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Geology and Structure of the Western and Southern Margins of Twin Sisters Mountain, North Cascades, Washington

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GEOLOGY AND STRUCTURE
OF THE
WESTERN AND SOUTHERN MARGINS
OF
TWIN SISTERS MOUNTAIN,
NORTH CASCADES, WASHINGTON

A Thesis

Presented to

The Faculty of

Western Washington University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

by

Frederic I. Frasse

June, 1981

MASTER'S THESIS

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ABSTRACT

Detailed mapping of the Goat Mountain dunite and the western and southern margins of the Twin Sisters dunite indicates that the structural setting of these bodies is dominated by high-angle northwest-trending fault zones. The Goat Mountain dunite overlies rocks of the Chilliwack Group and Yellow Aster Complex as a low-angle, west-dipping slab approximately 2500 feet thick. Cretaceous phyllite west of Goat Mountain overlies Chilliwack Group rocks along a similar low-angle west-dipping fault contact. These structures are both truncated by high-angle fault zones.

The timing of faulting is poorly constrained. High-angle faulting is at least post-Eocene through Holocene (?), and may have begun as early as Late Cretaceous. Thrust emplacement of the Cretaceous phyllite over rocks of the Chilliwack Group may or may not have been contemporaneous with dunite emplacement.

ACKNOWLEDGEMENTS

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INTRODUCTION

Statement of Problem

The study area is along the western and southern margin of Twin Sisters Mountain located in northwestern Washington (Fig. 1). The Twin Sisters are underlain by an alpine-type ultramafic body, exposed over approximately 35 square miles. The nature of emplacement of this ultramafic rock (the "Twin Sisters dunite") has been debated in the literature for the past two decades. This debate is due in large part to the lack of a detailed study of the structural setting of the dunite, discerning whether high-angle, low-angle or both high and low-angle faulting are responsible for emplacement.

The geologic maps available for the region are generalized, lacking topography and sufficient detailed information for accurate structural interpretation (1961 Geologic Map of Washington; Ragan, 1961, 1963; Misch, 1966, 1977). A map produced by Bechtel Corporation for a report on geologic hazards in the Skagit Valley (1979) extends into the southern Twin Sisters area. It is on a topographic base at a useful scale of 1 to 62500. Unfortunately most of this work is of reconnaissance nature and lacks detail.

I have mapped in detail the geology from the Middle Fork of the Nooksack River over Bowman Mountain, along the northern, western, and southern margins of Twin Sisters Mountain, over Goat Mountain to the Skagit River valley (Fig. 1; and Plate I). The topographic base map is at a scale of 1 to 31680 (2 inches to one mile) and is compiled from topographic base maps for the Wickersham (1979), Van Zandt (1951), Mt. Baker (1972 revised), and Hamilton (1972 revised) quadrangles. The area studied covers approximately 88 square miles.

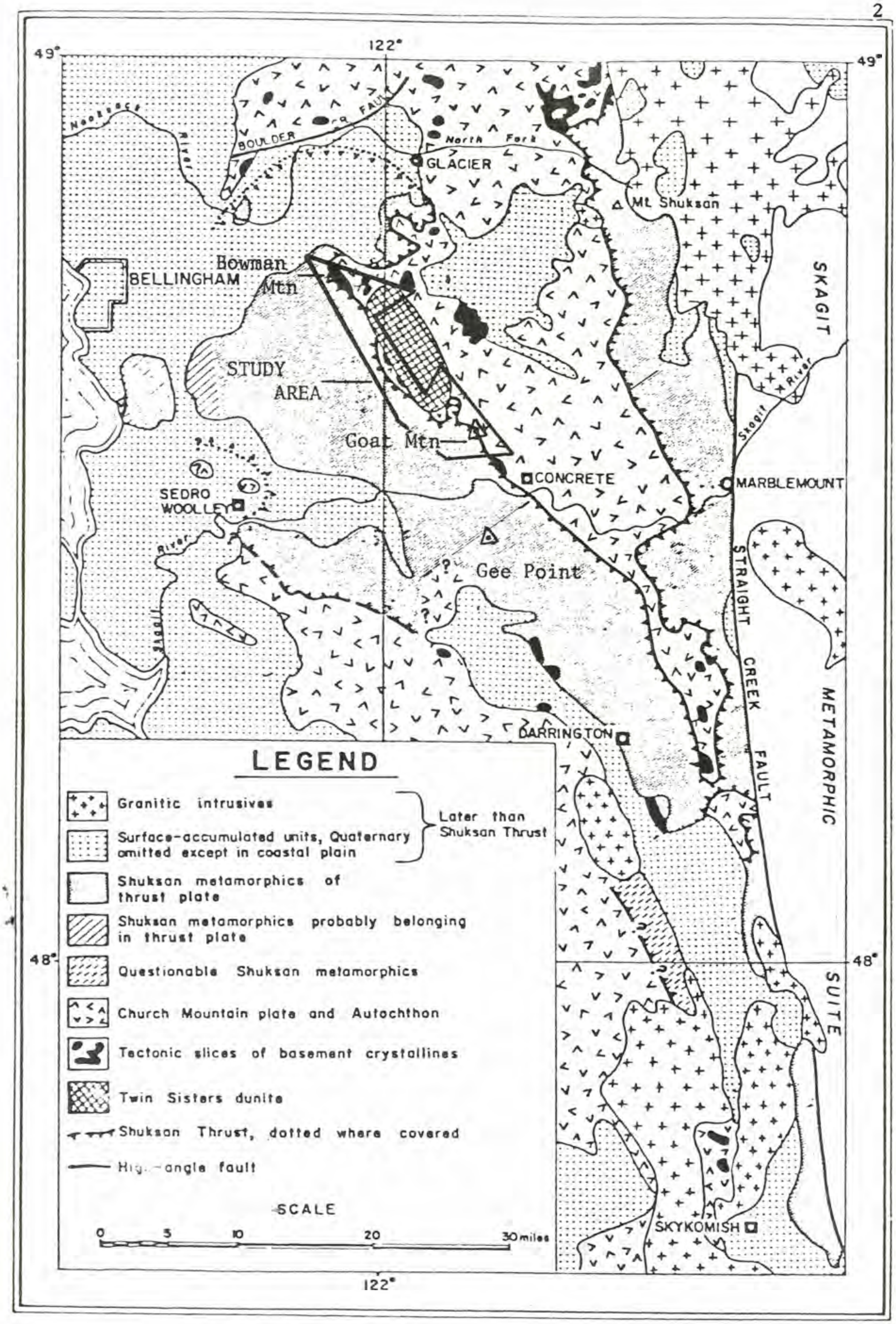


Figure 1. Diagrammatic geologic map of the western North Cascades, Washington (from Misch, 1966).

Individual outcrops are denoted on the map to fully describe the data available. Because of the poor exposure of bedrock in this area, it is particularly important to define precisely the location of individual outcrops, as well as their aerial extent.

Mapping was considerably helped by many logging roads in the area, which ease access and expose bedrock in areas where outcrops are either rare or nonexistent. In general, ridges, creek beds, and steep slopes are good prospects for bedrock exposures. Mapping was carried out from July through mid-November, 1980.

Geologic Setting

The Twin Sisters and associated Goat Mountain ultramafic bodies are on the western flank of the North Cascades Mountains, an area of highly complex geology which has been studied most extensively by Peter Misch, his colleagues, and his students at the University of Washington. The resulting interpretation of the regional geology is summarized from Misch (1966, 1977) below.

The western flank of the North Cascades, west of the Straight Creek fault (Fig. 1), is a structurally complex region predominantly of low-grade metamorphic rocks. The structure is interpreted as a series of at least two stacked thrust plates emplaced during the mid- to Late Cretaceous. Thrusting was westward-directed, originating at a root zone in the Mt. Shuksan and Baker Lake areas (Fig. 1). At least one episode of Tertiary folding folded the thrust plates and the unconformably overlying continental deposits of the Paleocene-Eocene (Johnson, 1980, personal commun.) Chuckanut Formation. Late Pliocene to Early Pleistocene broad uparching along a north-south

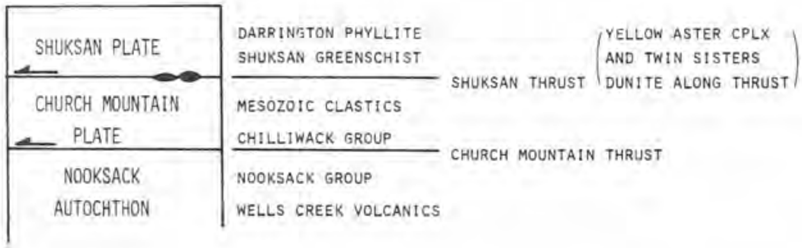


Figure 2. Diagrammatic tectonic stratigraphy of the northwest Cascade Range (after Misch, 1966; Christensen, 1971).

* * *

axis caused the formation of a fenster between Twin Sisters Mountain and Mt. Shuksan. Misch (1966) suggests a tectonic stratigraphy for the western North Cascades consisting of, from lowest to highest, the Nooksack autochthon, Church Mountain plate, and Shuksan plate (Fig. 2).

The autochthonous rocks consist of the Wells Creek Volcanics, overlain by sedimentary rocks of the Nooksack Group. The Middle Jurassic Wells Creek Volcanics consist of calc-alkaline volcanic rocks, slate, and volcanic wacke. Volcanic wacke, siltstone, slate, and phyllite comprise the Jurassic to Lower Cretaceous Nooksack Group, which disconformably overlies the Wells Creek Volcanics. Both units are metamorphosed to prehnite-pumpellyite facies (Misch, 1966; Brown and others, 1981).

The Church Mountain plate is composed of Devonian through Permian Chilliwack Group rocks composed of locally aragonite-bearing (Vance, 1968), prehnite-pumpellyite facies, meta-volcanic and meta-sedimentary rocks. An island arc depositional setting is suggested by the presence of reef limestone, thick accumulations of volcaniclastic sandstone and conglomerate, and abundant volcanic rocks (Misch, 1966; Christenson, 1980, personal commun.).

The overlying Shuksan plate is composed of the Shuksan Metamorphic Suite, in turn composed of Darrington phyllite and Shuksan greenschist (actinolitic greenschist with intercalations of blueschist). The age of the protolith is probably Jurassic (Armstrong, 1980, as cited in Vance and others, 1980), and metamorphism of the Shuksan Metamorphic Suite occurred in the Early Cretaceous (Armstrong, 1980). Slices of pre-Devonian crystalline basement of the Yellow Aster Complex are reported along the Shuksan thrust (Misch, 1962, 1966). Along with the Yellow Aster rocks, serpentinized peridotite, including the anomalously larger unserpentinized Twin Sisters dunite (Christensen, 1971), is incorporated along the fault. Yellow Aster rocks were mapped by Ragan (1961) around the margins of the Twin Sisters dunite.

Ultramafic bodies are common in northwestern Washington (Fig. 3). Southeast of the Twin Sisters along the structural trend of the region are the Darrington and Sultan ultramafic bodies, which were intruded in a solid state along high-angle northwest-trending Tertiary faults (Vance and Dungan, 1977). The Ingalls Complex occurs further to the southeast, in the central Cascade Range. This is an extensive sequence of mafic and ultramafic rocks of an ophiolite, thrust northward over the Chiwaukum Schist of the high-grade metamorphic core of the North Cascades (Miller, 1977; Vance and others, 1980).

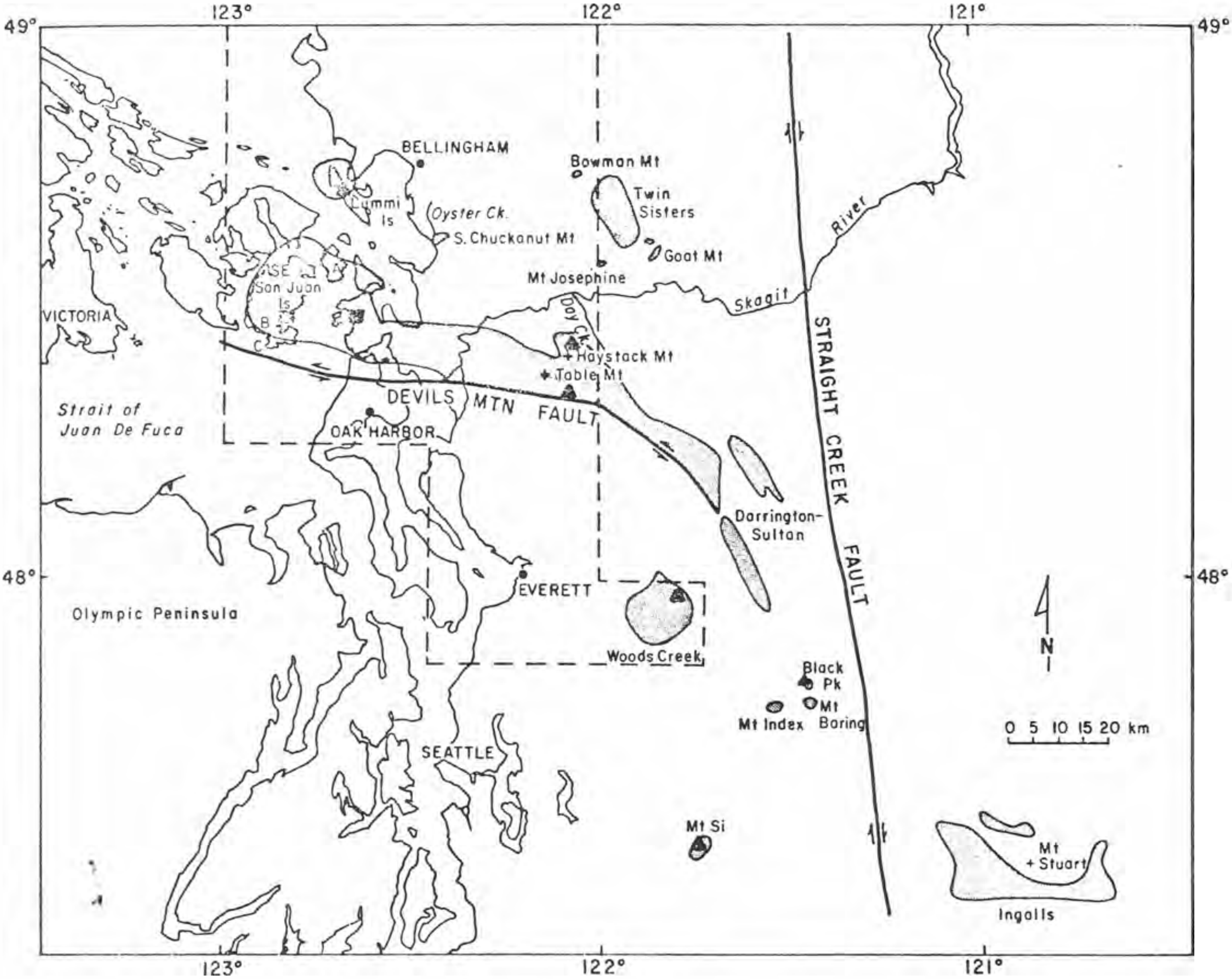


Figure 3. Sketch map showing major mafic and ultramafic bodies in the northwest Cascades Range (from Whetten and others, 1980).

In the San Juan Islands ultramafic rocks are associated with the Fidalgo Ophiolite (Brown and others, 1977), and peridotites similar to the Twin Sisters dunite occur on Cypress Island (Raleigh, 1965; Carlson, 1972).

The relationship of these ultramafic bodies to the regional geology is poorly understood. Published discussions of the regional relationships of ultramafic rocks are examined at the end of this paper.

PREVIOUS STUDIES OF THE TWIN SISTERS DUNITE

The first major study of the Twin Sisters dunite (Ragan, 1961) focused on petrology and structure. Ragan found that the Twin Sisters body (as well as the associated Goat Mountain body) is predominantly dunite, composed of olivine (Fo_{90} and more), with lesser enstatite, chromite, and clinopyroxene. He recognized four stages of deformation and recrystallization of probable mantle origin: (1) primary?, (2) early flow, (3) transitional, and (4) cataclastic. Associated fold axial planes and shear planes trend northwestward and are inclined steeply. Marginal fault contacts and absence of a metamorphic aureole suggest cold tectonic emplacement of the body. Fault contacts between the Twin Sisters dunite and Chuckanut Formation led Ragan to conclude that emplacement was post Paleocene. (The present Paleocene-Eocene age, Johnson, 1980, personal commun., given to the Chuckanut Formation implies post-Eocene emplacement.)

A study of seismic anisotropy of the dunite (Christensen, 1971) supported the concept that deformational events studied by Ragan (1961, 1963, 1967) represent flow in the upper mantle. Based on the present orientation of the dunite fabric, Christensen inferred emplacement of the dunite along the Shuksan thrust, followed by regional Tertiary folding.

Gravity and aeromagnetic surveys (Thompson and Robinson, 1975) showed that the Twin Sisters body is lenticular and approximately 6000 ft. thick. The survey also suggested that there is a zone of serpentinite 6000 ft. thick at a depth of 4500 ft. below the ground along the western margin (Fig. 4).

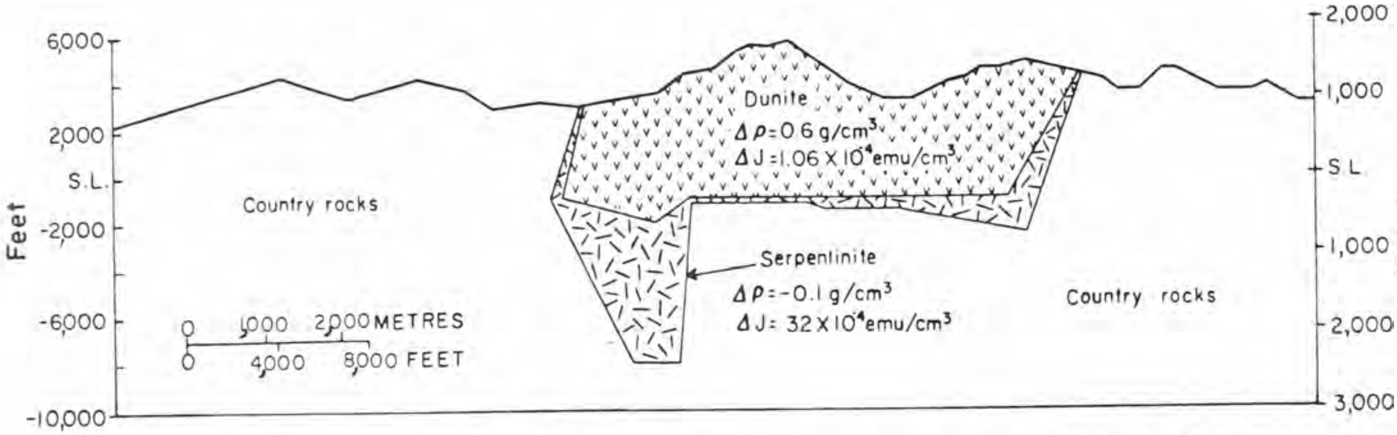


Figure 4. Magnetic and gravity based east-west cross sectional model to the Twin Sisters body (from Thompson and Robinson, 1975).

* * *

At the surface only minor amounts of serpentinite are seen along the contacts (Ragan, 1961). Thompson and Robinson also calculated steep marginal and shallow basal fault contacts (Fig. 4), implying that two different types of faults are involved in emplacement of the dunite.

A homogeneous remnant magnetism of the Twin Sisters dunite was measured by Beck (1975) and found to be directed nearly due east and inclined about 60 degrees below horizontal. Beck accepted the concept that emplacement was Early Tertiary and hypothesized that cooling below the Curie point occurred at this time too. However, the direction of the measured field is discordant from the expected Early Tertiary pole for North America, for which Beck proposed two alternate explanations: (1) westward tilting along a northwest trending axis together with substantial folding about a northeast trending axis; or (2) clockwise rotation about a vertical axis accompanied by northward transport. There is no mapped evidence for northeast-trending structures required by the former explanation, whereas the latter hypothesis is in agreement with other paleomagnetic evidence from the western Cordillera (Beck, 1975).

Onyeagocha's (1978) petrologic study of the dunite, based largely on electron microprobe analyses, refined Ragan's (1961) work. Onyeagocha reorganized Ragan's first three stages of crystallization into two, and added a third stage distinguished by metamorphic minerals accompanied by cataclasis. The minerals formed during the third stage were tremolite, anthophyllite, and talc, which apparently resulted from the introduction of fluids into fractures during tectonic transport into the upper crust.

The Bechtel Corporation published a map for their geologic hazards report (1979) from which the section around the Twin Sisters is reproduced in figure 5. This map contains little detail of the Twin Sisters and Goat Mountain dunite bodies that was not in the original studies by Ragan (Fig. 6) and Misch (Figs. 1 and 7).

Four hypotheses have been proposed for emplacement of the Twin Sisters and Goat Mountain dunite bodies. Ragan (1961, 1963, 1967) suggests post-Chuckanut, vertical, piston-like emplacement of the dunite through the pre-existing mid- to Late Cretaceous thrust plates. Christensen (1971) proposed that the dunite bodies were imbricated along the Shuksan thrust similarly to Yellow Aster rocks described by Misch (1966). Whetten and others (1980) suggest that the dunite bodies are part of the Haystack terrane, thrust over the Shuksan plate during the late stages of Shuksan-Church Mountain thrusting (Fig. 3). The Haystack terrane was subsequently dissected by Tertiary folding and high-angle faulting. Vance and

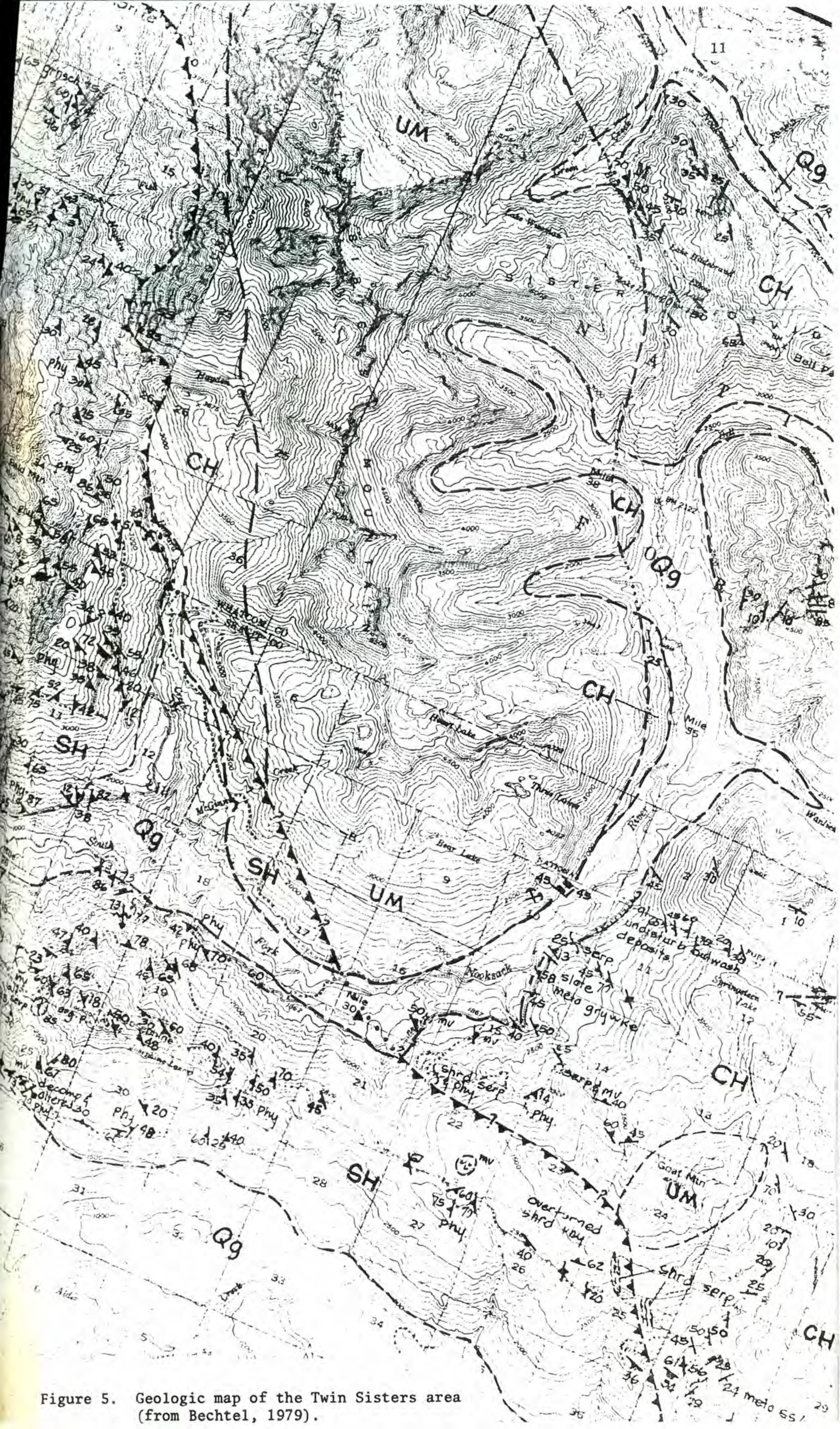


Figure 5. Geologic map of the Twin Sisters area (from Bechtel, 1979).

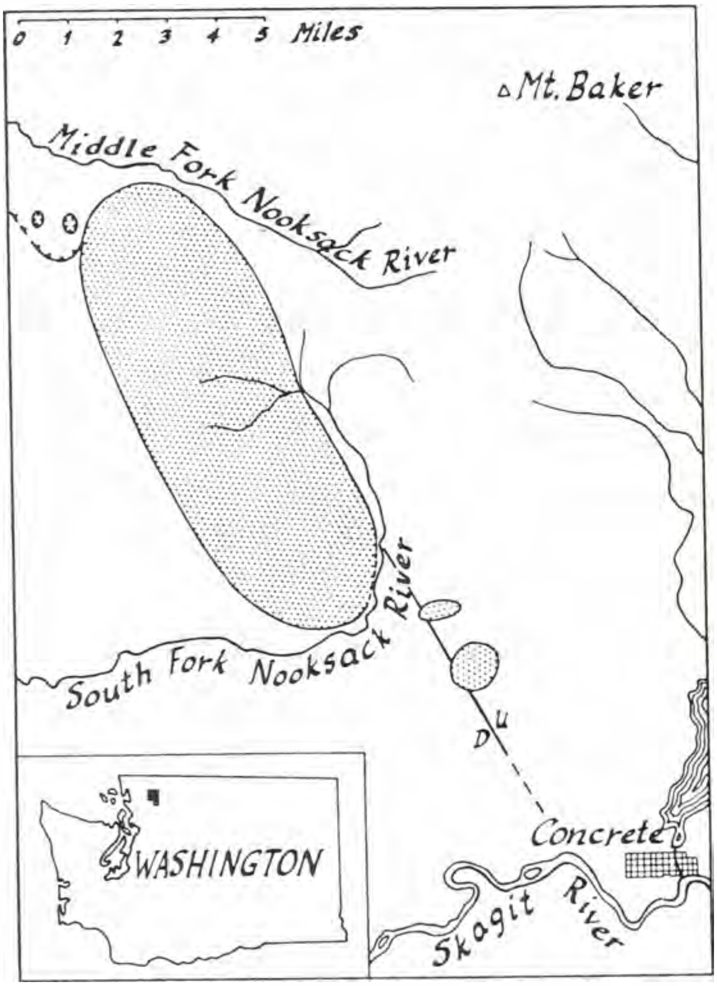


Figure 6. Geologic map of the Twin Sisters area (from Ragan, 1963).

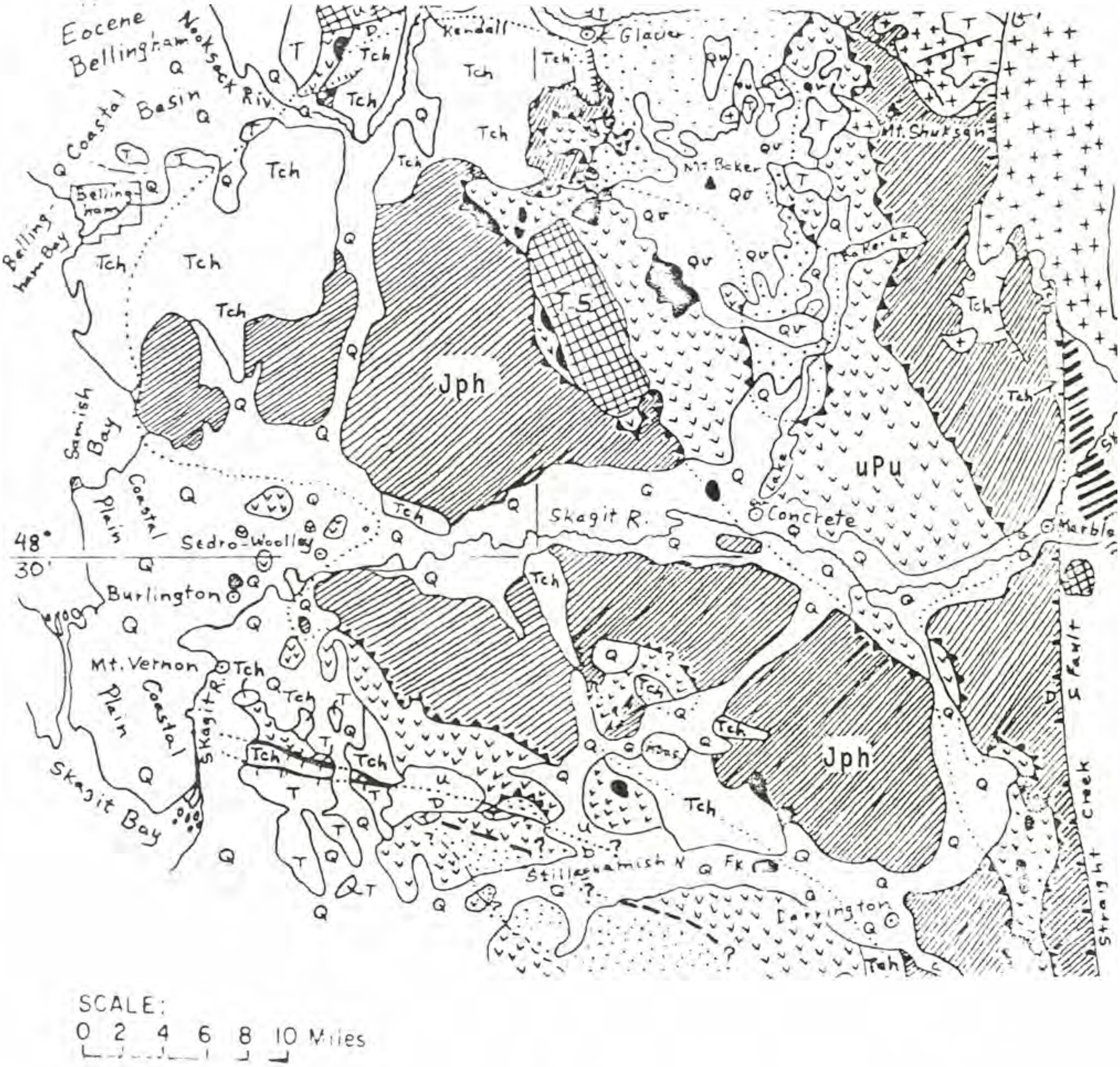


Figure 7. Geologic sketch map of the Twin Sisters region from Misch (1977) (Jph=Darrington phyllite; uPu=Chilliwack Group; Tch=Chuckanut Fm.; TS=Twin Sisters Dunite; black=Yellow Aster Complex).

others (1980) postulate that the dunite bodies were once part of a Jurassic ophiolite emplaced in the mid- to Late Cretaceous, prior to Shuksan-Church Mountain thrusting, and that this terrane was subsequently affected by Tertiary deformations as well.

Though the Twin Sisters has been studied extensively in many of its aspects, there is still no consensus as to its mode of emplacement. The purpose of the present study is to solve this problem through detailed geologic mapping of the structures surrounding the Twin Sisters dunite.

ROCK UNITS

Dunite

The Twin Sisters and Goat Mountain bodies are composed of orange-brown weathering enstatite-bearing dunite. Unaltered dunite is composed of magnesium-rich olivine (Fo_{90} to Fo_{93}), enstatite, chromite, and lesser clinopyroxene with only slight compositional differences throughout the mass (Ragan, 1961, 1967; Onyeagocha, 1978). Clinopyroxene (chromium diopside) is only a trace constituent of the dunite (Ragan, 1961). In thin section, all samples have a tectonite fabric exhibiting superimposed stages of deformation, evidenced by a crude foliation as well as segmentation, cataclasis, and displacement of mineral grains.

Within 50 meters of the western margin of the Twin Sisters body (up to 300 meters on the southeast margin) and over much of the Goat Mountain body there is partial serpentinization of the dunite (Ragan, 1961). In outcrop this rock also weathers orange-brown; pyroxene crystals weather in positive relief, and chromite banding usually is still evident. The unweathered serpentinized dunite appears massive, microcrystalline, and dark-green to black.

Serpentinite

Well developed serpentinite is found restricted to shear zones, which are well exposed along the western margins of the Twin Sisters and Goat Mountain bodies (Plate I). These zones are commonly defined by serpentinite displaying a well developed foliation (Fig. 8). The serpentinite is mylonitized, and fibrous asbestos is well developed along shear surfaces. Away from shear zones, fibrous

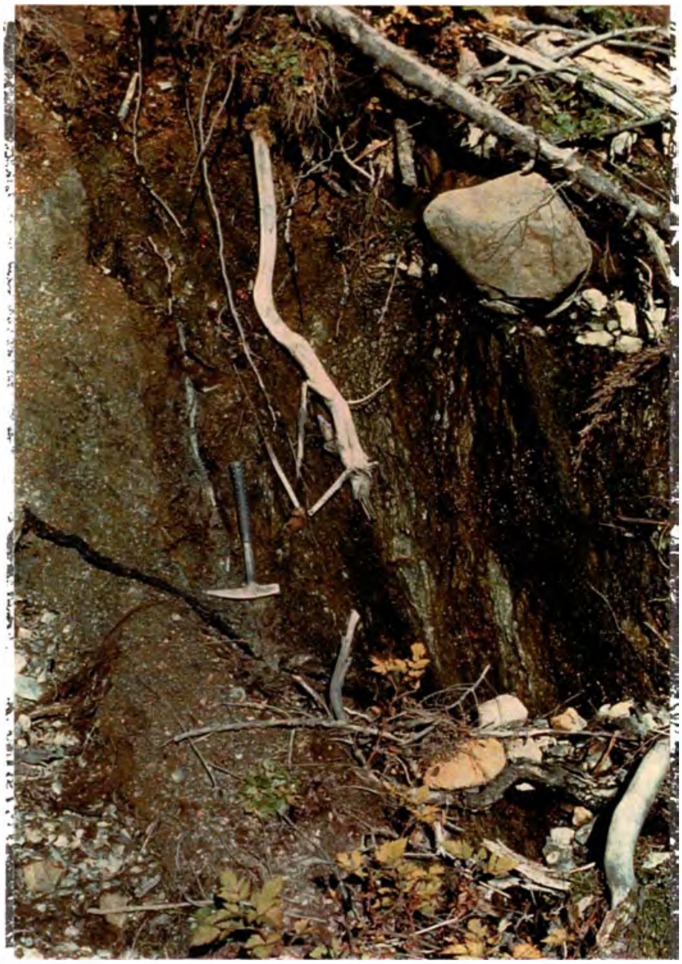


Figure 8. View facing N15°W along strike of sheared serpentinite in Hunter Creek fault zone.

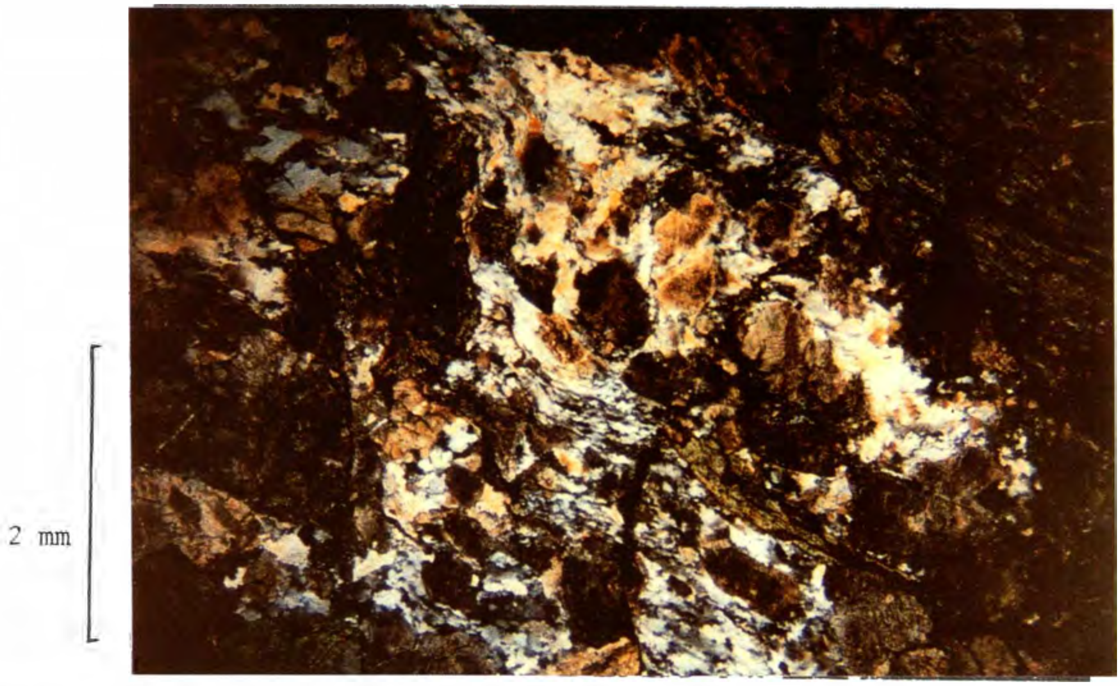


Figure 9. Highly strained quartz and feldspar lenses in Yellow Aster meta-tonalite (sample no. 92-AE_6).

asbestos is less abundant; the serpentinite is highly polished and has phacoidal texture.

Yellow Aster Complex

Three types of rocks representing the Yellow Aster Complex as defined by Misch (1966, 1977) occur in this area: (1) meta-tonalite, (2) meta-gabbro, and (3) clinopyroxenite.

Meta-tonalite contains highly strained quartz and feldspar, relict coarse-grained plutonic plagioclase lathes, and hornblende. Plagioclase lathes are replaced to a varying extent by epidote, as are the hornblendes by actinolite. Actinolite appears to replace clinopyroxene in some samples, and also occurs in veins. Prehnite and chlorite are common in younger, cross-cutting veins. Mylonitization and segregated bands of highly strained quartz and plagioclase are both common to these rocks (Fig. 9), but are developed to greatly varying extents. Large exposures of meta-tonalite occur in the vicinity of Hayden Creek along the central western margin of the Twin Sisters and at Washington Monument (Plate I). This rock also commonly occurs as small fault-bound blocks (ca. 30 ft. in diameter) in shear zones throughout the area.

Meta-gabbro and meta-diorite of early Paleozoic age (Whetten and others, 1980) occur on Bowman Mountain. These rocks have been correlated with the Yellow Aster Complex (Misch, 1966, 1977). Meta-gabbro is not restricted to Bowman Mountain, as exposures of these rocks are also mapped south of Washington Monument (Plate I).

The meta-gabbro contains epidote, actinolite, and iron oxide which are pseudomorphs after the igneous phases. These rocks have no tectonite fabric (Fig. 10), though they are complexly interfaulted with clinopyroxenite and Chilliwack rocks. They are presently being studied in detail by Misch (1980, personal commun.).

Clinopyroxenites in the study area are observed in thin section to contain 0 to 40 percent olivine or serpentine after olivine. Traces of bastite pseudomorphs after enstatite are also observed. This rock is observed on Bowman Mountain, along the western side of Twin Sisters Mountain, and west of Goat Mountain (Plate I). At the dunite margin on the spurs between Hayden and McGinnis Creeks (Fig. 11), a crude layering is evident, with alternating olivine-rich and clinopyroxene-rich layers approximately 15 centimeters thick (Fig. 12).

Vedder Complex

Rocks of the Late Paleozoic Vedder Complex (Armstrong and others, in preparation, occur as small tectonic blocks (three to thirty feet in diameter) along faults in the area north of Hayden Creek. The Vedder Complex occurs in greater abundance in the Groat Mountain area just to the north across the Middle Fork of the Nooksack River (Rady, 1980). In the present study area, the Vedder Complex is coarse-grained amphibolite (Fig. 13), containing barroisitic hornblende, almandine garnet, epidote, albite, muscovite, and chlorite. The rocks have been tightly folded, and microscopic examination indicates a complex history of crystallization and deformation.

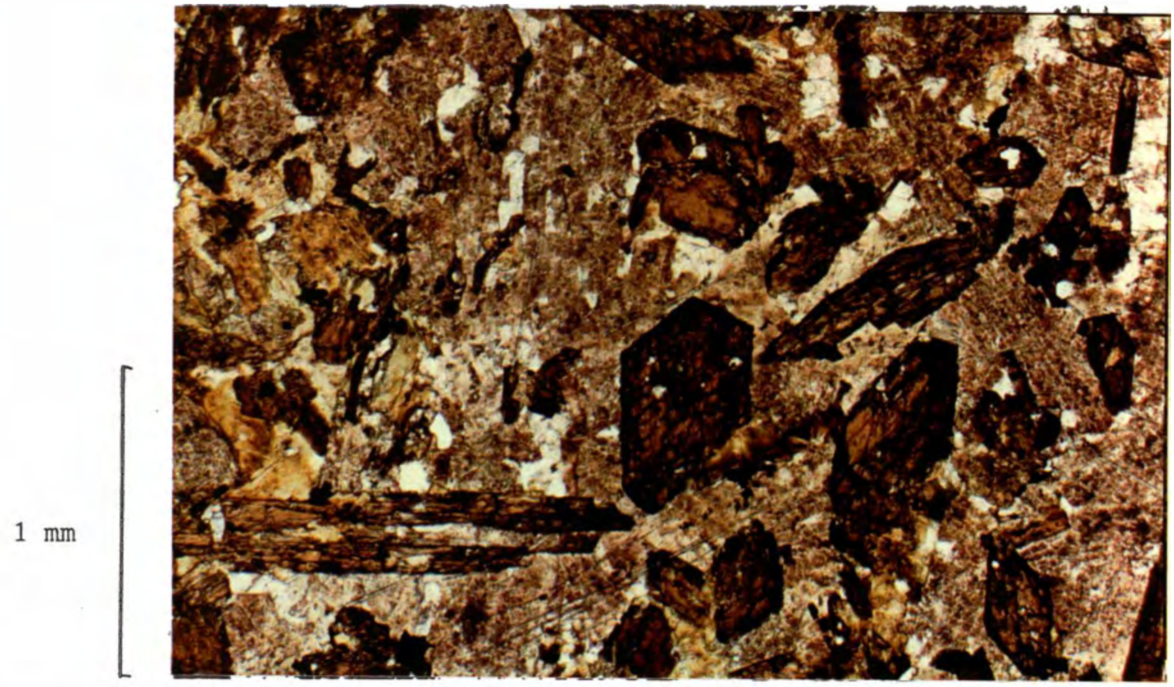


Figure 10. Yellow Aster meta-gabbro; note absence of tectonite fabric (sample no. 92-AM_{1B}).

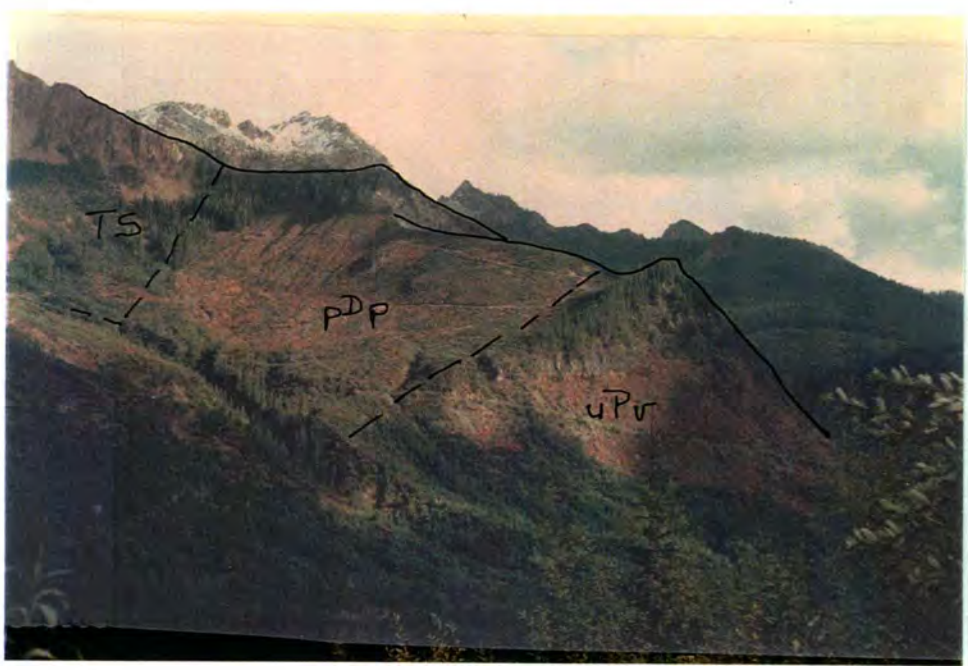


Figure 11. View facing south along western margin of Twin Sisters Mountain (TS=dunite, pDp=Yellow Aster clinopyroxenite, uPv=Chilliwack meta-volcanic rocks).

Figure 12. Dunite, clinopyroxenite layering in Yellow Aster clinopyroxenite unit.

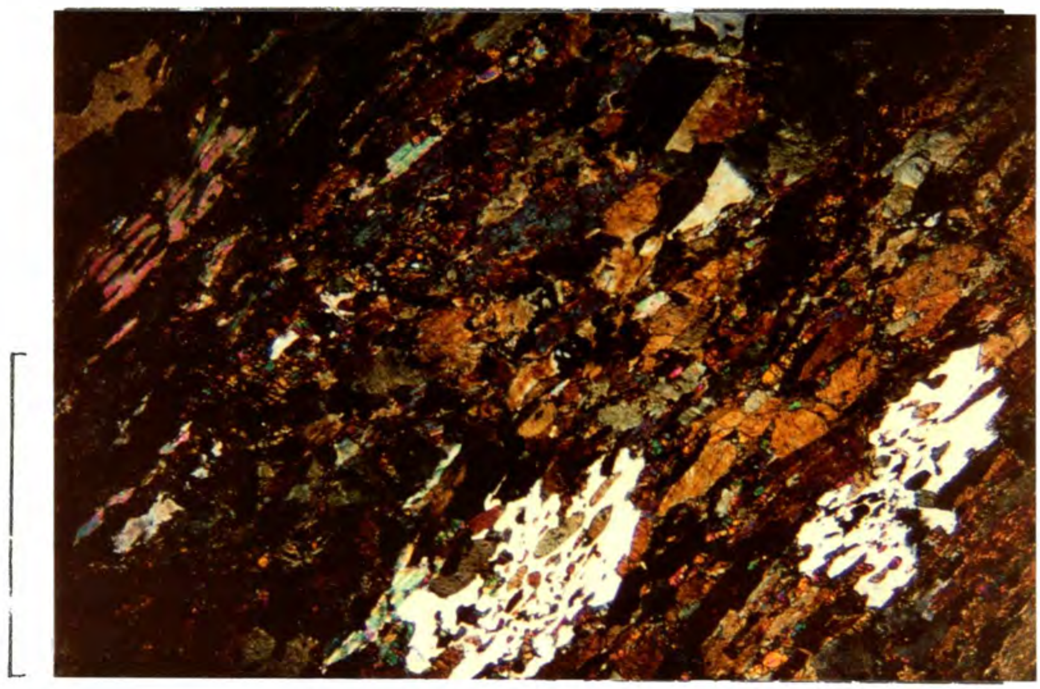


Figure 13. Photomicrograph of barroisitic schist from Hayden Creek fault (sample no. $92\text{-}Q_{11B}$).

Chilliwack Group

Rocks of the Chilliwack Group are mapped throughout the study area. Fine-grained meta-volcanic rocks and meta-volcanic wackes predominate. Meta-chert is encountered in the valley of the Middle Fork of the Nooksack River and on the western front of Goat Mountain, between dunite and Cretaceous phyllite. A large flat-lying unit of limestone occurs at Washington Monument (for further details see Smith, 1961); limestone also occurs as small pods a few tens of centimeters long in sheared Chilliwack slate along the Hayden Creek fault, north of Hayden Creek. In general, foliation is better developed in meta-sedimentary than in meta-volcanic types. Pumpellyite and chlorite are the most commonly observed metamorphic minerals. Chilliwack rocks along the Hayden Creek fault contain prehnite in cross-cutting veins. This is apparently a local phenomenon. Although lawsonite is reported in other parts of the Chilliwack Group (Brown and others, 1981), none was observed in these rocks. The Chilliwack Group is dated on fossil evidence as ranging from Devonian through Permian (Danner, 1966; Misch, 1966).

Metamorphosed volcanic rocks along Orsino Creek and north of the Middle Fork of the Nooksack River contain particularly iron-rich pumpellyite (strongly pleochroic green in thin section), chlorite, and aragonite (samples 92-AB_4, 92-AG_1, 92-AG_3). These rocks are identical in thin section to rocks that overlie and are interbedded with Cretaceous phyllite on Mt. Josephine (6 miles west of Goat Mountain). The rocks observed in the study area and north of the Middle Fork therefore are questionably Chilliwack and may instead correlate with Jurassic mafic and ultramafic rocks scattered at various structural positions throughout the North Cascades (Whetten and others, 1980; Vance and others, 1980).

Cretaceous Phyllite

Phyllite and phyllonite occur along the western margin of the map area. These rocks yield a whole rock K/Ar date of 108 ±4 million years (Misch, 1963). Ragan (1961, 1963) and Misch (1966) correlate these rocks with the Darrington phyllite of the Shuksan Metamorphic Suite. This correlation is based on the occurrence of greenschist interbeds on Bowman Mountain that are comparable to Shuksan greenschist (Misch, 1980, personal commun.).

Isoclinally folded intercalations of greenschist in phyllite are observed in this study on Bowman Mountain (Fig. 14), as well as at two localities by the South Fork of the Nooksack River (Plate I). The greenschist contains quartz, albite, epidote, bluish-green actinolite, stilpnomelane, and iron-oxide (?) (Fig. 15). The Fe^{3+} ion content of the epidote was estimated using the maximum birefringence method described by Tröger (1971) (sample 92-T_{2A}). It was determined to be 60 percent $HCa_2Fe^{3+}Al_2Si_3O_{13}$ end member, which is somewhat higher than is typical of Shuksan greenschists (Brown and others, 1981).

The phyllite and phyllonite in the study area are not as texturally mature as those of the Gee Point area to the south or the Mt. Shuksan area to the east (Fig. 1). Graded bedding and lamination are easily discerned in many outcrops. In thin section at least some original sand and silt grains are usually evident, and there is relatively little recrystallization of quartz and feldspar.

Figure 14. Isoclinal fold in greenschist intercalation on southwest Bowman Mountain.

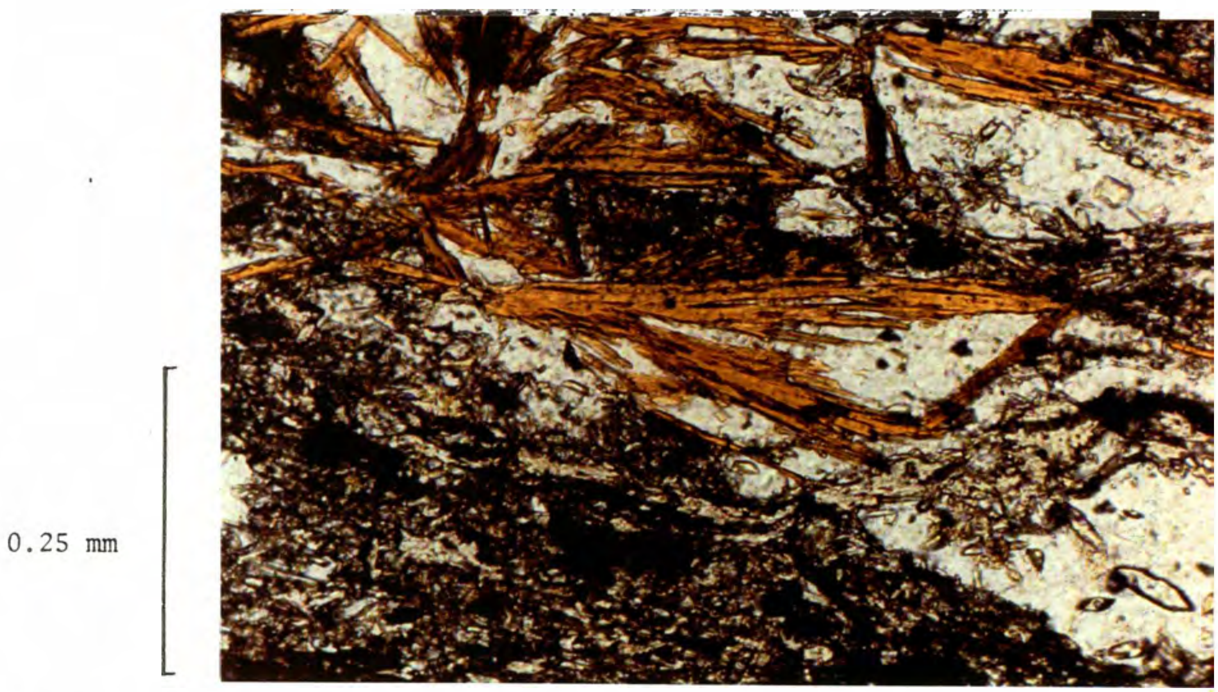


Figure 15. Photomicrograph showing stilpnomelane in greenschist intercalation from exposure in figure 14 (sample 92-E_1).

In an attempt to objectify comparisons between phyllites, I have subdivided the different textures of the phyllite that I observed in thin section into textural groups (Figs. 16a-e). These categories are subdivided by degree of destruction of the original detrital grains and subsequent development of recrystallized and segregated quartz and feldspar. Textural zones presented here are based on those defined by Blake and others (1971) for Franciscan meta-graywackes. The boundaries between groups I, II, and III are identical to those of Blake and others; modification to the subdivision of group III is based on observations of rocks from northwest Washington. Whereas Franciscan meta-graywackes of zone III are subdivided by the presence or lack of small scale isoclinal folds, folding is independent of textural maturity in the rocks observed in this study; consequently, further subdivision is by grain size. Grain sizes of quartz and feldspar in thin sections generally occur in two groups, greater and less than 0.06 mm, consequently this was chosen as the boundary between zone IIIa and IIIb. Increase in grain size is due to increased ionic mobility, due to the elevated temperatures of higher-grade metamorphism (Spry, 1979).

Rocks in the study area mapped as "Cretaceous phyllite" are predominantly of zone IIb, and rarely of zone IIIa. Phyllite observed from Mt. Shuksan is predominantly zone IIIa, although IIIb is also present. Phyllite observed from the Gee Point area is of zone IIIb.

Dioritic to tonalitic rocks exhibiting relict medium-grained hypabyssal and volcanic textures are exposed on southern Bowman

Figure 16a-e. Textural zonation of meta-graywackes and meta-siltstones in northwest Washington.

Zone I.	NO DEFORMATION OF FRAMEWORK GRAINS
Zone IIA.	CATACLASIS AND/OR FLATTENING OF FRAMEWORK GRAINS; FOLIATION PRESENT; SOME ORIGINAL GRAIN BOUNDARIES INDISTINCT
Zone IIB.	CATACLASIS OF FRAMEWORK GRAINS INTENSE; MOST ORIGINAL GRAIN BOUNDARIES INDISTINCT; RECRYSTALLIZATION AND INCIPIENT QTZ+FELD SEGREGATION
Zone IIIA.	ORIGINAL GRAINS OBLITERATED; QTZ+FELD SEGREGATED INTO FINE-GRAINED LAMINATIONS: QTZ+FELD GRAINS LESS THAN 0.06 mm in diameter
Zone IIIB.	QTZ+FELD SEGREGATION LAMINATIONS COARSER GRAINED AND IN WELL DEVELOPED LENSES: QTZ+FELD GRAINS MORE THAN 0.06 mm in diameter

1 mm

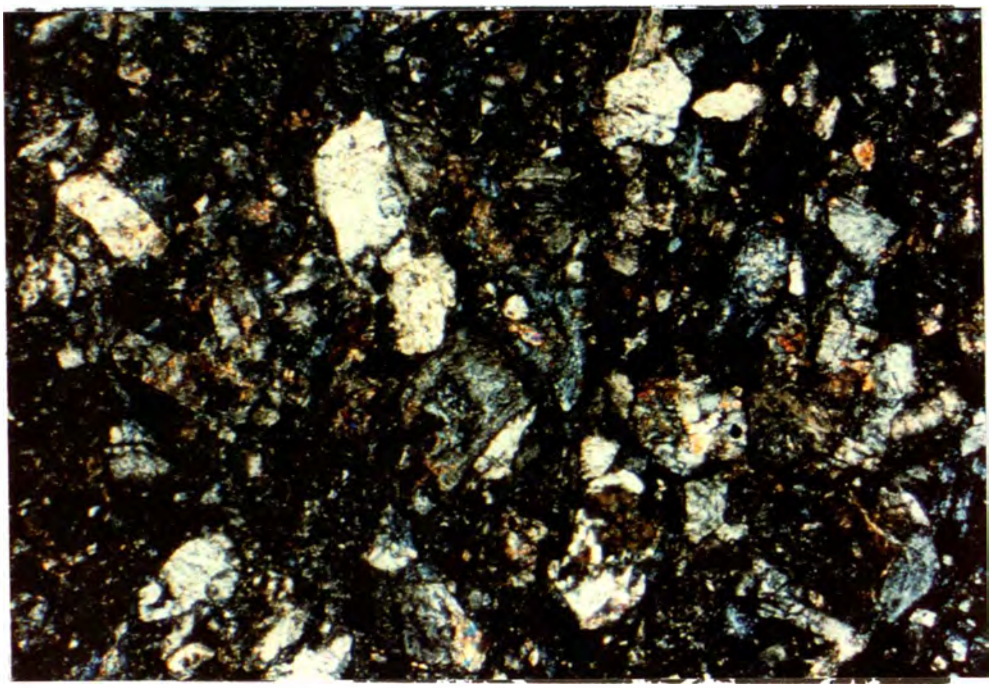


Figure 16a. Textural zone I; (sample no. 92-AJ_3) from Goat Mountain.

.25 mm

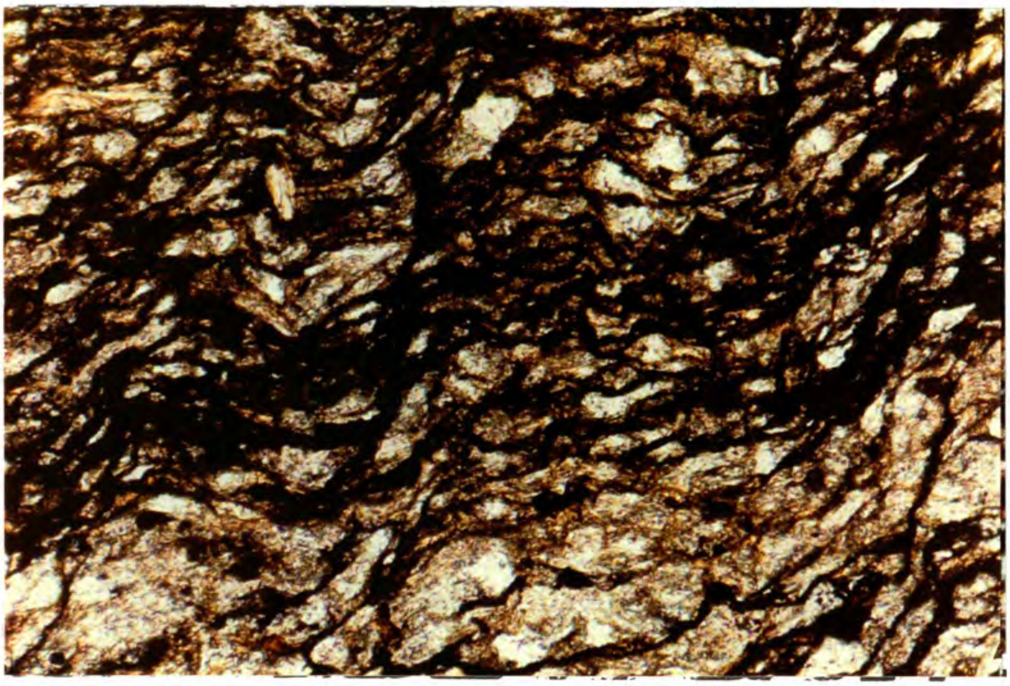


Figure 16b. Textural zone IIA; (sample no. 72-3) from Finney Creek.

1 mm

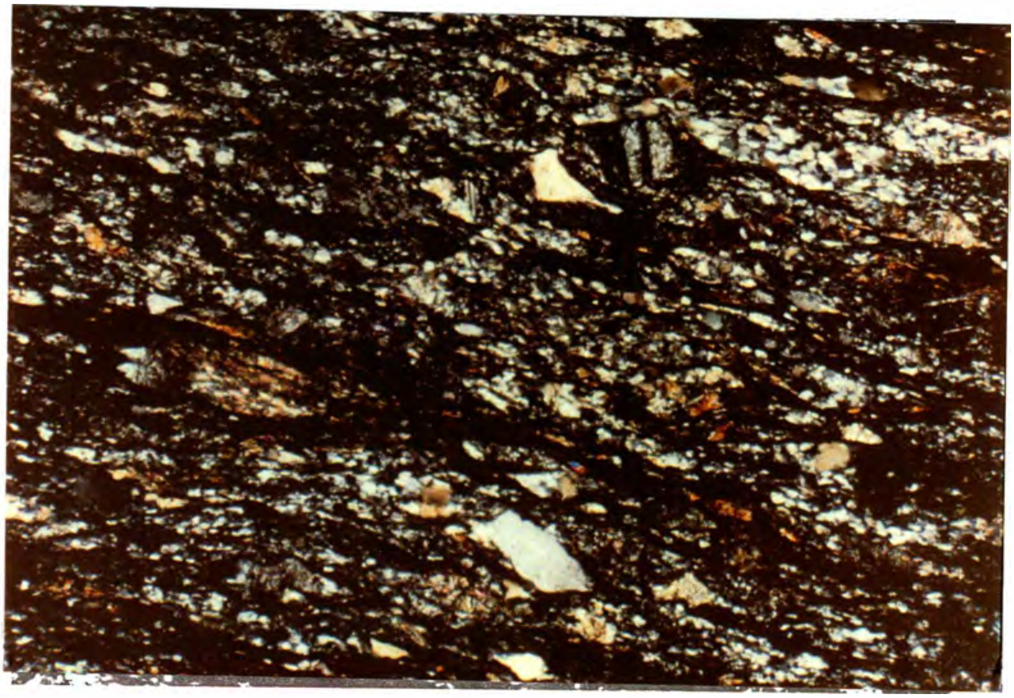


Figure 16c. Textural zone IIB; (sample no. 92-Z_1) from Goat Mountain.

1 mm

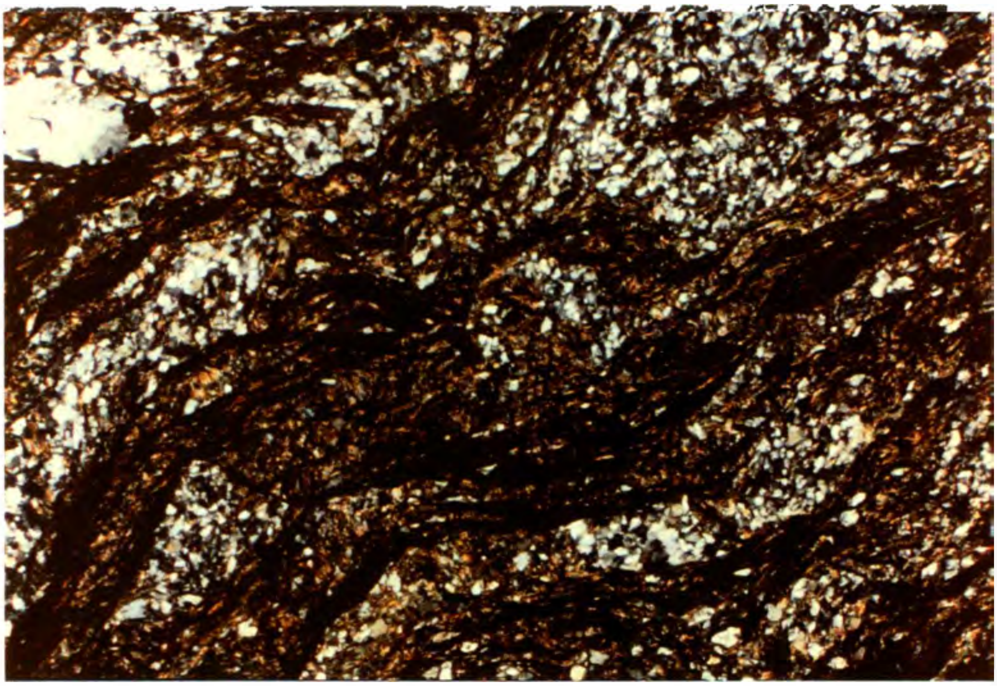


Figure 16d. Textural zone IIIA; (sample no. 55-10) from Gold Mountain, Darrington.

1 mm

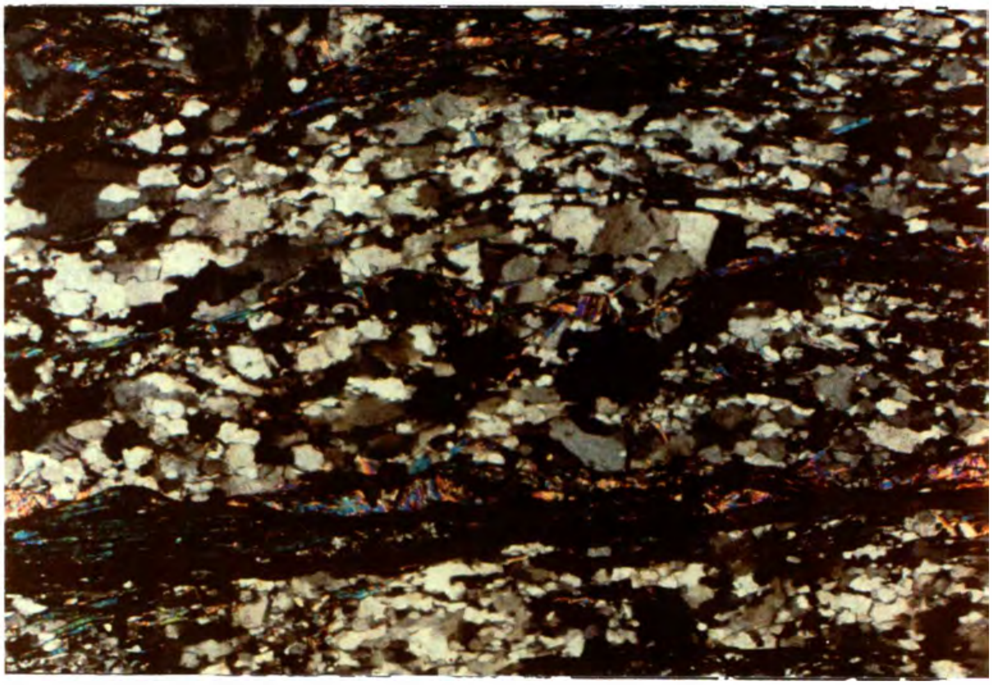


Figure 16e. Textural zone IIIB; (sample no. Gee Point) from Gee Point.

Mountain and appear to be in original stratigraphic position within the Cretaceous phyllite. In thin section this rock contains quartz, albite, chlorite, pumpellyite, aragonite, variable amounts of muscovite, and synkinematic actinolite defining a crude foliation. This mineralogy is comparable to the Haystack unit and differs from the Shuksan by the presence of aragonite instead of calcite (Brown and others, 1981). Coarse-grained volcanilithic meta-sandstone and meta-conglomerate are associated with the meta-igneous rocks and appear to contain clasts of the same material. These sedimentary deposits are interpreted to have been derived from the volcanic center defined by the meta-volcanic-hypabyssal rocks, and to have subsequently undergone metamorphism together with the remainder of the Cretaceous phyllite, phyllonite, and greenschist.

Because of the differences in mineralogy and texture between these rocks and the Darrington phyllite, the phyllite-phyllonite unit west of Twin Sisters Mountain and north of the Skagit River is either: (1) a lower metamorphic and textural grade zone of the Darrington phyllite, or (2) a different unit from the Darrington phyllite. The presence of a granitic dioritic protolith unlike any materials in the Darrington phyllite, suggests that the two units should not be correlated.

In order to differentiate the phyllite-phyllonite unit of the present study from the Darrington phyllite, this unit is mapped simply as "Cretaceous phyllite".

Cretaceous phyllonite on Groat Mountain (Misch, 1963, 1966; Rady, 1980) is texturally similar to phyllonite in the study area and consequently is assumed to be correlative.

Tertiary Sedimentary Rocks

Poorly bedded, medium- to coarse-grained sandstone and conglomerate occur along the northwest margin of the Twin Sisters dunite (Plate I). These deposits are considered to be Tertiary based on lack of metamorphic minerals (only a yellow-brown chlorite cement is present) and total absence of secondary fabric (Figs. 17a and b). Coalified plant fossils collected at one locality were not identifiable.

This unit was mapped by Ragan (1961) to be part of the Upper Cretaceous-Paleocene Swauk Formation (= Chuckanut Formation); its high-angle fault contact with the dunite was used as evidence of a Tertiary piston-like emplacement of the Twin Sisters body.

I found this unit to be much more extensive than previously mapped. It is juxtaposed along high- and low-angle faults with the Chilliwack Group, Vedder Complex, and Yellow Aster Complex (Plate I).

Point count analysis was carried out to compare this rock with the Chuckanut and Huntingdon Formations. One hundred points were counted on each of seven stained thin sections of the Twin Sisters Tertiary rocks and six samples from the Chuckanut Formation from the area immediately north of the Middle Fork of the Nooksack River. The Chuckanut samples are from an interval from the base up to 900 feet into the Chuckanut Formation. Three point counts of Huntingdon Formation are compared; two from Frizzell (1979) and one from Suczek (1981, personal commun.). Frizzell's samples are from Squalicum Mountain in Whatcom County, and the Suczek sample is from Canadian Sumas Mountain, British Columbia. Standard ternary

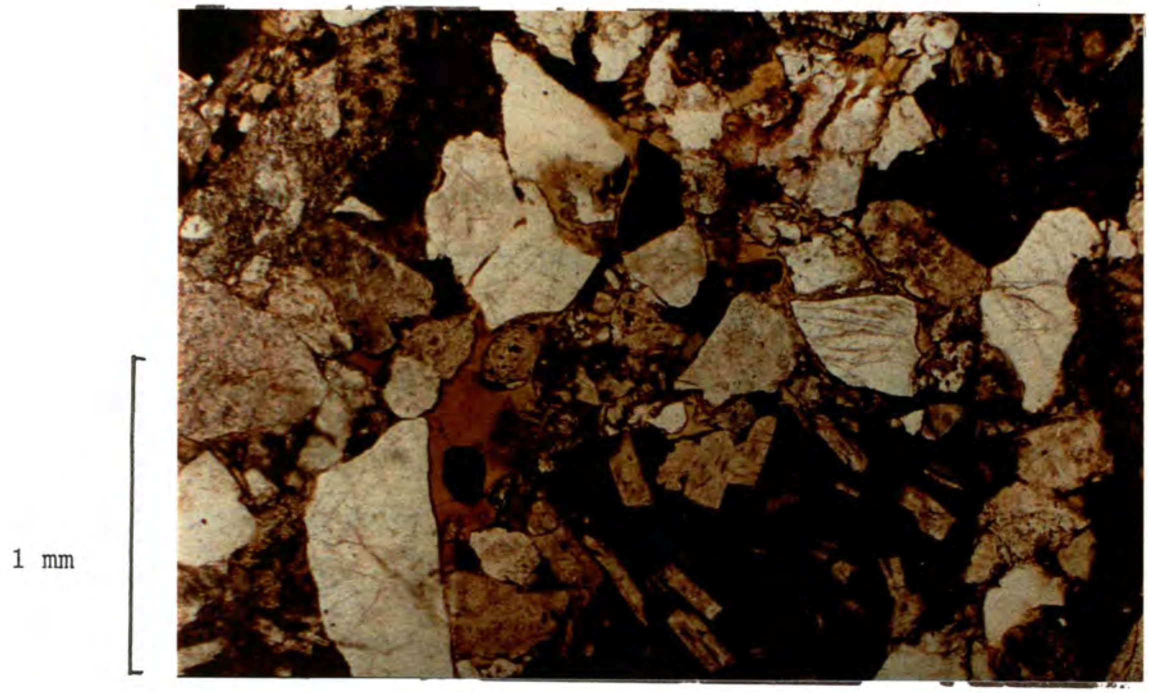


Figure 17a. Photomicrograph of Tertiary sedimentary rocks from study area (plane polarized light) (sample no. 92-AN_2).

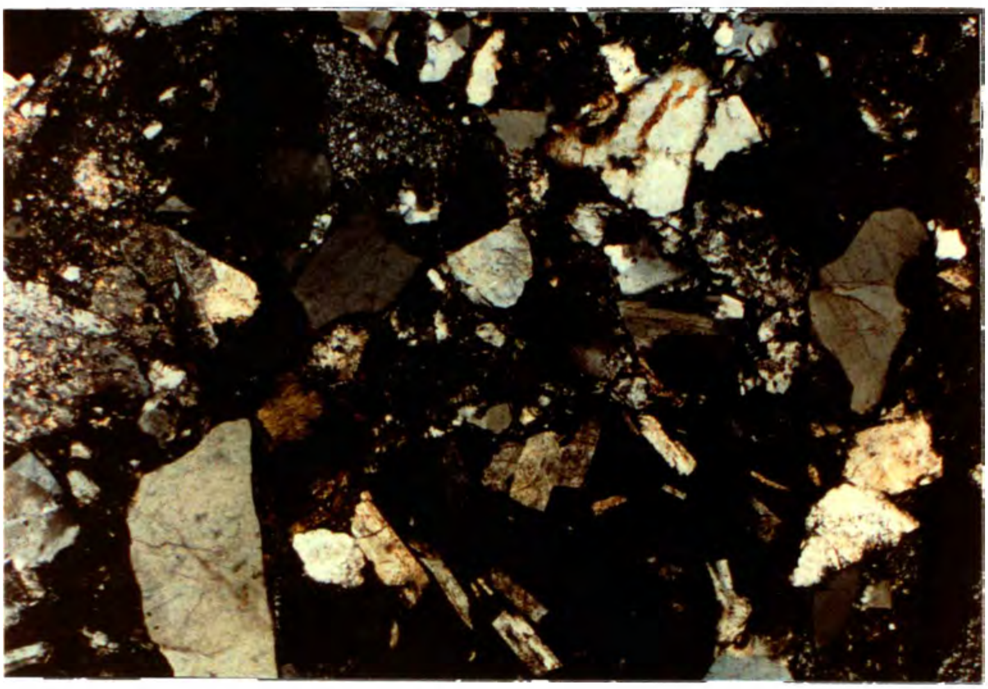


Figure 17b. Photomicrograph of sample 92-AN_2 under cross polarized light.

plots (Figs. 18a-e) are used for broad comparison purposes; these plots would require considerably more data to be considered fully representative of the units.

Twin Sisters Tertiary sedimentary rocks are distinguished in four ways from the observed Chuckanut and Huntingdon rocks: (1) greater abundance of volcanic lithic grains, (2) more polycrystalline quartz, (3) less mica in any size fraction, and (4) no potassium feldspar. Basal Chuckanut and Huntingdon samples from Frizzell contain volcanic lithic grains and are similar in this respect to the Twin Sisters deposits. Typically the Chuckanut Formation is deficient in volcanic lithic grains (Suczek, 1981, personal commun.). The large spread in the Chuckanut points in figure 18b reflects this variation in composition.

Dacitic volcanic lithic grains are abundant in the Twin Sisters sedimentary rocks, although more mafic volcanilithics are present in lesser amounts. The matrix of dacitic grains appears identical to polycrystalline quartz except that euhedral and subhedral quartz and feldspar phenocrysts are present (Fig. 19). When disaggregated into finer fractions the matrix of these grains would probably be counted as polycrystalline quartz. Nevertheless, where identifiable as volcanic matrix, these points were counted as such to indicate the provenance. This method of counting affects comparison of these rocks with other finer-grained polycrystalline quartz-bearing sediments. Thus, other workers possibly would have percentages in which these rocks group closer to the two basal Chuckanut samples in figures 18a and b.

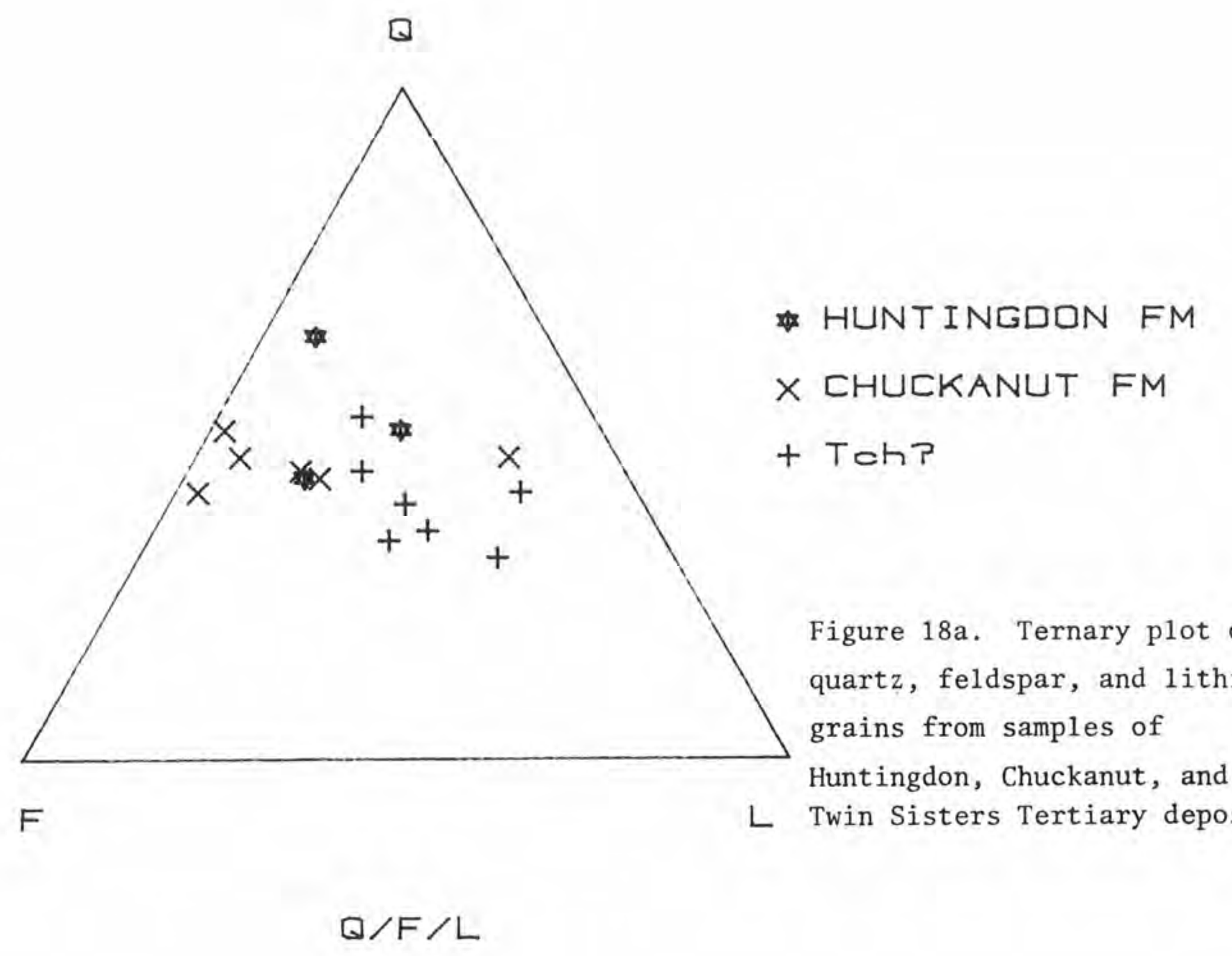


Figure 18a. Ternary plot of quartz, feldspar, and lithic grains from samples of Huntingdon, Chuckanut, and Twin Sisters Tertiary deposits.

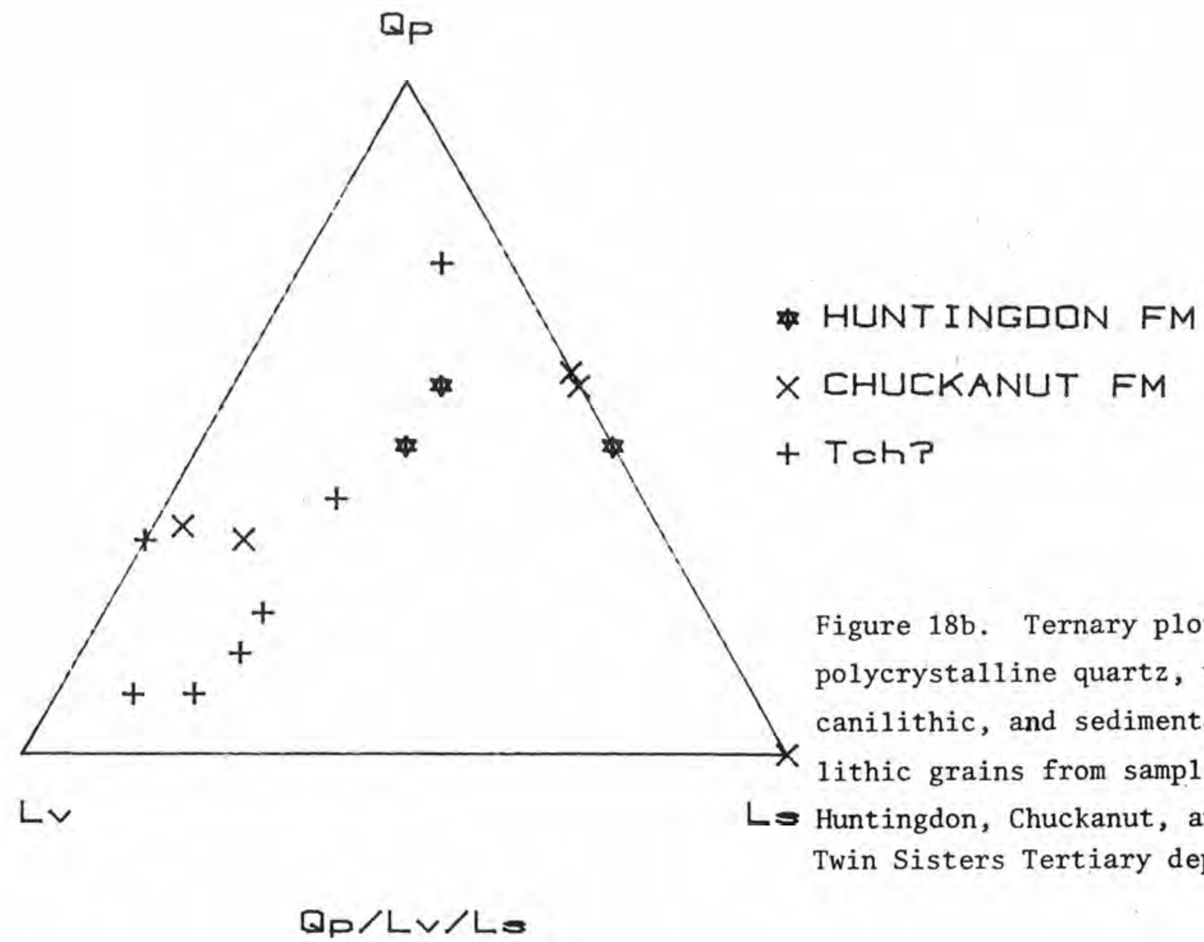


Figure 18b. Ternary plot of polycrystalline quartz, volcanilithic, and sedimentary lithic grains from samples of Huntingdon, Chuckanut, and Twin Sisters Tertiary deposits.

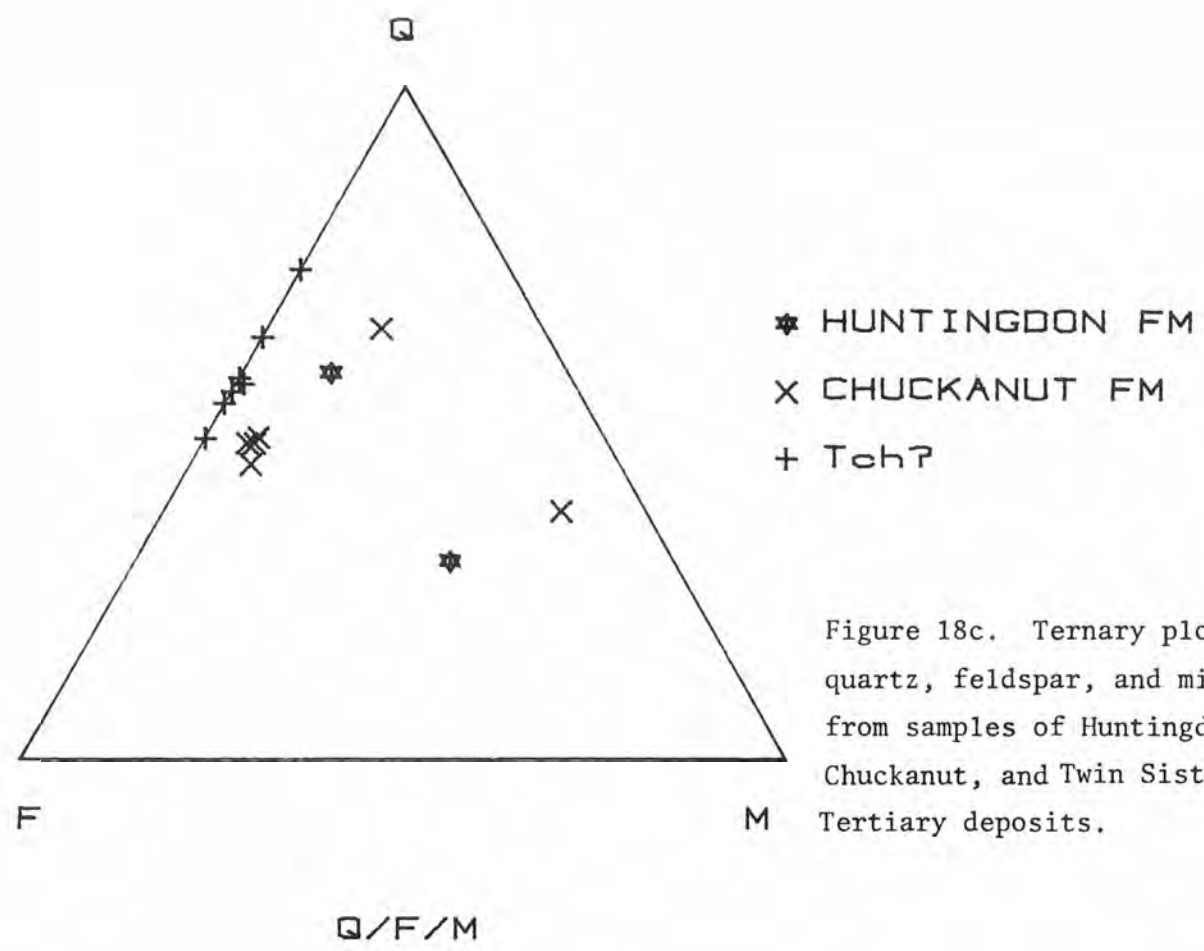


Figure 18c. Ternary plot of quartz, feldspar, and mica from samples of Huntingdon, Chuckanut, and Twin Sisters Tertiary deposits.

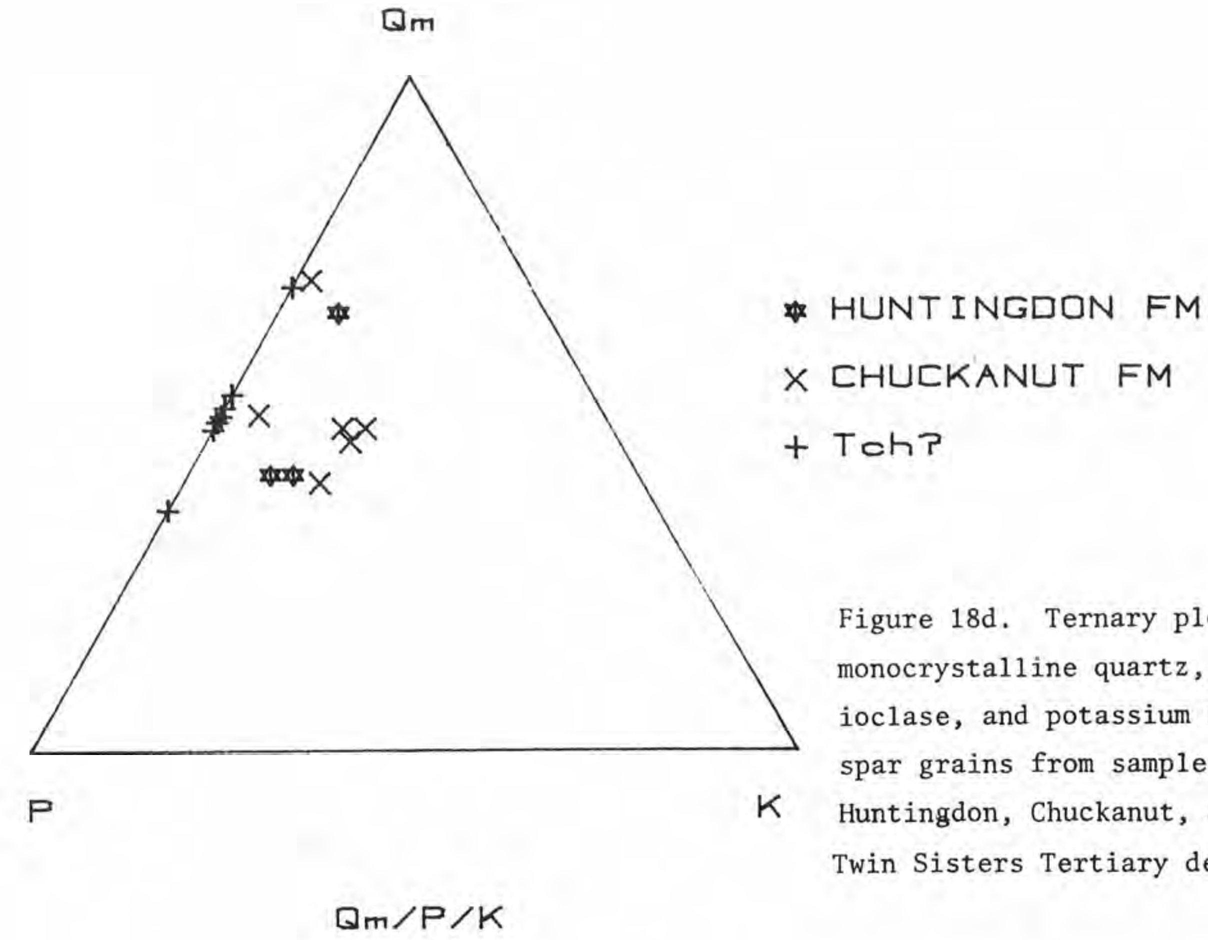


Figure 18d. Ternary plot of monocrystalline quartz, plagioclase, and potassium feldspar grains from samples of Huntingdon, Chuckanut, and Twin Sisters Tertiary deposits.

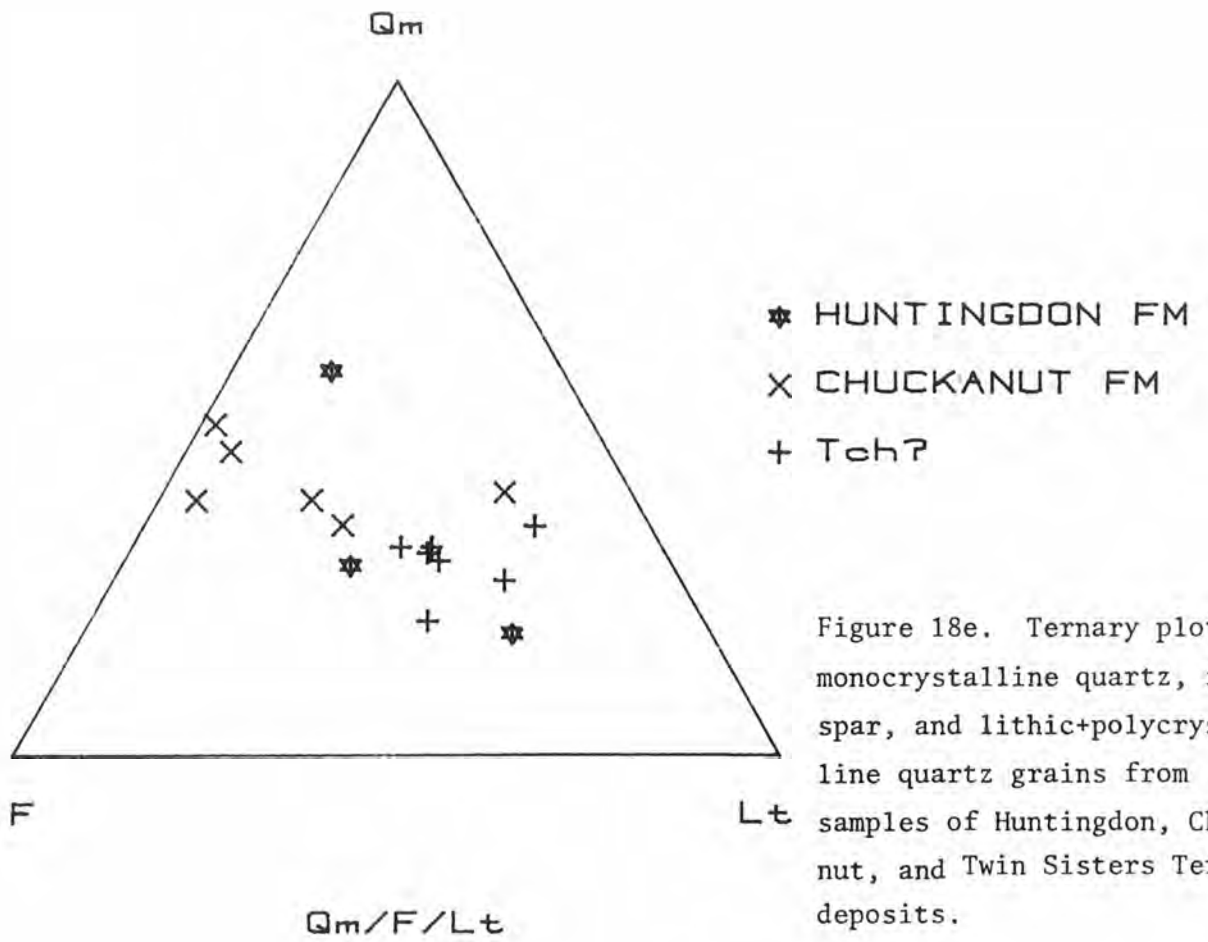


Figure 18e. Ternary plot of monocrystalline quartz, feldspar, and lithic+polycrystalline quartz grains from samples of Huntingdon, Chuckanut, and Twin Sisters Tertiary deposits.

0.25 mm

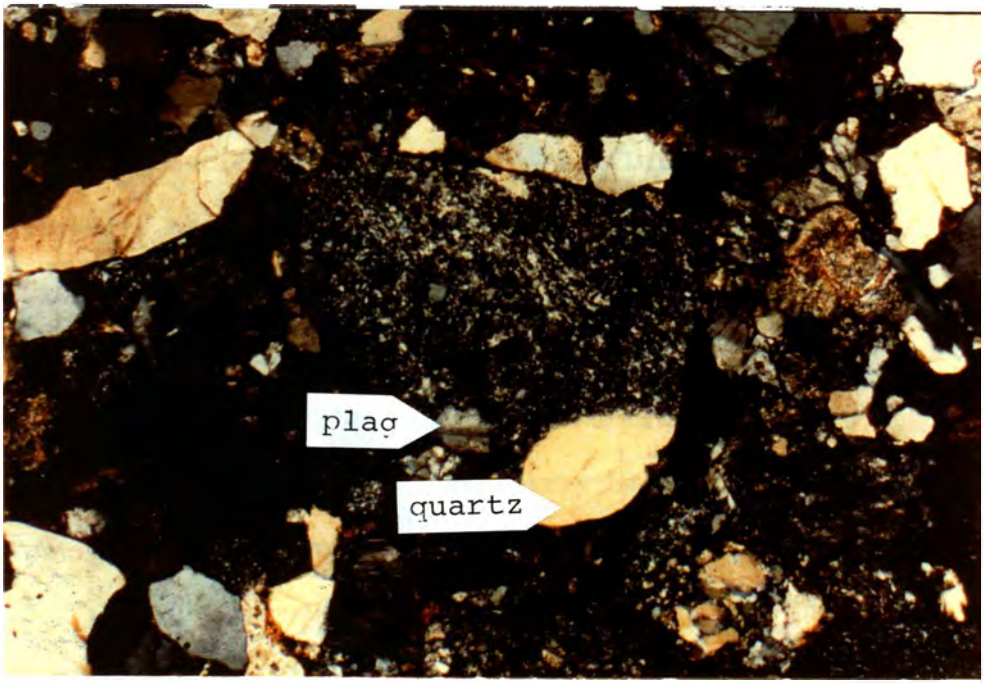


Figure 19. Dacitic volcanilithic grain; resembles polycrystalline quartz grain (sample no. 92-AN_2).

Mica content of the Tertiary rocks in the study area (Fig. 18c) indicates that the provenance was different from that of the Chuckanut Formation across the Middle Fork of the Nooksack River and the Huntingdon Formation.

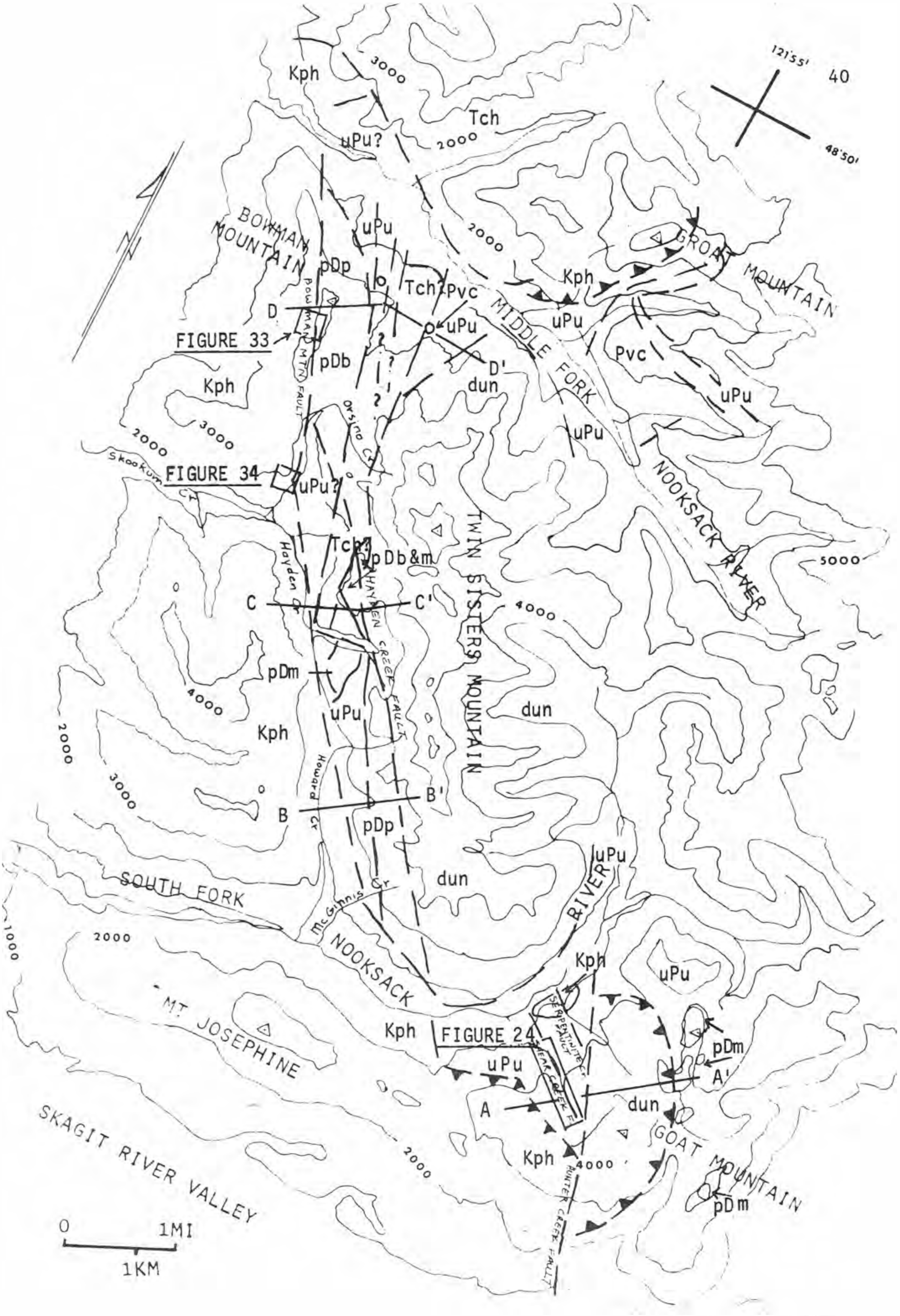
Lack of potassium feldspar in samples from the study area (Fig. 18d) may indicate a different provenance; alternatively it may be caused by diagenetic processes related to fluid migration along the many faults here, and insufficient sampling. Diagenetic alteration of potassium feldspar is known to occur in Chuckanut deposits (Pevear, 1981, personal commun.).

Although distinct from typical Chuckanut Formation, these deposits do bear some similarities to the nearby basal Chuckanut and more distant Huntingdon Formations. Comparison of the Twin Sisters deposits with Chuckanut and Huntingdon deposits are inconclusive regarding correlation, thus the assignment of these rocks to the Chuckanut Formation is tenuous at best. It follows the designation made by Ragan.

Figure 20. Explanation and simplified geologic map of the study area.

Tch?	CHUCKANUT FORMATION (QUESTIONABLE)
Kph	CRETACEOUS PHYLLITE
Pvc	PERMIAN VEDDER COMPLEX
uPu	CHILLIWACK GROUP (UNDIFFERENTIATED)
	YELLOW ASTER COMPLEX
pDb	META-GABBRO
pDp	CLINOPYROXENITE
pDm	META-TONALITE
dun	DUNITE
	FAULT TRACE, HIGH-ANGLE
	FAULT TRACE, DIP LESS THAN 30 DEGREES

(GEOLOGY NORTH OF MIDDLE FORK NOOKSACK FROM RADY, 1980; AND JOHNSON, 1981, PERSONAL COMMUN.)


121°55'
48°50'
Kph
3000
Tch
uPu?
2000
BOWMAN MOUNTAIN
uPu
2000
GOAT MOUNTAIN
pDp
Tch?
Pvc
Kph
MIDDLE FORK
D
D'
uPu
FIGURE 33
BOWMAN MTN FAULT
pDb
Pvc
Kph
dun
uPu
Orsino Cr
uPu
2000
3000
Skookum Cr
FIGURE 34
uPu?
NOOKSACK RIVER
TWIN SISTERS MOUNTAIN
Tch?
pDb&m
5000
Hayden Cr
HAYDEN CREEK FAULT
C
C'
4000
pDm
4000
dun
uPu
Kph
2000
Howard Cr
3000
B
B'
pDp
uPu
SOUTH FORK
dun
McGinnis Cr
RIVER
1000
2000
NOOKSACK
Kph
uPu
MT JOSEPHINE
Kph
FIGURE 24
SERPENTINITE FAULT
pDm
uPu
BEAR CREEK F
A
A'
dun
SKAGIT RIVER VALLEY
2000
Kph
4000
GOAT MOUNTAIN
HUNTER CREEK FAULT
pDm
0
1MI
1KM

STRUCTURAL INTERPRETATION

The structure of this region is dominated by northwest-trending high-angle fault zones (Fig. 20). These structures are observed along the western side of Twin Sisters Mountain and west and northwest of Goat Mountain. Low-angle faults are also present on Goat Mountain and Bowman Mountain, and are truncated by through-going high-angle fault zones.

High-angle northwest-trending fault zones are mapped along the western margin of the Twin Sisters body, as far north as the Middle Fork of the Nooksack River (Fig. 20). These structures are observed in drainages where erosion of the mantle of Quaternary sediments exposes them. Generally they strike N35°W and dip 50 to 90 degrees. Major faults are mapped in the field on the basis of lithologic discontinuities, and colinear exposures of sheared serpentinite and other bedrock. Prominant trenches (Fig. 21) are commonly the topographic expression of these faults, as they occur along trend of faults defined by the outcrop pattern (Plate I). Shear zones, bedrock exposures, and trenches are plotted on Plate I. High-angle faults are interpreted as major through-going structures because two of the best documented faults, over Bowman Mountain and by Hayden Creek, are traced over several miles. Slickensides, drag folds, and oriented thin sections of folds from within fault zones were observed in order to detect sense of displacement along the faults. However, too few were observed to allow any certainty in the interpreted motions.

West of Twin Sisters Mountain, high-angle fault zones are observed to truncate shallow-dipping structures such as faults,

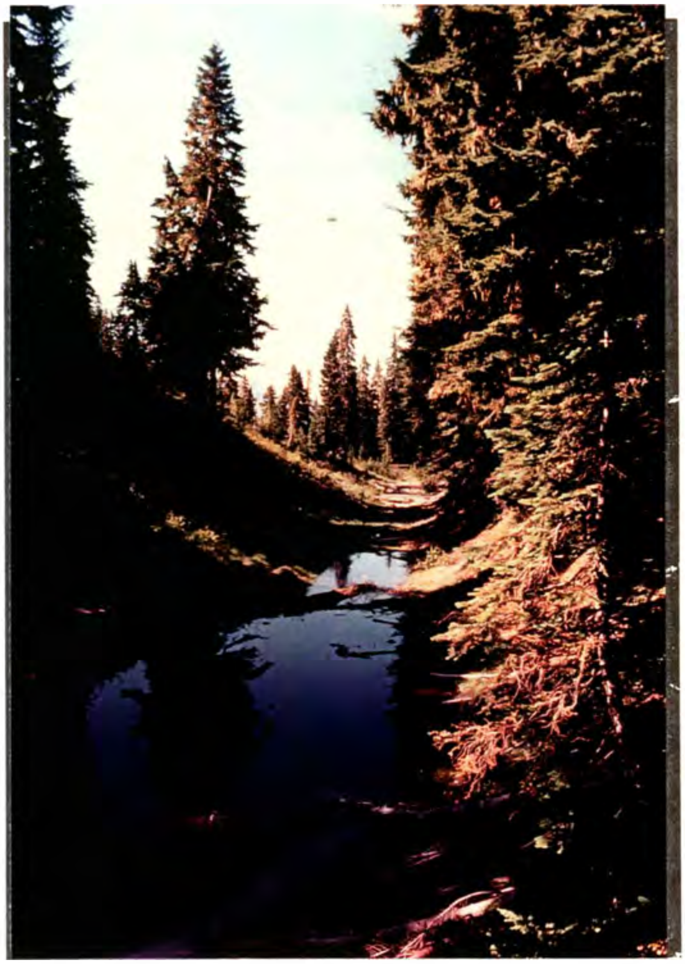


Figure 21. Prominant trench observed along eastern margin of Goat Mountain dunite body.

mylonite zones, and sub-horizontal foliated serpentinite zones. These relationships are evident along the crest of Bowman Mountain, near the junction of Orsino and Skookum Creeks, and immediately to the south of Hayden Creek.

Five major fault zones are mapped in the southern part of the area, in the vicinity of Goat Mountain. The Shear Creek and Serpentinite Creek faults (informally named in this work) are vertical to steeply-inclined serpentinite shear zones exposed along drainages west and northwest of Goat Mountain. The Hunter Creek fault (informally named in this work) is a similar serpentinite shear zone exposed on the wouth side of Goat Mountain. These high-angle structures truncate the west-dipping basal thrust faults of the Goat Mountain dunite and Cretaceous phyllite.

Structural relationships and field observations are described in four east-west cross sections across the study area (Fig. 20). The region is described from south to north, starting with the Goat Mountain area where exposures permit the most detailed analysis of structures in the study area.

Goat Mountain

On Goat Mountain, both westward dipping thrust faults and cross-cutting high-angle faults are mapped. The low-angle west-dipping fault separating Cretaceous phyllite from Chilliwack rocks west of Goat Mountain is not actually observed (Fig. 20, Plate I). Its trace on the geologic map (Plate I) is controlled by exposures of the two units. Similarly, the trace of the low-angle west-dipping base of the dunite body is controlled by bedrock exposures, and only at one point was observed in contact with underlying Chilliwack rocks at a locality in an unnamed creek bed east of Goat Mountain (Plate I). In contrast, the vertical to 70 degree-east-dipping Hunter Creek fault is easily observed in roadcuts and gullies on the southern face of Goat Mountain (Fig. 8). As the fault contact between Cretaceous phyllite and Chilliwack rocks dips westward at a low angle (as defined by bedrock exposures) and the observed fault zone is vertical to east-dipping, the Hunter Creek fault is interpreted to truncate the low-angle structure (Fig. 22). Previously the Hunter Creek fault was mapped as the southern exposure of the low-angle fault, and interpreted by Misch (1966) to be part of the west-dipping Shuksan thrust.

A half-mile long segment of the Shear Creek fault exposed on northwest Goat Mountain allows detailed study of the structure within the fault zone (Fig. 23). Along the exposed fault, the

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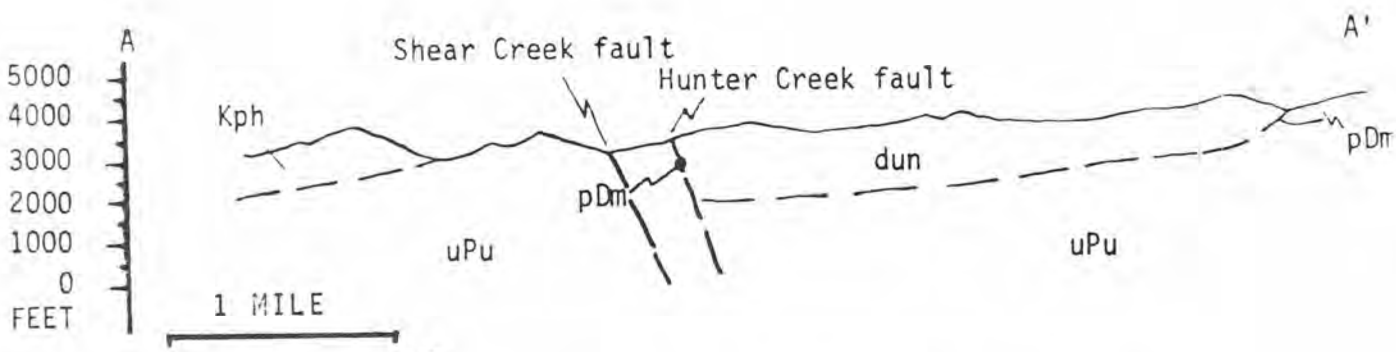

Figure 22. Goat Mountain structural cross section (see figure 20 for legend).

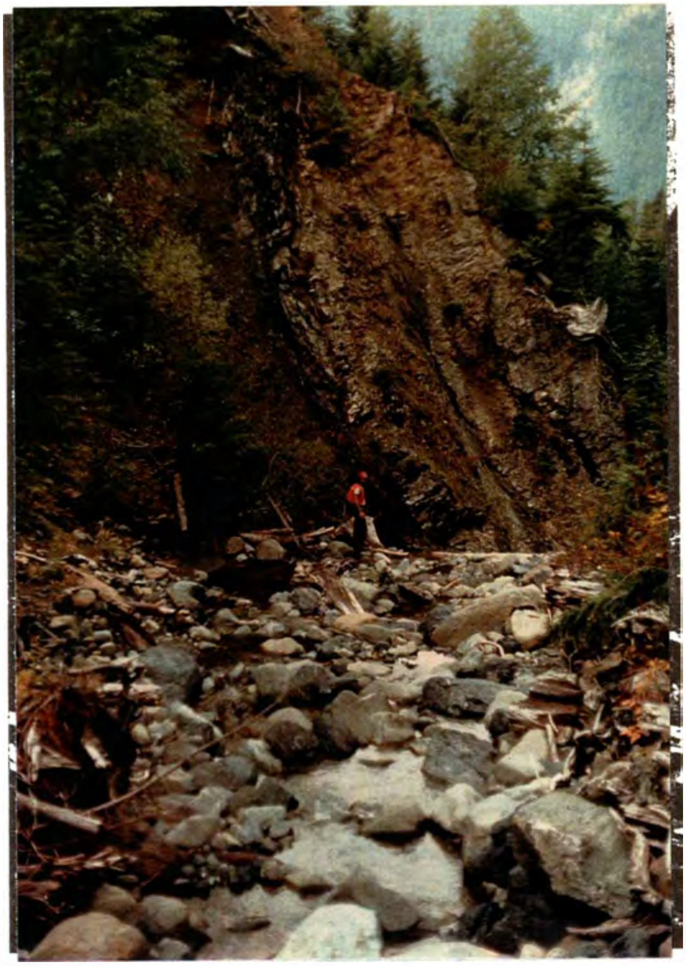

Figure 23. North-facing view along Shear Creek fault zone.

* * *

fabric of the foliated serpentinite strikes N30-50°W, and dips 60 to 90 degrees eastward. The serpentinite is bounded on both sides by sheared and folded Chilliwack slate and meta-volcanic rocks. The attitude of the foliation of the serpentinite varies slightly along the length of the fault, as in the Hayden Creek, Serpentinite Creek, and Hunter Creek shear zones.

The sheared fabric in the Shear Creek fault zone was examined in order to establish the sense of motion along the fault. Both sub-horizontally and steeply plunging folds are observed in the sheared serpentinite (Fig. 24). Sub-horizontal folds are interpreted

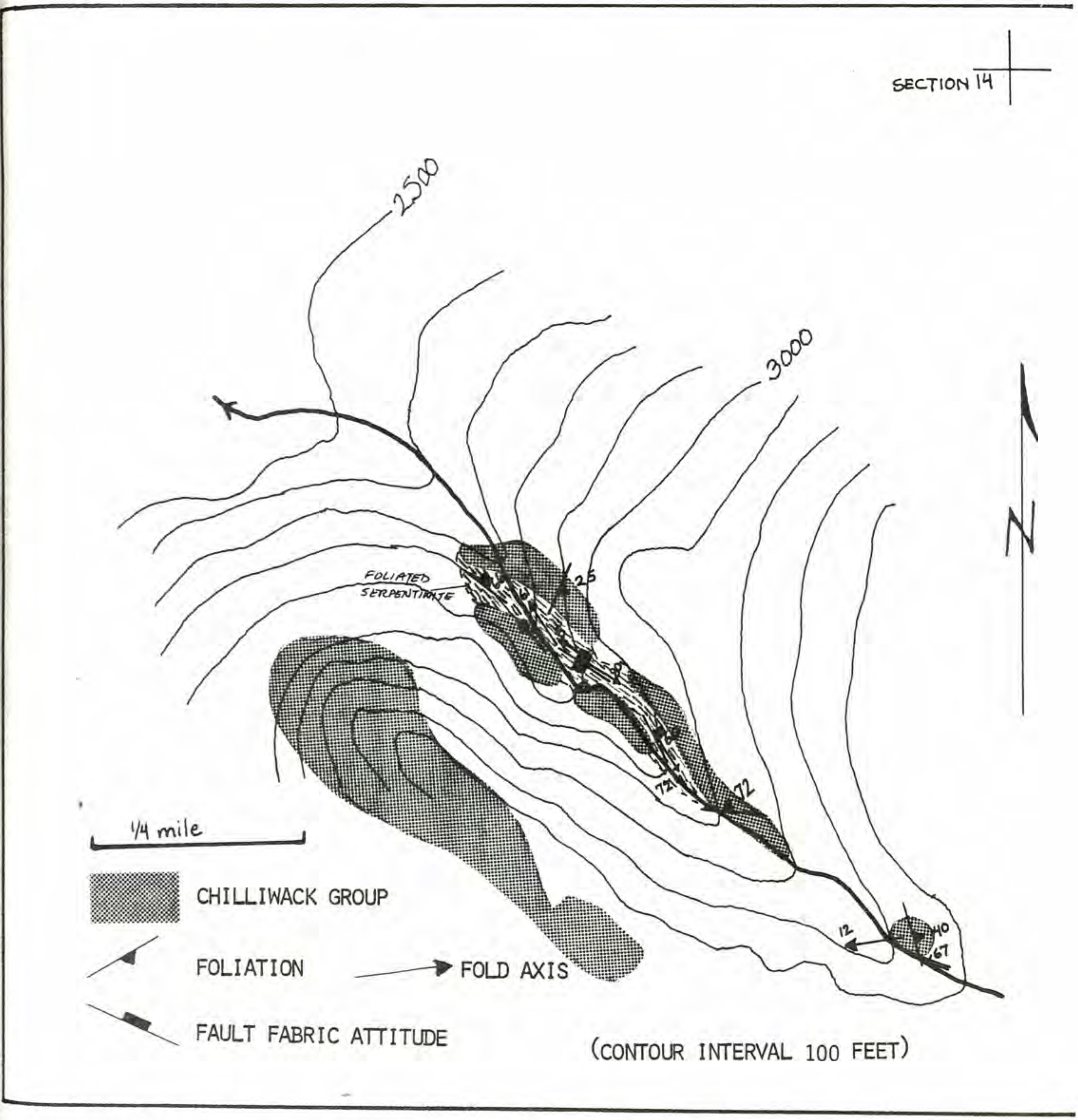

Figure 24. Shear Creek fault expanded geologic sketch map.

to result from dip-slip motion along the fault, whereas steeply plunging folds are the result of a strike-slip component of movement.

Examination of the configuration of units in figure 22 indicates that dip-slip displacement along the high-angle faults was most likely normal. As Chilliwack rocks lie below the tabular dunite body a normal component of movement appears to be responsible for juxtaposition of the Chilliwack rocks with dunite along the body's western margin. Alternately, reverse faulting is conceivable, if the dunite was first imbricated into the Chilliwack rocks, and exists at least 1500 ft. below the ground surface of the footwall block (as this much Chilliwack Group is exposed immediately west of the Hunter Creek fault).

Fault-bound blocks of Yellow Aster meta-tonalite (ca. 15 ft. in diameter) occur along the Hunter Creek fault and along the base of the dunite body (Plate I). If blocks underlying the dunite were incorporated and moved upward along the Hunter Creek fault, there would have to be a normal component of movement. However, the Yellow Aster block observed along the Hunter Creek fault did not necessarily lie at the base of the dunite prior to high-angle faulting. As with other Yellow Aster rocks in the study area, the structural relationships are unclear.

Howard Creek

Figure 25 is an east-west cross section showing the structural relations across the southwest margin of the Twin Sisters body.

Attitudes of the faults are examined in drainages from Twin Sisters Mountain into Howard Creek. The faults in Cretaceous

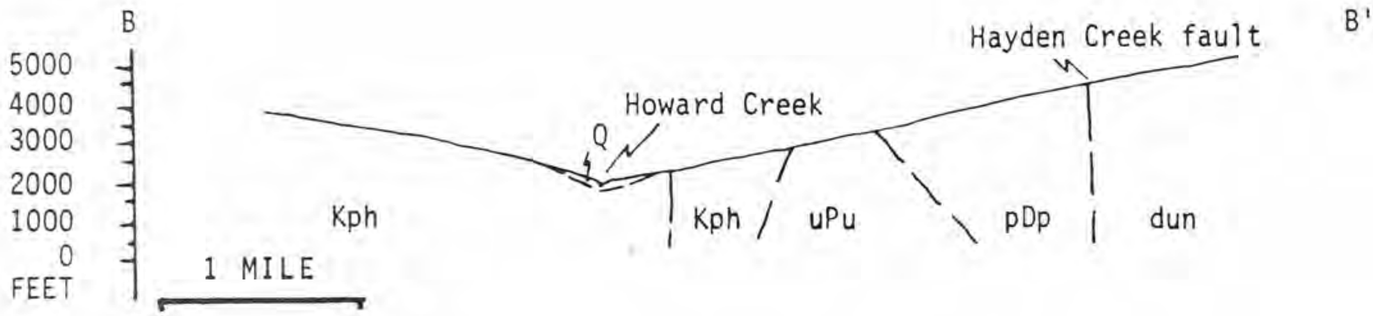

Figure 25. Howard Creek structural cross section (see figure 20 for legend).

* * *

phyllite are exposed in the unnamed creek north of McGinnis Creek, and trend N40°W and dip 80 to 90 degrees eastward. The fault separating Chilliwack rocks from the Cretaceous phyllite is observed in the same creek to be a sheared and deeply weathered fault zone trending N40°W and dipping 70 degrees westward. The fault which juxtaposes Chilliwack rocks and Yellow Aster pyroxenite in McGinnis Creek (Fig. 11) is a well developed, east-dipping serpentinite shear zone 45 ft. wide (Fig. 26). Developed within this zone is a 30 centimeter wide, highly sheared serpentinite zone which trends N50°W, and dips 50 degrees eastward. This attitude is assumed to be the same 1.5 miles northward, along the line of section, as the fault is not observed in this area. The Hayden Creek fault, which separates Yellow Aster pyroxenite from Twin Sisters dunite, is exposed in the gorge at the head of Hayden Creek from where it can be traced south along the dunite margin. The

Figure 26. Fault plane in serpentinite shear zone along western margin of clinopyroxenite unit exposed in McGinnis Creek.

Figure 27. Northwest-facing view of drag folds in Cretaceous phyllite (eastern block was uplifted).

fault is topographically expressed as a series of aligned trenches each occurring in a small saddle along the dunite margin between Hayden and McGinnis Creeks (Fig. 11).

Although high-angle faults are well documented in this area, no evidence suggests the presence of low-angle structures comparable to those mapped on Goat Mountain.

Structures associated with some of these faults allow determination of their sense of motion. Drag folds developed in phyllite along the faults (Fig. 27) in the western part of figure 25, plunge 28 degrees, N24°W. This attitude together with the observed vergence provide evidence for uplift and northward displacement of the northeastern block relative to the southwestern block along this fault. Slickensides are well developed in the 30 centimeter-wide sheared serpentinite observed in McGinnis Creek. The horizontal attitude of the slickensides indicates that at least the latest displacement was strike-slip, provided the fault has not been substantially folded. Evidence for movement along the Hayden Creek fault is examined in the next section.

Hayden Creek

A structural cross section across the area just north of Hayden Creek (Fig. 28) shows the complex relationships seen in this area. The greatest variety of rock types and faults of the entire study area occurs here. The dominant structure is the Hayden Creek fault zone, which varies in width from ten to three hundred feet (Fig. 29). Incorporated along the fault are blocks of Yellow Aster meta-tonalite, Vedder Complex barroisitic schist, and Chilliwack limestone and slate. Oriented thin sections of sheared rock from

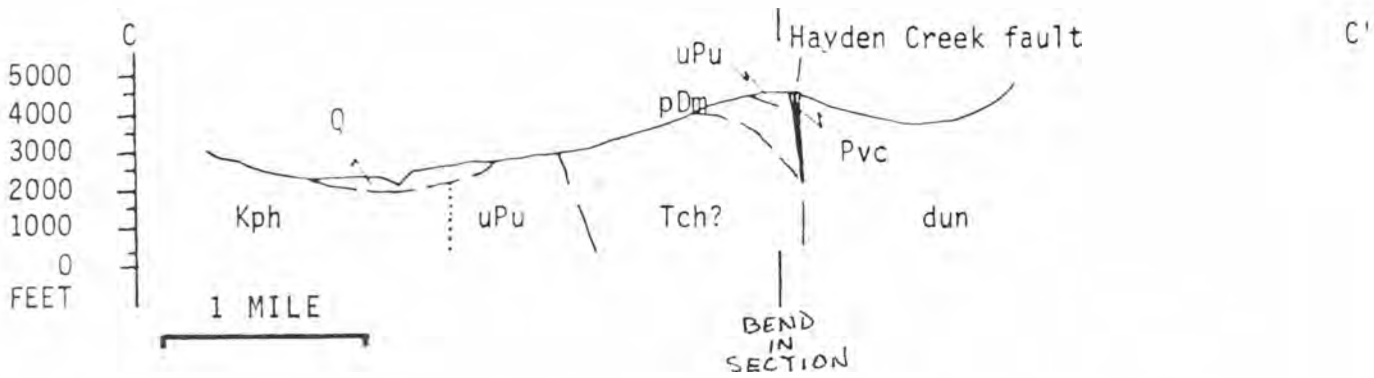

Figure 28. Hayden Creek structural cross section (see figure 20 for legend).

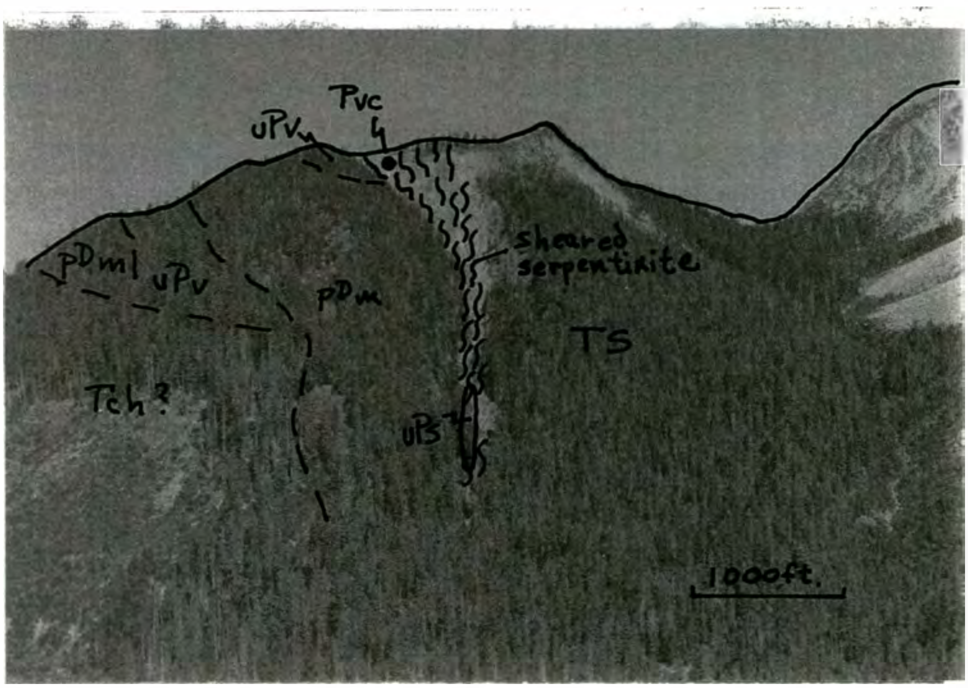

Figure 29. North-facing view of Hayden Creek fault zone in the vicinity of structural cross section C-C' (TS=dunite, pDm=Yellow Aster meta-tonalite, uPv=Chilliwack volcanic rocks, uPs=Chilliwack slate and limestone, Tch?=Chuckanut Fm.?).

the fault zone indicate a left-lateral sense of strike-slip displacement and relative down-dropping of the northeastern block (Fig. 30).

Yellow Aster meta-tonalite and Chilliwack meta-volcanic rocks overlie Tertiary sedimentary rocks adjacent to the Hayden Creek fault, mostly along high-angle faults dipping 40 to 60 degrees east, however at one locality the contact is observed to be horizontal. These structures seem to be related to the high-angle Hayden Creek fault.

Low-angle structures may be preserved in rocks immediately south of Hayden Creek, where well developed sub-horizontal faults, fractures, and mylonite zones (Fig. 31) are exposed in Yellow Aster meta-tonalite. These Yellow Aster rocks may have been imbricated

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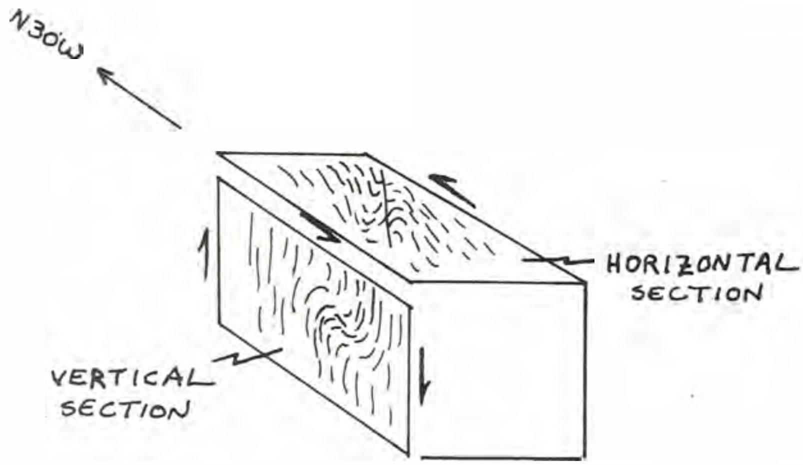

Figure 30. Diagrammatic representation of two oriented thin sections taken from Chilliwack meta-sediments in the N30°W trending Hayden Creek fault zone.

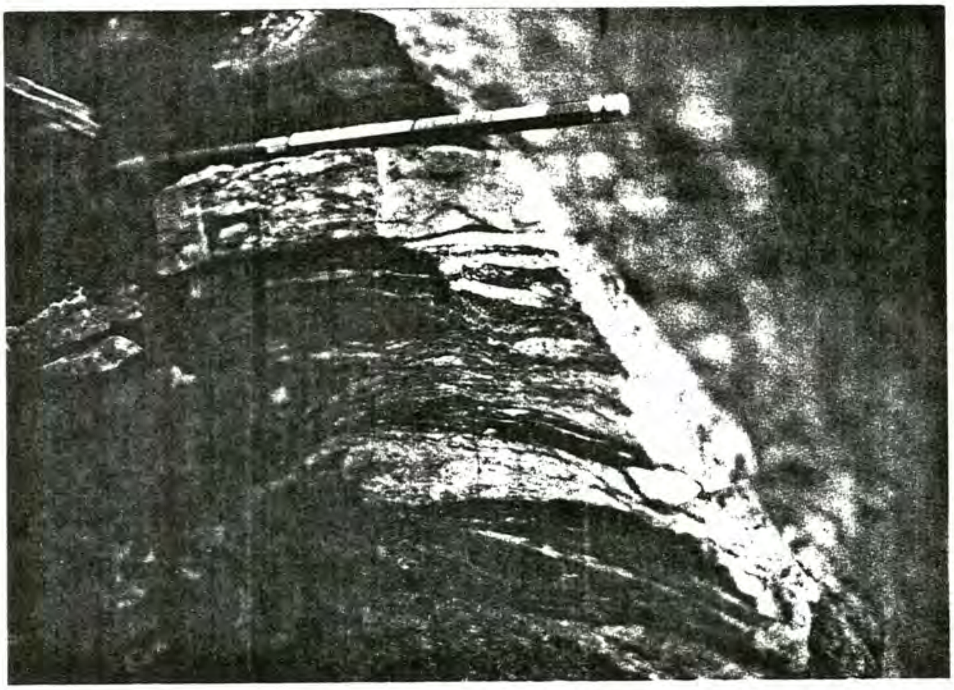

Figure 31. Sub-horizontal mylonite fabric in Yellow Aster meta-tonalite south of Hayden Creek.

* * *

into Chilliwack rocks in a manner similar to that described elsewhere by Misch (1966), where the structures pre-date high-angle faulting.

Bowman Mountain

Structures in the Bowman Mountain area consist principally of steeply-dipping northwest-trending faults (Fig. 32). Due to poor exposures at low elevations, structural relationships below 3000 feet are vague. Bowman Mountain is a complex of fault-bounded units of meta-gabbro, meta-diorite, Chilliwack meta-sedimentary rocks, and Tertiary sedimentary rocks (Fig. 20, Plate I). At the top of Bowman Mountain (Plate I), Chilliwack slates and phyllonites are faulted against meta-gabbro along both vertical and moderately inclined faults. The base of the gabbroic rocks appears to dip

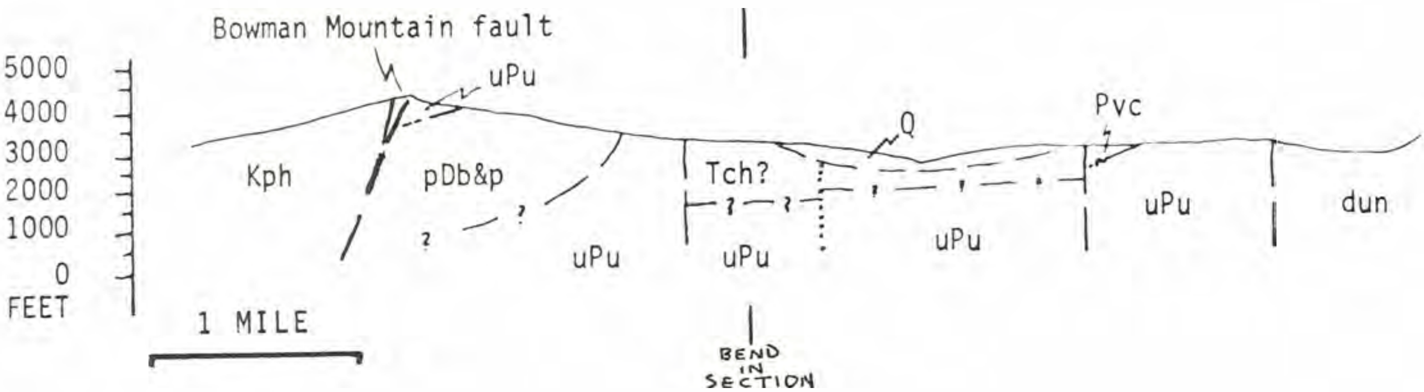

Figure 32. Structural cross section of the Bowman Mountain area.

* * *

westward toward the Bowman Mountain fault (informally named in this work), but due to poor exposure in the Middle Fork valley, there is little structural control. Exposures in the saddle to the south display a low-angle serpentinite shear zone.

Low-angle structures on Bowman Mountain may be related to the orogenic episode(s) responsible for thrust faults on Goat Mountain and structures south of Hayden Creek. In the saddle two-thirds of a mile south of Bowman Mountain, a low-angle serpentinite shear zone (N10^{o}E, 20E) is overlain by Cretaceous phyllite (Fig. 33). This shear zone terminates on the west against the high-angle Bowman Mountain fault. This structural configuration is similar to truncated thrust faults observed on Goat Mountain (Fig. 22). Figure 34 is an expanded sketch map of the southern Orsino Creek area in which are exposed similar structures to those observed in the Bowman Mountain saddle. This area also has an eastward-inclined serpentinite shear zone overlain by Cretaceous phyllite. High-angle faulting cross-cuts this structure and deforms the phyllite so that foliation is vertical to near-vertical adjacent to the serpentinite.

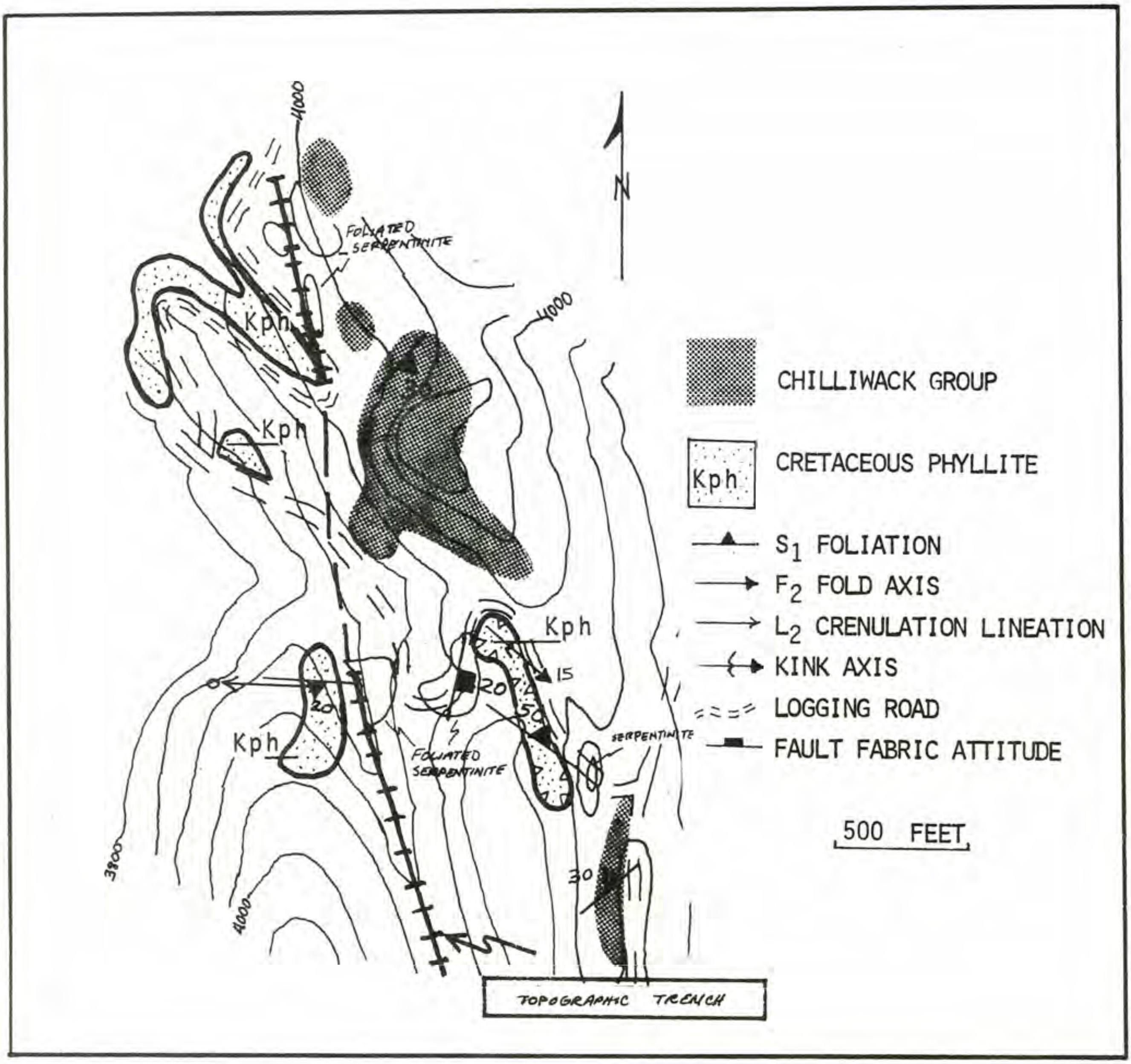

Figure 33. Bowman Mountain saddle expanded geologic map.

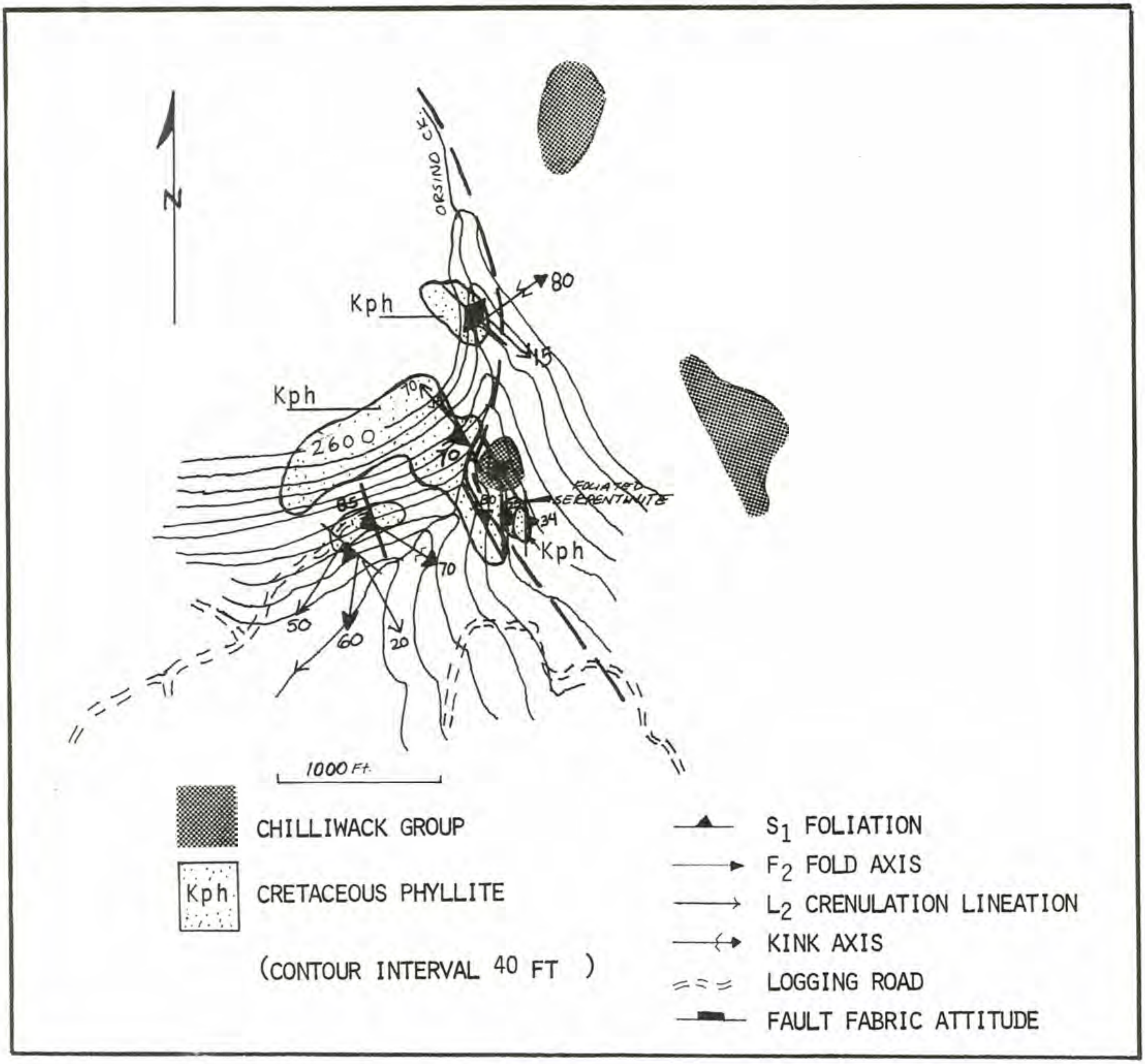

Figure 34. Orsino Creek expanded geologic sketch map.

The Bowman Mountain fault, based on the mapped trace (Plate I), strikes N27^{o}W, dips 60 to 90 degrees westward. It was previously interpreted by Misch (1966) as the folded Shuksan thrust. The attitude of this fault is consistent with those of other high-angle faults in the study area (Hayden Creek, etc.) and it therefore is interpreted in this study to be the northern extension of one of these structures.

Many of the minor faults observed on Bowman Mountain strike nearly east-west, at a high angle to other structures observed in the area. These are perhaps (1) structures related to Chilliwack-Yellow Aster juxtaposition prior to the development of northwest trending faults, or (2) synthetic faults associated with inferred faulting along the Middle Fork of the Nooksack River (see Summary and Discussion).

Tertiary sedimentary rocks occur in this area. Fault contacts are observed on logging roads on northwest Bowman Mountain between the Tertiary rocks and Chilliwack meta-sedimentary rocks. These faults are generally high-angle, although a low-angle (30^{o} north-dipping) fault is also exposed. The absence of a wide band of sheared rock along the low-angle fault (in contrast to that observed along the vertical fault) suggests it is a slightly sheared depositional contact. As Tertiary rocks are not encountered below an elevation of 2000 feet on the south side of the Middle Fork of the Nooksack valley, it is probable that they overlie Chilliwack rocks which are found below this elevation.

The fault-bounded nature of these deposits suggests the possibility of deposition in a faulted basin. Insufficient knowledge of the stratigraphy of this unit does not preclude this possibility, thus

SUMMARY AND DISCUSSION

Field evidence indicates that at least two episodes of faulting were involved in emplacement of the Twin Sisters and Goat Mountain ultramafic bodies. Exposures on Goat Mountain suggest that the Goat Mountain dunite and Cretaceous phyllite were emplaced onto Chilliwack rocks along thrust faults. The relationships of these two thrusts to each other prior to high-angle faulting is not known. High-angle oblique-slip faults are superimposed on the low-angle structures.

The Twin Sisters dunite body apparently underwent a similar history to the Goat Mountain body. Thompson and Robinson (1975) concluded from gravity and aeromagnetic studies that the Twin Sisters body is a flat-based, sub-horizontal slab 6000 ft. thick. This corresponds with the general shape of the Goat Mountain body as determined in this study by mapping.

High-angle faults in this area are through-going structures that cut across and juxtapose the various rock units. This interpretation is in contrast to the hypothesis of Thompson and Robinson (1975), who suggest that high-angle faults observed by Ragan (1961) were probably the result of remobilization of the dunite due to serpentinization. They cite the high aeromagnetic anomaly along the western margin of the Twin Sisters and Goat Mountain bodies as evidence for the presence of serpentinite below the dunite in this area. Serpentinite is highly magnetic due to the presence of magnetite derived from alteration of olivine during serpentinization of the dunite. Thompson and Robinson postulate that the serpentinite is extensive at depth as indicated by the broad magnetic anomaly. In the Goat Mountain body a well developed basal serpentinite zone is not present. Thus, if high-angle faults on Goat Mountain are not caused by remobilization of the dunite due to basal serpentinization, those west of the Twin Sisters probably are not either. The high aeromagnetic anomaly registered in these areas is probably caused by serpentinite observed along the high-angle fault zones.

Three hypotheses have been advanced which attempt to explain thrust emplacement of the Twin Sisters dunite. Christensen (1971) suggested that the dunite was imbricated along the Shuksan thrust in the same manner as rocks of the Yellow Aster Complex. As no Cretaceous phyllite overlies the dunite, and the west-dipping thrust faults may not represent the Shuksan thrust (as discussed earlier), I must question the validity of this model. Another model (Whetten and others, 1980) correlates the Twin Sisters and Goat Mountain dunite bodies, serpentinized peridotites, and tentatively the Bowman Mountain meta-gabbro, with mafic and ultramafic rocks of the Haystack thrust plate. This plate would have been emplaced in the Late Cretaceous and would be the highest thrust in the Shuksan thrust system. Subsequent dissection by erosion and Tertiary faulting would account for its scattered distribution. Alternately, Vance and others (1980) suggest that many of these same rocks define a similar Jurassic ophiolite which was emplaced in the mid- to Late Cretaceous, prior to major Shuksan-Church Mountain thrusting. Results of the present study are consistent with both of these hypotheses.

The structural association of the Yellow Aster and Vedder Complex rocks relative to the dunite bodies is unclear. On Goat Mountain, Yellow Aster rocks occur along the basal thrust of the dunite and may subsequently have been carried upward along the high-angle Hunter Creek fault. There is not sufficient information to indicate whether the Yellow Aster Complex and the dunite were emplaced over Chilliwack rocks at the same time or in separate events. However, the dunite lacks sub-horizontal shear zones corresponding to mylonite zones observed in the Yellow Aster meta-tonalite, suggesting that two separate events are responsible for their emplacement.

The timing of the faulting is poorly constrained in the study area. High-angle faults are interpreted to have had at least some Tertiary or Quaternary movement, as they cut Paleocene-Eocene sedimentary rocks of the Chuckanut Formation, mapped north of Hayden Creek (Fig. 20). Generally, Quaternary glacial deposits are not cut by the fault zones. However, at some localities (along the Hayden Creek fault and along the eastern margin of the Goat Mountain dunite) well defined trenches are developed in Quaternary (Holocene?) deposits along these fault zones. These trenches are perhaps due to minor Holocene? re-activation along the fault zones. The mid-Cretaceous age assigned to the phyllite constrains the oldest movement possible along the basal phyllite thrust. The thrust emplacement of dunite over the Chilliwack may or may not have occurred contemporaneously with phyllite emplacement. A pre-Paleocene age for thrusting is indicated by the presence of

Chuckanut Formation unconformably overlying Cretaceous phyllite north of the Middle Fork of the Nooksack River. High-angle faults cut Paleocene-Eocene strata, indicating at least latest Eocene movement. However, there is no constraining evidence regarding possible Paleocene-Eocene, or even pre-Paleocene (to post mid-Cretaceous) displacement along the high-angle faults. In summary, thrusting can be documented to have occurred in this area sometime between the mid-Cretaceous and the Paleocene; high-angle faulting occurred sometime from the mid-Cretaceous through the Tertiary, and perhaps as recently as the Holocene.

As a result of the relatively sparse exposures of bedrock, there are alternative ways of locating some of the contacts and fault traces presented on Plate I (Figs. 35a and b).

Particularly noticeable is the fact that high-angle faults west of Goat Mountain and Twin Sisters Mountain appear to be major deep-seated structures, and are not continuous across the South and Middle Forks of the Nooksack River. Sam Johnson, of the University of Washington, has mapped the undisturbed basal contact of the Chuckanut Formation north of the Middle Fork of the Nooksack, where faults from the study area project northward. Northwest of Goat Mountain, the Shear Creek, Hunter Creek, and Serpentinite Creek faults terminate at the South Fork, with only massive dunite along trend to the north. These faults either are discontinuous over large distances and do not cut the Chuckanut or dunite deposits, or else there are faults along the South and Middle Forks of the Nooksack River which truncate them. The latter argument requires

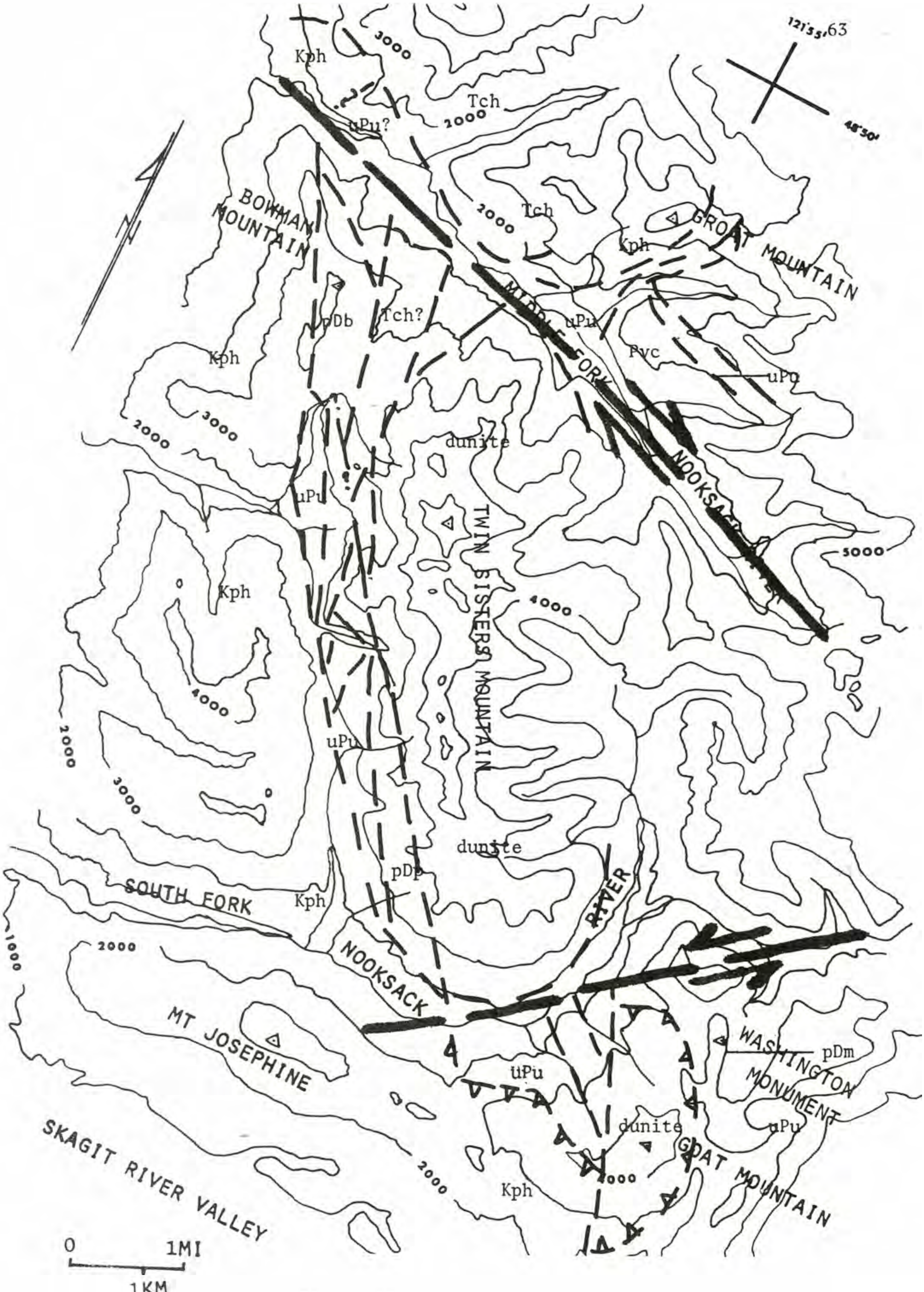

Figure 35a. Simplified geologic map of Twin Sisters area showing faults inferred along South and Middl Forks (see Fig. 20 for legend).

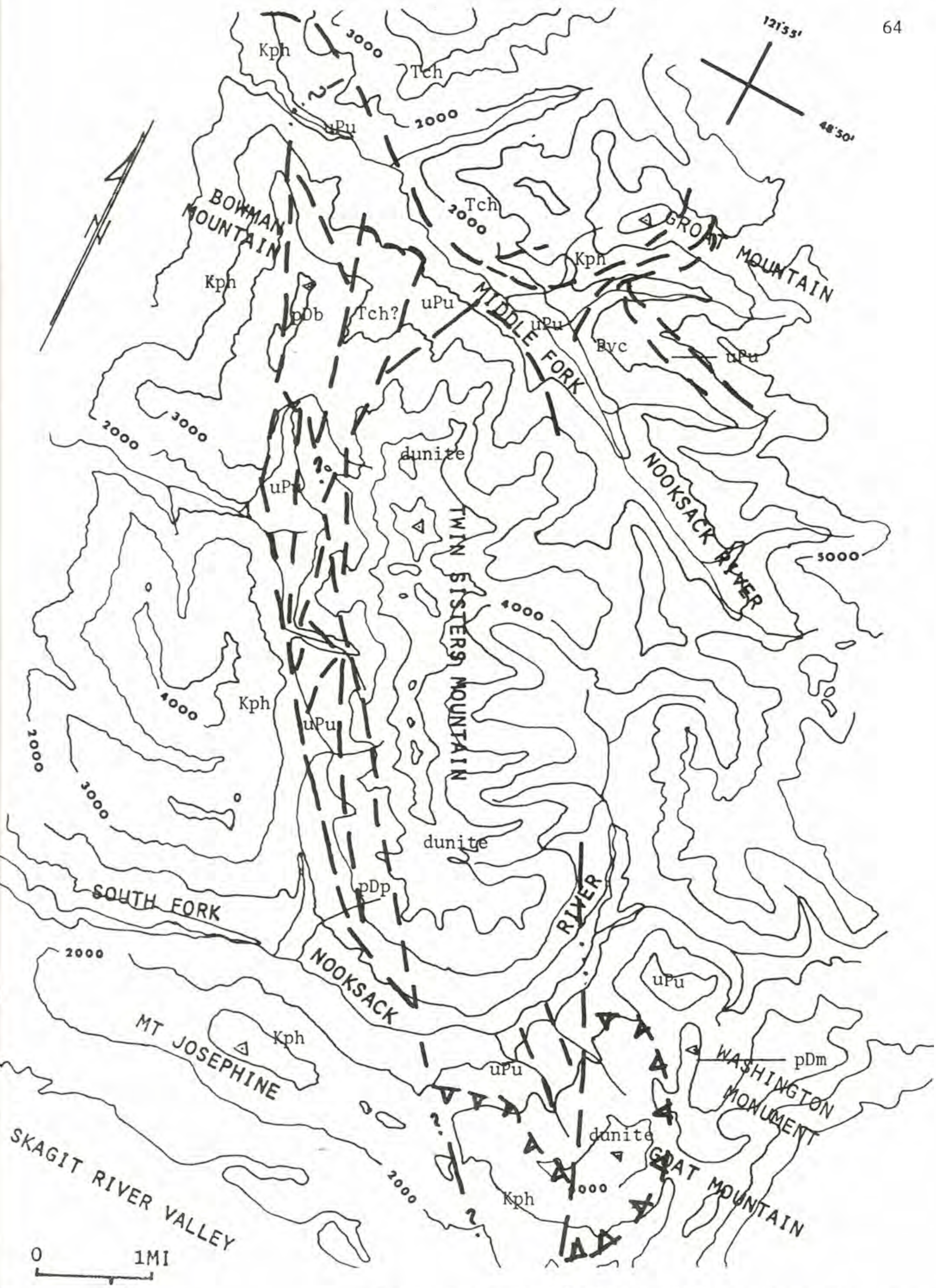

Figure 35b. Simplified geologic map of Twin Sisters are without faults along South and Middle Forks but with possible extensions of high-angle faults (see Fig. 20 for legend).

that major high- and low-angle fault zones west of Goat Mountain and Twin Sisters Mountain and east of Groat Mountain were once a continuous structurally complex belt approximately one mile wide. The fault inferred along the Middle Fork would trend approximately N70°W and coincide with a prominant topographic lineation which can be traced along the Middle Fork valley north and east of the study area (Fig. 35a). The fault inferred along the South Fork of the Nooksack, trending approximately N50°E, is based in part on the postulated offset of the high- and low-angle fault zone, and in part on a possible continuation of the structure eastward through a serpentinite shear zone north of Tuckway Lake. Field mapping testing the existence of these structures east of the study area is in progress (Blackwell, 1981, personal commun.).

Four regionally significant conclusions are documented in this study:

1) the Goat Mountain and presumably the Twin Sisters dunite bodies and Cretaceous phyllite were emplaced along thrust faults prior to high-angle faulting;
2) major high-angle oblique-slip fault zones modify the pre-Late Eocene geology and may be active as late as Holocene;
3) faults may exist along the Middle and South Forks of the Nooksack River, truncating high-angle northwest-trending faults;
4) the Cretaceous phyllite unit may not be correlative with the Darrington phyllite, with which it was previously correlated.

Field evidence presented in this study for the Goat Mountain area, as well as geophysical evidence in the Twin Sisters area (Thompson and Robinson, 1975), indicate that these dunite bodies were emplaced over Chilliwack rocks along thrust faults. The fault below the Goat Mountain body presently dips westward, but no evidence was found to determine the direction of thrusting. Both bodies are assumed to have been emplaced during the same orogenic event, due to the similarity of the rock types, and the proximity of the bodies to each other.

The orogenic event that emplaced Cretaceous phyllite over Chilliwack rocks on Goat Mountain may or may not be the same as the event responsible for dunite emplacement. The orogenic event(s) responsible for both these structures is probably correlative with mid- to Late Cretaceous thrusting recognized elsewhere in the North Cascades (Misch, 1966).

High-angle oblique-slip Tertiary fault zones, some containing wide serpentinite zones, dominate the structural grain of the study area. Previous studies placed little or no significance on the presence of such structures. However, the preponderance of high-angle faults in this area suggests that they should be observed in the surrounding areas as well and have perhaps been overlooked or misinterpreted in past studies. The high-angle Sutter Mountain fault was originally extended into this area by Ragan (1961), who later retracted this hypothesis (in Misch, 1966). In light of the present study, the original extension of the Sutter Mountain fault may indeed be valid.

Similar but larger structures than those observed on Goat Mountain are described in the Darrington and Sultan areas (Vance and Dungan, 1977) south of the Skagit River (Fig. 3). These are northwest-trending steeply-west-dipping en echelon fault zones containing sheet-like peridotite masses. Tertiary sedimentary and volcanic rocks are cut by the fault zones. These structures are not precisely along strike with structures in the Twin Sisters area, but might be either southern en echelon continuations, or the same complex zone offset along a possible fault in the Skagit River valley. The latter idea is consistent with offset of the structural belt suggested in this study.

Phyllite and phyllonite in the western part of the study area are similar to Cretaceous rocks on Groat Mountain. These rocks are texturally different from the Darrington phyllite with which they were previously correlated. This correlation was the prime evidence for the concept of a west-dipping continuation of the Shuksan thrust. If these rocks are a lower grade variant of the Shuksan Metamorphic Suite the concept remains intact. Alternately, rocks west of Twin Sisters Mountain may be allochthonous blocks unrelated to the Shuksan plate, transported primarily along en echelon strike-slip faults. These faults might be related to the right-lateral Straight Creek or left-lateral Devil's Mountain faults (Fig. 3).

Topics requiring further study are the phyllite-phyllonite unit, the Tertiary sedimentary rocks, the clinopyroxenite, and the high-angle faults. Further detailed structural and petrologic studies of the phyllite-phyllonite unit is required before conclusive correlation of these rocks is possible with other meta-sedimentary rocks in northwest Washington. A detailed study of Tertiary sedimentary rocks in the North Cascades should include those mapped in this study. Understanding the precise stratigraphic relation of these deposits to other Tertiary deposits in the region would add constraints on the type and amount of displacement along the Tertiary high-angle faults. The relationship of the clinopyroxenite to the Twin Sisters and Goat Mountain dunite bodies and to the Bowman Mountain meta-gabbro and meta-diorite might be resolved with a detailed study of the clinopyroxenite. Further detailed field mapping is also needed to determine the extent of high-angle faulting in the surrounding areas or northwest Washington.

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APPENDIX A. Mineral assemblages of samples
from study area.

For map units see Plate I.

*1 Hypabyssal-plutonic rock interbedded with Cretaceous phyllite on Bowman Mountain.

*2 Meta-volcanic rocks petrographically similar to rocks interbedded with, and overlying meta-sediments on Mt. Josephine.

I, IIa, IIb, IIIa, IIIb, refer to textural zonations discussed in text.

sphe=sphene, gt=garnet, limon=limonite, stil=stilpmonelane, musc=muscovite, arag=aragonite, cc=calcite, serp=serpentinite, barr=barroisitic, grn=green, myl=mylonite, amyg=amygdular, porph=porphyroblast, //s_1=parallel s_1 foliation

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
Kph*1		x	x		x				x							92-dd_1/8A
Kph*1			x		x	x			x							92-dd_2/8A
Kph*1	arag		x			x										92-dd_3/8A
Kph*1	arag	x	x		x	x	x		x							92-dd_4/8A
Kph*1	arag	x	x		x			musc								92-dd_5/8A
Kph*1			x		x				x							92-$8A_2$
Kph*1			x		x	x									sphe	92-$8A_3$
Kph*1	arag		x		?			musc								92-$8A_3$
Kph*1			x		x	x			x							92-$8A_4$
gs	x		x		x	x			x					Fe-ox?	stil	92-E_1
uPs								x								92-E_7
pDb					?	x							relict			92-F_{2B}
uPs					?			x							IIa	92-F_{2C}
uPs								x							I?	92-F_4
uPs					x	x		x							IIa	92-F_{4B}
uPs					?	x		x							I	92-G_{2B}
uPs		x	x			x		x							IIa	92-G_{3A}
pDb+uPs				x	?	x			x							92-G_4
Kph?						x		x							IIa	92-G_5
Kph?					porph			x								92-G_6
Kph?		x	x			x		x							IIb	92-H_1
uPc		x				x										92-H_8

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
Kph?								x							IIa	$92\text{-}I_4$
Kph		x	x					x							IIIa	$92\text{-}J_5$
Kph								x							IIIa?	$92\text{-}J_{11}$
Kph		x	x		?			x							IIb	$92\text{-}J_{14A}$
gs		x	x		x				x							$92\text{-}J_{16}$
pDb?			relict			x							x	x		$92\text{-}K_2$
uPs					?	x		x						x	IIa	$92\text{-}L_2$
pDm		x	x			x	x									$92\text{-}L_{3A}$
uPs						x									I	$92\text{-}L_{3B}$
dun											x	x	x	x		$92\text{-}L_4$
pDm		x	x			x		x	x							$92\text{-}L_5$
Tch?	cc					x		x							I	$92\text{-}M_1$
Tch?	cc					x									I	$92\text{-}M_4$
uPv					x	x										$92\text{-}M_5$
Tch?						x									I	$92\text{-}M_6$
uPv							x							hi%		$92\text{-}M_{6A}$
uPv?							x		?					hi%		$92\text{-}M_{6B}$
uPs					?	x									I	$92\text{-}N_1$
uPv	cc					x										$92\text{-}N_{2B}$
uPv		x	x		?											$92\text{-}N_{2C}$
uPv	cc				x	x	x	x								$92\text{-}N_3$
uPs						x	x	x							IIa	$92\text{-}N_3$
uPv					x	x							relict?			$92\text{-}N_{16}$

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
uPv				x	x	x	x									92-O$_2$
uPv						x	x									92-O$_4$
pDb?		x	x	x	x		x		x							92-O$_5$
pDb	cc	x	x		x	x			x							92-O$_6$
pDp											relict		x		serp	92-O$_7$
uPs					?	x	x								IIa	92-O$_8$
uPv					?	x	x									92-O$_{8X}$
pDm						x		x	x	relict						92-O$_9$
pDm?	x					x	x									92-P$_1$
uPv					?		x									92-P$_{1?}$
uPv?	x				x	x	x									92-P?$_1$
uPs					?			x							IIa	92-P$_2$
uPv	x				x	x										92-P$_3$
uPs	x				?	x									limon IIa	92-P$_{4B}$
pDm		x	x			x		x	x							92-P$_5$
pDm		x	x	x		x										92-P$_6$
uPs						x		x							IIa	92-P$_7$
uPv					?	x								x		92-Q$_{1A}$
Tch?						x									I	92-Q$_3$
uPv					x	x		musc								92-Q$_4$
pDb						x			x							92-Q$_{5A}$
uPv					x	x		x								92-Q$_{5B}$

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
pDm		x	x			x		x								$92\text{-}Q_6$
uPv					x	x		x						x		$92\text{-}Q_7$
pDm		x	x		x	x	x									$92\text{-}Q_8$
pDm		x	x		x	x	x	x								$92\text{-}Q_{9B}$
uPs						x		x							IIa	$92\text{-}Q_{9C}$
uPv?						x	x									$92\text{-}Q_{11A}$
Pvc		x	x	x			x	musc		barr						$92\text{-}Q_{11B}$
pDp						x					relict		x		serp	$92\text{-}Q_{11C}$
pDp						mg							x			$92\text{-}R_1$
pDp											x	bas-tite	x		serp	$92\text{-}R_2$
pDp											x		x		serp	$92\text{-}R_3$
pDp													x		serp	$92\text{-}R_4$
rodingite						mg									gt	$92\text{-}R_8$
uPs						x		x							limon IIa	$92\text{-}S_1$
uPv	x				?	x										$92\text{-}S_2$
pBm					x	x			x							$92\text{-}S_3$
gs		x	x			x	x		x					Fe-ox?		$92\text{-}T_{2A}$
gs		x	x		x	x	x		x					Fe-ox?		$92\text{-}T_{2B}$
uPv	x				?	x										$92\text{-}T_5$
uPs	x					x								x	I	$92\text{-}T_5$
pDp												bas-tite	x			$92\text{-}T_6$
dun	arag?													x	serp	$92\text{-}U_2$

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
pDm?	x				x	x		x								92-U$_3$
uPv	x				x			x								92-U$_3$
uPv*2					x	x							relict			92-U$_6$
uPv?		x	x		x	x										92-U$_7$
uPs								x							IIa	92-U$_8$
uPs						x		x							IIa	92-U$_9$
uPs?	x							x							IIa	92-V$_1$
Kph		x	x					x							IIIb	92-V$_2$
uPs								x							IIa	92-V$_3$
uPs								x							IIa	92-V$_4$
uPs					?			x							IIa	92-V$_6$
Kph		x	x					x							IIb	92-V$_{7A}$
Kph		x	x					x	x						IIb	92-V$_{7B}$
uPv				?		mg										92-V$_8$
gs?		x	x						x							92-V$_9$
uPs						x		x							IIa	92-V$_{12}$
uPs								x							IIa	92-V$_{12}$
uPv					x	x										92-V$_{13}$
uPs								x							IIa	92-V$_{15}$
Kph	x	folded vein						x							IIIa?	92-W$_1$
Kph		x	x					x							IIIa	92-W$_2$
uPs	x							x							IIa	92-W$_5$

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
uPc								x								$92\text{-}X_{1}$
dun												bastite		x	serp	$92\text{-}X_{3}$
dun											x		trace	x		$92\text{-}X_{4}$
Pvc		x	x			x	x			barr				x	gt sphe	$92\text{-}Y_{3}$
Pvc		x	x			x	x			barr				x	gt sphe	$92\text{-}Y_{3}$
uPs								x							IIa	$92\text{-}Y_{3}$
Kph		x	x				x	x							IIb	$92\text{-}Y_{4}$
pDp											relict		x		serp	$92\text{-}Y_{5}$
uPs								x							IIa	$92\text{-}Y_{6}$
uPs								x							IIa	$92\text{-}Z_{10}$
pDp											x	bastite	x			$92\text{-}AA_{1A}$
pDb					?				x	x						$92\text{-}AA_{1B}$
Tch?						x									I	$92\text{-}AA_{5}$
uPs						x		x							IIa	$92\text{-}AA_{6A}$
pDb					?		x		x					x		$92\text{-}AA_{6C}$
uPs						x		x	in source						IIa	$92\text{-}AA_{6D}$
uPs					?			x							IIa	$92\text{-}AA_{8}$
Tch?						x									I	$92\text{-}AA_{11B}$
Tch?						x									I	$92\text{-}AA_{11B}^{1}$
Tch?						x									I	$92\text{-}AA_{11C}$
gs		x	x		x	x	x		x				relict			$92\text{-}AA_{12A}$
Pvc		x	x			x	x			barr					sphe	$92\text{-}AA_{12B}$

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
Pvc		x	x			x	x	musc		barr					sphe	92-AA_{12Bb}
Tch?						x										92-AA_{14}
uPc		strained						x								92-AB_1
kPh?					x			x	in source							92-AB_2
uPv?*2	arag?				grn	x							relict			92-AB_{2A}
uPv?*2	arag				grn	x							relict			92-AB_4
uPs?	x				?			x							IIb	92-AC_1
pDp												x	x			92-AC_2
uPv?*2					x	x							relict			92-AC_{2C}
pDp													x		serp	92-AC_3
uP1	x															92-AD_3
pDm	x	x	x	x	x	x										92-AD_4
pDm				x		x										92-AD_{4B}
uPs								x						x	myl	92-AD_{4Cii}
uPs					x	x		x							myl	92-AD_{4Ci}
uPs						x		x							myl	92-AD_{5Xi}
uPs						x		x							myl	92-AD_{5Xii}
uPv				?		x								x		92-AD_8
uPs?				x	x			x							myl	92-AE_1
pDm		x	x			x										92-AE_{2A}
uPs	x				x	x		x							IIb	92-AE_{2B}
uPv	arag?				x			x								92-AE_3
pDm		x	x		x	x		x								92-AE_6
pDp												trace	x		serp	92-AE_7

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
pDp											x		x		serp	92-AE_9
pDp											?		x		serp	92-AF_2
pDp											x		x			92-AF_4
pDp											x		x	x	serp	92-AF_5
uPs						x	x	x							IIa	92-AF_{6A}
uPs					x	x		x							IIa	92-AF_{6B}
uPs						x		x								92-AF_{6C}
uPc				x		x										92-AF_{6D}
uPs						x		x							IIa	92-AF_{6E}
uPv*					x	x							relict			92-AG_1
pDp											x		grn			92-AG_2
uPv*2					x	x							relict			92-AG_3
Kph		x	x					x							IIb	92-AG_5
uPv	arag?				x	x										92-AG_{7A}
uPs?	arag?					x	x								IIa	92-AG_{7B}
uPv?*2	arag?				x	x							relict			92-AH_6
pDm						x	x									92-AI_{3A}
pDm					x				x							92-AI_{3B}
uPs						x		x							IIa	92-AI_{4A}
uPs					x	x		x								92-AI_{4B}
uPs					x	x		x							IIa	92-AI_{6A}
uPs								x							IIa	92-AI_{6B}
uPs						x		x							IIa	92-AI_{6C}

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
uPs					x	x		x							IIa	92-AI_{7A}
uPs	x							x							IIa	92-AI_{7B}
dun											x		x	x		92-AJ_1
pDm					x	x	x									92-AJ_2
uPs						x									I	92-AJ_3
pDm						x										92-AJ_5
pDb					?	x	x									92-AJ_{5B}
pDm		x	x			x			x	x						92-AJ_6
pDm		x	x			x		x		x						92-AJ_7
uPs	arag?					x								x	IIa	92-AJ_8
uPv						x		x								92-AJ_9
pDm				x	?	x										92-AK_1
uPl	x															92-AK_2
pDm		x	x					x								92-AK_4
uPs						x	x								IIb	92-AK_5
uPv	x					x										92-AK_6
pDb						x	x		x					Fe-ox?		92-AK_7
uPs					?	x		x							IIa	92-AL_1
uPv				x	x	x										92-AL_2
dun						x							x		talc	92-AL_3
mylonite															myl	92-AL_{3B}
uPl	x	x														92-AL_{5A}
uPl	x	x	x													92-AL_{5B}

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
pDm		x	x			x	x	x		relict						92-AL$_{5C}$
pDm	x	x	x			x	x		x	x						92-AL$_{5D}$
dun?	x														talc	92-AL$_{5E}$
pDb						x	trace		x	x				x		92-AM$_{1}$
pDb						x			x	x				x		92-AM$_{1B}$
Tch?								x								92-AN$_{1}$
Tch?						x										92-AN$_{2}$
pDm		x	x						x							92-AO$_{1}$
Kph		x	x					x							IIb	92-AO$_{4A}$
Kph		x	x					x							IIb	92-AO$_{4B}$
Kph															IIIa	92-AO$_{7}$
mylonite?		?	?				?									92-AP$_{5}$
uPs								x							IIa	92-AP$_{8}$
pDm?	x					x			x							92-AQ$_{1}$
uPv					?	x			x							92-AR$_{1}$
uPv					?	x										92-AR$_{2}$
uPs					x	x									IIa	92-AR$_{2A}$
uPv					?	x									amyg	92-AR$_{3}$
pDb					?	x										92-AR$_{3}$
uPs					x	x									IIa	92-AR$_{5}$
uPv					trace	x									amyg	92-AR$_{10}$
uPv	x				x	x										92-AR$_{11}$
uPv					x	x	x									92-AS$_{1A}$

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
uPv	x				x	x										92-AS$_{1B}$
uPl	x															92-AT$_{3A}$
uPl	x															92-AT$_{3B}$
uPv					x	x								x		92-AT$_{4}$
uPs								x							IIa	92-AV$_{1}$
uPs					?	x									IIa	92-AV$_{4}$
uPv					?	x										92-AV$_{5}$
uPs					x	x									I	92-AV$_{5}$
Kph		x	x					x							IIIa	92-AV$_{12}$
pDm		x	x	?		x									myl	92-AW$_{1A}$
pDm?		x	x		?	x									myl	92-AW$_{iB}$
pDm	x	x	x			x									myl	92-AW$_{1C}$
uPs								x							IIa	92-AW$_{2}$
pDm?					?	x			x						myl	92-AW$_{3A}$
uPs								x							myl	92-AW$_{3B}$
uPs					?	x									IIa	92-AX$_{1}$
uPs								x							IIa	92-AX$_{4}$
pDb					x	x	x	x	x							92-AX$_{5}$
uPv?*2					x	x							relict			92-AX$_{5A}$
uPv						x									limon	92-AZ$_{3}$
uPv	x				x	x	?						relict			92-AZ$_{6}$
uPv					x	x		x						x		92-AZ$_{10}$
Tch?	x					x									I	92-C$_{1A}$

MAP UNIT	Carbonate	Quartz	Albite	Prehnite	Pumpellyite	Chlorite	Epidote	Mica	Actinolite	Hbl	Olivine	Opx	Cpx	Opaque	Other	Sample #
Tch?						x									I	92-C_{1B}
Kph?		x	x					x						x	IIb	92-H_1
Kph?		x	x		x	x		x							IIb	92-I_3
Tch?						x									I	92-M_2
Kph		x	x			x		x	x						IIb	92-Z_1
Kph?		x	x			x		x	$//s_1$						IIb	92-CA_2
Kph?		x	x			x		x							IIb	92-CA_3

APPENDIX B. Point count data of Huntingdon, Chuckanut, and Chuckanut? deposits.

number of points

Qm	Qp	Biot	Musc	Ls	Lm	Lv	K	P	Sample #
53	7	7	2	3	5	12	23	35	SJ-149 *
47	10	7	2	1	6	18	19	35	SJ-221
59	0	10	1	0	8	0	21	43	SJ-212
68	0	7	1	0	3	0	7	61	SJ-204
48	4	14	1	3	0	0	22	51	SJ-214
35	12	10	1	10	32	0	1	14	SJ-213
45	17	1	0	10	5	18	0	48	92-$AA_{11B}1$ **
41	32	0	0	8	15	4	0	43	92-M_2
49	10	0	0	15	6	44	0	22	92-C_{1B}
43	10	0	0	10	6	28	-	43	92-AN_2
37	6	0	0	13	3	53	0	33	92-AAs
45	4	0	0	5	10	38	-	43	92-AA_{11C}
30	19	0	0	0	7	40	0	53	92-AA_{11B}
28	13	-	-	8	-	8	8	33	Frizzell 1
18	31	-	-	7	-	0	7	23	Frizzell 2
56	6	-	-	7	-	0	7	23	Suczek

* SJ- samples from Sam Johnson, University of Washington

** 92- samples from this study