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Title: STRUCTURAL GEOLOGY AND METAMORPHIC PETROLOGY OF THE ILLABOT PEAKS AREA, SKAGIT COUNTY, WASHINGTON

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The Illabot Peaks area is composed of several essentially homoclinal eastward dipping thrust blocks of Shuksan Schist which are comprised of olivine-free calc-alkaline basalt that has been metamorphosed under greenschist to blueschist facies conditions. The structurally lower portions of the Shuksan Schist are occupied by a soda amphibole-bearing rock that probably originated from intercalations of high P_{O_2} and high ferric iron content. The blocks of Shuksan Schist rest upon ductile mega-shear zones of lower greenschist facies quartz-muscovite-graphite phyllite that have been tentatively correlated with the Darrington Phyllite. The Shuksan Schist and Darrington Phyllite, forming the Shuksan metamorphic suite, were syntectonically metamorphosed in the late Permian to early Triassic. The primary foliation, the amphibole lineations, and the intrafolial F_1 folds were formed at this time.

The blocks of Shuksan Schist were emplaced during the Middle to early Late Cretaceous by movements on the large displacement Shuksan thrust. The thrust system in the Illabot Peaks area dips in a concave upward manner to the east, has a large westward displacement, and is highly imbricated. Small lenticular pods of brecciated blueschist fragments and meta-igneous basement rock slivers have been tectonically emplaced along the margins of the thrust. The blueschist pods, retrogressively metamorphosed, are possible indicators of a rock unit at depth of a higher facies than the typical Shuksan Schist.

Movement on the Shuksan thrust produced small northeast trending F_2 drag folds and large scale, nearly horizontally plunging F_3 folds that trend to the northwest. Kink folds occurred in the better foliated rocks at this time. Slight recrystallization and retrogressive metamorphism are associated with the thrusting. The heavy greenschist blocks resting on the ductile phyllite produced a vertical preferred orientation of quartz optic axes.

A large northeast trending, high angle, strike-slip fault has offset the thrust system 1.1 km in a right lateral sense. Movement was sometime between the Late Cretaceous thrusting and the onset of movement on the Straight Creek fault.

The Straight Creek fault, active from the late Mesozoic to the Miocene with main movement in the early Eocene, is a complexly braided, highly cataclasized fault zone that contains slivers of gneiss, greenschist, phyllite, and Swauk Formation arkoses and arenites. The fault, determined by kink analysis to have a right lateral sense of displacement, separates the lower T/P Shuksan metamorphic suite on the west from the higher T/P Skagit metamorphic suite on the east. Large amplitude, steeply plunging F_4 folds and related kinks were caused by stress systems associated with the fault.

Small minor faults are ubiquitous, though displacements of these faults are unknown.

Structural Geology and Metamorphic Petrology of the Illabot Peaks Area, Skagit County, Washington

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STRUCTURAL GEOLOGY AND METAMORPHIC PETROLOGY OF THE ILLABOT PEAKS AREA, SKAGIT COUNTY, WASHINGTON

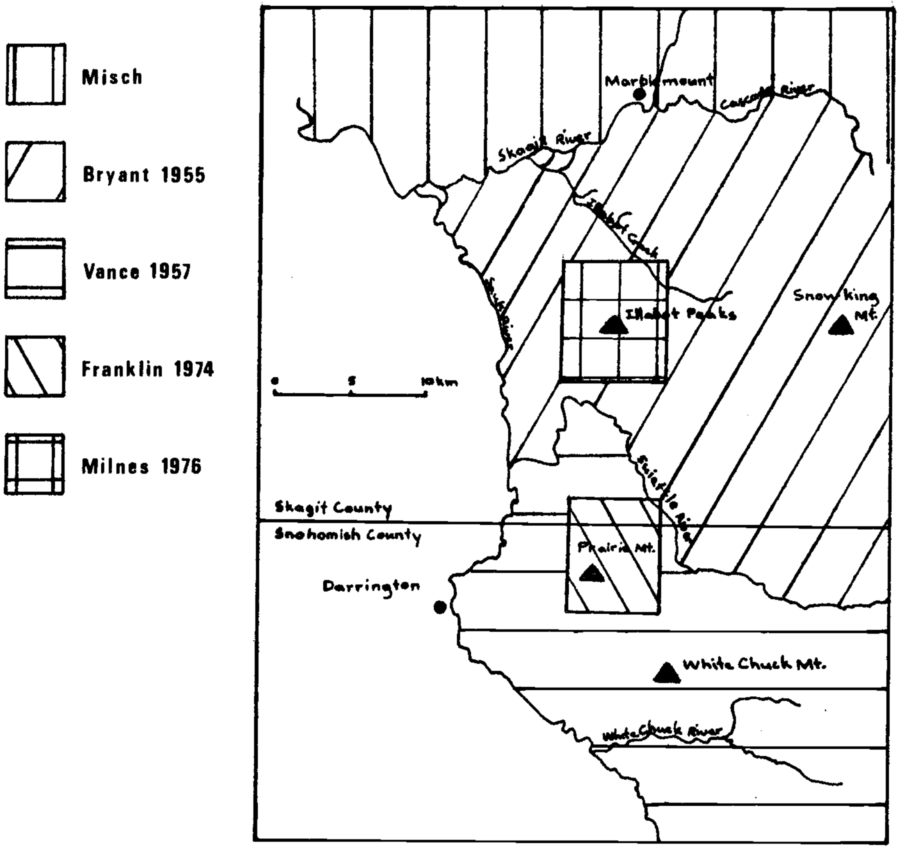
INTRODUCTION

The principal purpose of this thesis is a study of the structural elements of the Shuksan Schist, and associated units, in the Illabot Peaks area, Washington in relation to regional structural events and metamorphic history. The thesis area occupies roughly 40 km^2 and lies approximately 17 km (map distance) northeast of the town of Darrington, Skagit County, Washington. (See Figure 1B.)

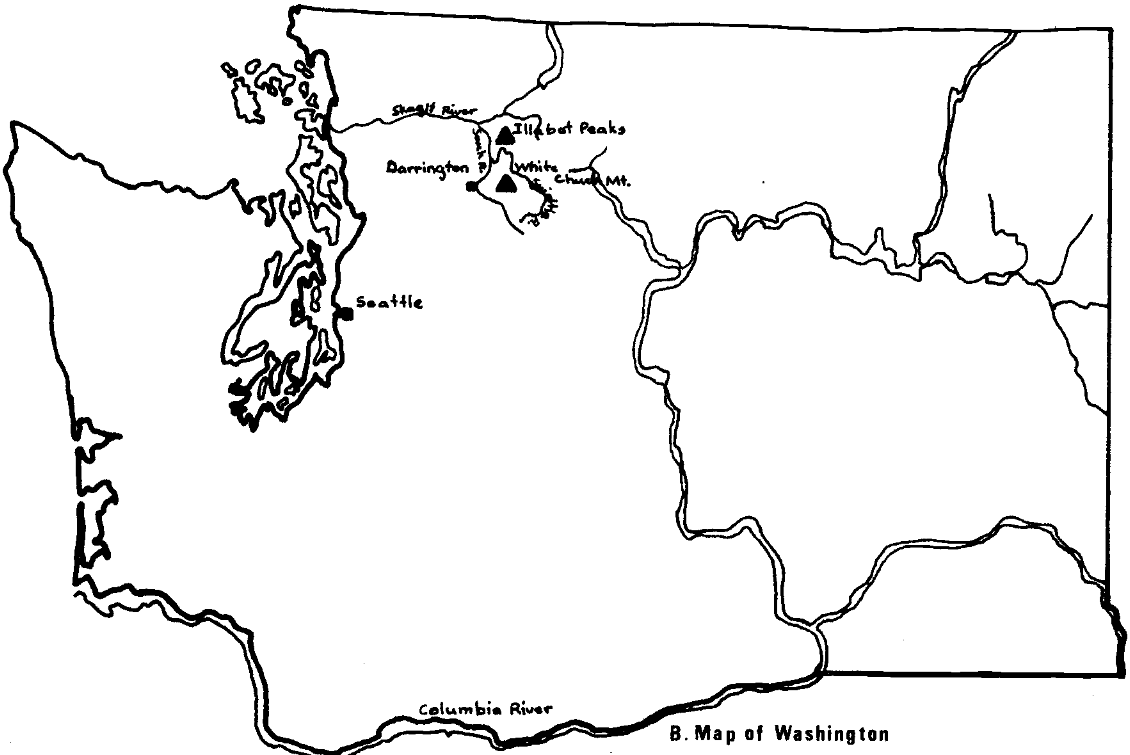
The two main units in the area are the Shuksan Schist, which is divided into several types of greenschist and blueschist, and a quartz-muscovite-graphite phyllite. The two units are separated by a series of imbricated thrusts and high angle reverse faults of the Shuksan thrust system. Both units have a history of three, and possibly four, periods of clearly demonstrated deformation. The earliest deformation was synmetamorphic, the next two were caused by the stress systems associated with the Shuksan thrust, and the last was a minor episode related to faulting.

Small meta-igneous and blueschist fragments have been faulted into the greenschists near the margins of the Shuksan-thrust through zones of ductile quartz-muscovite-graphite phyllite.

The greenschists, blueschists, phyllite, and meta-igneous



A. Study Areas



B. Map of Washington

Figure 1. Map Location

fragments are separated by the Straight Creek fault zone from units of the Skagit Gneiss to the east. Lensoidal slivers of greenschist, phyllite, gneiss, and Swauk Formation sedimentary rocks are contained in the fault zone.

REGIONAL GEOLOGIC SETTING

The rocks of the Illabot Peaks area are immediately to the west of the crystalline core of the North Cascades and belong to what Misch (1966) terms the Shuksan thrust belt. The rocks of the core are composed of the Skagit metamorphic suite, which contains the meta-sedimentary Cascade River Schist and the migmatized Skagit Gneiss. (See Vance, 1957, for more data.) The Skagit rocks were metamorphosed under the barrovian metamorphic facies series, probably during Permian-Triassic time, though the original dates of intrusion and deposition are not clearly established. Mattinson (1972) found a Precambrian age for the oldest rocks, though many are considerably younger.

The Skagit metamorphic suite is separated from the Shuksan belt to the west by the large displacement, north-south trending, right lateral Straight Creek fault. The fault may have been active from the late Mesozoic until the mid-Tertiary. The Straight Creek fault extends for 125 km south of the Canadian border and may connect with the Fraser River fault zone that extends 230 km north of the international border.

The Shuksan thrust belt is mainly composed of the greenschists, blueschists, and graphitic phyllites of the Permo-Triassic Shuksan metamorphic suite. The Shuksan suite forms the Shuksan thrust plate of Misch (1966) that has been thrust over the Middle Devonian to Permian Chilliwack Group meta-sediments and younger sediments of the Church Mountain plate. The Shuksan thrust belt is traceable from south of the Cle Elum region to a short distance into Canada for a total length of around 270 km. Displacement on the thrust, according to Misch (1966), may be up to 62 km in a westward direction with parts of the belt occurring near the coast.

The thrust belt has also emplaced tectonic slices of mafic and ultramafic meta-igneous material along the complex imbricated margin. Some of these slices are quite large (see Vance, 1957, and Franklin, 1974). Misch (1966) has termed these rocks the heterogeneous Yellow Aster Basement Complex that has been dated at 1,452 to 2,000 m.y. and 415 m.y. by Mattinson (1972). The older rocks are clinopyroxene-plagioclase-quartz gneisses and the younger rocks range from meta-gabbros to meta-trondhjemites. All the basement rocks have been metamorphosed to at least the amphibolite facies.

The western foothills of the North Cascade Mountains are mainly Mesozoic and Cenozoic sedimentary rocks. These include the Late Cretaceous-Paleocene continental arkosic sandstones and conglomerates of the Chukanut and equivalent Swauk formations. The Late Triassic to Early Jurassic graywackes of the Cultus and Bald Mountain formations, the Middle Jurassic andesitic to dacitic flows and associated marine sediments of the Wells Creek volcanics, and the Late Jurassic to Early Cretaceous graywackes of the Nooksack Group occupy smaller areas mainly in the foothills in the northwest corner of Washington.

The North Cascades had a very active Mesozoic to Tertiary intrusive history. The Marblemount Quartz Diroite (dated by Mattinson, 1972, at 220 m. y.) is immediately east of the Straight Creek fault and northeast of the Illabot Peaks area. Small meta-gabbro to meta-diorite bodies intruded during metamorphism of the Skagit suite (Permo-Triassic) also occur east of the fault. Numerous small batholiths and stocks of granodiorite to quartz diorite were intruded near the crest of the North Cascades in the Late Cretaceous to Middle Tertiary. During the Oligocene to Miocene, the complex composite Chilliwack batholith (predominantly quartz diorite and granodiorite) and the Snoqualmie batholith were intruded along the trace of the Straight Creek fault, obliterating much of the fault.

PREVIOUS WORK

The Illabot Peaks area lies in the western corner of the reconnaissance study of Bryant (1955) in a University of Washington Ph. D. thesis under Misch. (See Figure 1A.) Though the area around Illabot Peaks was not his main area of concentration and not studied in detail, Bryant reported some valuable petrographic work. Vance (1957), also studying under Misch, worked in the area south of the Suiattle River and provides a detailed study of the Shuksan metamorphics and meta-igneous rocks. Misch (1966, 1973) has compiled data gathered since 1949 in the North Cascades by himself and his students into a concise summary of the regional geology. Franklin (1974), working under Lawrence of Oregon State University, mapped in detail the geology around the Prairie Mountain region. Danner (1966) and Grant (1969) offer syntheses and summaries of the North Cascades geology. Mattinson (1970, 1972) has made some useful radiometric dates on units in the region. Johnson and Couch (1970) have made seismic refraction studies of the crustal structures of the range. Lawrence has mapped in several areas surrounding the thesis area and extensively in the White Chuck Mountain area. Several theses, under Lawrence, are currently in progress immediately to the south of the Illabot Peaks area. Numerous other workers have done studies farther to the northeast and southeast of the area.

METHODS OF INVESTIGATION

Field work was undertaken from July 3 to September 5 of 1975. The U. S. G. S. Illabot Peaks 7 1/2' quadrangle (1:24, 000) was used as a base map for the geologic mapping with complimentary use of aerial photographs in the laboratory to help determine linear trends, such as faulting. Large scale aerial photographs (1:12, 000) and small scale U-2 photographs (1:65, 000) were both used. The extensive snow cover in the higher elevations for the majority of the summer made field use of the photographs difficult.

All linear and planar fabric elements were measured with a brunton compass in the field. Where practical, oriented hand specimens were taken for detailed laboratory work, both on the hand specimen and through the use of oriented petrographic thin sections. All fabric elements were segregated according to domain and plotted on equal area stereonet diagrams to determine general structural trends. Kink geometry was measured in the field and laboratory to determine principal stress directions. Two hundred optic axes of quarts were measured in oriented thin sections selected to relate to possible structural features.

Fifty petrographic thin sections from the Illabot Peaks area were studied to determine microfabric elements, mineral content, and metamorphic facies of the rocks. The x-ray diffractometer was used on several samples to compliment petrographic work. An attempt was made to magnetically sort and also sort by density the Na mineral jadeite from the blueschist tectonic breccias, but all attempts were unsuccessful.

DESCRIPTION OF ROCK UNITS

Introduction

The rocks of the Illabot Peaks area can be divided into three regional, as well as petrological, types that are separated by the Straight Creek fault zone: 1) the rocks east of the fault; 2) rocks in the fault zone; and 3) rocks west of the fault.

The rocks east of the fault zone include members of the high T/P Skagit metamorphic suite, as described by Misch (1966). The rocks in this area are granodiorite gneisses, hornblende-diorite gneisses, and hornblende-garnet feldspathic gneisses and appear to be similar to the heterogeneous gneiss unit of Vance (1957). The rocks of the Skagit suite are believed by Misch (1966) to have undergone metamorphism of the greenschist to albite-epidote amphibolite facies during early Mesozoic time, though there are some indications (Mattinson, 1972) that the Skagit rocks may be as young as early Tertiary and not related to Mesozoic Shuksan metamorphism. The rocks east of the fault were not mapped in detail.

Rocks of the Swauk Formation, the Shuksan Schist, the quartz-muscovite-graphite phyllite, and the Skagit suite have been caught up as cataclasized lensoidal slices in the Straight Creek fault zone. The rocks of the Eocene Swauk Formation sliver are fine-grained, fossil-bearing arkoses that grade upward into coarse-grained lithic arenites.

No primary sedimentary structures, other than a crude graded bedding, were observed. The tectonic sliver of arenites and arkoses consists of a jumbled pile of material with no consistent structural trends.

West of the Straight Creek fault, the main rocks are the members of the Permo-Triassic Shuksan metamorphic suite, associated blueschist fragments, and tectonically emplaced meta-igneous fragments. The Shuksan metamorphic suite, defined by Misch (1966), contains the Shuksan Schist and the Darrington Phyllite. The dominant member of the Shuksan Schist is a calc-alkaline basalt, and associated sediments, that has been metamorphosed to the low T/P greenschist to greenschist-lawsonite-glaucophane schist transition facies. Herein, the greenschist is subdivided into four informal units based upon textures and lithologies. The greenschists grade downward into soda amphibole-bearing rocks. The Shuksan Schist occurs as two major, and several minor, eastward-dipping tilt blocks up to 1 km thick that have been thrust upon the quartz-muscovite-graphite phyllite.

The phyllite, which is very ductile, black, graphitic rock that originated from pelitic to semi-pelitic sediments, has been tentatively correlated with the Darrington Phyllite. The phyllite unit mainly occurs in a north-northeast trending east-dipping belt that is 500-700 m thick. Small outcrops of phyllite have been emplaced elsewhere by small faults.

Small lensoidal pods of blueschist (lawsonite-glaucophane schist facies) fragments and retrogressively metamorphosed mafic meta-igneous rocks have been tectonically emplaced in and near the margins of the Shuksan thrust. These blueschist fragments are breccias. They probably reflect the presence at depth of another unit of a higher metamorphic facies than the greenschist. The meta-igneous fragments are highly altered gabbros that probably were faulted up from the basement complex of early to middle Paleozoic age and probably represent fragments of a dismembered ophiolite assemblage.

Most rock units within the map area are cataclastically deformed to some extent, with the degree of cataclastic deformation depending on the fault type and the rocks involved. Cataclastic rock terminology used is described in Table 1 from Higgins (1971). Near the margins of the Shuksan thrust, the greenschists and phyllites have typically been brecciated, with mylonitization being very rare. The greenschists near the Straight Creek fault have also been brecciated, but are, more characteristically, slightly recrystallized mylonites or protomylonites. The phyllites near the fault have been intensively cataclasized to mylonites and protomylonites. The Swauk sediments and the intrusive rocks east of the fault also exhibit very intense shearing effects. The deformed

Table 1.—*Classification of cataclastic rocks*

[Porphyroclastic, protoclastic, diaphthoritic, pseudotachylitic, polymetamorphic, polycataclastic, phyllitic, and other terms are used as modifiers. See text and glossary]

Approximate volume percent porphyroclasts in rocks *with* fluxion structure. or Approximate volume percent fragments in rocks *without* fluxion structure.	Rocks *without* primary cohesion	Rocks *with* primary cohesion				Approximate size of *most* porphyroclasts in rocks *with* fluxion structure. or Approximate size of *most* fragments in rocks *without* fluxion structure.
		Cataclasis dominant over neomineralization-recrystallization			Neomineralization-recrystallization dominant over cataclasis	
		Rocks *without* fluxion structure	Rocks *with* fluxion structure		Rocks *with* fluxion structure	
>50	Fault breccia	Microbreccia	Protomylonite		Mylonite gneiss (mylonite schist)	Visible to naked eye
<50			Mylonite	Phyllonite (variety)		
30	Fault gouge	Cataclasite			Blastomylonite	>0.2mm
>10						
<10			Ultramylonite			<0.2mm

All rocks are gradational

from Higgins (1971)

equivalents of the sediments and the Skagit gneisses are slightly recrystallized protocataclasites. The areas around some small faults exhibit unique mechanically deformed rocks, usually being some type of foliated muscovite-rich rock or slightly serpentinized breccia. When seen in road cuts, the small shear zones are represented by shallow depressions where the softer fault gouge has been selectively removed. Almost invariably, some textural variety of quartz-muscovite-graphite phyllite occurs within the fault zones. The more intense the shearing, the more cataclasized and graphite-rich the phyllites in the shear zones are. Mylonites in some of the fault zones have been metamorphically differentiated, separating the more silicic minerals from the others. The most noticeable of these is in the shear zone near Lake Louise where the rock is a mylonite of 75% quartz, 10% albite, and 15% hematite.

Shuksan Metamorphic Suite

Quartz-Muscovite-Graphite Phyllites

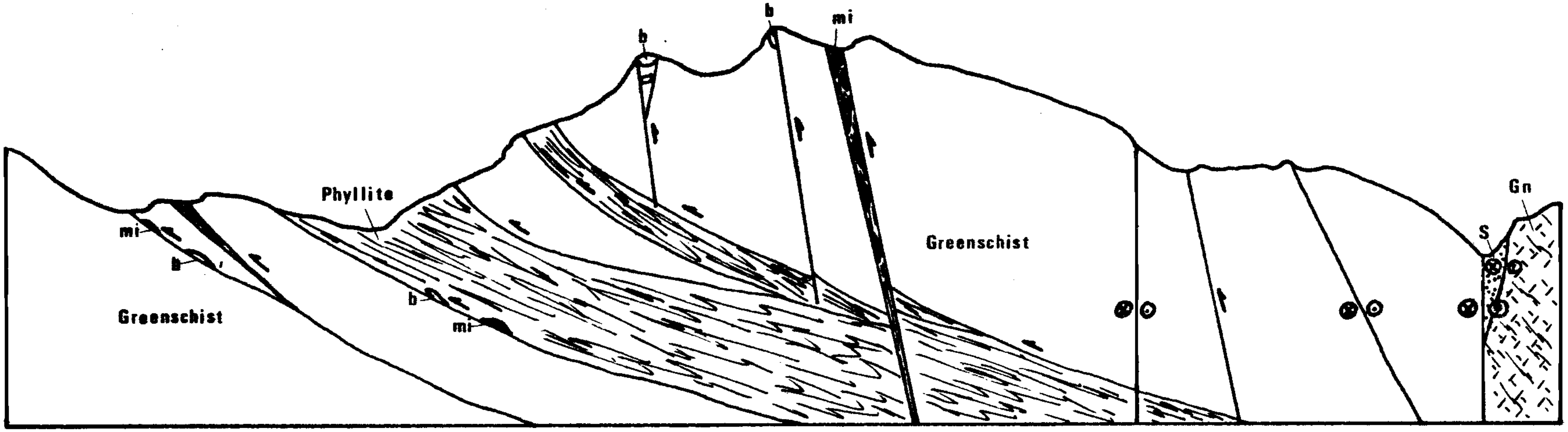
Field Descriptions and Relationships. The quartz-muscovite-graphite phyllite (hereafter, the phyllite) occurs in very poor, highly weathered outcrops and is generally responsible for gentle slopes. The best outcrops are found in road cuts on the Illabot Road (F. S. road 347) and the Illabot Peaks Road (F. S. road 3414) in the northwestern section of the thesis area and on the West Boundary Road in the southwestern corner of the field area. Several of the deep creek gullies, especially on the east side of White Creek, contain excellent exposures. Elsewhere, most exposures are very poor.

The main occurrence of the phyllite is in a broad north to northeast trending belt in the western portion of the thesis area where, unfortunately, the outcrops are mostly covered by glacial and slope debris and a very dense forest growth. The belt extends the length of the thesis area, varying in map width from 1,400 m at the southern end to around 100 m at the northern end. The southern portion of the belt has been displaced 1,100 m to the southeast by a right lateral tear (?) fault. All other occurrences of the phyllite are found in fault zones throughout the area and are often associated with exotic blueschist pods, Swauk sediments, and partially serpentinized meta-igneous pods that have been tectonically emplaced. These are often mylonitized and brecciated phyllites that vary widely in outcrop size, the widest occurring along the large subvertical northwest trending fault that is just west of Illabot Peaks.

Invariably, the contacts between the phyllite and the other units are sheared. The foliation of the phyllite is warped such so that it approaches parallelism with the contacts of the adjacent units within a few meters where the contacts are discrete. The only places where the contacts are other than sharp are in small shear zones. In such zones, the phyllite and the contacting unit (usually a greenschist, have been brecciated with the contact up to a meter wide. Small serpentinized meta-igneous pods, blueschist fragments, and small greenschist blocks appear to have been cold emplaced within the more ductile phyllite. Most zones of phyllite in which the exotic blocks have been emplaced are vertical to near vertical in dip with the attitude of the phyllite foliation sub-parallel to that of the zone. (See Figure 2.)

The western contact of the phyllite belt, when seen, is highly irregular, consisting of a series of greenschist, blueschist, and meta-igneous pods emplaced along the margins of the Shuksan thrust. In cross section, the main portion of the phyllite unit is a concave upward, steeply northeast dipping belt that is roughly 500-700 m thick, though some of the width may be caused by imbrication of the thrust contacts. The dip of the phyllite belt flattens eastward with depth, ranging from 60° -70° at the 4, 000 ft. elevation to nearly horizontal at the 1, 500 ft. elevation. Several large eastward dipping greenschist blocks are found within the belt.

The small slices in the Straight Creek fault, which separate the heterogeneous gneisses east of the fault, the greenschist, and the Swauk sediments also contain highly brecciated and mylonitized quartz-muscovite-graphite phyllite. The phyllite has been pulled up along the fault contacts and is less than 50 m wide



b—blueschist fragments

mi—meta igneous pods

Gn—Skagit Gneiss

S—Swauk Fm.

Figure 2. Diagramatic Location of Rock Units

at its widest occurrence. The other phyllite zones are only a few meters wide. The angles of dips of the contacts are unclear, but they are probably near vertical. Bryant (1955 Ph. D. thesis) described the quartz-muscovite-graphite phyllite in the region of the Straight Creek fault as being pebble-bearing and interbedded with the other units along the fault. Evidently, Bryant did not recognize the mylonitized and brecciated nature of the phyllites in the area.

The phyllite unit has a dark grey to black color with a silvery sheen imparted by the distinctive appearance of muscovite (actually determined to be sericite by x-ray analysis). Generally, discontinuous quartz bands and pods (1 to 20 mm thick) with some minor albite bands alternate with dark graphite and sericite layers to give the rock a banded appearance. In the least deformed phyllites, the banding parallels S_1 and is probably the result of transposition of primary sedimentary layering enhanced by metamorphic differentiation. The quartz and albite pods are generally elongated with their long axes parallel to the dip of the foliation. The degree of induration varies from very poor in quartz-poor rocks to hard in quartz-rich ones.

The phyllite is nearly uniform in composition throughout the area under investigation. Minor variations include a phyllite found at the 4, 680 ft. level in the stream that heads at Lake Louise and one along a small fault in the valley of Grade Creek. The phyllite near Lake Louise is noticeably more micaceous and quartz-rich than in other areas and has apparently been tectonically emplaced. This unit is discussed in more detail in the section on petrography. The phyllite near Grade Creek is extremely soft and composed almost completely of graphite with some minor quartz and is probably related to intense shearing action from the Straight Creek fault zone.

The phyllite has an extremely well developed and very closely spaced S_1 foliation that is often highly contorted and crumpled. The close examination of a phyllite outcrop reveals that the contortions represent three, and perhaps all four, folding episodes discussed herein. (See structural geology section.) Texturally, the phyllite varies greatly; from highly cataclasized tectonic breccias found near the Straight Creek fault, to highly folded outcrops in the north-northeast trending phyllite belt in the western portion of the field area.

Petrography. The typical quartz-muscovite-graphite phyllite is composed of a relatively small mineral suite. The phyllites may contain:

Major minerals	% range	% average
quartz	10-75	60
muscovite (sericite)	10-36	15
graphite	5-20	15

Major minerals	% range	% average
albite	1-40	difficult to determine, usually about 6
Chlorite (penninite)	1-25	4

Minor minerals

spessartite (?) garnet	leucoxene
hematite	apatite
magnetite	clinozoisite
actinolite	stilpnomelane
sphene	epidote (rarely)
pyrite	

Quartz is the most abundant mineral, occurring in quartz bands and elongate lensoidal pods or irregular aggregates composed of mosaics of quartz grains. The quartz grains may be up to 0. 3 mm in diameter with the pods being up to 2 cm across. The quartz-quartz grain boundaries are usually irregular and slightly embayed. The quartz grains outside the pods are quite small, 0. 15 mm in diameter or less, and have been recrystallized. Deformation lamellae are present but not abundant. The quartz grains are preferentially elongated in the foliation plane. Many of the large quartz clumps or pods have graphite and sericite wrapped around them. In some sections, the pods are rounded aggregates of recrystallized quartz, and in others, the pods are irregular and are composed of recrystallized quartz and albite. The majority of the quartz pods are probably transposed metamorphic quartzose beds separated by argillaceous material. The quartz-albite pods often delineate relict synmetamorphic fold noses. The sections exhibit irregular pods of quartz-albite aggregates immersed in the graphite-sericite matrix that are interpreted as tectonic breccias. The breccias often exhibit slightly rotated fragments and probably developed from the transposed lenses after intense shearing from the Shuksan thrust.

Most rocks have abundant sericite, but along shear zones sericite may make up the vast majority of the rock. The sericite occurs as long, thin plates that have grown parallel to the S_1 foliation. The individual mica plates have been bent by the later folding episodes and have commonly been kinked, indicating a pretectonic and probably synmetamorphic origin.

Graphite, though characteristic of the phyllites, never makes up more than about 20% of the rock except along shear zones where it is locally very abundant. Brandis (1971) related the degree of disorder of graphite (through x-ray diffractometer studies) to metamorphic grade with a fully ordered graphite not appearing until the amphibolite facies. Though my own x-ray diffractometer analyses were unclear, it does appear that the "graphite" in the phyllites is not completely crystalline and is a relatively unordered amorphous carbonaceous material with a graphite structure. It usually occurs interbedded with the sericite in discrete layers that parallel the foliation.

Albite in localized areas may make up a considerable proportion of the rock but it is usually very minor and difficult to distinguish from quartz. The albite may exhibit polysynthetic twinning, though it is never abundant.

The phyllites generally contain very little syntectonic chlorite (penninite variety) and that which exists is usually in very small plates. The rocks containing the most chlorite occur near fault zones. Anomalous "Berlin blue" interference colors are commonly seen. A yellow to yellow-green chlorite occurs as a post-tectonic mineral.

Accessory minerals include hematite, magnetite, pyrite, sphene, leucoxene, actinolite, apatite, clinozoisite, spessartite(?) garnet, stilpnomelane, and rarely epidote. The stilpnomelane (red to red-brown in color) occurs mostly as a post-tectonic mineral that fills in the fractures. Calcite, while common in the greenschists and the blueschists, is not present.

Metamorphic Facies. Winkler (1974) defines a metamorphic assemblage only by those minerals that are in direct contact with each other. By that definition, the typical assemblage for the quartz-muscovite-graphite phyllite includes quartz-sericite-graphite-albite-actinolite ± sphene. Stilpnomelane, in most cases, is post-tectonic and not included. Clinozoisite may be included in the assemblage but it is only minor. Epidote is present, though minor, and may be included in the mineral assemblage. No lawsonite, soda amphiboles, or any other higher pressure minerals were seen. Therefore, the assemblage would place the phyllite within the chlorite zone of the greenschist metamorphic facies, according to Turner (1968).

One notable occurrence of a very different (tectonically emplaced?) phyllite lies approximately 100 m west of Lake Louise. The sample at this locality contains up to 36% sericite, 60% quartz, and the only abundant spessartite(?) garnet in the area. The small garnets are contained in the sericite rich layers. Franklin (1974) interpreted a similar rock in his thesis area as associated with shear zones and brecciated meta-igneous rocks and concluded that the rocks are of a higher metamorphic grade than the adjacent Late Paleozoic(?) meta-sediments. Kurata and Banno (1974) note a politic schist in the Sanbagawa metamorphic terrane that is similar to this garnet-bearing phyllite. Kurata and Banno attribute the garnet-bearing pelitic schist to what they term Zone C of the greenschist facies. Zone C is a higher grade than the typical chlorite zone but not equivalent to the lower pressure Barrovian zone. If a comparison can be drawn between the Sanbagawa rocks and the quartz-muscovite-graphite phyllites, it can be deduced that there are at least two dfifferent metamorphic facies represented in the phyllite.

The above greenschist facies assemblages have their origins, according to Turner (1968), from pelitic to semi-pelitic sedimentary rocks. The original rocks probably contained interlayered clays and fine-grained quartz-rich layers that were more completely segregated upon metamorphism to yield the common metamorphic banding in the rocks. The abundance of pelitic material and quartz is typical of a greywacke. Bryant (1955) assigns the rocks to a Na_2O rich "micro-greywacke" or "submicrogreywacke" origin.

Age and Possible Correlation with Other Units. Though the phyllite is similar in appearance to highly sheared members of the Middle Devonian to Middle Permian eugeosynclinal rocks of the Chklliwack Group, the correlation does not appear likely. Franklin (1974) implies that the metamorphic grade of the phyllite unit is slightly higher than the Chilliwack Group and that it has more similarities with the Darrington Phyllite. Misch (1966) and Vance (1957) assign the phyllite to the Darrington Phyllite. Misch (1966) describes the Darrington Phyllite, which may be upwards of 3,000 m thick, as pelitic and semi-pelitic, quartz-rich phyllites that grade into feldspathic metagreywackes so that a correlation with the phyllite unit in the Illabot Peaks area does not seem unreasonable. Differences in outcrop appearance can be explained by the intense cataclastic deformation of the phyllite. In regions to the south of the Illabot Peaks area (Lawrence, person. commun.) rocks of the Chilliwack Group contain small clastic fragments of what appears to be

Darrington Phyllite. The differentiation, though, is not clearly established. Misch (1966) notes that the retrograde mylonitization of Shuksan phyllites and simultaneous cataclastic deformation of the Chilliwach Group rocks have locally resulted in a metamorphic convergence of the two units.

The age of the Shuksan metamorphic suite is not clearly established but Misch (1966) believes that the depositional age is Paleozoic and is probably pre-Middle Devonian. According to Misch, the metamorphism of the Darrington Phyllite and the Shuksan Schist were simultaneous with K-Ar dates of 218±40 and 259±8 million years (Permian to Early Triassic) on the Shuksan Schist. Whole rock ages of mid-Cretaceous for the phyllites can be correlated with dynamic metamorphic recrystallization caused by the Shuksan thrust subsequent to the main Permo-Triassic metamorphism.

Greenschist (Types 1-4)

Field Descriptions and Relationships. The greenschists form spectacular cliff exposures up to 300 m high. The most notable is the narrow, nearly east-west trending ridge in the center of the field area. Outcrops in the lower valleys are obscured by rock slides, glacial till, and thick forest cover. The contact with the quartz-muscovite-graphite phyllite is usually represented by a sharp break in slope.

The Shuksan greenschist contains a wide variety of textural and compositional types. Four broad categories of these are crudely mappable. Type 1 consists of massive, poorly foliated to non-foliated greenschist. Type 2 is a soft, well foliated, actinolite and chlorite rich greenschist. Type 3 is made up of albite-quartz banded, chlorite-rich greenschists. Type 4 is a soda amphibole-bearing greenschist. These are gradational and are not sharply distinguishable from one another. Other minor variants occur.

The type 1 greenschists are poorly foliated to nonfoliated rocks that make up about one quarter to one third of the total greenschist outcrop area. They are green to dark blue-green in color, and are generally very fine-grained but somewhat coarser than the other greenschist types. Type 1 is extremely hard and very dense, but it is often fractured to such an extent that foliation readings are impossible. Albite-quartz lenses commonly occur as very narrow discontinuous stringers and rootless fold noses parallel to the S_1 foliation. The albite-quartz lenses occur within a matrix of chlorite, epidote, and small albite-quartz pods. Small albite-quartz boudins elongated parallel to the lineation occur. The albite-quartz lenses generally are made up of irregular particles (up to 5 mm in diameter) that appear to have a cataclastic origin. In contrast to the other greenschist rock types in the area, the massive greenschists are not banded in appearance, though the rocks may exhibit areas slightly enriched in chlorite. Epidote occurs as small pods and discontinuous lenses that vary widely in abundance. The epidote occurs in a manner similar to the albite and quartz and is often interlayered with them. Calcite is very abundant both as a fracture-filler and as cross-cutting veinlets. Quartz veins occur, but are not abundant. Post-tectonic pyrite cubes are commonly scattered throughout the rock.

The most notable occurrence of the type 1 greenschist is in a zone roughly 1 km wide west of the Straight Creek fault. The outcrops in this zone generally form massive cliffs overlooking the fault valley. The small slivers of greenschist east of the main fault trace are also type 1. Other occurrences of the rock type are sporadic, but appear to be closely associated with major fault zones, especially near the margins of the Shuksan thrust. Characteristically, the type 1 greenschists are slickensided and slightly serpentinized and generally appear to be dominated by a cataclastic texture. A good foliation is not present.

The type 2 greenschists are soft well-foliated, actinolite and chlorite rich rocks that are very distinctive in appearance, but make up a very small percentage of the total greenschist outcrop area. The rocks are light green to light blue-green in color. Large bands of quartz or albite are absent. Thin (1 mm or less) albite bands are present, but they are generally rare. Epidote, if present, is very minor. These well foliated greenschists can be distinguished by their remarkable homogeneity in appearance, the foliation of the type 2 greenschist is extremely well developed with parting occurring very easily along the foliation plane.

The type 2 greenschists are extremely restricted in occurrence, apparently occurring as pods or interlayers among the other greenschist types, but the contact relationships are not clear. The most notable occurrence is on the valley floor south of Illabot Peaks within the northwest trending high angle reverse fault zone in that area. Evidence for fault emplacement is only by association and is very scanty due to the extensive snowfields in the area most of the summer. The unit does not appear to be in contact relationship with the quartz-muscovite-graphite phyllite. On the western edge of one of the branches of the Shuksan thrust near the Suiattle Mountain Road, an extremely well foliated greenschist occurs, but it does not appear to have more than superficial similarities to the type 2 unit near Illabot Peaks. The well foliated greenschist near the thrust contact appears to be a product of intense shearing. The rock has abundant sericite and only exhibits a shear foliation.

The most abundant greenschist rock, type 3, is not actually a single lithological type, but, rather, a series of lithologies that can best be described under one category. It makes up two thirds to three quarters of the total greenschist outcrop area. These rocks vary from a light green to a very dark green to a light blue-green depending upon the ratio of chlorite to quartz-albite to amphibole. Most rocks are slightly tinted blue, but this is a function of the fine grained quartz content rather than the presence of a soda amphibole.

The type 3 greenschists are commonly fractured, poorly to well foliated, and generally fine grained. The S_1 foliation is created by the alignment of the platy chlorite minerals and the elongated amphiboles. No relict igneous textures were seen.

In the greenschists, unlike the phyllites, albite appears to be dominant over quartz. Albite-quartz bands and pods are very abundant and are characteristic of type three. Bands range from several centimeters to a fraction of a millimeter in thickness. Locally, the albite and quartz may make up the dominant fraction of the rock. The pods, which are mostly albite, are lensoidal in shape and can be in excess of 10 cm in length. Epidote pods are not a major feature of the greenschists, but are locally abundant. The epidote pods may occur in pods or boudins in the same manner as the albite-quartz pods or as localized epidote rich bands. The albite, quartz, and epidote pods have had the S_1 foliation slightly wrapped about them and are at least partially caused by the attenuation, "smearing out," and rotation of the intrafolial fold noses. The pods are also characteristically broken into angular fragments that are strung along the strike of the foliation. Narrow cross-cutting quartz veinlets occur and post-tectonic calcite is very common, sometimes making up as much as 20% of the rock. Post-tectonic pyrite cubes are common in some rocks.

The type 3 greenschist occupies the majority of the ridge outcrops. Almost invariably, the contacts between the greenschist and other units are the loci of intense weathering effects and are covered by slope or forest debris. When seen, the contacts between the greenschist and the phyllite are sheared with a serpentinite sometimes squeezed up between the two units. As a fault is approached from a few meters in distance, the greenschist usually shows some increase in ductile deformation or is brecciated. Little deformation is noted near small faults. As discussed in the section on structural geology, the greenschist represents, essentially, several large homoclinal tilt blocks that are up to 1 km thick. The structurally higher portions of the tilt blocks are occupied by the type 3 greenschists.

The type 4 greenschists occur in outcrops similar to the type 3 rocks. The best exposures occur in road cuts in the northwest sector of the field area. Typically, the soda amphibole-bearing greenschists (type 4) are blue-grey to grey-green in color, though they may be similar to the other greenschists in appearance. The rocks are very fine-grained with a well developed foliation. Thin albite bands parallel to the foliation planes and small, slightly rotated albite pods occur, but are characteristically rare. Visible quartz grains are non-existent or very minor. The abundance of epidote, which averages about 30% of the rock, is a very distinctive feature of the soda amphibole-bearing rock. The epidote occurs as small grains interspersed throughout the rocks, as epidote rich bands, or as elongated pods or boudins. The foliation wraps about the pods of epidote. Concentrations of epidote occur in the rootless fold noses of the intrafolial folds and typically mark the presence of the folds. Calcite is generally absent. The soda amphibole appears as blue-black to black layers in the schists, though individual grains are much too small to be identified in hand specimen. Oxidized pyrite cubes are common.

The type 4 greenschists occur in the western section of the field area. The most readily distinguishable outcrops are in the northwest portion of the area east of the phyllite. This unit is separated from the phyllite by the eastern branch of the phyllite belt. The soda amphibole greenschists appears to grade upward into the type 3 greenschist and occupy the structurally lower portions of the homoclinal tilt blocks. In the center of the phyllite, a small tectonically emplaced eastward dipping sliver of the type 4

Mineral	Greenschist Type 1	Type 2	Type 3	Type 4	Phyllite
pistacite	M+	M+	M+	M+	m-
penninite	M+	M+	M+	M+	m+
actinolite	M+	M+	M+	M+	m+
albite	m+	M+	M+	M+	m+
quartz	M+	m+	m+	m+	M+
sericite			m-	m-	M+
calcite	M+	m+	M-	m+	
leucoxene	m+	m+	m+	m+	m-
sphene			m-	m-	m-
magnetite	m+	m+	m+	m+	m-
hematite	m+		m+	m+	m-
pyrite			m-	m-	m-
stilpnomelane	m-		m-	m-	m+
apatite			m-	m-	m-
zircon			m-	m-	
graphite			m-	m-	
hydrous iron oxide	m+	m+	m-		
soda amphibole	m-		m-	M+	
clinozoisite					m-
spessartite(?)					M-

M+	Major mineral - nearly always present
m+	Minor mineral - nearly always present
M-	Major mineral - occasionally present
m-	Minor mineral - occasionally present
blank	Not present

Figure 3. Mineralogy of the Shuksan Metamorphic Suite.

greenschist occurs, bounded on all sides by thrust contacts. The relationship of the soda amphibole greenschists to the other units in the southwest portion of the thesis area is not clear. It does appear that the type 4 greenschists are completely interlayered with the other greenschists and that they are in fault contact with the phyllites.

Petrography. Because there appears to be a mineralogical basis for separation, the greenschists will be discussed in two groups: 1) types 1-3 and; 2) type 4.

Greenschists of types 1-3 are composed of the following minerals:

Major minerals	% range	% average
epidote (pistacite)	1-60	8
chlorite (penninite)	13-82	50
actinolite	4-25	12
albite	10-50	25
quartz	0-15	5

Minor minerals	
leucoxene	hydrous iron oxide
sphene	sodic actinolite
magnetite	sericite
hematite	pyrite
apatite	zircon
calcite	stilpnomelane

On the average, the penninite variety of chlorite is the most abundant of the greenschist minerals. It occurs in thin platy masses, with their basal sections parallel to the foliation plane. Unlike the chlorite in the quartz-muscovite-graphite phyllites, the chlorite in the greenschists does not show the anomalous "Berlin blue" interference colors. Though highly variable in abundance, it imparts a strong schistosity to the rocks with discrete bands of chlorite averaging 0.075 mm or less wide. Microcrystalline calcite, kaolinite, and some of the iron oxides are commonly interbedded with the chlorite layers. The chlorite is synmetamorphic.

Albite occurs as irregular grains, bands parallel to the foliation plane, in discrete grains interspersed throughout the rock, or as rounded or irregular aggregate pods. The albite bands, in many sections, trace out relict F_1 intrafolial fold noses. The size of the albite grains is highly variable, ranging up to 2.5 mm in diameter. Polysynthetic twinning of the albite is common and often well exhibited and was probably the result of mechanical twinning. The albite grain boundaries are usually irregular and intermediate between lobate and dentate, indicating frozen mobile boundaries of the grains. Spry (1974) suggests such irregular boundaries may be caused by crushing and then recrystallization. The albite pods are actually aggregates of quartz, albite, some calcite, and perhaps some actinolite. The rocks or regions of rocks that contain the albite pods generally have less chlorite, fewer coarse albite grains, less actinolite, and much more epidote than the other areas. As a general rule, the percentage of albite increases in a section as the amount of actinolite decreases.

Quartz is a minor constituent of most greenschists. Thin quartz veins that cut across the foliation are present though not common. Quartz-quartz and quartz-albite boundaries are irregular and slightly embayed to lobate.

The actinolate present in the greenschists is generally the green ferroan variety, though minor, blue-tinted, Na rich actinolite is present in some sections. The content of actinolite is variable with the largest percentage occurring in the type 2 greenschists in the valley south of Illabot Peaks. It commonly forms as segmented, elongate prisms, with the long axes arranged in the foliation plane to yield a very strong amphibole lineation. The actinolite is very small, usually 0. 03 mm wide and up to ten times as long. Though not clearly discernible, it appears to be zoned, in some examples, from a green ferroan core to a blue-tinted sodic rim (cf. Misch, 1969, and Franklin, 1974). The actinolite is usually interwoven with the chlorite layers.

Epidote is usually of the nearly colorless iron-poor pistacite variety and is generally not zoned. At least one section exhibits a slight outward zoning to a green ferroan epidote. Epidote commonly occurs as small, discrete, irregular particles interspersed throughout the rock, as highly fractured, rounded prophyroblasts, or rarely as aggregate clumps of anhedral grains. Though it can locally make up a large proportion of the rock, epidote normally does not exceed 10%. In most sections, epidote occurs as fractured, irregular grains around which the S_1 foliation wraps. The grains may be slightly rotated and may show excellent pressure fringes of quartz and chlorite. In most of the greenschists, the epidote is altered to a hydrous iron oxide and has been replaced by microcrystalline calcite. The epidote predates most tectonic activity in the area.

Calcite is very abundant in the greenschists, commonly occurring in coarse post-tectonic veins or as a replacement epidote or feldspar, though some calcite is a a metamorphic product. Near fault zones, it may make up more than 20% of the rock. It can be twinned. Stilpnomelane usually occurs in fractures that cut across the foliation, but it can also occur as growths parallel to the foliation, indicative of a primary metamorphic origin. Sericite, though rare, is bent by the folding of the rocks, indicating a possible pre-tectonic origin. Sphene is present, though it has usually altered to leucoxene. Magnetite, sodic actinolite, apatite and zircon also occur in the greenschists.

The relative proportions of the major minerals vary widely, though generally the dominant minerals in decreasing order are chlorite, albite, epidote, and actinolite.

The type 4 greenschists contain the following minerals:

Major minerals	% range	% average
albite	5-35	25
epidote (pistacite)	5-60	35
chlorite (penninite)	5-45	25
actinolite	1-18	10
soda amphibole	2-20	?
quartz	0-15	less than 5

Minor minerals

leucoxene	hydrous iron oxide
sphene	sodic actinolite
magnetite	sericite
hematite	apatite
pyrite	zircon
calcite	stilpnomelane

The type 4 greenschists differ only slightly from the other greenschist types. The epidote, typically, makes up a larger proportion of the soda amphibole greenschists than in the other types. The epidote may be slightly rotated, rounded prophyroblasts with pressure fringes of albite and actinolite. Epidote and chlorite are inversely proportional to each other in abundance. All other minerals, both major and minor, with the exception of the soda amphiboles, are similar to those in the other greenschists. The soda amphibole can be crossite, glaucophane, soda actinolite, or all three together. When grains are large enough to be identified, the blue amphiboles are typically zoned from cores of glaucophane or crossite to outer rims of green actinolite. The soda amphibole commonly occurs as segmented elongate prisms or platy masses. The soda amphiboles never occur alone; at least two blue amphiboles occur in a thin section. Either crossite or glaucophane may be the dominant blue amphibole. The soda amphibole content is highly variable. It usually occurs in discrete bands interlayered with the chlorite-actinolite bands. The soda amphibole bands are relatively poor in actinolite and are commonly separated from the albite-quartz-epidote-rich bands. Where the contacts between bands are observed in thin section, they are gradational with the chlorite bands becoming increasingly rich in blue amphibole with the distance away from the contact. Brown (1974), Misch (1969), and Vance (1957) discuss the soda amphiboles in detail and should be consulted for greater detail on the types of occurrences and zoning.

Metamorphic Facies. The metamorphic mineral assemblages in the greenschists of type 1-3 are nearly the same as for the quartz-muscovite-graphite-phyllite. The typical assemblage includes chlorite (penninite)-epidote-(pistacite)-albite-actinolite-quartz + calcite ± stilpnomelane. Sphene, altered to leucoxene, sodic actinolite, and sericite are present and may be part of the assemblage, though the relationship of these minerals to other minerals is not clear. The above assemblage, according to Turner (1968) would place the rocks in the chlorite zone of the greenschist facies. The original rock was a mafic igneous rock, probably basalt, and associated sediments. The slight zoning of the epidote and the alteration of the epidote to a hydrous iron oxide hint at possible retrogressive metamorphic effects.

With the addition of the soda amphiboles, the minera assemblage for the type 4 greenschist is the same as for the other greenschist types. The addition of lawsonite and/or glaucophane to the chlorite-epidote-albite-actinolite-quartz±calcite±stilpnomelane would push the facies into the greenschist-lawsonite-glaucophane schist transitional facies as indicated by Turner (1968). According to Brown (1974), the presence of epidote with glaucophane or crossite indicates the blueschist facies. Brown also suggests that the presence of soda amphibole is related to a high ferric iron content and a high oxygen partial pressure (P_{O_2}). The complex intergradations of the glaucophane-crossite portions of a rock may be caused by changes in the iron oxide content and oxygen partial pressures. The blueschist-greenschist intercalations do not necessarily imply changes in the T/P regime or metamorphic grade. Localized high P_{O_2} and high ferric iron content could just as easily cause pockets or lenses of soda amphibole schists in a greenschist terrane. It is not clear whether the differences in oxygen partial pressures were primary or induced at some later time. Vance (1957) holds that the greenschists and the soda amphibole greenschists represent an isochemcial series that formed under uniform physical conditions. The differences in rock types are attributed by Vance to early metamorphic differentiation of iron into iron-rich layers. Vance believes that unpublished chemical analyses by Misch indicate that no Na metasomatism took place and that the Na is bound up in the albite and the soda amphiboles. The outward zoning of the soda amphiboles to a ferroan actinolite and the alteration of the epidotes to a hydrous iron oxide suggest either slight retrogressive metamorphic effects or a change with time to a lower P_{O_2} and ferric iron content. The first possiblity is more probable.

Age and Correlation. The greenschists in the Illabot Peaks area are believed by Misch (1966) to be part of the Shuksan Schist (type locality is Mt. Shuksan, Washington) which, along with the Darrington Phyllite, belongs to the Shuksan metamorphic suite. The Shuksan Schist is believed to be more than 1.5 km in thickness and extends from just south of the Canadian border near Mt. Shuksan to over 150 km south along strike to south of White Chuck Mountain. Rocks of the Easton Schist are described by Vance (1957) as being similar in the Shuksan Schist and are known from areas southeast of

Snoqualmie Pass, approximately 160 km south of Illabot Peaks. Vance (1957) cites unpublished chemical analyses by Misch that indicate that the Shuksan Schist formed by regional greenschist metamorphism of large volcanic flows and interbedded sediments. The original volcanic rock exhibits a chemical composition similar to olivine-free calc-alkaline basalts or basaltic andesites.

According to Misch (1966), no unmetamorphosed equivalents of the Shuksan Schist are known, but they do have similarities to the Late Paleozoic basalts of the Chilliwack Group. The Shuksan Schist is believed to be co-depositional with the Darrington Phyllite with both being deposited probably before the Middle Devonian. There is the possibility that the Shuksan suite predates the Chilliwack Group in depositional age.

The age of Shuksan metamorphism is not clearly established, but Misch (1964) has two K-Ar dates of 218± 40 and 259±8 million years (Permian to Early Triassic) for the metamorphism of the units. Some recrystallization and cataclastic deformation of the greenschists occurred during the mid-Cretaceous movements on the Shuksan thrust.

Blueschist Tectonic Fragments

Field Descriptions and Relationships

The blueschist tectonic breccias occur in very restricted outcrop localities. The only outcrops are in road cuts in the western portion of the map area and very deep canyon cuts. Normally, these tectonic breccias are found in fault bounded pods that are 10-15 m long and lenticular in shape.

Most of the tectonic pods are highly jumbled and crumpled with no obvious structures other than the serpentinized slickensides. Some pods, on the other hand, contain good amphibole lineations and may e xhibit a shear foliation. The breccias have a very dark green to blue-green fine-grained matrix composed chiefly of chlorite and dark amphibole layers. Large irregular epidote fragments and hydrous iron oxide fragments that have been altered from the epidote are contained within the chloritic matrix. Vein quartz and vein calcite are abundant and commonly fill fractures. Angular fragments of quartz are also present. A high degree of induration and a high specific gravity are characteristic features of the breccia pods.

The blueschist tectonic fragments are confined to the margins of the branches of the Shuksan thrust and the associated subvertical reverse faults. The pods most commonly occur along the sole of the thrust plane or are bounded by near-vertical shear zones. The breccia pods have mostly been squeezed up in the ductile quartz-muscovite-graphite phyllite that occupies the spaces between the shears. The pods appear to have been tectonically cold-emplaced because the margins of the pods are very discrete, do not interfinger or grade into the phyllite, and are highly slickensided. The foliation of the phyllite is usually wrapped about the pods with the long axes of the pods arranged down-dip of the foliation.

Petrography

The blueschist tectonic fragments generally contain the following minerals:

Major minerals	% range	% average
epidote (pistacite)	5-54	53
soda amphibole	15-29	24
chlorite (penninite)	1-10	9
actinolite	1-15	2
hydrous iron oxide	0-10	5
quartz	3-10	4
albite	2-40	3

Minor minerals	
magnetite	stilpnomelane
pyrite	graphite
hematite	calcite
leucoxene	

The tectonic fragments are fairly uniform in composition except for the pods that are found just east of Suiattle Mountain near the West Boundary Road. Near the road, the pods contain less epidote but more actinolite and albite than at the other localities.

The predominant mineral is an epidote that is an iron-poor pistacite variety. It most frequently occurs as rounded to angular clumps of aggregate epidote grains, but it may occur as rounded porphyroblasts. The epidote porphyroblasts are commonly highly fractured, slightly rotated, and may be wrapped about by the platy minerals. Chlorite occurs as pressure fringes about the epidote porphyroblasts. Zoning is not clearly established. Commonly, the epidote is being altered to a blood-red hydrous iron oxide. Locally, the hydrous iron oxide may make up 10% or more of the rock and can totally replace the epidote.

The tectonic pods characteristically contain approximately 20% soda amphibole. The soda amphibole occurs as platy sheaths, often filling interstitial spaces between other minerals. It is usually zoned from cores of glaucophane or crossite to rims of a green actinolite. The dominant soda amphibole is a deep blue crossite.

Actinolite is generally a minor mineral. When it occurs separately from the soda amphiboles, the actinolite is in long, slender, segmented prisms of the non-ferroan variety.

Chlorite is generally of minor importance and, where present, is usually penninite. The chlorite, along with the platy amphiboles, imparts what little foliation structure that there is to the breccias.

Quartz occurs as thin veins or irregular fragments and is typically slightly more abundant than albite. The quartz, along with the albite, may occur in the aggregates of epidote.

Albite, though normally less abundant than quartz, may comprise as much as 40% of the rock, with the albite increasing as the epidote decreases. The occurrence of albite is similar to that of quartz.

Post-tectonic calcite is very abundant in he tectonic breccias and may be coarsely crystalline. Minor primary calcite may also be present. Stilpnomelane and a yellow chlorite may also occur as minor post-tectonic minerals. Magnetite, hematite, pyrite, and leucoxene also occur. Examination of thin sections suggests the possible presence of small amounts of jadeite, but attempts to separate it for x-ray analysis failed.

Most tectonic breccias have a non-foliated appearance. The only dominant texture is an elongate amphibole lineation.

Metamorphic Facies

The presence of soda amphibole combined with abundant epidote and the dominance of crossite over the other soda amphiboles indicates a higher pressure metamorphic grade than the typical greenschists. As mentioned earlier, the presence of glaucophane or crossite with epidote in an otherwise typical greenschist facies rock indicates the lawsonite-glaucophane schist facies. The outward zoning of the blue amphiboles from glaucophane to crossite to green actinolite and the alteration of epidote to a hydrous iron oxide indicate an increase in the T/P ratio and retrogressive metamorphic effects. Apparently, the tectonic breccia pods were originally a higher grade (lower T/P) metamorphic facies (lawsonite-glaucophane schist facies) that has been partially retrogressively metamorphosed to the lower grade greenschist facies.

Correlation and Tectonic Implications

Though Franklin (1974), Misch (1966), Vance (1957), and Lawrence (person. commun.) note the appearance of tectonically emplaced exotic pods of limestones, ultramafics, meta-igneous fragments, greenschists, and blueschists near the sole of the Shuksan thrust and high angle faults, no occurrences are known for the Shuksan Schist. Franklin (1974) notes that the exotic blueschist pods have been tectonically emplaced in the Chilliwack Group meta-sediments on Prairie Mountain to the south of Illabot Peaks. These blueschist fragments appear to resemble the blueschist tectonic breccias that I have found near Illabot Peaks but are not as brecciated. The blueschist breccias do not have similarities with the other soda amphibole-bearing rocks in the area (greenschist type 4) and, in fact, appear to be of a slightly higher metamorphic grade. Though the mapped occurrences of the blueschist breccias are very few, I suspect that the rocks may occur more extensively near the southern contact of the phyllite with the greenschist. The presence of the breccias in structurally lower portions of the greenschist blocks, their occurrence in high angle fault zones, their occurences on or near the sole of the Shuksan thrust, their immersion in the phyllite, and the slight retrogressive metamorphic effects that the breccias show suggest that the rocks have been brought up from a lower T/P regime at depth.

Blueschist facies rocks on or near the sole of a thrust pate are not unknown. Blake et al. (1967) describe their presence along the sole of a large regional thrust fault in southwestern Oregon and northwestern California. They ascribed the presence of the blueschists to local low T/P conditions caused by extensive underthrusting. Davis (1968) notes a blueschist, along with associated ultramafic fragments, near the Siskiyou thrust fault in the Klamath Mountains of northern California. Gresens (1969) notes, also, the common association of blueschists with serpentinites and suggests that where the blueschists are present without serpentine, an ultramafic body may have been present and squeezed out during thrusting.

Though the evidence is not clear, it appears that the blueschist tectonic breccias have been squeezed up from some depth into the ductile phyllite unit by movements on the Shuksan thrust. It is uncertain whether the blueschists form locally near the thrust contacts or represent a larger underlying rock unit. The Shuksan Schist probably can be divided into at least two mappable units of different metamorphic grade with the stratigraphically higher portions belonging to the chlorite zone of the greenschist facies and the lower areas belonging to the blueschist greenschist transitional facies or the lawsonite-glaucophane schist facies. More evidence is needed to clarify this problem.

The blueschist pods have important geometric implications for the tectonic framework of the North Cascades, suggesting a series of eastward dipping branches of the Shuksan thrust rather than a large concave-downward geometry suggested by Misch (1966). This will be discussed in more detail in the section on the meta-igneous fragments.

Mafic Meta-Igneous Fragments

Field Descriptions and Relationships

Metamorphosed mafic igneous rock fragments are present as small (less than 15 m long) tectonic fragments in shear zones and are generally poorly exposed. Three occurrences of this unit are known in the Illabot Peaks area, though it is likely that more exist. Franklin (1974) extensively discussed the meta-igneous fragments and the reader is referred to his thesis for more data. In the westernmost section of the field area along the West Boundary Road, several of the meta-igneous fragments are exposed. The fragments are dark grey to black in color, 10-15 m in length, and about one half as wide. The units are lenticular shaped pods similar in outcrop appearance to the blueschist tectonic breccias and are bounded by high angle shear zones. The pods are generally immersed in quartz muscovite-graphite phyllite. They are highly fractured, making identification difficult, though they appear to be of gabbroic affinities. A small highly sheared and serpentinized body appears northwest of Lake Tupso. The pyroxenes have been almost completely serpentinized and the rock has been cataclasized, making identification of the original rock very difficult. A highly serpentinized series of pods occur along the offset high angle reverse fault that trends northwest near Illabot Peaks. On the southern reaches of the fault, a highly ductile, well foliated green serpentinite exists. The serpentinite is in fault contact with quartz-muscovite-graphite phyllite. The original source rock is unidentifiable. Farther north on the fault, the serpentinite forms a saddle near Illabot Peaks. At this location, the serpentinite is very massive and dark blue green in color. It is bounded by (actually immersed in) the phyllite unit and encloses a small, highly serpentinized sliver that is unidentifiable, in hand specimen. All the mafic fragments are highly slickensided.

The meta-gabbros and serpentinites occur near the sole of the Shuksan thrust and associated high angle reverse faults. The quartz-muscovite-graphite phyllite, in which the mafic fragments are immersed, probably acted as a ductile lubricant through which the tectonic fragments have been cold-emplaced with the foliation of the phyllite wrapped about and distorted by the fragments. Evidence for normal igneous contacts or contact metamorphic effects does not exist. No conduits were seen.

Petrography

A general feature of the metamorphosed mafic rocks is that they are highly altered and serpentinized. They range from antigorite with minor calcite, magnetite, pyrite, and leucoxene to highly altered gabbros. The gabbros contain sericitized labradorite laths and serpentinized and chloritized pyroxenes (probably orthopyroxenes) as the major minerals. Most of the original mafic constituents are now antigorite. Post-tectonic calcite and chlorite are very common. Albite, quartz, magnetite, sericite, epidote, actinolite, and sphene may also be present. The highly altered gabbros have an ophitic texture with long slender laths of low An labradorite arranged in an almost glomeroporphyritic manner about the pyroxenes. The untwinned feldspars may be slightly zoned. Blue amphibole appear as platy masses altering from the pyroxenes and may indicate the original source of the blueschist tectonic breccias. The original rock was probably a norite. The mineral assemblages present indicates that there is some upper greenschist facies metamorphic overprinting, though no foliation or lineation structures are present. Bryant (1974) and Vance (1957) note that the mafic rocks in the Prairie Mountain area also show a greenschist facies overprinting.

Correlation and Tectonic Implication

Tectonically emplaced meta-igneous fragments are not known for any other locality of the Shuksan suite. Bryant (1974) and Vance (1957) find similar rock fragments of a variety of mafic rock types tectonically emplaced in the Chilliwack Group rocks but they have found no occurrences within the Shuksan rocks. Bryant (1974) believes that the meta-igneous fragments were tectonically emplaced after being metamorphosed prior to the metamorphism of the Chilliwack Group and, hence, the Shuksan suite. He reasons that the Shuksan suite fabric and metamorphism can not be correlated with that in the meta igneous fragments. Misch (1966) assigns similar rocks, including those near Prairie Mountain, to what he termed the heterogeneous Yellow Aster Basement Complex, which he believes to be pre-Middle Devonian and perhaps Precambrian. The Yellow Aster Complex rocks occur as allochthonous slices on the western flank of the North Cascades that have been pushed up by the Shuksan thrust. Misch believes that the latest basement rocks are intrusives of gabbro to leucocratic trondhjemites that postdate the major basement metamorphism. Mattinson (1972), has determined two original dates for zircons of the Yellow Aster Complex: 1) 1,452 to 2,000 m.y. for the older gneisses and; 2) an original age of 460 m.y. (late Ordovician) for the younger rocks of the complex and for the Turtleback Complex of the San Juan Islands. Both underwent metamorphism 415 m.y. ago (mid-Silurian) though the later rocks were affected by Permo-Triassic metamorphism to varying degrees with the allocthonous slices being the least affected.

Misch (1966) claims that the basement rocks represent old continental crust that has been displaced by thrusting from east to west. Vance (1974) prefers the hypothesis that the various meta-igneous rocks are old continental crust that has been displaced by thrusting from east to west. The meta-igneous fragments are believed by Mattinson and Hopson (1972) to represent dismembered ophiolite sequences. Franklin (1974) suggests that the meta-igneous fragments represent segments of an island arc that was positioned off North America in the early to middle Paleozoic and was incorporated into a subduction zone.

In the local tectonic framework, the position of the meta-igneous fragments in the Shuksan Schist is significant. These fragments are believed by Misch (1966) to have been dragged up from depth along the sole of the Shuksan thrust and then become complexly imbricated with the upper Paleozoic rocks of the Church Mountain thrust plate beneath it. In this imbricate zone, rocks of the Chilliwack Group, basement crystalline rocks, ultramafics, and a few slivers of Shuksan suite phyllite are complexly faulted together, breaking up, or imbricating the Shuksan and underlying Church Mountain thrusts. The presence of the meta-igneous fragments and the blueschist breccia pods in the eastward-dipping high angle shear zones and what I have mapped as the soles of thrust faults indicate that a complex imbrication of the Shuksan thrust plate (the Shuksan suite rocks) has also occurred. The phyllite unit, along the contacts of which the blueschist breccias and the meta-igneous fragments have been emplaced from depth, is described by Misch (1966) as being a series of small, tight, anticlinal folds. Complex folding could not have forced the tectonic fragments from the Church Mountain plate where they are commonly found, up into the greenschists and the phyllites of the Shuksan thrust plate. Extensive faulting must have occurred. In fact, I interpret the phyllite belt and the loci of meta-igneous fragments, which originated from depth, as representing eastward-dipping thrust contacts of what are considered as a complexly imbricated portion of the Shuksan thrust system. Such a complex series of shear zone phyllites and tilted greenschist blocks stacked together like a pile of eastward tilted plates does not allow for a westward dip of the Shuksan thrust, as Misch (1966) requires, immediately to the north and to the south of the Illabot Peaks area.

Lawrence (unpublished manuscript, and person. commun., 1975) has pointed out this inconsistency in diagrammatic form. The concave downward geometry of the Shuksan thrust does not, apparently, exist for at least within the Illabot Peaks area. The blueschist and meta-igneous fragments have been dragged upward along the bases of several eastward-dipping greenschist thrust blocks. (See Plate 2.)

Plutonic Rocks East of the Straight Creek Fault

Field Description

The rocks east of the Straight Creek fault were not studied in detail and will only be discussed briefly. The area east of the fault contains various lithological types in complex and, as yet, undetermined relationship to each other. The high ridge east of the fault predominantly contains fine-grained to very coarse-grained hypidiomorphic granular, slightly cataclasized and metamorphosed granodiorites to hornblende diorite porphyries. Hornblende phenocrysts may locally be up to several centimeters in length and may make up more than 90% of the rock. The top of the ridge was not visited but it appears to offer excellent exposures.

Farther to the west and lower in elevation, the rocks begin to definitely have a cataclastic overprint. The typical rocks in the lower elevations are very coarse-grained hornblende-garnet feldspathic gneisses, though the lithologies vary widely. The garnets are large (up to 0.5 cm in diameter) and dodecahedral in shape. The hornblende is idiomorphic and, along with the biotite present, is aligned into a very strong lineation.

Immediately in contact with the Straight Creek fault in the southwestern portion of the plutonic terrane is a wide shear zone of light brown to orange-brown cataclasized igneous rock. The rock is a protomylonite and is foliated with steep dips predominantly to the east. Apparently, other shear zones exist, but they were not mapped.

Near the Straight Creek fault, the metamorphosed plutonic rocks are in fault contact with the Swauk Formation and Shuksan Schist slivers and are separated from them by thin zones of mylonitized quartz-muscovite-graphite phyllite. Small pieces of mylonitized and brecciated gneissic(?) rocks appear immersed within the phyllites. These bodies, which appear very similar to silicic dike intrusions are too small to be accurately represented on the map.

Correlation

The gneisses east of the fault are similar in appearance to what Vance (1957) has described to the south as the heterogeneous gneiss unit. The heterogeneous gneiss unit is assigned to the Shagit metamorphic suite by Misch (1966) and Vance (1957). Misch (1966) believes that the metamorphic age is pre-Jurassic and probably pre-Mesozoic, though Mattinson (1972) implies that it could be as young as early

Tertiary (46 m. y. ?).

Swauk Formation

Field Descriptions and Relationships

Rocks of the Swauk Formation occur in a small tectonic slice in the Straight Creek fault zone. Pieces of the Swauk Formation are also present immediately to the south of the map area.

The Swauk rocks are light to dark grey in overall color and range from very fine-grained arkoses to lithic quartz arenite conglomerates. The clasts of quartz and lithic fragments may be up to 2 cm in diameter with the quartz clasts being round to angular. Small flattened grains of biotite and small feldspar particles are also present. All the coarser rocks exhibit a crude cyclical graded bedding with the grain size increasing downward, indicating no overturning of the units. The fine-grained sediments do not exhibit obvious bedding surfaces except where plant stem and leaf fossils exist. The plant fossils are roughly 7 cm long by 2 cm wide, or larger. The plants are angiosperms.

The sliver of Swauk sedimentary rocks shows no consistent structural trends or arrangement of bedding planes. The sliver is probably lensoidal in shape and may be up to 1 km long, though less than one half of it is exposed. The sliver is in fault contact with the greenschists, the phyllites, and the metamorphosed intrusive rocks east of the Straight Creek fault. Cataclasized phyllites always separate the sedimentary rocks from other units.

Petrography

The lithic arenites contain the following minerals:

Major minerals	% range	% average
quartz and chert	45-55	50
plagioclase	15	15
lithic rock fragments	20-30	25
biotite	10	10

Minor minerals

magnetite	hornblende
hematite	chlorite
pyrite	apatite
leucoxene	calcite
muscovite	

The lithic arenites are predominantly composed of quartz and lithic rock fragments. The quartz occurs as separate grains and in recrystallized rock fragments. The majority of the lithic fragments are from fine-grained phyllitic rocks and quartzites. The feldspars are usually twinned andesine laths and twinned labradorite laths. The plagioclase has been slightly sericitized and slightly deformed. The biotite occurs parallel to the bedding and has been slightly deformed.

The average whole rock grain size is greater than 1 mm in diameter (very coarse to fine sand size). The grains are angular to subangular, well sorted and very clean. The binding material appears to be mainly chert and siliceous cement. A crude bedding plane exists, mainly evidenced by the alignment of the lithic fragments and biotite.

The fine-grained arkoses contain the same suites of minerals as the lithic arenites with the addition of minor albite and hornblende with a matrix of very fine-grained, intimately mixed chlorite, kaolinite, and oxides. There is generally slightly less quartz than plagioclase and there are fewer lithic fragments in the arkoses than in the arenites. The average grain size is 0.05 mm-0.1 mm (very fine sand size). The arkose contains kinked biotites and very poorly preserved relict fluxion folds, indicating some cataclasis. In all other aspects, the arkoses are similar to the lithic arenites, and, in fact, grade into them.

Age and Correlation

The silty shales, arkoses, conglomerates, and their intergradations in the region of Prairie Mountain and the Straight Creek fault are assigned by Lawrence (person. commun.), Misch

(1966), and Vance (1957) to the Swauk Formation. Vance (1957), on the basis of angiosperm fossil leaves, assigns a Cretaceous age or younger to the unit with a probable late Upper Cretaceous to Paleocene age. Both Vance and Misch (1966) correlate the Swauk rocks with the Chuckanut Formation of comparable age and lithologies. The Swauk-Chuckanut rocks were deposited, according to Misch (1966) and Vance (1957), by streams in flood plains and locally in temporary swamps and shallow lakes in a long (approximately 160 km) narrow continental trough that extended from south of Mt. Stuart to near Bellingham.

Dikes

Field Descriptions and Relationships

Within the map area, dikes are extremely rare. Only three were recognized, and these have no consistent orientation. The dikes are grey to dark grey in color, very dense, and somewhat altered. Except where exposed in road cuts, the outcrops are usually very poor and extremely small. The two dikes west of the Straight Creek fault are relatively fresh augite diabases. The dikes are highly fractured with jointing perpendicular to the contacts. The small dike that occurs in the phyllite near the Straight Creek fault has been highly altered and is almost unrecognizable in hand specimen. The dike has abundant fractures that have been filled with secondary calcite. This dike may be a small tectonically emplaced sliver but the contact relationships are vague. Serpentinized slickensides are present in all but one of the dikes.

Petrography

The dike sectioned was found near Illabot Peaks. The minerals present include:

Major minerals	%
augite	60
labradorite	20
biotite	15
magnetite	5

Minor minerals

chlorite	apatite
microcline	actinolite
calcite	sphene
orthoclase	antigorite
sericite	

The diabase has an ophitic texture with augite enclosing large laths of labradorite that are being altered to sericite. The other feldspars are also undergoing seritization. The augite may be twinned and altered to chlorite or antigorite. The bioties have almost completely been altered to chlorite. Calcite is present as a minor secondary mineral.

Age

The age of the diabase dikes could not be determined in the field. The dikes do not show any Cascade metamorphic effects of Permo-Triassic age. Deformational effects caused by the Cretaceous Shuksan thrust or the early Tertiary Straight Creek fault are not present. The dikes are, most likely, related to early Tertiary (Eocene?) volcanic rocks found in scattered localities in the North Cascades, e. g. Vance's Barlow Pass volcanics.

Metamorphic History

The region of the North Cascades has undergone a multiphase metamorphic history. The earliest period of metamorphism involved the Yellow Aster Basement Complex. The basement rocks were divided into original age groups by Mattinson (1972): 1,452 to 2,000 m. y. for the pyroxene gneisses of the complex; and 460 m. y. for the Turtleback Complex of the San Juan Islands and for a younger ortho-gneiss of the Yellow Aster Complex. Both these rock groups have a metamorphic age of 415 m. y. The basement rocks, according to Misch (1966), were metamorphosed to the amphibolite facies at this time and possibly into the granulite facies.

The next period of metamorphism involved what Misch (1966) termed Cascade metamorphism of Permo-Triassic time. The main rocks affected were the Shuksan suite, the Skagit suite, and the rocks east of the crystalline core of the North Cascades, though some low grade overprinting occurred in the basement rocks. Shuksan suite metamorphism has been dated by Misch at 218± 40 m. y. and 259± 8 m. y. The rocks were metamorphosed at the chlorite zone of the greenschist facies to the lower portion of the blueschist at essentially low T/P conditions. The T/P ratio decreases to the west. The Skagit suite, separated from the Shuksan suite by the Straight Creek fault, is believed by Misch (1966) to have undergone chlorite zone of the greenschist facies to sodic andesine-epidote amphibolite facies metamorphism at high T/P during the latest Permian to pre-Late Jurassic time. Mattinson (1972), on the other hand, indicates that it is possible that the Skagit suite is considerably younger with a possible migmatitic age of 46 m. y.

The North Cascades underwent extensive structural deformation associated with the Shuksan thrust. Misch (1966), through regional geologic work, places this deformational episode at mid-Cretaceous. Mattinson (1972), by dates on zircons, suggests a 60-90 m. y. age date. At this time, intense cataclasis and mylonitization of all rocks near the thrust contacts occurred with the basement rocks being overprinted by a slight prehnite-pumpellyite facies metamorphism

(Misch, 1966) The quartz-muscovite-graphite phyllites, and probably some greenschists, were slightly recrystallized by this deformational episode.

The Straight Creek fault, dated by Vance (1957) at early Eocene with some probable pre-Tertiary movement, may have been active up until the Miocene (McTaggart, 1970). Very localized, but intense, cataclastic deformation is associated with the fault.

STRUCTURAL GEOLOGY

Introduction

The Illabot Peaks area is structurally complex. At least four distinct folding episodes and three periods of major faulting have been identified.

The first major deformation created intensely deformed, rootless F_1 intrafolial folds with axial planes parallel to the synmetamorphic S_1 foliation. Both axial planes and foliation strike slightly west of north and dip to the east. All other deformational episodes affect S_1 and F_1. The deformation probably occurred synmetamorphically in Permo-Triassic time.

The F_2 folds are small scale and tight, trending approximately N50°E with a moderate plunge and a subvertical axial plane. These folds are restricted to the ductile type 2 greenschist and are only slightly antecedent to the F_3 folds.

The major folding episode is F_3, consisting of open folds that trend N25° W with a horizontal plunge and vertical axial plane. The F_3 folds are large scale and dominate all other folding episodes.

Both the F_2 and F_3 deformational periods occurred during the middle to late Cretaceous thrusting of the north-south trending, eastward-dipping Shuksan thrust. This major thrust system may extend for more than 270 km with large displacements from east to west. The Shuksan thrust plate, which includes Darrington Phyllite and Shuksan Schist, has been highly imbricated, dragging up slices of basement rocks, ultramafics, and blueschist fragments along the soles of the thrusts. The stress systems that caused thrusting also produced intense cataclasis, slight retrogressive metamorphic effects near the thrust margins, and major deformation by the F_2 and F_3 folding episodes. Kink folding also occurred in the better foliated rocks during the deformational episodes. In the Illabot Peaks area, several large, essentially homoclinal, eastward-dipping blocks of greenschist have been thrust upon ductile shear zones of the quartz-muscovite-graphite phyllite unit. The imbricate slices of the thrust are concave upward and probably connect to some master thrust at depth. Many smaller high angle faults are associated with the thrust system.

Between the time of the Shuksan thrust and the onset of the Straight Creek fault (late Mesozoic to early Miocene?), right lateral strike-slip movements on NE-trending faults occurred. One of these faults bisects the Illabot Peaks area, offsetting the Shuksan thrust by 1.2 km.

The F_4 folds have predominantly large amplitudes with near vertical plunges and axial planes. This folding episode is not well exhibited in the map area. The F_4 folds and minor kinking are associated with the stress systems that produced the Straight Creek fault.

The Straight Creek fault zone of late Mesozoic to early Miocene(?) time with movement mainly in the early Eocene, forms a major discontinuity between the gneissic and granitic rocks of the Skagit suite to the east and the Shuksan metamorphics to the west. The fault is actually a complexly braided fault zone that has caught lensoidal slivers of intensely cataclasized greenschists, phyllites, gneisses, and Swauk sedimentary rocks within it. Movement, though not clearly established, was probably considerable with a right lateral sense.

Structural Analysis of Shuksan Schists and Phyllites

Introduction

Deformational episodes have not been transmitted equally throughout the Shuksan Schist and the quartz-muscovite-graphite phyllite because the units are not homogeneous. The four folding episodes (F_1-F_4) are generally not seen together in a single outcrop. Moreover, the often featureless outcrop appearance of the greenschists and the extremely contorted structures of the phyllites make the observance of large, macroscopic folds extremely difficult. Complicating an already complex problem, a few large faults, and numerous small ones, transect the Illabot Peaks area disrupting the structural trends, sometimes very completely. Intense cataclastic deformation near fault zones has often obliterated nearby structural features.

In order to overcome the above difficulties, several techniques were used. Measurements on S_1 foliation, mineral and crinkle lineations, elongate albite pods, and fold axes were taken in the field and laboratory for all rock types. The data points were separated into 27 subdomains which were grouped into three larger domains in order to separate out the individual fault blocks and differences in deformational sequences, if any. The data sequences were plotted separately on equal area stereonet diagrams to determine structural trends according to subdomain and then combined with adjacent subdomains when no differences in structural trends were noticed. Five large domains were formed; three greenschist domains, one phyllite domain, and one gneissic domain, though data east of the Straight Creek fault are sparse. Lineation data were plotted on stereonets and contoured. Kink folds from the Shuksan Schist were observed in detail, in the field and laboratory, and the principal stress directions were determined from geometric relationships and then related to larger stress systems. Optic axes of quartz were determined from oriented thin sections of quartz-muscovite-graphite phyllite, contoured on stereonets, and correlated with the tectonic framework following Turner and Weiss (1963). Individual outcrops were observed in the field and studied in detail to determine sequences of deformation. Microscopic studies of the rock units were also undertaken.

Mesoscopic Analyses

Greenschists. The Shuksan Schist in the Illabot Peaks area was originally divided into 21 subdomains on the basis of fault location and type of unit. The data from individual subdomains were plotted separately and then compared to other subdomains. Similar plots in adjacent domains were combined until three large domains with significant differences were created, though smaller greenschist blocks exist outside of the domains (see Figure 4 and Plate 1). Domain 1 is the area north of the NE tear fault, west of the Straight Creek fault, and east of the Shuksan thrust. Domain 2 is east of the tear fault and west of the Straight Creek fault. Domain 3 is west of the Shuksan thrust. (See Figure 4 for location of domains.) S_1 foliation data indicate that domains 1 and 2 are similar and structurally continuous. Apparently, the right lateral NE-trending tear fault that separates the two domains only offsets the structural trends of the domains. Domains 1 and 2 belong to the same structural tilt block. The block that comprises domains 1 and 2 strikes roughly N25^{o}W and dips in a concave upward manner, slightly north of east. Domain 3 is composed of two tilt blocks that strike N20^{o}W with the same dip as the block to the east. (See Plate 2.) All three greenschist domains exhibit

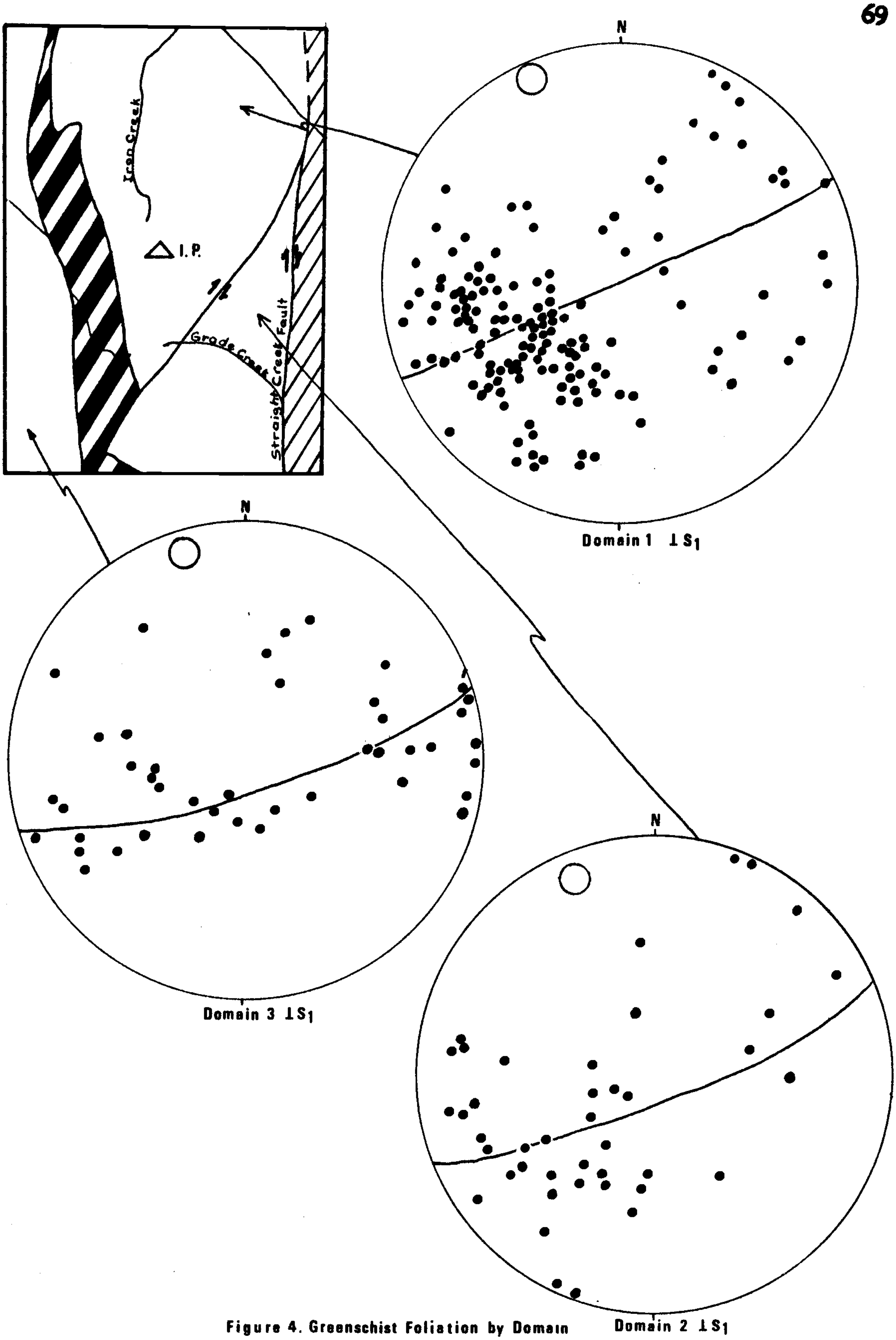


Figure 4. Greenschist Foliation by Domain

similar minor structural features with the same trends. These tilt blocks will be discussed in greater detail in the section on the Shuksan thrust system.

The S_1 foliation is the result of metamorphic differentiation and synmetamorphic transposition of any or all primary bedding or volcanic flow features and is enhanced by the shearing of the intrafolial folds. Inside fault zones, some of the greenschists exhibit a cataclastic fluxion foliation that obliterates the earlier primary metamorphic foliation. There are no later penetrative planar features. The S_1 foliation, plotted as pole to planes, shows little variation in the greenschist domains. The strike and dip of the foliation, on the average, parallels the orientation of the thrust blocks and the axial planes of the F_1 folds. Differences in the foliation trend occur near the margins of the Shuksan thrust where the foliation has been crumpled by movements on the thrust. Though all folds later than F_1 fold S_1, F_3 is the most important deformational episode, folding the foliation about a N25°W, nearly horizontal axis.

Most of the greenschists exhibit two folding episodes, some exhibit three, whereas very few exhibit all four folding episodes. The F_1 folds are extremely tight, rootless intrafolial folds with the axial planes of the majority of the folds parallel to the S_1 foliation at N25°W 50°-60°NE. The plunge of the folds roughly parallels the strike of the foliation. The folds trend roughly NW-SE with the position and angle of the plunges of the fold axes varying greatly because of the effects of the three later folding episodes. The folds are relatively non-penetrative and can only be traced for short distances. Complete folds are extremely rare. The hinge zones of the F_1 folds are characteristically much wider than the limbs of the folds and were probably created by synmetamorphic passive flow. Isolated pods of epidote or albite exist as rootless relicts of fold noses. (See Figure 5A.)

There is no indication that the F_1 folds are small representative folds of a much larger eastward-dipping recumbent isoclinal fold system. The F_1 folds are on a very small scale, commonly no more than several centimeters in wavelength, and usually much less. No larger F_1 folds were seen. These folds or their rootless equivalents are ubiquitous. Sequential transposition of folds into metamorphic bands can be seen in some outcrops. Such extreme transposition of folds and ductile folding would only occur during a synmetamorphic deformational episode.

The F_2 folding episode is restricted in its occurrence to those greenschists that are extremely ductile and well foliated, such as the type 2 greenschist. The type 2 greenschist lacks the more competent minerals such as quartz and albite and, therefore, have been more easily folded. The F_2 folds are tight with fairly sharp and angular hinges which are almost Chevron-like in appearance. Some small

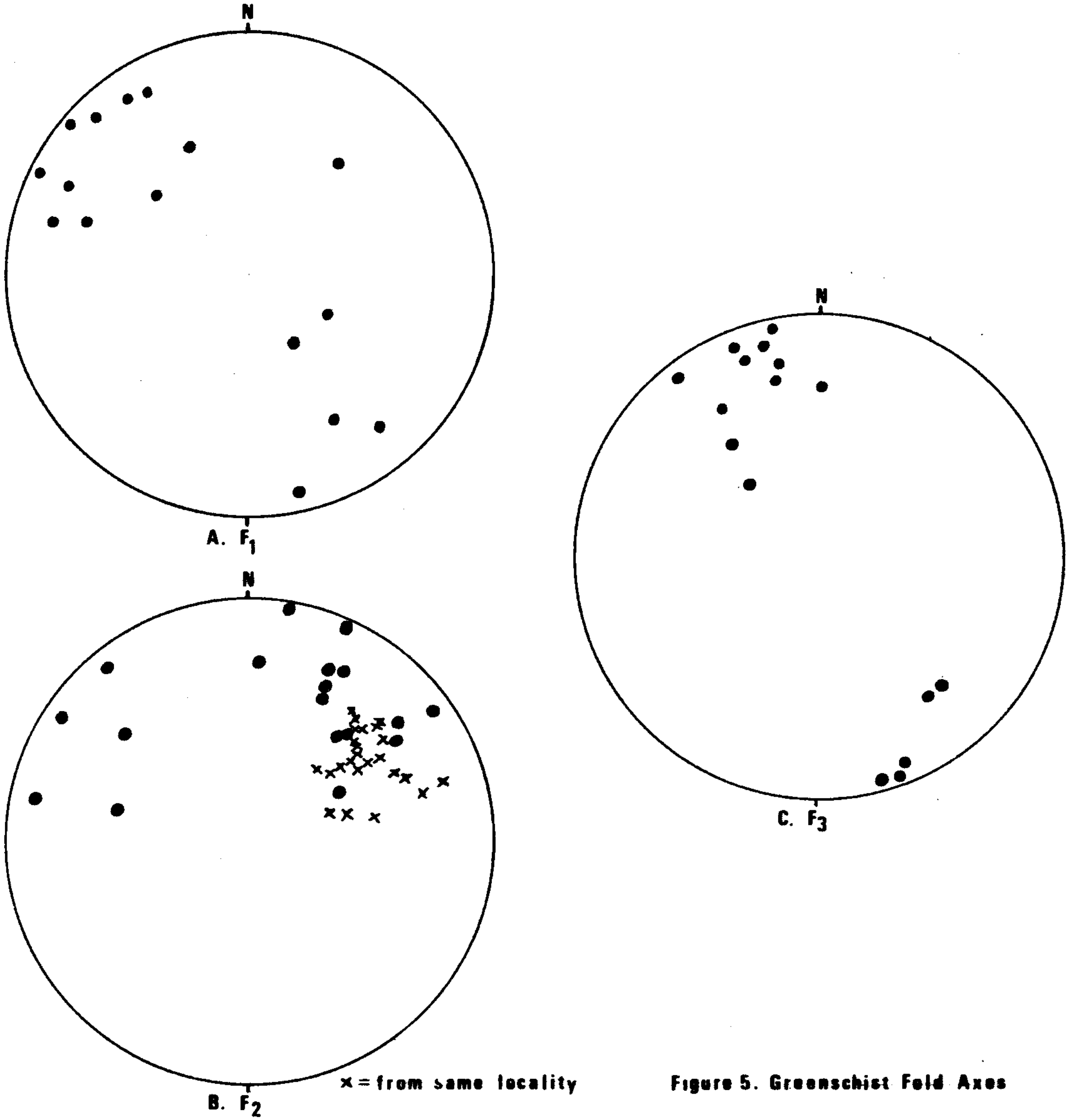


Figure 5. Greenschist Fold Axes

box-like folds also exist. Most folds are nonsymmetrical with some overturning to the northwest, though the overturning is not consistently in one direction. The axial planes are subvertical with the majority of the folds plunging N50°E 40°, though these have been folded by the broad F_3 folds. (See Figure 5B.) The F_2 folds are fairly penetrative, roughly 0.5 m or less in wavelength, and generally less than 10 cm in amplitude. No larger scale folding was seen. The folds exist, apparently, as a very ductile response to either movement on the Cretaceous Shuksan thrust as drag folds, or as a direct response to the NE trending right lateral tear fault that transects the Illabot Peaks area. The stress systems and the timing of the former would be more consistent with the formation of the F_2 folds. Misch (1966) associates the second period of folding elsewhere with drag fold effects.

The most pervasive and dominant folding episode is F_3. Every rock unit in the Shuksan suite and every fabric element in all the rocks is dominated by this episode. The F_3 folds are very broad and open with near vertical axial planes and nearly horizontal fold axes that trend N25°W-S25°E with plunges less than 20°. (See Figure 5C.) The folds are disharmonic. In outcrop, the folds are very nearly concentric, with a nearly constant thickness of the bands near the hinges and the limbs. The F_3 folds can be up to 100 m wide in half wavelength as obtained from the map, though the largest seen in outcrop was only

15-20 m wide. Most of the narrow north trending ridges in the Illabot Peaks area are at least partially occupied by the F_3 antiforms. The long narrow ridge west of Lake Tupso exhibits a large F_3 fold that I interpret as a result of overfolding near the edge of a thrust block. The F_3 folding is associated with the major thrusting during the Cretaceous. (See section on Kink Analysis.)

The F_4 folding episode is very poorly represented in the greenschists and, then, only close to the Straight Creek fault in the more ductile rocks. The F_4 folds are very broad and open with a subvertical axial plane and a plunge that is directed in a very steep angle to the east. (See Figure 5D.) Lawrence (unpublished manuscript) and Lawrence and Milnes (1976) suggest that in the greenschists near White Chuck Mountain, the F_4 folds may be up to several kilometers in wavelength and in amplitude and that they die out very rapidly to the west away from the Straight Creek fault. No such large folds were noticed in the greenschist in the Illabot Peaks area. The differences in response between the two areas may be the result of the more massive nature of the rocks in the Illabot Peaks area in contrast to the more ductile behavior of the better foliated greenschists near White Chuck Mountain as suggested by Lawrence and Milnes (1976).

Several types of lineations occur, including one elongated amphibole lineation, one elongate albite pod lineation, and at least one crenulation lineation. Other minor fabrics exist. Though the differentiation of the types of lineations was extremely difficult in the field, a distinction was possible between the mineral lineations and the crenulation lineations. The mineral lineations consist of elongated amphiboles parallel to the strike of the foliation with a "b" fabric symmetry and elongated albite pods subparallel to the foliation. The mineral lineations, when plotted on a stereonet, yield a small circle that centers about an axis that is identical to that of F_3. (See Figure 6C.) Both mineral lineations are believed to be synmetamorphic in origin. These lineations were then folded by the later folding episodes.

The majority of the lineation readings are of crenulations caused by the intersections of the strain-slip cleavages parallel to the fold axial planes with the S_1 foliation. These lineations could not be clearly differentiated in the field. Some consistent patterns emerged when all the linear fabric elements were plotted together on a stereonet (see Figure 6E). Three distinct maxima exist with a fourth more subjective one present. The large maximum at N70°W 15° is probably formed by the synmetamorphic lineations associated with the F_1 axes and S_1 foliations that have been folded by all the later episodes. The position of lineations on the stereonet is no longer reflective of the original maximum. A large maximum at N20°W-S20°E and nearly horizontal is associated with the F_3 axes and is taken to represent

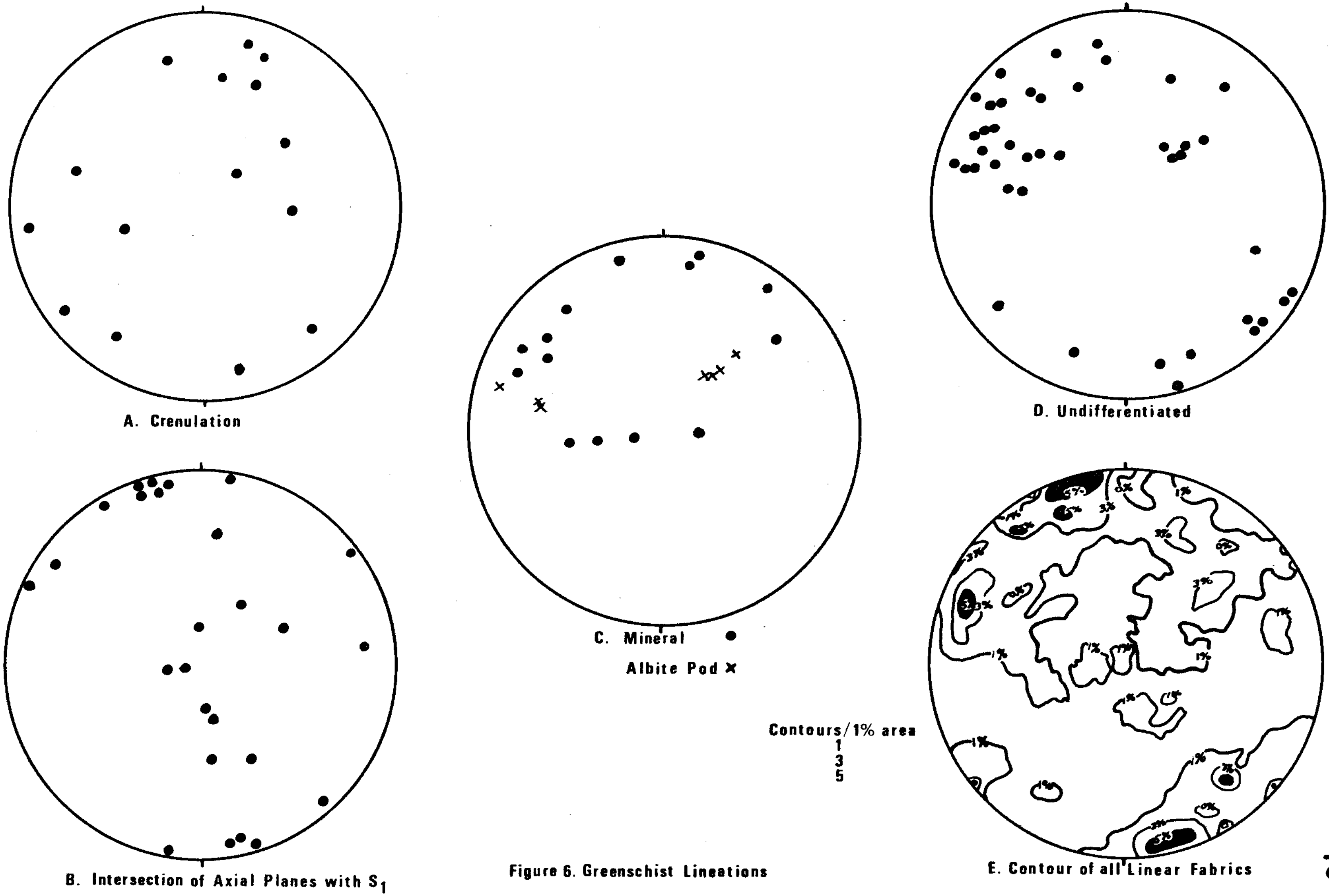


Figure 6. Greenschist Lineations

the trace of the strain-slip cleavage of the F_3 folds on the foliation plane. The F_3 folds represent the major folding episode and this is reflected by the plots of all the linear fabric elements occurring in a broad, ill-defined small circle about the F_3 axis, indicating folding about this axis. A smaller maximum at around N35°E40° is believed to be a representation of the trace of the strain-slip cleavage of F_2 fold axes on S_1. The broad slight concentration of points just east of vertical is believed to be associated with the plunge of the F_4 fold axes. The maximum is weak because the F_4 folding episode was not well represented in the Illabot Peaks area.

Quartz-Muscovite-Graphite Phyllite. The separation of the phyllite into domains for structural analysis was not as simple as for the greenschists. The main occurrence of the phyllite is in the northwest trending phyllite belt, but numerous very small outcrops have been tectonically emplaced throughout the area. Differences in structural trend among the various outcrops are minute so that all the phyllite data were plotted together. Information on the phyllite is not as well documented as for the greenschists because the unit outcrops poorly.

As with the greenschists, only one foliation (S_1) was noted. This foliation is extremely well developed, and is believed by Vance (1957) to probably be the result of intense synmetamorphic transposition of the original sedimentary bedding. S_1 probably parallels the original bedding, except where it is a fluxion structure, though this is not clearly established. S_1 also parallels the synmetamorphic intrafolial F_1 fold axial planes. A stereonet plot of all the poles to S_1 planes for the phyllite (see Figure 7A) indicates that the general trend is very similar to that of the greenschists. The foliation has been broadly folded about an axis of N6°W 10°, with the major dips of the foliation planes being 50°-60° slightly north of east. The foliation of the phyllite, as with the greenschist foliations, becomes less steep with depth to the east. The S_1 foliation was formed simultaneously with the S_1 of the greenschist. The slight differences in trend were caused by differences in the response of the rocks to deformation and the more ductile deformation of the phyllites. The extremely ductile deformation of the phyllite caused great difficulties in obtaining foliation data.

All folding episodes present in the greenschists (F_1-F_4) are also present in the phyllite though the orientations are slightly different. The frequency of occurrence of fold episodes, though, varies greatly from the greenschists. Data on F_1, the axial plane of which parallels S_1 in a manner similar to that of the greenschists, could not be accurately singled out because of the high degree of contortion caused by the later folding episodes. The differentiation of F_2 from F_3, because of their similarities, was also extremely difficult. Lineations, though abundant and of the same types as in the

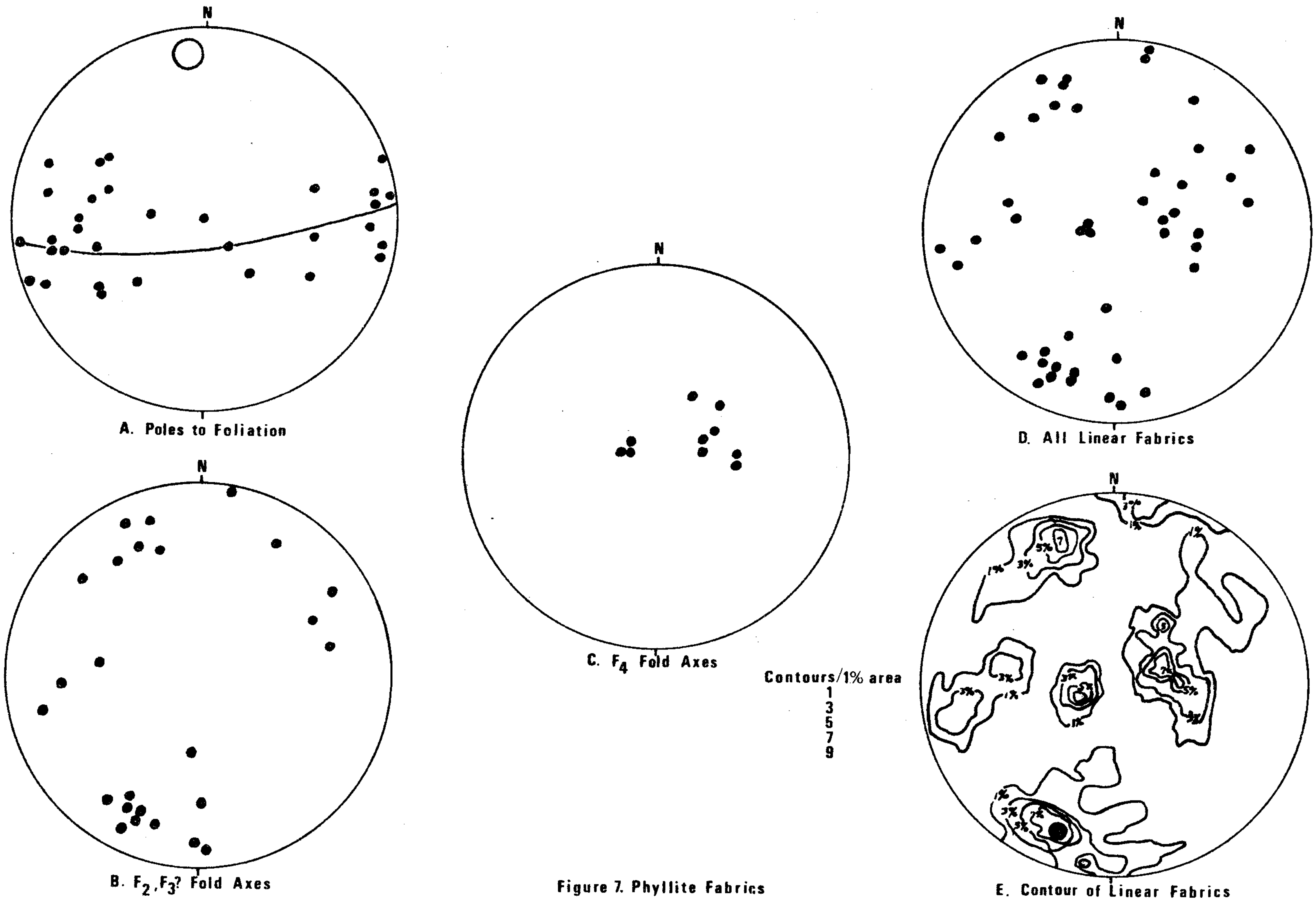


Figure 7. Phyllite Fabrics

greenschist, were difficult to obtain in the field due to the weather conditions and the outcrop limitations, though laboratory analyses could be made.

To overcome these problems, a stereonet plot of all the linear fabric elements was made for the phyllite and then contoured. As with the greenschists, four basic maxima of the linear fabric elements exist (see Figures 7D and E). The maxima pair that straddles due west and plunges at 20^{o}-45^{o} probably represents the extensively refolded F_2 axes. The large maximum at S20^{o}W 20^{o} represents the refolded F_2 axes. The maximum at N20^{o}W 20^{o} is the concentration of the axes of the dominant F_3 folding episode. The two maxima that center about the vertical belong to the very steeply dipping F_4 fold axes. Evidently, the massive greenschists east of the phyllite belt transmitted the stresses to the phyllites which deformed by F_4 folding. The differences in orientation of the lineations (fold axes included) and the foliations are interpreted to be caused by different reactions of the extremely ductile phyllite to the same stresses as those that involved the greenschists. Unlike the majority of the greenschists, the phyllite very commonly responded strongly to both the F_2 and F_4 fold episodes. Though the deformational episodes of the greenschists and the phyllite are comparable, there is a slight clockwise shift of the loci of the phyllite F_1, F_2, and F_3 axes from the position of the greenschist axes. The shift in axes is caused by the broad, nearly vertical folding of the F_4 episode. All indications point to the co-metamorphic and co-deformational history of the phyllite and the greenschists.

Microscopic Analysis

Greenschists. The greenschists range from poorly foliated and brecciated rocks near the Straight Creek fault to extremely well foliated, ductile schists near Illabot Peaks. The greenschist S_1 is caused by the alignment of the basal sections of the platy chlorite minerals in the plane of the foliation, the alignment of the elongated amphiboles within the foliation, and the alignment of rare muscovite plates. The foliation is enhanced by the metamorphic bands and F_1 fold axial planes paralleling S_1. The amphibole lineation is a "b" lineation (parallel to the fold axes) formed synmetamorphically at the hinges of the F_1 intrafolial folds.

In thin section, the F_1 folds generally have the same appearance as their outcrop form. The folds are extremely tight, nearly always rootless, intrafolial fold noses. Albite tends to be concentrated in the hinge regions of the folds where the bands are thicker because of the flowage. The fold noses have been slightly rotated by shearing on the foliation planes. The albite and quartz are usually strained though there is no fracturing of individual grains. Irregular grain contacts exist in the regions of the fold hinges. It appears that crystal growth was mostly syntectonic though some growth may have occurred before deformation. The F_1 folds are best exhibited in the albite-quartz bands.

The later folds are generally on too large a scale to be identified in thin section. When seen, the folds are broad and show little evidence of crystal growth during deformation. Some recrystallization of quartz and albite occurred in the fold noses, but most albite, quartz, and actinolite are in discrete segments or broken grains, indicating that the F_2, F_3, and F_4 folds occurred, for the most part, after metamorphism.

Quartz-Muscovite-Graphite Phyllite. In thin section, the phyllites are highly contorted, highly sheared, and often brecciated. The main foliation, S_1, is usually extremely well developed, with S_1 parallel to F_1 axial planes. S_1 is created by the alignment of the platy minerals, such as muscovite, chlorite, and graphite, and the minor amphibole minerals present. Muscovite is the most important planar element in the rock and is, apparently, pretectonic in origin. As in the greenschists, the metamorphic banding and the tight F_1 folds enhance the foliation. The S_1 surfaces of the phyllites have probably originated from the combination of metamorphic segregation and transposition of primary sedimentary bedding, though the S_1 of the greenschists formed primarily by metamorphic differentiation. I believe that the foliations of both units are comparable and related to the same metamorphic and tectonic conditions.

The folding in the phyllite is also comparable to the greenschists but is present on a smaller scale. The tight intrafolial F_1 is best exhibited within the very ductile muscovite-graphite layers while the later, broader folding episodes are best exhibited by the more competent quartz-albite layers. A synmetamorphic "b" amphibole lineation is present, but it is not as well defined as in the greenschists.

Many of the quartz grains have been slightly recrystallized. This period of recrystallization is believed to have occurred during the movements on the Shuksan thrust.

<u>Analysis of Quartz Optic Axes.</u> The orientation of the optic axes of quartz [0001] were determined for five samples, four of the phyllite and one of a quartz mylonite, in order to relate the orientation of the grains to the tectonic framework. Though much work has been done with quartz optic axes, definite relationships between orientation and stress directions are only beginning to be established experimentally. The symmetry of quartz optic axis, on the other hand, has been well studied and related to S surfaces and lineations with S perpendicular to the girdle of C axes. (See Turner and Weiss, 1963.) Turner and Weiss (1963) state ". . . that syntectonic recrystallization of quartz yields patterns whose symmetry approximates that of the stress system. . . " and that departure from perfect symmetry is attributed, mainly, to pre-existing anisotropy of the rock. It has

also been shown (summarized by Turner and Weiss, 1963) that during syntectonic recrystallization, grains are flattened perpendicular to σ_1 and that the C axes can be parallel to or perpendicular to σ_1.

The five samples observed in oriented thin section exhibited monoclinic, nearly orthorhombic, symmetry. For each sample, the other known fabric elements were plotted on the same stereonet diagram as the optic axes, and some relationships were found to exist (see Figure 8). The main girdle of the C axes is always nearly perpendicular to the primary foliation S_1. The main girdle of the C axes is also perpendicular to the F_3 axes with F_3 always on S_1. The F_4 fold axes, when seen, always occur in or close to the near vertical main maximum of C axes. The F_2 fold axes occur at some position away from the maxima and do not appear related to the quartz fabrics. The two samples that exhibit a different pattern from the others, PTM-LLW-III and PTM-LLF-I, are a quartz mylonite and a garnet-bearing phyllite, respectively, that are intimately fault related. (See Figures 8C and E.)

A simple tentative interpretation, based on all data, can be made for the "normal" phyllites. The quartz fabrics present are related to syntectonic recrystallization of the quartz during the movements of the Shuksan thrust. (See section on metamorphic history.) No earlier fabrics are observed. The principal stress direction is placed perpendicular to the foliation (which is

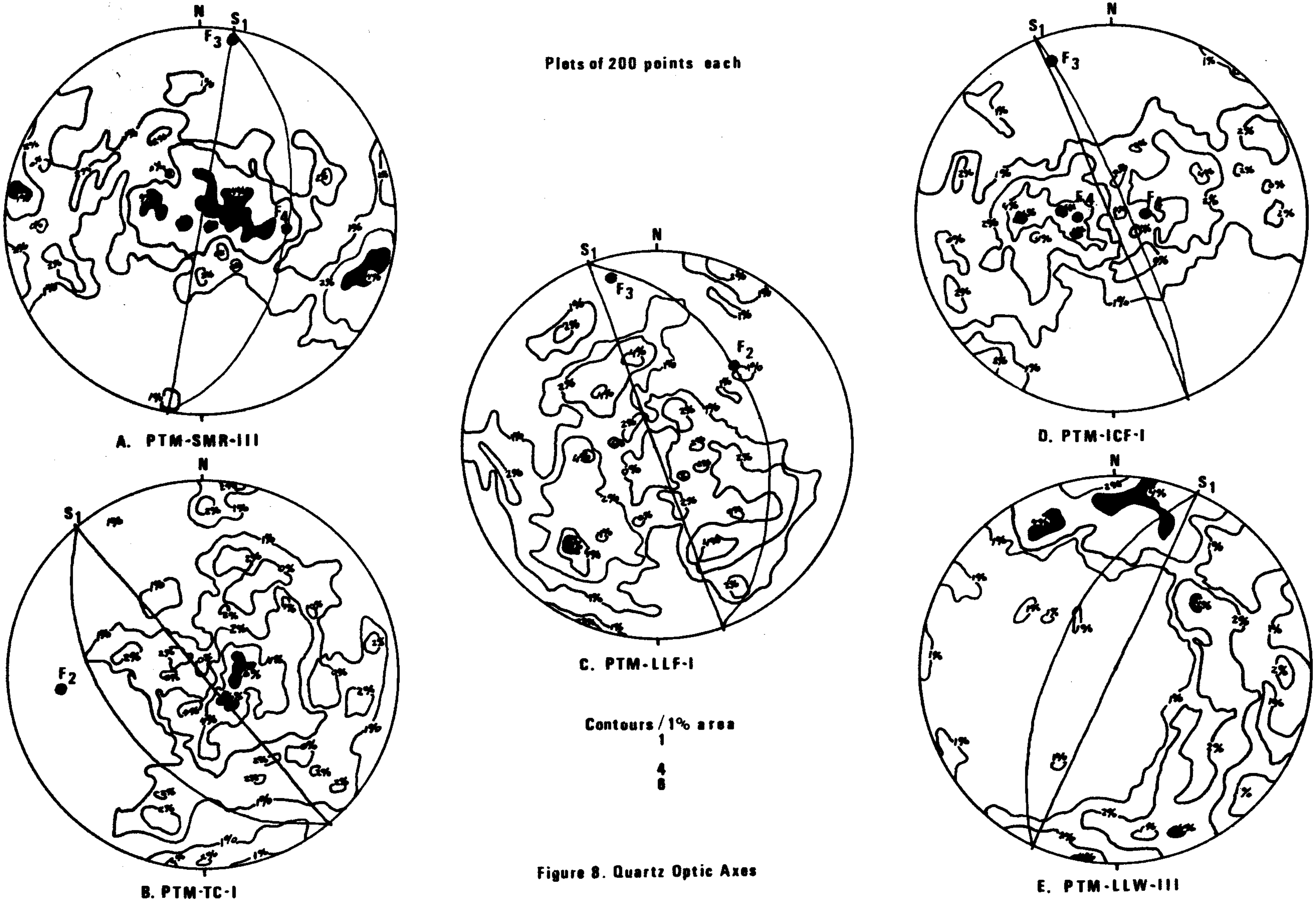


Figure 8. Quartz Optic Axes

perpendicular to the F_3 fold axes. This stress direction is nearly horizontal and closely associated with that determined by the kink analyses to be related to the F_3 folds. The near vertical C axis maxima, as suggested by Lawrence (person. commun.), is attributed to a vertical stress system created by the overlying weight of the greenschist blocks emplaced by the Shuksan thrust upon the more ductile and incompetent phyllite unit. The relationship between the F_4 fold axes and the near vertical main maxima concentrations is not clearly understood, though the F_4 folds may simply have been formed along the vertical zones of weakness created by the heavy overlying blocks of greenschist.

The remaining two samples are a little more difficult to interpret. The tectonically emplaced garnet-bearing phyllite (PTM-LLF-I) maintains the same relationships to the other fabric elements as do the other phyllites, except that the C axis maxima are in a rather tight small circle about the vertical. The orientation of the optic axes indicate that the main stress direction is nearly vertical. A tight small circle girdle (Lawrence, person. commun.) is a ductile feature that occurs at relatively low temperatures. The above observations suggest that the main fabric element of this rock was formed by downward exerted pressure of the overlying greenschist blocks and was probably enhanced by vertical movement along the fault that emplaced this rock unit. A stress direction related to the

Shuksan thrust movements can be demonstrated though it is not as clear as in the other samples.

The quartz mylonite (PTM-LLW-III) exhibits a broad small circle separated by a symmetry element that closely approaches the orientation of the fluxion structure or shear foliation of the rock. Placing the principal stress direction perpendicular to the fluxion structure, the symmetry plane, and in the direction of the main C maxima concentrations, one arrives at a fairly close match at around N30°-50°W. Such a stress orientation would be compatible with right lateral movement on a small northwest trending fault that the mylonite borders.

Kink Analysis

Introduction. Most of the following discussion on kinks closely follows Paterson and Weiss (1966). Kinks are, essentially, parallel sided domains that have sharp boundaries at which the foliation is bent through a large angle. The deformed domains are separated by undeformed domains. The boundary of each kink is the axial plane of a kink and is inclined from the principal stress directions at a high angle. The kink boundary is a reflection plane with respect to the orientation on either side of it. Only the material inside the boundary is deformed by gliding; outside the boundary, no deformation occurs.

Kinking is caused by gliding on restricted parts of closely spaced planes parallel to the foliation and is caused by mechanical instability in the material involved. Inhomogeneity is generally required. When gliding begins, the glide plane is rotated to an orientation that is more favorable to gliding. The gliding of the planes over each other will continue in that region until the shear stress on the glide plane can be supported by the resistance to gliding. Kinks will begin at local imperfections of the material. The kinks may grow by either simple migration of the kink boundaries without a change in the axial angle, or by rotation of the kink boundaries.

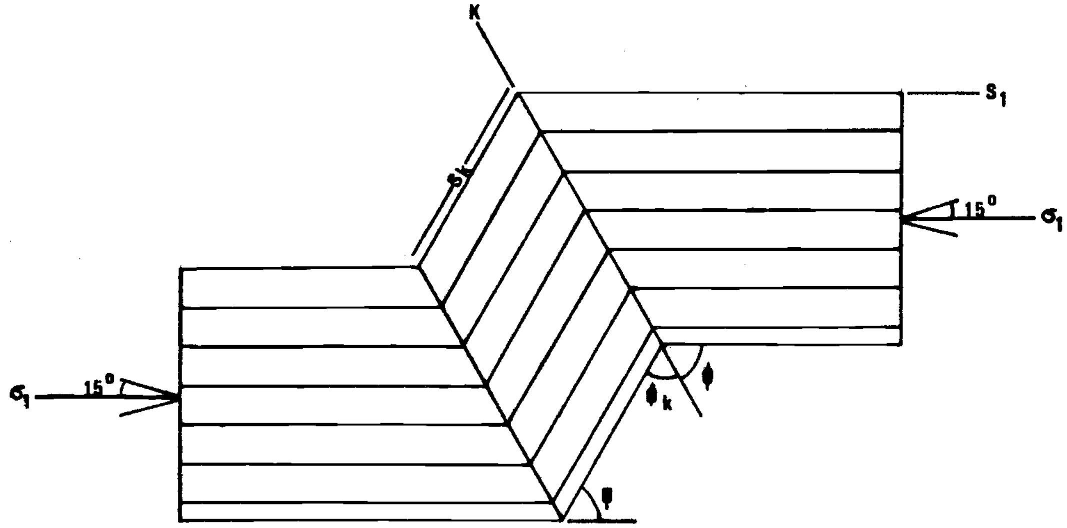
The geometry of kinking can be complex and will not be dealt with. The reader is referred to Paterson and Weiss (1966) and Gay and Weiss (1974) for greater detail. Paterson and Weiss (1966) find that kinking occurs under rather restricted circumstances. Compression parallel to and up to 10^{o} inclined from the foliation produces mainly kinking. Gay and Weiss (1974), through experimental work on computer cards representing ideal foliated bodies, extend the angle of inclination up to 15^{o} away from the foliation. Compression at 45^{o} to the foliation causes planar gliding, and very rarely, at 25^{o}, kink deformation. Compression perpendicular to the foliation causes shear planes at 30^{o} to σ_1. Gay and Weiss also suggest that kinking may also originate as broad open folds that are later modified to kinks.

The sharpness of the kink boundary and the degree of kinking depends upon composition. Well foliated or laminated micaceous material can exhibit excellent kinking with sharp boundaries. Very coarse and siliceous material will exhibit broad kink boundary edges. Non-foliated material probably will not kink.

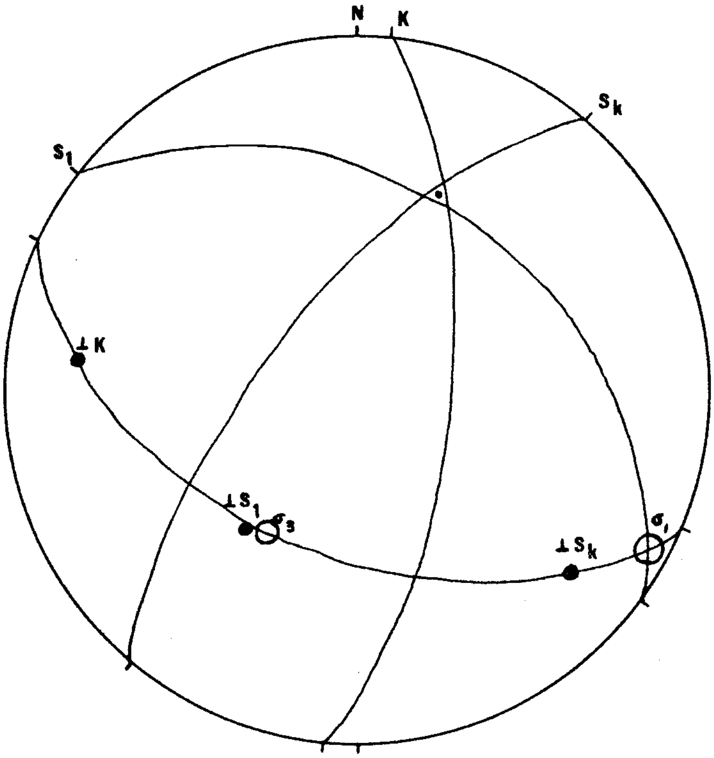
Following Lawrence and Milnes (1976), Gay and Weiss (1974), and Paterson and Weiss (1966), $\sigma_1 \pm 15^\circ$ is placed in the foliation plane and perpendicular to the intersection of the foliation, the kinked foliation, and the kink boundary (kink axis). The orientation of σ_3 is probably not important as it will always be inclined at 90° to the local foliation.

The purposes of studying the kinks in the Shuksan Schist are twofold: 1) to arrive at possible orientations of the principal stresses acting upon the units in the Illabot Peaks area and; 2) to correlate the principal stress directions with a tectonic framework of the area.

Methods. The methods used in the study were fairly simple. Measurements were made on the planes involved in kink geometry in the field and in oriented hand specimens in the laboratory. These include: S_1-the main rock foliation; S_k- the plane of the kinked (or deformed) foliation and; K- the plane of the kink boundary or axis. (See Figure 9A.) These three planes and the respective poles to planes were plotted on a Schmidt equal area stereonet. Ideally, the intersection of the planes should occur as a single line, which serves as a check on the accuracy of the field measurements. The



A. Kink Plane Geometry



B. Determination of σ_1 from Kink Geometry

Figure 9. Kinks

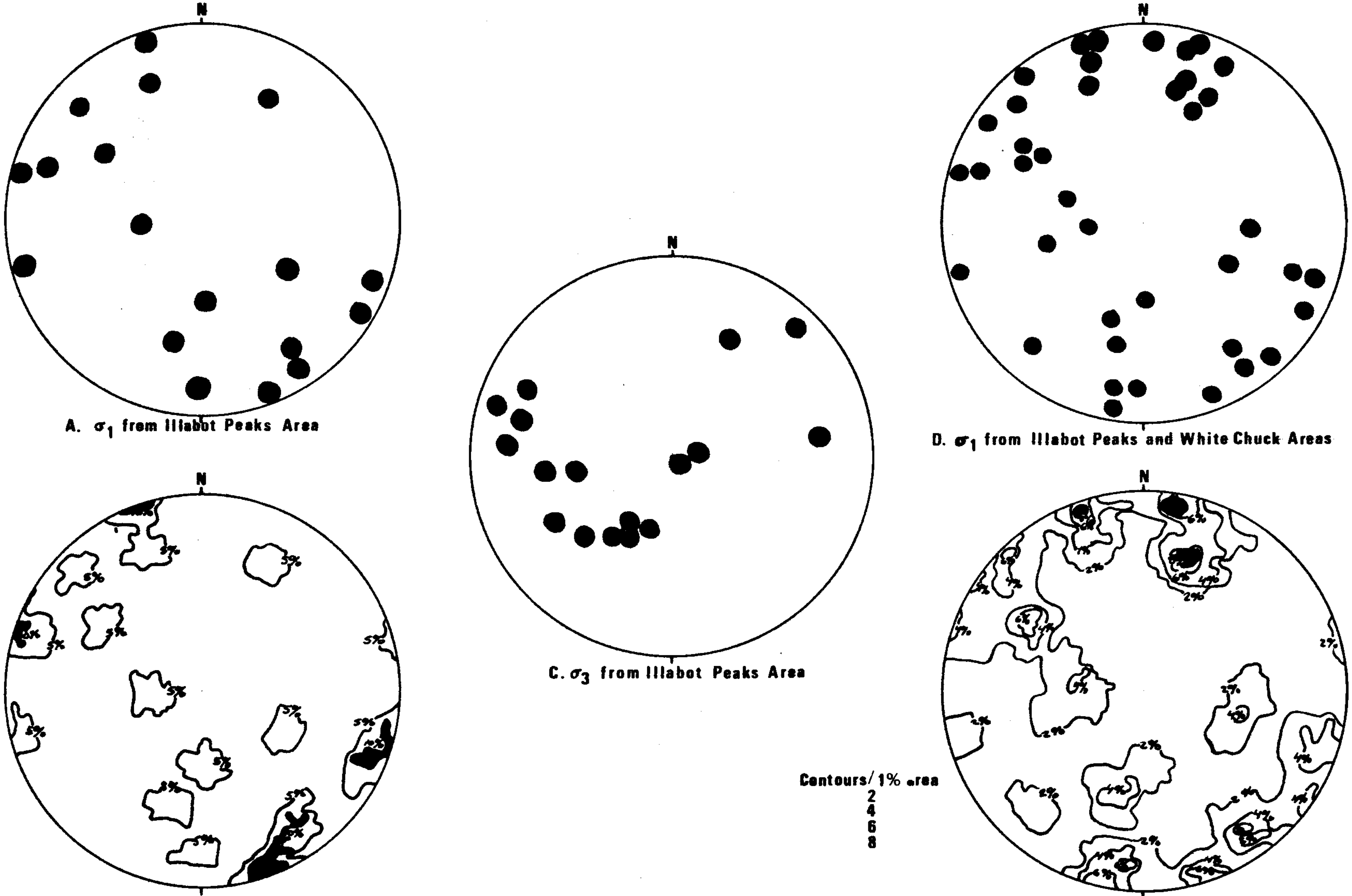
poles to the planes should, ideally, fall upon a great circle plane that is perpendicular to the foliation and also intersects it. σ_1 is placed, ± 15°, at the intersection of the foliation plane and the great circle formed by the poles to S_1, S_k, and K. σ_3 is perpendicular to σ_1 and also on the plane formed by the poles to planes. (See Figures 9A and B.) Eighteen measurements were made for σ_1 and σ_3 values throughout the outcrop area of the Shuksan Schist around Illabot Peaks. Twenty-two more pairs of points were borrowed from Lawrence (unpublished data) from the White Chuck area. The values for all the σ_1 data and all the σ_3 data were plotted on two stereonet diagrams, and then were contoured per 1%.

Results. The kinks observed in the Illabot Peaks area appear to have grown by simple extension of the kink boundaries by gliding of planes over each other. No rotations of axial surfaces are seen. The kinks often die out in small offsets along the trace of the kink boundary.

The plots of the σ_1 directions for the Illabot Peaks area and the White Chuck Mountain area are nearly identical so they were combined on one diagram. There are slight differences in concentrations of points and these may be due to differences in location of data sites. The points in the White Chuck area were obtained near the Straight Creek fault, while those in the Illabot Peaks area were at least 1-2 km away from the fault.

Three main concentrations of points exist. (See Figure 10E.) The largest maximum (mainly the result of points from the White Chuck area) occurs around N10°-20°E with a plunge of 10°-30°. The next largest maximum is somewhat broader in shape with the main concentration of points occurring at approximately N20°W 10°. The smallest maximum is also quite irregular in shape. It occurs slightly north of west with a variety of plunges, though the majority are less than 25°. The first and last concentrations of points were noticed by Lawrence and Milnes (1976) but I feel that the second maximum is discrete and separated from the other two.

Interpretation. The σ_1 directions that lie in the gently plunging maximum at N10°-20°E are consistent with the stress systems to be expected from right lateral displacement on the early Tertiary north-south trending Straight Creek fault (Lawrence and Milnes, 1976). This stress system is also believed responsible for the relatively non-penetrative, very large scale (1-2 km in amplitude), very steeply plunging east-west trending F_4 folds associated with the fault. The scarcity of data from the Illabot Peaks area on this stress system is explained by the rapid dying out of deformational sequences away from the fault (within several kilometers) and the fact that the data were not obtained near the fault. The data from the White Chuck area, on the other hand, exhibits more effects of the Straight Creek fault stress systems because the data were collected closer to the fault.



B. Contour of A above

Figure 10. Kink Data

E. Contour of D above

The gently plunging maximum that trends north of west is attributed to the mid-Cretaceous stress system that caused movement on the Shuksan thrust (Lawrence and Milnes, 1976), and caused the broad, nearly horizontal, very open F_3 folds that plunge slightly west of north. The lack of perpendicularity of σ_1 to the F_3 fold axes is believed to be caused by the anisotropy of the greenschists.

The very gently plunging, slightly west of north maximum can be attributed to several possible stress systems, though the most likely is that the kinks associated with this system may have arisen through anisotropic responses to drag folds of the Shuksan thrust - a feature noted by Misch (1966). In this case, the stresses that formed the NW maximum probably also caused the northeast trending F_2 drag folds. A second possibility is that the maximum is equivalent to the maximum slightly east of north attributed to the Straight Creek fault.

Gay and Weiss (1974) noted that there was a strict relationship between the angles ϕ, ϕ_k, ψ, and σ in kinked slates and ideal foliated materials (see Figure 9A). Angle ϕ is the angle between undeformed foliation and the kink boundary, angle ϕ_k is the angle between the kink boundary and the internal foliation, angle ψ is the angle between external and internal foliations, and α is the inclination of the principal compressive direction away from the foliation. No consistent relationships between these angles were found in the greenschists in the

Illabot Peaks area (Lawrence and Milnes, 1976). The inconsistencies in the geometry for kinks in the greenschists is probably the product of the inhomogeneity of the rocks.

Major Structures

Folds

Unlike the Shuksan suite elsewhere (Misch, 1966; Lawrence, person. commun.), the rocks in the Illabot Peaks area rarely exhibit any large scale folding features. Misch (1966) describes the main belt of the Shuksan Schist east of the Shuksan thrust root as being folded into a complex synclinorium which has been pierced by steep narrow anticlines of Darrington Phyllite. In the individual thrust blocks that comprise the Illabot Peaks area, no evidence was found to indicate that any large synclinal structures exist. The greenschists, rather, form essentially homoclinal tilt blocks that dip to the east in a concave upward manner. The narrow phyllite belts (The Darrington Phyllite of Misch) that transect the Illabot Peaks area dip in a manner similar to that of the greenschists. Evidence for large anticlinal structures does not exist, though the phyllite, like the greenschist, is complexly folded on a minor scale.

The largest scale folds present are of the F_3 folding episode. Lawrence (unpublished manuscript) describes these folds around

White Chuck Mountain as nearly horizontal, open F_2 folds with wavelengths of up to several kilometers that are overturned slightly to the west. The large open folds in the Illabot Peaks area are similar in all respects to those in the White Chuck area except that they are on a much smaller scale. The F_3 folds may be up to 100 m in half-wavelength and occupy the north trending ridges in the area, though the largest outcrop occurrence is only 15-20 m wide. The trace of the fold axes, apparently, follows a mildly undulating path, though generally in a north-northwest direction. The differences in scale between the Illabot Peaks area and the White Chuck area are attributed to differences in ductile responses of the rock types during Cretaceous thrusting. The general character of the greenschists in the White Chuck area (Lawrence, person. commun.) is better foliated and more incompetent than the massive rocks in the Illabot Peaks area.

Lawrence (unpublished manuscript) notices large scale sub-vertical plunging folds associated with the Straight Creek fault in the White Chuck area. These folds are up to 10 km in wavelength and 1 or 2 km in amplitude. This folding episode (F_3 of Lawrence, my F_4) is present in the Illabot Peaks area, but only discernible on a very minor scale. No large scale folds were seen. The differences in response between the two areas is the same as for the F_3 folds.

Thrust System

In the Illabot Peaks area, the thrust system is severely imbricated, breaking the area into a series of concave upward, east-dipping greenschist thrust blocks that have been emplaced upon the more ductile phyllite unit. The imbricated thrusts have created two major nearly homoclinal tilt blocks in the map area with several more observed to the west. At least four smaller east-dipping greenschist thrust blocks were seen, generally as slivers in the phyllite belt, with the possibility of others existing. The structural trend of the faults is slightly west of north. The thrust planes are generally steeply dipping (50°-60°) at the higher elevations to the west with a flattening of the dips to the east in the lower elevations. If it were not for the variable dips of the thrusts, they would probably be better termed high angle reverse faults. The imbricated fault zones probably connect with a single low angle thrust plane at around sea level. The evidence for this, though, is not clear. Overfolding and crumpling of the greenschists occurred near the thrust margins, most notably on the ridge just west of Lake Tupso. Cataclastic deformation on or near the fault contacts was severe, as discussed in the sections on the rock units, with recrystallization of some of the minerals, most noticeably quartz, and slight retrogressive metamorphism occurring at this time.

When faulting began (Middle to early Late Cretaceous, according to Misch, 1966), movement occurred along the planes of weakness of the interbedded meta-volcanics (greenschists) and the pelitic sediments (the phyllite unit). These planes of weakness were parallel to the foliation in the soft and ductile phyllite with the phyllite acting as a lubricant upon which the more competent, massive greenschist blocks were slid to the west. The phyllite unit belts, as observed from its extremely complex deformation and common cataclastic structures, are interpreted as types of mega-shear zones between the blocks of greenschist. It is along the contacts of the overlying greenschist and the phyllite that the tectonic fragments have been emplaced.

The thrust faults have been complicated by at least one major high angle reverse fault and several more minor ones. This large fault trends north-northwest through the cols slightly west of Illabot Peaks. The fault has a near vertical dip, probably close to 80^{o} to the east. The dip of the fault was determined to be very steep because the fault trace is deflected very little through great topographic relief and through the orientation of fluxion folds in serpentinite pods. Fault contacts were observed in two locations. The fault has brought up a belt of phyllite, ductile F_2 greenschists, nearly pure antigorite serpentinite pods, and meta-gabbro fragments, attesting to the similarity with the lower angle thrusts to the west and its probable correlation in time with the thrusts. It is not unusual, according to Lawrence (person. commun.), for a thrust segment to reorient itself into a high angle reverse fault in the later stages of its development or when frictional forces became too great to allow the low angle movement. Displacement is not known, but it is probably considerable. Minimum displacement is probably on the order of the thickness of the greenschist blocks (1 km).

Misch (1966), on the basis of comparisons of lithologies and folds overturned to the west, assigns a westward movement to the Shuksan thrust system. Total displacement is believed to be at least 47 to 62 km. Displacement in the Illabot Peaks area is not clearly established.

NE-Trending Fault

On the basis of ground mapping and aerial photographic work, a large northeast-trending fault was established. The fault passes near Lake Tupso (see Plate I for location), disrupts the drainage in several stream gullies, and nearly transects the length of the field area. Since very little deflection of the fault trace occurs as it passes over a great amount of topographic relief, the fault is believed to be vertically dipping. The fault displaces the Shuksan thrust and the associated high angle reverse fault near Illabot Peaks about 1.2 km in a right lateral direction. The foliation of the greenschists near the fault exhibits distortions consistent with right lateral drag effects of the fault.

Though the age of the fault is not positively known, it can be narrowed down. It offsets the Middle to early Late Cretaceous Shuksan thrust and it appears, in turn, to be cut off by the Eocene(?) Straight Creek fault. Lawrence (unpublished manuscript) finds a similar fault with a slightly larger offset that trends between Prairie Mountain and White Chuck Mountain and I suspect that there are at least several more in the general area. Grant (1969) notices several transverse structural belts that trend nearly perpendicular to the structural trend. These belts are characterized by a series of east-west to northeast-southwest en echelon shears, along which mineralization has occurred, that may extend more than 150 km across the North Cascades. Grant believes that the transverse belts are deeply seated in origin and suggests three hypotheses of origin: 1) the belts are the result of tensional adjustments to northwest trending zones of movement; 2) they may be a high level expression of an older deep-seated zone of movement; and 3) northeast trending structures may have influenced the position of the transverse belts.

The fault in the Illabot Peaks area may represent a small portion of what Grant (1969) terms the Buckindy structural belt that extends northeast of Darrington for over 75 km. If the fault belongs to this transverse belt, it is probably at least early Tertiary in age, as the Buckindy belt transects the early Tertiary Buckindy massif.

Straight Creek Fault Zone

The Straight Creek fault zone separates the low T/P greenschists and phyllites of the Shuksan suite on the west from the higher T/P rocks of the Skagit metamorphic suite on the east. The fault, named by Vance (1957), trends in a north-south direction with a near vertical dip for at least 125 km until it is intruded by the Tertiary Chilliwack batholith. Misch (1966) and Vance (1957) date the fault as early Eocene with probable pre-Tertiary movement because the fault cuts the Late Cretaceous-Paleocene Chuckanut rocks and is cut by the main phase (Late Eocene?) of the Chilliwack batholith. McTaggart (1970) suggests that movement began in Late Mesozoic time and perhaps persisted until the Miocene. McTaggart believes that the Straight Creek fault zone is a southern extension of the 230 km long Fraser River fault zone of British Columbia. The amount of offset is unknown, but it is probably considerable as no units can be accurately matched across it. Lawrence and Milnes (1976) on the basis of kink geometry, Misch (1966), and Vance (1957) suggest a right lateral sense of motion for the main movement of the fault.

In the Illabot Peaks area, the fault appears similar to what Higgins (1971) describes as a braided fault zone and what Kingma (1974) describes as piercement structures in New Zealand. The

Straight Creek fault zone consists of a series of small lensoidal slivers of greenschist, phyllite, Swauk sedimentary rocks, and gneisses emplaced along both sides of the fault. Previously, these fault slivers were known only from the west side of the fault (Misch, 1966). Large fault slivers, though not clearly established, appear to have been spalled off the main fault. Lawrence (person. commun.) has observed asimilar fault geometry to the south of the field area. According to Higgins (1971), a braided fault zone is created when differences in lithology (greenschist vs. Skagit gneiss) produce frictional differences and irregular movements creating an undulatory fault movement. Such a braided fault system, with variations in the degree of cataclasis, would also be consistent with repeated movements in the fault zone. The degree of cataclastic deformation was discussed in the rock description sections and will not be further discussed here.

Minor Faults

Most minor faults were not traceable on the ground except where seen in road cuts and deep stream gullies. A variety of lineaments suggestive of faulting were seen in aerial photographs but were not placed on the map unless there was some ground control. The Illabot Peaks area is transected by a very large number of small faults, many of inconsequential displacement. Most of the minor faults are high angle reverse faults as established by ground exposures, the study of small fluxion folds in fault zones, and the presence of small blueschist or meta-igneous fragments brought up from depth. The reverse faulting is probably associated with movement on the Shuksan thrust, faulting up some tectonic slivers scraped off by the thrust. Almost invariably, small zones of quartz-muscovite-graphite phyllite have been emplaced inside the small fault zones. Contacts, though rare, are always sheared.

Three basic trends of faulting appear to exist. The majority of the small faults extend in a slightly west of north-east of south direction. Another set, far fewer in number, trends to the northeast. Boththese sets appear to have high angle dips. Several faults of unknown magnitude and displacement, trending about N45^{o}W, were delineated by topographic lineamants, disturbances of foliations, and alignment of small lakes. The most noticeable of these follows the break in slope in which Lake Tupso is situated. These faults appear to transect all faults older than the Straight Creek fault and appear to be related in timing to this fault.

Chronology of Structures

The following is a chronological summary of the geologic structures in the Illabot Peaks area.

1) During the latest Permian to early Triassic (age dated by

Misch, 1966, at 218± 40 m. y. and 259± 8 m. y.) the rocks of the Shuksan suite were synmetamorphically deformed to create the F_1 intrafolial folds, the S_1 foliation, and the elongated amphibole lineation.

2) A peried of quiescence existed until the Middle to early Late Cretaceous movement of the Shuksan thrust. The movement on the thrust is believed to be in excess of 60 km. Numerous small high angle reverse faults are associated with the thrusts. Two sets of folds and related kinking are closely associated with the thrusting. Small drag folds plunging northeast and a set of kinks, slightly predating the larger F_3 folds, originated from a slightly west of north stress system. The F_3 folds trend very nearly horizontally at N25°W and are large open folds that are associated with crumpling set up by stresses of the main movements on the Shuksan thrust. Large kinks are associated with the gently plunging north of west stress direction that caused the F_3 folds.

3) Some time after the Middle to early Late Cretaceous deformation by the Shuksan thrust and probably before the movements of the Straight Creek fault (late Mesozoic to Miocene?), a northeast trending right lateral strike-slip fault of 1.1 km displacement occurred. This fault is associated with a larger regional transverse structural belt.

4) Movement began in the large displacement Straight Creek

fault system in the late Mesozoic. Deformation was predominantly early Eocene but it may have persisted until the Miocene. Large amplitude and wavelength, vertically plunging F_4 folds are associated with the fault. Deformation by kinking also occurred at this time in the better foliated rocks. Minor faulting was pervasive in the area.

SUMMARY AND CONTRIBUTIONS

The Illabot Peaks area consists of a series of essentially homoclinal eastward dipping thrust blocks of greenschist to blueschist facies metamorphosed olivine-free calc-alkaline basalt forming the Shuksan Schist. These thrust blocks represent highly fabricated portions of the Middle-Late Cretaceous Shuksan thrust that have been emplaced along shear zones of extremely ductile lower greenschist facies quartz-muscovite-graphite phyllite. The phyllite can probably be correlated with the Darrington Phyllite. Both the Shuksan Schist and the Darrington Phyllite were intensely synmetamorphically deformed in the late Permian to early Triassic. The primary foliation, lineations, and intrafolial F_1 folds were formed at this time. The structuralllly lower portions of the Shuksan Schist are occupied by a Na amphibole-bearing rock that probably originated as intercalations of original high P_{O_2} and high ferric iron material, as suggested by Brown (1974). It is also possible that the garnet-bearing phyllite unit seen may represent a slightly higher metamorphic grade, faulted up from depth, than the "normal" phyllite. Along the steeply eastward dipping margins of the Shuksan thrust, small lenticular pods of brecciated blueschist fragments and meta-igneous slivers have been tectonically emplaced. The blueschist pods, slightly regressively metamorphosed, are possible indicators of a rock unit at depth at a higher facies than, and different from, the typical greenschists.

My studies indicate that the large nappe-like folds of the Shuksan thrust indicated by Misch (1966) do not occur in the regions around the Illabot Peaks area. The thrust system, rather, consists of a series of imbricated thrusts that dip to the east in a concave upward pattern and connect at some depth with a master thrust. The geometry of the thrust, as I have observed it in the field, is inconsistent with closure of what Misch (1966) terms the "Concrete half-window." Associated with the movements of the Shuksan thrust are numerous small high angle reverse faults. During thrusting, the rocks of the Shuksan suite were deformed by small northeast trending drag folds (F_2) and large scale, northwest trending, open F_3 folds with horizontal plunges. Each fold episode was accompanied by kink deformation in the better foliated rocks. Slight recrystallization of quartz and retrogressive metamorphism is associated with the Shuksan thrust.

A large northeast trending, high angle right lateral strike-slip fault has offset the Shuksan thrust system in the Illabot Peaks area by 1.1 km. This fault is later than the Cretaceous thrusting and earlier than movements on the Straight Creek fault.

The Straight Creek fault, of possible very large right lateral displacements, is believed to be late Mesozoic-Miocene in age with the main displacements occurring in the Early Eocene. This fault in the Illabot Peaks area is a highly intricate braided fault zone that separates the low T/P rocks of the Shuksan suite from the higher T/P rocks of the Skagit metamorphic suite to the east. The Straight Creek fault system has caught small tectonic slivers of greenschist, phyllite, gneiss, and Swauk Formation sediments in the fault zone and has cataclastically deformed them. Cataclastic deformation effects are exhibited by the greenschist for up to a kilometer west of the fault. Associated with the stress systems that caused the Straight Creek fault are large amplitude (1-2 km) steeply plunging F_4 folds that die out very rapidly to the west. Kink deformation also occurred at this time. The F_4 folds in the more massive rocks of the Illabot Peaks area are generally quite small in amplitude, in contrast to the folds in the more ductile greenschists of the White Chuck Mountain area. The size of all foding episodes is greatly reduced in the Illabot Peaks area due to the more massive rocks there.

BIBLIOGRAPHY

Billings, Marland P., 1972, Structural Geology, 3rd Edition: Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 606 pages.

Blake, M. C., Jr., Irwin, W. P., and Coleman, R. G., 1967, Upside-down-metamorphic zonation, blueschist facies, along a regional thrust in California and Oregon: U. S. G. S. Professional Paper 575-C, p. C1-C9.

Blake, M. C., Jr., Irwin, W. P., and Coleman, R. G., 1969, Blueschist facies metamorphism related to regional thrust faulting: Tectonophysics, v. 8, p. 237-246.

Brown, E. H., 1974, Comparison of the mineralogy and phase relations of blueschists from the North Cascades, Washington, and greenschists from Otago, New Zealand: Geol. Soc. America, v. 85, p. 333-344.

Bryant, B. H., 1955, Petrology and reconnaissance geology of the Snowking area, northern Cascades, Washington: University of Washington Ph. D. thesis, 352 pages.

Carmichael, I. S. E., Turner, F. J., and Verhoogen, John, 1974, Igneous Petrology: McGraw-Hill Book Company, New York, 739 pages.

Danner, W. R., 1966, Limestone resources of western Washington: Washington Div. Mines and Geology Bull. 52.

Davis, G. A., 1968, Westward thrust faulting in the south-central Klamath Mountains, California: Geol. Soc. America, v. 79, p. 911-934.

Deer, W. A., Howie, R. A., and Zussman, J., 1966, An introduction to the rock forming minerals: John Wiley and Sons, Inc., New York, 528 pages.

Ernst, W. G., 1973, Blueschist metamorphism and P-T regimes in active subduction zones: Tectonophysics, v. 8, p. 255-272.

Metamorphism and plate tectonic regimes, 1975, ed. W. C. Ernst: Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pennsylvania.

Franklin, Wesley, 1974, Structural significance of meta-igneous fragments in the Prairie Mountain area, North Cascade Range, Snohomish County, Washington: unpublished Oregon State University M. S. thesis, 109 pages.

Grant, A. R., 1969, Chemical and physical controls for base metal deposition in the Cascade Range of Washington: Washington Div. Mines and Geology Bull. 58.

Gresens, R. L., 1969, Blueschist alteration during serpentinization: Contr. Mineral. Petrol., v. 24, p. 93-113.

Higgins, M. W., 1971, Cataclastic rocks, U. S. G. S. Professional Paper 687.

Hsü, K. J., 1968, Principles of melanges and their bearing in the Franciscan-Knoxville paradox: Geol. Soc. America, v. 79, p. 1063-1074.

Hsü, K. J., 1971, Franciscan melanges as a model for eugeosynclinal sedimentation and underthrusting tectonics: Jour. Geophysical Research, v. 76, p. 1162-1170.

Huntting, M. T., Bennet, W. A. G., Livingston, V. E., Jr., and Moen, W. S., 1961, Geologic map of Washington: Washington Div. Mines and Geology Map, 1:500,000.

Johnson, S. H., and Couch, R. W., 1970, Crustal structure in the north Cascade Mountains of Washington and British Columbia from seismic refraction measurement: Seismol. Soc. America, v. 60, no. 4, p. 1259-1269.

Kerr, P. F., 1959, Optical Mineralogy: McGraw-Hill Book Company, New York, 442 pages.

Kingma, J. T., 1974, The geologic structures of New Zealand: John Wiley and Sons, New York, 407 pages.

Kurata, Hisayuki, and Banno, Shoshei, 1974, Low grade progressive metamorphism of pelitic schists of the Sazare area, Sanbagawa Metamorphic Terrane in central Sikoku, Japan: Jor. of Petrology, v. 15, part 2, p. 361-382.

Landis, C. A., 1971, Graphitization of dispersed carbonaceous material in metamorphic rocks: Contr. Mineral. and Petrol., v. 30, p. 34-45.

Lanphere, M. A., and Reed, B. L., 1973, Timing of Mesozoic and Cenozoic events in Circum-Pacific North America: Geol. Soc. America, v. 84, p. 3773-3782.

Lawrence, R. D., Plate tectonic interpretation of major structures, northern Cascade Range, Washington: unpublished manuscript.

Lawrence, R. D., Tectonic analysis of possible subduction complex of the White Chuck Mountain-Illabot Peaks area, North Cascades, Washington; unpublished manuscript.

Lawrence, R. D., and Milnes, P. T., 1976, Late stress systems deduced from kins in Shuksan Schists, White Chuck Mountain and Illabot Peaks area, Washington: Geol. Soc. America Abstr. with programs, v. 8, no. 3, p. 389.

McTaggart, K. C., and Thompson, R. M., 1967, Geology of part of the northern Cascades in southern British Columbia: Canadian Jour. Earth Sciences, v. 4, p. 1191-1228.

McTaggart, K. C., 1970, Tectonic history of the northern Cascade Mountains: Geol. Assoc. of Canada, Special Paper No. 6, p. 137-149.

Mattinson, J. M., 1970, Uranium-lead chronology of the northern Cascade Mountains, Washington: Geol. Soc. America Abstr., v. 2, no. 2, p. 116.

Mattinson, J. M., 1972, Ages of zircons from the northern Cascade Mountains, Washington: Geol. Soc. America, v. 83, p. 3769-3784.

Miller, G. M., and Misch, Peter, 1963, Early Eocene angular unconformity at the western front of the Northern Cascades, Whatcon County, Washington: Bull. American Assoc. Petrol. Geol., v. 47, p. 163-174.

Misch, Peter, 1964, Age and determinations on crystalline rocks of Northern Cascade Mountains, Washington, in Kulp, J. L., and others, Investigations in isotopic geochemistry: U. S. Atomic Energy Commission, Pub. NYO-7243 App. D., p. 1-15.

________________, 1966, Tectonic evolution of the Northern Cascades of Washington state; H. C. Cunning and W. H. White (eds.): Tectonic history and mineral deposits of the western Cordillera: Canadian Inst. Mining and Metallurgy Sp., v. 8, p. 101-148.

Misch, Peter, 1969, Paracrystalline microboudinage of zoned grains and other criteria for synkinematic growth of metamorphic minerals: Am. Jour. Science, v. 272, p. 629-656.

_______________, 1971, Metamorphic facies types in North Cascades: Abstr. in Metamorphism in the Canadian Cordillera: Geol. Assoc. Can. Cordilleran Section, Programs and Agstracts, p. 22-23.

_______________, 1973, The North Cascades in geotectonic perspective: Geol. Soc. America Abstr. with Programs, v. 5, no. 1, p. 82.

Monger, J. W. H., and Ross, C. A., 1971, Distribution of Fusulinaceans in the western Canadian Cordillera: Can. Jour. Earth Sciences, v. 8, p. 259-278.

Monger, J. W. H., Souther, J. C., and Gabrielse, H., 1972, Evolution of the Canadian Cordillera: a plate tectonic model: Am. Jour. Science, v. 272, p. 577-602.

Miyashiro, Akiho, 1973, Metamorphism and metamorphic belts; John Wiley and Sons, New York, 492 pages.

Page, B. M., 1970, Sur-Nacimiento fault zone of California: continental margin tectonics: Geol. Soc. America, v. 81, p. 667-690.

Paterson, M. S., and Weiss, L. E., 1966, Experimental deformation and folding in phyllites: Geol. Soc. America, v. 77, p. 343-374.

Pettijohn, F. J., Potter, P. E., and Siever, Raymond, 1973, Sand and sandstone: Springer-Verlag, New York, 618 pages.

The facies of metamorphism, 1970, V. S. Sobolev (ed.), translated by D. A. Brown; Dept. of Geology Publication No. 214, Australian National University, Canberra, Australia, 417 pages.

Dobretsov, N. L., Khlestov, V. V., and Sobolev, 1972, The facies of regional metamorphism at moderate pressures, V. S. Sobolev (ed.), translated by D. A. Brown: Dept. of Geology Publication No. 236, Australia National University, Canberra, Australia, 297 pages.

Spry, Alan, 1974, Metamorphic textures: Pergamon Press, Oxford, 350 pages.

Tabor, R. W., and Crowder, D. F., 1969, On batholiths and volcanoes-intrusion and eruption of Late Cenozoic magmas in the Glacier Peak area, North Cascades, Washington: U. S. G. S. Professional Paper 604.

Turner, F. J., and Weiss, L. E., 1963, Structural analysis of metamorphic tectonites: McGraw-Hill Book Company, Inc., New York, 545 pages.

Turner, F. J., 1968, Metamorphic petrology: McGraw-Hill Book Company, Inc., New York, 403 pages.

Vance, J. A., 1957, The geology of the Sauk River area in the Northern Cascades of Washington: unpublished University of Washington Ph. D. thesis.

____________, 1974, Mid-Paleozoic Stratigraphy and Metamorphism in NW Washington: Geol. Soc. America Abstr. with Programs, V. 6, p. 269.

Williams, Howel, Turner, F. J., and Gilbert, C. M., 1954, Petrography: W. H. Freeman and Company, San Francisco, 406 pages.

Winkler, H. G. F., 1974, Petrogenesis of metamorphic rocks, 3rd Edition: Springer-Verlag, New York, 320 pages.

APPENDIX

APPENDIX I Catalogue of Oriented Hand Specimens

Sample No.	Rock Type	S_1 (foliation)	Lineations: Mineral	Lineations: Crinkle	Axial Plane of Fold	Fold Axis	Qtz. Fabric Determined
PTM-IP-I	gm-3	N-S 64°E		N15°E 13°	F_1 N-S 64°E		
PTM-IP-II	gm-3	N15°E 70°E					
PTM-IP-III	phy	N°9E 74°E			F_2 N65°E 73°N	N65°E 32° N20°W 18° N36°E 59°	
PTM-IP-IIIa	gm-3	N14°W 74°W			F_1 N14°W 74°W		
PTM-IP-IV	gm-3	N9°W 55°E		N51°E 45°	F_1 N9°W 55°W		
PTM-IP-V	gm-3	N20°W 57°E	S81°W 50°	S12°E 14°	F_1 N20°W 57°E		
PTM-IP-VI	gm-3			S15°E 1°	F_3 N14°W 51°E	S14°E 1°	
PTM-IP-VII	gm-1						
PTM-IP-VIII	gm-3				F_3 N18°W 45°E	N2°W 21°	
PTM-IP-IX	gm-3						
PTM-IPX	gm-3						
PTM-IP-XI	gm-3	N32°W 66°W	S54°W 16°		F_1 N32°W 66°W		
PTM-IP-XII	diabase						
PTM-SMR-I	gm-2	N9°W 43°W	N53°W 25°	S26°W 19°	F_1 N9°W 43°W	$F_?$ N80°W 12°	
PTM-SMR-II	gm-3	N78°W 40°S	S52°W 25°		F_1 N78°W 40°S		
PTM-SMR-III	phy	N10°E 52°E		S85°W 53°	F_1 N10°E 52°E F_3 N10°E 16°W	N10°E 3° F_4 S85°E 53°	X
PTM-SMR-IV	gm-4	N36°W 23°E			F_1 N36°W 23°E		
PTM-Q-III	phy	N2°E 76°W			F_1 N2°E 76°W F_2 N86°E 90°	S86°W 78°	
PTM-SCW-I	protomylonite	N26°W 38°N					
PTM-SCW-II	protomylonite						
PTM-SCW-VI	hornblende gneiss						

APPENDIX I (Continued)

Sample No.	Rock Type	S_1 (foliation)	Lineations: Mineral	Lineations: Crinkle	Axial Plane of Fold	Fold Axis	Qtz. Fabric Determined
PTM-MS-I	cataclasized greenschist	N16°W 25°E	N35°E 10°		N16°W 25°E		
PTM-MS-II	phy	N5°E 23°E					
PTM-MS-IV	serpentinite	N5°W 68°E	S85°E 76°				
PTM-MS-V	phy	N83°E 72°N		N46°E 72°	F_1 N83°E 72°N	S76°W 16°	
PTM-MS-VI	phy					85°W 54°	
						N88°W 46°	
PTM-MS-VII	gm-3	N82°E 21°S		S52°W 11°	F_1 N82°E 21°S		
PTM-TC-I	phy	N40°W 50°S			N18°W 27°W	S85°W 27°	X
PTM-TC-II	phy	N5°W 80°W	S64°W 69°		F_1 N5°W 80°W		
			S22°W 37°				
PTM-TC-III	gm-4	N-S 89°W			F_1 N-S 89°W		
PTM-SCS-I	protomylonite	N50°W 49°E					
PTM-SCS-II	protomylonite	N2°E 20°W					
PTM-SCS-III	hornblende-garnet gneiss						
PTM-SCS-X	hornblende gneiss		N68°W 9°				
PTM-LL-I	gm-3	N60°W 63°E			F_1 N60°W 63°E		
PTM-LL-II	gm-3	N20°W 67°N			F_1 N20°W 67°N		
					F_3 N28°W 26°E	N20°W 14°	
						N35°W 9	
PTM-LL-III	quartz-mylonite						
PTM-LL-IV	gm-3						
PTM-LL-V	phy	N53°E 15°N		S82°W 9°		N52°W 22°	
PTM-LLW-I	gm-3	N5°W 14°W			F_1 N5°W 14°W		
PTM-LLW-II	gm-3	N60°W 36°N	N53°W 1°				
PTM-LLW-III	mylonite	N25°E 65°N					X
PTM-LLF-I	phy	N20°W 45°N			F_1 N20°W 45°N	N40°E 40°	X
						F_2 N45°E 42°	
					F_3 N15°W 50°W	N15°W 10°	

APPENDIX I (Continued)

Sample No.	Rock Type	S_1 (foliation)	Lineations: Mineral	Lineations: Crinkle	Axial Plane of Fold	Fold Axis	Qtz. Fabric Determined
PTM-LIF-II	gm-4	N85°W 42°N			F_1 N85°W 42°N		
PTM-LIF-III	gm-3	N40°W 35°E			F_1 N40°W 35°E		
PTM-ICF-I	phy	N23°W 83°E			F_1 N23°W 83°E		X
					F_3 N13°E 55°E	N19°W 15°	
					F_4 N89°E 72°N	S89°W 76°	
PTM-ICF-II	gm-3	N81°W 65°N			F_1 N81°W 65°N		
PTM-WBR-II	gm-3	N66°W 12°N			F_1 N66°W 12°N		
PTM-WBR-III	phy	N28°E 54°E	S13°W 19°		F_1 N28°E 54°E	F_2 S63°E 51°	
PTM-WBR-IV	cataclasized greenschist						
PTM-WBR-V	phy	N10°W 72°N	S12°E		F_1 N10°W 72°N		
PTM-WBR-VI	gm-3	N85°W 20°N	N8°E 14°		F_1 N85°W 20°N	$F_?$ N80°W 7°	
PTM-HR-I	gm-3	N63°W 40°N	N86°W 0°	N9°E 31°			
PTM-HR-II	gm-3	N49°W 83°S			F_1 N49°W 83°S		
PTM-IR-VI	gm-4	N35°W 62°S		S74°W 55°			
PTM-IR-IX	phy	N9°E 85°W	N10°E 6°		F_1 N9°E 85°W		
					F_3 N10°W 40°W	S15°W 15°	
PTM-HC-I	gm-4	N35°W 57°N	N28°E 58°		F_1 N35°W 57°N		
PTM-HC-II	gm-4					S25°W 34°	
PTM-HC-III	diabase						
PTM-HC-IV	gm-4	N65°W 57°N	N65°W 1°		F_1 N65°W 57°N		
PTM-HC-V	gm-4	N15°W 55°N	N15°W 8°	N22°E 31°	F_1 N15°W 55°N		
					F_3 N20°W 32°S	S20°E 3°	
PTM-HC-VI	gm-4	N45°E 56°W	N22°E 17°		F_1 N45°E 56°W		
PTM-HC-VII	phy	N9°E 50°N		N79°W 43°	F_1 N9°E 50°N		
PTM-HC-IX	gm-4	N5°W 59°W	S80°W 61°		F_1 N5°W 59°W		
PTM-EC-I	gm-3				N40°W 90°	N40°W 40°	
PTM-EC-II	gm-3	N82°E 47°S			F_1 N82°E 47°S		
PTM-LT-I	meta-igneous rock	N54°W 29°N			F_1 N54°W 29°N		
PTM-LT-III	gm-3	N24°W 16°N			F_1 N24°W 16°N		

APPENDIX I (Continued)

Sample No.	Rock Type	S_1 (foliation)	Lineations: Mineral	Lineations: Crinkle	Axial Plane of Fold	Fold Axis	Qtz. Fabric Determined
PTM-LT-IV	gm-3						
PTM-LT-V	gm-3	N78°W 66°N		N74°W 33°		S68°E 62°S	
PTM-LT-VII	gm-3	N60°W 81°S	S75°W 76°		F_1 N60°W 81°S		
PTM-LT-VIII	gm-3	N35°W 65°N			F_1 N35°W 65°N		
PTM-LT-IX	gm-3	N30°W 31°N			F_1 N30°W 31°N		
PTM-OR-I	gm-3	N52°W 41°N	S63°E 6°		F_1 N52°W 41°N		
PTM-OR-II	gm-3	N27°E 72°E			F_1 N27°E 72°E		
PTM-OR-III	serpentinite						
PTM-OR-V	serpentinite				horizontal	N48°E 9°	
PTM-OR-VI	gm-1						
PTM-OR-VII	gm-2				F_2 N27°E 47°N	N27°E 24°	
PTM-OR-VIII	gm-2	N32°E 45°E			F_1 N32°E 45°E	F_2 N2°E 27°	
PTM-SZ-I	serpentinite						
PTM-GC-I	gm-1						
PTM-GC-II	gm-1						
PTM-RIP-IV	gm-1		N65°E 22°				
PTM-RIP-V	phy	N8°W 89°W					
PTM-RIP-VI	phy	N13°W 72°E				F_3 N18°W 31° F_4 S81°E 54°	
PTM-RIP-VI	phy (sheared)						
PTM-RIP-VII	gm-1						
PTM-RIP-VIII	phy	N5°W 59°E			F_1 N5°W 59°E	F_3 S1°E 30° F_4 N72° 62°	
PTM-RIP-IX	gm-3	N51°W 41°N			F_1 N51°W 41°N		
PTM-RIP-X	gm-3	N39°W 37°N			F_1 N39°W 37°N		
PTM-RIP-XI	gm-3	N5°W 29°E	N50°E 25°		F_1 N5°W 29°E		
PTM-RIP-XII	gneiss						
PTM-RIP-XIV	gm-1						
PTM-SC-II	phy (mylonite)	N45°W 40°N					
PTM-SC-IV	phy	N17°E 45°E		N46°E 38°			

APPENDIX I (Continued)

Sample No.	Rock Type	S_1 (foliation)	Lineations: Mineral	Lineations: Crinkle	Axial Plane of Fold	Fold Axis	Qtz. Fabric Determined
PTM-SC-VI	grn-1						
PTM-SC-VIII	phy (mylolite)						
PTM-SC-IX	Swauk	N75°E 60°N					
PTM-SC-X	Swauk	N75°E 60°N					
PTM-SC-XI	Swauk	N58°E 67°N					
PTM-SC-XII	Swauk	N69°W 87°S					
PTM-SC-XIV	grn-1						
PTM-SC-XV	grn-1						
PTM-SI-I	grn-3						
PTM-SI-II	grn-3						
PTM-SM-I	grn-4	N5°W 68°W			F_1 N5°W 68°W		
PTM-SCF-I	phy					S22°W 19°	