Mountains. Origin in a back-arc environment cannot yet be completely discounted.

GREENHORN CONGLOMERATE

An unbedded, highly indurated and silicified conglomerate containing clasts of metagabbro, chert, volcanic greenstones, and mafic schists is exposed in scattered outcrops of low relief, section 16, T. 10 S., R. 35 E. about one to two miles (1.7 to three km) south of Greenhorn. The unit consists of a red-brown matrix (green to blue green on a fresh surface) which encloses angular fragments of marked variation in size. Metagabbro clasts are angular to subrounded and are generally the largest and most common rock type present. They are less than one inch to nearly a foot (two-30 cm) in diameter and vary from tectonite to cumulates. Tectonite clasts predominate, forming 41 percent of 200 clasts tallied in the field; cumulate metagabbro accounted for 14 percent of the total. Most metagabbros show some degree of veining which is truncated at the clast boundary. Cherts, and possibly some siliceous keratophyre tuffs, are the next most common lithology represented in outcrop, forming 32 percent of the 200 clasts tallied. They are white, light grey or dark blue-grey, small in size (0.5 to three inches, or one to eight cm), angular, and irregular.

Volcanic greenstone clasts of probable spilitic composition are round to subround, and relatively uncommon, forming seven percent of clasts tallied. They are commonly altered, but volcanic texture is evident in the field from altered porphyritic plagioclase.

The remaining clasts are fine grained, or extremely small, and their exact nature could not be determined in the field.

Petrography

Lithic fragments noted microscopically include the rock types observed in the field, as well as angular clasts of schistose rocks lithologically equivalent to Bennett Creek Schists. The schistose fragments contain chlorite, epidote, quartz, albite, amphiboles, white mica, and granular sphene. The amphiboles are blue-green actinolitic hornblende, suggesting either a slight variation from the blue amphibole paragenesis of the Bennett Creek Schists or additional thermal metamorphism of the fragments in the conglomerate. The acicular nature of the groundmass amphiboles suggests that the second alternative is correct.

Volcanic and metagabbro fragments show little textural or mineralogical variance from rocks in the Greenhorns. The volcanic fragments are diabasic to sub-ophitic, and contain a groundmass of chlorite, actinolite, and epidote. Actinolite occasionally has a more distinctly acicular habit than in parent greenstones. Plagioclase is largely replaced by chlorite and some white mica. Plagioclase phenocrysts are unzoned, altered as the groundmass plagioclase. Phenocrysts are terminated at clast boundaries, and hence are regarded as primary magmatic features rather than metamorphic porphyroblasts. No mafic phenocrysts or pseudomorphs after mafic phenocrysts were noted. The overall texture and spilitic nature of the volcanic clasts are similar to greenstones associated with the Vinegar Hill and Badger Creek Beds.

Metagabbro fragments contain blue-green hornblende, chlorite, epidote, albite, sphene and magnetite. Although they vary in texture, all are similar to metagabbro types in the thesis area.

Cherts and quartz keratophyre tuffs display granoblastic quartz-albite with mortar texture and slight wavy extinction of quartz, suggestive of syn- or post-metamorphic strain.

Age

Tectonite metagabbro and schist fragments in the Greenhorn Conglomerate indicate that the unit post-dates gabbro emplacement and metamorphism of the schists, both dated as Late Triassic. The unit, as far as examined contains no clasts of granitic rocks, and thus pre-dates granitic intrusion. The Bald Mountain batholith has been dated at 147 ± 7 m.y. by Armstrong et al. (1977), and other dates by the same workers for granitic rocks near the thesis area range from 145 to 158 m.y.

The probable age of the Greenhorn Conglomerate, then, may be rather narrowly defined as from Late Triassic to Early Jurassic.

Origin and Significance

Although the Greenhorn Conglomerate is spatially associated with serpentinite, and the contact between the units is concealed, the Greenhorn conglomerate appears to overlie the serpentinite unconformably. No cleavage or lineation is evident in the conglomerate. Angularity of many clasts suggests a tectonic origin for the unit, as a fault or emplacement breccia of the type common to the Klamaths and other ultramafic terranes (Lockwood, 1971). However, examination in thin sections reveals no cataclastic textures such as would develop during brecciation, and should persist through low-temperature metamorphism which effected the well indurated and silicified rock. The restricted occurrence of the unit, and the inclusion of locally available rock types suggest that the Greenhorn conglomerate formed as a local deposit, during initial uplift and prior to or contemopaneous with serpentine intrusion. The unit indicates that uplift and exposure of the ophiolitic terrane was followed by a subsequent episode of burial metamorphism which preceded or possibly accompanied granitic intrusion.

JURASSIC INTRUSIVES

Mesozonal granitic and gabbroic intrusives occur throughout slightly more than 12 square miles (27 km^2), or nearly 15 percent of the thesis area. In lithologies, texture, and composition they resemble the composite intrusives of the Bald Mountain batholith (Taubeneck, 1957) 25 miles (41 km) to the northeast. Seven intrusive units are recognized in the Greenhorns, ranging from norite to granodiorite.

Quebec Hill Intrusives

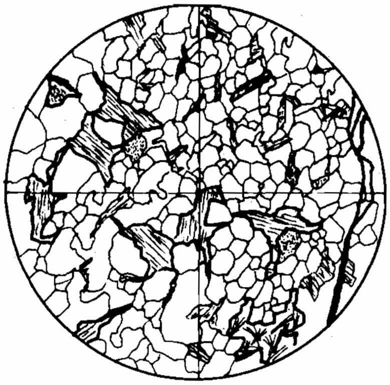
Two separate intrusions occur on Quebec Hill. Boundaries between the two are sharp where observed, but also highly irregular in areal distribution, so that the extent of each unit could not be confidently mapped due to pervasive forest cover and poor exposure.

Quebec Hill Norite

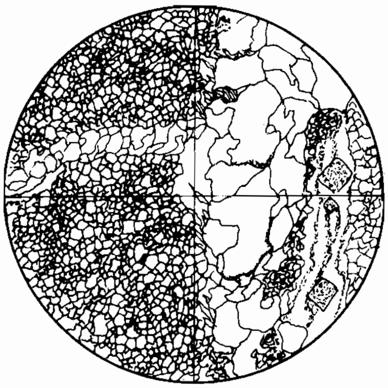
The earliest of the two intrusions on Quebec Hill is a hornblende quartz norite. It occurs in a coarse (one-seven mm) and fine (0.5 to three mm) facies with little modal difference in composition and texture aside from grain size. Both rocks are medium reddish-grey on a weathered surface, and a nearly uniform dark grey on a freshly broken surface. In coarse-grained rocks, large, dark green to black amphiboles form protrusive knobs four to seven millimeters in diameter. Plagioclase laths and small flecks of biotite are also distinguishable in hand specimen. Neither the fine-grained nor coarse norites display any lineation of mafic constituents; however, amphiboles and biotite form clots seven to 15 mm in diameter in some exposures of the fine-grained type. Layering, in four to six cm wide bands of alternate leucocratic and melanocratic norite, occurs in a 20-foot (six meters) wide exposure at an elevation of 5610 feet (1850 m) on the south side of Quebec Hill.

In thin section the norite consists of subhedral, randomly oriented laths of plagioclase, normally zoned An_{60-54}. Larger crystals contain a band of up to 12 oscillatory zones between the outer laboradorite rim and more calcic core. Carlsbad and albite twinning are common; pericline twins are rare. Plagioclase of cumulate norites noted above (W-19) is slightly higher in An content (An_{64-59}), with strong development of patchy zoning which is frequently altered to s ericite or sericite and calcite. The cumulate norite is characterized by a distinctly heteradcumulate texture (Wager et al., 1960) with euhedral to slightly subhedral laths of plagioclase, one to two mm in length and augite or hypersthene-cored amphiboles three to four mm in diameter enclosed in a matrix of subhedral plagioclase (An_{58-53}), and anhedral amphibole and quartz.

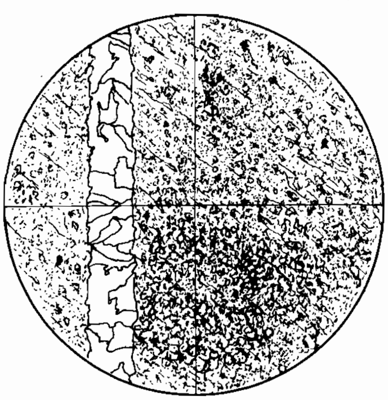
The principal mafic constituent of the norite is green to



A-81 Quartz, biotite (lines) and white mica (stippled). Granoblastic texture. Note presence of some embayed quartz-quartz boundaries.



A-82 Quartz, chlorite, and white mica. Elongate white mica developed along edges of quartz veins. Note hydrous iron oxide (limonite?) pseudomorphs of magnetite octahedrons. Finer grained, granoblastic texture.



A-86 Micro-crystaline quartz (chert) with contact effects nearly absent. Chlorite defines an apparent S_2 which extends diagonally from upper left to lower right. Veins contain quartz and hydrous iron oxides, but no white micas.

Figure 28. Progressive Metamorphism, Quebec Hill Thermal Aureole

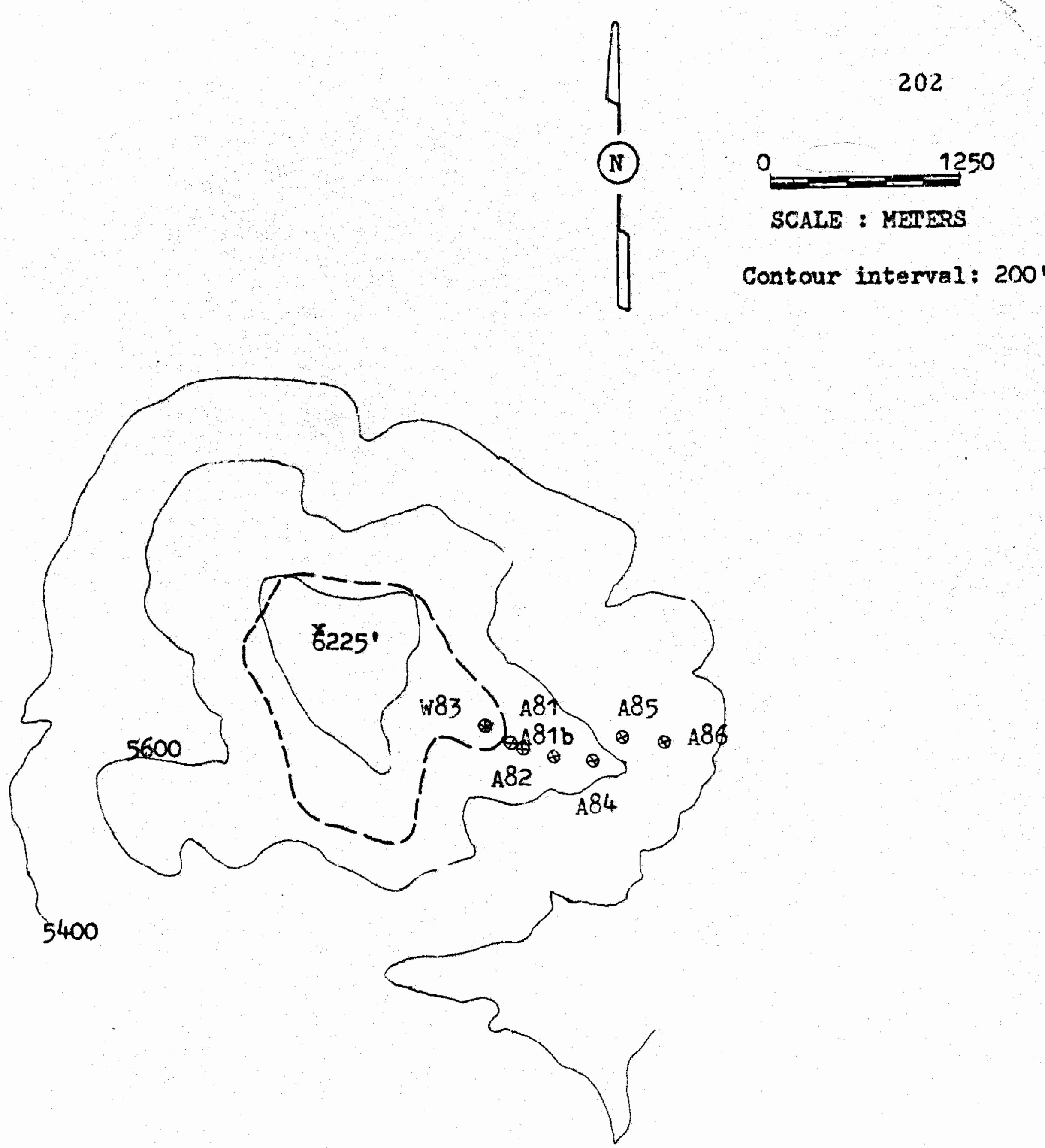


Figure 29.
Sample locations
QUEBEC HILL CONTACT AUREOLE

bluish-green poikilitic hornblende which rims and replaces cores of prismatic augite and corroded hypersthene. Hypersthene cores suggest predominantly elongate primary crystal morphology. Schiller structure is present in these pyroxenes. Commonly amphiboles contain bleached cores with wormy, irregular or sympectic inclusions of quartz which testify to the former presence of pyroxene (Taubeneck, 1967). Brown biotite occurs as further reaction rims around amphiboles or as anhedral crystals, 0.5 to one mm in length. Biotite inevitably includes irregular iron ore, a probable reaction product of the late stage conversion of hornblende. Actinolite and epidote are present as secondary reaction products in mafic constituents. Epidote also occurs as small blebs in plagioclase. Actinolite forms fibrous to uralitic overgrowths around green hornblende where the initial amphibole is not immediately rimmed by biotite. Acicular crystals of actinolite are in interstitial quartz.

Apatite, in small, euhedral prisms is the most abundant accessory. It is included in interstitial quartz, but also may be clustered near quartz-plagioclase boundaries. Granular sphene rims the irregular iron-ore inclusions, and light green chlorite occasionally replaces biotite along 100 cleavages. Fine, needle-like, highly birefringent crystals of (probable) rutile occur singularly or in randomly oriented groups in quartz.

Leucocratic, fine-grained dikes of tonalite crosscut the Quebec

TABLE 17. MODES OF QUEBEC HILL AND OLIVE CREEK INTRUSIONS

	Quebec Hill									Olive Creek			
	W-5	W-6	W-7	W-8	W-12	W-14	W-16	W-19	W-83	W-1	W-9	W-2	W-3
Plagioclase	62.5	51.5	54.5	57.1	75.3	59.9	64.4	56.3	64.5	47.8	47.1	51.7	51.9
Quartz	11.7	28.0	26.9	12.8	10.7	9.8	8.1	12.2	9.2	34.6	34.1	18.2	18.8
Orthoclase	--	2.6	4.6	0.5	0.6	2.1	0.2	--	0.1	8.8	10.7	--	--
Muscovite	--	--	--	--	--	--	--	--	--	3.2	2.0	--	--
Biotite	4.7	10.9	9.0	6.3	0.8	5.6	4.6	--	3.5	5.6	5.6	13.8	13.4
Hornblende	3.6	6.2	5.0	7.5	5.9	9.3	3.6	20.4	3.8	--	--	14.8	14.9
Augite	--	--	--	3.3	0.8	2.8	3.5	4.0	13.2	--	--	--	--
Hypersthene	--	--	--	3.2		8.6	3.2	1.5	13.5	--	--	--	--
Opaque	1.6	tr	tr	tr	1.6	0.3	1.2	tr	1.1	tr	tr	0.7	1.0
Accessory	0.7	0.6	tr	--	2.8	tr	--	tr	0.2	tr	tr	0.7	0.1
Epidote	15.2	--	--	--	0.3	0.1	9.5	4.8	0.8	--	--	--	--
Actinolite	--	--	--	8.8	1.2	1.5	1.7	--	0.1	--	--	--	--
SUM	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.00	100.0	100.0	100.0	100.0	100.0

Hill norite, and differ only in slightly higher modal quartz and orthoclase from the main body of tonalite on Quebec Hill.

Quebec Hill Tonalite

The Quebec Hill tonalites, like the norite, consist of both a coarse and fine grained facies which differ little from one another in modal constituents. Plagioclase is present as subhedral laths with intricate oscillatory zoning, An_{56-32}. Calcic cores commonly alter to sericite or calcite; prehnite was noted in W-6. Patchy zoning is faintly visible in some larger plagioclase. Quartz and potassium feldspar are anhedral and interstitial, except where orthoclase forms irregular replacements within plagioclase laths, possibly coincident with sites of early patchy zones. Myrmekite is present in most slides examined, but not common. It forms bulbous interfaces between orthoclase and plagioclase. String perthite and microperthitic textures occur though subdued in most interstitial potassium-feldspars of the Quebec Hill tonalite. The interstitial quartz is slightly strained and shows wavy extinction. Small (0.1-0.4 mm) prisms of quartz are gathered along an exterior zone within plagioclase in slide W-8, suggesting that nucleation of quartz in this rock was coincident with the final stages of plagioclase crystallization, and that possibly a slight change in magmatic temperature or pressure stopped SiO_2 nucleation and allowed resumption of andesine crystallization.

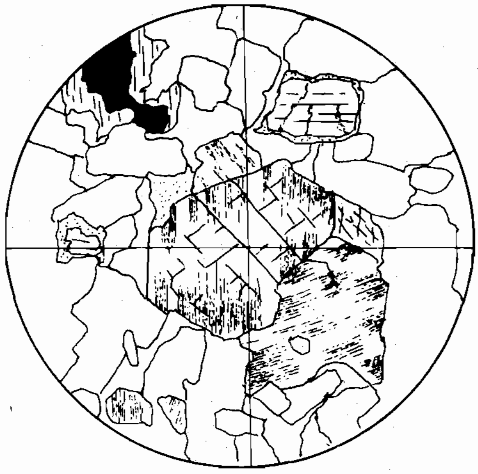


Figure 30a. Augite and hornblende, Quebec Hill Norite. W-16. x 40.

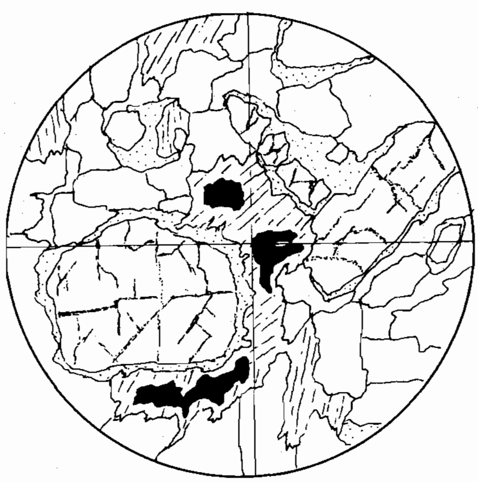


Figure 30b. Reaction series hypersthene - cummingtonite biotite - magnetite. Quebec Hill Norite. x 40

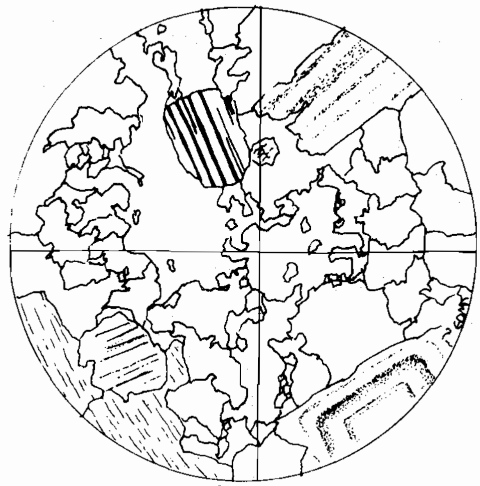


Figure 31a. Slight mortar texture in tonalite. W-87 x40.

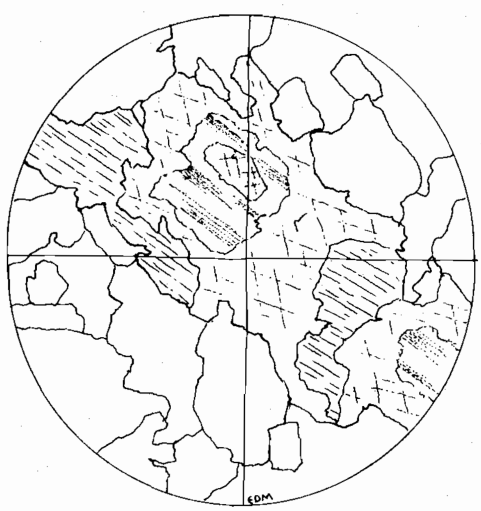


Figure 31b. Reaction sequence hypersthene - clinopyroxene - blue-green hornblende - biotite, Quebec Hill Norite. W-83 x 40.

Mafic minerals of the tonalite are predominantly hornblende and biotite. Green to light brown poikilitic hornblende contains small prismatic inclusions of quartz and euhedral to subhedral plagioclase which is usually calcic andesine. Euhedral to subhedral hornblende is partly replaced by a mat of fibrous actinolite. Biotite occurs both as independent euhedral to subhedral crystals and as overgrowth or reaction rims around hornblende. In W-6 biotite forms euhedral, hexagonal prismatic sections parallel to (001), and is frequently altered to chlorite. Radiogenic zircons are common inclusions in biotite of Quebed Hill tonalite, and appear in some hornblendes. Short prisms of apatite, interstitial calcite, and sphene surrounding irregular iron ore are common accessories.

The distinct bimodal differences in mineral composition and abundance suggest intrusions of Quebec Hill are discrete and separate bodies. Noritic rocks show some evidence of strain--undulatory extinction in quartz, abundant chlorite veining--and of late hydrous and high temperature alteration--development of epidote and actinolite--which might be attributed to the intrusion of the tonalite after consolidation of the norite. Crosscutting veins of tonalitic composition are unmistakable indications of later intrusion of the Quebec Hill tonalite.

Thermal Aureole of Quebec Hill

Granitic rocks of Quebec Hill (Quebec Hill norite and Quebec Hill tonalite) intrude a sequence of Permian siliceous sediments and cherts of the Elkhorn Ridge Argillite. Although the contact between granitic rocks and the metasediments is not exposed, it can be located to within ten meters. The east-facing promontory of Quebec Hill provides nearly continuous exposure of similar lithologies from the contact at an elevation of 5725 feet (1753 m) to Olive Creek, 400 feet below at the base of Quebec Hill. Hence this is a good locality to observe thermal metamorphic effects of a relatively small intrusion.

Six samples of siliceous metasediments of Quebec Hill were selected for petrographic study according to distance from the granitic contact. A-81 was collected within ten meters of the contact at an elevation of 5720 feet (1723 m). A-81 is from the same outcrop, four meters farther from the contact. Both rocks are medium reddish brown. Biotite and quartz can be identified in hand specimen, and there is an apparent, though poorly developed schistosity which strikes obliquely to bedding. A-82 is a fine-grained, uniform siliceous argillite with fine quartz veins from elevation 5640 feet (1710 m), 200 meters from the contact. A-84, A-86, and A-87 all resemble A-82 in hand specimen and are situated at approximately 500, 800 and 1200 meters from the contact.

A-81 contains about 80 percent quartz which is granoblastic but shows no wavy extinction. Triple-point junctions between quartz grains abound, indicating recrystallization of SiO_2 in a low stress environment with high uniform interfacial energy. Embayed quartz-quartz boundaries occur infrequently. They have been attributed to coalescence in the solid state under stress or to differential growth rates (Spry, 1969). Of these two alternatives, the latter is most satisfactory because strain effects are absent in quartz. Bright red-brown oxy-biotite which includes fine rutile needles, constitutes up to ten percent of the rock. Biotite is anhedral, and interstitial to quartz grains. White mica and chlorite constitute the remainder of the rock.

A-81b is slightly finer grained than A-81, but is texturally similar and appears to contain slightly less white mica than A-81. This may be a function of rock chemical variation, sampling bias, or may reflect a lower P_{H_2O} or lower penetration of alkalis at the small increase in distance from the contact. Similarly, chlorite increases with respect to biotite, and this change may reflect metamorphism at slightly decreased temperatures, or maintenance of elevated temperatures for a shorter period. Chlorite in both samples is colorless.

In A-82, 200 meters from the contact, biotite is absent. The texture is granoblastic, but considerably finer grained than A-81 and A-81b. Triple points and straight edges characterize quartz-quartz boundaries; embayments are very rare. Fine quartz veinlets bordered by white mica crosscut the rock, and subtle relict bedding occurs on a scale of several millimeters. On sample A-84, 500 meters from the contact, biotite is absent, white mica is restricted to vein fillings, and chlorite is pleochroic, from clear to medium green. The rock is fine grained, recrystallized but only partly granoblastic in texture and can be characterized as microcrystalline quartzite.

White mica is absent from A-85. Chlorite is green and pleochroic. Quartz constitutes 80-90 percent of the rock, as in all previous slides. The rock fabric is isotropic and non-directional.

A-86 is a chert which contains chlorite, magnetite, and hydrous iron oxides. Contact metamorphism is not readily apparent and the S_2 developed regionally has not been obliterated or overprinted.

X-ray Diffraction Results

X-ray diffraction studies were run on powders of whole rock and hand-picked vein minerals from A-81 and A-84 to confirm optical determination of mineral assemblages--in particular, the absence of biotite in A-84, the type of white mica in A-81, and the absence of feldspars in both whole rock and vein assemblages.

Peaks at 9.92 (002), 4.98 (004), and 3.46 (110, 111) indicate that the white mica is most likely $2M_1$ muscovite. Peaks diagnostic of biotite were absent in A-84, but were dominant in A-81 (10.6 Å, 4.56 Å, 3.36 Å).

Chlorite peaks located at 7.07 Å, and 3.53 Å in A-81 most closely fit the pattern of clinochlore, a conclusion consistent with the observed optical properties of some chlorites. Clinochlore may be present as a colorless phase.

Feldspar peaks were not observed in whole rock or vein separates, confirming optical determination of the monomineralic nature of the veins and highly siliceous nature of the sediments.

Thermal Metamorphism and Temperature of Intrusion

Petrographic effects of contact metamorphism by Quebec Hill intrusions can be traced at least 800 meters from the inferred contact. A-86, approximately 1200 meters, shows little effect of thermal metamorphism, although the quartz veins may represent migration of fluid from the intrusive bodies.

The highest grade observed in the aureole, A-81, is albite-epidote hornfels, correlative to the biotite zone of the greenschist facies (Turner, 1963). The highly siliceous and restricted chemistry of the metasediments precludes formation of some phases which might be diagnostic of higher grades of metamorphism. According to Vernon (1975), biotite can form in Al-poor rocks at very low grades where chlorite + white mica = biotite at temperatures where chlorite would still be stable in more pelitic, Al-rich rocks. The most diagnostic reaction which can be used to place an upper P-T limit on the conditions of contact metamorphics is the Quebec Hill aureole are those shown by Winkler (1974):

$$1 \text{ muscovite} + 1 \text{ quartz} = 1 \text{ potassium-feldspar} + 1 \text{ Al SiO}_2 + H_2O$$

or

$$6 \text{ muscovite} + 2 \text{ biotite} + 15 \text{ quartz} = 8 \text{ potassium-feldspar} + 3 \text{ cordierite} + 8\, H_2O.$$

These are high temperature reactions in the range of 580°C at one kilobar and 660°C at three kilobars, and are used to define the onset of "high grade" metamorphism (Winkler, 1974), and the upper limit of the hornblende-hornfels facies (Turner and Verhoogan, 1960). The absence of sufficient calcium for the production of hornblende or actinolite makes it difficult to assign an firm facies designation for the upper limit of contact metamorphism at Quebec Hill. It can be determined, however, that the grade does not exceed the hornblende-hornfels facies in those samples examined.

Progressively lower grade paragenesis are observed with increasing distance from the contact. These assemblages also may reflect decreasing P_{H_2O} and alkali transport. The apparent decrease in muscovite content between A-81 and A-81b, separated by a distance of four meters, may reflect lower concentration of available or transported alkalis at the greater distance. Presence of muscovite in the otherwise monomineralic quartz veins, and its concentration along vein boundaries indicates that some transported alkalis were present and responsible for the generation of white micas. Both sodium and potassium were available from the granitic intrusives for mica formation, though potassium in only trace amounts from the norite.

Decreasing grade of thermal metamorphism is reflected in the following paragenetic sequence in the Quebec Hill thermal aureole:

1. Quartz (chert) + chlorite + clays — Assembledge 1

   (clays + quartz + introduced alkalis → muscovite

   Reaction 1

2. Quartz + chlorite + muscovite — Assembledge 2

   (chlorite + O_2 → oxychlorite) — Reaction 2

   (chlorite + alkali + quartz → biotite

3. Quartz + biotite + chlorite + muscovite — Assembledge 3

It should be noted that the location and convex shape of the Quebec Hill intrusives at the site sampled here are conditions which allow for development of minimal contact effects. For a salient, exterior angle such as this, a temperature approximately 25 percent of the magma temperature can be achieved at contact with country rocks (Loomis, 1966). If this estimate is valid, and a temperature of 750°C is assumed for the intruded norite, then the allowable minimum contact temperature is 188°C. Another estimate of a minimum temperature at the contact is provided by the temperature of conversion from 1M clay structures to $2M_1$ muscovite at the lower end of the greenschist facies--in the range of 250°C. The upper limit for contact temperature can be established by the reaction:

muscovite + quartz → potassium-feldspar

and if P_{total} is assumed to be between two and three kilobars, then a temperature of 600-620°C is the maximum which could have been attained by A-81.

This is an extremely wide range of possible temperature (188°-625°C). Temperatures close to the upper limit may have been reached at the margins of the intrusion, and the rapid change in mineralogy over a distance of 1200 meters suggests that the temperature gradient was steep and perhaps not long maintained.

Olive Creek Intrusives

Two small intrusives occur along the upper part of Olive Creek in sections two and 11. Both are small, with areal extents of less than one square mile each. The precise extent of each body was difficult to ascertain due to heavy vegetative cover across most of their outcrop area.

Olive Creek Two-Mica Granodiorite

Exposures are poor, and generally confined to exfoliating boulders, and bedrock uncovered in blast pits near the head of Olive

Creek north of San Lou Flat. Varicolored gruss with concentric and oblong patterns has formed from this granitic rock in areas to the north of the exposures just mentioned.

On fresh and weathered surfaces the rock is light grey to white, with randomly scattered 0.5 to two mm mafic specks which on close inspection can be identified as brown biotite. White mica appears as clear flecks of 0.2-0.7 mm size; quartz and small plagioclase laths are apparent upon close inspection.

The rock contains normally zoned plagioclase An_{54-20} with finely developed albite twinning. Oscillatory zoning is not apparent. Plagioclase laths vary from 0.5 to 2.0 mm in length, and are subhedral with few inclusions and no evident clouding. Quartz and orthoclase are interstitial, with irregular quartz sometimes enclosed by orthoclase. Extinction of interstitial orthoclase occurs simultaneously across several interstitial areas, indicating growth as a single anhedral "crystal." String perthite and microperthite are present throughout orthoclase. Characteristic microcline polysynthetic twinning is absent. Alteration of orthoclase to brown kaolinite, and plagioclase to sericite and calcite in core areas is common. Myrmekite was seldom noted in sections of this rock.

The only mafic constituent of the two-mica granodiorite is biotite, which occurs as poikilitic euhedral to subhedral prismatic crystals usually parallel to (100), and less commonly as interstitial, anhedral aggregate growths between plagioclase laths. Plagioclase (An_{52-45}), quartz, and zircons form inclusions. Broad, unmistakable pleochroic halos encompass zircons in these biotites. Alteration of biotite to pale green chorite in thin strips parallel to (100) is common.

Primary white mica constitutes two to three percent by volume of this rock, but is a distinctive and significant mineral. It is rare among the granitic rocks of northeast Oregon. In the granodiorite of Olive Creek white mica occurs as sheaf-like growths radiating from apexes of plagioclase intersections, and interleaved with biotite.

Crystallization of muscovite directly from a melt of granitic composition can take place only at temperatures above 700°C and P_{H_2O} in excess of 1500 atmospheres (1.52 kb) (Yoder and Eugster, 1954). It is not inconceivable that these conditions prevailed in the Olive Creek mesozonal body. Presence of excess silica in the melt, however, may depress the muscovite stability curve below the granite melting curve (Barth, 1967) and thus prevent crystallization of muscovite as a primary phase below 3 kb P_{H_2O}. If excess high pressure aqueous fluids remove alkalis from the melt, however, muscovite may regain stability as a lower P_{H_2O} (Luth, 1964). An alternative mechanism for the development of white micas is by fluorine or chlorine (or any halide) metasomatism (greisenization) as a post-consolidation reaction (Evans, 1965).

Petrographic relations in W-1, W-4 and W-9 do not clearly indicate which of these two alternatives generated white micas in the Olive Creek granodiorite, but suggest origin by a combination of processes at high P_{H_2O}. Muscovite occurs as singular, euhedral to subhedral crystals, 0.2-0.8 mm in length. Such crystals are frequently isolated or in groups which separate large single-crystal areas of anhedral orthoclase or orthoclase-quartz. This muscovite may be marginally poikilitic with small inclusions of quartz; more commonly it is free of inclusions. Textural relations suggest that this muscovite crystallized prior to completion of quartz and orthoclase solidification and prevented quartz and orthoclase single-crystal growth.

Sheaf-like, radiating leaves of white mica, 0.1-0.4 mm in length, and smaller individual crystals, commonly internal to areas of potassium feldspars, are too large to properly be termed "sericite," and are of post-consolidation origin. Similarly, muscovite in parallel intergrowths with slightly strained biotite, appears to be post consolidation.

Tone Spring Tonalite

Tone Spring marks the east extent of an irregular, poorly exposed granitic body approximately 0.5 square miles (1.3 km^2) in area. The rock is fine grained with few constituents exceeding 1.0 mm in diameter, and most in the range of 0.3-0.7 mm. Fabric is generally non-directional, although subtle lineation was noted at the location of W-3. The rock is light pinkish grey on a weathered surface, and white to light grey on a fresh surface. Fine biotite, hornblende, plagioclase and quartz may be identified macroscopically. This rock weathers to a sandy gruss which is darker brown and seems not as strikingly patterned as that produced by the muscovite granodiorite.

Small plagioclase is subhedral and displays multiple cycles of oscillatory zonation, An_{45-30}. Patchy zones altered to white micas crosscut the oscillatory zones, and indicate several episodes of resorption and re-equilibration in the melt after initial stability had been attained (Vance, 1965). Quartz and orthoclase are interstitial. Orthoclase shows limited microperthitic textures and myrmekite, and is altered to light-brown areas of kaolinite. Quartz displays undulatory extinction characteristic of slight strain.

Dark to light green corroded subhedral, poikilitic hornblende ranges in sizes from 0.4 to 1.0 mm in length and contains irregular inclusions of quartz, opaques and some plagioclase. Hornblende commonly is rimmed by biotite in a late stage or possibly post-consolidation reaction relation. Red-brown biotite is also poikilitic with inclusions of quartz, opaque iron ores, and zircons. Significantly, there are no pleochroic halos surrounding the zircons, indicating that they are much lower in radiogenic content than zircons of the nearby granodiorite.

Both biotite and hornblende alter to chlorite. Alteration of biotite follows cleavage parallel to (100), and may be late magmatic. Some hornblende is completely transformed to pseudomorphs of aggregate calcite, chlorite, and iron oxide. More commonly, alteration of amphiboles takes the form of patches and veins or stringers along cleavage planes.

Sphene and apatite are the only noteworthy accessories aside from zircons. Both are spatially associated with the mafic constituents. Sphene both rims iron ores and is found among the granular alteration products of hornblende. Apatite forms elongate prisms up to 0.3 mm in length and is frequently found along biotite-plagioclase interfaces in small randomly oriented clusters which probably coincided with late crystallization of biotite and slightly preceded quartz and orthoclase.

Granodiorite-Tonalite Relation

Previous workers (Pardee *et al.*, 1941; Perkins, 1976) mapped the intrusions of upper Olive Creek as a single unit. Several criteria, however, indicate that they are two separate units which are autonomous and not gradational in nature.

1. Careful examination of field relations revealed a screen of volcanic greenstone which appears to separate the two intrusions

in the ravine of Olive Creek.

2. Presence of marked pleochroic halos around zircon in biotite in the Olive Creek granodiorite, and the absence of any similar radiogenic effect around zircons in biotites of the Tone Spring tonalite strongly suggest that a distinctly different assemblage of zircons is in each intrusive unit. It has been noted by Groves (1930), that dissimilarities in zircon suites are suitable criteria for distinguishing between different intrusions. Although zircon shape appears similar in thin section, certainly radiogenic composition varies between the two intrusions. (This argument assumes that zircon-biotite pairs, and both intrusions are of roughly equivalent age. No evidence to the contrary has been observed.)

3. Marked development of oscillatory zoning in plagioclase of the Tone Spring unit, and its near absence in the granodiorite strongly suggests crystallization under different magmatic conditions. This observation suggests origin of these intrusions as separate bodies of relatively small areal extent.

4. No concentric, regular variation in modal composition or grain size could be established. Although limited exposures provide severe constraints on systematic sampling and investigation, the six slides examined from these two intrusions were unequivocally classifiable as hornblende-biotite tonalite or biotite-muscovite granodiorite.

Tone Spring Tonalite Thermal Aureole

The Tone Spring tonalite along the east bank of Olive Creek intrudes volcanic greenstones which may be of original alkalic affinities and contain a high percent of carbonates as alteration products. Contact effects of the granitic intrusion are pronounced although they do not persist farther than 200 meters from the tonalite.

The contact between intrusive and greenstone is sharp. No assimulation or partial melting of the intruded country rock was noted. Apophyses and thin veins of granitic material project irregularly into the greenstone, however. Grain size in these injections is finer than in the parent tonalite, and is suggestive of aplites. Volatile content of the veins was probably minimal.

Within three feet (one mm) of the granitic contact, carbonate filled vesicles 0.5-three mm in diameter in the greenstones are altered to a strikingly concentric series of minerals most commonly associated with scarns and calc-silicate hornfels. The center of these former vesicles is filled with carbonate and/or plagioclase which takes the form of several large crystals with triple-point junctions. Surrounding the carbonate is an irregular highly embayed and usually discontinuous rim of andradite garnet clear to brown in thin section. Microprobe analysis reveals that the garnet is melanite, high in TiO_2, CaO, Al_2O_3, and FeO, with negligible contents of MgO. Virtually all alumina is in six-fold coordination.

Clinozoisite fills some garnet embayments; fine mats of prehnite are also associated with garnet and most commonly intercede between calcite and andradite. Small (0.1-0.5 mm) irregular crystals of scapolite rim the garnet, and are found at infrequent intervals throughout the matrix of the rock. Scapolite is high in calcium (17.6 percent), (mizzonite) and thus indicates crystallization under equilibrium conditions at high temperatures (Deer et al., 1966; Shaw, 1960).

The matrix of V-85 is comprised of fine-grained equant or granular actinolite, finely disseminated untwinned plagioclase which displays occasional triple-point boundaries with the actinolite, and granular epidote aggregates. Sphene occurs as large rhomboidal fragments as well as in anhedral masses, and is also dispersed randomly throughout the plagioclase-actinolite matrix as fine granules. Prehnite is in fibrous, highly birefringent mats and in vein fillings where "bow-tie" structure is well displayed. Prehnite is commonly present in vesicular fillings with albite and calcite. White micas are also present in relict vesicles. Green to blue-green hornblende persists as coarse relicts, with embayments and irregular boundaries.

Textures in a sample (V-206) collected ten meters farther from the tonalite contact are radically different from those of V-85. Some of this variation may be attributed to variation in original greenstone

TABLE 18. MICROPROBE ANALYSES OF TONE SPRING TONALITE THERMAL AUREOLE.

		V-85 Garnet	Scapolite
SiO_2		37.30	45.48
Al_2O_3		11.56	33.77
TiO_2		1.40	0.01*
CaO		32.98	17.59
Na_2O		na	1.67
MgO		0.36*	0.00**
Fe*O		13.68	0.09
MnO		0.41*	0.00**
Cr_2O_3		0.04**	0.00**
SUM		97.73	98.60
	Al^{IV}	0.006	
	Al^{VI}	1.087	
	Fe2+	0.093	
	Fe3+	0.826	

*Standard deviation exceeds 5.

**Near or below detectable limits.

textures and chemistry. Actinolite is developed in radiating acicular bundles and as replacements of green to blue-green hornblende. Epidote is in strings of granular aggregates which are an unmistakable yellow, and as slightly less pleochroic rectangular aggregates. Formation of epidote preceded the growth of actinolite, as actinolite often radiates from or clearly crosscuts areas of epidote. Biotite is red, subhedral, and occurs in clusters of individual crystals which frequently meet in triple junctions.

The most revealing texture in this thin section is that of the magnetite. It forms elongated (0.2-one mm), strikingly dendritic growths which are randomly oriented. According to Spry (1969), the dendritic pattern is indicative of rapid crystal growth along the migration paths of the constituents. This, in turn suggests the mobilization of iron, probably in the reaction

$$\text{hornblende} \rightarrow \text{actinolite} + \text{iron ore}$$

and the recrystallization and recombination of existing disseminated iron ore. In summary, the dendritic texture is good evidence that growth and reactions in V-206 were rapid.

<u>Conditions of Thermal Metamorphism and Temperature of Intrusion</u>

Textures in V-85 clearly indicate that crystallization of scapolite occurred early in the hornfels sequence, and was

THERMAL AUREOLE TEXTURES: TONE SPRING TONALITE

Figure 32a. Twinned, sparry calcite (large stipples), and clinozoisite in center. Andradite (melanite) garnet (heavy outline) around rim. Scapolite (clear, fine outline) exterior to garnet. Matrix of albite and actinolite. Note triple-point junctions of interior minerals and severely embayed nature of garnet and scapolites. V-85. X 100.

Figure 32b. Dendritic magnetite, acicular actinolite and granular epidote (stippled). Intergrown anhedral biotite with some triple-point junctions. Note replacement of hornblende, top of drawing, by acicular and fibrous actinolite, and close association of iron ore. V-206 X 100.

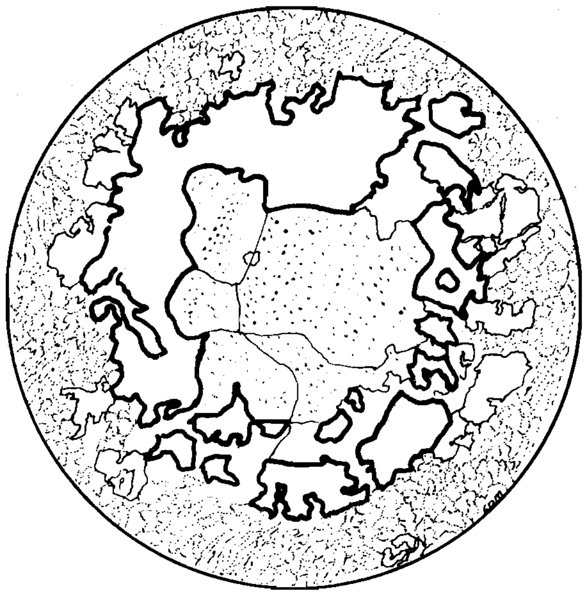


Figure 32a

Figure 32b

succeeded by andradite garnet with clinozoisite. With decrease in temperature albite, prehnite, and finally calcite formed as central phases in the concentric structures.

Scapolite has been reported in thermal aureoles from pyroxene hornfels to zeolite facies (Shaw, 1960), and is a poor indicator of P-T conditions during metamorphism. More calcic varieties such as mizzonite in V-85 are often associated with upper epidote-amphibolite hornfels (Deer, 1962; Shaw, 1960). The calcic nature of the metavolcanics, however, may have contributed to the high calcium content of scapolite. Scapolites of similar composition (46 percent SiO_2, 20 percent Al_2O_3, 17 percent CaO, three percent Na_2O) occurs in pyroxene hornfels aureoles in skarns of the San Gorgiano Mountains, California (Shay, 1975), which show the same sequence of scapolite (grossular) + epidote, although not in a radial arrangement. Pyroxene was not observed in V-85, and its absence indicates that the scapolite developed in conditions equivalent to the upper ranges of the hornblende hornfels facies.

Temperature-pressure conditions for the growth of andradite garnet are more readily estimated. Liou (1974) noted that the upper stability limit of andradite + quartz is strongly dependent upon oxygen fugacity. At high values, andradite is stable to 600°C at 0.5 kb, and 650°C at two kb P_{fluid}. At low fO_2 ($\log fO_2$ = -25), the upper range of stability for andradite = quartz is 350° - 400°C. At high fO_2, andradite + quartz + fluid react to form wollastonite + magnetite + quartz. The common presence of magnetite in both V-85 and V-206 suggests that fO_2 was at least moderate, if not high during thermal metamorphism.

Neither scapolite nor epidote are considered in Liou's Ca-Fe-Si-O-H system, and a possible buffering effect of these phases cannot be excluded. However, stability relations indicated for the assemblage andradite + magnetite + quartz (+ calcite) suggest that the garnets developed at an fO_2 in the range of log -10 to -20, at temperatures between 550° and 670°C. This temperature range is slightly below the maximum estimated for the Quebec Hill intrusion, and seems reasonable considering the somewhat more silic nature of the Tone Spring tonalite.

Desolation Norites

The most characteristic and common exposure of gabbroic intrusive rocks in the Greenhorns are augite norites scattered in discontinuous outcrops along the steep, heavily forested sides of the South Fork of Desolation Creek. This noritic gabbro is not confined to the area of Desolation Creek, however. Isolated occurrences of small areal extent are distributed through the granitic terrane, although more prevalent in the west part of the thesis area. The outcrops display minor petrographic variation on a localized scale,

Figure 33a. Xenoliths from intrusion breccia Sunrise Butte granodiorite.

Figure 33b. Primary layering: Desolation norite.

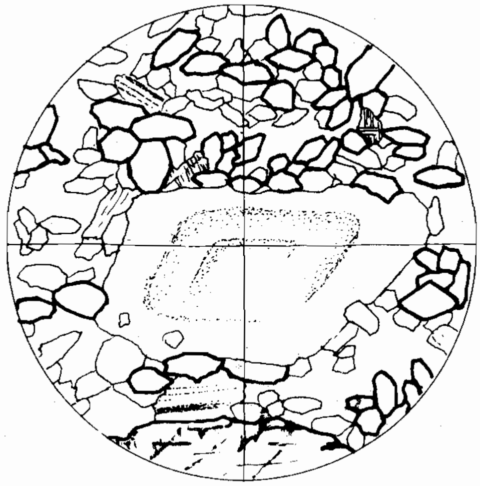


Figure 34.

W86: Orthocumulate hornblende (clear prisms) and plagioclase. From a xenolith in Boulder Butte tonalite. Origin probably from Desolation norite. x 100.

TABLE 19. MODES OF DESOLATION NORITES.

	W-223	W-10	Willow Lake Norite Mean*
Plagioclase	62.7	63.8	69.72
Quartz	tr	0.3	0.10
Orthoclase	--	--	--
Hypersthene	1.0	1.5	4.11
Augite	7.8	15.2	
Brown hornblende	23.8	10.5	
Green hornblende	3.3	--	16.31
Biotite	tr	tr	0.20
Epidote	tr	2.1	--
Chlorite	0.6	4.7	0.29
Sericite	0.3	0.2	--
Actinolite	0.5	1.3	7.21
Cummingtonite	tr	tr	--
Opaque	0.2	0.4	1.36
Accessory	tr	tr	0.70
SUM	100.0	100.0	100.0

*Taubeneck (1957).

but in general their mineralogy and textural characteristics are so similar that they are described as one intrusive unit, with significant texturel anomalies noted. The norite of Quebec Hill is (probably) related to the Desolation norites. As might be expected, field relations indicate that the Desolation norites are the earliest of exposed granitic rocks.

The Desolation intrusives are coarse grained (0.5-4.0 mm), light-to-medium red-brown rocks, dark brownish grey on a fresh surface, with protruding knobby hornblende-pyroxenes, and conspicuous plagioclase. They show no true lineation of mafic components, but about 40 percent of the exposures display some degree of cumulate layering. This layering ranges from subtle gradation between slightly darker and lighter bands several centimeters in width, to the development of pronounced mafic and leucocratic stratification on a similar scale. In no case was this primary cumulate layering observed in excess of three meters vertically. This observation may be partly due to limited rock exposures. In style of layering, grain size, and general field appearance, these rocks are markedly similar to layered portions of the Southern California batholith's San Marcos gabbro noted by Miller (1938), Larson (1942), and by this writer and to the Willow Lake norite (except comb layering) described by Taubeneck and Poldervaart (1960). Desolation mafic bands are discontinuous over distances greater than ten feet and tend to curve or undulate slightly. Mafic components are commonly lineated parallel to layering. The rock fabric is anisotropic where layering is absent. Xenoliths are rare, less than six inches (15 cm) in diameter, and probably represent metagabbro inclusions. Mafic autoliths of similar size also occur.

Both layered and homogenous augite norites contain subhedral to euhedral laths of plagioclase which are complexly twinned according to albite, carlsbad, and/or pericline laws. The plagioclase, An_{52-42}, is normally zoned. Patchy zoning usually predominates, and is most common in cores. Plagioclase cores in some rocks, notably W-10, contains patchy zones rimmed by four to ten narrow oscillatory zones and jacketed by sodic andesine. Areas of mottled resorption and re-equilibration of calcic-sodic andesine are present in plagioclase adjacent to this outer zone. In all sections of Desolation norite, plagioclase is rarely deformed or strained. Most laths are unclouded, with edges marked by a band of fine opaques and tiny granules of sphene. These impurities were excluded from slowly crystallizing plagioclase, but are common as disoriented inclusions in interstitial quartz which solidified too rapidly in waning stages of consolidation to selectively exclude such impurities. Plagioclase alters to sericite or mats of sericite and calcite. Such alteration is pronounced in core regions, and less extensive toward the rims of the normally zoned crystals.

Orthoclase constitutes less than 0.10 percent of the rock. It forms extremely thin rims between interstitial quartz and laths of plagioclase, or fine divisions between subhedral plagioclase, with which it may be reacting. Myrmekite was not noted in Desolation norites.

Quartz is interstitial, shows broadly spaced undulatory extinction, and as noted above, is clouded by inclusions.

Hypersthene is not plentiful, but occupies about two percent (by volume) of the Desolation norites. Prior to postconsolidation alteration it may have constituted up to 10 percent of the rock. Hence the rocks should be classified as augite norites. Orthopyroxenes examined in thin section were optically negative, with a 2V of 70-75°, an intermediate hypersthene. Most crystals form faintly pleochroic, light green to light reddish-brown rectangular prisms with fine exsolution of clinopyroxene (Schiller structure) parallel to (100). Irregular fractures which crosscut the pyroxenes, and cleavage traces along (100) are filled with a dark greenish-brown, birefringent alteration product which is probably nontronite. Crystals are rimmed by narrow bands of fine-grained, light-brown to clear phylosilicates which were too fine for confident optical identification, and are tentatively identified as phlogopite, or coarse nontronites. Cummingtonite rims orthopyroxene as narrow subhedral lathlike crystals with lamellar twinning. Cummingtonite is also found as nearly euhedral, but more acicular growths within orthopyroxene. The development of cummingtonite is restricted to areas immediately adjacent to hypersthene.

Clinopyroxene (augite) is light green to clear, and is severely resorbed and altered to amphiboles throughout the Desolation norites. Uralitic actinolite fringes and corrodes augite; brown or blue-green hornblende replaces augite in all slides of Desolation norite. Most slides examined contained only one variety of hornblende. However, in W-223, light red-brown hornblende rims the blue-green variety. Where both hornblendes have been observed from a single outcrop, brown (oxy?) hornblende is best developed adjacent to country rock, while blue-green hornblende is found in locations farther removed from the intrusive contact. No attempt has been made to quantify this relation as it would be difficult on the basis of available exposure and present sampling.

Bleached hornblende cores with symplectic inclusions of quartz and iron ore are common where relict clinopyroxene is absent, and indicate the former presence of augite (Taubeneck, 1967). Fibrous actinolite fringes globular masses of magnetite enclosed in amphiboles, and in W-223 is present as a discontinuous rim of uralitic crystals which protrude into interstitial quartz and adjacent laths of plagioclase. Red-brown hornblende also occurs as anhedral, interstitial crystals which are markedly poikilitic, containing inclusions of quartz and minor accessories. Hornblende is altered to irregular, 0.5-1.0 mm patches of epidote. In W-10 it is locally developed in a "micrographic" pattern, suggesting simultaneous crystallization with hornblende, as alteration of clinopyroxene.

Biotite constitutes less than one percent of the Desolation norites and is developed as tiny equant prisms 0.05-0.2 mm in length, as thin irregular jackets on hornblendes and some opaques, and in interstices between euhedral-subhedral plagioclase. Sphene, apatite, zircon, and iron ore are common inclusions in biotite, and occur in all three characteristic biotite habits.

Chlorite forms irregular replacement patches in amphiboles, and less commonly, in clinopyroxene. In biotite it forms parallel intergrowths along (001) and occurs in crosscutting veins which may extend into adjacent plagioclase.

Accessory minerals represented in Desolation norites include apatite as small elongate prisms distributed in outer zones of plagioclase, clustered in radiating groups in interstitial quartz, and as poikilitic inclusions in biotite. Sphene is granular and anhedral. Zircons are small and usually rectangular.

Development of oxidized brown hornblendes close to intrusive borders suggests that adjacent country rock may have contributed volatiles, notably H_2O and O_2, in small amounts to a highly crystallized and dry noritic magma which was in last stages of solidification, inducing syn- or post-consolidation development of oxyhornblende. The dry nature of the magma is supported by the unclouded plagioclase (Smith, 1972). Strong evidence for the presence in and migration of volatiles (H_2O) from rocks of greenschist facies intruded by the Willow Lake norite has been cited by Taubeneck and Poldervaart (1960). Movement of country-rock volatiles away from the intrusion resulted in effective transport of magmatic heat, maintaining supercooling of the norite, and the consequent development of comb (Willow Lake) layering. If escape of volatiles were blocked by lack of fractures or other suitable avenues, they might instead react with the adjacent magma, producing hydration and oxidation.

Evidence for the initial dry condition of Desolation norites is also found in the low An content (An_{52-42}) of the plagioclase which coexists with primary pyroxenes (Yoder, 1976), and the prevalence of patchy zoning in plagioclase cores (Vance, 1967).

Initial crystallization of cumulate plagioclase and hypersthene, with probable slightly later addition of augite which forms occasional tecoblastic growths with hypersthene, occurred at low P_{H_2O} and temperatures in the range of 1200-1300°C (Bowen, 1913; Tuttle and Bowen, 1958; Carmichael et al., 1974). Rise of the relatively fluid magma resulted in a decrease in confining pressure, and probably concomitant addition of water as crustal rocks with higher contents of H_2O were encountered. These changing conditions resulted first patchy resorbtion. If the magma then ceased to rise, or slowed its rate of ascent, changing partial pressures of volatiles and water content would result in a fine rim of oscillatory zones surrounding the core. Early crystallizing mafic constituents formed uralitic reaction rims of actinolite around augite and thin jackets of cummingtonite over hypersthene probably during this stage of intermediate temperature and unstable but increased P_{H_2O}. Resorption and re-equilibration of oscillatory zones in the feldspars occurred with final emplacement into greenschist-facies metamorphics. Growth of hornblende was syn- to post-consolidation and the development of oxy-hornblende with the increase of fO_2 probably related to influx of volatiles may have been slightly subsequent to crystallization of green to blue-green varieties.

The Desolation norites represent an early suite of intrusions emplaced before the granitic rocks. Petrography and modal analyses of noritic rocks from widely separate locations are strikingly similar, and it is suggested that if initial intrusion was not as a single large magmatic body, then the magma of each intrusion was similar in its composition and history, and all may have been cogenetic.

Further studies of whole rock major and trace element composition are desirable in order to unequivocally support this suggestion. In particular, investigation of plagioclase and pyroxene compositional variations, and determination of Ba, Ni, and K/Rb would provide valuable additional insight to the interrelationships of the Desolation norites.

Boulder Butte Tonalite

Coarse to medium grained (4.0^{+}-0.5 mm) hornblende biotite tonalites are exposed in approximately six square miles mapped for this thesis. They are the dominant granitic rock type of the west half of the area, and form the precipitous outcrops of Boulder Butte. Similar granitic rocks of apparently the same age are exposed to the north in an extensive, four-mile long, east-west salient which consists of multiple intrusions of Desolation, Boulder Butte, and minor Sunrise Butte rocks. Boulder Butte-type tonalites predominate.

Tonalites of Boulder Butte are medium grey, distinctly phaneritic rocks which are bimodal in grain size distribution. Coarse-grained varieties contain hornblende prisms one to six mm in length and long plagioclase crystals which approach 10 mm in length. Biotite forms the fine-grained constituent, and is 0.1-one mm in length. Clots of mafic minerals up to 10 mm in diameter are disbursed throughout the rock. The fine-grained tonalite is far less common than the coarse, and constitutes only about ten percent of the Boulder Butte rocks. Its largest mafic mineral grains are about 1.5 to two mm in length; plagioclase reaches lengths of one mm. Fine plates of biotite are common to coarse and fine grained types. In most hand specimens of Boulder Butte tonalite, hornblende is more abundant than biotite. Quartz is readily distinguished in the field.

Fabric of the tonalites is most commonly non-directional. However, linear parallelism of mafic constituents occurs locally in as much as 30 meters of outcrop width.

Even in the best examples, uniform orientation of all crystals includes only 40-50 percent of the mafic constituents of the rock, and possibly a smaller percent of the plagioclase. Lineation is most common adjacent to country rock where it usually sub-parallels the contact, or in narrow apophyses projecting into Desolation norite. Platy parallelism is rare, but where adjacent to older rocks is near-vertical, and suggests that the Boulder Butte intrusion is steep-walled. Layering and flow banding of the type described by Balk (1937) and common to granodiorite--quartz diorite intrusion in the Sierra Nevada (Presnall and Bateman, 1973; Bateman et al., 1963) was not observed in the Boulder Butte tonalites.

Mafic inclusions, schleiren, and xenoliths are widespread in the tonalite, and most common adjacent to country rock. There is no consistency to their shape, size or composition. In size they range from dark clots less than an inch (2.5 cm) in diameter, barely distinguishable from clusters of mafic minerals, to large, rounded inclusions of norites which exceed ten feet (three m) in breadth. Inclusions are angular as well as rounded, and range from almost completely assimulated autoliths to only slightly effected chert and metagabbro. This range in assimulation indicates that stoping and circulation of country rock fragments occurred throughout a lengthy magmatic history, and probably persisted until late in the cooling history of the tonalite.

Many autolithic clots are elongated in a direction subparallel to intrusive contacts. Most retain an elliptical shape; schleiren are developed in clots whose mineralogy is strongly suggestive of an autholithic origin. Lineation of inclusions rarely approaches platy parallelism. However, lineation of mafic clots and xenoliths is sometimes pronounced where no apparent directional fabric occurs in the mineral grains of the host tonalite. In such situations, the aligned inclusions are frequently stretched into highly elongate forms and partly assimulated. These relations imply that the segregation and lineation of clots and inclusions occurred early in the intrusive's history and that they were partly assimulated with time. Small scale, weak, and omni-directional movement of late-crystallizing components then created an anisotropic pattern on a small scale by disorientation of adjacent minearl grains.

Boulder Butte tonalite contains subhedral plagioclase with thin, strong oscillatory zoning, from cores of An_{58-55} to rims of An_{40-38}. Some crystals show patchy zoning in the core, similar to that of Desolation norites, but usually less pronounced. Albite and carlsbad twinning occur in majority of crystals, whereas pericline twinning is present in only about 20 percent of the crystals. Plagioclase is commonly jacketed by untwinned plagioclase which has a lower index of refraction and is optically negative, implying an oligoclase with composition of about An_{21}. Deformation of plagioclase varies from slide to slide, but is not intense. Twin lamellae are broken and slightly offset in W-36; in some thin sections plagioclase is broken and with segments slightly rotated, though never more than about 10°. Such fractures are filled by the mantling oligoclase. Plagioclase is altered to sericite in patches and along preferred zones. Chlorite has migrated into the feldspar along crosscutting fractures.

An older generation of plagioclase crystals is present in the Boulder Butte tonalites. In some thin sections they comprise up to ten percent of the total plagioclase. These crystals are untwinned, and show three or four thick oscillatory zones. They are subhedral, and contain a patchy veined network of replacement andesine. Alteration to zoisite is common in these crystals, and absent in the twinned plagioclase. These older phenocrysts occur frequently in pairs which display synneusis relationships, implying their formation, or at least suspension in a circulating melt (Vance, 1969).

There are two possible explanations for the origin of these older plagioclase crystals:

1. They may be xenocrysts from assimulated older granitic rocks

such as the Desolation norites. If so, presence of some related mafic phenocrysts would be expected. Some corroded and hornblende-rimmed augites (W-41, 46), and clotted groups of green-to-brown hornblende (W-93) may be of such origin, but evidence is equivocal. It is also noted that the un-twinned plagioclase did not serve as nucleation centers for the evidently later, twinned laths, and so its xenocrystic origin might be suspect. However, this older plagioclase may have been freed after major plagioclase nucleation by slow assimilation of Desolation norites.

2. The crystals may represent an early formed, slowly crystallized plagioclase which subsequently began re-equilibration with the melt. (Vance, 1961; Buerger, 1945; Emmons and Gates, 1943). The absence of a twinned mantle on these feldspars is difficult to explain under these conditions but could be ascribed to regular, subhedral crystal faces which allowed ordered secretion of additional plagioclase. The presence of synneusis relations between untwinned crystals is a critical consideration, as it requires their presence in a fluid magma (provided Vance's interpretation is correct). It is doubtful that this condition could be met if the crystals represented un-assimulated xenocrysts because such an interpretation suggests prolonged previous nucleation and crystallization of plagioclase. Thus it is

tentatively concluded that the untwinned, zoisite bearing plagioclase probably represent early crystallization products of the tonalite.

Orthoclase constitutes up to 5.9 percent of the Boulder Butte and north salient tonalites. It is interstitial, altered to sericite and, more commonly, kaolinite. In some slides it occurs only in very thin irregular strings along corroded junctions of large plagioclase laths, and is merely a trace constituent. In slides where it is more plentiful, adjacent areas of interstitial orthoclase undergo simultaneous extinction and represent a single, large, and extremely anhedral crystal. Microperthite is faintly developed in some larger orthoclase. Microcline twinning was not observed in the Boulder Butte tonalites.

Boundaries between plagioclase and orthoclase are frequently straight and apparently uncorroded. However, they are also irregular in a few slides, with considerable corrosion and replacement of more sodic plagioclase by orthoclase. Irregular patches or orthoclase are also present as replacements in plagioclase cores. Myrmekite is scarce, and projects as bulbous growths from plagioclase into orthoclase, or in rare instances, from biotite into orthoclase. Some rounded protruberances of plagioclase appear to contain no symplectic quartz on first inspection, but closer examination reveals extremely fine intergrowths of quartz, which might justifiably be termed micro-myrmekite. A few isolated globules of myrmekitic texture occur in large areas of orthoclase. Rarely an entire interface between subhedral plagioclase and interstitial orthoclase is occupied by a thin fringe of wormy quartz-plagioclase intergrowth. However, myrmekite seems to be less prevalent in the Boulder Butte tonalite than in correlative intrusives of the Bald Mountain batholith (Bald Mountain tonalite, Taubeneck, 1957).

Quartz is restricted to interstitial occurrences and is optically continuous across interconnected and some apparently isolated interstices. Therefore large anhedral crystals occur up to 12 mm in width. Quartz-quartz and quartz-orthoclase boundaries are sharp and linear. Undulatory extinction is ubiquitous, but not extreme. It occurs in parallel bands which are generally about 0.1 to 0.05 mm in width and extend across the entire crystal.

Severely corroded clinopyroxene (light green to clear, 2V 45-50°) is replaced and surrounded by an aggregate of light olive green to blue-green hornblende. The replacement texture is not necessarily concentric, but is often a chaotic mixture of relict clinopyroxene and amphibole. Hornblende forms single twins on both (001) basal and (010) elongate sections. 2V of hornblende approaches 75°, suggestive of intermediate Mg/Mg + Fe + Mn (Deer et al., 1966).

Actinolite occurs in two habits. Blades and basal sections of fresh, very pale green actinolite, 0.5-0.1 mm in length form random intergrowths in centers of bleached hornblende cores and extend as acicular protrusions into olive green hornblende. Actinolite more commonly is developed in granular patches as augite replacements.

Biotite forms small rectangular plates and interstitial growths between laths of plagioclase. In the rectangular, subhedral habit, inclusions of quartz, small plagioclase crystals, and fragments of hornblende occur along with iron ore and accessories such as zircon (with pelochroic halos) and apatite. Interstitial biotite seems to contain fewer inclusions, particularly of plagioclase, and may have formed somewhat later in the crystallization history of the tonalite. Biotite which is free of poikilitic inclusions is uncommon in the rocks of Boulder Butte type. Occasionally it forms thin fringes around irregular or globular magnetite.

Apatite and zircon are the predominant accessory minerals. Unzoned apatite occurs as stubby prisms clustered within areas of interstitial quartz or along borders of plagioclase. Apatite is infrequently enclosed in oligoclase mantles and is occasionally found as randomly oriented laths within plagioclase. Crystals included within plagioclase are slightly clouded by fine inclusions or alteration. Apatite is rarely enclosed by hornblende, but is common in biotite. Petrographic relations of apatite suggest that it crystallized after plagioclase and hornblende and had completed crystallization prior to the solidification of quartz.

TABLE 20. MODES OF BOULDER BUTTE TONALITE

	W-40	W-52	W-93b	W-24	W-34	W-37	W-38	W-41	W-46	W-47	W-56	W-220
Plagioclase	49.2	42.5	44.6	50.2	43.6	55.3	55.6	51.1	46.1	41.7	45.3	44.4
Quartz	21.5	28.4	26.1	21.5	23.1	37.2	35.3	20.8	16.3	27.9	22.5	20.6
Orthoclase	4.3	--	2.7	2.9	4.7	1.0	--	5.9	1.9	3.4	4.5	--
Biotite	10.1	13.7	11.1	10.9	11.2	5.8	7.6	8.9	13.0	10.4	10.5	13.7
Hornblende	14.4	15.0	15.2	14.3	17.3	0.7	1.0	13.1	21.7	16.5	16.9	20.8
Augite	--	--	--	--	--	--	--	tr	0.4	--	--	--
Hypersthene	--	--	--	--	--	--	--	--	--	--	--	--
Opaque	0.3	0.3	tr	tr	0.1	tr	0.6	tr	0.1	0.1	0.1	0.6
Other accessories	0.2	0.1	0.3	0.2	tr	tr	0.5	0.2	0.6	tr	0.1	tr
SUM	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Counts per 2500 points:												
Apatite	5	3	8	2	--	3	5	6	4	2	--	2
Sphene	--	--	--	1	--	1	2	1	--	3	3	--
Zircon	--	--	--	1	--	--	--	--	--	1	--	--
Calcite	--	--	--	--	1	--	--	--	2	--	--	--
Epidote	--	--	--	--	--	--	--	--	10	--	--	--
Opaque	7	6	8	3	2	1	9		6	1	2	10

Zircon forms strikingly large, euhedral, clear to faintly brown crystals, up to 0.3 mm in length and commonly slightly embayed or corroded. Generally it is associated with biotite or iron ore, and generates faint pleochroic halos in biotite. All optic figures obtained for the large zircons were uniazial +. Several smaller, less euhedral crystals of slightly yellow color gave ambiguous positive figures, and probably represent monazite. Granular sphene is present in most sections and usually forms thin rims around iron ores or clusters along the edge of biotite. It is also present as clear, euhedral crystals up to 0.5 mm in length and frequently embayed. Stringy patches and granular clusters of sphene are included in poikilolitic hornblende.

Fine, acicular, and highly birefringent needles occur individually and as radiating clusters in interstitial areas of quartz. Form, parallel extinction, and high birefringence suggest rutile. The crystallization sequence inferred from petrographic relations might be expected in a fairly dry mesozonal granitic magma. Very early crystallization of augite and untwinned plagioclase was interrupted by changing conditions of equilibrium, possibly a decrease in pressure and slight addition of water due to ascent of the melt and emplacement into crustal rocks. Stoping and partial assimulation of norites and country rock was widespread, and suggests vigorous early circulation of the magma; xenoliths are common throughout the tonalite.

Crystallization of twinned plagioclase and hornblende commenced following this re-equilibration, and hornblende was succeeded by biotite first as subhedral flakes, and with increasing solidity, as interstitial, poikilitic anhedral crystals. Commencement of orthoclase crystallization only slightly preceded that of quartz: orthoclase occurs as rare subhedral inclusions in interstitial quartz, but crystallization of these two components was mostly simultaneous. Alteration of augite to acicular actinolite and hornblende occurred syn to post-consolidation, and may be considered deuteric.

Sunrise Butte Granodiorite

Granitic rocks on Sunrise Butte and in much of the salient to the northeast are more leucocratic than the Boulder Butte tonalite, and are designated as a distinct rock type. Sharp boundaries between the tonalite and granodiorite could not be located in the field. The contact appears to be gradational in nature, with the granodiorite representing a more silicic and later phase of Boulder Butte magma.

Sunrise Butte granodiorites are light grey to white and occasionally pinkish grey on a weathered surface, with a usually non-directional fabric of medium to small mafic constituents. Hornblende, one to two mm in length can be identified in some exposures, particularly on the west and south sides of Sunrise Butte. Biotite occurs in all Sunrise Butte rocks as small plates, 0.3-one mm in

Figure 35 a. Biotite lineation in Sunrise Butte granodiorite.

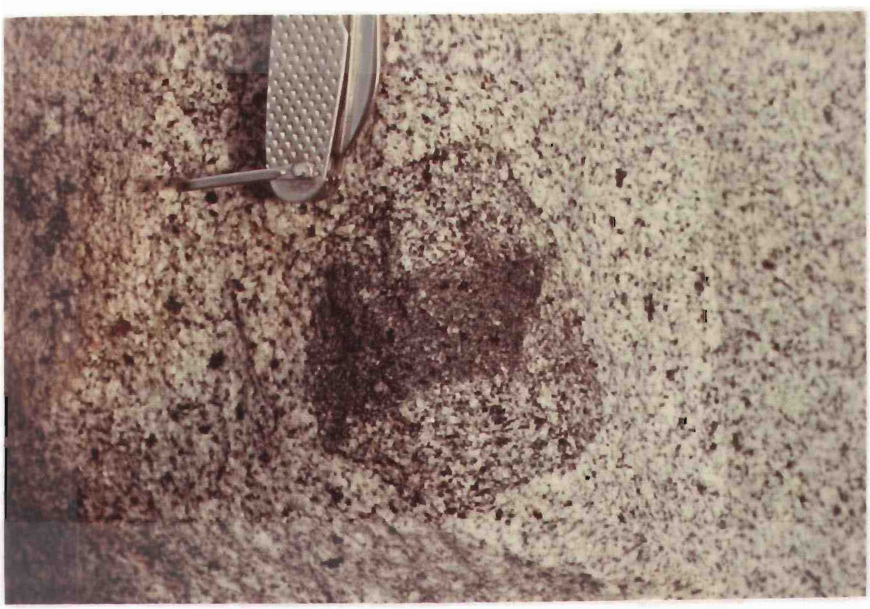


Figure 35b. Angular xenolith enclosed by mafic-enriched clot, Boulder Butte tonalite.

length. Where lineation is present in the rock, hornblende may be disoriented whereas biotite is preferentially aligned. Plagioclase and quartz are visible in all specimens; orthoclase is recognizable in rocks from easterly exposures on Sunrise Butte. Accessory minerals are notable in rare samples, and consist of sphene and iron ores where observed.

Xenoliths and mafic clots are most common near pluton borders and are increasingly rare in the east and south exposures of the granodiorite. Schleiren and elongate clots are most frequent in western exposures of the rock, where spindle-shaped mafic segregations up to two feet (0.7 m) in length were noted. These schleiren, however, are usually isolated in occurrence, or are adjacent to several small rounded autoliths in the granodiorite.

Strong lineation of mafic components of the Sunrise Butte granodiorite was observed near margins with country rock. In these instances, lineation is near vertical implying steep contacts as in the tonalite. Occasionally faint lineation of fine mafic components is developed in interior portions of the intrusion, where mineral alignment ranges from steep to nearly horizontal and resulted from weak circulation of magma. Layering is absent.

Many petrographic textures of the Boulder Butte tonalites are common to the Sunrise Butte granodiorite. Modally, the rocks of Sunrise Butte include granodiorite and some tonalites, although the

TABLE 21. SUNRISE BUTTE GRANODIORITE

	W-30	W-45	W-48	stained W-48	W-49	W-50	W-42	W-60	W-64	W-67	W-68	W-70	W-71	W-72
Plagioclase	60.2	54.3	56.7	56.6	54.5	56.3	61.2	55.2	46.1	57.5	50.3	58.1	47.0	38.5
Quartz	23.4	34.9	29.4	32.5	31.9	28.2	30.1	29.4	33.5	27.4	29.8	30.3	33.4	33.2
Orthoclase	0.29	4.5	3.8	4.2	6.8	1.0	0.3	8.2	14.4	2.7	14.2	5.9	12.7	25.5
Biotite	9.5	6.3	9.3	6.2	6.2	9.3	7.3	6.2	5.9	7.1	5.7	5.7	6.9	2.8
Hornblende	4.7	--	0.2	--	--	4.0	0.2	1.0	--	5.3	--	--	--	--
Augite	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Hypersthene	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Opaque	1.4	tr	0.2	0.1	0.4	1.2	0.7	tr	tr	--	--	tr	--	tr
Accessory	0.5	--	0.4	0.4	0.2	tr	0.2	--	tr	tr	--	--	0.3	tr
SUM	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Counts per 2500 points:														
Apatite	--	3	4	6	1	--	--	3	5	--	1	--	2	3
Sphene	2	--	1	--	--	2	4	--	--	3	--	2	10	--
Zircon	1	1	1	--	--	--	--	2	--	1	2	--	3	1
Calcite	4	2	2	--	--	10	5	--	--	3	--	2	--	--
Epidote	5	--	--	--	--	--	--	--	--	--	--	2	--	--
Opaque	40	1	7	3	12	35	21	3	3	--	--	4	--	1

granodiorite predominates.

Plagioclase cores vary between An_{52-47}, are bordered generally by three to four oscillatory zones, and are mantled by an untwinned oligoclase jacket which is severely corroded by orthoclase and often riddled on at least one side by long, stringy myrmekite perpendicular to the crystal face. Large, untwinned plagioclase, about An_{58-50}, with strong oscillatory zoning are similar to those from the Boulder Butte tonalite, but less frequently show syneusis relations (possibly a function of sampling). Plagioclase is twinned according to albite and carlsbad laws. Pericline twinning is virtually absent. Rare diagonal carlsbad twinning was noted in one plagioclase of W-72.

Myrmekite has three modes of occurrence: 1. It fringes borders between orthoclase and plagioclase, and is usually restricted to the oligoclase mantle; 2. It projects in bulbous, irregular, and dendritic growths from plagioclase into orthoclase, and also occurs in a few isolated globules of assimulated plagioclase in the midst of orthoclase; 3. It is developed as thin, discontinuous fringes on biotite on interfaces with orthoclase. Commonly such biotites contain opaques with a symplectic-like texture along biotite-quartz boundaries.

Consideration of the occurrences and textural relations of myrmekite in the granitic rocks of the Greenhorns leads to the following observations: 1. Myrmekite is restricted to rocks of tonalitic or more silic composition; 2. it is most common in rocks which are high in modal orthoclase, and which show clear evidence of strain (i.e. W-71, W-72), but it is poorly developed or present only in fragments where true orthoclase is limited to interstitial occurrences and corrosive replacements of plagioclase. Typically, orthoclase-plagioclase boundaries of the granodiorites are more highly irregular, and embayed than those in tonalites. Quartz displays wavy extinction in parallel bands in much the same manner as the eastern tonalite. Mortar texture occurs in the quartz of the granodiorites and increases in intensity eastward.

Hornblende is a minor component in Sunrise Butte granodiorite. Where present it is usually subhedral and embayed, showing evidence of attempted reequilibration with an increasingly silicic magma.

Biotite is the dominant mafic constituent of the granodiorite. It occurs in two habits with gradations between--as generally fresh interstitial crystals which contain small, doubly terminated zircons, apatite, and quartz, and as subhedral laths which are usually altered to chlorite along (010) cleavage and are frequently strained, with angular rotation of bent parts of up to 30°.

Accessory minerals include zircon, zoned apatite in small clusters along the edges of plagioclase, and granular sphene associated with subhedral biotite. Allanite was noted in W-72 as a small

(0.1 mm) dark brown- to light brown-rounded crystal in quartz. Allanite has also been reported in the rocks of Sunrise Butte by Taubeneck (1976, pers. comm.).

Petrographic relations in Sunrise Butte granodiorite indicate that nucleation and slow growth of a few calcic plagioclase occurred early in the magmatic history, similar to the sequence ascent led to patchy replacements in these crystals, and changing conditions of equilibrium resulted in the more rapid crystallization of twinned plagioclase and hornblende. With increase in P_{H_2O}, concentration of K, and decreasing availability of Ca, formation of biotite commenced. Crystallization of oligoclase mantles on plagioclase slightly preceded development of orthoclase, and may have been a slow process at equilibrium conditions since the mantles are only rarely twinned. Orthoclase crystallized slightly earlier than quartz as it often presents a slightly euhedral outline at quartz orthoclase boundaries. Intergrowths of quartz and feldspar were not observed. Deformation of the granitic rocks commenced before growth of oligoclase, and probably continued throughout the crystallization of the remaining components. Both the laminar strain of quartz and the presence of conjugate cross joints (see Granitic Structure) suggest that stress was imposed along one major axis. Slight volumetric adjustments during final emplacement and cooling resulted in development of marginal upthrusts in east exposures of the unit. Increased

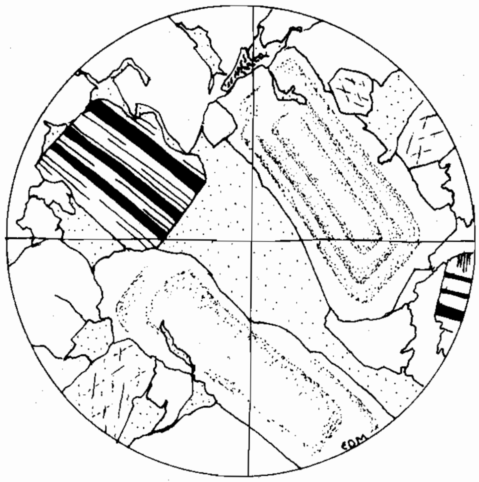


Figure 36a. Smooth orthoclase-plagioclase boundaries. Slight corrosion of some plagioclase interiors. Boulder Butte tonalite. W-93b x 40.

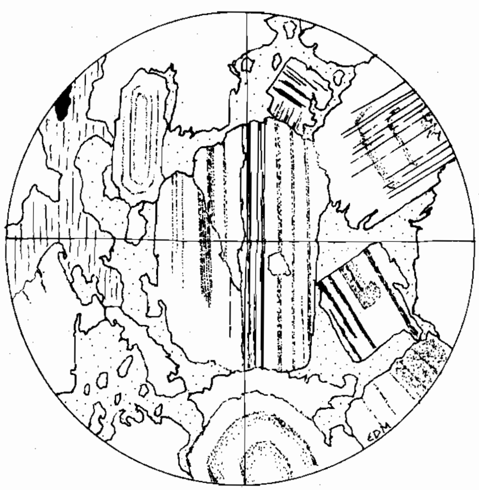


Figure 36b. Embayed and corroded boundaries between orthoclase and plagioclase. Sunrise Butte granodiorite. W-97 x 40.

strain in rocks with increased eastward location in Sunrise Butte granodiorite, and a concomitant trend towards more leucocratic rocks suggests that emplacement of Sunrise Butte granodiorite proceeded from west to east.

Granitic Dikes

Aplites are the most common dikes associated with the Jurassic plutons. Except near the head of Desolation Creek, they are generally narrow (two to three) feet maximum; one to two feet in normal width and are commonly isolated. In section 4 near McAlpine Meadows, numerous aplites of up to four feet in width crosscut one another in a random pattern. The aplites are usually fine-grained, light pink on a weathered surface, and speckled white on fresh exposure. All exhibit saccroidal texture. Biotite is the only mafic constituent.

Pegmatites are rare. Only two occurrences were noted, one of which, 1.5 feet in width crosscuts layered Desolation norites. The other intrudes Sunrise Butte granodiorite. Orthoclase, quartz, and biotite are the main constituents of the pegmatites. No unusual minerals were identified at either location.

Mineralization

Late stage deposits of gold, silver, molybdenum, as well as

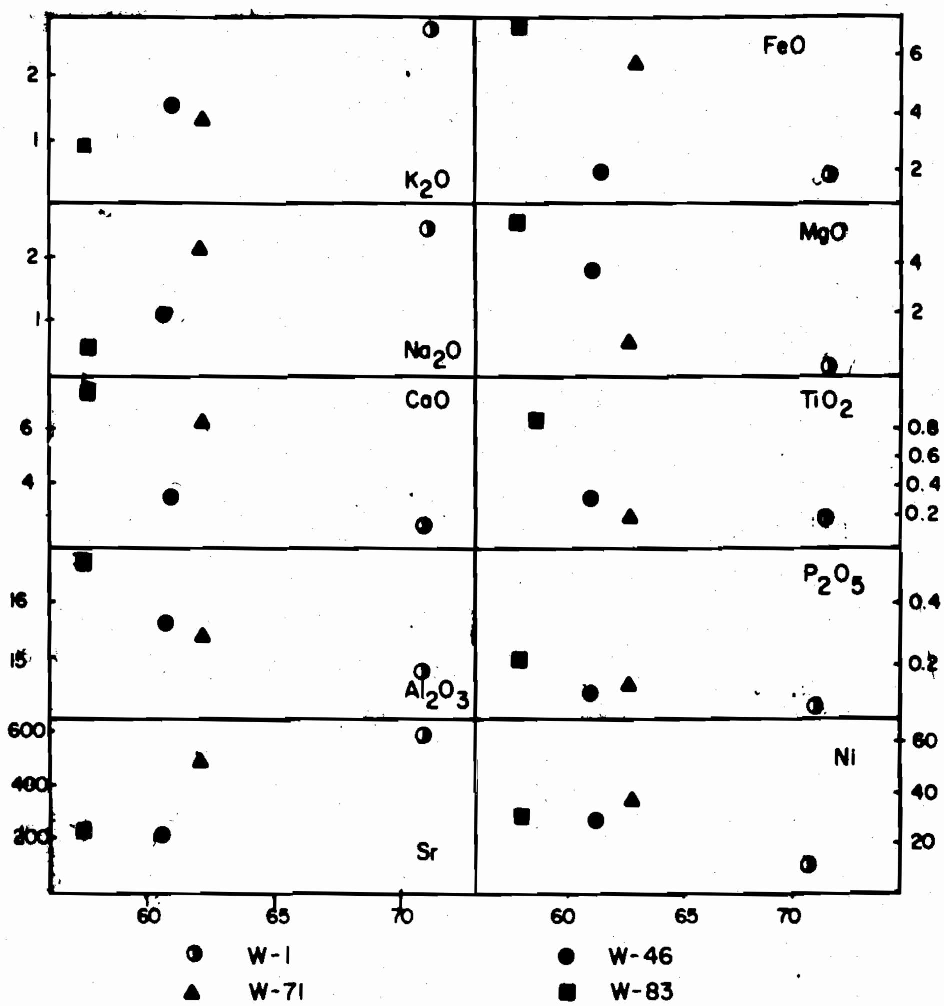


Figure 37. SiO_2 variation with major oxides and trace elements, granitic rocks.

sulfides are associated with granitic intrusions of the Greenhorn Mountains. The deposits commonly reside in metasediments adjacent to pluton boundaries or at the periphery of the plutons.

Willow Lake Layering

At one location in the north extremity of the Sunrise Butte intrusion there is a limited but striking development of layered granitic rocks characterized by elongate and branching growth of hornblende crystals perpendicular to banding. This type of harrisitic crystal growth was recorded by Taubeneck (1957) in the Willow Lake norite of the nearby Bald Mountain batholith, and was first described in detail by Taubeneck and Poldervaart (1960).

At the Sunrise Butte location, layered rocks occur as detached boulders rather than as solid bedrock, so original orientation could not be determined. Banding in these specimens ranges between 0.5 to 1.5 inches (1.3-3.8 cm) in thickness, constitutes a maximum of eight layers, and does not exceed a total thickness of 2.5 feet (0.7 m). No difference was observed between granitic rock at the top or the bottom of the layering. In both cases it is a hornblende rich phase of Sunrise Butte granodiorite.

Layering varies between the "top" (last-formed) layer composed of coarse, singular, elongate, and slightly branching hornblendes up to 1.5 inches in length, to bottom layers in which the elongate hornblende is only barely discernible. In these bands, hornblende and rare biotite are developed as elongate strings of detached prisms which give the overall impression of harrisitic growth. Layering is discontinuous in the bands.

The country rock adjacent to the layered rocks is severely fractured and intruded by quartz veins; it constitutes a good example of an intrusion breccia.

Taubeneck and Poldervaart (1960) have attributed the development of this texture to supercooling of a granitic melt by rapid conduction of heat away from the magma through fractures in the adjacent country rock. Field relations in the Greenhorn Willow Lake exposures indicate a similar mechanism of formation.

Chemistry

Four samples of granitic rocks were analyzed for major oxides and trace elements by X-ray fluorescence and atomic absorption methods. Initially, nine samples were chosen for analysis, but due to limited flux compounds, complete analyses were run on only four. These rocks are: W-1, two-mica granodiorite, Olive Creek; W-71, a Sunrise Butte granodiorite with fairly high orthoclase content (12 percent); W-46, Boulder Butte tonalite, and W-83, Quebec Hill norite. Although desirable, no attempt was made to determine chemical zonation in the major plutons, or to systematically investigate the

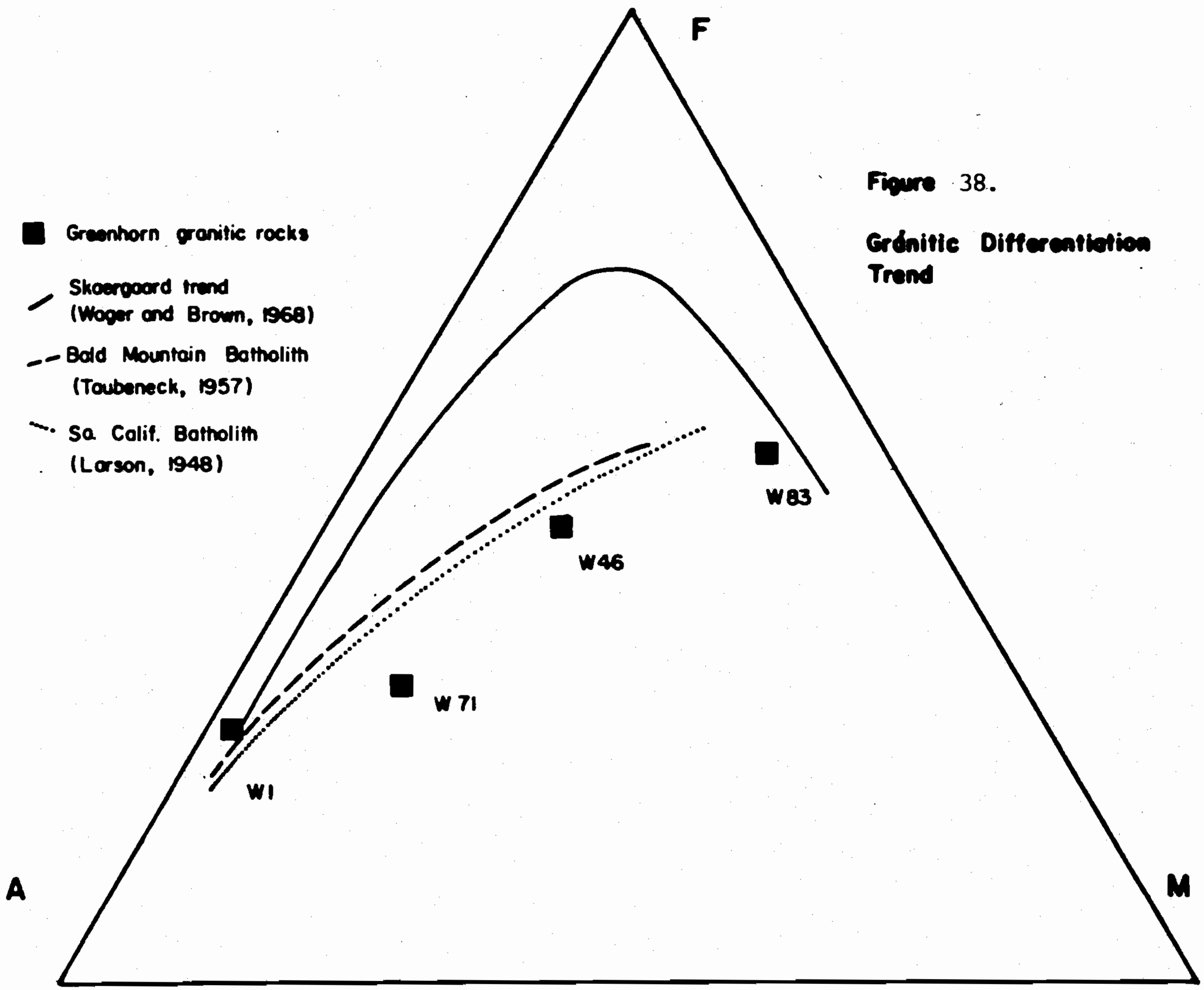


Figure 38.

Granitic Differentiation Trend

Desolation norites.

Major oxide variations plot in a generally linear relationship on Harker variation diagrams of major oxide v. SiO_2, as might be expected if the plutons of the Greenhorns originated from a related and differentiating range. W-71 falls slightly off the linear trend, and this variance may be attributed to differences in the entire intrusive series which are not apparent in the other three rocks analyzed, a different source for the Sunrise Butte magma, or to contamination of the Sunrise Butte magma by crustal and mafic components.

Significantly, W-46 (Boulder Butte tonalite) is enriched in Ni compared to the trend of other samples. W-46 is also among the most mafic of Boulder Butte rocks, with 0.4 percent augite, and represents the mafic end member of the Boulder Butte-Sunrise Butte tonalite-granodiorite series. If this interpretation is followed, then the higher nickel content of W-46 probably represents a real, rather than contaminated value, and the norite of Quebec Hill should be considered a separate magma not intimately connected to the western tonolite-granodiorite intrusions. As a word of caution, however, it should be noted that values for Ni in both W-46 and W-83 are close, and within experimental error. It is unusual, however, for nickle contents of a rock with nearly 17 percent pyroxene (W-83) to overlap so closely with one containing 0.4 percent pyroxene (W-46).

Data for Sr tend to support the observation that the Quebec Hill

TABLE 22. CHEMICAL ANALYSES OF JURASSIC INTRUSIVES

	W-1	W-71	W-46	W-83
SiO_2	73.87	71.70	63.04	57.56
Al_2O_3	15.02	15.45	15.67	16.69
TiO_2	0.20	0.32	0.19	0.80
CaO	2.55	4.41	7.10	7.98
Na_2O	2.58	2.87	1.35	0.66
K_2O	2.84	1.69	1.48	0.91
Fe*O	1.99	2.07	6.76	7.50
MgO	0.15	0.29	3.58	5.91
P_2O_5	0.09	0.11	0.15	0.21
SUM	99.29	99.00	99.32	98.49

*See Appendix 2 for sample descriptions.

norite--and the Olive Creek granodiorite--were produced by separate pulses of magma. Two additional samples were included in Sr analysis: W-232 is a Sunrise Butte granodiorite slightly more leucocratic than W-71, and W-218 is an intermediate tonalite of Boulder Butte type. Sr content of the Boulder Butte-Sunrise Butte series ranges from 226 ppm in W-46 to 765 ppm in W-232, in a linear fashion. Sr in W-83 (248 ppm) slightly exceeds that in W-46. Again, due to overlap in experimental error, these values should be considered roughly equivalent, but the marked similarity in Sr values for a norite and a tonalite suggest that the two magmas were distinct. Sr c0 ntent of the Olive Creek granodiorite (514 ppm) is roughly equivalent to that of intermediate tonalite (W-218; 506 ppm) in the Boulder Butte intrusives, and again suggests that the Olive Creek rocks were a separate pulse of magma.

For both Ni and Sr, the possibility of contamination by country rock is an explanation for the anomalous trace element values discussed above. The Quebec Hill norite in particular intruded highly silicic sediments, while the Boulder Butte tonalites encountered volcanic greenstones and arc-derived sediments which would have been more compatible in trace element content. Reliable trace element analysis of cherts compatible with Elkhorn Ridge Argillites have not appeared in the literature, so estimates of volume of assimulated sediments required to significantly effect trace element abundances in norite cannot be confidently made.

Granitic Structure

Limited structural studies of granitic rocks of the west part of the thesis area were undertaken in part to determine whether separate intrusions of Desolation, Boulder Butte, and Sunrise Butte granitic types could be distinguished by differences in joint or lineation patterns.

Lineation and features of platy parallelism are discussed separately with each unit above. In general, lineation patterns are steep and subparallel to contacts with the country rock, indicating lineation by flow mechanisms fairly early in the intrusive history (Balk, 1937). Schleiren are more common in the Boulder Butte tonalites than in other granitics, and are usually elongate ellipses in two dimensions, rather than true spindle shapes. They are aligned parallel to lineation where both occur.

Cross joints represent the earliest formed fractures in a cooling granitic mass (Balk, 1937; Billings, 1958). In west Greenhorn granitic rocks, they are in steeply dipping conjugate pairs. Occasionally there is marked development of green hornblende and chlorite on joint surfaces. The conjugate, paired nature of the cross-joints implies probable compression perpendicular to lineation which was present during the final cyrstallization history of the magmas. The mafic coating on joint planes is of late-stage or deuteric origin.

To determine whether any pattern of jointing was peculiar to one rock type measurements of 82 cross-joints in Boulder Butte and Sunrise Butte rocks were made. Only two measurements of Desolation norite were made due to the poor and usually limited nature of its exposure. However, cross joints in these rocks are consistent between the two exposures, and are of slightly different orientation than joints in adjacent tonalite. This is suggestive of separate intrusion of the norite and tonolite, but is neither conclusive nor compelling evidence due to the dearth of data on norite and the small magnetude of variation.

	DES	DES	BB	BB	BB
Set A	N50E 78°SE	N50E 74°SE	N30E, 78°NW	N30E 66°NW	N72E vert.
Set B	N68W 86°NE	E-W 60°N	N71W, vert.	N72W 35°SW	N60W vert.

No apparent difference or abrupt change in cross-joint patterns occurs between rocks designated as Boulder Butte tonalite and nearby granodiorites. Like the modal mineralogy, joint patterns between the two apparently are gradational.

Marginal upthrusts (Balk, 1937; Billings, 1958) are infrequent, and as might be deduced from the increasing deformation of granitic rocks apparent in thin section, are most common in east exposures of Sunrise Butte granodiorite. Their hornblende-chlorite coating is similar to that of cross joints but they lack the conjugate pair relation evidenced by the former, and are strongly slickensided. Slickensided cross joints were also noted in a few exposures of Boulder Butte tonalite, and undoubtedly served as a means of adjustment during late cooling stages in a manner similar to marginal upthrusts.

Granitic Rocks: Conclusions

Field, petrographic, and limited chemical study of granitic plutons of the Greenhorn Mountains confirms that the mesozonal intrusives represent discrete pulses of magma rather than only one intrusive event. Seven intrusions can be identified. In the thesis area major intrusives become increasingly more leucocratic eastward. However, reconnaissance of exposures west of the thesis area boundary indicates that the granitic rocks also tend toward increase in silica, orthoclase, and biotite content westward. If this is true, then the granitic rocks of Boulder Butte-Sunrise Butte sequence probably represent a zoned plutonic sequence of large proportions (ten mile minimum diameter).

Considerable petrographic evidence has been cited which indicates that the major intrusions of the Greenhorns crystallized from rather dry magmas, similar to the Bald Mountain batholith in many respects. Granitic rocks of theGreenhorns appear to follow a calc-alkaline to calcic trend of K/Na enrichment also similar to the

Bald Mountain batholith, rather than following the tronjemitic trend noted by Taubeneck (1967) in the Cornucopia stock of the Wallowa Mountains, although late enrichment in Na is slightly greater in the Greenhorns than Bald Mountain batholith. The marked similarity of petographic and most chemical relations suggests that granitic rocks of the Greenhorns are closely related to the Bald Mountain batholith in age and origin.

CRETACEOUS GRAVELS

Stream and lacustrine deposits of probable Late Cretaceous age outcrop in only one locality in the thesis area, but there is good evidence that they were once more widespread.

The single exposure is at the Parkerville placer mine. Fine, moderately indurated gravels with a sandy clay matrix are layered in one to two foot (0.5 m) alternating red-brown and blue-grey beds which strike northeast and dip very gently northwest. Clasts range from less than an inch (one mm) to about three inches (7.5 cm) in diameter. Clast lithologies include granitic rocks, chert, and metagabbro. Volcanic clasts were not noted in the field. In overall composition the Cretaceous conglomerates might best be characterized as petromict type, the coarse-grained equivalent of lithic sandstone. Limited exposure makes it difficult to estimate thickness of the unit; 30-50 feet seems the maximum accumulation.

These gravels represent the first erosional remnants from the Late Jurassic plutons, and are in most cases fluvial in origin. They were early repositories for gold and other heavy minerals eroded from the newly exposed grainitic plutons. This concentration of placer ore resulted in their virtual removal from several locations in the Greenhorns by hydraulic mining in the early 20th century (Potter, 1976). At the former locations of placer mines along Lightning Creek, eroded channels and barren exposures of Elkhorn Ridge Argillite are nearly all that remain of Cretaceous gravel deposits.

Only one fossil species has been noted from the gravels and related deposits in the Greenhorn area. Fragments and entire root-bulbls of the late Early Cretaceous fern Tempskya sp. (Ash and Read, 1976) were collected from the Lightning Creek and IXL Mine area by Pardee (1914), and later by many. Tempeskya has also been collected from gravels at the Parkerville site.

Fossils of Tertiary age have commonly been attributed to the auiferous gravels both in the Greenhorns (Perkins, 1976) and in the Blue Mountains northeast of the thesis area (Mobley, 1956). However, the gravels are everywhere overlain by Clarno mudflow and stream deposits which contain the same fossil species as that commonly "identified" from the auiferous gravels. Material eroded from the Clarno mudflows and mixed with Cretaceous gravels is responsible for the co-existence of Tempskya with Tertiary species.

Due to the nearly universal association of the fern Tempskya with late Early Cretaceous (Albian) strata (Ash and Read, 1976), and its presence in the indurated red-to-blue-grey auiferous gravels of Parkerville, an Albian age is assigned to this unit. Similar gravels occurred along Lightning Creek prior to extensive placer and hydraulic mining in the area. Fern fragments from Cretaceous gravels were probably also reworked and incorporated in the lowermost portion of the Clarno-equivalent mudflow unit, possibly as poorly indurated stream gravels.

TERTIARY UNITS

Clarno-equivalent Mudflows, Tuffs, and Flows

The base of the Tertiary volcanic assembledge in the Greenhorns is a complex and diverse group of mudflows, tuffs and ignimbrites, overlain by alkalic basaltic to basaltic-andesite flows which strongly resemble the Clarno Formation of central Oregon and the west parts of the Blue Mountains (Oles and Enlows, 1971). Three inter-related units can be distinguished in the Greenhorns and in the valley of the North Fork of the Burnt River.

Clarno-equivalent Mudflows (Tcm)

Poorly consolidated, chaotic mudflow and lahars are exposed in the southern, eastern, and northern-most portions of the thesis area. They are best observed along the road from Austin Junction to Greenhorn, and form ragged, dark grey cliffs along the Middle Fork of the John Day River, west of Bates.

Occasionally the mudflow deposits form dark grey to nearly black low, irregular hoodoos where exposed on ridgecrests and some north-facing slopes. Gentle slopes are more typical of this unit, however. The matrix consists of volcanic ash, sand-sized fragments of feldspars and quartz, and rare volcanic lapilli. Clays and volcanic ash are by far the most prevalent constituent, generally forming

90 percent or more of the matrix. On fresh exposures, the matrix is a light yellow brown to pinkish buff, and can be readily excavated with shovel or trowel. More indurated parts of the unit occur as evidenced by the presence of stark, columnar hoodoos.

Fluvial channel deposits tens of feet in cross-section are found in fresh roadcut exposures near Greenhorn. Clasts in these channel deposits are lithologically similar to clasts within the mudflow deposits; pre-Tertiary clasts are not evident in streams which transect mudflows.

Clasts in the Clarno-equivalent lahars range in size from rounded pebbles less than an inch (2.5 cm) in diameter to boulders over three feet (one m) in diameter. Small and intermediate sizes are most prevalent. Bedding is present only on a large scale with the exception of channel deposits mentioned above. Each separate lahar forms its own, usually unstratified, singular "bed."

The included clasts are volcanic. They are generally red to pinkish grey and occasionally dark grey on weathered surfaces, and pinkish grey to grey-brown on fresh ones. Most are porphyritic, with small laths of feldspar, and are commonly vesicular.

Six samples of large boulders in the mudflows were taken for examination of the petrography of flow rocks associated with the lahars. Three lithologies were identified: a hypersthene andesite, two-pyroxene andesite, and clinopyroxene andesite. It is possible that T-6, the hypersthene andesite, may include clinopyroxene, but none was identified in the single thin section made from that sample.

In thin-section, samples of mudflow volcanic clasts display pilotaxitic texture. They contain small one to two mm plagioclase phenocrysts which are complexly twinned (albite, carlsbad, and pericline) and occasionally display fine, oscillatory zoning with some preferential alteration to sericite. T-2 and T-4 are two-pyroxene andesites with five to eight mm long prismatic phenocrysts of hypersthene sometimes intergrown with prismatic augite. Groundmass clinopyroxene is slightly pinkish and may tend towards titanaugite. Plagioclase phenocrysts are An_{65-58}; matrix microlites are too fine for confident determination of An content by Michel-Levy methods, but appear to be andesine. Hornblende is absent even as a late reaction product. Calcite fills some small vesicles and forms anhedral masses in the altered glass and microlite matrix.

Textures of single-pyroxene(?) andesites are similar, but An content of plagioclase phenocrysts is lower, An_{42-38}. Only one flow (T-2--a medium pinkish grey rock with one to two mm phenocrysts of plagioclase) of lithology corresponding to the clasts within the mudflows was found in the Greenhorns, intercalated with upper portions of the mudflows, and three miles southeast of the thesis area's southern boundary along the main road to Greenhorn. Data from Oles and Enlows (1971) are recorded for comparison. There is considerable

TABLE 23. MODES: CLARNO ANDESITE

	T-2	Lower Clarno*	Upper Clarno*
Plagioclase (phenocrysts)	27.0%	74%	80%
Groundmass (plagioclase and alteration)	63.6		
Clinopyroxene	0.5	20	12
Hypersthene	7.2	1	2
Opaque	1.5	4	6
Hornblende	--	tr	tr
Quartz	--	1	tr
Glass	tr	tr	tr
Sum	100	100	100

*Data from Oles and Enlows, 1971.

discrepancy between modes cited for Mitchell rocks and the andesites of the Greenhorns. It is not inconceivable, however, that they could be related, as some Greenhorn units may be substantially higher in clinopyroxene than indicated by T-2.

In addition to the single flow unit intercalated with the mudflow deposits, a thin (six to eight feet, or about two m) uniform light pinkish grey welded tuff was noted along the road to Greenhorn, 2.5 miles south of the thesis area. Although the unit lacks the classical zonation of the typical ignimbrite unit (Smith, 1960), examination in the field by hand lens reveals welding; emplacement occurred at temperatures slightly in excess of 500°C (Smith, 1960). Inclusions of charred organic material are common in the unit. Combustion and alteration of plant detritus had progressed too far to allow for fossil identification.

Wheeler (1977) recovered leaves from the lahar unit along the Middle Fork of the John Day river 12 miles (20 km) south of this thesis area which have been dated as probably Late Eocene. Similar fossils from the south parts of the Bates 15' quadrangle were also determined to be Late Eocene in age (Mobley, 1956). Hence, a Late Eocene age is assigned to the lahar units and intercalated flows and ignimbrites of the Greenhorns. The lithologies of the units correspond closely to the Upper Clarno assembledge described near Mitchell, Oregon by Oles and Enlows (1971), to which a Late Eocene to Early

Oligocene age has been ascribed (Oles and Enlows, 1971; Swanson and Robinson, 1968). Accordingly, the mudflow and related units of the Greenhorns are tentatively correlated with the upper Clarno.

Clarno-equivalent Basalts and Basaltic Andesites

A thin mantle of basalt and basaltic andesite overlies the andesitic lahars and covers many of the hilltops in the east part of the thesis area. Except in some roadcuts, exposure is seldom as a coherent basalt flow. The unit must frequently be identified by the occurrence of subrounded basalt regolith or rubble on characteristic reddish soils. Relief associated with this unit is subdued. Two noteworthy exposures display different styles of jointing and weathering in Clarno-equivalent flows.

The west summit of ridge 6267 in section 14, three miles east of Greenhorn, is a basaltic andesite (C-10) which weathers dark olive grey to olive brown, is olive grey on a fresh surface, and is jointed in four-inch vertical columns across most of the exposure. Approximately two miles northeast of that location dark pinkish-grey Clarno-equivalent flows display thin, easily parted and usually curved platy jointing.

Several dikes which probably were sources for flows have been noted in the Greenhorns. Several en echelon dikes (C-15), approximately 20 feet in width and traceable for distances of up to 200 feet

C-7

Augite phenocrysts and intergranular augite in pilotaxitic plagioclase microlites.

C-10

Augite and altered olivine phenocrysts; lath-shaped plagioclase phenocrysts and microlites. Intergranular texture.

C-6

Large, equant plagioclase phenocrysts, with smaller phenocrysts of augite and altered olivine; pilotaxitic plagioclase laths.

Figure 39. Textural variations in Clarno-equivalent basalts.

Figure 40 a. Platy jointing, Olive Butte volcanics, Olive Butte.

Figure 40 b. Angular columnar jointing, Clarno Basaltic andesite, section 14, elevation 6267.

in length were first noted in section four near Sunrise Butte by Taubeneck (1976, pers. comm.). Additional related dikes of similar dimensions and orientations occur in section 29 near Boulder Butte, and a large cluster of dikes was located on the south summit of Rabbitt Butte (C-200).

Petrography

Mafic flows mapped as Clarno-equivalent are intergranular or pilotaxitic and display a wide range of grain sizes and textures. Phenocrysts of olivine 0.5 to 1.5 mm in diameter and laths of plagioclase one to two mm long are common. Olivine is faintly zoned and optically negative with a large 2V of about 100°, and is therefore in the range Fo_{65-60}. In most samples it is veined or rimmed by alteration products--principally nontronite and "iddingsite" which are olive-brown to red-brown in plane light. In C-1, C-13, and C-17 alteration products entirely pseudomorph olivine.

Plagioclase phenocrysts are normally zoned from labradorite cores to calcic andesine rims. They are NOT present at all in sample C-7, and only rarely do they display oscillatory zoning. Size distribution of plagioclase varies widely. A nearly bimodal size distribution between phenocrysts and groundmass plagioclase occurs in samples C-8, C-13, and C-1, which are among the least siliceous flows. Plagioclase size is gradational from elongate phenocrysts to

TABLE 24. MODES OF TERTIARY BASALTIC ROCKS*

	C-1	C-6	C-8	C-10	C-13	C-15	C-16	C-17	C-18
Plagioclase	61.89	74.41	65.56	50.62	63.10	54.2	71.80	56.79	55.13
Olivine		7.00	10.37	4.15	5.25	2.1	6.40	0.20	17.60
Orthopyroxene	--	--	--	--	--	--	--	--	--
Clinopyroxene	26.55	11.33	17.72	37.92	18.61	19.3	17.60	20.82	22.73
Opaque	3.36	3.47	4.53	6.38	4.37	4.8	4.20	2.33	4.37
Glass	3.80	1.14	0.63	0.13	2.15	--	--	7.55	0.12
Apatite	0.14	1.52	0.34	0.26	0.11	0.3	--	--	--
$CaCO_3$	--	1.09	--	--	--	0.4	--	0.38	--
Alteration products	4.26		1.19	0.85	6.52	18.9	--	--	0.61
SUM	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

*See Appendix 2 for sample descriptions.

groundmass microlitesin C-4, C-5, and C-10. Sample C-6 contains distinctive squarish prismatic plagioclase phenocrysts, instead of more common, lath-like morphology.

Groundmass plagioclase is unzoned, has fine carlsbad and albite twinning, and in samples checked is intermediate andesine An_{45-40}.

Clinopyroxene phenocrysts (0.5 to two mm) are frequently more common than olivine, less altered, and are sometimes embayed or corroded. They are clear to light green in color, rarely twinned, and sometimes have a subtle, zoned rim. 2V is fairly small, in the range 45-50 degrees. Precise determination of groundmass pyroxene proved difficult, but the apparently small 2V and high birefringence suggested pigeonite. Groundmass clinopyroxene may be high in TiO_2 in C-7 and C-6 where it displays a faintly rosey pleochroism. Alteration of pyroxenes occurs as rims, veins, and irregular patches of smectites, and rare chlorite.

Chemistry

Chemical variation among Clarno-equivalent mafic volcanics is substantial. The rocks range from basalts of about 51.5 percent SiO_2, to basaltic andesites with nearly 56.0 percent SiO_2. Al_2O_3 is fairly consistent at about 17 percent, but other constituents fluctuate between samples. Alkalis comprise two to four weight percent of the rocks; K/Na ranges between 0.25 and 0.4. CaO constitutes roughly nine to ten percent of the rocks. Iron ranges between nine and 11 percent, and is more abundant than magnesium which varies from five to seven percent. On the basis of major element abundances, the basalts (C-13, C-200) are classified as alkali-olivine basalts, and samples with silica above 53 percent (C-10, C-15, and C-210) are assigned to alkalic low Si andesite.

Trace element data are equivocal regarding the chemical affinity of the Clarno-equivalent mafic extrusives. Ba ranges from 712 ppm in one of the most silicic samples (C-15) to 284 ppm in the least silicic (C-13). Similarly, Sr is higher in andesites than in the basalts, but by a narrow margin over a wide range. Ni decreases generally with increase in silica as expected; its relatively high abundance in andesitic rocks (83-73 ppm) is attributed to the persistence of olivine. Zr ranges from 133 ppm to 244 ppm, and is poorly related to content of any major oxide.

Major and trace element abundances in the Clarno-equivalent volcanics show similarities to rocks of both oceanic islands and island arcs. Abundance of K (0.7-1.6 percent), and sum of alkalis closely resembles the data reported for rocks of equivalent silica content from island arc suites, and is substantially less than abundances of alkalais generally noted in rocks from oceanic island suites (Carmichael, 1974; Clague, 1974; Natland, 1975; Batiza, 1977). If the relations between depth of origin and K-content postulated by

TABLE 25. CHEMICAL ANALYSES OF TERTIARY VOLCANICS*

	C-10	C-13	C-15	C-200	C-210	C-208	C-212	Average Pict. Gorge **
SiO_2	55.11	51.68	54.88	52.50	55.98	49.83	--	50.47
Al_2O_3	16.80	17.10	16.72	16.53	17.13	15.73	--	15.00
TiO_2	1.22	1.67	1.52	3.08	1.89	1.35	--	1.72
CaO	10.45	9.76	9.81	9.56	8.44	11.04	--	9.59
Na_2O	2.08	2.05	1.82	2.21	1.47	1.51	1.45	3.03
K_2O	0.69	0.66	1.59	1.06	1.48	1.08	0.77	0.76
Fe*O	8.80	10.61	9.82	10.05	10.56	10.56	--	12.23
MgO	5.51	5.82	4.13	4.78	5.01	7.64	6.00	5.54
P_2O_5	0.27	0.32	0.55	0.55	0.49	0.36	0.29	0.26
SUM	100.93	99.67	100.84	100.32	102.45	99.10	--	99.92
Ba	340	284	712	418	503	102	212	440
Ni	83	96	77	63		105	67	44
Sr	498	345	666	436	628		259	241
Zr	173	145	244	203	133	145		160

*See Appendix 2 for sample descriptions. **McDougal, 1976.

Kuno (1966) is valid, the Clarno equivalent basalts were generated at intermediate to shallow depths. Fe*O/MgO ratios are much lower than ratios characteristic of equivalent Samoan and Line Island rocks (Natland, 1975), but are not vastly different from other oceanic island suites.

The abundance of Ni is far higher than that reported for calc-alkaline island arc rocks, and is roughly equivalent of slightly lower than Ni in rocks of equivalent silica from oceanic islands where direct partial melting of a mantle source, rather than differention form a tholeiitic parent has been invoked as an oriign (Kay and Hubbard, 1978). Significantly, in all samples of Clarno-equivalent basalts, Ni is approximately twice as abundant as in upper Picture Gorge and Yakima Columbia River Basalt, and is slightly higher than reported for the basal flows of the Picture Gorge sequence (McDougal, 1976). Abundance of barium is also greater than arc basalts and basa... andesites, and equivalent to or lower than oceanic island basalts (Carmichael _et al_., 1974; Natland, 1975; Clague, 1974). Barium is also equivalent to or higher than Ba reported from the type section Picture Gorge (McDougal, 1976), and higher than Picture Gorge basalt exposed near Indian Rock in the west portion of the thesis area. Neither Sr nor Zr concentrations are correlative to either suite of rocks, but vary throughout a wide range.

Trace and major element data, then, suggest that the alkali-olivine basalt suite of the Greenhorns originated by partial melting of mantle material at shallow to intermediate depth, with little contamination by crustal material of at leas the early lavas. This suggestion, however, cannot be firmly supported by the limited number of analyses presented here. Further work and determination of K/Rb ratios is desirable to substantiate this conclusion.

Olive Butte Volcanics

About 40 percent of the north and east parts of the thesis area is covered by light to medium grey and light pinkish brown porphyritic volcanic rocks which range from hornblende andesite to biotite-bearing dacite and rhyolite, which overlie the Clarno basalts and basaltic andesites.

The most common variety of the volcanics is on and around Olive Butte and near Sheep Rock north of thesis area. The monotonously light to medium grey rock at these locations contains one to five mm elongate hornblende phenocrysts commonly aligned with flow direction, and pinkish plagioclase which attains a length of nine mm, but more often ranges between one and five mm. Both columnar and platy jointing occur in exposures of this rock. Columns on Olive Butte vary from slightly more than two inches (one cm) in width to over 14 inches (36 cm) in diameter. Flow rocks near the summit of

Olive Butte at el. 6260 display fine platy jointing less than 1/4 inch (six mm) in width. Platy jointing on a slightly larger scale is evident in flows near Sheep Rock. The well-formed and complex joint structure of these rocks and their relatively siliceous and resistant character results in craggy topography and abrupt relief. West-facing cliffs on Olive Butte rise nearly 500 feet (160 m) above basalts and pre-Tertiary rocks at their base. Steep-sided, well exposed hummocks of this rock are scattered throughout its areal extent.

Pinkish-brown dacites are much less well exposed, and were found only along the south side of Beaver Creek where they overlie the more common grey volcanics. One occurrence of pink, flow-banded rhyolite was noted overlying the grey andesitic volcanics at the head of Buck Gulch, west of Olive Butte. This flow appears to underlie white to pink, deeply weathered air-fall tuffs which also are exposed in Buck Gulch, and which are also correlated with the Olive Butte volcanic series.

Olive Butte Flows: Petrography

Textural characteristics and compositions of the Olive Butte lava series are diverse. In virtually all sections examined, plagioclase phenocrysts 0.7 to five mm display complex albite, carlsbad, and pericline twinning, fine oscillatory zoning, and patchy zoning in calcic cores. An content of these phenocrysts ranges from An_{68-65}

(calcic laboradorite) in 0-11 to An_{42-38} (intermediate andesine) in 0-15. In most specimens, plagioclase compositions varied between An_{50-48} (calcic andesine) to An_{62-58} (intermediate laboradorite). Plagioclase phenocrysts are commonly corroded and embayed, from disequilibrium with the late-stage melt. In some slides (0-8, 11, and 13) the plagioclase crystals are complexly intergrown, later fragmented and overgrown by less calcic plagioclase indicating a probably turbulent early magmatic history. Phenocrysts in 0-12 are fractured and filled with microlite matrix, which implies that breakage of the crystals occurred during late transport. Overgrowths appear to be absent. Oscillatory zoning is present only in occasional crystals in 0-14, and is also rare in 0-12. Alteration of plagioclase cores to calcite and minor prehnite, and development of sericitic alteration along preferred zones occurs in all sections of Olive Butte volcanics examined. Development of smectite and chlorite in plagioclase is not uncommon, and may be attributed to the inclusion of many impurities--especially iron ores--and blebs of glass along selected zones and in random distriubtion within phenocrysts.

Mafic phenocrysts range from augite through biotite; hypersthene was observed in only one (0-13) thin section. Augite is light green to colorless in thin-section and seldom exceeds 0.5 mm in diameter. It is frequently corroded and altered to chlorite, or may be entirely replaced by iron-rich phylosilicates. Dark-green to light green-brown, euhedral to subhedral hornblende is the most common mafic constituent throughout the series, occurring in all thin sections, and ranging from 0.5 to three mm in size. Hornblende has a small extinction angle (16-19 degrees), and moderate 2V (45-50 degrees) suggestive of high iron content. Fresh hornblende is virtually absent. Large phenocrysts are corroded and embayed; smaller phenocrysts are less corroded, and formed later and in equilibrium with the melt. Alteration to chlorites and smectites along cleavage planes, and in patches is widespread. Hornblende is completely replaced by the deuteric reaction products in 0-4. Late-stage biotite replaces hornblende in 0-7. Striking kelyphitic reaction rims occur around corroded hornblendes in 0-4. Nearly all amphiboles in this sample are surrounded by a granular and occasionally symplectic intergrowth of iron ore and clinopyroxene, which attests to their instability at high temperatures and low pressures. Prismatic plagioclase and small apatite are included in hornblendes.

Red-brown biotite, altered frequently to light green chlorite, constitutes one percent or less of the Olive Butte flow rocks. It occurs as small, nearly prismatic euhedral crystals, and rarely exceeds 0.2 mm in length.

Small orthoclase phenocrysts (0.2-0.7 mm) were noted only in 0-13 where they are euhedral, fresh, and also uncommon (less than one percent of the section). Few phenocrysts of quartz in the andesite-dacite series of Olive Butte showed slight, irregular corrosion on some faces.

Groundmass textures are pilotaxitic or hyalopilitic. Distinctive red-brown glass, rimmed by opaques, is frequently altered to brownish-green smectite. Occasionally it forms fine rims on plagioclase phenocrysts. Plagioclase microlites show compositional variation equivalent to that of the phenocrysts, and range from An_{67-64} (calcic labradorite) in 0-11, to An_{30} in 0-15. Composition of microlites in most sections is commonly An_{50-42}, slightly less than phenocrysts in the same rock. Iron ore occurs as an alteration product of mafic minerals and as evenly dispersed globular particles spread throughout the matrix. Undoubtedly oxidation of the opaques explains the frequent pinkish hue of the rock.

Both orthoclase and quartz are abundant in the groundmass of dacitic rocks; orthoclase constitutes ten percent or less of the groundmass in andesites.

Sources of Olive Butte Volcanics

Numerous north to northwest striking dikes of andesitic affinity crosscut pre-Tertiary and granitic units throughout the thesis area. The lithology of these dikes is similar to grey, porphyritic andesites and dacites of the Olive Butte series. Such dikes probably served as sources for some flows.

TABLE 26. MODES OF OLIVE BUTTE VOLCANICS.

	0-11	0-12	0-14	0-13
Plagioclase	73.8	65.7	58.3	65.2
Quartz	7.3	3.7	15.4	8.3
Orthoclase	--	3.5	9.7	--
Biotite	tr	1.4	3.2	tr
Hornblende	15.6	12.1	11.8	12.8
Augite	--	9.7	--	8.7
Hypersthene	--	--	--	2.1
Glass	tr	tr	tr	tr
Accessories	1.0	tr	tr	--
Alteration	2.3	3.9	1.2	2.9
Sum	100.0	100.0	100.0	100.0
Phenocryst An	68-65	54-50	50-48	58-52
Microlite An	67-64	43-40	47-42	50-45 (?)

Point-source vents are volumetrically more significant sources of the Olive Butte volcanics. These vents are evident in three locations across the thesis area: 1) Vertical alignment of plagioclase and mafic phenocrysts at Olive Butte volcanics exposures in section 23 near Lost Meadow, and lack of platy jointing suggest this area is a former vent. 2) Similar evidence near Sheep Rock indicates another vent as mapped by Brown and Thayer (1968). 3) The dominating relief of Olive Butte strongly hints at a vent or plug origin. This may, indeed be the case for lower, or to date unexposed interior portion of the butte. Flow vectors from phenocryst alignment in nearby flow rocks of similar lithology point generally toward Olive Butte, but could be strongly influenced by local topography or abberations in flow. However, vertical alignment of phenocrysts was not observed in the rocks of Olive Butte. Platy jointing is common above 6000 feet, and two zones of vesicular, slightly oxidized flow rocks were noted on west exposures, at elevations 6015 (2105 m) and 6250 (2188 m). Although this does not preclude consideration of Olive Butte as a possible vent, it indicates that the butte is not exclusively a plug.

Olive Butte Tuffs

An isolated occurrence of poorly consolidated tuffs and one pink, flow-banded rhyolite outcrop in the vicinty of Buck Gulch. The rhyolite unit apparently overlies Olive Butte andesite exposed nearby, and in turn seems stratigraphically lower than the tuffaceous unit which it does not contact. The rhyolite contains plagioclase phenocrysts (An 38, intermediate andesine), and quartz in a felsitic groundmass which encloses randomly oriented plagioclase microlites (An 28-30), biotite, and rare apatite. Finely disseminated red-brown glass and dust-sized opaques are dispersed throughout the groundmass. Flow-banded appearance of this unit results from systematic variation in quantity of iron ore in the groundmass.

These units are tentatively assigned as more silicic members of the Olive Butte volcanics due to their areal and stratigraphic proximity to andesitic units, and the apparent tendencey for the Olive Butte series to include relatively silicic (dacitic to rhyolitic) fractionation products. This association, however, is not unequivocal.

Age and Association of Olive Butte Volcanics

Age of Olive Butte units is problematic. They apparently overlie Clarno-equivalent basalts in several locations, and their more silicic nature suggests that they are later magmas. However, one flow of Clarno-equivalent basaltic andesite (C-8) may overlie lower portions of the andesites and dacites on Olive Butte. The stratigraphic relation of these two units is not completely resolvable, because critical exposures of both units in contact are frustratingly absent within the thesis area and environs.

The Olive Butte volcanics are considered to be roughly equivalent to the John Day formation of eastern and central Oregon due to their silicic composition and hence Early to Middle Oligocene in age.

This tentative correlation with the John Day Formation also allows simultaneous eruption of Olive Butte and Clarno-equivalent flows, as overlap in ages for John Day and Clarno volcanism has been noted by several workers (Swanson and Robinson, 1968; Wheeler, 1977).

However, additional field work and radiometric dating would be desirable to determine the age of the Olive Butte volcanics. Trace element geochemistry, particularly for Ba, Zr, and Ni could help resolve their petrogenetic relations to Clarno-equivalent basalts.

Columbia River Group

Basalts of the Miocene Columbia River group occur only in the western-most parts of the thesis area near Squaw Rock and Indian Rock where they directly overlie Jurassic intrusives.

Two distinctly different flows can be identified: The lower flow is dark grey to black on a fresh surface, and commonly displays hackly jointing where freshly struck. It contains large (one to four mm) phenocrysts of fresh olivine which are an unmistakable clear, yellow green on a fresh surface. Smaller randomly oriented phenocrysts of clinopyroxene and plagioclase, 0.3 to one mm in length are visible in

Figure 41. Flows of Columbia River Basalt at Squaw Rock and Indian Rock in the background overlie granitic terrane. Boulder Butte visible as steep white cliffs, far right.

reflected light on fresh surfaces. Near the top of the flow around Squaw Rock, large vesicles, to five mm in diameter, are partly filled with zeolites, amorphous silica, and calcite. The lower flow extends from Boulder Butte to Indian Rock as a subdued, undulating erosion surface.

Overlying this olivine-rich basalt is a dark grey to black, uniformly textured flow which contains small phenocrysts of olivine, clinopyroxene, and plagioclase, and which is far less vesicular in its upper parts. This flow, or one similar to it, caps several topographic highs in the area, including Jump-off Joe peak to the northwest of Indian Rock where it directly overlies granitic rocks. Flow vectors indicate southwest to northwest movement. The total thickness of the flows is about 260 feet.

Columbia River Group: Petrography

Basalts of the lower flow are pilotaxitic and contain intergranular pigeonite. Phenocrysts of olivine are optically negative, with a 2V of 85°-90° and about Fo_{80}. Plagioclase phenocrysts are often square, and have oscillatory zones, An_{75-60}. Microlites of plagioclase have carlsbad twins, and are in the range calcic andesine to laboradorite. Iron ore is large and irregular. Light green to brown glass alters to yellow-green smectites and chlorophaeite. Olivine occasionally shows brown rims of fractures filled with smectites, but generally is quite fresh.

The upper flow is intergranular, with small grains of pigeonite clustered between plagioclase microlites. Plagioclase phenocrysts occur as laths 0.5 to one mm in length, and are zoned An_{65-52}. Microlites are An_{40} and show distinctive albite twinning. Phenocrysts are sporadically clustered in glomeroporpyritic groups. Olivine phenocrysts are similar to those of the lower flow in composition, but are smaller (±1.0 mm) and less numerous. Clinopyroxene phenocrysts are slightly larger, -2 mm maximum diameter. Light brown glass alters to yellow-green chlorophaeite, and some olivine is sometimes rimmed by brown smectite alteration. Dusty clots of fine opaques, and small clusters of fine apatite occur as inclusions in plagioclase phenocrysts.

Textures and modal composition of the two basalt flows at Indian Rock are similar to those described by many workers for Picture Gorge Basalt (esp. Wright, Grolier and Swanson, 1975; Waters, 1961). The calcic and zoned nature of the plagioclase, the high percentage and large size of the olivine, and the nearly holocrystalline nature of the rocks, as well as the prevalence of phenocrysts are all consistent with Picture Gorge flows. Fairly low Al_2O_3 and SiO_2 of 49-50 percent is also characteristic of the Picture Gorge (Waters, 1961). Chemical data indicate that the Indian Rock basalts are probably representative of upper sequences of Picture Gorge

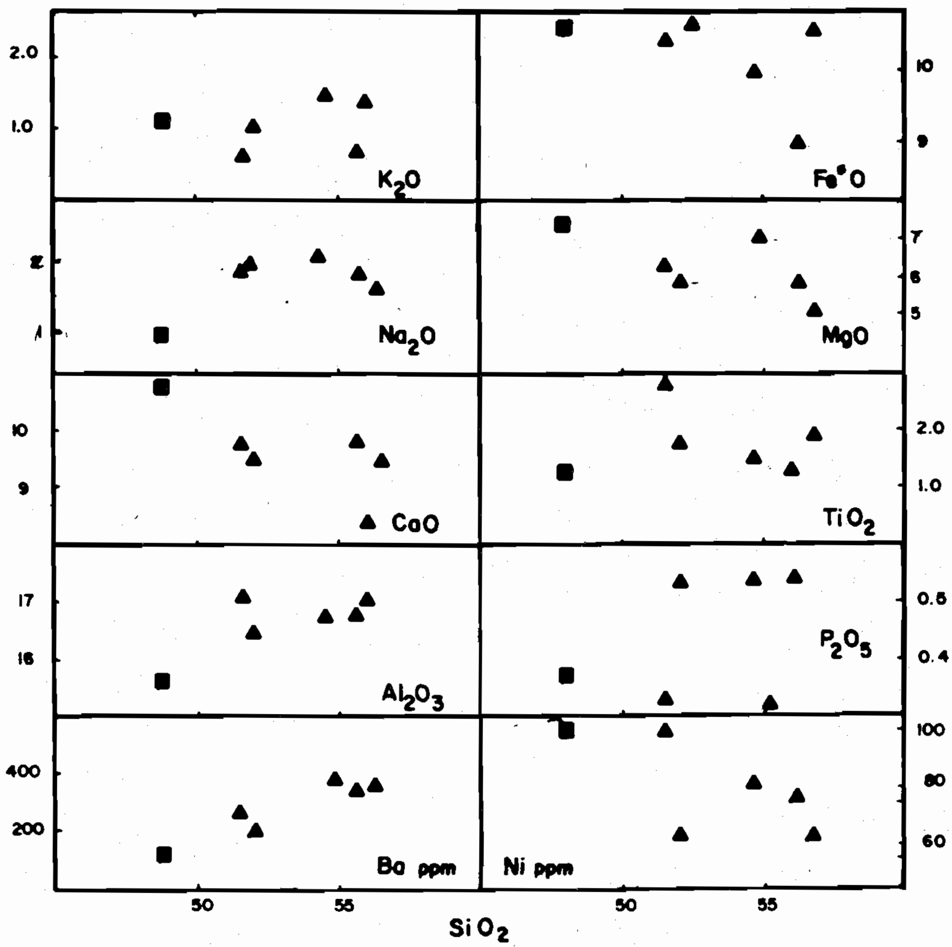


Figure 42

Major and Trace Element Variation

in

Tertiary Basalts

■ Tpg (Columbia River group)

▲ Tc (Clarno equivalent)

Basalt. Data from Waters (1961) and MacDougal (1976) indicate a differentiation through the Picture Gorge series from total iron content of 11.3 percent in the basal flows, to 13.3 percent at the top of the Picture Gorge section, and concomitant variation from 6.3 percent to 4.6 percent MgO. Total iron of the lower flow at Indian Rock is 10.7 percent, which suggests its association with the lower part of the Picture Gorge. The higher Fe*O content of C-212 indicates it is higher in the sequence.

Trace element data also suggest that the flows are representative of different portions of the Picture Gorge section. According to data from MacDougal (1976), Ba increases from 300 to 600 ppm from bottom to top in the Picture Gorge flows. Ba reported from C-208 (bottom rock) is in the range of 120 ppm, lower than reported by MacDougal, but not out of character for a basalt. Ba from the overlying flow is nearly double, 212 ppm, though somewhat below that expected for Picture Gorge Basalt. Poor precision in analysis may be responsible for these results.

Nickel is predictably higher in C-208 than C-212 as expected from the substantially higher olivine content of the lower flow. The broad range in Ni between the two flows again suggests a wide "stratigraphic" separation between them, with the upper Indian Rock flow a much later Picture Gorge basalt than the lower flow.

Variation in strontium is in accord with the range anticipated in

Picture Gorge Basalt and shows, again, that there is a wide stratigraphic separation between C-208 and C-212. Data for Zr is not as clear-cut, primarily because there is no definitive trend in Zr for Picture Gorge or Yakima Basalt.

In summary, petrographic and chemical data from the basalts at Indian Rock indicate that the rocks represent two flows of Picture Gorge Basalt widely separate in Picture Gorge stratigraphy. The basalts are fairly aluminous tholeiites, and are distinct from and not related to the alkalai-olivine basalts common to the east thesis area.

QUATERNARY AND PLEISTOCENE GEOLOGY

Effects of Pleistocene alpine glaciation in the Greenhorns are dramatic and pronounced in the higher, western portions of the thesis area.

Stark granitic cliffs plummet hundreds of feet to secluded alpine meadows which mark the emerald castings of old tarns; mile-wide u-shaped valleys are unmistakable footprints of their powerful sculptors.

Alpine glaciers appear to have been restricted in final altitude to elevations above 7000 feet (2450 m) as the approximate bottom level for their cirques. Altitudes at which they started must have been considerably higher, probably exceeding the present 8200 foot (2870 m) maximum elevation at Vinegar Hill.

Glacial cirques form steep-sided headwalls of north, west, and east facing valleys which head along the northwest trending ridgecrest from the "greenhorn" east of Vinegar Hill to Indian Rock and Saddle Camp. The average relief from top to bottom of the steep headwalls is about 500 feet (175 m); the glacial valleys are generally 800 to 1000 feet (280 to 350 m) in depth from ridge-crest to floor. Stream valleys most notably of Clear Creek, Lightning Creek, and the South Fork of Desolation Creek extend in a classical, flat-floored U-shape for up to five miles (8.2 km) from their source. One small hanging valley is developed on the west side of the east fork of Clear Creek.

Most Greenhorn cirques contain a nearly central tarn, or basin depression which has been filled by alluvium, and is now an alpine bog or meadow. The common development of these depressions is good evidence that cirques did not develop by processes of nivation alone, but that active removal of detritus was effected by glacial ice (Flint, 1971). Remnant tarns and riegels are common to all glaciated valleys in the Greenhorns. Particularly good examples of filled tarns are found in the upper reaches of Granite Boulder Creek and Lost Creek.

Glacial polish, glacial striations, and glacially sculptured small scale features are common in the high country. Polish is particularly well retained on exposed surfaces of greenstone, and on some protected peridotite. Striations, as expected, point generally down the valleys, and where preserved may be accompanied by chatter marks and crescentic gouges. Whale-back forms are best developed in north-facing exposures of the Ben Harrison peridotite body. True roche moutonnée (stoss and lee forms) are carved into the amphibolites, gabbros, and greenstones in the basin of Lake Creek and in Upper Olive Lake.

Morainal material veneers the walls of glacially carved valleys to nearly 300 feet (90 m) above valley floors along the South Fork of Desolation Creek and along Clear Creek. Lateral moraine was apparently extensive. Two small, recessional moraines were mapped. The most readily accessible, and also most easily discernible is at elevation of 6400 feet (1920 m)along Salmon Creek, approximately 1.8 miles (2.9 km) from the source cirque. The other is at an elevation of 5800 feet (1770 m) along Clear Creek.

Periglacial features are not well developed in the Greenhorns. Extensive talus slopes may be readily attributed to the ordinarily harsh winter climate and frequency of freeze-thaw cycles in spring and fall, as well as to more strident conditions during the Pleistocene.

Distinctive "china caps" or small conical peaks on the summits of Ben Harrison peak, Sunrise Butte, and at lower elevations near Greenhorn may be largely products of Pleistocene mass wasting. At these locations, heavy lichen cover is developed on talus fragments. Such cover, with the absence of any fresh rock, has been noted previously (Pewe, 1969) as characteristic of deposits formed by rapid Pleistocene weathering. In all instances examined, however, no indication of blockstream movement or frost-effected orientation of talus detritus was detected.

Mazama Ash

Deposits of bone-white volcanic ash, up to six feet (1.8 m) in thickness occur sporadically along streams throughout the Greenhorns. They reach a maximum thickness along Olive Creek near the Yount Brothers' Eureka mine in Three Cent Gulch. This fine, abrasive ash was the bane of placer miners on Olive and Clear Creeks, as it often got into their eyes and nose, abraded their skin, and even invaded their food.

The ash depostis are apparently non-stratified, semi-consolidated, and discontinuous. They represent accumulations of air-fall volcanic debris washed into stream valleys and perhaps ponded by cross-stream barriers or "dams" (fallen trees, etc.).

In thin section, samples of the ash include angular fragments of plagioclase which shows oscillatory zoning, quartz with random, globular iron ore and glass inclusions, and clear brown cuspate glass shards (n balsam). Euhedral constituents include hornblende altering to chlorite and epidote, clinopyroxene altering to chlorite, fresh clinopyroxene, and hypersthene. Plagioclase (An_{36-22}) is frequently unzoned, but always twinned, and contains glass or quartz inclusions aligned along twin planes. Both albite and carlsbad twinning occur.

X-ray diffraction patterns from the ash indicate an appreciable content of orthoclase, as well as the quartz and plagioclase already noted.

The ash exposed in placer and hydraulic cuts in Three-cent Gulch overlies boulders and outwash deposits which are interpreted to be Pleistocene in age. The white color, general texture, and stratigraphic position are similar to ash-fall deposits from the eruption of Mount Mazama, at 6, 600 years which are widespread across northeast Oregon (Williams, 1942). Accurate determination of the refractive indices of glass shards included in the ash might enable definitive correlation of the Greenhorn ash with the 6, 600 year eruption of Mazama, and allow determination of the ash's position in the Mazama eruptive sequence (Noble et al., 1969), but was not attempted in this thesis.

Quaternary Alluvium

Post-glacial stream deposits consist largely of re-worked glacial debris. Thickest accumulations of coarse, rounded boulders and cobbles are found along Olive and Clear Creeks where they have been piled into somewhat sterile unsightly tailings by gold dredges during the early 1900's. The drainage of Beaver Creek intersects no (known) gold-bearing granitic bodies, and has remained in a more natural state with broad, boggy open meadows up to 1/2 mile wide. Sediment exposed in stream banks is fine, silty clay with a large component of organic matter. Cross-bedded sandy gravels are intercalated with the silts and clays in two to seven inch (five to 18 cm) beds. Coarse boulder-to cobble size gravels were not observed in the Beaver Creek area, but may be buried beneath a cover of finer alluvium.

In the portions of the thesis area directly effected by alpine glaciers, fine sediments of probable post-glacial origin have filled basins (tarns) left by glaciation, and occupy the broad depressions which served as late source areas for glacial ice. These sediment traps now form boggy alpine meadows which are, surficially, silts, clays and organic detritus, but which no doubt contain coarse gravels and cobbles with increasing depth.

Quaternary Landslides

Small landslides of a rotational slump type occur along streambanks of the North Fork of the Burnt River, and resulted from oversteepening of Clarno-equivalent mudflows during high runoff probably at the close of the Pleistocene. There is no evidence to indicate that they are presently active. Active slumping is evident, however, east of Upper Olive lake where oversteepened gravels overlie Olive Butte tuffs and volcanics.

SUMMARY: STRUCTURAL GEOLOGY

Evidence for at least two major deformations occurs in the pre-Tertiary sediments. The pervasive regional northeast trending cleavage of the argillites and pre-Jurassic units parallels probable near vertical axial planes of isoclinal folds. Local deviation from this northeast regional trend, noted in Vinegar Hill conglomerates and volcanics and Badger Creek Beds from western portions of the thesis area are due to forceful tectonic emplacement of serpentinite and tectonite metagabbro. The deviations--which strike west-northwest instead of east-northeast--parallel the contacts with the mafic-ultramafic intrusives, and gradually revert to east-northeast trends with distance from the intrusions.

Small but fairly regular F_2 folds are over-printed in the more schistose and highly deformed metasediments. The F_2 folds' axial planes strike northwest where noted across the thesis area, and exhibit uniform orientation throughout formations of widely different lithology and apparent metamorphic grade. F_2 fold axes of Bennett Creek Schist, Vinegar Hill Beds, pumpellyite greenstone, and siliceous Vinegar Hill Beds sediments of Rosey Finch Ridge (plot between N46W and N65W, and dip uniformly northeast. These units form a sub-linear northwest trending series of exposures in the serpentinite melange. Development of parallel F_2 folds may be related to northeast-southwest compression during emplacement of the serpentinite in probable mid to late Triassic.

Structure of gabbros and peridotites has been discussed separately in conjunction with each rock type. Gabbros exhibit at least four separate defomations, and probably five. The initial deformation (F_1 and F_2) were developed prior to emplacement, and involve elongation of mineral grains (F_1) and small-scale folding of cumulates (F_2). Mylonites developed during F_3 crosscut these structures, and are related to Late Triassic east-west compression and emplacement. Shear zones and faults which trend north-south and east-west, and are marked by serpentinite in the west part of the thesis area are the last pre-Cretaceous (Pre-Tertiary?) deformations recognized in the Greenhorns and slightly post-date the emplacement of the metagabbros. This F_4 deformation appears to involve primarily vertical emplacement of serpentinites and only moderate lateral movement of country rock. It is probably Late Triassic to Early Jurassic.

Serpentinized peridotites are in general too highly altered and dissected to provide a cogent structural history. Two episodes of deformation are apparent, however: elongation of olivines during upper mantle flow, and east-west compression associated with emplacement.

Small-scale north-south and east-west near vertical shear

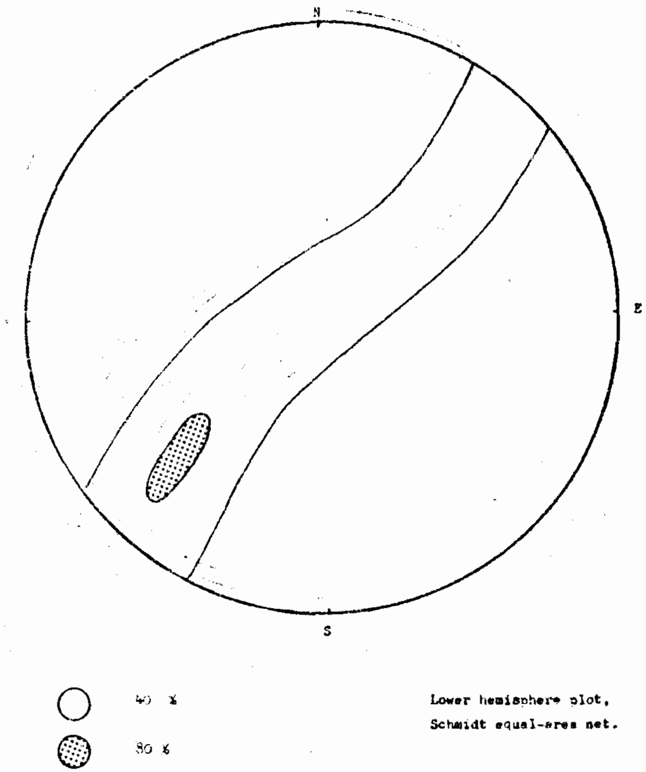


Figure 43. F_2 folds in cumulate metagabbro. Poles to planes of igneous layers.

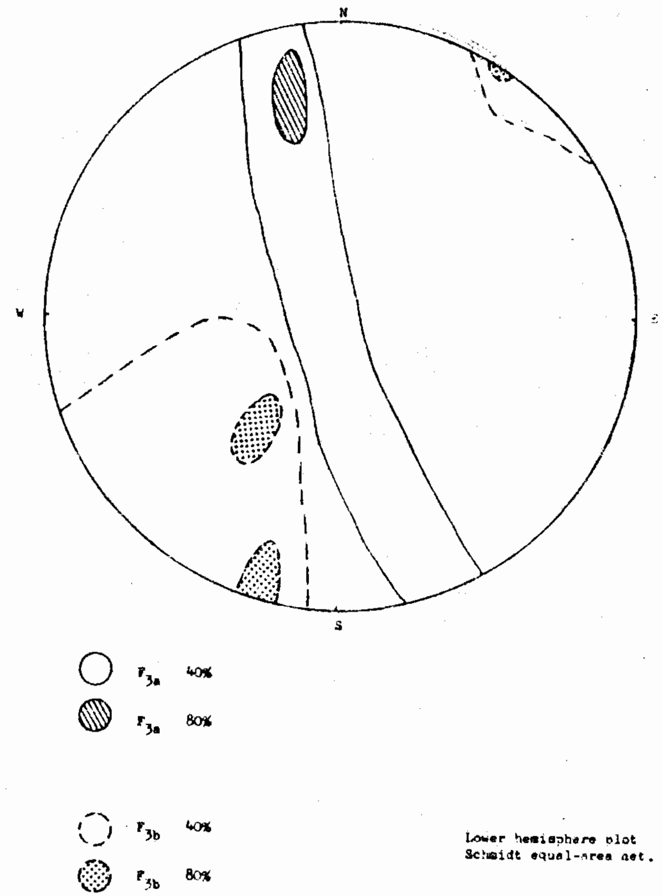


Figure 44. F_3 mylonites in metagabbro. Poles to mylonite shear planes.

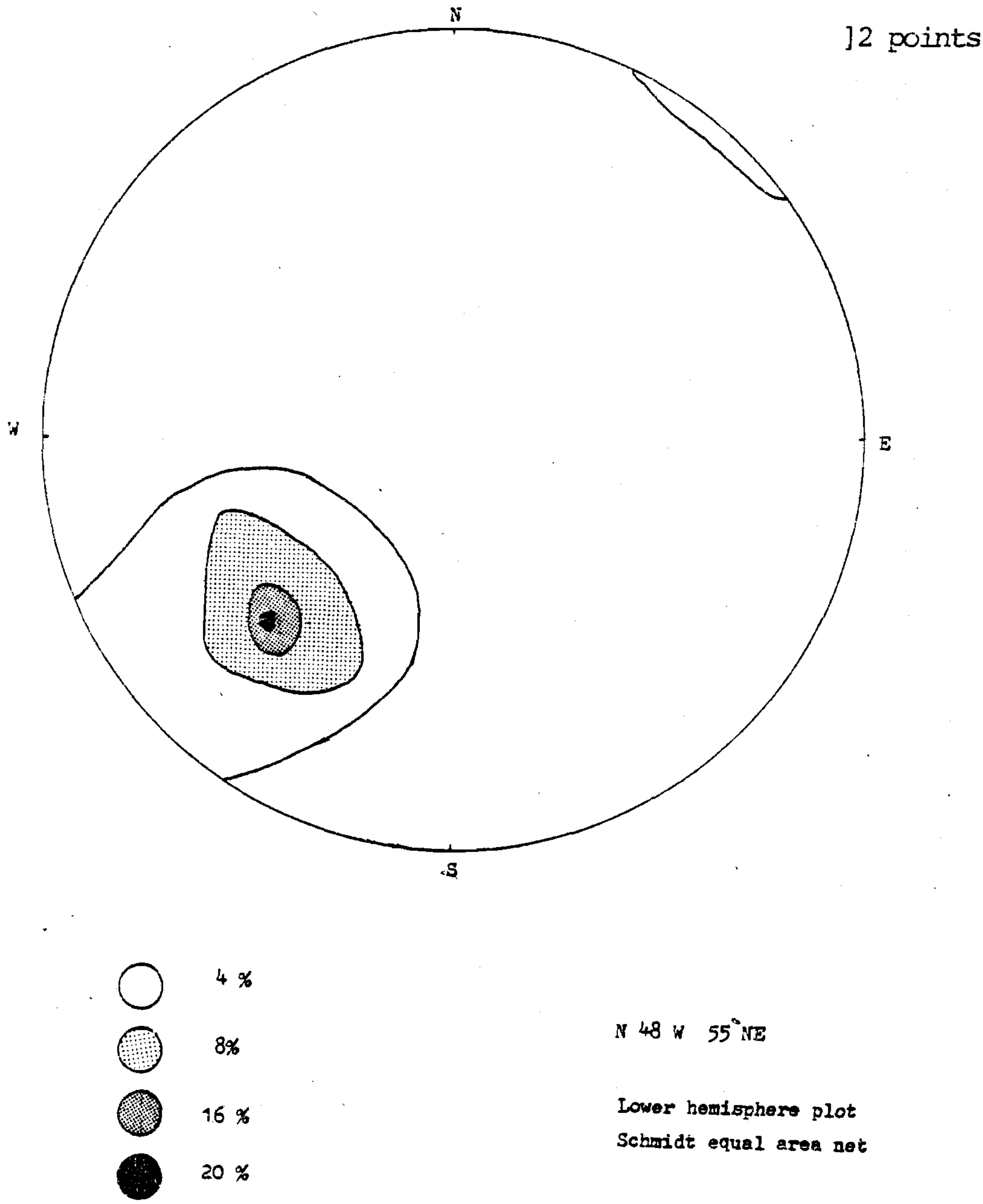


Figure 45. Poles to axial planes, F_2 folds. Rosey Finch Ridge, Vinegar Hill Beds.

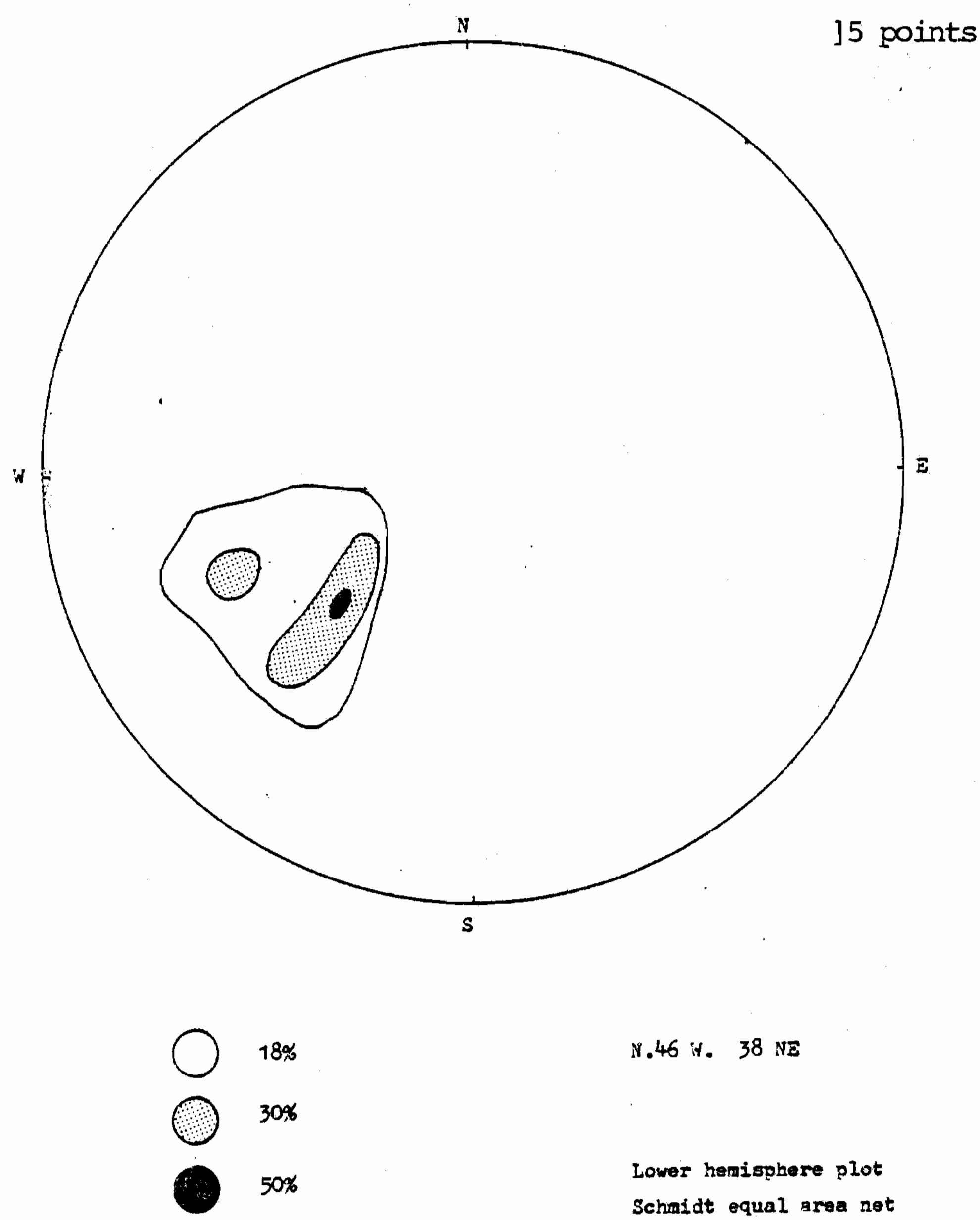


Figure 46. Poles to axial planes, F_2 folds. Bennett Creek Schist.

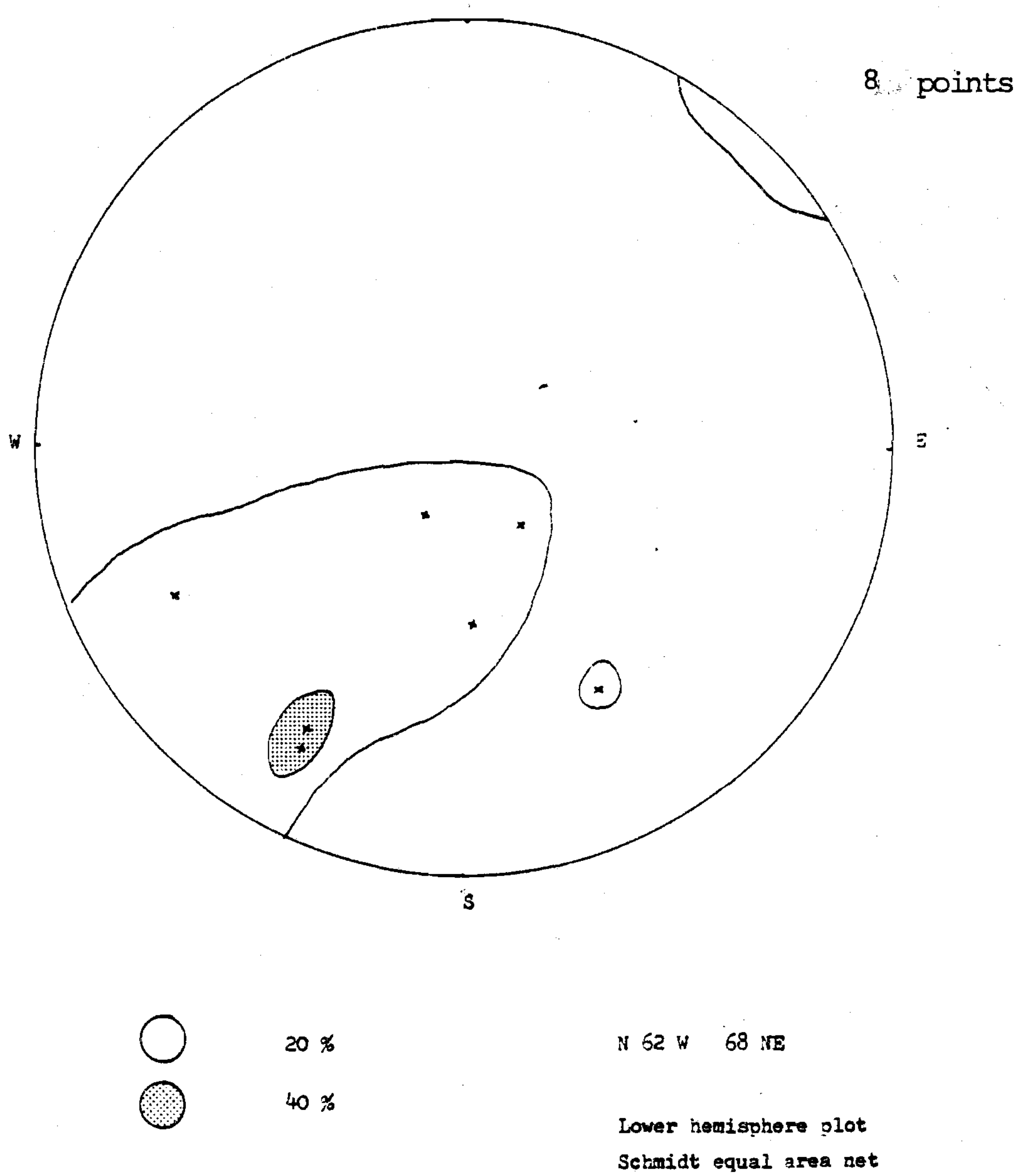


Figure 47. Poles to axial planes, F_2 folds. Burnt River pumpellyite greenstone, Vinegar Hill Beds.

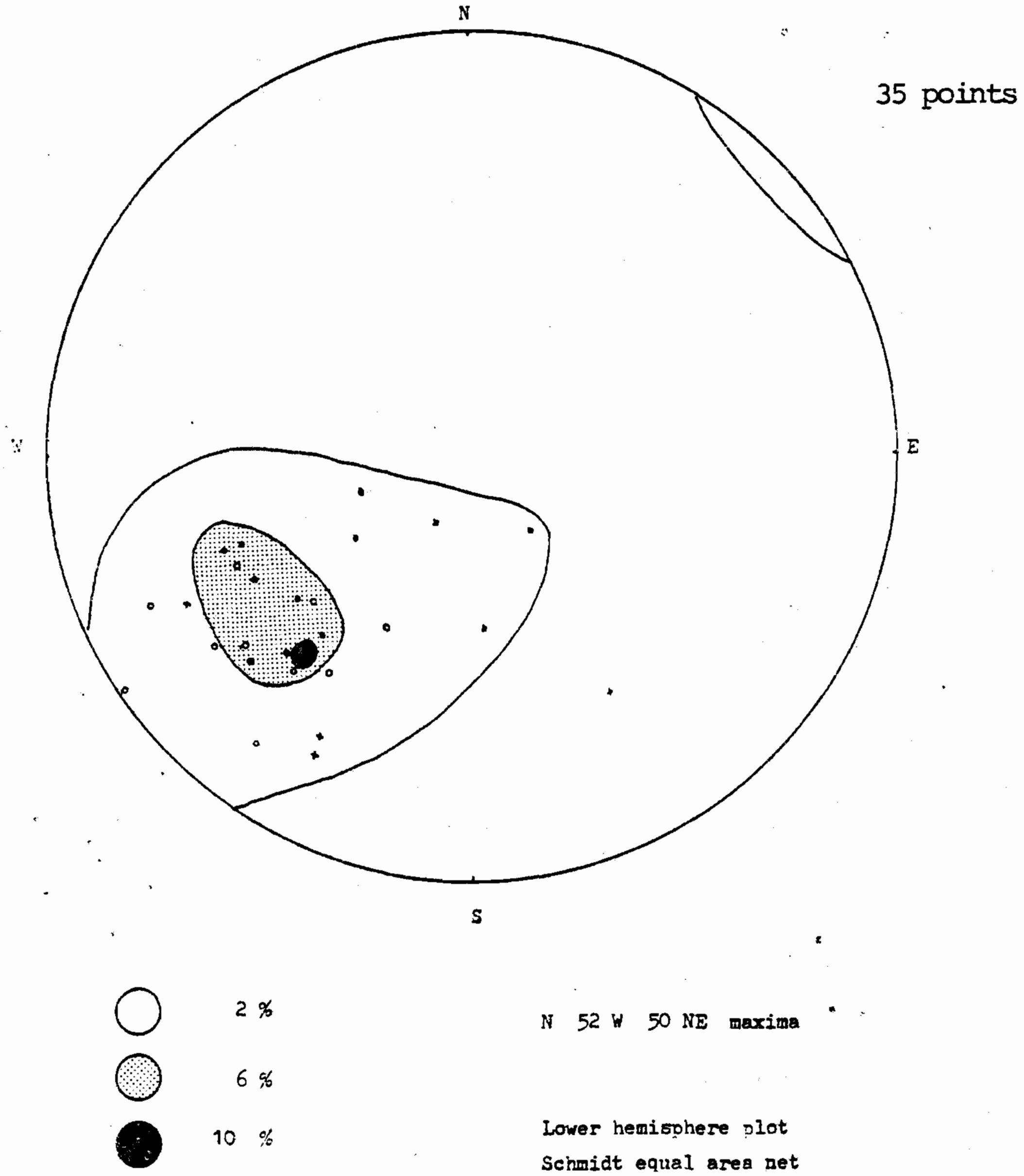


Figure 48. Poles to axial planes, F_2 folds. Combined Rosey Finch Ridge, Bennett Creek, and Burnt River pumpellyite greenstone.

zones such as those along Snow Creek and McWillis gulch are post-Jurassic in age. A small granitic intrusion associated with the Quebec Hill intrusion is thoroughly cataclastized by this generation of shears. Pervasive development of sericite, epidote, and chlorite within the sheared granitic rock indicates that shearing was post-consolidation, but allowed extensive hydrothermal alteration of the rock. Dates of similar granitic intrusions in the nearby Bald Mountain batholith are 147-155 m.y., and time of shearing is approximately equivalent or later.

Broad northwest trending folds are a late Tertiary development. The Vinegar Hill anticline trends approximately through the center of the thesis area, but limited exposure of Tertiary rocks from which an attitude can be determined does not allow the precise location of the anticlinal axis.

GEOLOGY OF THE GREENHORN MOUNTAINS, NORTHEASTERN OREGON

Summary: Results of Investigations

1. Fauna collected from limestone lenses in flysch-like metasediments of the Bates, Oregon quadrangle, previously mapped as Jr-Tr (Brown and Thayer, 1966; Walker, 1977) included corals, brachiopods, bryozoans, crinoids, fusulines, and conodonts. Fusulines have been identified by Dr. D. Bostwick (O.S.U.) as a North American fauna of lower Permian (probably Wolfcampian) age. Conodonts have been dated by Dr. Bruce Wardlaw (U.S.G.S.) as Leonardian. The allochthonous biohermal limestones are probably contemporaneous with the enclosing sequence of arc-derived conglomerates and proximal turbidites, and it is strongly suggested that the entire sequence of these sediments (Pb on plate 1) is lower to middle Permian in age.
2. Microprobe studies of relict clinopyroxene is partly spillitized greenstone pillow lavas intercalated with cherts of the Elkhorn Ridge Argillite (Pev, plate 1) indicate that they are titan augites characteristic of alkalic lavas from seamounts or fracture zones. They are not related to pyroxenes from typical oceanic spreading centers. Relict pyroxenes from remnant basaltic

pods in peridotites (not mapped as a unit) plot on a distinctly different and more tholeiitic trend, and also display $MnO/Na_2O/TiO_2$ compositions characteristic of volcanic arc pyroxenes. Dikes intruded into the peridotites prior to obduction may represent early arc volcanism.

3. Microprobe studies of amphiboles in rocks previously reported to contain glaucophane (Perkins, 1976) reveal that the amphiboles are compositionally zoned with cores of sodic amphibole (magnesioarfedsonite) and rims of barroisitic hornblende. Garnets display a similar zonation from high pressure, low temperature metamorphism to higher temperature compositions with time. Plots of amphibole NaM_4/Al (after Brown, 1977) suggest an initial pressure of 6.5 to 7 kb, decreasing to four to five kb with time. Temperature of metamorphism (final) indicated by conodont fragments from nearby limestones was 400° + (Wardlaw, pers. comm., 1978). This unit (Pmrs) is equivalent to the Mine Ridge Schist (Lowry, 1968). Probe work by this writer on amphiboles from MRS near Hereford, Oregon suggests similar P and slightly higher T conditions at that locality.

4. Metamorphic spinifex texture similar to that reported by Hietanen (1977) is developed in two localities in the Greenhorns. In one location, a porphrytic metagabbro dike appears

responsible for development of this unique texture in the peridotite. Although major and trace element analyses are similar to those reported by Snoke and Calk (1978) for metagabbro and ultramafic rocks in the Klamaths, field and petrographic evidence suggest migration of water from the heated peridotite into an initially anhydrous dike as a mechanism for generation of this texture. Existence of a water-poor basaltic dike again suggests early-arc tholeiitic volcanism associated with the peridotite.

5. Structural studies of metagabbro and peridotite confirm that the mafic-ultramafic sequence of the Greenhorns is analogous to the Canyon Mountain Complex. Directions and styles of deformation are equivalent generally to those reported by Ave Lallemant (1976). F_1 folding and foliation developed in spinels indicate east-west compression during emplacement of the peridotites. Broad F_2 folds are displayed in cumulate gabbros; F_3 deformations are best seen in mylonitic amphibolites with left and right lateral offsets. F_4 and F_5 are not well represented in the Greenhorns and are post-Jurassic.

SUMMARY OF GEOLOGIC HISTORY: GREENHORN MOUNTAINS, NORTHEASTERN OREGON

The geologic record in the thesis area commences in Early Permian with a reef-flanked volcanic arc which shed coarse sediment both into a marginal basin to the east and into a fore arc basin to the west. Pre-Tertiary sediments probably represent a fore arc wedge although a back arc basin depositional environment cannot be conclusively eliminated. Volcanic activity of the arc ceased by Late Permian as the site of volcanism shifted eastward. Tectonic intrusion of metagabbro may have commenced as early as Middle Triassic, and was followed by slight uplift and localized erosion by Late Triassic time. Northwest-southeast compression and intensive isoclinal folding of the sediments and some intruded gabbro occurred in Late Triassic time with closure of the marginal basin due to collision with westward-moving North America. Tectonic emplacement of alpine peridotites occurred in the final stages of basin closure and was closely followed by intensive (vertical?) shearing and intrusion of diapiric serpentinite.

Calc-alkaline intrusives related to the Bald Mountain batholith were emplaced in at least five, and probably seven discrete pulses during the Late Jurassic. Subsequent uplift and rapid erosion resulted in exposure of granitic rocks by Mid to Late Cretaceous time when fluvial and lacustrine gravels bearing *Tempeskya* were deposited.

The Tertiary volcanic sequence began with wide-spread extrusion of two-pyroxene andesite followed by the deposition of lahars and mudflows. The abundance of the lahar units suggests that the initial phase of andesitic volcanism culminated in extrusion of tuffs from volcanic edifaces of considerable relief.

Localized outpourings of alkalic basalts from north-east striking dikes occurred in Late Eocene to Early Oligocene time. The subsequent, calc-alkaline Olive Butte volcanics were extruded in Oligocene time, and were increasingly siliceous.

The trend of calc-alkaline volcanism was interrupted in Miocene by the tholeiitic Columbia River basalts. Two flows of the more primative Picture Gorge group are represented in the westernmost part of the thesis area.

Gradual uplift and gentle folding in the Blue Mountains occurred throughout the Tertiary as a result of northeast-southwest compression. Columbia River Basalts near Indian Rock dip gently southwest at about ten degrees. The Vinegar Hill anticline (Brown and Thayer, 1966) trends diagonally across the thesis area, and is a result of this deformation. Slight oroclinal bending of the anticline in the thesis area may be a result of slight east-west compression.

Pleistocene alpine glaciation significantly effected the local topography, cutting deep U-shaped valleys and steep cliffs in the western portions of the thesis area. Deposition of ash from the eruption of Mount Mazama, 6,600 years ago is evident from localized stream-bank deposits.

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APPENDICES

APPENDIX 1

Metamorphic Spinifex Texture

Randomly oriented blades of serpentinized and recrystallized olivine 0.5 to two cm in length are found in two widely separated outcrops of serpentinized peridotite. Similar textures have been recognized and discussed by Hietanen (1977) and Snoke and Calk (1978). For simpler nomenclature, the name "metamorphic spinifex texture" of Hietanen (1977) is used in this report.

The serpentinized peridotite in outcrop is a smooth dull red brown suggestive of original dunite. Slightly darker red-brown blades of serpentinized olivine frequently crosscut one another. The olivine is more intensely developed along broad, gently curved and widely spaced five to seven cm wide bands, and is sometimes clustered in irregular splotches.

Metamorphic spinifex texture in section 12, T. 10 S., R. 34 E., about one mile northwest of the Vinegar Hill summit, is adjacent to sheared serpentinite, and is tectonically contacted within 300 feet (90 m) by tectonite metagabbro. The metamorphic spinifex texture at this location occurs in an area approximately 180 feet (55 m) in length and ten to 20 feet in width (three to six meters) parallel to the trend of the sheared serpentinite.

The second site of metamorphic spinifex texture is along an unexposed contact of the ultramafic body and a distinctive, coarsely porphyritic amphibolitized metagabbro dike, section 28, T. 9 S., R. 34 E. Spinifex textures here extend for a distance of 45 feet (14 m) in length and about 15 to 25 feet (four to eight m) in width. Jurassic intrusives do not contact the peridotite at either location, although granitic rocks were mapped nearby.

Petrography

The rock is composed of criss-crossing blades of serpentinized length-fast optically positive olivine. The olivine occurs as clear granules, three to ten mm in diameter, in the serpentinized matrix of what was once an elongate acicular crystal. X-ray diffraction patterns indicate that the serpentinite consists of crysotile, lizardite and antigorite. Elongate, occasionally acicular optically positive anthophyllite is commonly associated with the altered olivine blades. It crosscuts the serpentinite matrix, and is in many locations partly altered to serpentinite. Tremolite, optically negative with angles of ten to 12^{o}, occurs as singular crystals similar in habit and appearance to anthophyllite, and as radiating fasicular sheaves. The tremolite increases in abundance with distance from the amphibolite (section 28) and the sheared serpentinite (section 12) contacts. Tremolite is not as intimately associated with the serpentinized olivine blades as is the anthophyllite, and commonly occurs in

Figure 49 a

(M-222) Metamorphic spinifex texture. White blades are serpentinized olivine, dotted interstitial area represent talc aggregates, and lines represent radiating talc. X25.

Figure 49b

(M-222) Detail of olivine blade. Clear areas represent recrystallized olivine in serpentinite matrix. Blades of anthophyllite at bottom and upper left. Clear area to the right is talc aggregate. X40.

Figure 50 a.

(P-1) Cumulate clinopyroxene in P-1. Rimmed by blue-green hornblende. Epidote and acicular actinolite included in interstitial plagioclase. X 10.

Figure 50 b.

(P-1) Clinopyroxene centers in blue-green hornblende. Bent lath and basal prisms of apatite, with epidote and acicular actinolite in interstitial plagioclase. X 40.

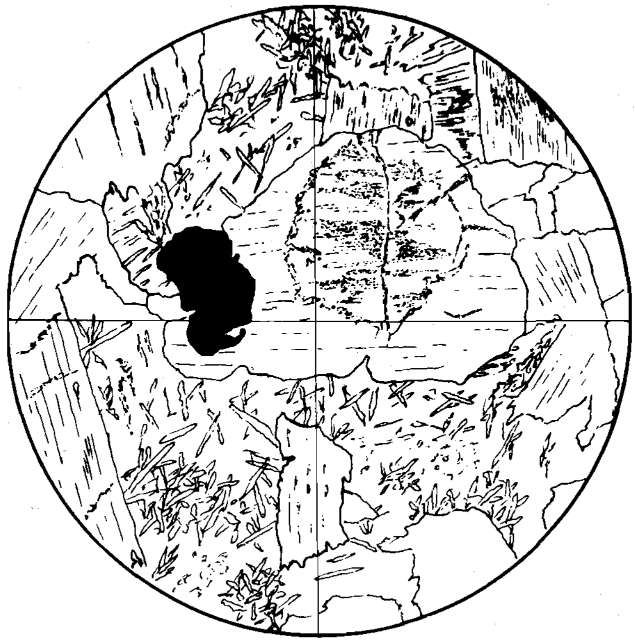

Figure 50a.

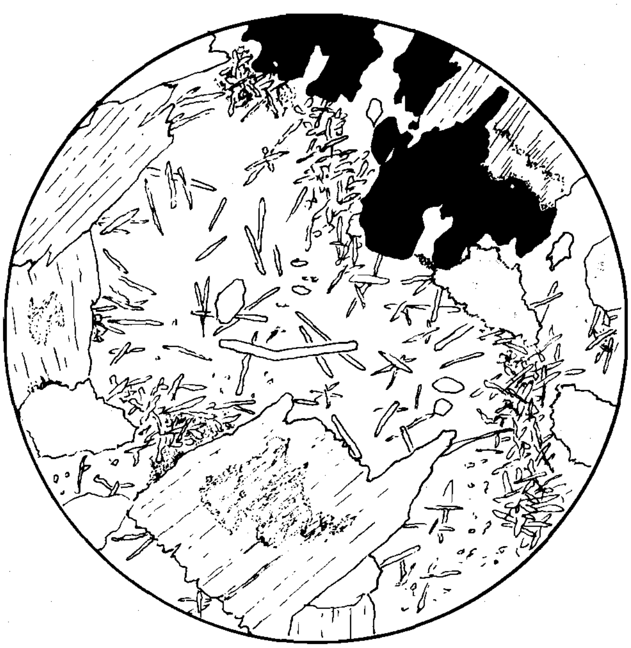

Figure 50b.

interblade areas. Opaque iron oxides are disseminated through the serpentinite and occasionally cluster around olivine granules.

Areas interstitial to serpentinized olivine blades are polygonal and almost entirely filled by talc which is developed in two distinctive habits: 1) radiating sheaves which frequently emanate from apexes of olivine blade intersections or, more rarely from the sides of olivine blades, and 2) granular aggregates. Colorless chlorite occurs infrequently as a mat of low birefringence in areas of aggregate talc. Iron oxides are in interstitial areas as disseminated, dust-like particles where metamorphic spinifex texture is well developed.

With distance from the amphibolized dike, the bladed texture of the serpentinized recrystallized olivine becomes less distinct, until at approximately 35-40 feet olivine is recrystallized in formless blobs of serpentinite. The matrix of this rock is still composed of talc, but an increasing percentage of tremolite occurs. Discontinuous stringers and veins of serpentinite with recrystallized olivine cross-cut the rock. An appreciable component of sulfide, as iron pyrite, is in the less-bladed sample (M-224) where it is commonly restricted to inter-blade areas.

The petrography of the porphyritic amphibolite metagabbro is relevant to possible origins of the metamorphic spinifex texture. The dike contains uralitic blue-green hornblende which surrounds large tabular phenocrysts of plagioclase, two to 12 mm in length. The plagioclase is frequently offset along transverse fractures. Alteration to chlorite, epidote, calcite, and matted sericite occurs along fractures and relict zones. Plagioclase is rarely twinned, unzoned, and altered to albite, An_{1-2}, in all crystals analyzed by electron microprobe. Relict pyroxene was observed in seven thin sections of this dike (M-221). However, skeletal, hydrous ilmeno-magnetite appears to pseudomorph clinopyroxene, and some centers of uralitic hornblende are slightly bleached, suggesting former pyroxene. Apatite occurs as elongate prisms within plagioclase phenocrysts and as randomly oriented crystals scattered throughout the amphibole groundmass. Sphene is common, forming granular clusters which are altered to leucoxene.

Mineral Analyses

Olivine, serpentine, talc, and anthophyllite were analyzed in M-222 (metamorphic spinifex texture) to determine compositions and facilitate interpretation of the rock's origin. Olivine ranged from $Fo_{86.9}$ to $Fo_{90.4}$ and averaged $Fo_{89.3}$ for the four grains analyzed. Although the number of grains analyzed is small, and a conclusion cannot be made from the limited data, no zoning was apparent in the olivine. The magnesian nature of the olivine is consistent with origin by serpentine recrystallization.

Anthophyllite is high in magnesium (32.85 percent), as would be expected from the negative optic sign. Serpentine which replaces anthophyllite contains up to seven percent Fe*O.

Microprobe analyses of plagioclase and iron-titanium oxides in the porphyritic amphibolite (M221) were made to determine compositions. Plagioclase phenocrysts were analyzed across a traverse to determine any optically obscure relict zoning present. Results of scans of two crystals which both showed slightly zoned extinction indicate that very subtle zonation of albite, $An_{3.2}$ rims to $An_{2.0}$ core is present. However, albitization of plagioclase is pervasive.

Analysis of skeletal ilmeno-magnetite revealed surprisingly high H_2O (28.3 percent and SiO_2 15 percent). The composition of this phase is puzzling, and may represent an intergrowth of sphene and ilmeno-magnetite, although such an intergrowth was not noted optically.

<u>Major and Trace Element Chemistry</u>

The limited number of samples which could be analyzed for major oxides restricted analysis of samples related to metamorphic spinifex texture. Determination was made of TiO_2, P_2O_5, S, and Ni. One serpentinized peridotite from the Ben Harrison Peak body which contains no spinifex texture was analyzed for the same elements for comparison. This sample (M-91) is from a location <u>not</u> adjacent to any observed amphibolite, and was approximately 1800 feet (545 m) from the nearby granitic intrusion, an equivalent distance from M-222 and M-224 to the adjoining pluton. The same granitic body on Ben Harrison Peak intruded both M-222/M-224 and M-91, although M-222/ M-224 are on the east boundary of the intrusion and M-91 is west of the intrusion.

Results are in Tables 26-30. Abundances of Ni, TiO_2, and P_2O_5 in the spinifex peridotites are within the normal range for serpentinized alpine peridotite (Coleman, 1977). However, sulfur is greatly enriched in the spinifex rocks, 403 ppm in M-222 and 610 ppm in M-224. M-91, from a similar location, is also enriched in sulfur (272 ppm) with respect to usual alpine ultramafic abundances. The porphyritic dike (160 ppm) is also slightly enriched in sulfur with respect to normal oceanic basalts, and slightly enriched with respect to P-1, an amphibolite pod in the Ben Harrison ultramafic body. M-221 is highly titaniferous, which suggests that it may not be representative of oceanic basalt (Kay, 1978) or may have been contaminated by more sialic material.

Origin of Metamorphic Spinifex Texture

Petrographic relations indicate that spinifex texture developed after serpentinization of peridotite, probably as a consequence of thermal metamorphism due to intrusion of the amphibolite metagabbro dike. Presence of a similar dike at the section 12 location can only be postulated, although it is probable that initial intrusion of the now vanished dike occurred along a zone of weakness which was later intruded by sheared serpentinite during obduction and emplacement.

Growth of olivine was initiated at high temperatures. With slight cooling, to about 692°C (Greenwood, 1963) the reaction forsterite anthophyllite began, resulting in the initial growth of high Mg, low Ca amphibole. With continued decrease in temperature and evident increased hydration, serpentinization of bladed olivine and anthophyllite occurred, and growth of tremolite began. Crystallization of interstitial talc probably accompanied the initial development of the bladed olivine.

Several considerations are critical to the development of a metamorphic spinifex texture. The growth of elongate, branching or curving crystals of olivine has been attributed by previous workers in magmatic, komaatiite spinifex textures (Viljohen and Viljohen, 1969; Donaldson, 1964; and Nesbitt, 1971) and the harrisitic olivines of Rhum (Wager and Brown, 1967) to super-cooling or rapid quenching of magma. Knight (1967) showed that crystal morphology of a rapidly quenched or supercooled liquid is normally elongate, and that the degree of curvature and branching is a function of amount of supercooling and rate of growth. The crystal form of elongate, bladed olivines in M-222 strongly suggest that they developed in a rapidly "quenched" or cooled environment.

Sequence of crystallization and systematic change in mineralogy with decrease in temperatures, indicate that initial reaction in M-222 was dehydration at high temperature (serpentine olivine + H_2O) which occurred due to thermal metamorphism from the intruding dike, and movement of water along concentration gradients from the hydrous peridotite into the less hydrous basalt. This rapid removal of water also removed heat from the peridotite, resulting in a texture in the still-crystallizing olivines characteristic of quenching or supercooling. Sudden influx of water into the basaltic dike may have lowered the solidus sufficiently to allow continued crystallization of large phenocrysts of plagioclase, and resulted in uralization of pyroxenes, as well as some skeletal hydrous ilmeno-magnetite pseudomorphs after pyroxene. With time and falling temperatures, reequilibration of the water in the peridotite-basalt (amphibolite) system caused: 1) reaction of recrystallized olivine to serpentine, 2) hydration and reaction of anthophyllite to serpentine, and 3) probable transport of some mobile trace elements from the hydrated dike into the dehydrated serpentinite.

Snoke and Calk (1978) attributed development of metamorphic spinifex texture to the influx of hydrous fluids from a gabbroic dike into serpentinized peridotite primarily on the basis of an increased abundance of sulfur and a few other trace elements in serpentinite which contains the metamorphic spinifex texture. However, several observations from the Greenhorn localities argue persuasively against this interpretation:

1. The bladed morphology of olivines has been shown to originate by crystallization during quenching of supercooling processes. Rapid cooling would not be enhanced by addition of water from the heated dike to the peridotite.
2. It is difficult to start a dehydration reaction such as serpentine olivine + H_2O by adding water to the system. The reaction lizardite + crysotile antigorite + talc might be anticipated instead.
3. Few examples of hydrous basaltic magmas have been documented; gabbros are also relatively anhydrous. Snoke and Calk (1978) cited no unusual textures or compositions which might be considered evidence of hydrous melts.
4. In the Greenhorn localities and in metamorphic spinifex textures of the northern Sierra Nevada (Hietanen, 1977), the amphibole formed as a calcium-poor variety in conjunction with olivine recrystallization. Anthophyllite occurs near the contact in the Greenhorns; cummingtonite is in the Sierra. At increasing distance from the contact in the Greenhorns, tremolite becomes more abundant. If fluids emanating from a basaltic dike which should contain about ten percent calcium caused the development of the bladed olivine texture, and, as

TABLE 27. MODES OF METAMORPHIC SPINIFEX TEXTURED PERIDOTITE

	M222	M224	M91
Olivine	4.6	3.2	1.2
Clinopyroxene	--	--	tr
Anthophyllite	6.4	--	--
Tremolite	tr	9.1	tr
Talc	25.9	78.4	12.2
Serpentite	61.7	8.0	85.3
Chlorite	0.4	2.3	--
Opaque	1.0	1.0	1.3
SUM	100.0	100.0	100.0

TABLE 28. MODES: M221 METAGABBRO DIKE

Plagioclase	53.4
Hornblende	39.7
Ilmeno-magnet.	5.2
Sphene	1.5
Apatite	tr
SUM	99.8

TABLE 29. CHEMICAL ANALYSES

		M222	M224	M-91	Metagabbro M221
P_2O_5	(wt. percent)	0.00	0.03	0.15	0.35
TiO_2	(wt. percent)	0.03	0.03	0.16	3.26
Ni	(ppm)	1865	1887	581	29
S	(ppm)	403	610	272	160

TABLE 30. M-222 MICROPROBE DATA.

	Olivine					Anthophyllite	Talc
	101	102	103	104	105	101/102	103/102
SiO_2	41.79	40.91	41.32	41.37	41.49	59.71	57.53
Al_2O_3	0.00	0.00	0.00	0.00	0.25	0.62	0.00
TiO_2	0.00	0.00	0.00	0.17	0.01	0.01	0.00
CaO	0.01	0.03	0.00	0.00	0.05	0.04	0.00
Na_2O	--	--	--	--	--	0.01	0.00
K_2O	--	--	--	--	--	0.01	0.00
MgO	51.48	48.39	51.67	51.37	49.18	33.25	32.23
Fe*O	9.68	12.56	9.99	10.42	9.24	3.85	2.86
NiO	0.22	0.17	0.17	0.14	0.03	--	--
MnO	0.12	0.08	0.08	0.00	0.09	0.12	0.00
Cr_2O_3	0.10	0.06	0.01	0.01	0.31	0.00	0.00
SUM	103.6	102.6	103.6	102.8	100.65	97.62	92.67
Fo	90.4	86.9	89.7	90.2	90.3		

TABLE 31. M-221 MICROPROBE ANALYSES OF FELDSPAR AND OPAQUE.

	Feldspars					Opaque
SiO_2	65.24	66.29	66.11	66.27	64.78	15.20
Al_2O_3	18.93	19.15	19.02	18.27	18.65	1.37
Na_2O	10.46	10.84	10.80	10.82	10.62	0.00
K_2O	0.09	0.05	0.13	0.03	0.10	--
CaO	0.65	0.40	0.71	0.40	0.94	26.07
TiO_2	0.04	0.12	0.00	0.00	0.00	26.59
MgO	0.29	0.33	0.24	0.05	0.21	24.17
BaO	0.06	0.00	0.00	0.00	0.00	--
SUM	95.85	97.25	97.06	95.84	95.3	98.20
An	An_3	An_2	An_3	An_2	An_4	

suggested by Snoke and Calk (1978), those fluids transported some mobile ions, calcium-enriched amphibole might be adjacent to the intruding dike instead of a calcium-poor variety.

5. Furthermore, if hydration of the peridotite subjected to thermal metamorphism caused metamorphic spinifex texture, then bladed texture might be expected adjacent to relatively hydrous granitic intrusions where recrystallization of olivine occurs. The aureole of the tonalite on Ben Harrison Peak contains abundant recrystallized olivine and anthophyllite, but no spinifex texture. Similarly, thermally metamorphosed peridotites in the aureole of the Bald Mountain batholith contain recrystallized olivine, but bladed texture is not apparent (Taubeneck, 1978, pers. comm.). Although both intrusions are low in water content for typical granitic magmas, abundances of H_2O are close to that expected in most basalts (0.5 percent), and might be considered analogous to basalt-dike intrusion.

6. Lastly, it is not clear that the intruding dike was responsible for enrichment of the Greenhorn spinifex rocks in sulfides. The sample most enriched in sulfur has poor spinifex texture and is farther from the site of intrusion. Enrichment in sulfur occurs in a peridotite from Ben Harrison Peak (M-91) which is neither associated closely with amphibolite pods nor has any

recrystallized olivine present. Enrichment in sulfides may be linked to granitic intrusions previously noted rather than to the intrusion of basaltic magmas. Transport of mobile elements such as sulfur might be expected during re-equilibration after the initial movement of water from peridotite into the dike.

In conclusion, metamorphic spinifex texture developed in the Greenhorn Mountains seems to be the result of rapid dehydration of serpentinized peridotite by movement of water from serpentinized peridotite into an intruding dike of basaltic composition. Subsequent rehydration of the peridotite by returning water during equilibration and cooling caused serpentinization of newly formed olivine and anthophyllite, and possibly in the transport of mobile ions such as sulfur into the peridotites. Obduction and emplacement of the ophiolitic assemblage post-dates development of spinifex texture.

APPENDIX 2

Analyzed Samples

See Plate 2 for map locations.

Tertiary Volcanics - whole rock chemistry

C-10 Clarno-equivalent basalt. Sect. 14, T. 10 S., R. 35 E. Pilotaxitic. Plagioclase, clinopyroxene, olivine.

C-13 Clarno-equivalent basalt. Sect. 35, T. 10 S., R. 35 E. Pilotaxitic. Plagioclase (An_{45}), Clinopyroxene, altered olivine.

C-15 Clarno-equivalent basalt. Dike. Sect. 4. T. 10 S., R. 34 E. Diabasic. Plagioclase, clinopyroxene, altered olivine.

C-200 Clarno-equivalent basalt. Dike-Rebbitt Butte. Sect. 1. T. 8 S., R. 34 E. Diabasic. Plagioclase, clinopyroxene, olivine.

C-208 Picture Gorge Basalt (Columbia River Group). Squaw Rock (lower) flow. Sect. 30, T. 9 S., R. 34 E. Pilotoxitic. Plagioclase, clinopyroxene, olivine.

C-210 Clarno-equivalent basalt. Middle Fork, John Day River. Sect. 26, T. 10 S., R. 33 E. Plagioclase, clinopyroxene, olivine.

C-212 Picture Gorge Basalt (Columbia River Group). Indian Rock (upper) flow. Sect. 25, T. 9 S., R 33 E. Plagioclase, clinopyroxene, olivine.

Metagabbro and Peridotite - whole rock chemistry

M-46 Homogeneous cumulate metagabbro Sect. 27, T. 9 S., R. 34 E. Adcumulate. Plagioclase, blue-green hornblende, clinopyroxene.

M-91 Alpine peridotite, Ben Harrison ultramafic body. Sect. 34, T. 10 S., R. 34 E. Serpentine, clinopyroxene, olivine.

M-208 Homogeneous cumulate metagabbro. Sect. 26, T. 9 S., R. 34 E. Orthocumulate. Clinopyroxene, blue-green hornblende, plagioclase.

M-213 Layered cumulate metagabbro. Sect. 21, T. 9 S., R. 34 E. Orthocumulate with alternating leucocratic and melanocratic layers two to four cm thick. Blue-green hornblende, chlorite, plagioclase, clinopyroxene.

M-221 Porphyritic metagabbro dike. Sect. 21, T. 9 S., R. 34 E. Plagioclase, blue-green hornblende, ilmeno-magnetite (hydrous).

M-222 Metamorphic-spinifex textured peridotite. Sect. 12, T. 10 S., R. 34 E. Talc, serpentine, anthophyllite, olivine.

M-224 Recrystallized olivine peridotite. Sect. 12, T. 10 S., R. 34 E. Talc, serpentine, tremolite, olivine.

M-226 Sheared serpentinite. Layered complex, Meyer's Mine. Sect. 3. T. 10 S. R. 33 E. Serpentine (lizardite and crysotile).

M-240 Layered cumulate metagabbro. Sect. 18, T. 10 S., R. 34 E. Orthocumulate. Subtle one to three cm layers. Blue-green hornblende. Plagioclase, clinopyroxene.

M-250 Leucocratic hornblende metagabbro. Black Butte location. Sect. 14, T. 10 S., R. 34 E. Hypidiomorphic. Plagioclase, green-brown hornblende, chlorite, epidote.

P-1 Amphibolite pod. Ben Harrison ultramafic body. Sect. 34. T. 10 S., R. 34 E. Orthocumulate anorthositic gabbro. Blue-green hornblende, clinopyroxene, plagioclase.

Schists and Volcanic Greenstones - whole rock chemistry

MC-1 Meyers Canyon blueschist, Mitchell, Oregon. Sect. 13, T. 11 S., R. 21 E. Glaucophane, quartz, chlorite, lawsonite.

MRS-1 Mine Ridge Schist, Hereford, Oregon. Sect. 14, T. 13 S., R. 38 E. Chlorite, actinolite, quartz, albite, white mica.

MRS-2 Mine Ridge Schist, Hereford, Oregon. Sect. 14, T. 13 S., R. 38 E. Barroisite, white mica, chlorite, quartz.

V-27 Olive Creek pillow lava. Olive Creek. Sect. 2, T. 10 S., R. 33 E. Plagioclase, chlorite, clinopyroxene.

V-80 Pumpellyite greenstone, Vinegar Hill Beds. T. 10 S., R. 35 E. Chlorite, albite, quartz, epidote, pumpellyite.

V-89 Bennett Creek Schist. Pelitic member. Sect. 15, T. 10 S., R. 35 1/2 E. Quartz, albite, phengite, almandine-spessaritine garnet.

V-90 Bennett Creek Schist. Mafic member. Sect. 15, T. 10 S., R. 35 1/2 E. Chlorite, barrioisite, epidote.

V-207 Olive Creek pillow lavas. Royal White Mine. Sect. 3, T. 10 S., R. 35 E. Chlorite, plagioclase, epidote, calcite.

V-215. Olive Creek pillow lavas. Olive Creek. Sect. 2, T. 10 S., R. 35 E. Chlorite, plagioclase, epidote, sphene, calcite.

V-217 Olive Creek pillow lavas. Spring Creek. Sect. 5, T. 10 S., R. 35 E. Chlorite, plagioclase, epidote.

V-217a Olive Creek pillow lavas. Spring Creek. Sect. 5, T. 10 S., R. 35 E. Chlorite, calcite, ilmenomagnetite, sphene.

V-218 Badger Creek Beds keratophyre. Sect. 29, T. 10 S., R. 34 E. Albite, chlorite, actinolite.

V-219 Badger Creek Beds. Spilite. Sect. 29, T. 10 S., R. 34 E. Chlorite, actinolite, albite.

V-252 Vinegar Hill Beds (?) Spilite. Sect. 16, T. 10 S., R. 35 E. Chlorite, albite, epidote, clinopyroxene.

Jurassic Intrusive Rocks - whole rock chemistry

W-1 Two-mica granodiorite, Olive Creek granodiorite. Sect. 11, T. 10 S., R. 35 E.

W-46 Boulder Butte tonalite. North salient. Sect. 33, T. 9 S., R. 34 E.

W-71 Sunrise Butte granodiorite. Sect. 10, T. 10 S., R. 34 E.

W-83 Quebec Hill norite. Sect. 27, T. 9 S., R. 35 E.

Microprobe Analyses. (See above for sample descriptions and locations)

Metagabbro and Peridotites

M-221 4 of one plagioclase, single analyses of 3 other plagioclase. 1 opaque, 2 amphibole.

M-222 5 olivines, 1 amphibole, 1 talc

P-1 5 clinopyroxenes, 3 amphiboles, 4 plagioclase, 1 opaque.

Schists

MC-1 two analyses each of three different amphiboles. 1 pumpellyite.

MRS-1 4 amphiboles, two plagioclase.

MRS-2 5 amphiboles, two plagioclase

V-89 5 white micas 3 analyses of one fragmented garnet. Two analyses of a different fragmented garnet.

V-90 Two analyses of one amphibole, single analyses of seven amphiboles, three platioclase, two chlorite, three epidote.

Volcanic Greenstones

V-27 four clinopyroxenes, two amphiboles, two plagioclase, two chlorites.

V-85 1 garnet, 1 scapolite, one epidote, one quartz.

APPENDIX 3

Analytical Procedure

X-Ray Fluorescence Techniques

Sample Preparation. Rocks were selected for chemical analysis by thin section examination, field location, and association. Initially, 40 samples were selected for thorough analysis. However, a shortage of flux compounds allowed the complete analysis of only 30 whole rocks. Selected trace element and TiO_2, K_2O, and P_2O_5 determinations were made for some additional samples.

Each sample was sawed into thin slabs approximately 1/4 inch thick. Samples were then further trimmed to eliminate all but the freshest material, and cleaned on a diamond lap wheel. Slabs were dried for approximately 24 hours at 110°C, then crushed to two mm or less in size by a jaw crusher. The resulting rock fragments were placed in a tungsten-carbide canister with two tungsten carbide 1/2 inch balls in approximately ten gram batches and shaken in a Spex Mixer/Mill 8000 for 35 to 40 minutes. The resulting sample powder was then thoroughly mixed. For fine-grained, relatively homogeneous samples such as basalts, 85 to 100 grams of sample powder was prepared. For analysis of coarser rocks (granitic samples and some gabbros), 100 to 150 grams of sample powder was prepared to insure analysis representative of the whole rock. In one unusual layered gabbro (M-213), a 220 gram sample, carefully cut perpendicular to layering was prepared as the sample powder.

A split of each sample powder was then dried at 110°C for 24 hours, and to insure a finely uniform powder, samples were further ground in a Pulvessette pulverizer auto-morter for ten minutes, then subjected to at least three hours of additional drying.

Preparation for Analysis. For major oxide determinations, fused glass discs were prepared to eliminate grain size effects, insure homogenization of the sample, and provide sufficient dilution of major elements for reasonable count rates. A flux of lithium metaborate ($LiBO_2$), with lanthanum oxide La_2O_3 as a heavy absorber was utilized. The mixture for samples and standards used was 5.250 grams $LiBO_2$, 0.750 grams of La_2O_3, and 0.900 grams of sample. This mixture was placed in a 15 dram plastic vial and shaken in a Spex mixer mill for about one minute. The resulting powder was transferred to a graphite crucible, and heated to 1000°C in a muffle furnace for 15 to 20 minutes. The melt was then IMMEDIATELY poured into a brass ring on a heated graphite plate and molded into a flat disc by use of a brass plunger. Discs were transferred quickly into a second furnace, allowed to anneal at 400°C for at least one hour, then cooled slowly (overnight) to room temperature.

The fused glass discs were polished to a high gloss finish on diamond wheels and finally on 6-micron diamond paste. Some experimental analyses on Fe*O, CaO, Al_2O_3 and SiO_2 were run on the same discs before and after polishing to determine whether a high degree of surface polish is critical to an accurate analysis. Fe*O, CaO, and SiO_2 analyses were probably within experimental error--2.0 percent of the experimental result. Al_2O_3 analysis results were considerably different for polished and unpolished discs. However, an Al paste was utilized to obtain a flat surface on the "unfinished" discs, and residual alumina may have contributed significantly to higher results on Al_2O_3 for unpolished discs.

The one critical consideration in the production and polishing of the glass discs would seem to be avoiding water in all stages of their manufacture in order to maintain both the $LiBO_2$ and La_2O_3 in their anhydrous state. Failure to do so results in the development of a white chalky coating on the polished surface which may inhibit fluorescence or contribute to inaccurate results.

For trace element determination, powder pellets were made of three grams of sample powder and one gram of chromatographic cellulose (Wattman CF11). The mixture of powder and cellulose was mixed in a Spex mixer mill for about one minute, then molded at 25 tons psi between polished tungsten carbide pellets in a Research and Industrial Instrument Company 25 ton ring press.

Standards. A variety of standards were used in X-ray fluorescence analysis, each prepared in the same manner as the unknown samples. Although not all standards listed below were used in every run, most working curves utilized nine or ten standard values. Rock standards from the U.S. Geological Survey, with values as determined by Flanagan (1973) were: AGV-1, JG-1, BCR-1, DTS-1, G-2, GSP-1, PCC-1, and W-1. Standards from the Centre de Recherches Petrographiques et Geochemiques, Nancy, France were also utilized, and included GA, GH, BR, and DRN.

Atomic Absorption

Preparation and Analysis. Rock powder which had been prepared as described under X-ray fluorescence sample preparation procedures was weighted out in 0.5000 gram amounts and placed in a teflon lined one inch diameter decomposition bomb. The sample was then wet with 70 percent HNO_3, and covered with approximately six ml of 48 percent HF. Bombs were capped, sealed, and warmed at 100°C for 15 hours (overnight). They were allowed to cool to room temperature, then opened. Any condensate adhering to the cover was washed into the bomb with double-distilled water (DDW). The open bombs were then placed on a 70°C hotplate and dried. The resulting white powder was crushed with a teflon rod, and dissolved in 6.00 ml of 70 percent HNO_3. When dissolution was nearly complete, about five ml of DDW was added, and the entire contents of the bomb were washed into a 50 ml volumetric flask. The flask was filled to within five ml of volume with DDW, and slightly warmed to facilitate complete dissolution of the decomposed rock powder. Dissolution was allowed to proceed for a two-day period (over the course of a weekend). Flasks were then cooled to room temperature and filled to 50 ml with DDW. The resulting solution was one percent rock powder in a dilute nitric acid solution.

Analysis was by the method of additions, rather than by comparison to rock standards. Solutions of rock powder and various percentages of the element in question were prepared, and a linear curve derived from the results was utilized to determine percent of the element in the sample.

All analyses of Na and Mg were run on a Perkins and Elmer 403 spectrophotometer with deuterium arc background corrector. Machine settings were made first to P& E recommendations and then fine tuned to maximize the signal.

Electron Probe Microanalysis

Sample Preparation. Petrographic sections approximately 30 microns in thickness were prepared on pressed plastic one-inch diameter discs. Slides were polished on five micron diamond and finally three micron alumina paste to achieve as even a surface as possible. Detailed petrographic examination of each slide was undertaken to determine specific mineral grains for analysis. These grains were then sketched and photographed in order to: 1. enable their rapid identification when inserted in the probe, and 2. allow location of the exact points analyzed on the photograph of sketch for later reference.

Slides were carbon coated with a 30-35 nm film by evaporation of two carbon rods at 50 Amp current under high vacuum conditions immediately before insertion into the probe. Thickness of film was visually monitored by observation of a brass standard during the coating process. Slides were placed into the probe holder, and checked for conductivity prior to insertion into the vacuum chamber.

The electron probe microanalyzer utilized was a Materials Analysis Corporation three channel model 5-SA3 at Caltech Division of Geology and Planetary Sciences. Elemental standards were run on mineral samples and glasses of known composition for all analyzed elements. The instrument was operated at 15 kV, 50 ma. Sample current was 0.05 uA. Beam regulated mode was used at all times. Spot size for amphibole and pyroxene analysis was approximately 10 um, and for phases enriched in alkalais (micas, feldspars) spot size was increased to about 25 um. Focus, spot size and location were checked periodically during a run to insure accuracy.

Raw data from the probe spectrometers were analyzed in a coupled PDP-880/L computer (ULTIMATE program). Data output from the 880 gave raw background and peak counts for each analyzed element, and calculated weight percent and cation percent for oxides, and structural formula for the appropriate mineral (chosen by the analyst).

TABLE 32. X-RAY FLUORESCENCE INSTRUMENTAL OPERATING CONDITIONS

Element	Al	Si	P	K	Ca	Ti	Fe	Ba	Ni	Sr	Zr
Crystal	PET	PET	PET	PET	PET	LiF	LiF	LiF	LiF	LiF	LiF
Target	Cr	Cr	Cr	Cr	Cr	Cr	Cr	W	W	W	W
KV	30	31	31	25	20	20	20	40	30	25	35
MA	63	61	61	51	20	31	31	50	30	33	50
Counter	GFPC	GFPC	GFPC	GFPC	GFPC	GFPC	GFPC	SC	GFPC	SC	SC
Detect. Volts	1500	1500	1420	1500	1420	1500	1500	800	1500	750	750
Window	1.0	1.5	0.30	3.0	0.9	0.3	1.2	1.2	1.0		
Base	2.0	2.2	0.5	0.9	1.2	1.4	0.9	1.8	1.4		
Path	VAC	VAC	VAC	VAC	VAC	VAC	VAC	VAC	VAC	AIR	AIR
Spectra	Ka	Ka	Ka	Ka	Ka	Ka	KaK	L_B^2	Ka	Ka	Ka
Peak	115.35	78.9	59.0	19.67	14.62	86.50	57.20	73.05	48.3	24.40	21.7
Bkg.	117.5	76.55 80.95	62.10	22.50	12.00	89.20	59.40	72.3 74.5	46.3	23.5 26.0	21.0 23.5
Int. Std.	AGV	G-2	AGV	GSP W-1	AGV	BCR	AGV	G-2	DTS	AGV	AGV
Count time	100	100	100	50	20	20	20	100	20	50	100