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The Shuksan Metamorphic Suite and Shuksan Thrust Mt Watson Area, North Cascades, Washington

Ralph Albert Haugerud
Western Washington University

THE SHUKSAN METAMORPHIC SUITE AND SHUKSAN THRUST
MT WATSON AREA, NORTH CASCADES, WASHINGTON

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Presented to

The Faculty of

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In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

by

Ralph A. Haugerud

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Dean of Graduate School

Advisory Committee

Chairperson

MASTER'S THESIS

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Rocks of the Shuksan Metamorphic Suite exposed on Mt Watson are metamorphosed pillow basalts, basaltic flows(?), basaltic tuffs, carbonaceous sediments, Mn-enriched cherty sediments, rare calcareous sediments and rare ferromanganese nodules.

Greenschist of the Suite records the following history: 1) early static hydrothermal metamorphism; 2) Early Cretaceous (about 125 ma ago) synkinematic blueschist-facies metamorphism at $P \sim 7$ kb, $T \sim 350^{o}$ C, P_{fluid} near P_{total}, $X_{CO_2} < 0.1$, with production of S_1 and L_1; 3) late-metamorphic isoclinal folding (F_2) around axes commonly at high angles to L_1; 4) L_3 crenulation of S_1. Phyllite of the Suite has been more strongly affected by D_2, D_3 and post-D_3 events. This history appears typical for the Suite throughout NW Washington.

West of Mt Watson the Shuksan Thrust is a 3 km+ thick tectonic melange. Most of the melange is little-recrystallized rocks of the Chilliwack Group(?). Aragonite and lawsonite are present in Chilliwack(?) rocks. Minor elements in the melange include probable Shuksan Suite rocks, metaquartz diorite and exotic well-recrystallized high P/T metavolcanic rocks. The relations between metamorphism of Chilliwack(?) rocks, melange deformation, and blueschist-facies Shuksan metamorphism are not known.

A NNW-trending fault is inferred to pass between Mt Watson and Bacon Peak. Movement on the fault postdates D_3 and is probably post-Paleocene in part. Recognition of the probable continuity of this fault with the Shuksan Thrust further N suggests that in the "root zone" the Thrust may be a series of *en echelon* NNW-trending structures.

INTRODUCTION

The blueschist-facies Shuksan Metamorphic Suite (Misch, 1966) crops out over a large area in NW Washington and adjacent British Columbia (see figures 1 and 2). The general features of the Suite are known largely through the work of Peter Misch (1959, 1965, 1966, 1969, 1977) and his students (Vance, 1957, Bryant, 1955, Jones, 1959). The outline given here draws almost entirely from Misch's 1966 summary.

The Shuksan Suite has been divided into the metasedimentary Darrington Phyllite and the metavolcanic Shuksan Greenschist, both metamorphosed in a low-pressure variant of the blueschist facies (Misch, 1959, Brown, 1974). Rocks assigned to the Suite occur in two zones: a western belt which is mostly phyllite north of the Skagit River and an eastern "Shuksan Structural Belt" (Misch, 1977) which is mostly Shuksan Greenschist.

Between the two belts lies a complex pile of eugeosynclinal material. At the lowest visible levels lie the mid-Jurassic Wells Creek Volcanics and the Jurassic to Lower Cretaceous Nooksack Group which is largely composed of volcanic-derived sediments. These have been overthrust by the Church Mountain thrust plate, composed of the Chilliwack Group and Cultus Formation. The Cultus Fm is a poorly known lower Mesozoic flysch sequence (Monger, 1970). The Chilliwack Group is a thick volcanic and sedimentary sequence containing scattered limestone lenses, some of which have yielded fossils ranging in age from mid-

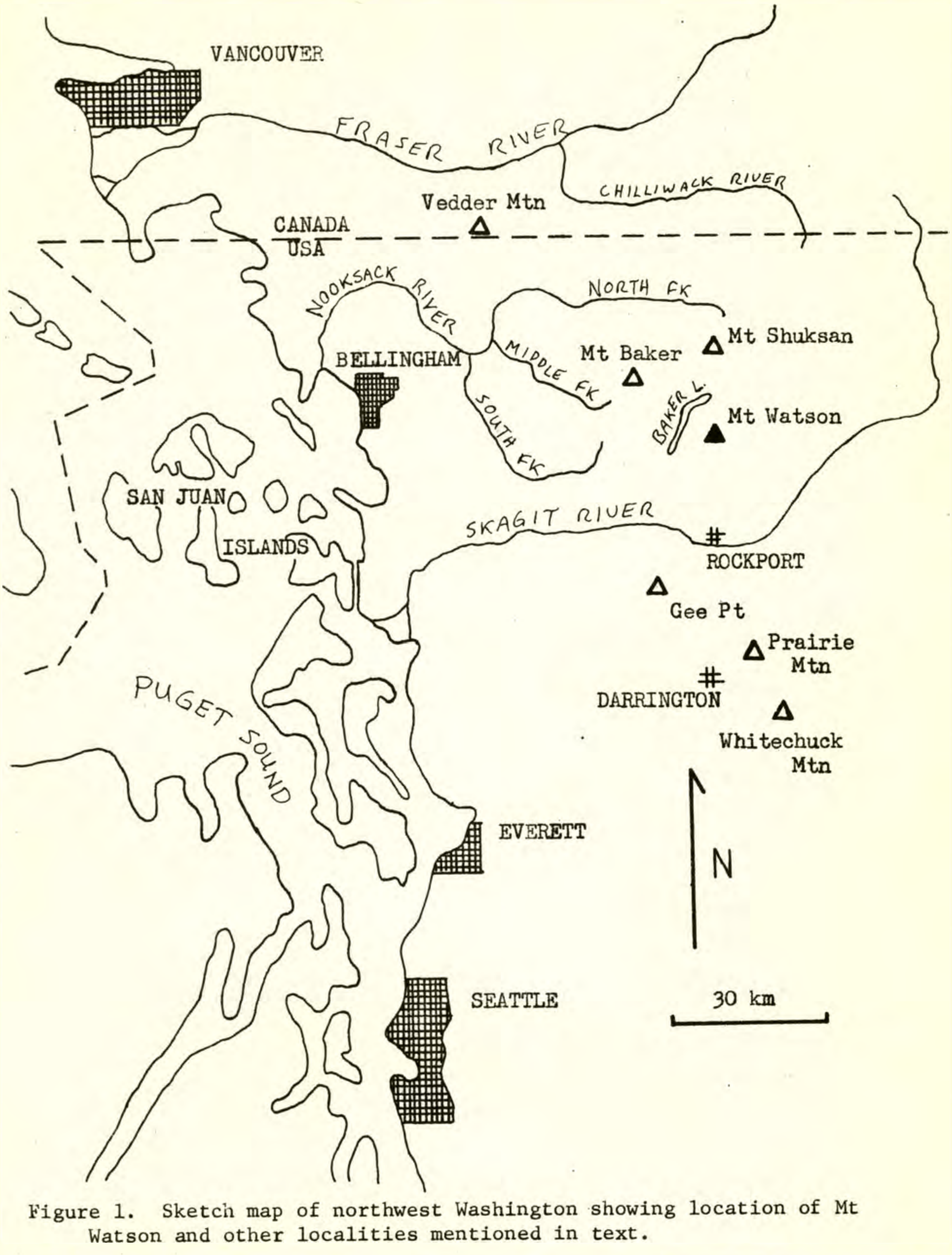
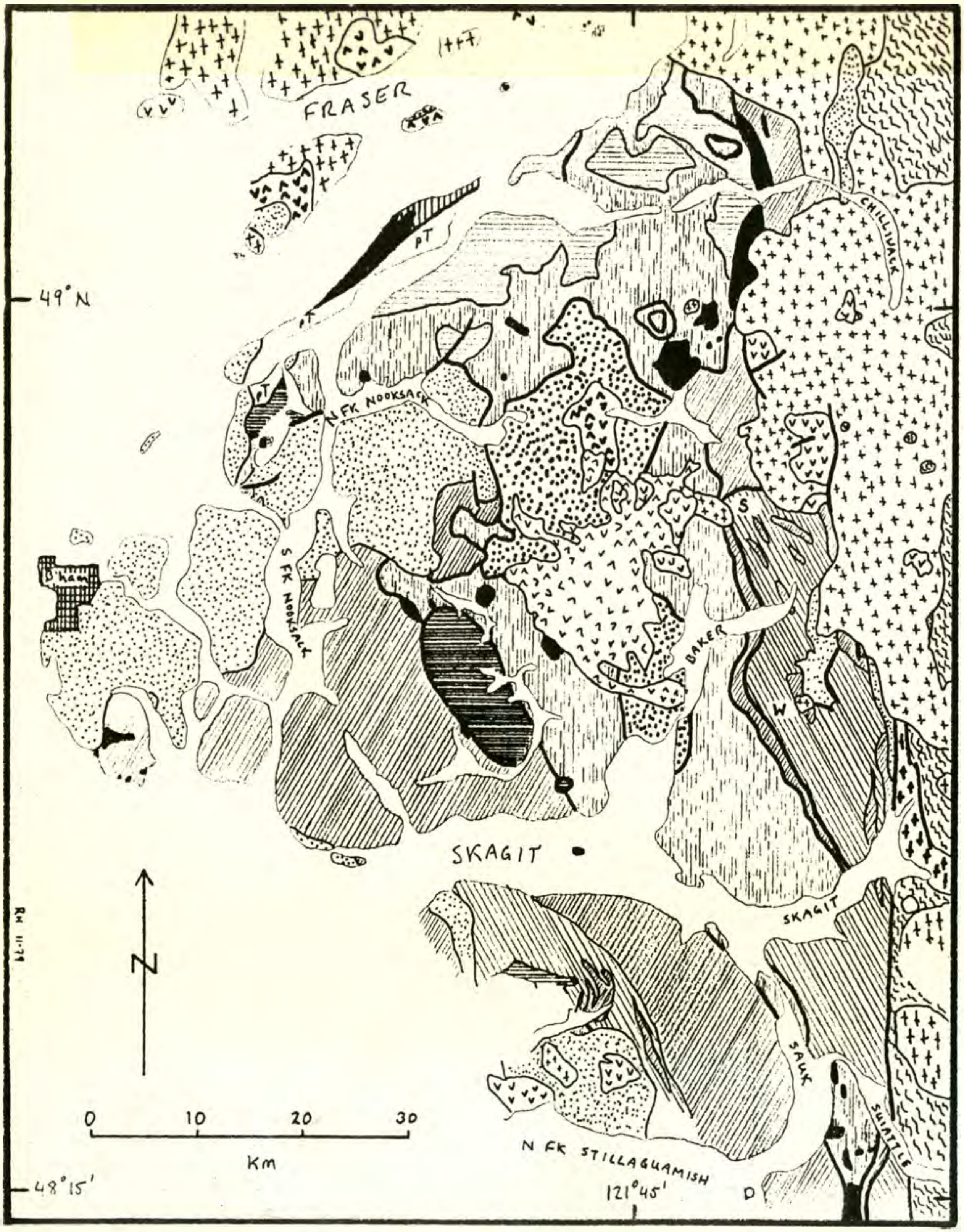


Figure 1. Sketch map of northwest Washington showing location of Mt Watson and other localities mentioned in text.



Quaternary Mt Baker Volcanics

Tertiary granitic rocks

Tertiary volcanic rocks

Tertiary continental sediments

U Jurassic-L Cretaceous Nooksack Group

M Jurassic volcanic rocks

lower Mesozoic Cultus Fm

upper Paleozoic -Triassic? Chilliwack Group

pre-Tertiary volcanic and sedimentary rocks

Darrington Phyllite

Shuksan Greenschist

Yellow Aster Complex and similar rocks

alb-ep-amphibolite and pelitic schist of Vedder Mtn

ultramafic rocks

granitic rocks, mostly Cretaceous

schist and gneiss of Skagit Met. Suite

Marblemount metaquartz diorite

fault

Figure 2. Geologic sketch map of western North Cascades, adapted from unpublished compilation by author. S = Mt Shuksan, W = Mt Watson, D = Darrington.

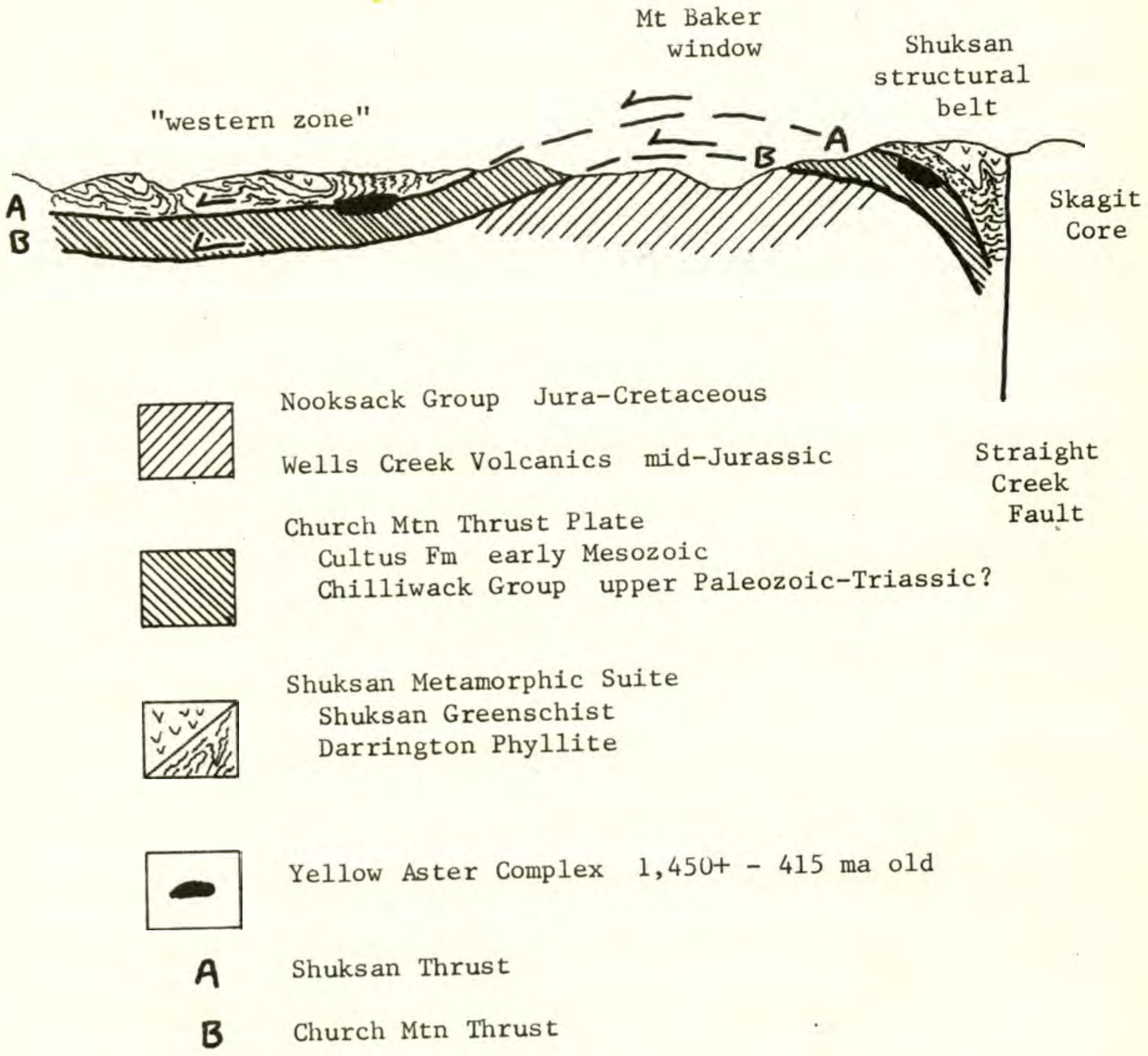


Figure 3. Schematic geologic cross-section of the northwest Cascades, following Misch (1966, 1977). Tertiary rocks have been omitted.

Devonian to Triassic (Danner, 1966; Evans and Savage, 1979). This sequence appears to have been overthrust by the Shuksan Metamorphic Suite along the Shuksan Thrust.

Thrusting has been dated as mid-Cretaceous. The youngest rocks involved are Valanginian sediments of the Nooksack Group. Sediments of the Santonian and younger Nanaimo Group (Muller and Jeletzky, 1970), exposed to the west on Vancouver Island, are considered by Misch to postdate thrusting, as they contain minor blue amphibole fragments and record no major orogeny during their period of deposition.

Along the Shuksan Thrust and in the upper levels of the Chilliwack Group lie scattered blocks of tectonically emplaced plutonic material. Misch (1966) has designated them the Yellow Aster Complex. Some of these blocks show petrographic evidence of a long igneous and metamorphic history. Material from the type area has given U/Pb ages of 1,450+ and 415 ma (Mattinson, 1972).

To the east, the entire northwest Cascades complex has been truncated by the Eocene(?) and older Straight Creek Fault. East of the fault lie schists and gneisses of the Barrovian facies-series Skagit Metamorphic Suite. Latest motion on the fault had a dip-slip component, with the west side dropped down. Earlier motion appears to have been right-lateral strike-slip. Misch has suggested 200 km of post-mid-Cretaceous offset.

Misch (1966) has interpreted these geological relations in terms of the scheme shown in figure 3. On the basis of regional reconnaissance study he has inferred the following history for the Suite:

1) Deposition of the Darrington Phyllite protolith (terrigenous muds, silts and sands) above an old and complex continental basement (Yellow Aster Complex), followed by eruption of the basaltic protolith of the Shuksan Greenschist.

2) Blueschist-facies Shuksan metamorphism, occurring in an unknown tectonic setting, perhaps at about 250 ma before present (on the basis of one K/Ar date from the western zone).

3) Mid-Cretaceous Shuksan Thrusting, juxtaposing the Shuksan Suite, Chilliwack Group and Nooksack Group, and fragmenting the old continental basement.

4) Subsequent erosion, then deposition of the early Tertiary Chuckanut Formation.

5) Mid-Eocene folding on predominantly NW trending axes.

6) Intrusion of the Chilliwack Composite Batholith, uplift, erosion, eruption of the Hannegan and Skagit Volcanics, and growth of the present Cascade Range. Mt Baker is a typical late development.

Modification of this scheme may be in order. Modern petrologic theory indicates that high P/T metamorphism such as that which produced the Shuksan Suite is characteristic of subduction zones (for example, Dewey and Bird, 1970, Ernst, 1971) and that the Shuksan Suite was probably metamorphosed at a convergent plate margin (Vance, 1974).

Several authors (Vance, 1974; Davis, 1977; Hamilton, 1978; and others) have suggested that oceanic material is present in the northwest Cascades. Detailed mapping in the western belt of the Shuksan Suite (Morrison, 1977) has shown that south of the Skagit River Darrington Phyllite overlies Shuksan Greenschist and a thin horizon of metalliferous metasediment separates the two units. The similarity of this sequence to modern oceanic crust led Morrison (1977) to propose that the Shuksan Suite is of ophiolitic affinity.

Numerous unpublished K/Ar and Rb/Sr dates (summarized in Appendix B) show blueschist-facies metamorphism of the Shuksan Suite to be Early Cretaceous in age (Wilson, 1978; R.L. Armstrong, personal communication, 1979). The closeness in age suggests that mid-Cretaceous orogeny and blueschist-facies metamorphism may have been part of the same process.

Mapping in the Darrington area by R.D. Lawrence and students from Oregon State University has cast some doubt on the interpretation of the eastern and western zones of the Shuksan Suite as parts of a once-continuous thrust sheet (Lawrence, personal communication, 1978).

A Jurassic ophiolite complex is well exposed in the San Juan Islands (Brown, 1977b). Work in progress is extending the mapped outcrop area of this ophiolite and its sedimentary and volcanic cover eastwards, and it appears that many of the rocks previously assigned to the Yellow Aster Complex and Chilliwack Group are part of this Jurassic ophiolite (Whetten and Zartmann, 1979).

Statement of Problem

In this study I have examined a small area within the Shuksan structural belt in an attempt to 1) establish a deformational and metamorphic history for the Shuksan Suite, 2) identify the protoliths of the Suite, and 3) determine the nature of the Shuksan Thrust. To do this, I have paid special attention to minor structures in the Suite and their relations to metamorphic assemblages, relict features, contacts between metasedimentary and metavolcanic members of the Suite, and structures and metamorphic assemblages that could be related to the Shuksan Thrust.

The internally-recorded history of the Suite should provide a useful guide for hypotheses on the tectonic evolution of the North Cascades. Morrison has suggested that the Suite is metamorphosed oceanic crust: confirmation (or rejection) of this suggestion is needed. The Shuksan Thrust is a rather enigmatic feature: physical conditions during thrusting, the mechanics of thrusting and the tectonic setting of thrusting are all unknown.

Study Area

The Mt Watson area lies on the west sid of the North Cascades approximately 20 km north of Rockport. Access is from State Route 20, via Baker Lake Road, across Baker Dam and up about 15 km of unpaved US Forest Service road. From near the road end at 4,200' elevation a trail network continues SE for 4 km. Branches lead to the west summit of Anderson Butte, lower Anderson Lake and Watson Lakes.

The area has been extensively glaciated. Small glaciers and permanent snowfields remain on Mt Watson and Bacon Peak.

With a few exceptions exposures below timberline are limited to recently built logging roads. Above timberline (5,000' to 5,500' elevation) exposures are excellent, especially on recently glaciated slabs. Most of the summer many of the more interesting outcrops are buried by winter snow. Some of the observations in this report were made possible by a light snowfall in the winter of 1977-78 and a field season that extended into October.

Cascade weather, difficult terrain and brush are respectable adversaries. Rewards for the persistent include exquisite views of the Twin Sisters Range, Mt Baker, Mt Shuksan and the Southern Pickets. Late season huckleberries were excellent. Mountain goats, conies, deer, marmots, an occasional raptor and a bear were field companions.

Previous Work

The only previous geological investigation of the Mt Watson area is the mapping by Misch (1952, 1966) done prior to extensive road building in the area. The eastern edge of the study area was included in a mineral resources survey by Staatz et al. (1972).

The Shuksan Metamorphic Suite has been studied in reconnaisance in other areas by Bryant (1955), Vance (1957), Jones (1959) and Misch (1966). Small areas within the Suite have been examined in detail by Milnes (1976; Lawrence and Milnes, 1976), Morrison (1977) and Wilson (1978). Rocks in the Darrington area similar to the melange unit of this report were studied by Franklin (1974). Misch (1959) and Brown (1974, 1977a) have discussed phase relations within the Shuksan Suite. Misch has also published two papers (1965, 1969) on textural details in the Shuksan Greenschist.

Methods

Field work was done in late summer and fall of 1978. A 4" = 1 mile enlargement of the Lake Shannon 15' quadrangle was used as a base map. Structural measurements were made at over 200 locations. Approximately 200 rock samples were collected and studied in thin section. A General Electric X-ray diffractometer was used as an aid in mineral identification. Three samples were chemically analyzed by the atomic absorption method, as described in Appendix C. Six chert samples were dissolved in dilute HF in a fruitless search for microfossils. K/Ar and Rb/Sr ages were determined by R.L. Armstrong at the University of British Columbia.

All sample numbers (e.g., D25) are preceded by 78RH or RH78. Underlined numbers (e.g., 153) refer to field localities shown on plate I.

Acknowledgements

Dr. E.H. Brown suggested the problem, accompanied me in the field, taught me metamorphic petrology and criticized several manuscript copies. His help and encouragement are greatly appreciated.

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I especially wish to thank my parents for their support and their tolerance.

SHUKSAN METAMORPHIC SUITE

I have divided rocks of the Shuksan Metamorphic Suite exposed on Mt Watson into three map units. These are: 1) fine-grained black to grey graphitic phyllite with associated minor calcareous schist, quartz-muscovite schist and well foliated chlorite-rich greenschist; 2) well-laminated grey to light green greenschist (hereafter called type A), commonly without visible epidote segregations and with white felsic flecks; and 3) heterogenous, mostly dark green greenschist (hereafter called type B) characterized by abundant epidote segregations, intercalated blueschist and common relict pillow structures.

Phyllite Unit

Field Appearance

Rocks of the phyllite unit are mostly black to grey micaceous phyllites, commonly with abundant quartz veinlets and lenses. Fresh foliation surfaces are shiny and almost everywhere are folded and crenulated. Small euhedral pyrite crystals are common.

Fissile, soft 'leuco-greenschist' is associated with thin layers of phyllite east of Mt Watson. Pyrite crystals (or limonite pseudomorphs) up to ½ cm across are present in this schist. Occurring in the same setting is a finely-laminated quartz-muscovite schist; at 22 this is interlayered with greenschist as well as occurring between greenschist and phyllite.

At 153 metalliferous carbonate nodules 4-10 cm long occur in black phyllite within a meter of the contact with rock transitional into mafic greenschist (see figure 4). Several meters below this contact a contorted 1 m thick band of light grey-brown weathering calcareous schist is intercalated in the black phyllite.

The phyllite unit is recessive. Except where hornfelsed, phyllite east of Mt Watson commonly crops out in gullies and low areas. West of Mt Watson all phyllite outcrops are below timberline.

The dominant schistosity in most outcrops appears to be S_2. At 153 S_2 has developed by transposition of S_1 by folding on NE plunging axes (figure 5). More commonly S_2 cuts across S_1 at a high angle (figure 6) and only locally can one see that S_2 is axial planar to folds in S_1.

Attitudes in the phyllite are extremely variable and, in good outcrops, folding in a variety of styles is visible. Because of this and the lack of outcrop, little effort was made to study mesosopic structures in the phyllite unit.

Occurrence and Contact Relations

Phyllite was mapped in three settings (see plate II). A narrow belt of phyllite lies west of the Anderson fault. The western boundary of this phyllite belt was drawn at the first appearance of structures or little-recrystallized lithologies typical of the melange unit. Outcrop in this area is poor, and as a result this contact is not well defined.

Phyllite is exposed east of the inferred trace of the Anderson

Figure 4. Transitional phyllite-greenschist contact at 153. Chisel is 16 cm long; mapboard is barely visible at upper edge. Metalleferous carbonate nodules (not visible) occur within phyllite horizon shown. Looking east.

Figure 5. S_2 developed by transposition of S_1. Folds are F_2. Foliation at top of view is S_1; at bottom, S_2. Looking NE at 153.

Figure 6. S_2 (parallel to pen) crossing S_1 (outlined by quartzose laminae) at high angles, in phyllite at 13.

fault at "Pipsqueak Pass."* At three outcrops (102, 211, 212) below timberline on the south side of Anderson Butte phyllite underlies type A greenschist. It is not clear whether the contact is conformable or faulted. Near the contact the phyllite is very deformed and locally is brecciated. At 102 on the ridge north of "Pipsqueak Pass" the contact is sharp and transgresses the dominant schistosity in the greenschist. Greenschist at the contact is pitted with small holes, suggesting the presence of abundant carbonate prior to weathering. The carbonate content could reflect original compositional variation or later alteration by carbonate-rich fluid infiltrating along the contact. Structural relations at 102 are diagrammed in figure 7. The southern contact of the phyllite at "Pipsqueak Pass" was not seen. It is presumed to be a high-angle fault, here called the "Pipsqueak Pass" fault.

Phyllite and associated other metasedimentary rocks were found east of Mt Watson as intercalations in greenschist. Some of these intercalations are faulted, while others are conformable. Many are intruded by post-metamorphic dikes. These phyllite intercalations appear to be zones of more intense deformation and in places the phyllite may have been tectonically emplaced along faults. West of the Noisy Creek-Diobsud Creek col at least six 1-10 m thick layers of phyllite are present. A few are shown on plate II. East of the col partly hornfelsed phyllite forms much of the ridge crest. On strike

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* The pass west of Watson Lakes is here informally named for the vocal coney population which inhabits a talus field next to the trail at the pass.

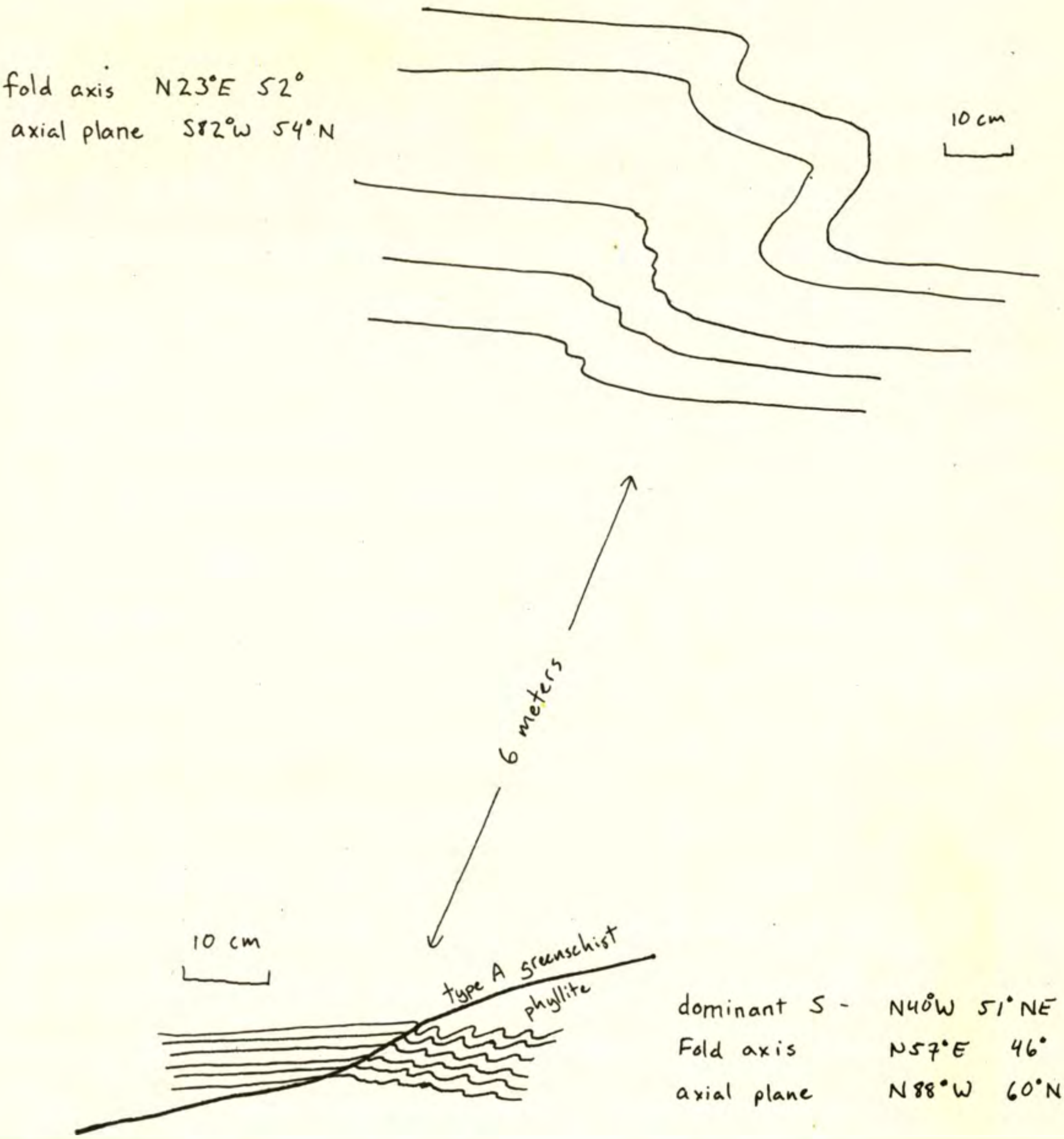


Figure 7. Sketch of structural relations at 102 north of "Pipsqueak Pass". View is to NE and down.

to the north, hornfelsed phyllite is exposed on peak 6420' and along the ridge running west. Four phyllite bands which appear concordant with the surrounding greenschist were mapped in the cirque above Diobsud Lakes. At the eastern contact of one band (162), phyllite is gradational into greenschist and a meter-wide zone at the contact is pockmarked with small holes, again suggesting the presence of abundant carbonate prior to weathering. A small lens of greenschist was seen at 161 in the westernmost of the phyllite bands above Diobsud Lakes. It was incorporated into the phyllite prior to the formation of the crenulation lineation, as it and the surrounding phyllite share minor folding associated with the crenulation. At 153 on the east end of Mt Watson the phyllite protolith appears to have been coeval with the greenschist protolith as there is a gradual transition from black phyllite to mafic greenschist, shown in figure 4. At nearby localities phyllite-greenschist contacts are faulted.

Phyllite-greenschist contacts in the Mt Watson area do not appear to be part of a single folded surface, or even a single surface modified by later faulting. Some of the concordant interlayering, especially on Bacon Peak, appears to be a primary depositional feature.

Petrography

Seventeen samples from the phyllite unit were examined in thin section. Phases observed are given in Appendix A.

Phyllite is composed of quartz + chlorite + muscovite + graphite + sphene, $\pm$ albite, sulphide and paragonite. Minor carbonate appears to post-date other minerals.

In samples which have not been strongly affected by post-S_2 deformation quartz forms an equigranular mosaic with straight grain boundaries. Individual grains may be fractured, show slightly undulose extinction and give biaxial interference figures. In brecciated samples (D22, E8, E59) and in samples which show F_3 (E61, E62) quartz shows strongly undulose extinction, grain boundaries are highly irregular, grain size varies widely, and some grains are 'sliced.'

Chlorite in the phyllite is pale green, without pronounced pleochroism and has very low birefringence. Interference colors are normal (dark drab-grey) or abnormal blue, in some cases in the same sample.

White mica is present as well defined plates, commonly intergrown with chlorite. X-ray diffractometer study (figure 8) of the 10 Å region in E1 shows a strong muscovite peak at 9.9 Å and a minor peak at 9.7 Å indicating the presence of paragonite. D19 shows a similar pattern. The 9.7 Å peak does not show in E30. Other samples were not examined.

Sphene is present as small granules or as larger spindle-shaped crystals. Some crystals in D61 show distinct twinning similar to the rhombohedral twinning common in calcite.

Graphite occurs as fine dust concentrated in phyllosilicate-rich layers. An attempt was made to measure the crystallinity of graphite by x-ray diffractometry, following the procedures outlined by Grew (1974). Results were not fully satisfactory, largely because of impurities in the graphite separates. Graphite from E1 is not well crystallized, lacking a distinct 3.36 Å peak, but is more ordered than

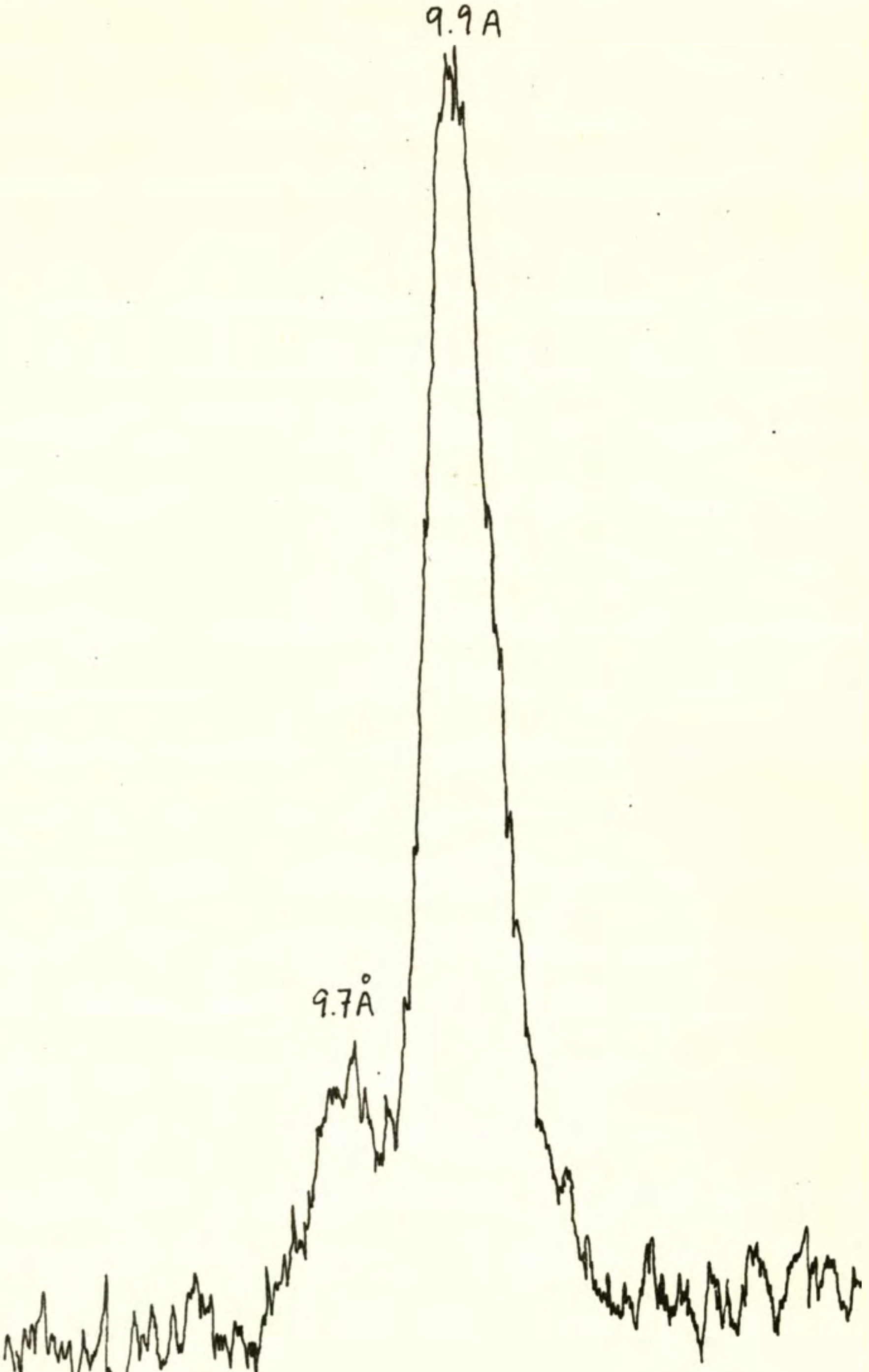


Figure 8. Typical x-ray diffractogram of sample E1, 10 Å region. D-spacings shown are averages of 3 reversed runs, indexed to the 3.34 Å quartz peak.

carbonaceous material from phyllite associated with poorly recrystallized volcanic rock in the melange unit.

Albite is similar to quartz in appearance. Some grains show twinning; otherwise positive identification requires an interference figure.

Several phyllite samples contain a strongly colored yellow to reddish-brown phyllosilicate with moderate relief, medium to high first-order birefringence and no pleochroism, although color-strength varies from place to place. This material often grades into adjacent chlorite without a distinct crystal boundary. It primarily occurs along fractures and near weathered iron minerals. It is probably altered chlorite.

Three samples of hornfelsed phyllite (D12, E8, E14) were examined. All contain mats of anhedral biotite instead of the chlorite + white mica assemblage present in unaltered phyllite. The biotite is pleochroic, pinkish brown $>$ pale brown, and the strength of the colors varies. D12, from the summit of Bacon Peak, contains white mica which appears to be newly crystallized, as a large crystal was seen traversing several quartz grains. Hornfelsing of E8 post-dates brecciation, as the rock is well indurated and the newly-crystallized biotite has not been disrupted. Quartz appears not to have recrystallized, as grains are still strained, grain boundaries are irregular and grain size varies widely.

Material called quartz-muscovite schist in the field is characterized by regular interlayering of quartz-rich and mica-rich layers. In thin section (D18) it is seen to be composed of quartz + albite +.

chlorite + white mica + garnet + Fe-oxide(,?) + sphene. Garnet, Fe-oxide(,?) and sphene are concentrated in the phyllosilicate-rich layers. The layering is S_1; it may also be a relict sedimentary feature. In the field (at 22) S_1 was seen in all stages of transposition into (or disruption by) S_2. S_2 is axial planar to small clockwise 'Z' folds in S_1. In places S_2 was seen to be crenulated. In thin section S_2 is similar to S_2 in the phyllite (discussed below). Mineralogy and textures are like those of the phyllite, but for the absence of graphite and the presence of garnet. The garnet forms small euhedral crystals which are presumably spessartine, stabilized by the presence of manganese.

'Leuco-greenschist' (D21) and the phyllite to greenschist transitional facies from 153 (E2) are mineralogically identical to the quartz-muscovite schist.

Calcareous schist from 153 (E39, E39b) is composed of chlorite + carbonate + white mica + quartz + albite + sulphide + sphene + graphite + apatite. Carbonate is present as elongate patches which look primary, as fillings in small gashes normal to the schistosity (S_2) and as late cross-cutting veins. Primary carbonate shows rhombohedral twinning. Well-developed twin lamellae sub-parallel to S_2 are present in some grains. The lamellae appear to have developed by gliding during D_2 deformation. All examined carbonate grains were biaxial, presumably from strain, with 2V ranging from near 0^o to about 30^o. X-ray diffractometry shows the carbonate to be calcite. Chlorite is pleochroic in pale greens, with normal interference colors. White mica is intergrown with chlorite and commonly is bent. Helicitic albite is less abundant than quartz. Some euhedral sulphide grains predate S_2, as they are cracked and extended parallel to S_2, with small quartz strain shadows. Spindle-shaped crystals of sphene are concentrated in chlorite-rich layers and are also present in equilibrium with adjoining quartz and carbonate. Scarce apatite forms large, colorless, anhedral crystals.

Metalliferous Carbonate Nodules

Metalliferous carbonate nodules from 153 (E4, E5) were examined with the thought that they might be pre-metamorphic features, perhaps ferromanganese nodules, occupying a stratigraphic position similar to the Fe-Mn rich metachert in the Gee Point area (Morrison, 1977).

Weathered surfaces of the nodules arecoated with a sooty dark brown to black powder. Fresh surfaces of E4 show abundant sulphide in a white to grey matrix. Larger sulphide crystals and a sulphide-rich vein are surrounded by sulphide-depleted zones. E5, when broken has a dark, fine-grained surface.

In thin section E4 shows an unidentified skeletal, high-relief, deep yellowish-brown mineral, subhedral sulphide, and garnet set in a mosaic of equigranular anhedral carbonate. Minor quartz and albite are present. Dusty opaque is widespread. Larger, more euhedral, in part helicitic, sulphide crystals are surrounded by sulphide-free zones. Carbonate is uniaxial and does not show good cleavage or twinning.

Sample E5 includes the phyllite border of the nodule, which is made of white mica, spessartine and graphite(?). The core is similar to E4, though poorer in sulphide and the dark yellowish-brown phase.

Garnet is more abundant than in E4 and is concentrated at the edge of the core. Also present in the core is an unusual, dirty yellow-green chlorite with yellow-grey interference colors. Between the phyllite border and the core is a zone with baffling mineralogy. Phases present include pumpellyite (?- pleochroic green to yellow-green, good relief, strong first-order birefringence, in feathery aggregates), stilpnomelane (?- very fine-grained) and a mineral present as sheaves of parallel, very fine dark needles which at high power resolve into strings of deep red granules (hematite?).

Emission spectroscopy shows the presence of large amounts of manganese, lesser amounts of iron and minor lithium in E4. X-ray diffractograms show a strong 2.60 Å spessartine peak and several unidentified peaks. A strong compound peak at 2.85-2.95 Å is probably Fe-Mg-Mn-Ca carbonate. No peaks for common Fe or Mn bearing sulphides were recognized.

The nodules could be either metamorphosed sedimentary features or largely the result of post-metamorphic hydrothermal activity. Schistosity in the phyllite (S_2) wraps around the nodules, suggesting they are not late replacement or fracture-filling features. Apparent metamorphic spessartine in phyllite adjacent to the nodules suggests the Mn content is primary. Minor hydrothermal mineralization has occurred nearby, as post-metamorphic breccia and volcanic dikes bear small amounts of pyrite. It is tentatively concluded that the nodules are metamorphosed sedimentary features.

The carbonate content makes these nodules unlike most modern ferromanganese nodules. However, shallow-water, manganese-rich carbonate concretions are known (Calvert and Price, 1977).

Structure

Structures observed in the phyllite unit are schistosities, intersection lineations, crenulation lineations, and small folds.

Where determined, the dominant schistosity in outcrop is S_2. Two schistosities are apparent in all thin sections of the phyllite unit (figure 9). S_1 is a crystallization schistosity defined by aligned phyllosilicates and alternating phyllosilicate-rich and quartz-rich layers. Where present, sphene, graphite, garnet, sulphide and Fe-oxide(?) are concentrated along the phyllosilicate-rich layers. In many sections S_1 is only present in small augen within which subparallel white mica flakes are normal to schistosity in the rest of the slide.

S_2 is defined by concentrations of aligned phyllosilicates and opaque material. Most commonly it crosses S_1 at high angles. S_2 appears to have been formed by the selective removal of quartz (and possibly chlorite and albite). In some samples white mica is bent into S_2, while in others it is unstrained, perhaps because realignment was by rotation of earlier formed crystals. No conclusive evidence was seen for mica recrystallization during the formation of S_2.

S_3 is the axial plane of small folds in S_2 and in some outcrops is present as a spaced cleavage. In thin section it is similar to S_2.

The intersection lineation measured is that of intrafolial S_1

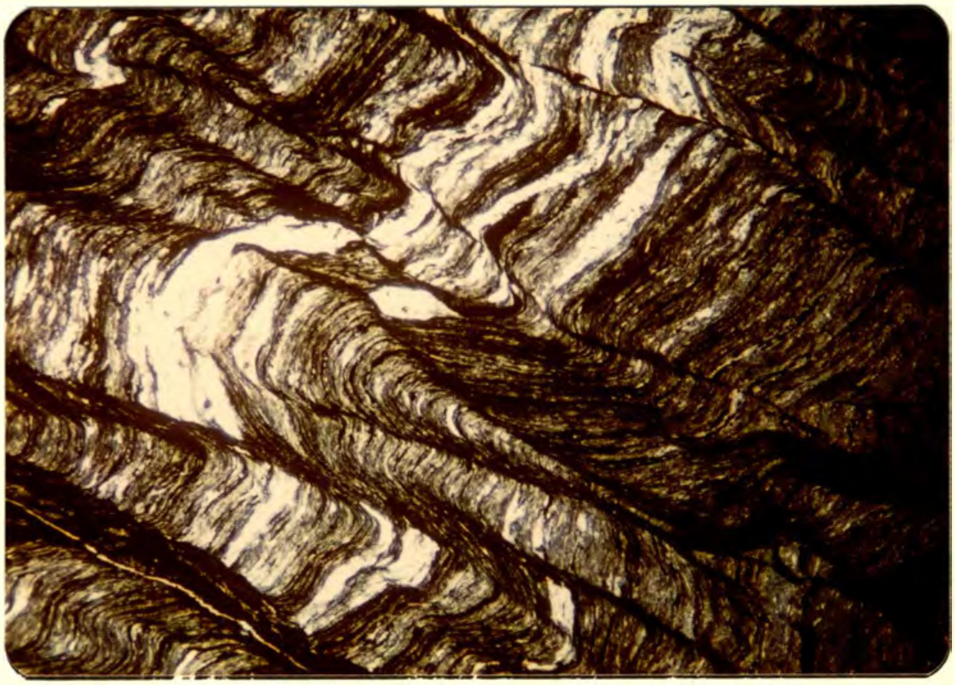
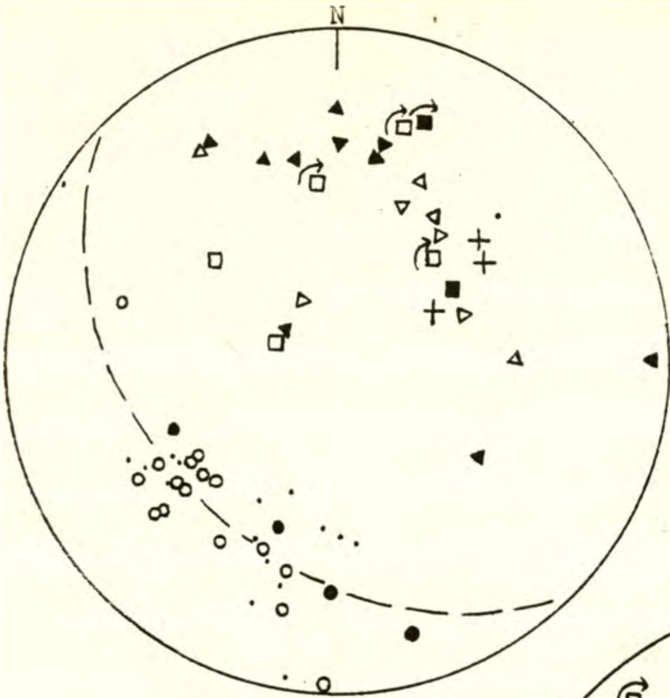
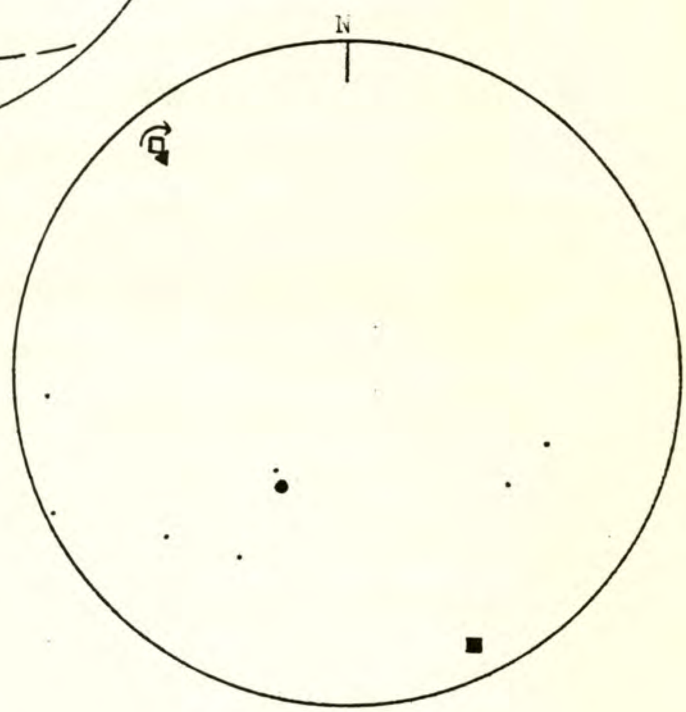


Figure 9. Photomicrograph of phyllite (D19) with well-preserved S_1 and crosscutting S_2; plane light.



a. Data from west of Noisy-Diobsud fault. Arc is trace of girdle to average F_3 orientation.



b. East of Noisy-Diobsud fault.

- · undifferentiated S
- ○ S_2
- ● S_3
- □ F_2 axis
- ↷ vergence of folding
- ■ F_3 axis
- + probable F_3 axis
- ▲ crenulation lineation
- △ $S_1 \wedge S_2$, = L_2

Figure 10. Equal area, lower hemisphere projections of structural data from the phyllite unit.

with S_2. Crenulation lineations are widespread, often with more than one set visible. They must be later than S_2 on which they are developed.

Brecciation of samples from the Noisy-Diobsud divide (D22,E8) and from north of "Pipsqueak Pass" (E59) also posdates S_2, as it is locally developed within rocks which elsewhere show S_2. E59 has a crude fluxion structure which is subparallel to the axial planes of nearby F_3 folds. D22 is poorly indurated mylonitic gouge associated with a faulted sliver of post-metamorphic volcanic rock.

Figure 10a is a plot of all structural data from the phyllite unit west of the Noisy-Diobsud fault. Two patterns are evident. Poles to S are girdled about the average F_3 axis N 45°E 50° (visual estimate). Post-S_2 linear elements lie in a girdle, also. This could be the result of post-F_3 folding about an axis normal to the average schistosity, but is more likely the result of inhomogenous deformation during F_3, as no other evidence was seen for post-F_3 folding.

Data from the phyllite unit are too few to permit separate analysis of smaller areas. Data from east of the Noisy-Diobsud fault (figure 10b) are too few to tell if the fault marks a discontinuity in structure, but are permissive of such an interpretation.

History

The following history is inferred for the phyllite unit:

deposition of locally manganiferous, locally calcareous, mostly carbonaceous silica-rich sediments;

D_1- synkinematic Shuksan metamorphism, development of S_1;

D_2- F_2 folding, development of S_2 and intersection lineation, recrystallization of quartz, calcite stable;

post-D_2 deformation- F_3 folding on axis N 45°E 50°, local development of S_3, local brecciation, straining of quartz.

Post-D_2 deformation probably includes more than one event, as indicated by multiple crenulation lineations developed on S_2. Contact metamorphism of phyllite on Bacon Peak postdates at least some of the post-D_2 deformation. Some late deformation west of the Noisy-Diobsud col post-dates the injection of post-metamorphic dikes.

Greenschist Units

The two greenschist units have undergone Shuksan metamorphism together, have similar mineralogy, and show the same structures and structural orientation. For these reasons they are here described together.

Field Appearance

Type A greenschists (figure 11) are very fine-grained light grey-green to grey schists which weather to shades of grey, brown and yellow. They are well laminated, with regular and even schistosity, and split easily along the schistosity. Crenulation of the schistosity is well developed and ubiquitous. In places a faint amphibole lineation or compositional banding is present. Two to ten mm diameter white flecks (probable relict plagioclase phenocrysts)

Figure 11. Type A greenschist at 195. Compositional banding L_1 is at high angle to handle. L_3 crenulation lineation is parallel to handle. Hammer is 38 cm long.

Figure 12. Eroded-out boudins in type A greenschist at 6.

flattened parallel to the schistosity are widespread, and in places appear to be elongate parallel to the mineral lineation. Visible epidote concentrations are rare.

Compositional layering in type A greenschist is almost everywhere parallel to the schistosity, and its evenness and regularity, coupled with relatively common relict textures (discussed below) indicative of minimal reconstitution of the rock during metamorphism, indicate that it is relict bedding. At 5, 171, 196 and other locations 10 cm to 1 m thick quartzite layers, possibly relict quartz-rich sedimentary beds, are present, usually associated with soft chlorite-rich schist.

In type A greenschist along the ridge crest east of Anderson Lakes are boudins of more competent, massive rock (figure 12). Schistosity wraps around these boudins. They usually occur in trains subparallel to the schistosity.

Type B greenschist is heterogenous. Most of it is dark green. The distinguishing features of the unit are visible epidote concentrations, irregular schistosity, a sporadically developed crenulation lineation, and intercalated blueschists. Also present in unit B are massive, poorly schistose epidote-rich greenschist showing a faint phacoidal structure, greenschist with small dark flecks elongate parallel to the mineral lineation, and light grey-green schist with felsic flecks identical to type A schist. Fine-grained, almost phyllitic blueschist on Bacon Peak (18) is considered to be part of unit B.

Much of the type B greenschist shows either of two types of

Figure 13. Elongate relict pillow structures in type B greenschist near 28. Looking up at cliff face; width of view is about 10 m.

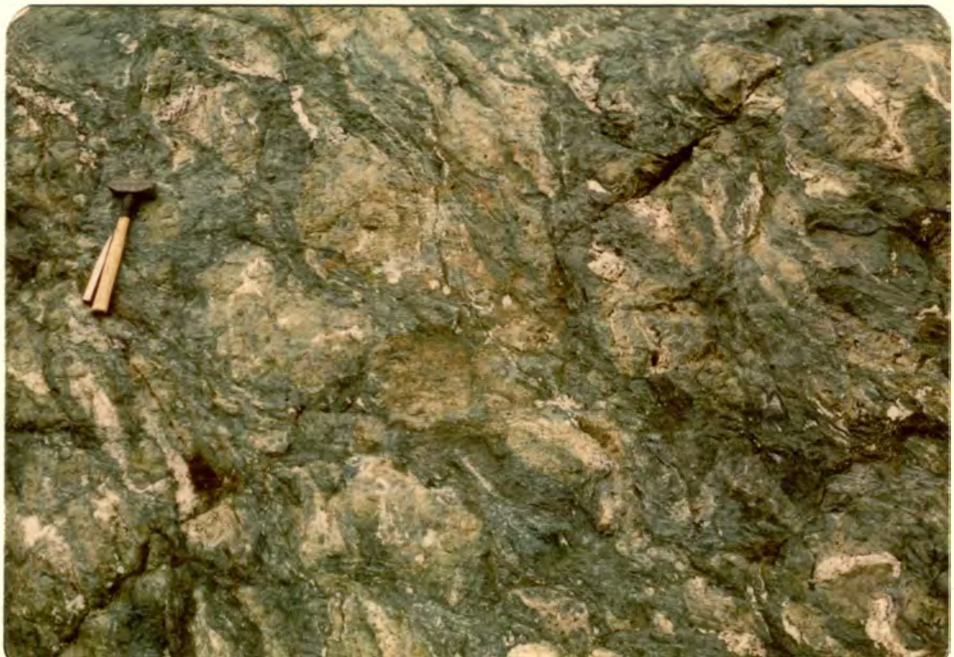


Figure 14. Massive epidote pods in type B greenschist at 189. Pods are considered to be relict pillows.

phacoidal structure, the more common of which is shown in figure 13. Elongate lenses of epidote-rich greenschist are surrounded by thinner selvages of blue-green chlorite-rich schist. The lenses are elongate parallel to the mineral lineation in the schist. Less common but extensively exposed on slabs below the small glacier NE of the summit of Mt Watson are pods of massive epidote set in a matrix of blue-green schist (figure 14). Schistosity and lineations in the schist wrap around the epidote pods. Both types of phacoids are considered to be relict pillows.

Both greenschist units are cut by irregular veins of quartz + carbonate $\pm$ albite, black chlorite, specular hematite and pumpellyite. Some of the veins are restricted to phacoid cores and may be pre- or synmetamorphic, while others cut across well-foliated schist and appear to be post-metamorphic. Near upper Anderson Lakes veining appears to be associated with tight folding of the schistosity.

Narrow brecciated zones crosscut the greenschist. Clasts within the breccia are identical with the country rock and are set in a brown-weathering matrix. At <u>199</u> on the south side of Mt Watson brecciation appears to postdate veining. Brecciation is most extensive near the Mt Watson fault.

Occurrence and Contact Relations

Type A greenschist is well exposed on the western part of Mt Watson and on Anderson Butte (see plate II). Underneath type A greenschist is concordant type B greenschist which outcrops in a narrow band along the Anderson fault scarp. The contact is gradational within a 3 m wide interval at 205. A transitional facies is exposed at the site of the Anderson Butte Lookout. The eastern boundary of type A schist is the Mt Watson fault. East of the fault type B schist is exposed.

East and south of the mapped breccia body on the ridge east of Mt Watson relations are not clear. Much of the rock, particularly that associated with thin bands of phyllite, is epidote-rich greenschist. Other areas, such as the knoll north of 23, NW of Diobsud Lakes, are underlain by epidote-poor greenschist with felsic flecks. All of this rock was mapped as type B greenschist. With more detailed work it might be possible to subdivide this area.

Contact relations between the greenschist units and the phyllite unit have been described above.

Petrography

Over 70 samples of greenschist were examined in thin section. Phases observed in each section are listed in Appendix A. Assemblages present are (all include epidote + albite + chlorite + sphene, $\pm$ quartz, white mica, apatite and sulphide):

actinolite (many samples)

sodic amphibole (many samples)

sodic amphibole + Fe-oxide (E77)

actinolite + calcite (D29, D78, E42)

calcite (E60, E85)

actinolite + pumpellyite (D6, E27)

Fe-oxide(?) (E76)

calcite + rutile, no sphene (E49)

In addition, the following vein assemblages were observed:

quartz + calcite + garnet (E40, 41)

quartz + chlorite + pumpellyite + stilpnomelane (E54).

All of the above appear to be equilibrium assemblages.

Sodic amphibole-bearing assemblages are restricted to type B greenschist. Samples with pumpellyite are type A greenschist.

Epidote is quite variable. Most is yellow-colored, slightly pleochroic and has brilliant second order interference colors. Zoning from yellow, high birefringence cores (Δ = .025, 60 % pistacite) to paler, lower birefringence rims (Δ = .010, 30 % pistacite) is common. Epidote coexisting with pumpellyite is colorless (Δ = .010, 30 % pistacite). In some samples (e.g., E44) epidote is beige to brown, without pleochroism. In several samples epidote is clouded with fine hematite dust, giving it a garnet-like color in hand specimen. In some rocks all epidote is in small granules, in others it is in large anhedral to euhedral crystals and glomeroblasts, and in most samples all sizes and shapes coexist. Strongly colored epidote is widespread in type B greenschist, giving the rock its characteristic deep green color. Most epidote in type A schist is finer grained and less strongly colored, apparently accounting for the light grey-green color of the unit. Evidence discussed below indicates much of the strongly colored epidote is relict from a pre-Shuksan metamorphic event.

Colorless and greenish amphiboles are considered to be actinolite while those with blue, purple, brown or beige in their pleochroic scheme are considered sodic. Complete solid solution between these varieties exists in the Shuksan Suite (Misch, 1959; Brown, 1974). Minor zoning in sodic amphiboles is indicated by small variations in birefringence and extinction angle.

Equilibrium Fe-oxide is present in one sample (E77) as small granules and granular masses.

Sulphide is widespread in outcrop and in thin section, commonly as large cubes. Some samples contain small opaque granules which give yellow reflections, suggesting they are sulphide.

Albite is present in all samples, usually as an equigranular mosaic of untwinned, equant grains. Quartz has a similar habit, and may be more widespread than recognized. X-ray diffraction analyses and diligent searching indicate that a significant number of samples are quartz-free.

Chlorite is variable in color and birefringence. Some varieties show strong green to beige pleochroism and anomalous blue to purple interference colors. More common are greenish chlorites with grey to brown interference colors. Chlorite coexisting with pumpellyite is Mg-rich as it is colorless and has a relatively high grey interference color.

Very small, irregular grey granules or larger spindles of sphene are present in almost all samples.

White mica is distinctly more common in sodic amphibole-bearing rocks. It is presumably phengitic muscovite. A few pale blue (chrome-bearing?) plates are present in E72.

Anhedral apatite is present in several samples of type B greenschist.

Calcite is present in over a third of the rocks examined. In most samples it is in veins and/or poikiloblastic replacement patches, and is not considered to be part of the primary metamorphic assemblage.

Pumpellyite in E27 and D9 (figure 15) is almost colorless, with moderately high relief and birefringence of about .015. Interférence colors are normal. It is present as small euhedral laths with almost rectangular cross sections and was at first mistaken for lawsonite. However, 2V is about 10°, crystals are elongate parallel to β , and end sections show parallel, not symmetric extinction--all inappropriate for lawsonite. As iron content in pumpellyite decreases, color decreases, refractive indices decrease, 2V decreases (Deer et al., 1966) and $\gamma \wedge C$ approaches 0° (Tröger, 1971). This pumpellyite appears to be an unusually iron-poor variety.

Samples E40 and E41 are float. They contain veins of quartz + carbonate + garnet. Garnet is in large (1-2 mm), fractured, euhedral, subhedral and skeletal crystals, not the tiny euhedra typical of the Shuksan Suite. These samples are probably glacially transported contact-metamorphosed material.

Coarsely crystalline veins of quartz, calcite, albite, actinolite and chlorite are widespread, and many seemto be synmetamorphic. Chlorite, black in hand specimen, is pleochroic, deep green and beige. Albite is commonly twinned. Sprays of exceedingly fine actinolite needles cut across quartz and albite crystals. A similar vein (E54) from an F_2 hinge in type A greenschist south of upper Anderson Lakes

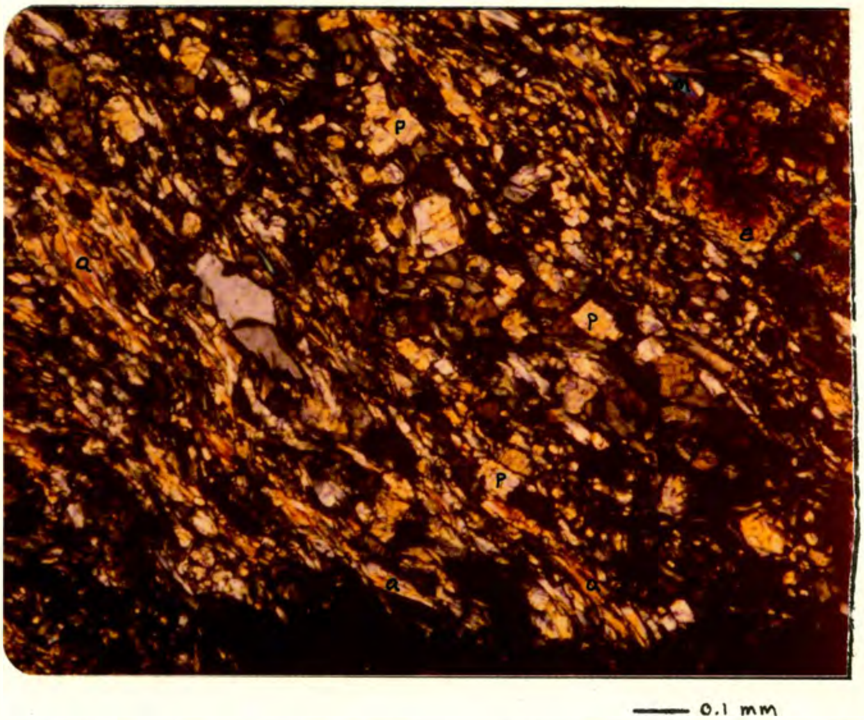


Figure 15. Photomicrograph of ideoblastic pumpellyite (p) in E27; crossed polars. Other minerals visible include epidote (e), actinolite (a), white mica (m), quartz/albite and chlorite.

is largely massive pumpellyite, colorless in thin section and green in hand specimen.

Rutile in E49 (from a brecciated zone at 199 along the Mt Watson fault) has the same habit as sphene in other samples. It is associated with small, irregular, elongate patches of carbonate which appear to have replaced amphibole. Small, high relief, highly birefringent yellowish grains which appear to be rutile coexist with sphene in epidote-chlorite greenschist (E61) from the phyllite-greenschist contact north of "Pipsqueak Pass" (103). Rutile(?) in E61 is concentrated along S_3 cleavage traces.

Coexisting chlorite and potassium feldspar in E7 (from north of the Noisy-Diobsud col) probably record contact metamorphism related to the granitic stock on Bacon Peak. The sample is unusual, as it contains two amphiboles, one colorless and the other blue-green. Both form fine needles and larger stout helicitic crystals.

Pre-Shuksan Metamorphism Relics

The irregular epidote pods exposed NE of the summit of Mt Watson (figure 14) pre-date blueschist-facies Shuksan metamorphism. Close examination shows that many of the pods are cut by veins roughly normal to the schistosity (S_1) with extension parallel to S_1. Vein fillings are quartz, albite and amphibole, with the amphibole needles parallel to S_1 (figure 16). Microscopic textures (figures 17,18) show that the epidote crystallized under low-strain conditions, as it overprints an undeformed basaltic texture. Epidote in the pods commonly contains reddish hematite dust which should not coexist

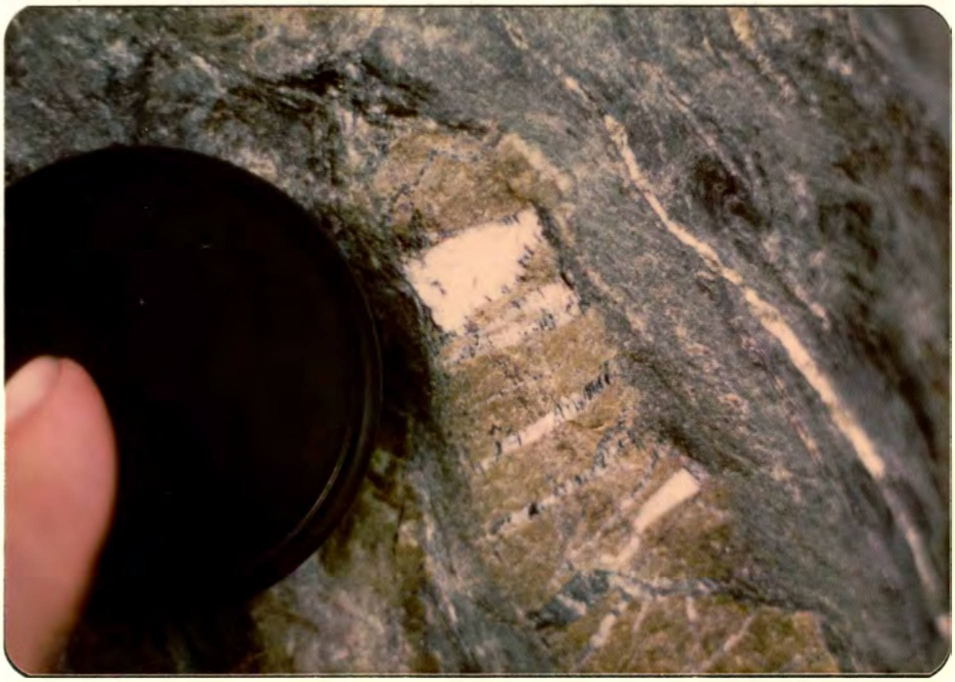


Figure 16. Close-up view of epidote pod in type B greenschist. Pod is cut by extensional fractures normal to S_1. Fractures are filled with quartz, albite and blue amphibole. Blue amphibole needles are parallel to S_1. Lens cap is 5.7 cm in diameter.

Figure 17. Photomicrograph of massive epidote in E43a, showing relict basaltic texture; plane light.

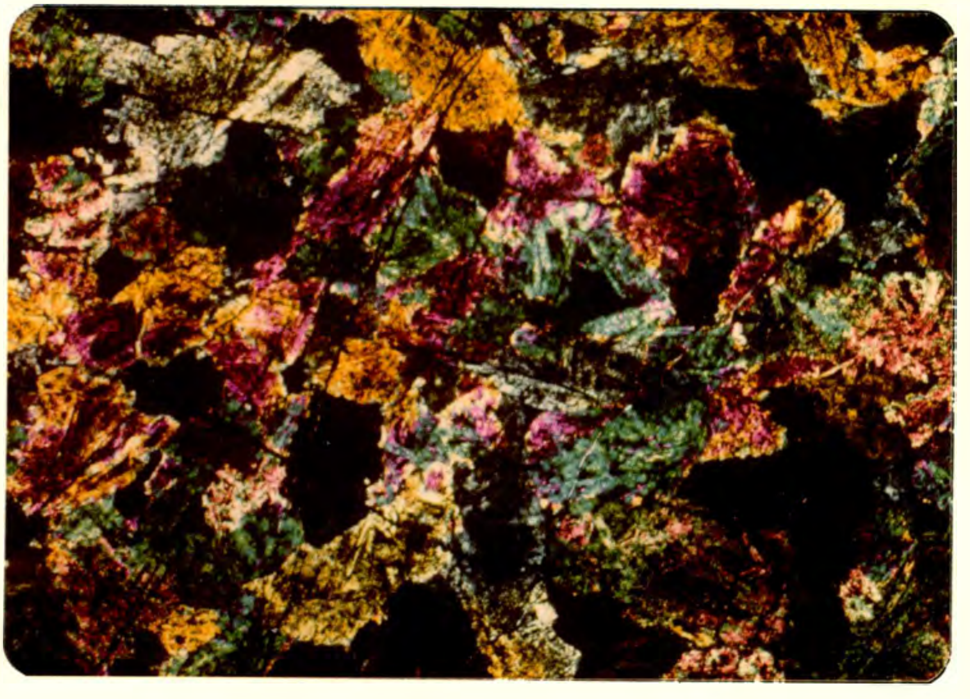
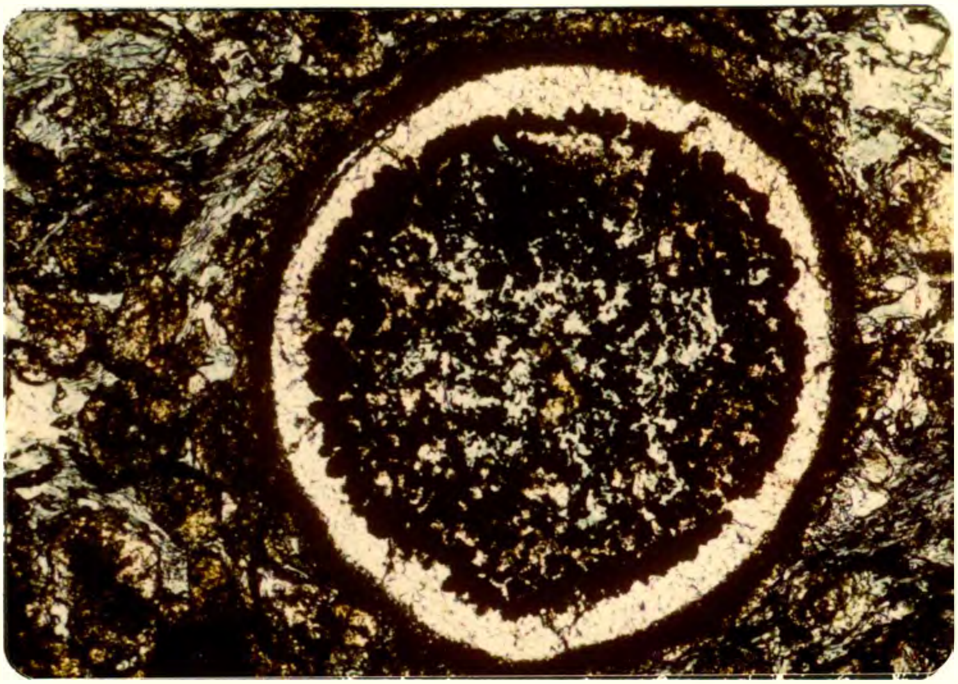


Figure 18. Same view as figure 17; crossed polars.

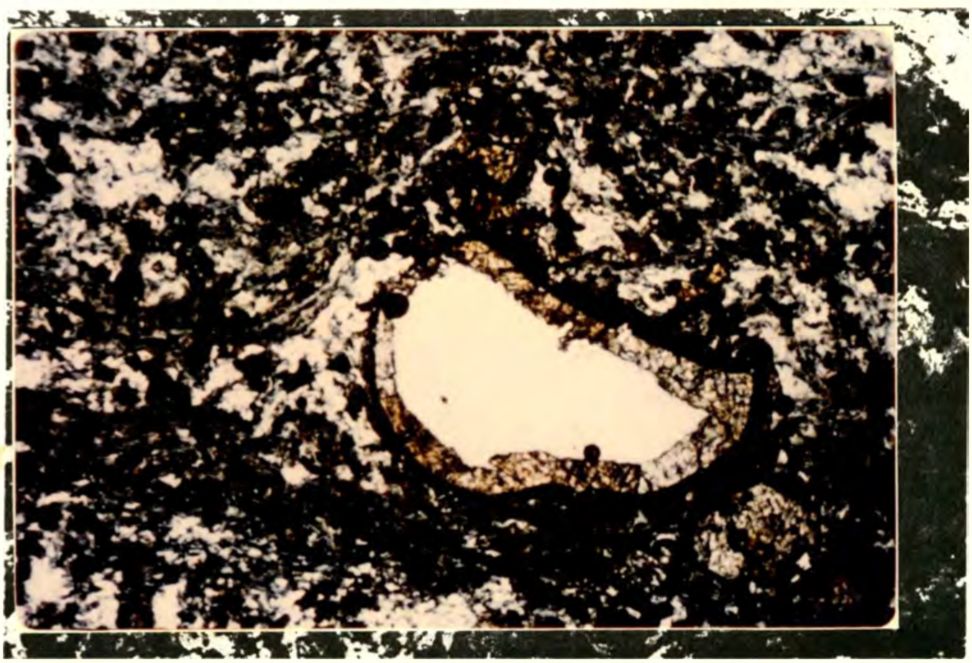
with surrounding actinolitic amphibole under the high pressure conditions of Shuksan metamorphism (Brown, 1974). In actinolitic assemblages this hematite is the only Fe-oxide present.

Grains and aggregates of epidote similar to epidote in the massive pods are widespread in type B greenschist, and occur sporadically in type A schist. Figures 19 and 20 are photomicrographs of epidote "balls" present in many samples. Most are circular in shape and 1 mm or less in diameter. A few appear to be broken, while others are composite. Some varieties are filled with a polygonal epidote mosaic, while others are composed of radial fibers, showing an extinction cross in all stage positions. The most dramatic have rims of epidote and chlorite cores, some with large grains of hematite in the core and inner parts of the rim. Misch (1965) has described identical epidote balls from the Shuksan Greenschist. He considered them to have formed by some unknown mechanism during synkinematic blueschist-facies metamorphism. Several kinds of evidence observed in this study indicate that the balls predate blueschist-facies metamorphism: schistosity commonly wraps around the balls and a few have chlorite strain shadows, some balls contain hematite in disequilibrium with the actinolitic assemblages surrounding them, the epidote is similar to relict epidote in the massive clots, and the delicate radial structures indicate formation of the balls under low-strain conditions. I have seen identical structures in Chilliwack Group greenstone from west of Mt Shuksan, where they are definitely vesicule fillings in basalt. D.R. Pevear (personal communication, 1979) has found similar balls (calcite rims with chlorite cores) in interpillow sediments of



— 0.1 mm

Figure 19. Photomicrograph of epidote ball in D28; plane light. Center of ball is chlorite, outer portion is polygonal epidote mosaic. Dark spots in center 4/5 of ball are hematite grains.



— 0.1 mm

Figure 20. Photomicrograph of epidote ball in D28; plane light. Core is chlorite; rim is epidote mosaic.

the Crescent Fm on the Olympic Peninsula. There the balls are altered microfossils. The occurrence of the Shuksan epidote balls in the cores of relict pillows indicates that they are vesicule fillings.

Primary igneous structures are relatively common in the greenschist. Much of the type B schist is pillowed (figures 13, 14). Relict basaltic textures are preserved in some massive epidote pods (figures 17, 18). Relict plagioclase phenocrysts are preserved in form in several samples (figure 21). The felsic flecks common in type A greenschist are mosaics of small albite grains, with little or no quartz. Some samples contain relict plagioclase surrounded by albite mosaic, suggesting that all the felsic flecks are the remains of plagioclase phenocrysts.

Boudins in type A schist (figure 12) show well-preserved basaltic texture in thin section (figure 22). The boudin have undergone Shuksan metamorphism: small actinolite needles, epidote and chlorite are developed in them. The surrounding greenschist has developed an excellent crystallization schistosity, while the boudins are largely unstrained, indicating a large competency contrast during metamorphism. In E44, from the edge of a boudin, mats of fine-grained, anhedral, brownish epidote are replacing probable volcanic glass. The boudins are either scattered pillows or remnants of original thin flows, dikes or sills. The surrounding type A schist was probably waterlaid tuff.

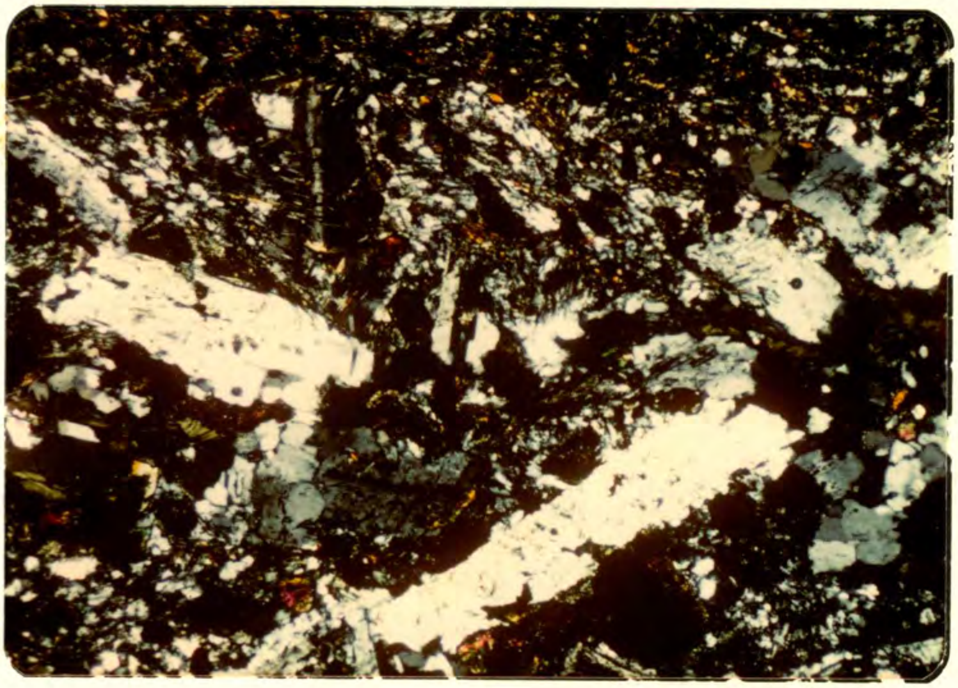


Figure 21. Photomicrograph of relict igneous plagioclase in greenschist (E83); crossed polars.

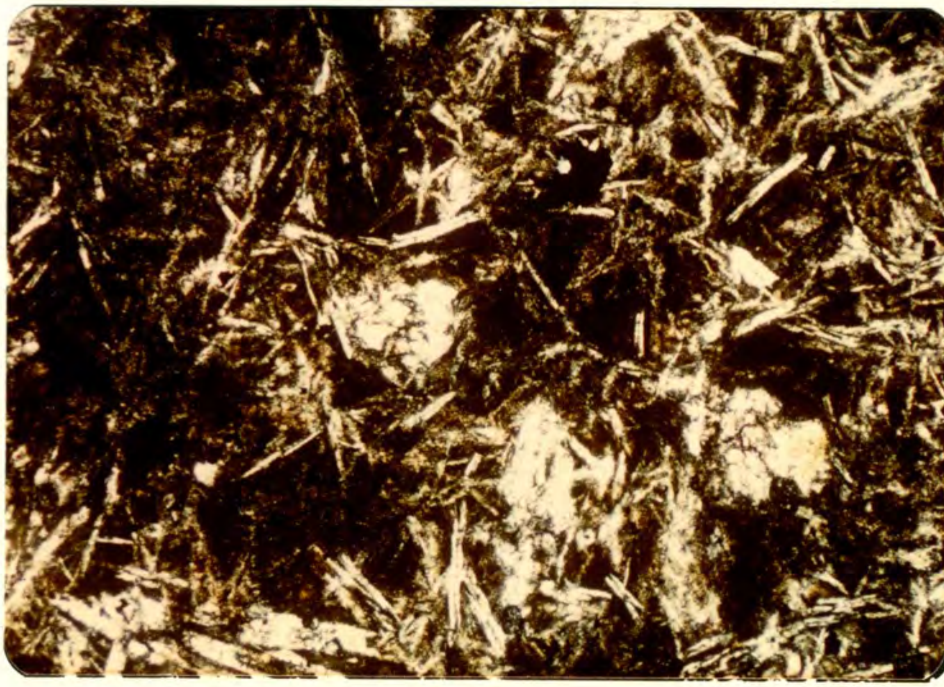


Figure 22. Photomicrograph of relict basaltic texture in boudin in type A greenschist (D7, from 6); plane light.

Structure

Structures recognized in the greenschist units are crystallization schistosity (S_1), metamorphic lineation (L_1), folds of the schistosity (F_2, F_3) and a crenulation lineation (L_3). A large F_1(?) fold appears to be present at 179, where two thin quartzite layers approach each other as they are followed along strike to the north. Amplitude is $>$100 m. This is the only F_1 structure recognized.

Measured attitudes of S_1, L_1, F_2 and L_3 in greenschist exposed between the Anderson fault and the Noisy-Diobsud fault are presented in figures 23 and 24a.

Amphibole lineations, intersections of compositional layering and S_1, pillow elongation and elongate mineral segregations are all considered L_1. Measured attitudes show considerable dispersion in the plan of S_1. In pillowed greenschist considerable local variation in L_1 is evident, the result of inhomogenous deformation during metamorphism. However, a map of L_1 (figure 25) shows that a bimodal pattern is also present, probably as a result of post-metamorphic isoclinal folding.

Isoclinal folds of the schistosity (F_2) are locally visible. Axial planes are parallel to S_1. Most F_2 axes trend NNE. Many folds are 'S' or 'Z' folds (figure 26); a sense of vergence was recorded for these. Eight of the 12 vergences recorded are clockwise. All folds with counterclockwise vergence are near upper Anderson Lakes or on the ridge crest to the east. Penetrative lineation associated with F_2 (L_2) was recognized at only one locality (6). Some elongate felsic mineral segregations recorded as L_1 may be L_2.

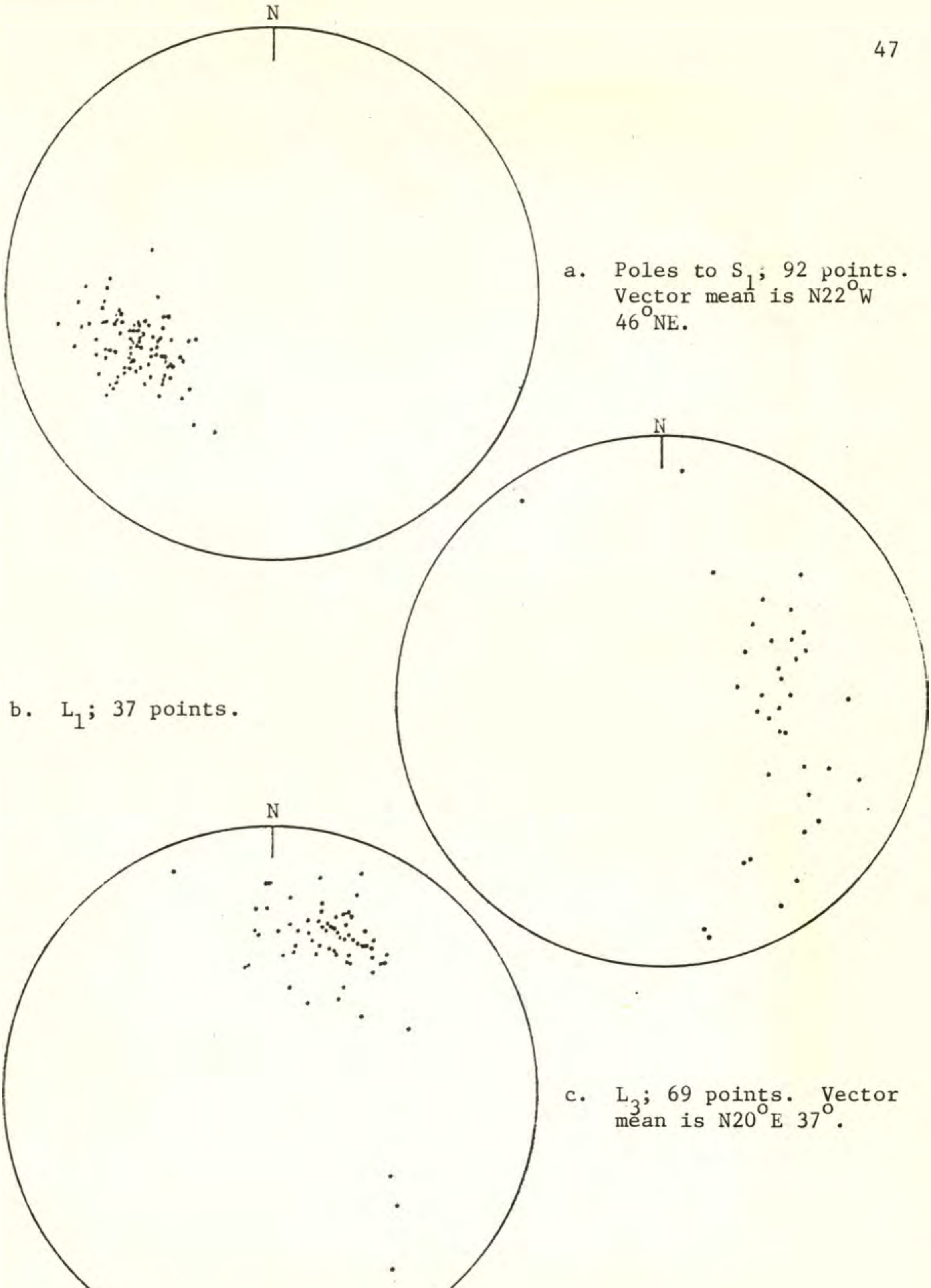
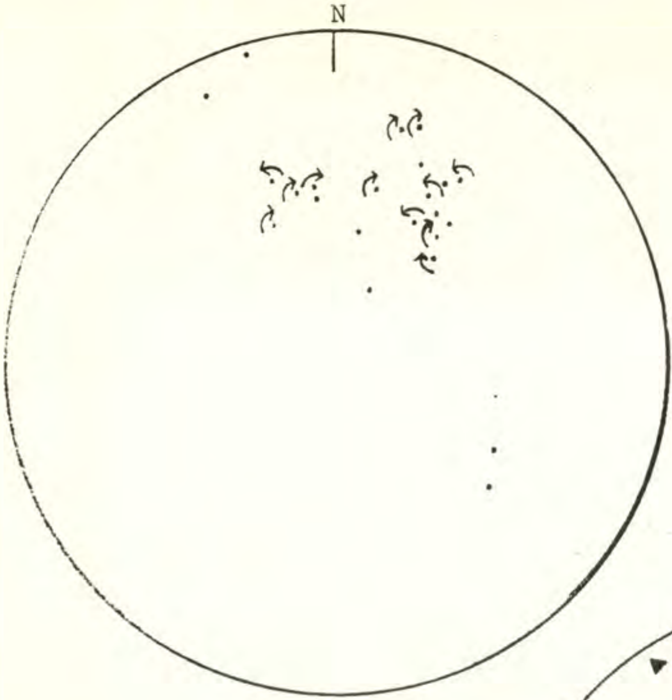
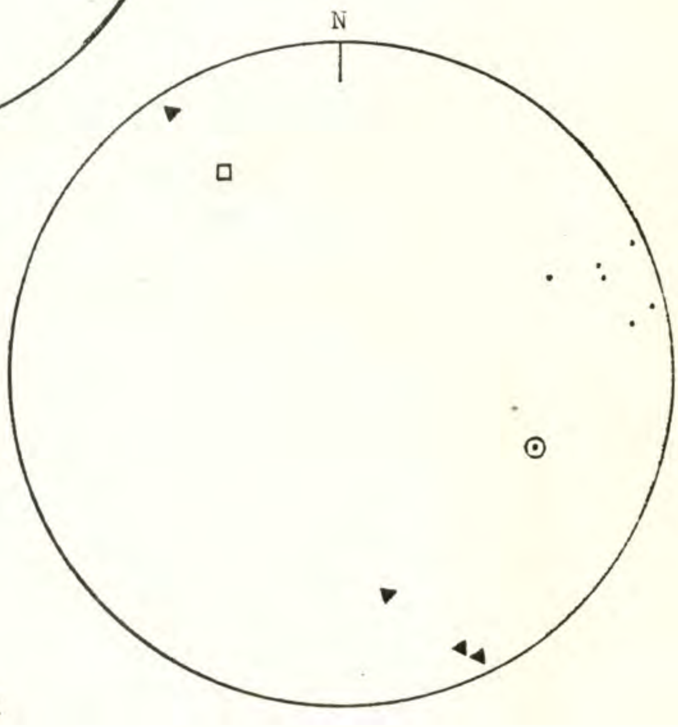


Figure 23. Equal area, lower hemisphere projections of structural data from greenschist west of Noisy-Diobsud fault.



a. F_2 fold axes in greenschist units west of Noisy-Diobsud fault. Arrows show fold vergence.



b. Attitudes from greenschist east of Noisy-Diobsud fault.

· S_1

□ L_1

▲ L_3

⊙ S_2? S_3? at 159

Figure 24. Equal area, lower hemisphere projections of a) fold axes in greenschist west of Noisy-Diobsud fault and b) attitudes in greenschist east of Noisy-Diobsud fault.

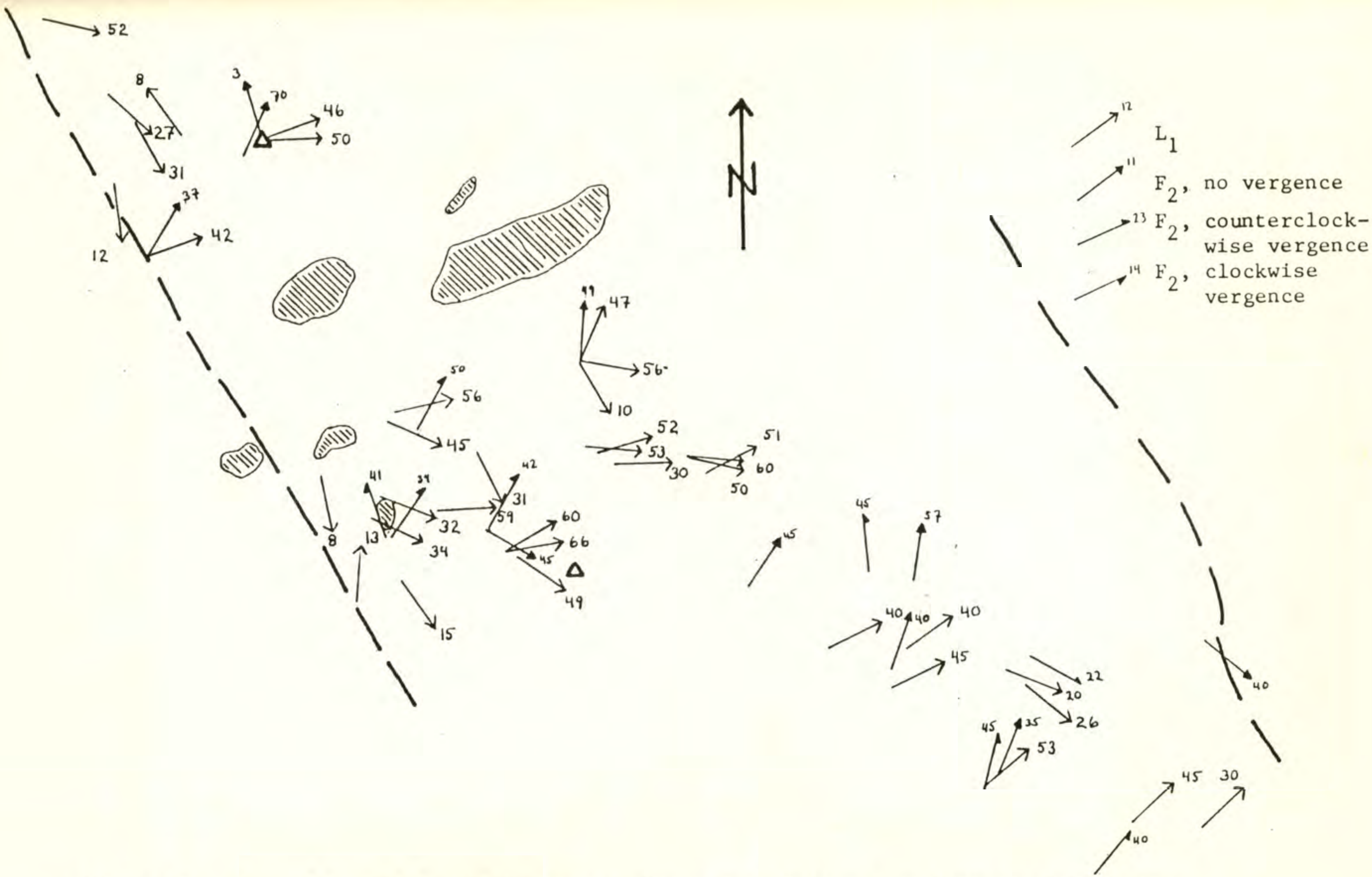


Figure 25. Map of L_1 and F_2 orientations. Heavy dashed lines are Anderson (left) and Noisy-Diobsud faults; ruled areas are lakes.

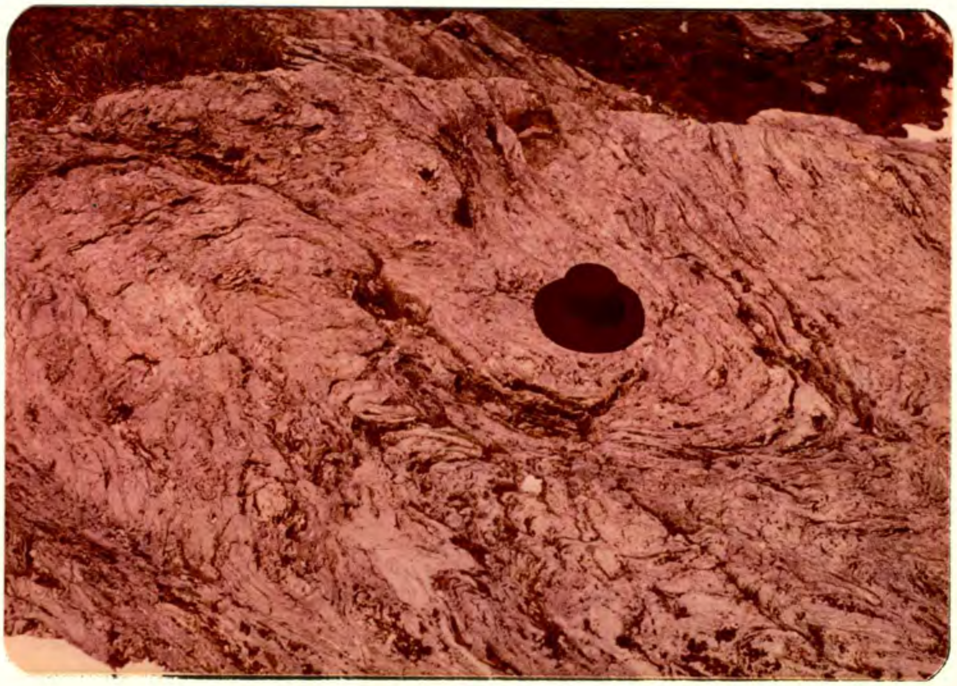


Figure 26. F_2 'Z' fold in greenschist at 22. Hat is 34 cm across. View is to NE.

Thin sections of several F_2 hinges in actinolitic greenschist were examined (D8, E55, E70, E71). Textures in them are similar. All show a strong axial planar orientation of actinolite and white mica (where present). The amphibole fabric is deflected around epidote grains and albite patches. Small areas within which actinolite needles are at high angles to the prevailing S are the sole relict of S_1. Thin sphene-rich layers outline F_2. Some amphiboles are bent, but most are straight, indicating recrystallization during or after F_2 deformation, or possibly that amphiboles were rotated as rigid bodies. In E76 actinolite heals a rupture in an epidote porphyroblast, showing that F_2 was at least partly synmetamorphic.

Crenulation of the schistosity (L_3) is seldom apparent in thin section. Where it is, white mica and amphibole are bent, while quartz and albite have been annealed. Associated with L_3 is open folding of the schistosity (F_3) with wavelengths up to 3 m and amplitudes less than 20 cm. F_3 axial planes are normal to S_1.

Fold style, axial plane attitude and amphibole fabric (reorganized in F_2, bent in F_3) indicate that F_2 and F_3 record separate events. F_2 and F_3 axes are parallel for the most part. The reasons for this are not readily apparent.

Attitudes from greenschist on Bacon Peak are shown in figure 26b and on plate II. While few in number, they are representative. L_3 and S_1 orientations from opposite sides of Noisy Creek are not consistent with post-L_3 folding. A post-L_3 rupture of some kind is indicated. This is perhaps the strongest evidence for the Noisy-Diobsud fault.

History

The following history is inferred for the Shuksan Greenschist in the Mt Watson Area:

subaqueous eruption/deposition of basaltic flows and tuffs; hydrothermal alteration under low-strain conditions with local epidote metasomatism and widespread crystallization of epidote + chlorite + hematite;

D_1- synkinematic blueschist-facies Shuksan metamorphism, development of S_1 and L_1;

D_2- Late-metamorphic isoclinal folding of S_1 (F_2) around axes commonly at high angles to L_1, development of axial planar S_2 parallel to S_1, some amphibole recrystallization;

D_3- L_3 crenulation of S_1 (= S_2), minor recrystallization of quartz and albite.

Irregular veining associated with F_2 hinges indicates high fluid pressures during D_2. Irregular veins may also have formed at other times. Widespread brecciation of greenschist probably postdates all other structures.

EVOLUTION OF THE SHUKSAN METAMORPHIC SUITE

Protoliths

The presence of ferromanganese nodules and calcareous schist in the phyllite suggests that at least part of the phyllite protolith was deposited in a regime of low detrital sediment input. Spessartine-bearing, graphite-free parts of the phyllite unit were probably Fe-Mn enriched cherty sediments. The local occurrence of paragonite requires some of the sediment to have been extremely aluminous. The carbon content of the phyllite does not require it to have been a near-shore sediment: black shales have been fairly common open-ocean deposits (Arthur and Kelts, 1979).

Pillow structures, metamorphic mineralogy and relict basaltic texture show that type B greenschists are largely metamorphosed su-aqueous basalts.

Relict bedding and quartzitic layers suggest that type A greenschists were originally water-laid tuffs. This impression is reinforced by the contrasting behavior during metamorphism of type A greenschist and contained bodies of crystalline volcanic material material. At one point in this study it was thought that Type A greenschists were originally felsic or intermediate tuffs (Haugerud, 1979). However, chemical analyses (Appendix C) show present compositions to be those of olivine-normative subalkaline tholeiitic basalts. The boudins in type A greenschist are probably dismembered basaltic dikes or sills.

In the Mt Watson area there is no evidence for stratigraphic order in the Shuksan Suite. The contact between phyllite and greenschist on the west side of the Shuksan structural belt was considered by Misch

(1966, 1977) to be a depositional or faulted depositional contact. This study shows that for part of its length this fault contact (the Anderson fault) truncates the phyllite-greenschist contact. Where the unfaulted contact is exposed, the contact may be depositional, but proof is lacking. Phyllite lenses east of Mt Watson have been described as anticlines (Misch, 1966). The western contact of the largest lens is a major fault. Smaller lenses are in part fault-bound and in part depositionally interlayered with greenschist. Large-scale isoclinal F_1 or F_2 folds may be present, but such an interpretation is not required by the data at hand.

All evidence points to a submarine origin for the Shuksan Suite. It is not clear if the Suite is of ophiolitic affinity as proposed by Morrison (1977). The association of calcareous sediment, ferromanganese nodules, pillow basalts and flows and water-laid basaltic tuff is known from modern midoceanic ridges (Lonsdale and Speiss, 1979). However, this assemblage is not diagnostic and could have formed in an oceanic island, immature island arc or spreading back-arc basin setting. Modern ferromanganese deposits are found in freshwater lakes, shallow seas and continental margin areas as well as mid-oceanic areas (Calvert and Price, 1977). Deposits from different settings have been distinguished by their chemistry (for example, Cronan, 1977; Calvert and Price, 1977; Heath and Dymond, 1977) but analyses are not available for the Shuksan Suite ferromanganese deposits.

Controversy over the origin of the better preserved Eocene Crescent Basalts of the Olympic Peninsula (Glassley, 1974a, Cady, 1975; Lyttle and Clark, 1975, Globerman, 1979) should illustrate some of the difficulties of assigning a tectonic setting to metamorphosed basalts.

Pre-Shuksan Metamorphism

The epidote + hematite + chlorite assemblages developed during pre-Shuksan metamorphism are not diagnostic of specific P-T conditions within the low to very low grade zone (below amphibolite facies). Pods of massive epidote up to 1 m across require considerable mass transfer, most likely by hydrothermal circulation. The lack of associated strain suggests shallow burial.

Likely environments for this metamorphism are zones of high heat flow found near mid-ocean ridges, in magmatic arcs and in back-arc basins.

D_1- Shuksan Metamorphism

Well-developed crystallization schistosity S_1 and amphibole lineation L_1 were formed during blueschist-facies Shuksan metamorphism, a point elegantly made by Misch (1969).

Brown (1977a) has assigned approximate P-T conditions of 7 kb and 350° C to Shuksan metamorphism. All primary assemblages found in the Shuksan Suite in the Mt Watson area fit the phase diagram proposed by Brown (figure 27). As expected, actinolite is not found in equilibrium with Fe-oxide; instead, sodic amphibole-bearing assemblages are developed.

Synmetamorphic veining (figure 16) indicates P_{fluid} was near P_{total}. Water was already present in the rock, acquired during earlier hydro-

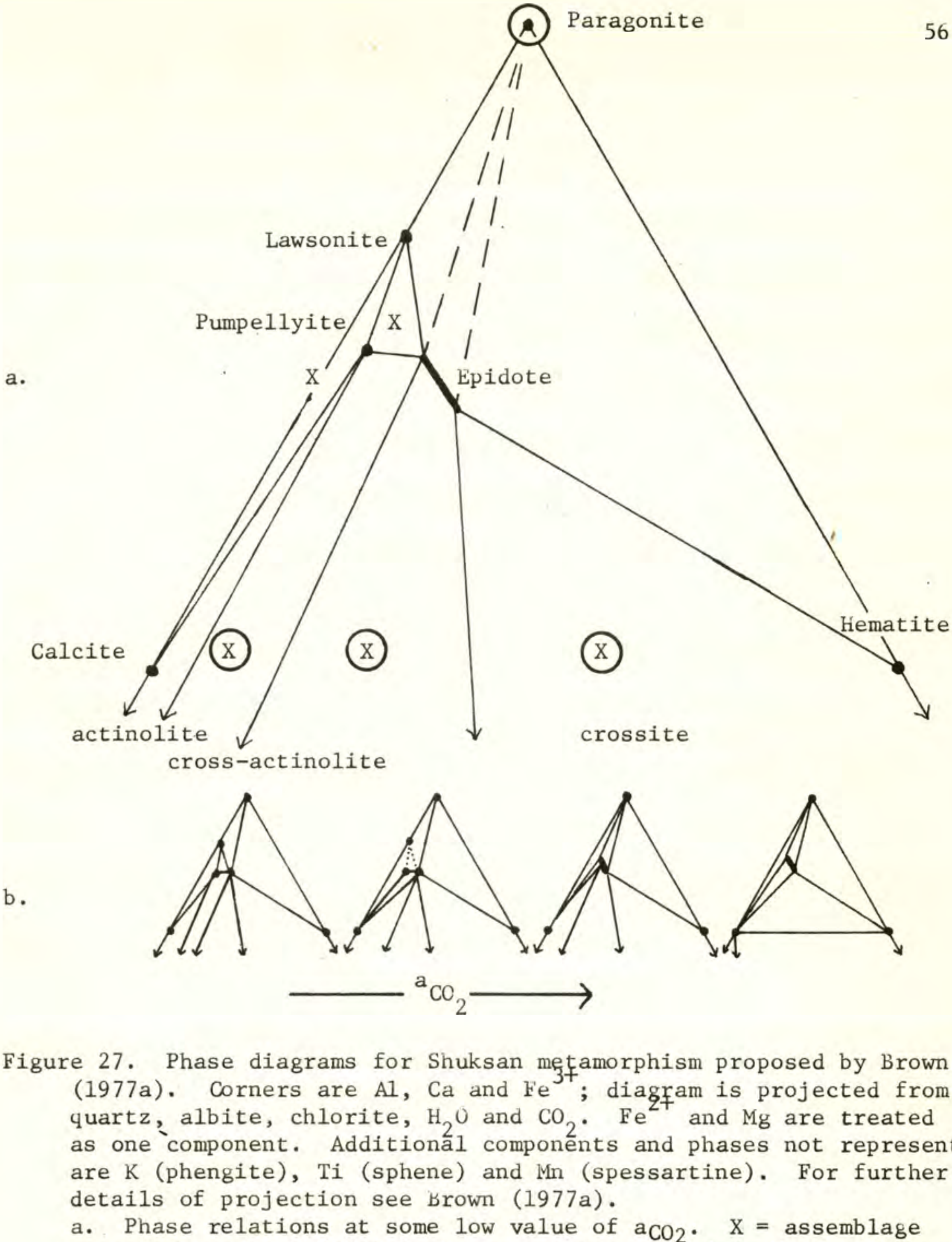


Figure 27. Phase diagrams for Shuksan metamorphism proposed by Brown (1977a). Corners are Al, Ca and Fe^{3+}; diagram is projected from quartz, albite, chlorite, H_2O and CO_2. Fe^{2+} and Mg are treated as one component. Additional components and phases not represented are K (phengite), Ti (sphene) and Mn (spessartine). For further details of projection see Brown (1977a).
a. Phase relations at some low value of a_{CO_2}. X = assemblage reported by Brown (1977a); O = assemblage found in Mt Watson area.
b. Phase relations with increasing values of a_{CO_2}. Epidote + actinolite + calcite, epidote + calcite and epidote + Na-amphibole + calcite assemblages present in Mt Watson area probably reflect locally higher a_{CO_2}. Epidote + Na-amphibole + calcite assemblage probably reflects a_{CO_2} values between those of third and fourth diagrams.

thermal alteration. Sphene is ubiquitous, indicating X_{CO_2} substantially below 0.1 (Hunt and Kerrick, 1977).

The relative lack of recrystallization in unstrained bodies (basaltic boudins, epidote pods) within the Shuksan Greenschist indicates that recrystallization and deformation were intimately linked.

K/Ar dating of sample E69 by R.L. Armstrong places Shuksan metamorphism at or before 122 ma before present. Other radiometric evidence (see Appendix B for discussion) indicates that metamorphism was not much earlier than 122 ma before present.

D_2

During D_2, S_1 in greenschist in the Mt Watson area was isoclinally folded (F_2) around axes commonly at high angles to L_1. Scarce L_2 lineations and local S_2 foliation were developed in greenschist. Pervasive S_2 in phyllite developed by F_2 folding and transposition of S_1 and by pressure solution and realignment of phyllosilicates.

D_2 was probably late-metamorphic as locally actinolite nucleated and recrystallized. Quartz was mobile during D_2 as quartz fabrics developed during D_2 are unstrained. White mica does not appear to have significantly recrystallized during D_2. Conditions were in the stability field of calcite (as opposed to aragonite) as calcite in E39 was deformed during D_2. Some of the widespread irregular quartz-carbonate-pumpellyite-chlorite-albite veins formed during D_2, indicating P_{fluid} near P_{total}.

D_3 and Post-D_3 Deformation

Shuksan Greenschist in the Mt Watson area was crenulated about an axis L_3 = N20°E 37° during D_3. Associated F_3 folds are very open, with amplitudes less than 20 cm and wavelengths up to 3 m. F_3 axial planes are perpendicular to S_1 (= S_2).

D_3 probably predates deposition of the overlying Chuckanut Fm. The absolute age and tectonic setting of D_3 are not known.

Phyllite was crenulated and locally tightly folded and brecciated after D_2. Some of this deformation is coaxial with L_3 in the greenschist and probably occurred during D_3. Severe post-D_2 deformation seems to be localized near the Anderson and Noisy-Diobsud faults. Brecciation of phyllite near the Noisy-Diobsud fault is associated with rotation of L_3, and thus must postdate D_3.

Quartz affected by post-D_2 deformation typically has not recrystallized, showing undulose extinction, sutured grain boundaries, inequigranular textures and local severe shattering.

Post-D_3 deformation along the Noisy-Diobsud fault can be dated as, in part, post-early Eocene, as it involves a post-metamorphic dike. Part or all of this deformation predates intrusion of the small stock on Bacon Peak as post-D_3 breccia is contact-metamorphosed by the stock.

Comparison with Previous Studies

Table 1 compares the history of the Shuksan Metamorphic Suite in the Mt Watson area with that deduced by Misch (1966) from his regional reconnaissance studies, Milnes (1976) in the Illabot Peak area and Morrison (1977) in the Gee Point-Finney Peak area. Overall, the

This study	Morrison (1977)	Milnes (1976)	Misch (1966)
D_1 - synkinematic S_1 N22°W 46°NE F_1 cryptic L_1 variable, trends E (amphibole L, elongate albite segregations, elongate pillows, comp. banding)	D_1 - synkinematic S_1 N40°W 63°SW F_1 NW trend, in ph only L_1 NW trend, (amphibole L, comp. banding	D_1 - synkinematic S_1 N25°W E dip L_1 amphibole L "F_1 intrafolial folds" ?	D_1 - synkinematic
D_2 - rare late-metam. F_2 F_2 axes trend NE at high angles to L_1 isoclinal calcite stable	D_2 - common late-met. F_2, S_2, L_2 F_2 axes trend NW, subhorizontal, isoclinal, overturned to E discordant to L_1		late-met. microscopic F_2 common Evans and Misch (1976) aragonite stable after D_2
D_3 - well developed L_3 crenulation N20°E 37° parallel open F_3	D_3 - open F_3, NE-E trend in gs only crenulation L	NE-trending F_2 drag folds subhorizontal large F_3, N25°W trend local kinking assoc. w/Thrust	post-crystalline F and secondary S related to Shuksan Thrust (in ph)
N-trending open fold in Chuckanut, faulting, melange movement?	fold axes in Chuckanut S19°E 5°	F_4 folds, kinks assoc. with Straight Creek Fault	local cataclasis at Chuckanut-Shuksan contact

Table 1. Comparison of history of Shuksan Suite deduced in this study with those deduced by other workers.

histories are similar, indicating a similar history for the Suite throughout northwest Washington. Milnes' structural sequence contains elements not found by other workers, but I suspect this reflects differences in focus and interpretation rather than differences in the rocks.

The following comparisons are noteworthy. 1) Milnes described pretectonic epidote glomeroblasts and porphyroblasts. Morrison noted abundant epidote lenses. Vance (1957) described epidote balls, some with chlorite cores, from Whitechuck Mtn east of Darrington. Radial epidote glomeroblasts described by Misch (1965) came from Mt Shuksan, the south side of the Baker River, and immediately north of the Skagit River west of Marblemount. Apparently the pre-Shuksan event was widespread. 2) F_1 intrafolial folding reported by Milnes appears identical with late-metamorphic F_2 folding described by other workers. The difference appears to be one of terminology. 3) Evans and Misch (1976) noted post-D_2 aragonite from the western belt of Shuksan rocks, in the lower Skagit Valley. In the Mt Watson area calcite was stable during D_2 and presumably afterwards. Either a metamorphic gradient exists within the Suite, or blueschist-facies rocks in the lower Skagit Valley are not strictly correlative with the Shuksan Suite. 4) In the Illabot Peaks area Milnes recognized folds in greenschist which he related to the mid-Cretaceous Shuksan Thrust. Other workers have not recognized outcrop-scale folds in greenschist which can be related to the Thrust. Attitudes and styles of Milnes' "mid-Cretaceous F_3 folds" are similar to F_2 folds described by Morrison. 5) With the possible exception of Misch (1966, Middle Fork Nooksack area) no one reports minor structures in the Shuksan Greenschist which can be attributed to Eocene folding of the Chuckanut Fm. The greenschist appears to have been rigid during this event.

Morrison and Milnes undertook structural studies similar to this one. Working largely in roadcuts, they found it was not possible to consistently map and use crenulation and mineral lineations--a striking contrast to my experience on Mt Watson. Apparently the slight weathering needed to bring the lineations into relief requires natural outcrops.

MELANGE UNIT

A tectonic melange is exposed west of Mt Watson and Anderson Butte. Observed lithologies are quite varied, including altered volcanic tuff, volcanic breccia, volcanic flow rocks, volcanic sandstone, intermixed chert and scaly argillite, ribbon chert, phyllite, massive and bedded limeston, arkosic sandstone, shale, quartz-mica semischist, tremolite-Mg chlorite chist, greenschist, massive blueschist and meta-quartz diorite. The unifying feature is a poorly developed, east-dipping, anastomosing network of subparallel shear surfaces. The thickness of the melange is estimated to be at least 3 km.

The unit shows a block-in-matrix structure, with unsheared or little-sheared bodies of chert, greenstone and other rock types set in a matrix of sheared pelitic and volcanic material. Primary contacts between lithologies were not seen. Bedding is preserved in blocks of arkosic sandstone (at 47), chert (at 66) and limestone (at 257).

These rocks are an "autoclastic melange" as described by Greenly (1919, quoted in Hsü, 1968). They fit the definition of melange proposed by Hsü (1968) as well as the revised definitions proposed by Hsü (1974) and Cowan (1974).

The Shuksan Thrust, as defined by Misch (1966), is the discontinuity that separates well-recrystallized Shuksan Suite greenschist and phyllite from less-metamorphosed volcanic and sedimentary rocks of the Chilliwack and Nooksack Groups. In the Twin Lakes-Yellow Aster meadows area this discontinuity is a zone of spectacularly intermixed Chilliwack Group, Shuksan Suite and Yellow Aster Complex rocks which Misch (1966) described as the imbricate zone below the thrust. The melange unit appears to be identical with Misch's imbricate zone. The term "melange unit" has been used for three reasons: to emphasize the tectonic style (block-in-matrix structure, association of diverse lithologies and juxtaposition of distinct metamorphic facies), to avoid presupposing a genetic relation between the melange unit and the Shuksan Suite, and to call attention to the similarities between the melange unit and similar terranes elsewhere.

Most of the melange unit is presumably Chilliwack Group; lithologies are similar to Chilliwack Group rocks described by Misch (1966) and Monger (1966). A K/Ar white mica age of 196 $\pm$ 7 ma (R.L. Armstrong, personal communication, 1979) for micaceous sandstone, now semischist (D61), is consistent with the upper Paleozoic age of most Chilliwack Group fossils.

Study of the melange unit was limited to describing the fabric, sampling the range of rock types present and examining the metamorphic assemblages in the rocks. Much of the unit would be amenable to a more detailed study of the primary rock.

Field Appearance

Almost all exposures of the melange unit are in roadcuts. Those shown in figure 28 are typical.

Matrix in the melange is mostly phyllite, scaly argillite, intermixed chert and scaly argillite, or a non-descript, sheared dark-green material. Phyllite is indistinguishable from, and may largely be, Shuksan Suite phyllite. Brown scaly argillite surrounds arkosic

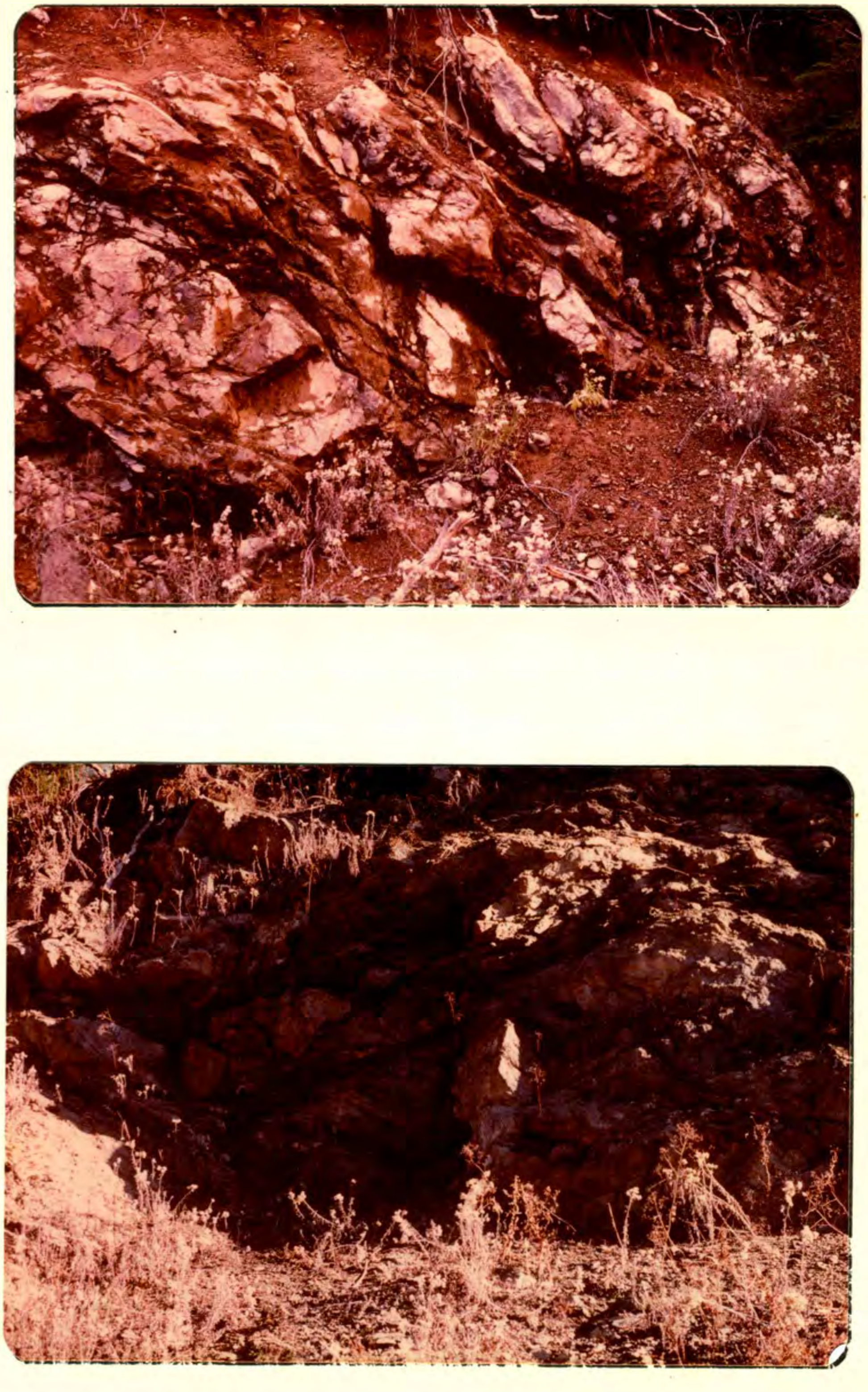


Figure 28. Typical exposures of melange unit at 242 (above) and 246 (below).

sandstone at 47. Elsewhere grey to black scaly argillite is found with varying amounts of quartz in thin lenses and ribbons. Much of this appears to have been ribbon chert with thick argillaceous partings. The dark-green material appears to be a sheard and flattened volcanic breccia. In places this is mixed with pelitic material to form a crumbly, scaly mass.

Blocks are mostly greenstones. Many show no fabric in the field and may largely be flows. Coarse breccias and pillows are also evident. Well-foliated greenstone at 240 is flattened tuff.

Grey ribbon chert is common and makes up most of the natural outcrops of the melange unit. As parting thickness increases, this grey chert grades into chert and scaly argillite. Micaceous metachert(?) forms several outcrops in the lower portion of the melange. The rock is laminated with ½ to 1 cm thick quartzose layers separated by less resistant micaceous partings. Rusty-weathering grey ribbon chert exposed at 66 is unique, in that ribbons up to 6 cm thick are tightly and irregularly folded without the development of a penetrative fabric.

Scattered small limestone bodies are massive, blotchy grey and white calcite marbles. An exception is a single large outcrop (257) of dark-grey, thin-bedded limestone with shaly interbeds.

A small, 1 m thick lens of thin-bedded arkosic sandstone is exposed at 47, set in an apparently codepositional brown scaly argillite matrix. Volcanic sandstone at 256 was distinguished from greenstones by the presence of black argillite chips. Several other sandstone bodies were identified in thin section.

Greenschist forms several blocks in the melange above the 4,000' level, near the contact with the Shuksan Suite. At 45 (figure 29) several 3 to 10 m long blocks of greenschist are set *en echelon* in a phyllite and tremolite-Mg chlorite schist matrix. At 104 greenschist-blueschist breccia (figure 30) is exposed on a cliff below timberline. The surrounding material is probably phyllite. The breccia is similar to breccia widely developed on Mt Watson, where it appears to be related to post-metamorphic faulting. Another block of greenschist and blueschist is exposed about 100 m to the NW. This block is clearly set in phyllite.

Massive blueschist which outcrops at 53, 54 and 64 is probably a single block over 650 m long.

At 69 unfoliated metaquartz diorite is exposed in a small quarry. The rock has a medium-grained green and white granitic texture. It is cut by closely spaced fractures that show no consistent orientation and are partly cemented with carbonate. The north contact of the body is tectonic, as the adjacent shale and semischist retain their fissility (and in thin section show no sight of contact metamorphism). Rocks surrounding the metaquartz diorite are iron-stained. This does not seem to be a gossan, but rather an effect of the impermeability of the plutonic rock which has concentrated groundwater around the margin of the block and promoted weathering.

Several patterns were observed within the melange unit. Greenschist, blueschist, metaquartz diorite and tremolite-Mg chlorite schist are confined to the upper levels of the melange. Argillaceous rocks are more common in the upper levels, whereas greenstones prevail in the lower levels. The amount of matrix, and of shearing, seems to decrease

Figure 29. En echelon greenschist blocks in melange unit at 45. Figures are pointing to layer of tremolite-Mg chlorite schist between blocks. Phyllite visible above figure on left.

Figure 30. Greenschist-blueschist breccia at 104.

as one descends in the melange. These patterns may be only apparent, the result of limited outcrop.

Contact Relations

Mapping did not extend to the western edge of the melange. The contact of the melange unit with the phyllite unit to the east has been described above.

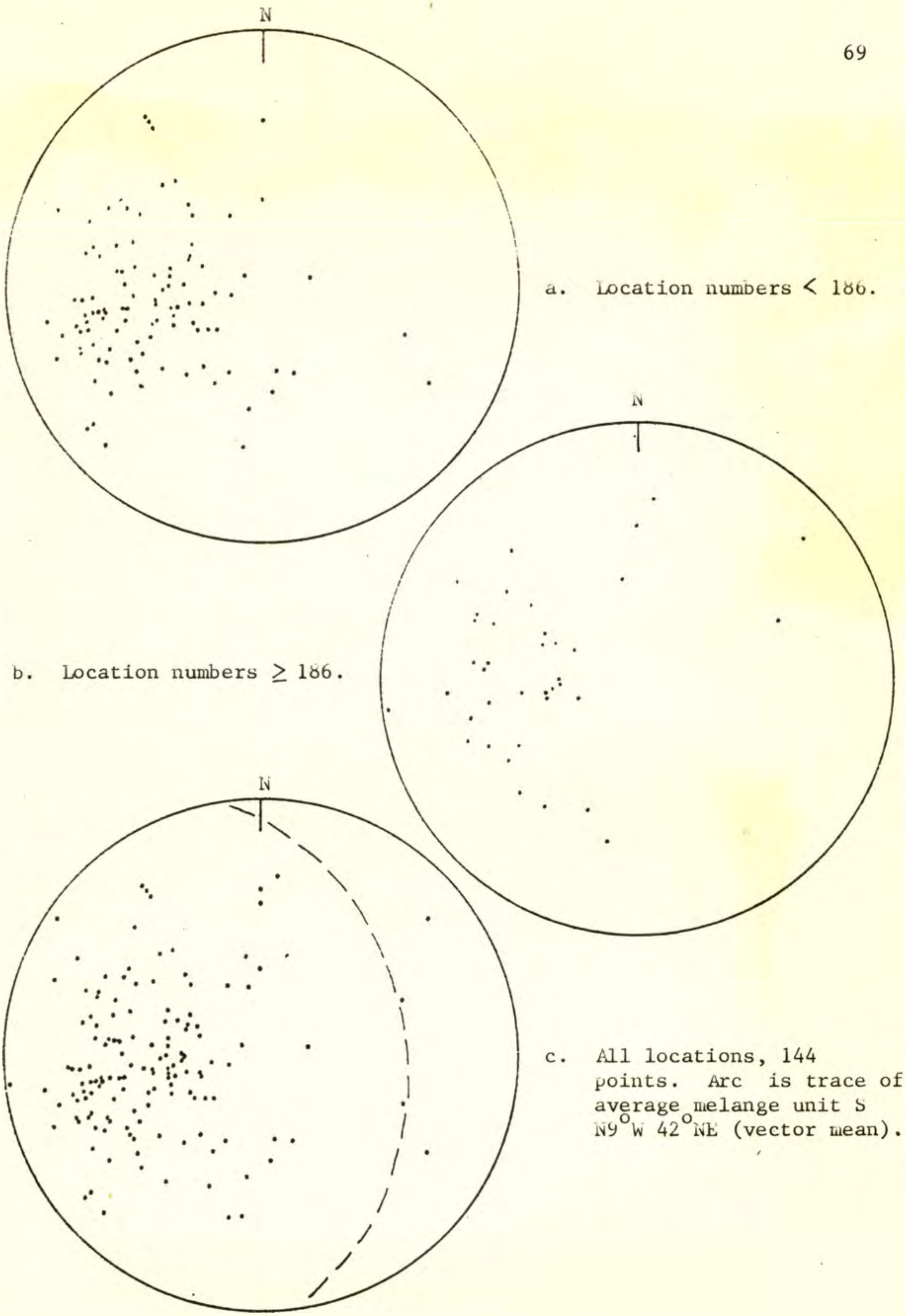
Structure

Structures measured in the melange are the characteristic crude foliation (S), rare minor folds and crenulations, joints and slickensides on joint surfaces.

Figure 31 is an equal area plot of poles to S. The vector mean of all S is N9^{o}W 42^{o}NE. To test for homogeneity the melange was arbitrarily split into higher-elevation and lower-elevation sub-areas and poles to S were plotted separately (figure 31a, b). There is no significant difference between the sub-areas; on this scale the melange appears to be homogenous.

Rare linear elements were observed mostly in blocks. They are plotted in figure 32. No pattern is evident. This is reasonable, as the blocks may have acquired their fabric early in their history and since then have been rotated.

A plot of poles to joints (figure 32) indicates that joints tend to be at high angles to S. The tendency probably is not real, as joints at low angles would have been considered part of S. Alternately, joints could largely be tensional fractures developed during extension

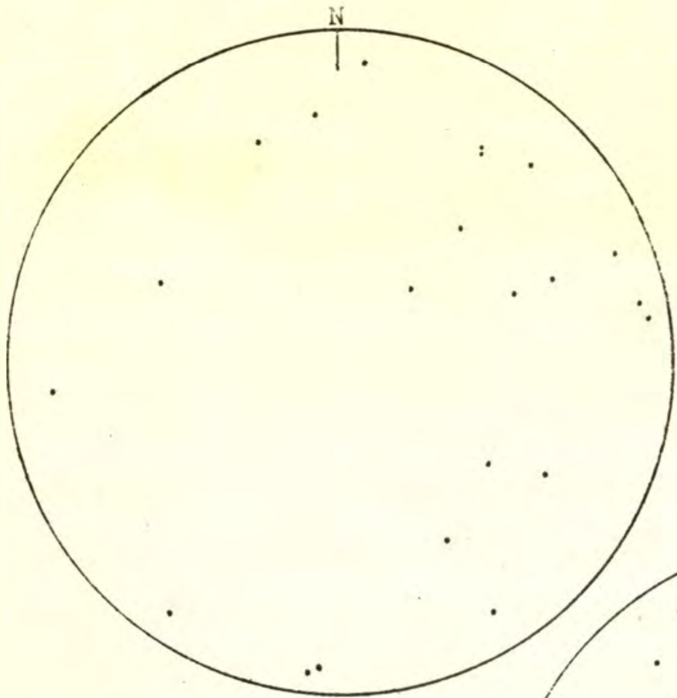


a. Location numbers < 186.

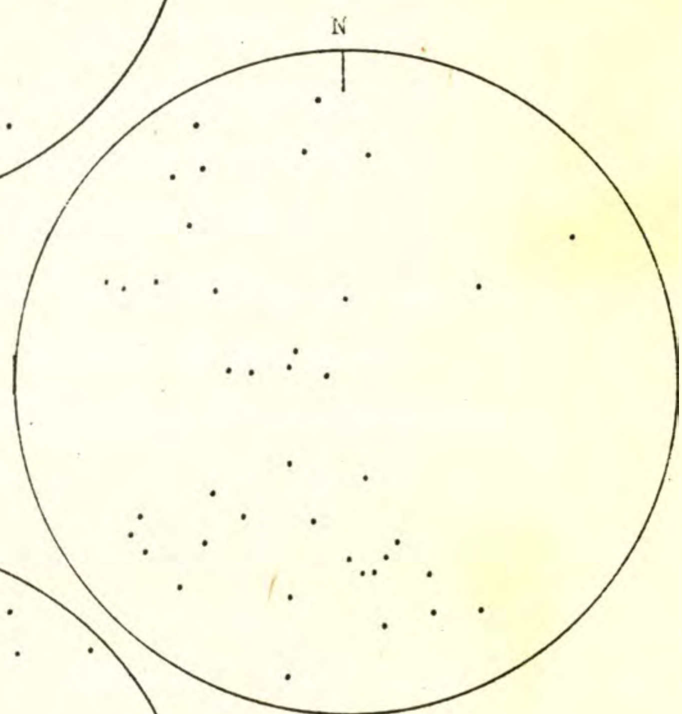
b. Location numbers ≥ 186.

c. All locations, 144 points. Arc is trace of average melange unit S N9°W 42°NE (vector mean).

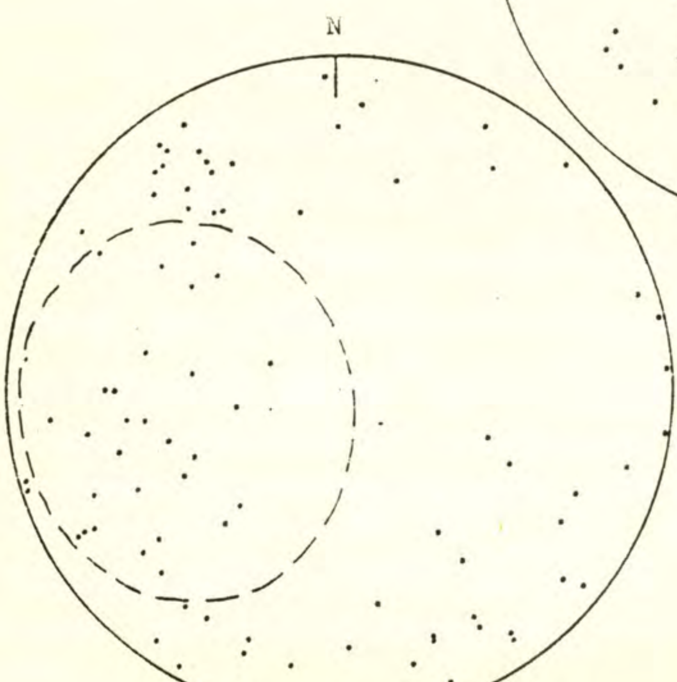
Figure 31. Equal area lower hemisphere projections of poles to S, melange unit.



a. Linear elements in melange unit.



b. Slickensides in melange unit.



c. Poles to joints in melange unit. Curve is locus of poles to planes at 45° angle to average melange unit S.

Figure 32. Equal area lower hemisphere projections of linear elements, slickensides and joint planes in melange unit.

parallel to S. Attitudes of slickensides on joint surfaces are plotted in figure 32b. No strong pattern is evident.

Microscopic structures are similar to those seen in outcrop. S is outlined by subparallel mylonitic zones, chlorite-white mica-stilphomelane filled shears, flattened amygdules and phenocrysts, flattened glass shards and flattened or rotated sedimentary grains. Most samples show some sort of S, while a few are massive. Some metasediments have developed a crystallization schistosity.

Petrography

Samples from the melange unit were examined in thin section in an attempt to determine the P-T conditions of melange deformation and the relation of melange deformation to blueschist-facies Shuksan metamorphism.

Metamorphic recrystallization in the melange unit (exclusive of well-recrystallized greenschist, blueschist, tremolite-Mg chlorite schist and phyllite) is largely incomplete: relict phases and textures predominate. Metamorphic minerals in the little-recrystallized rocks include quartz, albite, chlorite, stilphomelane, white mica, calcite, aragonite*, pumpellyite, lawsonite, epidote, amphibole and datolite

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* Aragonite is distinguishable from more common calcite by 1) a smooth appearance under crossed nicols, unlike the "twinkling" of calcite; 2) the presence of only one cleavage; 3) lack of twinning in most orientations; 4) lines of small inclusions parallel to the C-axis, and 5) partial replacement by randomly oriented grains of calcite (Vance, 1968). Identification of aragonite in D3 was verified by the universal stage technique described by Brown <u>et al</u>. (1962). The

($CaBSiO_4(OH)$). Very fine-grained unidentified phases are present in most samples. Prehnite was not identified in the melange unit.

In the little-recrystallized rocks metamorphic equilibrium probably was not reached over areas as large as a thin-section. Following Zen (1974), equilibrium assemblages are considered to be those with all phases in contact and without sign of disequilibrium, and those with all phases visible in the same high-power (½ mm diameter) field of view. Quartz, albite and chlorite are widespread in the little-recrystallized rocks, and it is assumed that all assemblages noted below are in equilibrium with these phases.

With two exceptions (exclusive of well-recrystallized, recognizably exotic rocks) schistose assemblages are limited to some combination of quartz, chlorite, white mica and stilpnomelane.

<u>Matrix</u> samples (D48, D64, D66, D68, D69, E92, E99a, E99b, F8, F15) show extreme shearing and mixing of differing lithologies (figure 33). Mylonitization is extensive. Schistose chlorite, white mica and stilpnomelane are ubiquitous in shears. Widespread transverse veins are mostly filled with quartz. Some also contain albite and calcite. At least some shearing postdates all veining. Quartz is commonly strained, sliced and granulated.

In intermixed chert and scaly argillite (D66), tectonic clasts of argillite contain schistose white mica. Schistosity and long dimensions of the clasts parallel the overall S in the sample.

F8 is intermixed chert and volcanic material. Extensional veins

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presence of aragonite in F8 was confirmed by x-ray diffractometry.

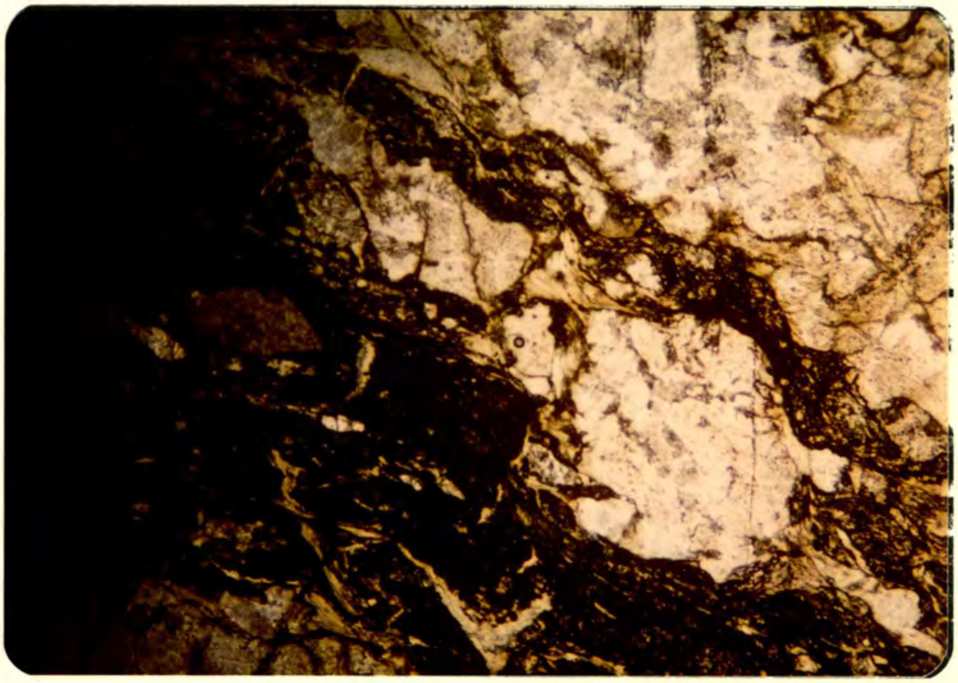

Figure 33. Photomicrograph of melange matrix (F8); plane light.
(Illumination of photo is uneven.)

in a chert fragment are filled with datolite and aragonite, the latter now largely reverted to calcite. Aragonite appears to have crystallized prior to some shearing, as there are datolite fragments in the mylonitic matrix around the chert fragment. Coarsely crystalline, well-twinned calcite in veins that crosscut the aragonite-datolite assemblage does not appear to have inverted from aragonite. Some coarsely crystalline calcite shows curved twin lamellae, indicating continued deformation after calcite crystallization.

E99a contains rounded, relict, drab green amphibole as well as newly crystallized, fine grained, very pale greenish amphibole in the assemblage:

actinolite(?) + chlorite + white mica + epidote(?)

Iron-rich epidote(?) forms very small yellow granules. Stilpnomelane, albite and quartz also coexist with newly crystallized amphibole. The assemblage is schistose, with S roughly parallel to the surrounding mylonitic zones, though both are folded and re-sheared.

D69 contains a cluster of randomly oriented lawsonite laths which is crosscut by veins and shears.

D64 and D68 are similar, containing abundant rounded clasts of relict green amphibole and minor relict pyroxene set in a matrix that is rich in fine-grained pumpellyite(?). Some rounded clasts are replaced by the assemblages:

pumpellyite + actinolite(?) (D64)

pumpellyite + epidote (D68).

Transverse veins in D64 are filled with quartz, albite, fine hairs of amphibole normal to vein walls, and granules of epidote. These rocks could be recrystallized and sheared sandstones which were unusually rich in detrital amphibole grains or highly sheared igneous rocks.

Greenstones (D47, D55, D62, D70, D71, D74, D77, E56, E57, E93, E94, E96, F13, F14, F16, F17, F18) are metamorphosed flows, tuffs and breccias. In most samples identifiable metamorphic minerals are limited to quartz, albite, chlorite, white mica and sphene, with late calcite in veins and patches. Strongly pleochroic blue-green pumpellyite is extensively developed in a few samples. Aragonite is present in a vein in E57. E93 contains scattered crystals of an unusual length-fast phyllosilicate(?) with deep golden-brown to blue-green pleochroism. Metamorphic assemblages of interest in greenstones are (all presumed stable with albite + quartz + chlorite):

pumpellyite + hematite + stilpnomelane (E94)

epidote + hematite (E94)

pumpellyite + stilpnomelane (E57, F17)

pumpellyite + carbonate (F18)

carbonate + Fe-oxide(?) (F18)

pumpellyite + Fe-oxide + epidote + stilpnomelane (F17)

Sandstones (D4, D56, D61, D76, E73, E75, E98, F2, F19) all contain metamorphic white mica and chlorite. Stilpnomelane is present in most samples. Arkosic sandstone (D4) from 47 is notable for its well preserved primary texture and the presence of large detrital flakes of muscovite and biotite, along with minor amounts of chert. D61, collected at 69 adjacent to the metaquartz diorite block, has a well developed schistosity. Angular detrital quartz grains and large plates of detrital muscovite are set in a foliated matrix of fine-grained white mica.

E73 contains pumpellyite and the assemblage lawsonite + hematite. Some lawsonite probably formed during deformation, as it is in veins which are parallel to S, with individual laths parallel to S. Other grains of lawsonite are broken and extended along S.

A sample of siltstone (F2) contains unoriented lawsonite laths.

Cherts (D58, D63, E91, F4, F5) and siliceous sediments (D49, D67, F3, F7, F11) are mostly composed of little-recrystallized quartz. Metamorphic assemblages are stilpnomelane + white mica + quartz in most samples. D63 contains chlorite. Epidote is present in E95. Albite is present as detrital grains and in veins in D49 and F7. E95, F4 and F5 contain fine dusty opaque that may be carbonaceous material. Phyllosilicates in most samples are schistose. In E95, F4 and F5 a second S is evident. Widespread quartz veining appears to be the same age as or older than schistosity.

D58 (from 66) is relatively undeformed and recrystallized. Carbonate forms small patches and veins. Small ovoid clear quartz patches are probably recrystallized radiolaria. Phyllosilicates in argillaceous partings show a preferred orientation that is probably not of metamorphic origin.

Phyllites (D37, D41, D44, E63, E64) are composed of quartz + white mica + chlorite + carbonaceous material, with albite in D44 and sphene and lawsonite in D41. All show S_1 and S_2. In D44 S_2 is crenulated, forming an incipient S_3. Quartz textures vary, ranging from polygonal equigranular mosaics (D37) to mosaics with sutured grain boundaries (most samples) to mortar textured (D41).

Carbonaceous shale (E88) from 69, next to the metaquartz diorite body, shows no sign of metamorphic recrystallization.

Limestones (D72, F10, F20) are mostly calcite with minor quartz and fine-grained bituminous(?) material. No aragonite was detected. Textures are inequigranular with highly irregular grain boundaries. Some grains are well-twinned, in places with bent twin lamellae, and many grains show undulose extinction. Trains of opaque material define an S in F10 and F20. It is not clear to what extent strain, inversion from aragonite or other processes have contributed to the present texture.

Metaquartz diorite (D59b, c) contains abundant quartz and plagioclase. Primary ferromagnesian minerals are entirely altered to deep-green chlorite, epidote, sphene and Fe-oxide. Epidote is mostly in large crystals unlike the small granules common in most of the melange, and is probably relict from earlier hydrothermal or deuteric alteraion. In D59b the assemblage

lawsonite + Fe-oxide + epidote (with epidote in small granules)

was found. Lawsonite is developed in veins and in plagioclase (figure 34).

Tremolite-Mg chlorite schist (D39) was found at 45 where it is matrix between blocks of greenschist. Two to five mm long augen of randomly oriented, relatively high birefringence, colorless chlorite are set in a matrix of schistose tremolite. Tremolite occurs as well defined blades with a strong linear preferred orientation and as masses of fine hairs lying in S.

D40, from the same location, is composed of similar magnesian

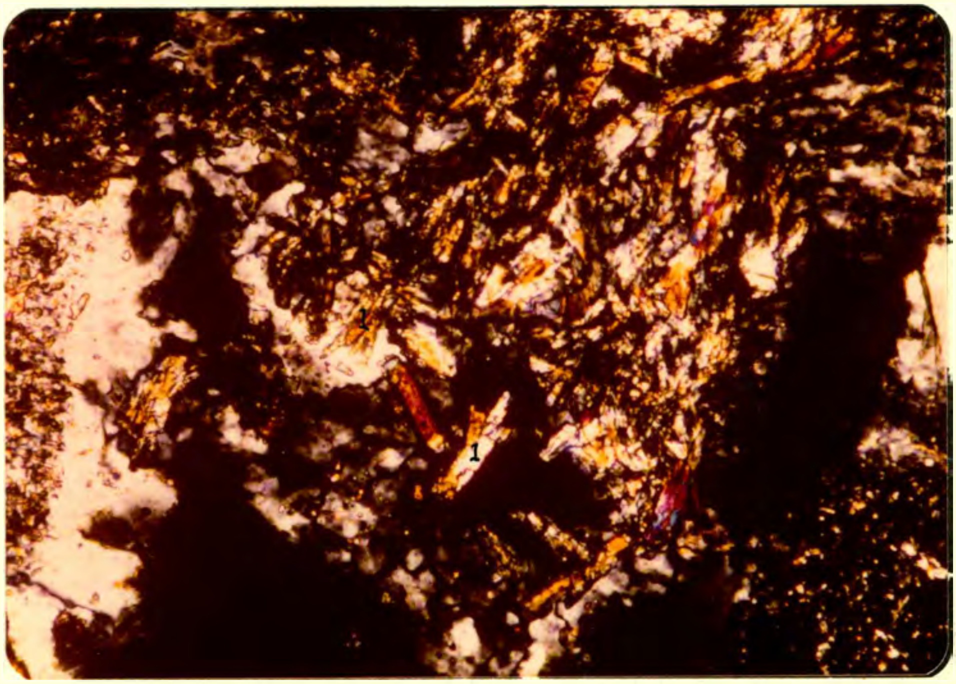

Figure 34. Photomicrograph of lawsonite (l) in metaquartz diorite (D59b); crossed polars.

chlorite with accessory sphene, epidote and apatite. A relict S is preserved within narrow zones, indicating that the dominant schistosity is at least S_2. Quartz in a vein has undulose extinction and sutured grain boundaries.

Most specimens of greenschist (D2, D3, D43, E30, E31, E32, E33) are similar to Shuksan greenschist.

Greenschist from 45 is mineralogically unlike any Shuksan Suite greenschist exposed on Mt Watson. D2 is epidote-poor actinolite-chlorite-albite-pumpellyite schist. Oriented, very small, euhedral prisms of iron-poor pumpellyite are concentrated in chlorite-rich layers. Sphene-rich actinolitic layers contain augen of randomly oriented, pleochroic, iron-rich pumpellyite. Figure 35 is a photomicrograph of a boudinaged augen with the break filled by low-iron pumpellyite and chlorite. D3 is epidote-free actinolite-chlorite-quartz/albite schist with minor amounts of green stilpnomelane. Crosscutting veins contain the assemblage quartz + albite + actinolite + green stilpnomelane + aragonite. Veins of deep green chlorite formed still later. D43 is albite-chorite-epidote-pumpellyite schist.

Blueschist (D50, D51, D52, E89a, E89b, E90a, E90b) is polymetamorphic. The original assemblage was blue-green amphibole + epidote + albite + white mica + chlorite + rutile (+quartz?) $\pm$ sphene. Amphibole does not form the small sharp needles typical of Shuksan Suite rocks, but occurs as stout helicitic blades up to 4 mm long. Helicitic albite porphyroblasts are as much as 2 mm in diameter. Rutile crystals are commonly skeletal, in some cases boudinaged, and up to 0.6 mm long. Sphene has a similar habit. The original rock must have been

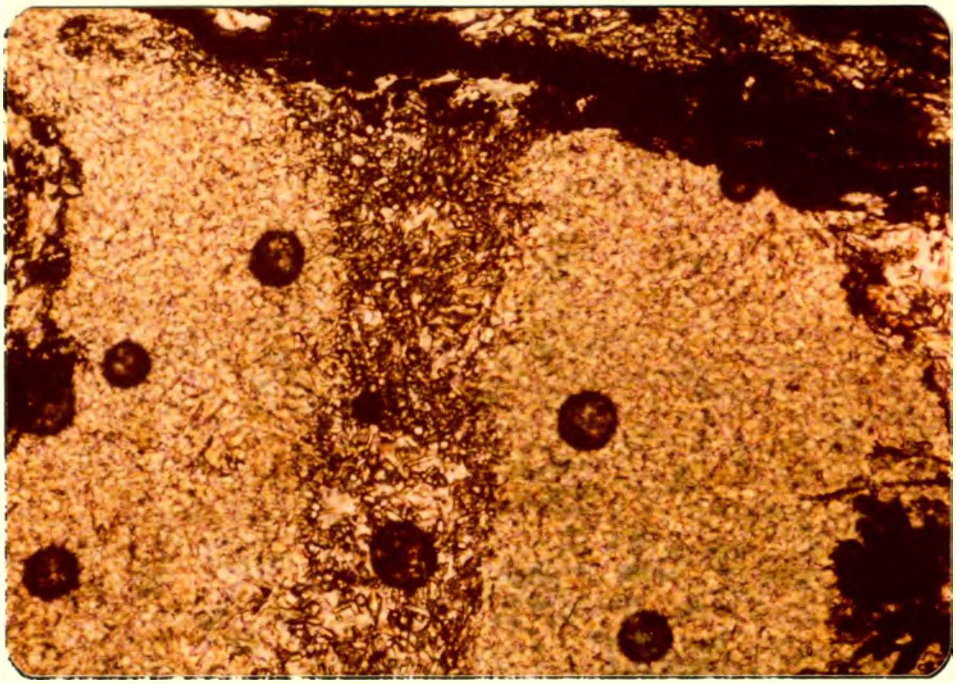

Figure 35. Augen of randomly oriented, feathery, green pleochroic pumpellyite in D2, plane light. Fracture in augen (vertical stripe) is filled with ideoblastic low-iron pumpellyite. S is parallel to top of picture. Large dark spots are bubbles in the thin section.

Figure 36. Blue Na-amphibole healing extensional fractures in blue-green barroisitic(?) amphibole in polymetamorphic blueschist (D50), plane light.

similar to barroisite schists from Vedder Mtn. (Bernardi, 1977) and Gee Point (Wilson, 1978).

Superimposed on this is the assemblage Na-amphibole + pumpellyite. Deep-blue to purple pleochroic amphibole has healed extensional fractures in primary amphibole (figure 36) as well as formed overgrowths and replacement patches on primary amphibole and separate, fine hair-like crystals. Slightly pleochroic pumpellyite forms fine-grained mats elongate parallel to the schistosity. It is considered coeval with Na-amphibole because 1) habit indicates it is not part of the primary assemblage and 2) pumpellyite mats and Na-amphibole are similarly affected by late folding and veining. In E89 pumpellyite and adjacent Na-amphibole seem to be in equilibrium. However, in E90 pumpellyite seems to be growing at the expense of Na-amphibole. Pumpellyite abundance is inversely related to epidote content in the samples examined.

In E89a a cross-cutting vein of quartz, aragonite (partially inverted to calcite) and fine-grained Na-amphibole appears to be in equilibrium with pumpellyite in the vein wall.

INTERPRETATION OF THE MELANGE UNIT

Aspects of interest in the melange unit include: What units contributed to the melange? What metamorphic conditions do assemblages in the melange record? Under what conditions did the melange fabric develop? When did the melange form, and has it been active since then? Each of these questions is addressed below. Suggestions for further research are then offered.

Contributing Units

The little-recrystallized volcanic and sedimentary rocks that make up the bulk of the melange unit are probably Chilliwack Group rocks.

Some greenschist and phyllite bodies in the upper levels of the melange are identical with Shuksan Suite rocks to the east. Other greenschist bodies are texturally similar but exhibit slightly different mineralogy, reflecting differences in composition (more Fe^{2+}-rich: stilpnomelane bearing, high pumpellyite content) and metamorphic conditions (higher P/T conditions: aragonite stable instead of calcite).

The polymetamorphic blueschist fragment is of unknown origin. Similar rocks in the Gee Point area are part of the Shuksan Suite (Wilson, 1978). Wilson suggested that the higher-temperature hornblendic and barroisitic assemblages are the result of contact metamorphism during subduction, with heat supplied by hot mantle rock. Bernardi (1977) described barroisitic schists from Vedder Mtn which are identical to the primary assemblage in the polymetamorphic blueschist but lack the Na-amphibole + pumpellyite overprint. The Vedder Mtn rocks give K/Ar and Rb/Sr ages of about 240 ma (Bernardi, 1977) and thus are not part of the Shuksan Suite.

Metaquartz diorite in the melange could be part of the Yellow Aster Complex. However, its apparently simple petrologic history and incomplete metamorphism suggest affinity with the Chilliwack Group(?) rocks that surround it. Several similar metaplutonic bodies to the west and south have given mid-Jurassic U-Pb ages (Whetten and Zartmann, 1979). These ages are much younger than the 415-1,450+ ma old Yellow Aster Complex (Mattinson, 1972) and suggest correlation with the Fidalgo Ophiolite exposed on the San Juan Islands.

Metamorphic Facies

Well recrystallized rocks in the melange unit contain assemblages recording several distinct metamorphic conditions. These are:

albite ± epidote + barroisite(?) + white mica + chlorite + rutile (+ quartz?) + sphene (primary assemblage in polymetamorphic blueschist)

Na-amphibole+ pumpellyite (+ albite + chlorite + quartz) (overprint in polymetamorphic blueschist)

Shuksan Greenschist (calcite stable)

aragonite + actinolite + stilpnomelane + albite + quartz (+ chlorite?) (vein filling in actinolite-chlorite schist at 45)

In addition, a Na-amphibole + lawsonite + aragonite + stilpnomelane + quartz + sphene(?) schist was found in the Shuksan Thrust zone on the north shore of Baker Lake (sample RH79-A25, from roadcut in sec. 34, T38N, R9E). Figure 37 is a petrogenetic grid (modified from Brown, 1977a) showing the relative stability fields of these assemblages. It is interesting to note that they could result from metamorphism at nearly constant pressure, with temperature varying.

Little-recrystallized rocks in the melange do not contain assemblages that specify P-T conditions well. Relevant experimentally determined equilibria are summarized in figure 38. Stable lawsonite + quartz in the melange indicates $P \gtrsim 3$ kb, with T between 180°-200° and 350°-400° C (Liou, 1971, Nitsch, 1968; Nitsch cited in Winkler, 1974, p. 184). Metamorphic albite is widespread, again indicating temperatures in excess of 170°-185° C (Thompson, 1971). Scattered aragonite attests to high P/T conditions. If aragonite and lawsonite in the little-recrystallized rocks formed in the same environment, conditions were $P > 5$ kb, $T \geq 190^{\circ}$ C. However, extensive post-metamorphic mixing may have occurred in the melange unit and there is no positive evidence that all metamorphic minerals and assemblages in the little-recrystallized rocks formed in the same environment.

Conditions of Melange Formation

Little is known regarding the conditons of melange formation. Melanges have been separated into two groups: deformed olistostromes, in which a tectonic fabric has been superimposed on a sedimentary mixture (see Cowan, 1978); and true tectonic melanges, in which "fragmentation and mixing...result from tectonic deformation under an overburden pressure" (Hsü, 1968, p. 1063). The melange unit of this

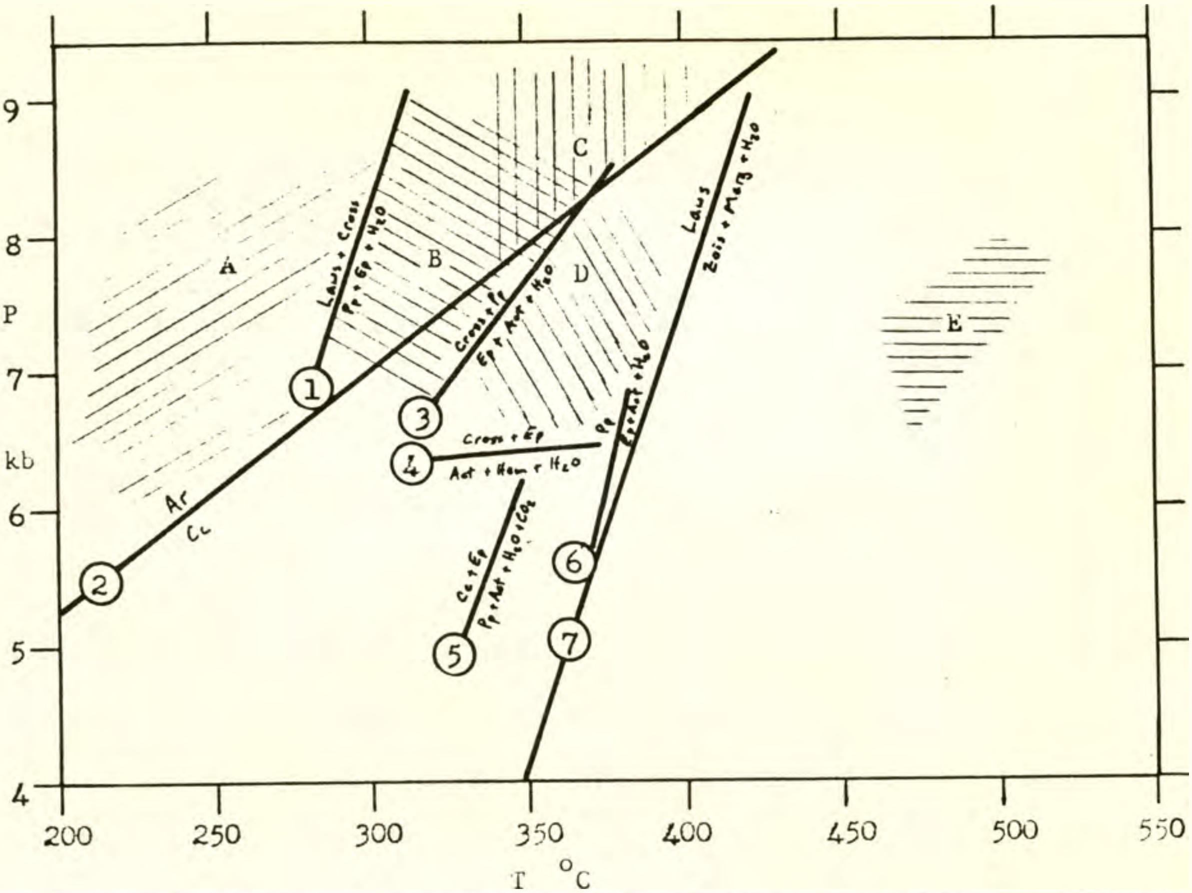

Figure 37. Petrogenetic grid for high-pressure metamorphism, modified from Brown (1977a). Positions of reactions 2, 6 and 7 are based on experimental work. Reactions 1, 3, 4 and 5 are deduced from natural assemblages and theoretical considerations, and are only approximately located in P-T space. Stability fields of assemblages in the melange unit are shaded. The boundaries of field E are those suggested by Wilson (1978).

A - Na-amphibole-lawsonite-aragonite schist (RH79-A25)
B - Na-amphibole-pumpellyite overprint in polymetamorphic blueschist
C - aragonite-bearing actinolite-stilpnomelane-chlorite schist (low temperature boundary of field C not defined)
D - Shuksan Greenschist
E - primary barroisitic assemblage in polymetamorphic blueschist

Abbreviations:		
	Act = actinolite	Hem = hematite
	Ar = aragonite	Laws = lawsonite
	Cc = calcite	Mar = margarite
	Cross = crossite	Pp = pumpellyite
	Ep = epidote	Zois = zoisite

All reactions also involve albite, chlorite and quartz.

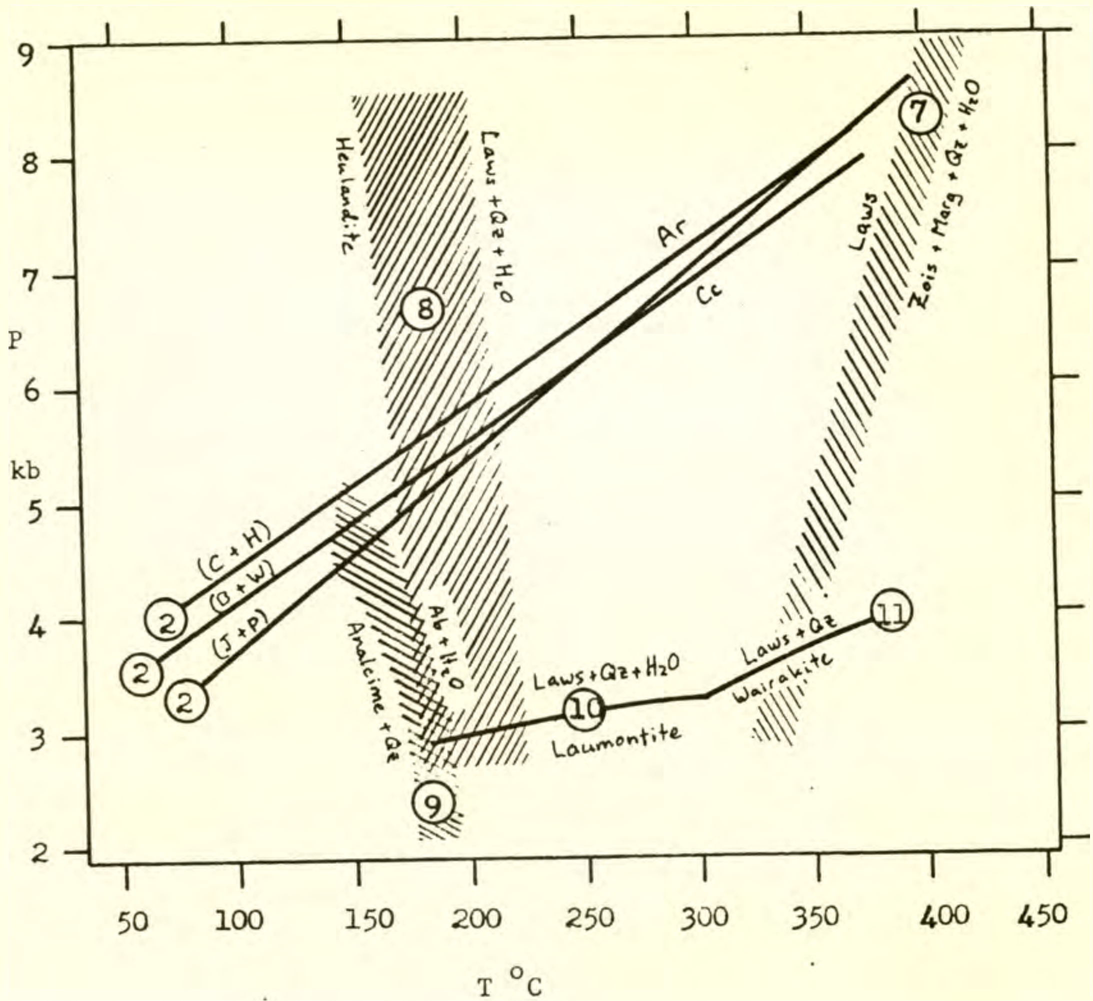

Figure 38. Summary of experimentally determined equilibria relevant to melange unit metamorphism. Ab = albite, Qz = quartz, other abbreviations as in figure 37. Aragonite-calcite equilibria are from Boettcher and Wyllie (1968) (B+W), Johannes and Puhan (1971) (J+P) and Crawford and Hoersch (1972) (C+H). Other reactions are as determined by Nitsch (1968) 8, Nitsch (cited in Winkler, 1974, p. 182) 7, Liou (1971) 10 11, and Thompson (1971) 9. Widths of shaded bands for reactions for 7, 8 and 9 correspond to reported accuracies in T and P measurement.

report appears to be of the tectonic variety.

Over 70 thin sections were examined in search of metamorphic assemblages that could be related to the melange fabric. With the exception of white mica ± chlorite ± stilpnomelane assemblages in shears and phyllitic metasediments, the search was almost entirely unsuccesful.

During deformation of the melange unit strain rates commonly exceeded recrystallization rates, as cataclastic fabrics are widely developed. Abundant veining probably indicates that high fluid pressures were present, at least locally. No P-T conditions for melange deformation can be specified.

A hypothesis for tectonic melange formation is presented in Appendix D.

Age

The presence of probable Shuksan Suite rocks in the melange unit requires that at least part of the mixing within the unit postdates Shuksan metamorphism. Beyond this there is no firm evidence in the study area for the age of melange movement.

Suggestions for Further Work

It has not been possible to establish any relation between deformation and metamorphism in the melange unit, and it is possible that the melange is polykinematic. As a result, this study has not succeeded in establishing the P-T conditions of Shuksan thrusting, the age of movement on the Thrust, or the relation of thrusting to blueschist-facies Shuksan metamorphism. Extensive careful sampling and petrographic work might succeed in establishing relations between melange deformation and metamorphism.

Some of the deformation in the melange unit may be early Tertiary in age. Two observations suggest this: the nearby Noisy-Diobsud fault has the same strike as the melange S and probably experienced post-mid-Eocene movement; and adjacent Shuksan greenschist on Mt Watson and Anderson Butte shows no evidence of deformation related to movement in the melange unit, suggesting that perhaps local juxtaposition of the greenschist and the melange unit took place at rather shallow depths.

Early Tertiary deformation on NW trends has been reported by other students of northwest Cascades geology. Crickmay, after studying the area between the North Fork of the Nooksack River and Harrison Lake, wrote ". . . the main compression which brought about the mountain building is of post-Paleocene date" (Crickmay, 1930, p. 490). Vance (1957) described an angular unconformity beneath the Barlow Pass volcanics SE of Darrington. The Barlow Pass volcanics have since been assigned an Oligocene age (Vance and Naeser, 1977). The underlying early Tertiary Swauk (= Chuckanut) Fm sediments are strongly folded on NNW trends. Miller and Misch (1963) described mid-Eocene orogeny on the basis of a major unconformity on American Sumas Mtn. Folds in the Chuckanut Fm produced by this event trend predominantly NW.

After detailed study of the Chilliwack Group in its type area south of the Fraser River, Monger (1966) recognized two deformation events. Post-Late Jurassic D_1 produced large NE trending recumbent folds, overthrusts and local penetrative S_1. Yielding was to the NW. F_1 axes appear to have been near horizontal. D_2 produced reverse faults, minor folds and local S_2. D_2 faults strike NW and dip steeply to the NE. Monger correlated D_1 with the mid-Cretaceous orogeny recognized by Misch, and suggested D_2 may be correlative with the Eocene event described by Miller and Misch.

Vance and Dungan (1977) reported early Tertiary movement in the Helena Ridge Tectonic Complex, a 3 km wide NW-trending serpentinite melange SE of Darrington. Two NNW-trending fault zones SW of Darrington also experienced Tertiary movement (Vance and Dungan, 1977). Available descriptions of the westernmost (Sultan) zone (Heath, 1971; Dungan, 1974) indicate melange structure is developed in a zone at least a mile wide.

Future studies should examine the possibility of extensive, locally intensive, early Tertiary deformation in the northwest Cascades. Much of the present distribution of rock units in the area may be the product of early Tertiary high-angle tectonism and may not reflect the geometry at the close of the Cretaceous orogeny that juxtaposed and metamorphosed the pre-Tertiary rocks of the northwest Cascades.

POST-METAMORPHIC ROCKS

Breccia Body

A breccia body 300 m in diameter forms a knob along the ridge east of Mt Watson. All clasts in the breccia are rounded to angular greenschist and phyllite; they vary from less than 1 mm to more than 10 m in diameter. In the field no matrix other than finely divided Shuksan Suite material is apparent. Voids are druzy with quartz, carbonate and pyrite. A pyrite-bearing volcanic dike traverses the body, suggesting that mineralization postdates formation of the breccia. The breccia is clearly intrusive; on the SE margin dikes of breccia crosscut the surrounding greenschist (figure 39). No magmatic phase is present, thus the breccia must have been gas-fluidized.

Thin sections (E9, E30) show altered phyllite and greenschist pieces set in a quartz-carbonate-sulphide matrix. Greenschist contains no amphibole; the assemblage is chlorite + epidote + carbonate + white mica + quartz + albite + rutile and indicates alteration under substantial CO_2 partial pressure.

Formation of the breccia may be associated with emplacement of the Tertiary Chilliwack Composite Batholith (Misch, 1966) which is exposed to the east. Alternately, the high fluid pressure necessary for the intrusion of the breccia could be associated with earlier deformation. Available evidence doesnot exclude either of these possibilities.

Chuckanut Formation

Well-indurated sandstone and siltstone exposed north of the summit of Bacon Peak has been assigned to the Chuckanut Fm (Misch, 1966). A

Figure 39. Breccia dike intrusive into greenschist north of 153.

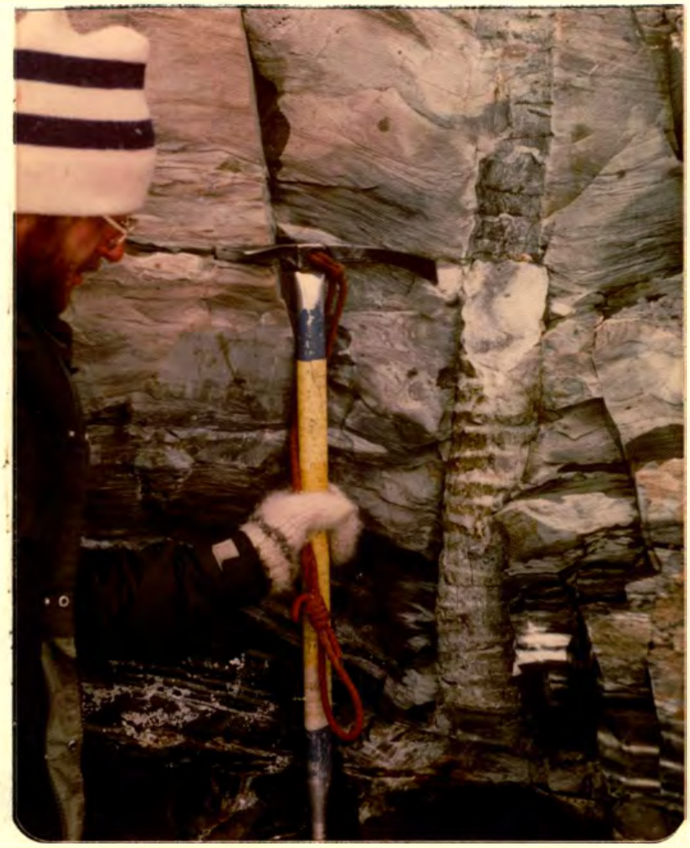

Figure 40. Sand-filled cast of palm trunk in growth position in Chuckanut Fm near 167.

sand-filled cast of a palm trunk in growth position at 168 (figure 40) reinforces this correlation.

The Chuckanut Fm occupies a north-plunging open syncline. The southern contact with the Shuksan Suite is inferred to be a high-angle fault with the north side dropped down. At 165 the Chuckanut Fm is intruded by a small granitic stock, with sills of the stock extending into the sediments. Thin sections (E15, E16) of the sediments show hornfelsing, with secondary epidote, chlorite, biotite, sericite, sulphide and calcite.

The Chuckanut Fm has been considered latest Cretaceous to Eocene in age on paleobotanical grounds (Pabst, 1968; Griggs, 1970). Recent radiometric dating (reported in Hartwell, 1979) indicates that at least part of the unit is post-lower Eocene.

Granitic Stock

A small granitic stock is exposed on the west side of Bacon Peak. It is intrusive into the Shuksan Metamorphic Suite and the Chuckanut Fm on its north, east and south margins. The western contact was not seen.

The one sample collected (E18) is fine-grained granodiorite. Normally-zoned plagioclase is subhedral and shows a weak preferred orientation. Potassium feldspar ($2V \sim 5^{\circ}$) and quartz are intergranular. Mafic minerals are hypersthene, clinopyroxene, green hornblende and biotite. Pyroxene is surrounded by green hornblende, most of which is rimmed with biotite. Accessory minerals include magnetite, apatite and zircon. The sample is identical to phases within the Lake Ann

Stock (Eric James, personal communication, April 1979), which is exposed 20 km to the north in a similar structural setting.

A hornfels (E17) from within 100 m of the contact at the 5,000' level (at 170) is composed of quartz spotted with rounded grains of magnetite, dark green spinel and tourmaline. Veins contain the assemblage potassium feldspar ($2V \sim 5^{o}$) + quartz + biotite + hypersthene + sulphide + tourmaline. The protolith is probably phyllite.

The stock is probably an outlier of the Chilliwack Batholith. Most K/Ar ages from the Batholith fall into the 18-35 ma range with the 3 ma old Lake Ann Stock the youngest known element (Engels et al., 1976).

Volcanic Dikes

Several kinds of volcanic dikes are present in the Mt Watson area.

Brown-weathering basaltic dikes are common in the phyllite bands east of Mt Watson, and are also intrusive into the greenschist. A little-altered sample (D20) from 22 contains plagioclase and clinopyroxene phenocrysts in a groundmass of labradorite (An 55) with minor quartz. Alteration products are calcite, chlorite and quartz.

A small slice of volcanic rock is in fault contact with surrounding mylonitic phyllite at 24, just west of the Noisy-Diobsud fault. It is probably a disrupted dike, now almost completely altered to carbonate and clay.

Felsic volcanic breccia spotted with tourmaline rosettes crops out on the north side of peak 6420'. Orange-weathering felsic volcanic float is present within the granitic stock south of the ridge crest east of peak 6420', and small amounts of similar material are intrusive into the Chuckanut Fm at 167. The occurrences follow the inferred fault on the south side of the exposures of the Chuckanut Fm. The felsic volcanics appear to have been intruded into the fault after emplacement of the granitic stock. Two small, highly weathered bodies of similar material are present on the east end of Mt Watson.

A sulphide-bearing lamprophyre dike (F12) is intrusive into the melange unit at 251. Three to four mm long brown hornblende needles and abundant apatite and magnetite are set in a groundmass of plagioclase laths. Accessory sphene is present, as well as late carbonate and chlorite.

These dikes are almost certainly Eocene or younger, as no pre-Eocene, post-Shuksan metamorphism igneous activity has been recognized west of the Straight Creek Fault (Engels et al., 1976; Vance and Naeser, 1978).

FAULTS

Anderson Fault

A high-angle fault is inferred to exist along the west edge of Anderson Butte and Mt Watson, traversing the head of the Anderson Creek drainage (plate II). Evidence for the existence of the fault includes: 1) a pronounced linear scarp along the west side of Anderson Butte and Mt Watson; 2) phyllite exposed up-dip of greenschist SE of lower Anderson Lake (at 205, 206); 3) truncation of the phyllite-greenschist contact north of "Pipsqueak Pass"; 4) aligned notches and gullies (in phyllite) in the spur ridges on the SW side of Anderson Butte, and 5) several small benches along the inferred fault trace.

The fault is considered to be high-angle on the basis of its linearity and the field relations at 205 and 206. Displacement probably was SW side up, truncating the greenschist east of the fault and uplifting phyllite which underlies the greenschist on the south slopes of Anderson Butte. Motion on the fault must postdate metamorphism of the Shuksan Suite. The aligned ridge notches and benches along the fault may be the result of differential erosion of gouged material along the fault or may indicate recent, post-glacial motion on the fault.

No relations between the melange unit and the Anderson fault were observed. The Anderson fault may be the easternmost expression of the shearing within the melange unit, although it is not parallel to the average S in the melange.

"Pipsqueak Pass" Fault

At "Pipsqueak Pass" phyllite is exposed along strike from greenschist several meters to the south. The intervening area is covered with talus, soil and brush. Presumably the contact is a fault, as all observed phyllite-greenschist contacts are no more than slightly discordant to the schistosity. The fault must extend farther to the east to form a southern boundary for the phyllite exposed at 212 on the south side of Anderson Butte, but there is no outcrop east of "Pipsqueak Pass". To the west the fault probably ends against the Anderson fault.

Presumably the north side of the fault has moved up, exposing the phyllite which underlies greenschist north of the pass. Motion on the fault must be post-metamorphic.

Mt Watson Fault

The Mt Watson fault is the only mapped fault seen in outcrop. On the ridgecrest west of the summit of Mt Watson the fault is a 2 m wide gouge zone juxtaposing type A and type B greenschist. A narrow dike is intrusive into the east side of the gouge zone. Five hundred m to the NE, at the 5,300' level, the lithologic contrast across the fault is not pronounced. However, a rubble-filled gully is present. On the east side of the gully at 172 there is a volcanic dike which grades east into well-indurated greenschist breccia with a fluxion structure parallel to the fault.

Rotated schistosity in large blocks in a brecciated zone on the south side of Mt Watson at 199 suggests the SW side moved relatively up. Motion must be post-metamorphic, and probably postdates crenulation of the schistosity (D_3).

Noisy-Diobsud Fault

A major fault is inferred to run through the Noisy Creek-Diobsud Creek col, with associated faulting present to the east and west. Evidence for this fault includes: 1) discordance in structural attitudes from opposite sides of the fault, as reported in the sections on structure in the Shuksan Suite; 2) lack of outcrop for over 50 m along the crest of the otherwise very rugged arete separating Noisy Creek and Diobsud Creek; 3) presence of numerous faulted zones where there is outcrop west of the Noisy-Diobsud col; 4) presence of brecciated phyllite in talus below the ridgecrest east of the Noisy-Diobsud col; and 5) the coincidence of this discontinuity and zone of weakness with a major lineament extending from the west face of Mt Shuksan 20 km to the north, across the head of Baker Lake, up Noisy Creek, down Diobsud Creek and across Helen Buttes towards Marblemount.

Along the west face of Mt Shuksan this lineament coincides with the Shuksan Thrust (figure 2). Recognition of the Noisy-Diobsud fault and its probable continuity with the Shuksan Thrust to the north suggests that the Shuksan Thrust may be a series of <u>en echelon</u> NNW-trending structures.

No sense of displacement is apparent for the Noisy-Diobsud fault.

The latest motion on the fault postdates crenulation of the Shuksan Greenschist and postdates intrusion of a now-altered volcanic dike found as a fault-bound sliver at <u>24</u>, west of the Noisy-Diobsud col. The dike is probably of post-Paleocene age, as no pre-Eocene magmatic activity has been recognized in the area (Engels *et al.*, 1976; Vance and Naeser, 1978). Brecciated phyllite from the Noisy-Diobsud divide has been contact-metamorphosed by the stock exposed on Bacon Peak, providing a possible upper age limit for motion on the fault. The stock is probably in contact with the fault under the brush and unconsolidated sediment of upper Noisy Creek, but the contact was not seen and could be either intrusive or faulted.

Bacon Peak Fault

The southern boundary of the Chuckanut Fm on Bacon Peak has been mapped as a fault by Staatz *et al.* (1972). This fault was crosscut by the granitic stock and then intruded by felsic volcanic breccia. Displacement is dip-slip, with the north side dropped down.

Other Faults

Minor faulting, usually with undeterminable displacement, is ubiquitous in the Shuksan Suite rocks on Mt Watson. Where offsets can be determined they are no more than a few meters. This faulting is associated with widespread minor brecciation of the greenschist, and may be coeval with the mapped breccia body exposed east of Mt Watson.

CONCLUSIONS

Rocks of the Shuksan Metamorphic Suite exposed in the Mt Watson area experienced the following history:

Formation of a series of pillow basalts, basaltic flows(?), basaltic tuffs and carbonaceous sediments, with static hydrothermal metamorphism of some basalts. During this hydrothermal event there was widespread crystallization of epidote and local intensive epidote metasomatism. Likely settings for this event are zones of high heat flow associated with mid-ocean ridges, island arcs and back-arc spreading centers.

D_1- Early Cretaceous (about 125 ma ago) synkinematic blueschist-facies metamorphism, with the development of S_1 and L_1. Metamorphic conditions were $T \sim 350^{\circ}$ C, $P \sim 7$ kb, P_{fluid} near P_{total}, $X_{CO_2} < 0.1$. H_2O was probably already present in the rock, as interstitial fluid in sediments and in hydrated phases created during the hydrothermal event. Substantial strain occurred during metamorphism and seems to have been genetically linked with recrystallization.

D_2- Late-metamorphic isoclinal folding (F_2) of S_1 around axes commonly at high angles to L_1, with the local development of S_2 in greenschist. S_2 is the dominant schistosity in phyllite. Quartz, albite, chlorite, and some amphibole recrystallized during this event.

D_3- L_3 crenulation of S_1 in greenschist. Axial planes of associated open F_3 folds in greenschist are normal to S_1. Phyllite structures formed at this time are not as well understood.

Post-D_3 deformation of phyllite is localized along faults. Comparison with other studies suggests that a similar history characterizes the Suite elsewhere. In particular, the early hydrothermal event appears to have been widespread.

Protolith materials for the Suite included basaltic tuff, intruded by basaltic dikes or sills, pillow basalts, carbonaceous pelitic sediments; Mn-enriched cherty sediments, rare ferromanganese nodules, and rare calcareous sediments. There is no evidence for relict stratigraphy in the Mt Watson area. Phyllite-greenschist contacts probably do not represent a single surface modified by folding and faulting, as locally phyllite layers appear to be primary depositional intercalations. All evidence points to a submarine origin for the Shuksan Suite. It is not clear from this study whether or not the Suite is metamorphosed oceanic crust, as proposed by Morrison (1977).

Post-metamorphic events recorded in the Mt Watson area include 1) formation of a small intrusive breccia pipe, 2) Eocene(?) deposition of the fluvial Chuckanut Fm, 3) widespread dike injection, 4) major faulting on the NNW-trending Noisy-Diobsud fault, and 5) intrusion of a satellite of the Chilliwack Composite Batholith.

The Shuksan Thrust remains poorly understood. In the Mt Watson area it is a 3 km + thick tectonic melange. Most of the melange is made of little-recrystallized Chilliwack Group(?) rocks. Aragonite and lawsonite are present in some samples of these rocks, suggesting that they were rapidly buried, presumably by subduction, possibly to depths comparable to that of blueschist-facies Shuksan metamorphism. Also present in the melange are probable Shuksan Suite greenschist and phyllite, metaquartz diorite, tremolite-Mg chlorite schist and exotic high P/T metavolcanic rocks. Well-recrystallized metavolcanoc rocks rcord a variety of distinct P-T conditions; they appear to be comparable to the "knockers" in some parts of the Franciscan Complex. The relations between metamorphism of Chilliwack Group(?) rocks in the melange, melange deformation, and blueschist-facies Shuksan metamorphism are not known.

The probable continuity of the Noisy-Diobsud fault with the Shuksan Thrust north of Baker Lake suggests that the Shuksan Thrust east of the Mt Baker Window may be a series of en echelon NNW-trending structures.

The tectonic setting and stratigraphy of the Shuksan Suite protolith remain unresolved. The nature of the Shuksan Thrust is largely unknown; further studies should try to establish relations between deformation and metamorphism along the Thrust as well as consider the possibility of early Tertiary deformation.

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Appendix A

Phases Observed in Thin Section, Shuksan Metamorphic Suite

Phases observed in Shuksan Suite rocks are listed below. An X indicates the phase is present, while a ? indicates that material that may be the phase is present but was not conclusively identified.

Quartz and albite are similar in appearance in these rocks and in many samples the two phases were not distinguished. In this case, an X is present between the quartz and albite columns. Similarly, fine-grained opaque minerals were not always identifiable and an X between the oxide and sulphide columns indicates that unidentified opaques are present. (Opaque oxides were distinguished from sulphides by color in reflected light using covered sections and a standard petrographic microscope.)

Notes

(1) "Boudin" sample, largely unrecrystallized. Phases noted are identified metamorphic minerals.

(2) Hematite present as fine-grained inclusions in epidote.

(3) Probable late, non-equilibrium assemblage calcite present.

(4) Paragonite identified by x-ray diffraction.

(5) Metalliferous carbonate nodule; see text.

(6) Sample of irregular cross-cutting vein.

(7) Garnet in vein with calcite and quartz, probably not part of the equilibrium assemblage.

(8) Unidentified phase (fine hairs with low refractive indices, low birefringence and parallel extinction) is also present.

(9) Rutile, no sphene.

(10) Stilpnomelane, no white mica.

(11) Holes in rock suggest carbonate present prior to weathering.

(12) Contact-metamorphic biotite.

(13) Contact-metamorphic(?) potassium feldspar.

sample number	quartz	albite	chlorite	pumpellyite	epidote	actinolite	Na-amphibole	calcite	oxide	sulphide	white mica	sphene	graphite	garnet	apatite	map unit
D5	X	X			X	X						X				gsA
D6	X	X	X	X	X	X				X		X				gsA
D7			X		X	X										gsA(1)
D8	X		X		X	X						X				gsA
D9	X	X	X		X	X					X	X				gsA
D10	X	X	X		X		X				X	X				gsB
D11	X		X		X	X				X		X				gsB
D12	X								?		X	X	?			ph (12)
D13	X		X		X		X		(2)		X	X				gsB
D14		X	X		X	X				?		X				gsB
D15		X	X		X	X					X	X				gsB
D16		X	X		X		X	(3)	X		X	X				gsB
D17	X	X	X		X	X						X				gsB
D18	X	X	X						?		X	X		X		ph
D19	X		X								X	X	X			ph (4)
D21	X	X	X								X	X		X		ph
D22	X	X	X								X		?			ph
D23	X	X	X		X	X				X		X				gsB
D24	X	X	X		X	X						X				gsB
D27	X	X	X		X	X		(3)				X				gsB
D28	X	X	X		X		X		(2)			X				gsB
D29	X	X	X		X	X		X			X	X				gsB
D30	X		X		X	X					X	X				gsB
D78		X	X		X	X		X		?	X	X				gsA-B
D79	X	X	X		X	X						X				gsA
D81	X		X		X						X	X				gsA
D82	X	?	X							X	X		X			ph
D83	X		X		X	X			X		X	X				gsA
D97	X		X		X	X					X	X				gsB

sample number	quartz	albite	chlorite	pumpellyite	epidote	actinolite	Na-amphibole	calcite	oxide	sulphide	white mica	sphene	graphite	garnet	apatite	map unit
D98	X	X	X		X		X	X(3)	(2)		X	X				gsB
D99	X	X	X		X	X		(3),	(2)		X	X				gsB
E1	X		X					X			X		?			ph (4)
E2	X	X	X								X	X		X		ph
E3	X	X	X		X	X		X	(2)			X				gsB
E4																ph (5)
E5																ph (5)
E6		X	X		X	X		(3)				X				gsB
E7	X		X		X		X	X		X		X				gsB(13)
E8	X										X		X			ph (12)
E10	X	X	X		X	X				?		X				gsA
E11	X		X		X					X	X	X				gsB
E13	X	X	X								X	X				gsB
E14	X		X								X	?	X			ph (12)
E19	X	X	X		X	X				X		X				gsA
E20	X	X	X		X	X				X		X				gsA
E21	X	X	X							?	X	X				gsA
E25	X	X	X		X	X		X		X	X	X				gsB
E26	X	X	X					X								gsB(6)
E27	X		X	X	X	X				?	X	X				gsA
E34		X	X		X		X	X(3)	?			X				gsB
E35	X	X	X		X	X		(3)			X	X				gsB
E36	X	X	X		X		X		X		X	X				float-gsB
E37	X		X		X	X		(3)		X		X				gsB
E39	X	X	X					X		X	X	X				ph
E40	X	X	X		X	X		(3)	X	X		X		(7)		float
E41	X	X	X		X	X		(3)	X	X		X		(7)		float
E42	X	X	X		X	X		X			X	X				float-gsB
E43	X	X	X		X		X		(2)		X	X			X	float-gsB

sample number	quartz	albite	chlorite	pumpellyite	epidote	actinolite	Na-amphibole	calcite	oxide	sulphide	white mica	sphene	graphite	garnet	apatite	map unit
E44		X	X			X						X		(8)		gsA(1)
E46	X	X	X		X				X			X				gsA
E47	X	X	X		X	X						X				gsA
E48	X		X		X	X		(3)			X	X				gsB
E49	X	X	X		X			(3)				(9)				gsB
E50		X						X							X	float
E51		X	X					X					X			float
E52		X	X		X					X		X				gsA
E54	X		X	X							(10)					gsA(6)
E55		X	X		X	X				X		X				gsA
E59	X		X								X					ph
E60	X		X					X(3)		X		X				gsA
E61	X	X	X		X						X	X				gsA
E61	X		X								X	X				ph
E62	X	X	X								X	X	X	X		ph
E65		X	X		X		X	(3)				X				gsB
E66		X	X		X	X		(3)		X		X				gsB
E67	X	X	X		X	X		X		X		X				gsB
E68		X	X		X	X		X	X			X				gsB
E69	X	X	X		X		X	(3)	?	X	X	X				float-gsB
E70		X	X		X	X					X	X				gsA
E71	X	X	X		X	X					X	X				gsA
E72	X	X	X		X	X					X	X				gsA
E76	X	X	X		X	?					X	X				float-gsB?
E77		X	X		X		X		(2)		X	X				float-gsB
E78		X	X		X		X	(3)	(2)	X	X	X		X		float-gsB
E79		X	X		X	X		(3)	(2)			X				float-gsB
E80	X	X	X		X		X	(3)	(2)		X	X				gsB
E81	X		X		X				(2)		X	X				gsB

sample number	quartz	albite	chlorite	pumpellyite	epidote	actinolite	Na-amphibole	calcite	oxide	sulphide	white mica	sphene	graphite	garnet	apatite	map unit
E82	X		X		X	X		(3)			X	X				gsB
E83	X	X	X		X	X		(3)			X	X				gsB
E84	X	X	X		X	X		(11)	(2)		X	X				gsB
E85	X	X	X					(11)			X	X				gsB

Appendix B

Age of Shuksan Metamorphism

Radiometric ages for the Shuksan Metamorphic Suite and similar rocks are summarized below.

sample #	rock type	material dated	method	age
	(location) (reference)			
PM 9	blueschist	crossite	K/Ar	218 ± 40 ma
	(not known) (Misch, 1966; Engels et al., 1976)			
PM 16	phyllite	whole rock	K/Ar	113 ± 3 ma
	(Groat Mtn?) (" ; ")			
PM 17	phyllite	whole rock	K/Ar	108 ± 4 ma
	(Bowman Mtn?) (" ; ")			
PM 18	phyllite	whole rock	K/Ar	105 ± 3 ma
	(Acme?) (" ; ")			
PM 24	blueschist	whole rock	K/Ar	259 ± 8 ma
	(Groat Mtn) (" ; ")			
27 Q	muscovite schist	musc.	K/Ar	127 ± 5 ma
	(S side Skagit River near Hamilton) (Fernette, 1980, date by R.L. Armstrong)			
27 Q	"	whole rock/musc.	Rb/Sr	126 ± 2 ma
	(") (" , ")			
38 S	muscovite schist	musc.	K/Ar	125 ± 4 ma
	(Finney Creek)(Wilson, 1978, date by R.L. Armstrong)			
78RH-E69	blueschist	whole rock	K/Ar	122 ± 4 ma
	(Mt Watson) (this study, date by R.L. Armstrong)			
78RH-E69	"	whole rock	Rb/Sr	105 ± 10 ma
78RH-E78	blueschist	whole rock	.7038 ± 2 initial $^{87}Sr/^{86}Sr$	
	(") (" , ")			
78RH-D19	phyllite	whole rock	Rb/Sr	173 ma
78RH-E1	phyllite	whole rock	.70536 initial $^{87}Sr/^{86}Sr$	
	(") (" , ")			

sample # (location)	rock type (reference)	material dated	method	age
67-53 (Gee Point)	epidote-amphibolite (Wilson, 1978, date by R.L. Armstrong)	hornblende	K/Ar	144 ± 5 ma
67-45b (")	epidote-amphibolite (" , ")	musc.	K/Ar	160 ± 6 ma
33-VM22C (Vedder Mtn)	mica schist (Bernardi, 1977, date by R.L. Armstrong)	musc.	K/Ar	233 ± 8 ma
33-VM22C (")	whole rock/musc. (" , ")		Rb/Sr	262 ± 10 ma
33-VM24B (")	albite-epidote-amph. (" , ")	hornblende	K/Ar	239 ± 10 ma
33-VM25B (")	Mica schist (" , ")	musc.	k/Ar	235 ± 9 ma
33-VM25B (")	" (" , ")	whole rock/musc.	Rb/Sr	250 ± 10 ma

Metamorphism of the Shuksan Suite was considered to be Permian or older, on the basis of the 259 ± 8 ma K/Ar age for blueschist from Groat Mtn near the Middle Fk of the Nooksack River (Misch, 1966). Cretaceous K/Ar ages from phyllite were considered to be the result of argon loss during mid-Cretaceous deformation associated with Shuksan Thrusting.

K/Ar and Rb/Sr dating of Shuksan rocks by R.L. Armstrong shows Shuksan metamorphism to be Early Cretaceous in age. Evidence for the Early Cretaceous age is: 1) K/Ar ages from the Gee Point-Finney Creek and Mt Watson areas overlap at about 122-126 ma. 2) Rb/Sr ages, while not precise, point to Early Cretaceous metamporphism. These ages are not likely to have been reset during later deformation. A 173 ma isochron calculated for two phyllite samples from the Mt Watson area may be the age of deposition. 3) The low initial strontium ratios calculated for rocks from the Mt Watson area preclude the possibility that these rocks are as old as Permian. 4) Albite-epidote-amphibolite facies minerals from the Gee Point area predate Shuksan Metamorphism (Wilson, 1978) and give K/Ar ages of 144 ± 5 and 160 ± 6 ma.

Permo-Triassic high P/T metamorphic rocks are also present in the northwest Cascades. Bernardi (1977) identified graphitic mica schists, albite-epidote amphibolites and barroisite schists on Vedder Mtn as possible higher-temperature equivalents of the Shuksan Suite, as they have similar chemistry and were metamorphosed at about the same pressure. K/Ar and Rb/Sr dating show these rocks to have recrystallized about 250 ma ago. Bernardi noted that amphibolites identical to those on Vedder Mtn crop out along the Middle Fork of the Nooksack River near Groat Mtn. This suggests that the Groat Mtn blueschist (PM 24) which yielded the 259 ± ma age is part of this older suite, not part of the Shuksan Suite.

The 218 ± 40 ma age reported for PM 9 is anomalous. There is no published location for this sample.

Appendix C

Chemical Analyses of Type A Shuksan Greenschist

Three samples of type A greenschist were analyzed by atomic absorption methods. Standards used were ARHCO, TON, NIM-G, NIM-D, BC4 and DIOR. Analyses were calculated from absorbance values using the computer program CURVE. Niggli norms were calculated assuming $Fe_2O_3/FeO = 0.25$.

Using the classification algorithm proposed by Irvine and Baragar (1971), all of these samples are chemically equivalent to olivine-normative subalkaline tholeiitic basalts.

sample	D9	E27	E72
SiO_2	53.01	49.37	49.84
Al_2O_3	16.87	18.42	18.75
TiO_2	0.54	0.11	0.73
Fe_2O_3*	8.47	8.04	8.83
MgO	9.88	10.34	7.40
MnO	0.27	0.27	0.26
CaO	9.44	11.75	10.05
Na_2O	2.68	1.25	2.70
K_2O	0.82	0.76	0.28
sum	101.98	100.31	98.94

* All Fe calculated as Fe_2O_3

Or	4.71	4.52	1.67
Ab	23.41	11.29	24.52
An	30.72	42.65	38.66
Mt	2.15	2.11	2.33
Il	0.73	0.15	1.03
Di	11.87	9.79	9.42
Hy	23.2	28.35	20.08
Ol	3.2	1.14	2.29
Plag	An 57	An 79	An 61

Or = orthoclase, Ab = albite, An = anorthite, Mt = magnetite, Il = ilmenite, Di = diopside, Hy = hypersthene, Ol = olivine, Plag = plagioclase.

Appendix D

An Origin for Tectonic Melanges

Many workers (for example, Cowan, 1974; Blake and Jones, 1974; Moore and Wheeler, 1978) have surmised that some tectonic melanges are essentially overthrust faults active during the subduction process. Here I wish to offer a possible origin for melange structure in which deformation is distributed through kilometers of rock (in contrast to classic overthrusts in which most of the deformation may be confined to a zone meters thick). In addition, I wish to show that differences in texture do not preclude the possibility that Chilliwack Group(?) rocks in the melange unit and nearby Shuksan Suite rocks experienced similar metamorphic conditions. I will assume that metamorphism of Chilliwack Group(?) rocks and melange deformation were simultaneous. The following observations provide starting points.

Chilliwack Group(?) volcanics	Shuksan Suite greenschists
little-recrystallized, cataclastic textures predominate	almost entirely synkinematically recrystallized
mechanically heterogenous	mechanically homogenous
largely composed of anhydrous igneous phases before metamorphism	in large part hydrated before Shuksan metamorphism, as result of pre-Shuksan event

Recrystallization within the Shuksan Greenschist on Mt Watson is genetically linked with strain. Unstrained domains within the Greenschist did not recrystallize during blueschist-facies metamorphism.

At least three factors other than temperature and pressure of metamorphism deserve consideration as causes for the difference in texture. Clearly all may have been effective.

A) Time. Chilliwack Group(?)rocks may have been subjected to metamorphic conditions for a shorter period of time than Shuksan rocks, and consequently are less recrystallized.

B) Strain Distribution. Metamorphism within the Shuksan Suite appears to have been dependent on distributed strain at the granular to intra-granular level, at rates low enough that recrystallization could keep step. Within the melange unit, strain was irregularly distributed. At the granular and inter-granular level melange rocks were divided into relatively rigid domains and domains which deformed so rapidly that recrystallization could not keep step, and cataclasites developed.

C) Availability of H_2O. Stable phases at these low temperatures are hydrous. In the volcanic rocks of the Chilliwack Group(?) anhydrous igneous phases were the reactants and reactions may have been stalled by the lack of H_2O. Within the Shuksan Suite rocks were, in part, hydrated during an early hydrothermal event and H_2O was available at the molecular level. (Extensive veining in melange unit rocks is good evidence for local high fluid pressures. However, throughout most of the rock H_2O may not have been available on the molecular, or even granular, level.)

Factors B and C interact, and may explain the formation of the multiple shears that characterize tectonic melanges, rather than the discrete shear surfaces found in classic overthrusts or the distributed shearing responsible for some schists.

Consider prograde regional metamorphism in which dehydration reactions predominate. Fluid is released at the molecular-level, and fluid loss is limited by low permeability. Fluid pressure will rise until it reaches some value > load pressure and hydraulic fracturing is initiated, resulting in the reduction of fluid pressure to values $\leq$ load pressure. Under these conditions rock strength is low. In homogenous rock directed stress will result in distributed shear, producing synkinematic crystallization schistosity if strain rates and recrystallization rates are in the proper proportion. This appears to have been the case during metamorphism of the Shuksan Greenschist.

A different picture arises when we examine an inhomogenous, in part anhydrous, rock subjected to increasing pressure and directed stress in conditions of low to very-low grade metamorphism. Consider an igneous rock mass made of relatively anhydrous, impermeable domains and hydrous domains (e.g., a water saturated, fractured basalt flow, a pile of pillow lava, or intercalated volcanic flows and sediments). During compression, fluid pressure will rise in the water-saturated domains until it approximates load pressure. Fluid pressure will also rise in the relatively anhydrous domains, but will be limited by the original lack of water and the slow rate of volatile transfer (by diffusion and intergranular flow) into the anhydrous domains. If the rock is subjected to directed stress, it will deform. Domains with high fluid pressure will be substantially weaker and will absorb all, or nearly all, of the strain. At any given time deformation will be concentrated in a fraction of the total rock volume. If this fraction is small enough, strain rates will be so high that recrystallization cannot keep step and cataclasites will form. Schistose assemblages will not. However, high fluid pressure and consequently shearing promote metamorphic reactions which use up H_2O, lower fluid pressure, and thus increase local rock strength. Rock strength may then be raised to values above those of other domains and local shearing will stop as directed stress is absorbed elsewhere. With continued compression and directed stress the rock mass will shear along numerous surfaces spread throughout a large volume.

In the relatively anhydrous domains recrystallization will not procede, as water is not available as a reactant, catalyst, or transport medium and there is no shearing to increase reaction rates. As water does diffuse and flow into anhydrous domains it will raise fluid pressures, promote shearing, and thus promote metamorphic reactions which absorb this water, reduce permeability and flow rates, and lessen the concentration gradient along which water is diffusing.

In such a rock mass the only places where synkinematic assemblages are likely to be preserved are slowly extending extensional fractures at high angles to the dominant shear planes and large hydrated domains in which strain rates are low because strain is distributed through a large rock volume.

Not enough is known to propose this hypothesis as a history for the melange unit. However, it fits the Chilliwack Group(?) rocks of the melange well. The block-in-matrix structure with anastomosing sub-parallel shear surfaces records irregularly distributed strain. Cataclastic deformation predominated. Crystallization schistosity is limited to metasediments which were possibly uniformly water-saturated prior to metamorphism. Metamorphic assemblages in igneous rocks (other than aligned phyllosilicates in shears) are largely restricted to vein fillings. Aligned phyllosilicates in shears probably reflect either a) greater growth rates of the phyllosilicates, fast enough to keep pace with high strain rates, b) the ability of phyllosilicates to absorb intracrystalline shear parallel to (001) without cataclasis; or c) the ability of optically homogenous aggregates of submicroscopic phyllosilicate crystals to absorb shear by grain boundary slip.

At least two rock types in the melange unit do not fit this scheme. Some massive volcanic sandstones show extensive growth of unoriented metamorphic minerals. Some tuffs were probably uniformly hydrated, and show distributed strain as predicted, but do not contain well-developed metamorphic minerals other than phyllosilicates and albite.