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Structure and Petrology of the Grandy Ridge-Lake Shannon Area, North Cascades, Washington

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MASTER'S THESIS

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STRUCTURE AND PETROLOGY OF THE

GRANDY RIDGE-LAKE SHANNON AREA,

NORTH CASCADES, WASHINGTON

By

Moira T. Smith

Accepted in Partial Completion

of the Requirements for the Degree

Master of Science

Dean of Graduate School

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MASTER'S THESIS

Moira Smith
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STRUCTURE AND PETROLOGY OF THE GRANDY RIDGE-LAKE SHANNON AREA, NORTH CASCADES, WASHINGTON

A Thesis
Presented to
the Faculty of
Western Washington University

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ABSTRACT

The Grandy Ridge-Lake Shannon area contains four major lithologic units: the Chilliwack Group, the Yellow Aster Complex, and the informally named "chert/basalt" and "Triassic dacite" units. The units are juxtaposed along anastomosing low angle faults of Late Cretaceous age. Additional deformation took place at a more recent time.

Lithologies of the Chilliwack Group predominate in the study area, with fine-grained sedimentary rocks of the lower clastic sequence present at lower elevations in the map area, and relatively mafic volcanic rocks present mostly at higher elevations. Sedimentary rocks in the vicinity of Upper Baker Dam, originally mapped as part of the Nooksack Group, are in this study assigned to the Chilliwack Group, based on lithologic, metamorphic, and structural considerations. The Chilliwack Group contains metamorphic mineral assemblages indicative of high pressure-low temperature metamorphic conditions. Reibeckite and crossite are reported for the first time in this unit.

Lithologies of the Chilliwack Group are present at the structurally lowest levels in the map area. A low angle thrust contact separates these rocks from overlying rocks of the Triassic dacite unit in many locations. The chert/basalt unit appears to be the structurally highest unit in the study area.

Evidence of two deformations is present in the Chilliwack Group. An early (D_1) deformation is manifested by a persistent, low angle, slaty to phyllitic cleavage (S_1) in fine-grained rocks, a northwest-trending stretching lineation (L_1) in volcanic and coarse clastic rocks, and by infrequent northeast-trending folds. The second deformation (D_2) is less extensive, primarily manifested by northwest-trending F_2 folds.

The L_1 lineations consist of stretched clasts and amygdules, and are most common along the top of Grandy ridge and in the vicinity of Upper Baker Dam. They are interpreted to represent the direction of shearing during the first deformation. Study of shear sense indicators suggests that the upper plate moved northwest relative to the lower plate. Strain magnitudes associated with these L_1 lineations vary, but average approximately 3.5:1 in the XZ principal plane. This evidence suggests a minimum of several kilometers of northwest displacement of the approximately one kilometer thick section of rock exposed in the study area. The first deformation appears to have post-dated crystallization of the high pressure minerals, as evidenced by the presense of cracked and boudinaged lawsonite grains.

Evidence for northwest-southeast directed movement is present elsewhere in the Chilliwack Group, and is also present along segments of the Shuksan Fault. This movement may be related to emplacement of the structural units present in the western North Cascades.

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Conversations with Dave Silverberg, Jeff Jones, Dave Blackwell, Greg Reller, Chuck Ziegler, and Rowland Tabor regarding the complexities of North Cascades Geology are greatly appreciated. Mike Hylland, Jeff Jones, Jennie DeChant, Ned Brown, and Keith Marcott accompanied me in the field one or more times. Jim Talbot provoked my interest in and explained the complexities of strain analysis. The assistance of George Mustoe, Patty Combs, and Vicki Critchlow has been invaluable.

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INTRODUCTION

The primary objective of this study was to map and study in detail the pre-Tertiary units that crop out in an area around Grandy Ridge and upper Baker Dam, and additionally to characterize the metamorphic structures and fabrics in the rock units present in this and the surrounding region. This study is part of a larger effort to map and interpret structures and lithologic units in the western North Cascades, in order to better interpret the tectonic events which formed this portion of the North American Cordillera.

The study area is situated in the western North Cascades, approximately 50 km. east of Bellingham (Figure 1). The area mapped includes a northwest-southeast-trending ridge (informally known as Grandy ridge) and the bedrock knobs present around Upper Baker Dam. The map area is bordered on the west by the field area of Blackwell (1983) and to the north by the field area of Ziegler (1985). Portions of the 1952 Hamilton and Lake Shannon 15 minute topographic quadrangle maps were enlarged to a scale of four inches equivalent to one mile (1 : 15,840) to use as base maps. In addition, an area on the east side of Lake Shannon, including the Thunder Creek and Jackman Creek drainages, and areas to the west of the map area, including the Wanlick Creek and South Fork Nooksack River drainages, were used for observation and data collection for structural analysis (Figure 1). This extended study area is bounded on the west by the Twin Sisters dunite body, and on the east by the Shuksan Fault.

Relief in these areas is moderate, with elevations ranging from 550 to approximately 4000 feet. Since the area is entirely below treeline, the vegetation is dense, particularly in recent clearcuts, which comprise well over half the area. Exposure is moderate, with numerous roadcuts, steep stream valleys and cliffs yielding the best exposures.

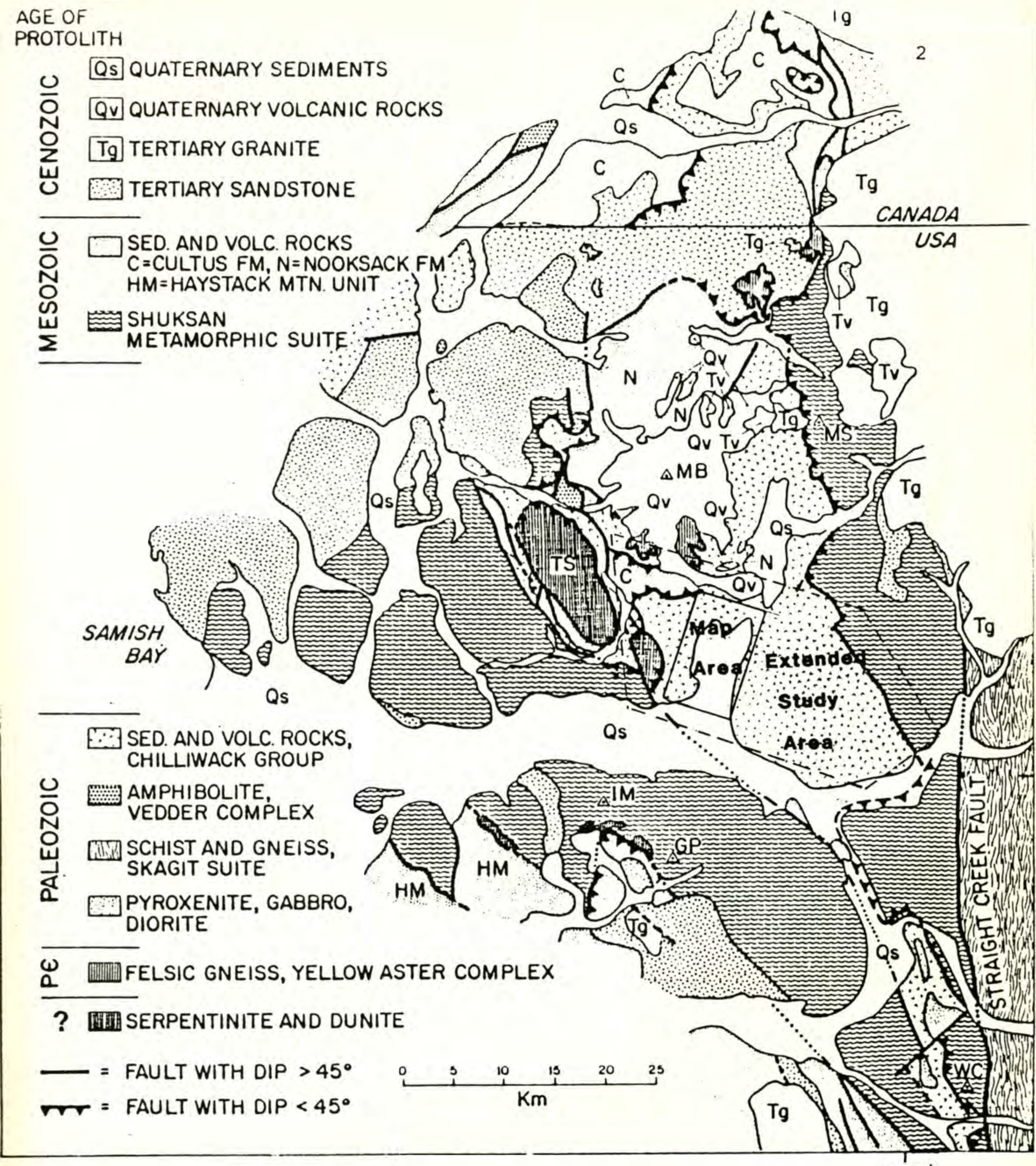


FIGURE 1: Regional geologic map of the western North Cascades, based on work by Vance (1957), Misch (1966, 1977), Monger (1966), Bechtel (1979), Vance and others (1980), Rady (1981), Frasse (1981), R. Lawrence (personal communication, 1981), Johnson (1982), Brown and others (1981), Blackwell (1983), Sevigny (1983), Jones (1984), Jewett (1984), Silverberg (1985), Ziegler (1985), and by P. Leiggi of Western Washington University. Figure from Brown (in press).

IM = Iron Mountain, MB = Mount Baker, TS = Twin Sisters, MS = Mount Shuksan, GP = Gee Point, WC = White Chuck Mountain.

This study involved approximately 50 days of fieldwork during the summers of 1984 and 1985.

GEOLOGIC SETTING AND PREVIOUS WORK

Until fairly recently, most work in the western North Cascades has been carried out in a reconnaissance fashion due to the inaccessability and precipitous nature of the terrain. Better access due to prolific road building has afforded a more detailed look at many areas. The following paragraphs summarize some of the more important contributions and introduce the geologic units and structures of the northwest Cascades and the geology of the areas in and around the current study area.

LITHOLOGIES

Chilliwack Group and Cultus Formation The earliest studies of the Chilliwack Group and Cultus Formation were focused primarily on areas well to the north of the present study area, in or near the type section in the Chilliwack Valley, British Columbia. In the type area, Daly (1912) mapped a lower sedimentary section termed the Chilliwack Series and an upper section of andesitic volcanics termed the Chilliwack Volcanic Series, which he deduced to be of Carboniferous age. He also mapped Mesozoic strata of the Cultus Formation in that area.

More recent contributions, notably by Danner (1957, 1966) and Monger (1966, 1977) have further defined the ages and lithologies present in the Chilliwack Group and Cultus Formation. Danner (1957, 1966) focused primarily on the fossiliferous limestones in the Chilliwack Group, ascribing Devonian, Late Mississippian to Early Pennsylvanian, and Early Permian dates to them. On the basis of these findings, he divided the Chilliwack Group into the lower Red Mountain Formation, consisting primarily of fine-grained volcanic siltstone and sandstone overlain by the Mississippian to Pennsylvanian limestone, and the Black Mountain Formation, consisting primarily of sandstone, massive cobble conglomerate, volcanic rocks, and the Permian limestone. Danner additionally mapped occurrences of Chilliwack Group limestone throughout the Cascades.

Monger further studied the lithologies and structures in the Chilliwack Group and Cultus Formation in the type area. His findings are summarized in Table 1. Monger (1966) restricted Danner's usage of Red and Black Mountain Formations to the limestones, and developed the following stratigraphy: a lower clastic sequence consisting of bedded volcaniclastic siltstone, with minor volcanic arenite, conglomerate, limestone lenses and volcanic rocks; the Red Mountain Formation limestone; an upper clastic sequence of coarse volcanic arenite, cobble conglomerate, and minor siltstone, argillite, and volcanic rocks; the Permian Black Mountain limestone; and a Permian volcanic sequence composed primarily of basic to intermediate flow rocks and tuffs. The contact between these and strata of the Cultus Formation was observed by Monger (1966) to be disconformable in the type area.

Monger (1966) characterized the structure present in the type area of the Chilliwack Group as two nappes overlying relatively autochthonous rocks. Additionally, he found the Chilliwack Group and Cultus Formation to contain isoclinal recumbant folds with northeast-trending axes. These features have been noted in other areas, e.g., Misch (1966), Jones (1984) and Blackwell (1983).

<u>Other Units</u> A unit consisting of ribbon chert, argillite, and and titaniferous-augite-bearing basalt, previously mapped as part of the Chilliwack Group, has been informally termed the "chert/basalt" unit. First recognised by Testa and others (1982), these rocks have since been

Table 1. CHILLIWACK GROUP STRATIGRAPHY
(from Monger, 1966)

Age		Name and apparent thickness (feet)	Lithology
Late Jurassic Middle Jurassic Early Jurassic Late Triassic		CULTUS FORMATION 4,000	Fine to medium grained volcanic arenites, argillites and slates; very minor flows
		disconformity	
Early Permian (Leonardian)	CHILLIWACK GROUP	Permian volcanic sequence 2,000-700 (conformable)	Altered basic to intermediate flows, tuffs, minor chert and minor argillite
Early Permian (Leonardian)	CHILLIWACK GROUP	Permian limestone 300 (conformable)	Limestone, typically cherty; in part laterally equivalent to the Permian volcanic sequence
Permian and (?) Pennsylvanian	CHILLIWACK GROUP	Upper clastic sequence 800-450 (conformable)	Coarse to medium-grained volcanic arenites, argillites, local conglomerates, tuffaceous towards top. This sequence may include one or more disconformities
Early Pennsylvanian (Morrowan)	CHILLIWACK GROUP	Red Mountain Limestone (restricted from Danner, 1957) 100 (conformable)	Limestone, typically argillaceous
Early Pennsylvanian (?)	CHILLIWACK GROUP	Lower clastic sequence 2,500 (base not recognized)	Argillites, fine to medium-grained volcanic arenites

mapped by numerous workers, including Lieggi (in progress), Sevigny (1983), Blackwell (1983), Jones (1984), Ziegler (1985), and Brown (unpublished). On the basis of differences in mineralogy, deformational history, and geochemistry, these rocks appear to represent a unit distinct from the Chilliwack Group.

Blackwell (1983) mapped large amounts of dacite and siltstone in areas around Loomis Mountain. Fossils from limestone clasts in a breccia found near the top of the dacite section yielded a Triassic age, and the dacite flows appear to interfinger with the Triassic Cultus Formation at the top of the section. This informally named "Loomis Mountain dacite center" is thought by Blackwell (1983) to be related to the Permian volcanic sequence in the Chilliwack Group or to be a previously unrecognised facies of the Cultus Formation. It will be referred to in the text as the Triassic dacite unit.

The Nooksack Group is a thick sequence of siltstone and volcanic arenite, with lesser amounts of conglomerate, argillite, and volcanic rock (Misch, 1966). Abundant Buchia, Pleuromya, belemnites, and other diagnostic fossils yield a Late Visean (Jurassic to Cretaceous) age (Danner, 1957).

The Precambrian Yellow Aster Complex, named by Misch (1966), is a diverse grouping of metaplutonic rocks, ranging from gabbro to trondjemite in composition. These rocks are present as tectonic slices along major faults and have been interpreted by Misch (1966) to represent slices of the original autochthonous basement.

Other units present in the western North Cascades include the Shuksan Suite, composed primarily of quartzose phyllite and greenschist; the Vedder Complex; the Wells Creek Volcanics; and various ultramafic bodies, including the Twin Sisters dunite body. None of these units are present in the map area, although all but the Wells Creek Volcanics are present in the extended study area.

STRUCTURE

The rocks of interest to this study lie west of the Eocene right-lateralStraightCreekfault(Vance, 1957), a major tectonic boundary.

Misch (1966) and his students at the University of Washington are primarily responsible for establishing the regional distribution of the various units found in the North Cascades and a basic structural interpretation of the area. Misch (1966, 1977) interprets the basic structure of the western North Cascades as two thrust plates overlying a relative autochthon, with rocks in the lower sections being exposed in the core of a large northwest-southeast-trending anticline known as the Mount Baker window. A structural stratigraphy based on this interpretation is outlined in Figure 2. Relatively autochthonous rocks of the Nooksack Group and Wells Creek Volcanics are separated from the overlying Church Mountain plate by the Church Mountain thrust fault. The Church Mountain plate, containing the Chilliwack Group and Cultus Formation, is separated from overlying rocks of the Shuksan Suite, a unit consisting of greenschist and phyllite, by the Shuksan thrust fault. The Shuksan thrust is characterized by the presence of a steep root zone and a wide imbricate zone of anastomozing faults containing exotic fragments of Yellow Aster Complex, Vedder Complex, and ultramafic rocks, thought to represent slices of the underlying basement (Misch, 1966). Movement along these thrusts is thought to have occurred in the Late Cretaceous, with the sense of motion dominantly westward (Figure 3).

METAMORPHISM

Beatty (1974) studied the Permian volcanic sequence of the Chilliwack

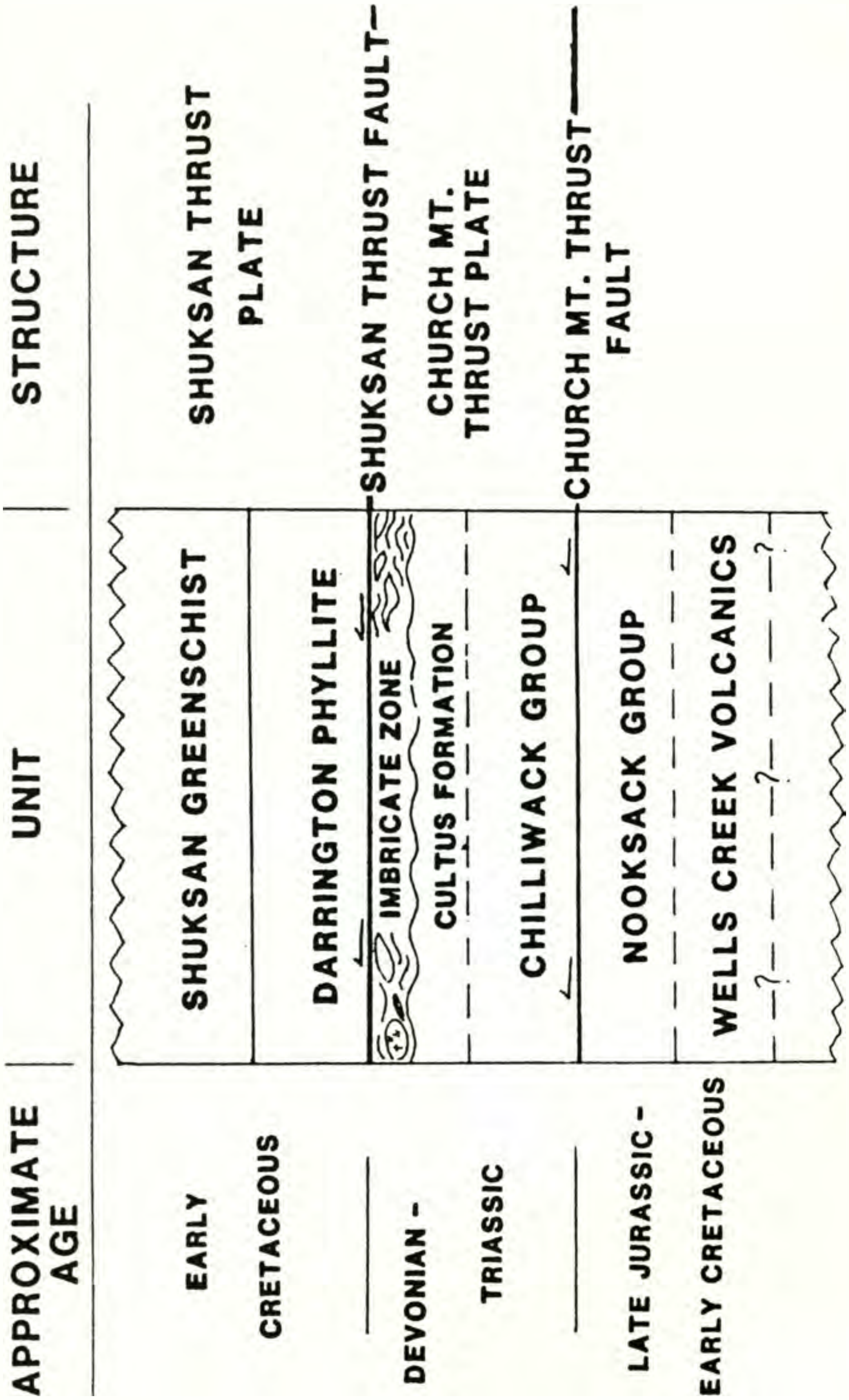


Figure 2: Diagrammatic structural stratigraphy of the western North Cascades (based on Misch, 1966).

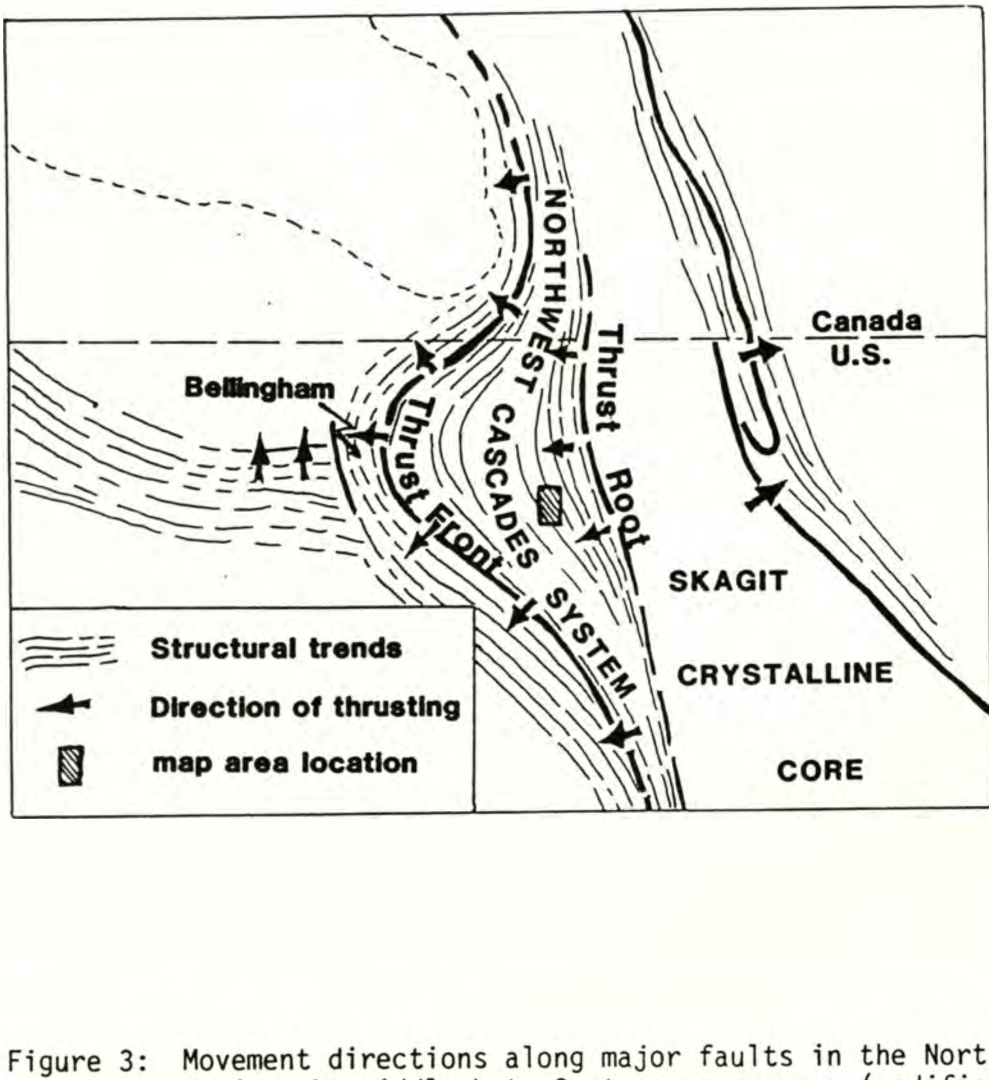


Figure 3: Movement directions along major faults in the North Cascades during the middle Late Cretaceous orogeny (modified slightly from Misch, 1966).

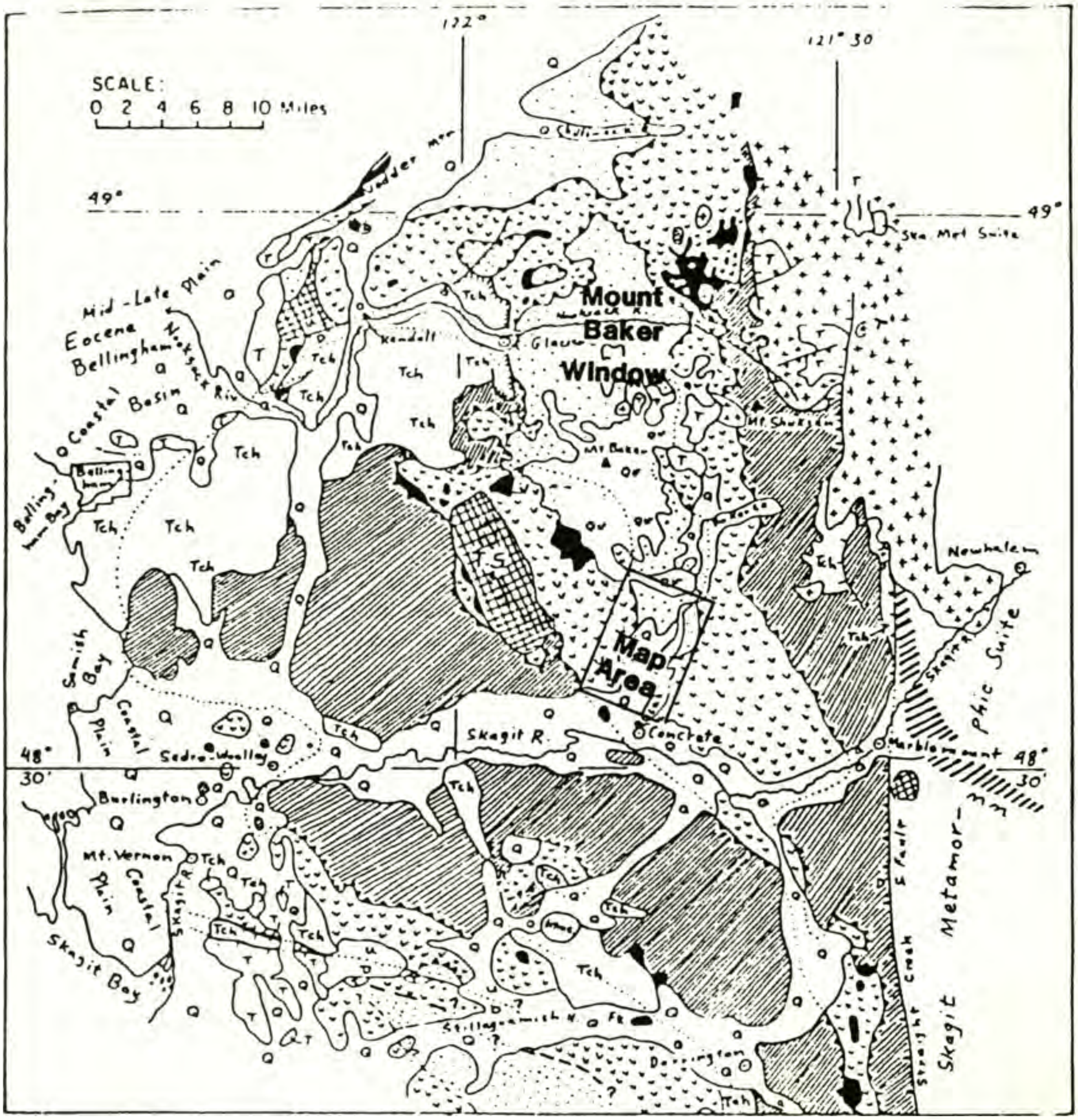
Group in the type area in Chilliwack Valley, British Columbia, and found an increase in metamorphic grade from west to east as follows: prehnite-chlorite, pumpellyite-lawsonite-chlorite, pumpellyite-actinolite, and epidote-actinolite. This change in grade was attributed to increased depth of burial towards the east.

Brown and others (1981) defined the characteristic metamorphic assemblages present in the North Cascades. The Chilliwack Group and Cultus Formation are characterized by assemblages containing lawsonite, aragonite, pumpellyite, epidote, and hematite, with ubiquitous albite, chlorite, and quartz. These high pressure - low temperature assemblages are thought to reflect conditions found in a subduction zone environment. Rocks in the Nooksack Group are similar, but contain prehnite, and calcite instead of aragonite.

Geology of the Grandy ridge/Upper Baker Dam area Reconnaissance mapping by Misch (1966) showed the present study area to contain the southern extent of the Mount Baker window (also referred to as the Concrete half window). Misch mapped Nooksack Group lithologies in the northeastern quarter of the map area, separated from the Chilliwack Group by the low angle Church Mountain thrust fault (Figure 4).

Danner (1966) mapped three small limestone bodies believed to be Pennsylvanian in age (part of Monger's (1966) Red Mountain Formation) in the vicinity of Dock Butte, on the western edge of the map area.

Many areas bordering the present study area have been mapped or studied in some detail (Figure 5). Frasse (1981) mapped an area that includes part of the southwest portion of the map area, considering it to contain mostly Chilliwack Group lithologies, with a few small tectonic fragments of Yellow Aster Complex cropping out along the top of Grandy



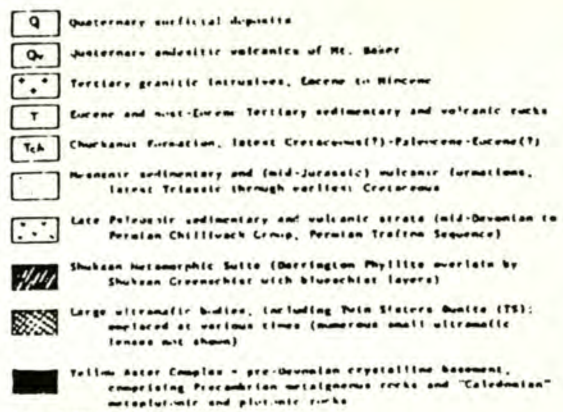


Figure 4: Geologic sketch map of the western North Cascades from Misch (1977), showing locations of map area and the Mount Baker window.

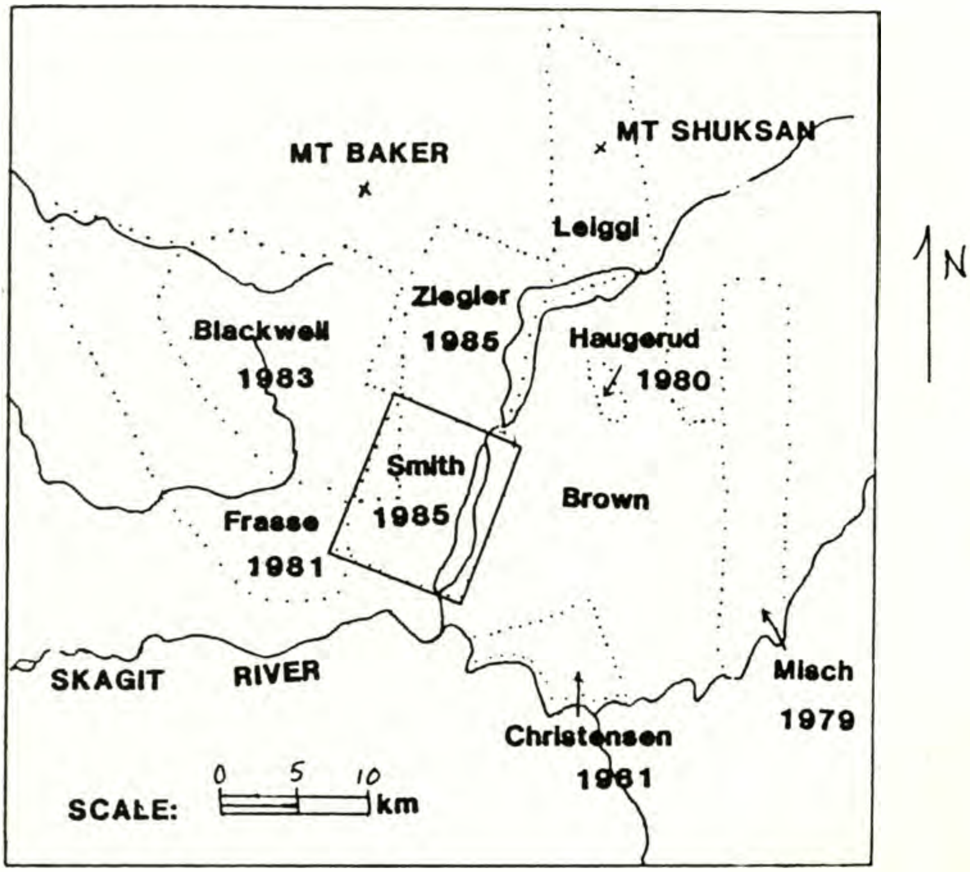


Figure 5: Approximate boundaries of study areas located near the present study area.

Ridge. Blackwell (1983) mapped an area to the west, projecting several structures into the map area, including a large tectonic block of chert/basalt unit, and a fault separating Chilliwack Group proper from his Loomis Mountain dacite center. He additionally reexamined the Yellow Aster Complex fragments mapped by Frasse (1981) on Grandy Ridge and interpreted them to be Chilliwack Group basalts.

An area bordering the northern edge of the field area has been mapped by Ziegler (1985), who projected numerous low angle structures southward until they are covered by more recent Mount Baker volcanics. Large areas of fine-grained sedimentary rocks, formerly assigned to the Nooksack Group in the Mount Baker window by Misch (1966), were reassigned to the Chilliwack Group by Ziegler (1985).

Christensen (1981) studied the Chilliwack Group structure and geochemistry in an area to the southeast of the study area, finding the volcanic rocks to reflect a tholeiitic to calc-alkaline trend. He found the Chilliwack Group to be extensively tectonised along low angle faults, so that no coherent stratigraphy could be deduced.

An area to the east of Lake Shannon has been mapped by Brown (unpublished), who found the chert/basalt unit to structurally overly the Chilliwack Group along a low angle thrust contact.

OBJECTIVES

The two primary objectives of this study were to map and interpret structures and lithologic units in the map area and to characterize the nature and extent of deformation and the direction of movement in areas of penetratively sheared or faulted rocks in the region around the map area. Hence, unlike most previous work, the main emphasis of this study was a characterization of deformation within the Chilliwack Group and other units, rather than the relationship between units.

Other goals were to establish:

A) The stratigraphy, depositional environments, and metamorphic histories of the units in the map area;

B) The validity (or lack thereof) of the thrust stratigraphy and the Mount Baker window conceptsas proposed by Misch (1966) in the map area;

C) The relationship of structures and lithologic units in the map area to those in adjacent areas.

LITHOLOGIES

Chilliwack Group

Rocks belonging to the Chilliwack Group comprise nearly all of the map area, with the exception of the chert/basalt unit, the Tertiary Baker Volcanics, and one small block that is questionably part of the Yellow Aster Complex.

Positive identification of many rocks was difficult. Large thicknesses of fine-grained clastic rocks are common in the lower clastic sequence of the Chilliwack Group, the Nooksack Group, and in the Cultus Formation. They are generally differentiated on the basis of fossil evidence, which is normally fairly abundant in the latter two and missing from the former. Where fossil evidence is lacking, as is the case in the map area, positive identification is difficult or impossible. Many of the sedimentary rocks in the northeastern portion of the map area were previously mapped as Nooksack Group by Misch (1966) but are here assigned to the Chilliwack Group, for reasons discussed in a later section. Coarse-grained igneous rocks, apparently plutonic in origin, are common in the map area, particularly on the south end of Grandy ridge. Previously assigned to the Yellow Aster Complex by Frasse (1981), they were later reassigned to the Chilliwack Group volcanic sequence by Blackwell (1983). In this study they are tenatively assigned to the Chilliwack Group. A characteristic apparently unique to the Chilliwack Group in the map area is the presence of sodic amphibole in a number of volcanic rocks.

Due to a high degree of tectonic fragmentation, poor exposure, lack of fossils, and rapid facies changes, relationships of units and positive correlation of the Chilliwack Group within the map area to the units found in the type area is difficult. A generalized stratigraphic column for the area is presented in Figure 6. Monger's (1966) lower clastic sequence of rhythmically bedded sandstone and siltstone appears to be fairly well represented in the lower elevations throughout the map area. A sequence of fairly coarse grained conglomerate, sandstone, siltstone, tuff, and minor flows on the south side of Grandy Ridge may be correlative with the upper clastic sequence. Abundant mafic volcanic rocks capping the top of Grandy Ridge may be part of the Permian volcanic sequence. Limestone is present in minor amounts, with recrystallization and limited lateral extent making positive identification of units difficult. Widespread dacite occurrences in the northern half of the field area are probably correlative with the Triassic dacite center of Blackwell (1983).

In this section, volcanic, clastic, and carbonate rocks will be described separately, the volcanic rocks by order of abundance, as they show little internal stratigraphic order, and the clastic rocks in presumed stratigraphic order. Sections on depositional environment and metamorphism will follow. Complete mineral assemblages for selected samples are listed in Appendix 1.

VOLCANIC ROCKS

Volcanic rocks dominate the lithologies present above an elevation of approximately 2700 feet throughout the study area, with sporadic occurrences below this elevation. In most locations, the contact of the volcanic unit with underlying sedimentary rocks is not exposed; but where contacts are exposed they are tectonic, particulary to the north.

Compositionally, basalt or basaltic andesite and dacite are the most voluminous volcanic rocks. Andesite is relatively rare. Texturally, the volcanic rocks range from flow rocks to lapillistone to very fine-grained

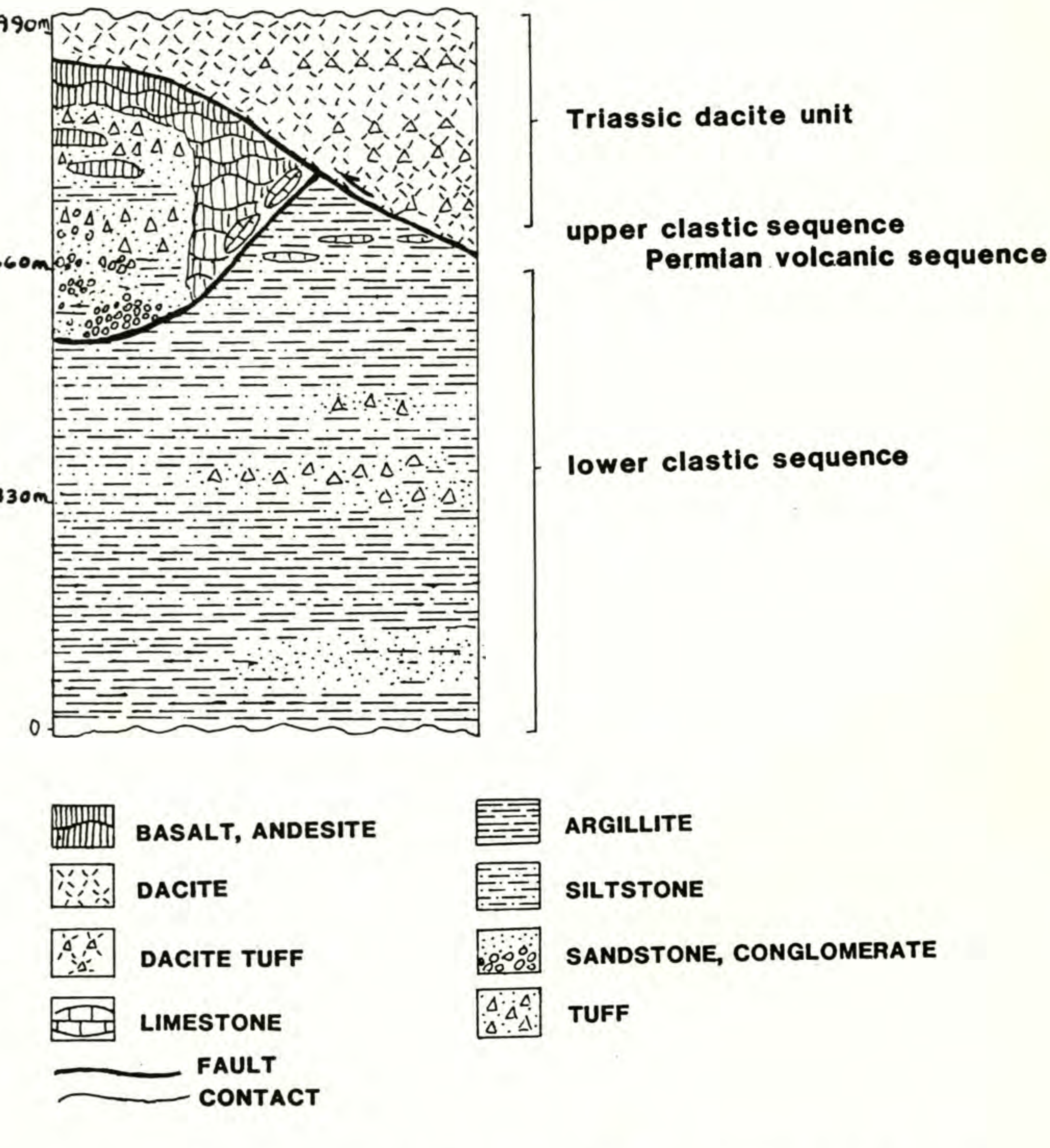


Figure 6: Generalized stratigraphic column of the Chilliwack Group and Triassic dacite unit in the Grandy ridge/Upper Baker Dam area. Thicknesses are approximate.

crystal, lithic, and vitric tuffs. Hypabbysal equivalents of the more basic varieties are very common.

DACITE

Large, often cliffy exposures of dacite are common, particularly in the northwest portion of the map area, along the north- and east-facing slopes of Grandy Ridge. The structurally lowest boundary of the dacite, where observable, is in fault contact with sheared, black, argillaceous sedimentary rocks lying beneath.

When these dacite outcrops are projected south and westward into the field area of Blackwell (1983), they appear to be associated with the Triassic dacite unit, dated as such by the presence of an interbedded sedimentary breccia containing fossiliferous limestone in the Loomis Mountain area. No fossils were found in association with dacite exposures in the map area, but lithologic similarities and structural setting suggest that they can be correlated with some confidence.

Outcrops of flow rocks and crystal tuffs are generally massive, blocky, and white to tan weathering, with few observable primary or metamorphic structures. Fresh surfaces are generally white to apple green or gray, often with a distinctive network of randomly oriented, weathered cracks. Dacitic lapillistones, often highly sheared, are common on the north-facing side of Grandy ridge. They are light green to maroon and form thick layers interbedded with the flows.

Petrographically, very fine-grained porphyritic flow rocks are the most common lithology. Plagioclase and quartz comprise most of the groundmass and phenocrysts. Feldspar phenocrysts are generally euhedral, while quartz crystals are strongly embayed. Myrmekitic intergrowths of these minerals are relatively common (Figure 7). Primary igneous mafic minerals are completely nonexistent, although small amounts of chlorite and iron-rich pumpellyite which are present in the groundmass may have replaced these original phases. Nearly all samples contain pyrite, occasionally in abundance. Coarser-grained equivalents of these rocks were found in a few places; they may represent feeder dikes or sills.

Because of the association of relatively sodic plagioclase and quartz with no K-felspar or mafic minerals noted, these rocks should probably be termed quartz keratophyres (Babcock, 1985, personal communication). However, because of the prior use of the word dacite to describe these rocks and name the unit to which they belong, the term dacite was adopted to avoid confusion.

Dacitic lapilli tuffs and finer-grained crystal and lithic tuffs are interbedded with the flow rocks. Crystal tuffs appear to be relatively common, although they are quite difficult to distinguish from the fine-grained flow rocks. The matrix is slightly less homogeneous, and phenocrysts are commonly cracked, broken, and unevenly distributed. The lapilli tuffs are composed of sheared dacite clasts in a groundmass composed of abundant chlorite, pumpellyite, and nearly opaque black material. Euhedral pyrite is very abundant in some samples.

BASALT, BASALTIC ANDESITE, AND DIABASE

Basalt or basaltic andesite and their shallow plutonic equivalents crop out predominantly above the 2800 foot level on the southern half of Grandy Ridge. The commonest occurrences are as coarse diabase and fine-grained flow rock. Exact categorization of these rocks by composition is difficult due to alteration of the feldspars to albite, and advanced replacement of mafic minerals.

Primary igneous minerals include plagioclase (now mostly altered to albite + epidote + lawsonite), augite, and ilmenite. Chlorite- and pumpellyite- filled spaces between plagioclase grains may indicate the original presence of an additional phase or phases.

The diabasic varieties are tan to greenish brown on weathered surfaces and dark green on fresh surfaces. They are subophitic to intergranular in texture, and range in composition from rocks containing large augite phenocrysts and abundant groundmass pyroxene, to varieties containing no pyroxene. Chlorite and pumpellyite are present in large quantities in the groundmass. Ilmenite is present as skeletal grains, now largely altered to sphene.

Finer-grained flow rocks are generally brown- to green-weathering and dark green on fresh surface. All varieties are porphyritic, with the proportion of phenocrysts ranging from 5 - 30%, and from approximately 90% plagioclase to 90% augite in composition. The groundmass is usually extremely fine grained and dark, consisting primarily of augite, epidote, illmenite, sphene, chlorite, and unidentified brown grunge. Textures range from massive to felty or trachytic where feldspar laths are well developed. Commonly amygdules are filled with radial chlorite and, rarely, quartz.

GABBRO

Coarse-grained, probably shallow plutonic rocks crop out in places along the top of Grandy ridge, in a drainage east of Dock Butte, at a location in the Bear Creek drainage, and at locations 10 and 54 in the extreme northern portion of the map area. These rocks are buff- to white- on weathered surfaces and light green to blue-green on fresh surfaces (Figure 8). A slight tectonite fabric is evident in sample 10e, but most samples have a random fabric.

Petrographically, the rocks are composed of approximately 70 - 90%

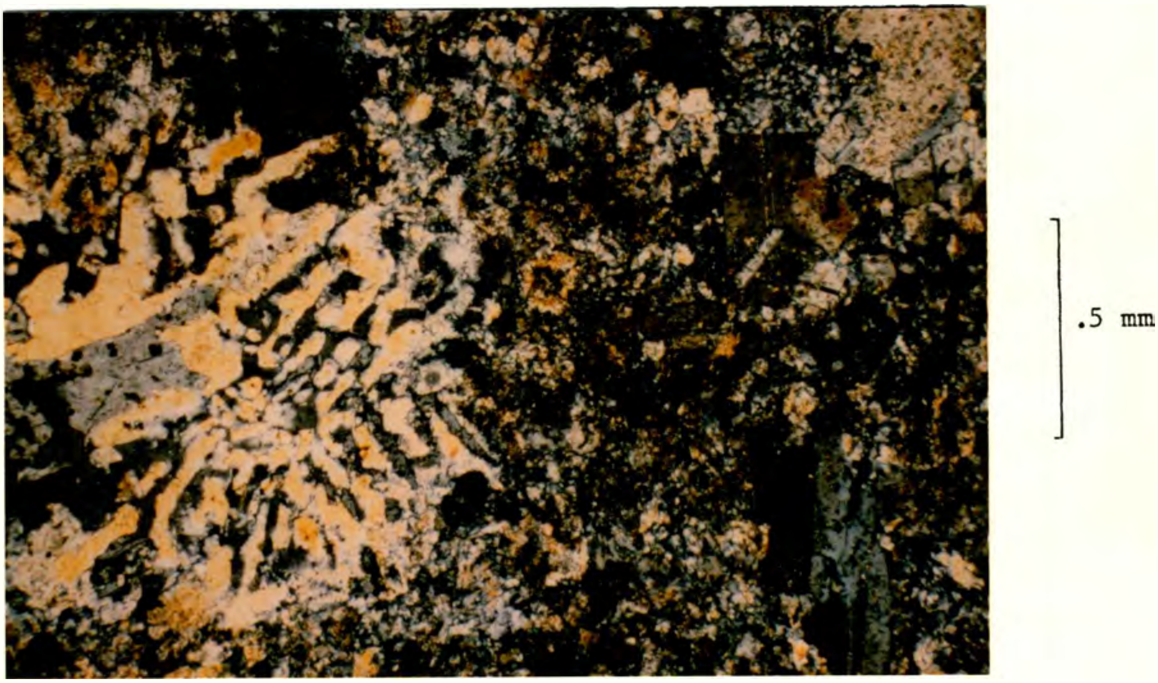


Figure 7: Photomicrograph of fine-grained porphyritic dacite flow rock showing granophyric texture (crossed polars).

Figure 8: Hand sample of Chilliwack gabbro showing plutonic texture. Scale at bottom of photo is in inches.

stubby, euhedral plagioclase crystals, which are often entirely recrystallized to dark, fine grained mats of epidote, sphene, albite, and chlorite. Spaces between plagioclase grains are filled with augite, now largely or entirely replaced by chlorite or pumpellyite and ilmenite, now replaced mostly by sphene (Figure 9). The rocks are coarsely crystalline in nature, and will be termed leucogabbros in future references.

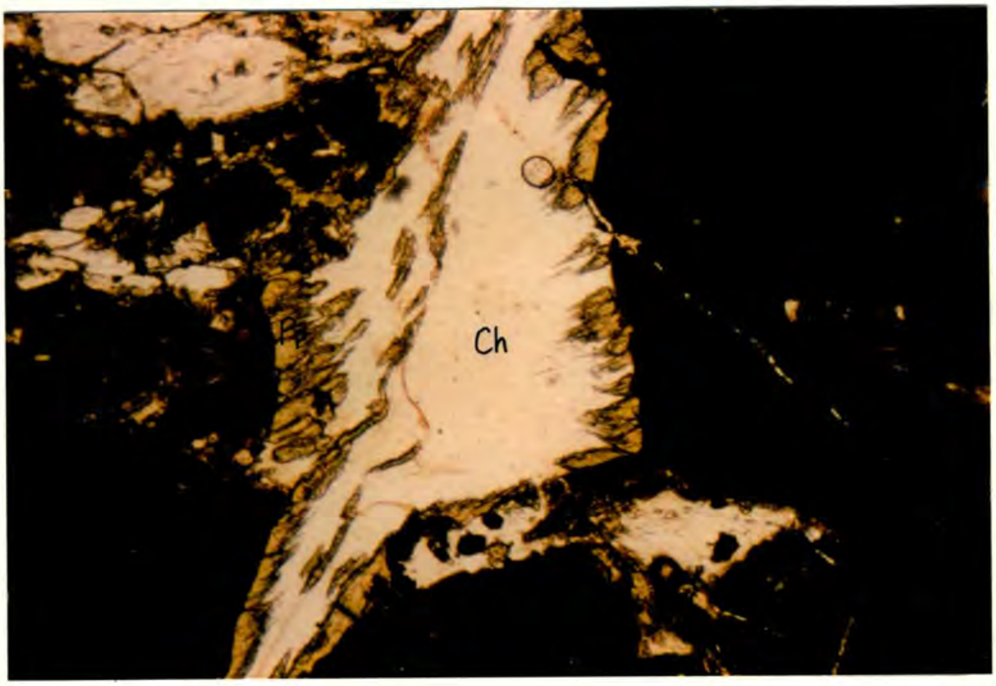
These rocks are tentatively assigned to the Chilliwack Group, rather than the Yellow Aster Complex, as they were previously assigned by Frasse (1981), based on the following evidence: absence of a tectonite fabric, frequently present in Yellow Aster Complex rocks, and absence of the typical Yellow Aster Complex metamorphic mineral assemblage, which includes abundant actinolite and clots of Fe-rich epidote. An exception to the latter is the rocks from sample localities 10 and 54, some of which contain both actinolite, present as small, green, irregular grains, and Fe-rich epidote, present as vein fillings and clots throughout the rock. The presence of these minerals could, however, be the result of hydrothermal alteration, particularly since the epidote is found in veins along with nearly equal amounts of pyrite and small amounts of calcite (Figure 10).

ANDESITE

Andesitic rocks are defined as those containing small amounts of quartz in the groundmass, relatively unaltered feldspar (suggesting less calcic varieties), and sparsely distributed mafic minerals. They are relatively uncommon in the map area, occurring primarily in section 28 as fine-grained porphyritic flow rocks.

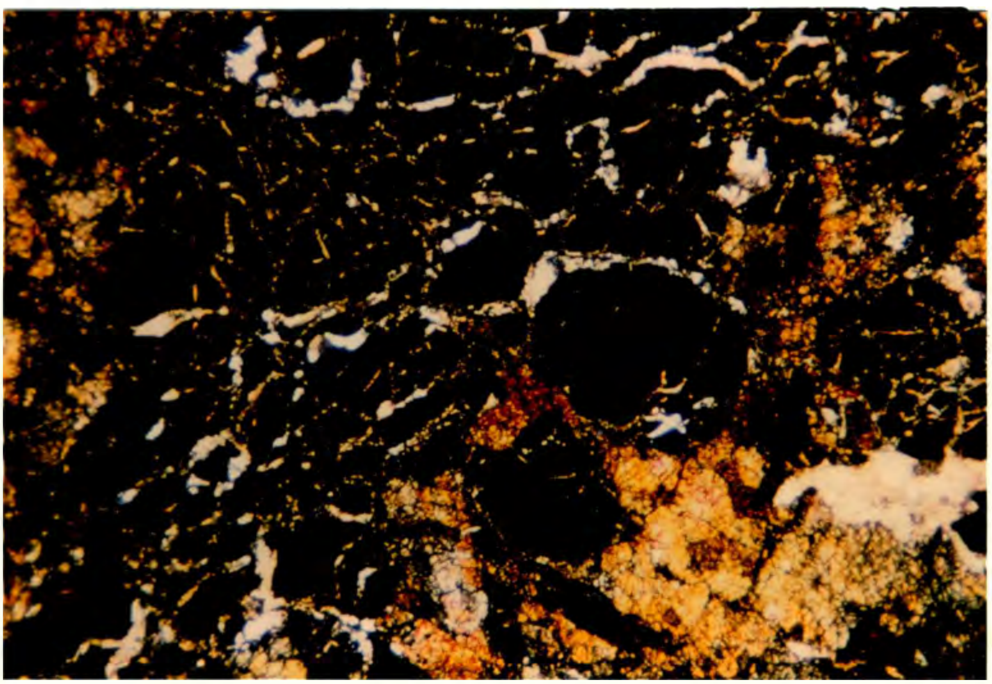
VOLCANICLASTIC ROCKS

Volcaniclastic rocks of intermediate to basic composition are



.5 mm

Figure 9: Photomicrograph of a gabbro, showing the habits of pumpellyite and chlorite. Many spaces such as the one illustrated are completely filled with metamorphic minerals, such that the original phase or phases are no longer in existence. (Plane polarized light. Pp=pumpellyite, Ch=chlorite, and dark areas are altered plagioclase.)



1 mm

Figure 10: Photomicrograph of vein in a coarse grained igneous rock from sample location 54. Fe-rich epidote and pyrite are the primary constituents, with quartz and calcite present as fracture fillings in the pyritized areas. (Crossed polars. Colored areas are composed of epidote; dark areas are pyrite.

extremely common in some areas. The most striking in appearance are green, massively-bedded lithic lapilli tuffs found primarily in sections 20 and 29 on the southeast end of Grandy ridge. A somewhat arbitrary distinction is made between rocks designated as lapilli tuff and rocks designated as pebbly volcanic arenite, based primarily on the percentage of non-volcanic grains present. Volcanic arenite contains a considerable percentage of non-volcanic grains, including limestone, argillite, and chert; and the grains are more well rounded. Rocks designated as lapilli tuff contain virtually no non-volcanic lithics and typically contain a high percentage of relatively unstable, fine-grained mafic lithic grains. In most cases, shearing has produced a distinct lineation, and, where the breakdown of mafic volcanic lithic grains has produced abundant chlorite, a good foliation also exists.

Petrographically, these rocks are composed of sand- to pebble-sized lapilli, with very little matrix. The lapilli are generally fine-grained, ranging from highly vesicular varieties containing abundant brown grunge (probably devitrified glass), to clasts with a felty or trachitic texture. Clast composition ranges from basalt to dacite (Figure 11).

Fine-grained, thinly bedded to laminated crystal, lithic, and vitric tuffs are frequent throughout the upper section of fine-grained sedimentary rocks, but are often quite difficult to distinguish from the fine-grained siltstones and argillites, since both have a similar appearance in the field and an appreciable degree of recrystallization. Relatively silicic tuff forms large cliffs at the 3500 foot level on the south face of Grandy ridge and, further north, on a north-facing exposure in section 20. The tuff is generally fairly resistant, white to buff on weathered surface, and light to dark green on fresh surface. Petrographic analysis often reveals nothing more than recrystallized brown grunge and

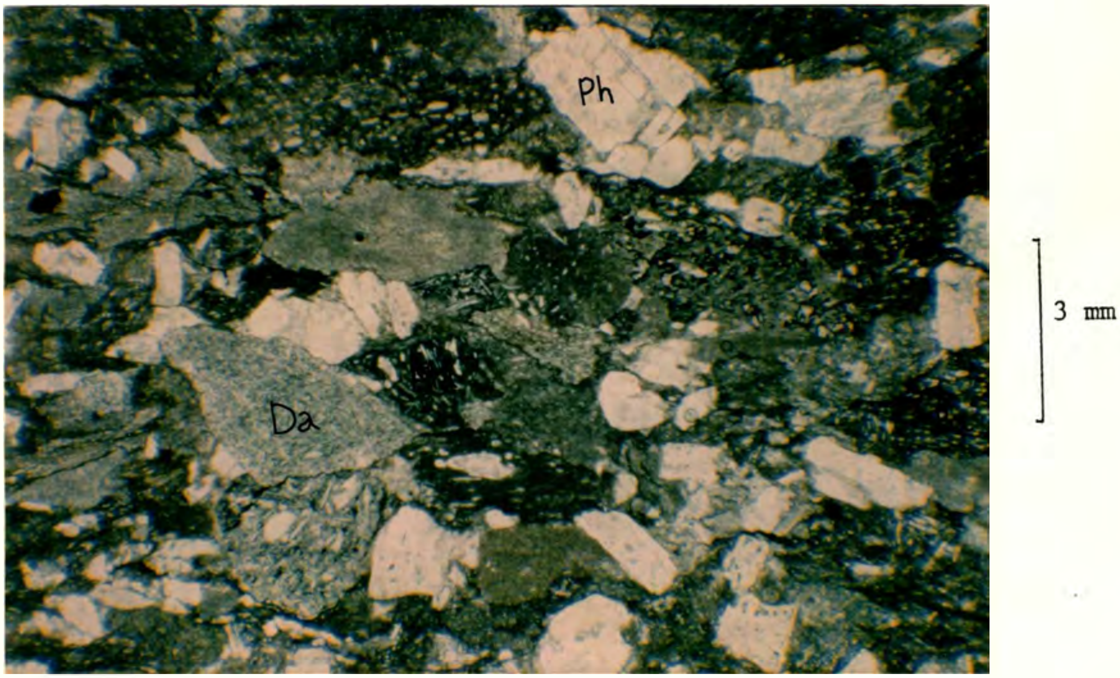


Figure 11: Photomacrograph of a lapilli tuff containing a variety of clast compositions and textures. Da=dacite, Ba=basalt, Ph=plagioclase phenocryst (plane polarized light).

opaque minerals, with occasional plagioclase phenocrysts.

LIMESTONE

Limestone is relatively uncommon in the map area. All limestones observed have undergone recrystallization to the extent that no distinctive fossil assemblages could be identified for dating. Crinoid columnals could occasionally be observed on weathered, silicified surfaces of some limestone outcrops; however, by themselves they are not diagnostic of a particular time period.

Danner (1966) mapped three small limestone bodies near Dock Butte on the western edge of the field area. He deduced that they are Pennsylvanian in age based primarily on stratigraphic relationships, as they are poorly exposed and recrystallized.

Within the field area, only three limestone bodies of any significant size were located. A 75-meter-thick layer is exposed in a stream-cut near the southern border of section 17. Sheared tuffaceous sediments were observed below it and volcanics above it, although the contacts were not visible. The limestone is yellow- to buff- weathering, extensively recrystallized, and partly silicified. A similar outcrop approximately 30 meters thick is located in the NW 1/4 of section 28, in roughly the same stratigraphic position as the first. It is markedly sandy near the top of the section. A third, sandy to conglomeratic limestone body approximately 30 meters thick is present in the extreme northwest corner of the map area. The bottom is not exposed, and it grades upward into a massive black sandstone layer, which in turn is truncated by a fault.

Small chunks of gray, recrystallized limestone containing abundant chert nodules are located on the top of Grandy Ridge, associated with faulted volcanics (location 90), and at the 3300 foot level on the south side of Grandy Ridge (location 93), associated with very strongly lineated sandstone and conglomerate.

A matrix of recrystallized limestone is present in some coarse conglomeratic layers, notably in the NE 1/4 of section 8 and in the northern portion of section 32. In some instances sparse silicified volcanic (often dacitic) cobbles can be observed floating in a limestone matrix.

Small limy lenses 1 to 2 meters long and roughly 20 to 30 cm. thick are common in sandy and argillaceous lithologies that crop out in stream valleys in the northeastern portion of Grandy Ridge.

CLASTIC SEDIMENTARY ROCKS

For purposes of discussion, the clastic sedimentary rocks in the map area are divided into three categories: rocks assigned to the lower clastic sequence; rocks assigned to the Baker Dam unit (probably part of the lower clastic sequence); and rocks assigned to the upper clastic sequence.

LOWER CLASTIC SEQUENCE SILTSTONE AND ARGILLITE

Laminated to thinly bedded siltstone, argillite, and fine sandstone apparently correlative with the lower clastic sequence of Monger (1966) comprise the most abundant sedimentary lithology in the map area. Large thicknesses crop out on the lower east-facing slopes of Grandy Ridge, where a stratigraphic section over 450 meters thick is present (assuming no structural repetition).

The rocks are rhythmically bedded, brown to black on weathered surfaces, and dark gray to black on fresh surfaces. Primary structures (other than bedding) are scarce, but include graded bedding, small scale crosslaminations, and scour marks. Close examination of some of the thicker (5 cm.) graded beds reveals them to be composed of thin, graded laminae in an overall fining-upward sequence. Abundant black, subhorizontal worm burrows roughly 5 mm. long and 1 mm. in diameter are characteristic in many areas (Figure 12) and have been noted by Blackwell (1983) and Ziegler (personal communication) in rocks from neighboring areas. Another persistant feature is the presence of resistant, white-weathering, silicic layers 2 - 20 cm. thick, which contain abundant (up to 20 - 30% of the rock) vertical quartz veins. Rarely present are small conglomeratic lenses containing well-rounded pebbles and granules.

Petrographically, the siltstones are composed of angular fragments of plagioclase and monocrystalline quartz in a dark, fine-grained, recrystallized matrix of chlorite, albite, pumpellyite, lawsonite, quartz, and unidentified brown grunge.

The argillite is dark and extremely fine grained, with a mineral composition similar to the groundmass of the siltstone. Organic material, stringers of euhedral pyrite grains, and scattered silt-sized fragments of feldspar and quartz are usually present. Many samples are silicified or replaced by patchy calcite. Radiolarian ghosts are common, becoming locally abundant in the light-colored silicic layers (Figure 13).

A thick section of massive, pebbly, volcanilithic arenite appears to be interbedded with the bedded, fine-grained sequence immediately north of the Skagit - Whatcom County line on Grandy ridge. The section approaches 90 meters in thickness. Coarser sections are massively bedded, relatively resistant, buff-weathering, and green on fresh surface, reflecting an abundance of volcanic material. Finer-grained sections are frequently

Figure 12: Photomacrograph of worm burrows in a siltstone from the lower clastic sequence (plane polarized light).

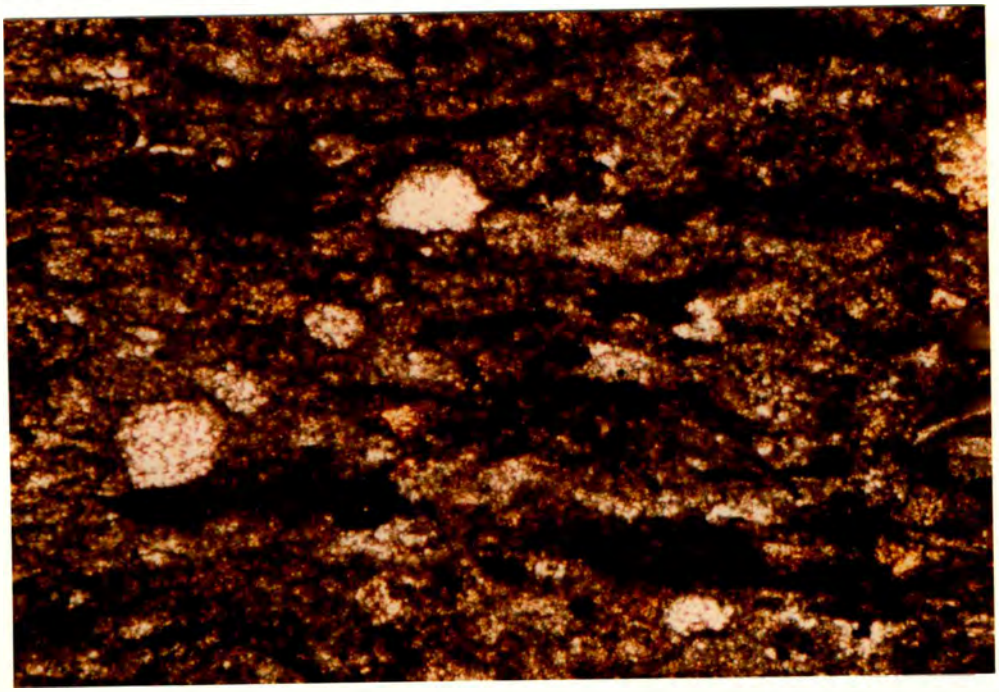


Figure 13: Photomicrograph of radiolarian ghosts in argillite from the lower clastic sequence (plane polarized light).

thinly bedded, with graded bedding and small scale crossbeds up to 20 cm. thick. Evidence of soft sediment deformation, including slump features and convoluted bedding, was noted in a few places. Petrographically, the sandstone is identical to that seen in the upper clastic sequence, described on page 36.

BAKER DAM UNIT

This unit differs from most other rocks of the Chilliwack Group in the map area in its higher degree of deformation and by the similarity of foliation attitudes over a large area (Plate 1). This unit and other very similar rocks west of Baker Lake were originally assigned to the Nooksack Group by Misch (1966). The very contorted nature of these rocks was ascribed to their proximity to the Church Mountain thrust. Ziegler (1985) reassigned most of the Nooksack rocks north of the map area to the lower clastic sequence of the Chilliwack Group, with only a few blocks of fossiliferous, relatively undeformed Nooksack Group imbricated within.

Thick, structureless to faintly bedded sections of dark gray argillite, separated by thin (1 - 10 cm.) white, gray, or light green, possibly graded sandy beds are the most common lithologic type, exhibiting a number of distinctive features:

A) slaty to phyllitic cleavage parallel to the sandy layers;

B) crenulation cleavage or kink folding with axial planes at right angles to the S1 cleavage;

C) abundant quartz and fewer calcite veins oriented at right angles to the bedding surfaces in the light-colored layers;

D) quartz and calcite veins frequently oriented subparallel to the S1 cleavage;

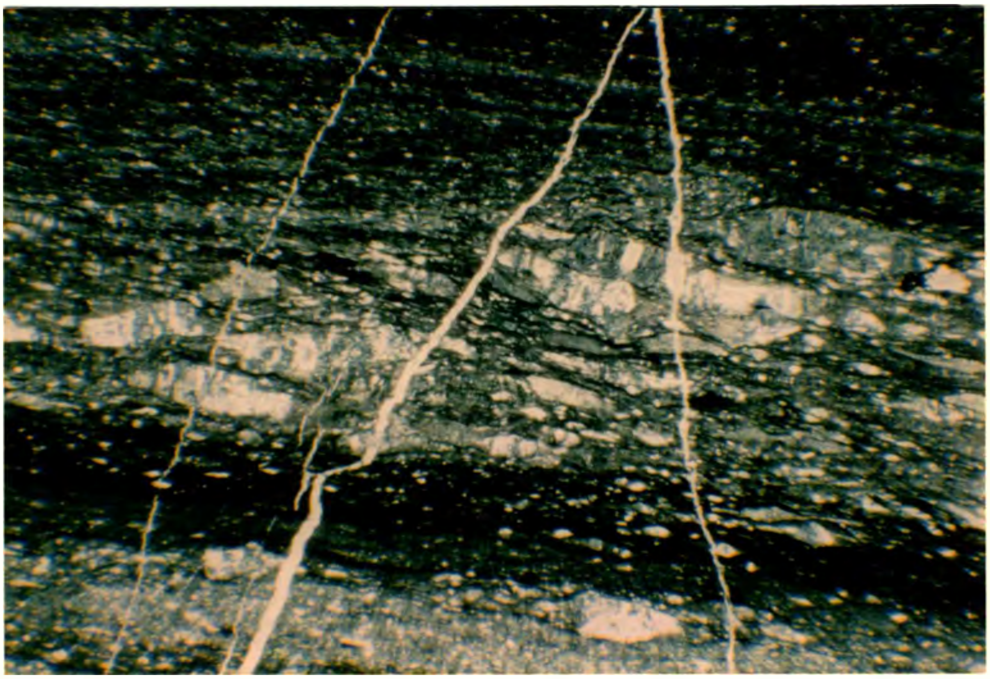
E) ellipsoidal, dark brown carbonate concretions, 5 - 20 cm long.

Petrographically, the argillite is extremely fine-grained, making positive identification of many of the mineral constituents difficult. The presence of albite, chlorite, quartz, lawsonite, calcite and white mica were detected in thin section and verified by x-ray diffraction. The slaty cleavage is defined by the preferred orientation of lawsonite, chlorite, and white mica. Stringers of small, euhedral pyrite grains parallel the foliation. Large areas of thin sections are almost completely replaced by patchy calcite. Highly boudinaged feldspar grains are found throughout, but they appear to be concentrated in horizons, which may have been depositional in origin (Figure 14). Radiolarian ghosts are present in less highly strained argillite. A very well preserved radiolarian (Figure 15) was observed in a concretion collected from north of Upper Baker Dam, and is currently being dated.

The light-colored layers are dominantly composed of boudinaged feldspar grains that have been extensively altered to lawsonite. In some areas the feldspar grains are strongly boudinaged, whereas in others the grains are stretched, and further attenuated by the presense of numerous small quartz veins. Flattening and boudinage of the grains parallels the bedding and cleavage. The structural and metamorphic aspects of these rocks will be discussed in further detail in other sections.

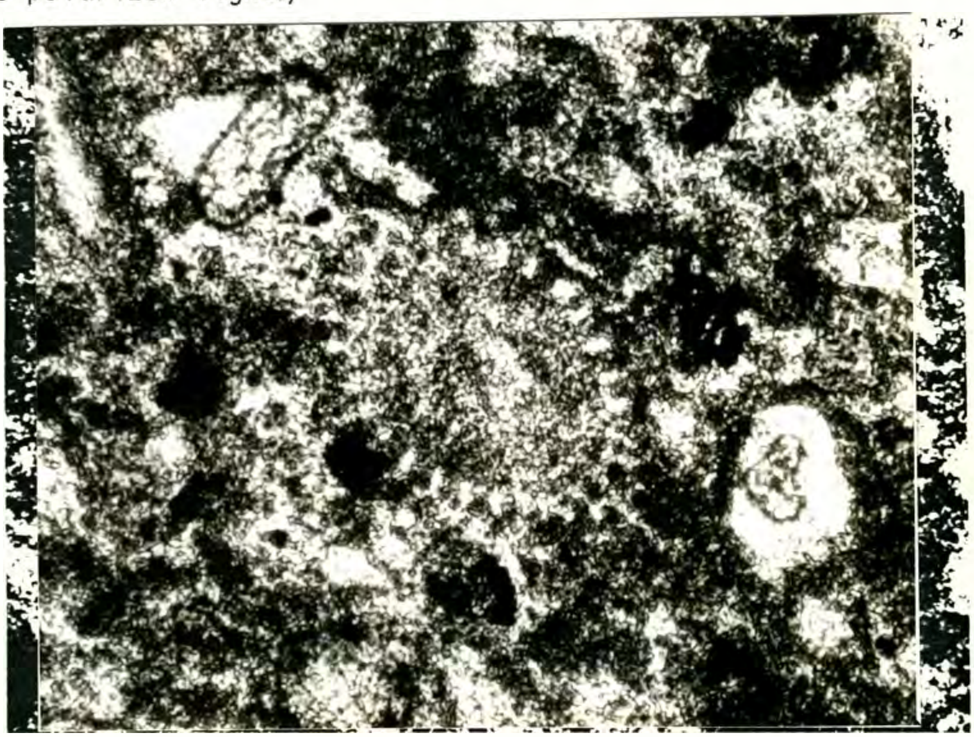
Rocks of this type crop out primarily on the Baker Highway north of Rocky Creek and on the slopes west of Rocky Creek, where they are in fault contact with dacite. The rocks near the top of the sequence on the west side of Rocky Creek grade into finely-laminated argillite and siltstone, containing small carbonate lenses.

Rocks that are essentially identical in terms of lithologic type, deformational style, and distinguishing features are also found on the lower, south-facing slopes of Grandy ridge, and in roadcuts along the



2 mm

Figure 14: Photomacrograph of a typical argillite from the Baker Dam unit, showing a layer containing highly boudinaged feldspar grains (plane polarized light.)



.1 mm

Figure 15: Photomicrograph of well preserved radiolarian from a concretion in the Baker Dam unit, from north of Upper Baker Dam (plane polarized light).

Baker Lake Highway. They are interpreted to be part of the same unit.

Other lithologies in this unit include coarse sandstone, volcanilithic conglomerate and pebbly sandstone, and tuff. All lithologies, including argillite, are present at location 110-49 on the Baker Highway. Massive, green, pebbly conglomerate containing argillaceous clasts grades into argillite containing cobble-sized clasts of green conglomerate. Interbedded tuffs are green and thin bedded. These coarser rocks are found throughout the southern extent of this unit, particularly in sections 11 and 12. Bedded tuff and pebbly sandstone are also found on the hill immediately north of upper Baker Dam, and on top of a hill (elevation 1799) north of Rocky Creek.

The bedding and foliation strike northwest and dip northeast in most areas in the Baker Dam unit. If the unit has not been markedly disrupted by faulting, then the coarser sediments are present primarily toward the bottom and again at the top of the section. There is some evidence that the massive pebbly sandstone described in the section on the lower clastic sequence may be correlative with the coarser-grained rocks in the Baker Dam unit, as the sandstone appears to lie along strike with these rocks.

The rocks of the Baker Dam unit are assigned to the lower clastic sequence of the Chilliwack Group based on the following observations:

1) Lack of megafossils. Although this lack does not eliminate the Nooksack Group from consideration, it is usually highly fossiliferous. Additionally, Ziegler (1985) found Paleozoic(?) forams in concretions from identical lithologies that crop out to the north.

2) High degree of deformation. Most accounts comparing the Chilliwack and Nooksack Groups note the generally lower degree of deformation sustained by the Nooksack Group, even in the proximity of major faults (e.g., Jones, 1984) in the Church Mountain area of the Church Mountain

thrust).

3) Style of deformation. Cleavage is typically at high angles to bedding in the Nooksack Group, whereas cleavage nearly parallels bedding in this unit.

4) Metamorphism. Large amounts of well-formed lawsonite crystals present in this unit are relatively uncommon for either group; however lawsonite appears to be more common in the Chilliwack Group. Prehnite, commonly found in the Nooksack Group, is absent from these rocks.

Dating of the previously mentioned well-preserved radiolarians may enable a more reliable unit designation for these rocks.

UPPER CLASTIC SEQUENCE

The upper clastic sequence is considerably coarser-grained than the lower clastic sequence. The former contains conglomerate, siltstone, tuff, volcanic arenite and minor flows and argillite, in descending order of abundance.

The conglomerates appear to be divisable into two types, based on clast lithology, grain size, and occurrence. A section at least 100 meters thick and 300 meters long is present in the north half of section 32. It consists of massively bedded, well rounded boulders, cobbles, and pebbles in a matrix of sand grains and calcite cement. Volcanic rocks of various compositions are the most common clast type, followed by limestone and coarse, felsic plutonic rock, which locally comprises over 30% of the clasts. Conglomerates of this type have been described by Ziegler (1985) and Christenson (1981) from adjacent occurrences of the Chilliwack Group.

Other conglomerates occur primarily as lenses up to 30 m. thick and 60 m. long interbedded with sandstone and siltstone, often with sheared contacts (Figure 16). They consist primarily of well-rounded pebble- to

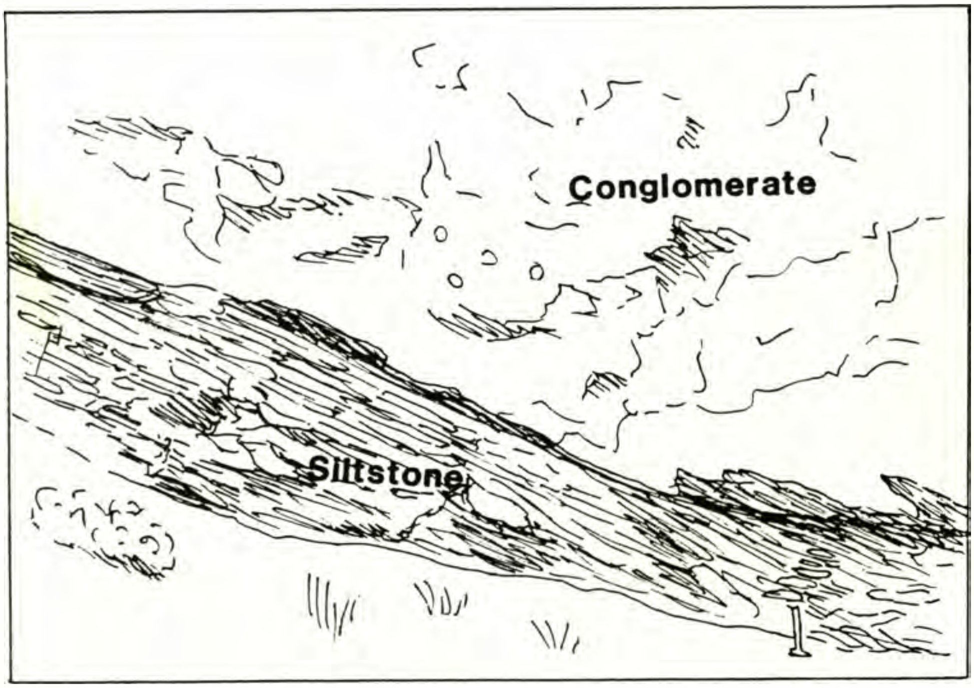


Figure 16: Conglomerate lens with sheared lower contact, from the upper clastic sequence of the Chilliwack Group on the southeast corner of Grandy Ridge. Rock hammer is in the lower right hand corner for scale.

cobble-sized volcanic clasts of andesitic to basaltic composition in a matrix of coarse sandstone and calcite cement. These rocks frequently exhibit a strong lineation defined by stretched mafic clasts, which are often entirely replaced by chlorite.

Thinly-bedded siltones and tuffs are found in close association with the conglomerates. On fresh surfaces, alternating green and black laminations seen in some samples may represent interbedded sedimentary and volcaniclastic lithologies. Most of the volcaniclastic rocks described in the volcanic section can tentatively be placed in the upper clastic sequence.

Volcanic arenite occurs in massive, pebbly lenses associated with volcanics and lapilli tuff on the south side of Grandy ridge, and with the large conglomerate outcrops. The sandstone is relatively resistant, green to gray or black on fresh surface, and buff-weathering.

Petrographically, the coarse sandstone is a volcanilithic arenite, the clast fraction of which is primarily composed of subrounded basaltic to dacitic volcanic lithic grains, feldspar, argillite chips, limestone, monocrystalline quartz, and epidote. Very little primary matrix is present in most samples, although up to half of some samples are composed of psuedomatrix formed by the breakdown of volcanic lithic grains. Monocrystalline quartz is rare, but may approach approximately 20% of the mean clast composition in rocks containing abundant dacite fragments.

DEPOSITIONAL ENVIRONMENTS/CORRELATION

It would be unwise to state that the Chilliwack Group, which spans a significant portion of the Paleozoic era, was deposited in a single basin associated with one plate margin. In addition to the long time interval, tectonic fragmentation and poor exposure hamper interpretation. Nevertheless, it would appear that the Chilliwack Group represents a shallowing-upward sequence of deposition in basins on and adjacent to a volcanic arc or arcs. The following interpretations can be made in the map area for various units, with no correlation implied between them:

The thick, relatively undisturbed sequences of rhythmically bedded siltstone, shale, and sandstone correlated with the lower clastic sequence of Monger (1966) resemble thinly-bedded turbidites (Figure 17). A, b, d, and e Bouma intervals are most frequently represented. Liszak (1981) has interpreted the lower clastic sequence to represent upper submarine fan lateral overbank deposits. Another interpretation might be that the turbidites represent deposition on more distal (lower) areas of a submarine fan. Evidence from rocks in the map area, including abundant horizontal worm burrows in some layers, and the presense of small lenses of sandy limestone in places near the top of the sequence may support the shallower water hypothesis.

The lower clastic sequence may represent a period of relative tectonic quiescence, but tuffaceous layers found near the top of the sequence and abundant radiolarians found in some layers (possibly indicative of a silica-rich environment) suggest nearby volcanic activity.

The limestones are characterized by their limited lateral extent, proximity to volcanics, abundance of chert, and the presence of shallow marine fossils such as crinoids. This evidence suggests that they could have formed as fringing or barrier reefs on a volcanic arc (Wilson, 1975). Similar deposits are being formed presently in tropical to subtropical volcanic arc settings.

The coarse-grained nature and the mixed volcanic, plutonic, sedimentary, and limestone clast lithologies of the upper clastic sequence suggest a more proximal source, which might have included the underlying

Figure 17: Turbiditic siltstone from the lower clastic sequence.

reefs and material from a partially eroded arc. The lack of bedding or grading in the thick, very coarse conglomerate in section 32 suggests that it could have been deposited in the proximal portion of a channel in a submarine fan (Walker, 1979). The alternating lenses of conglomerate, sandstone, siltstone, and one small coaly layer found on the ridge above the massive conglomerate are reminiscent of alluvial fan, flood plain, or deltaic deposits. Land plant fossils found in other locations (e.g. Jones, 1984, and Monger, 1966) also suggest partly subaerial deposition, although they are commonly found in submarine fan deposits as well. The lack of channel scours, abundant crossbedding, or other fluviatile structures suggest submarine deposition. Perhaps this sequence represents a nearshore environment that was briefly emergent at various times during its evolution. Interbedded volcanics, primarily tuffs, indicate nearby volcanic activity.

The volcanic sections show little internal order and contain no depositional structures. The abundant leucogabbros and diorites may represent thick feeder dikes or the central portions of volcanoes. Tuffs are unwelded, consistent with subaqueous deposition.

OTHER UNITS

YELLOW ASTER COMPLEX

One small tectonic block tentatively assigned to the Yellow Aster Complex is located in a fault zone between the chert/basalt unit and the Triassic dacite unit in the northern portion of the map area (location 194). It is a hornblende diorite with a slight tectonite fabric. The hornblende is dark green to brownish-green, irregular in shape, and largely replaced by actinolite. Large, euhedral to subhedral plagioclase crystals are replaced by nearly opaque, fine-grained mats of epidote, sphene, albite, and chlorite. Large clots of iron-rich epidote are also present. This tectonic block is assigned to the Yellow Aster Complex rather than the Chilliwack Group based on the following considerations: primary igneous mineralogy (hornblende was not observed in any Chilliwack Group rocks in the map area); metamorphic mineralogy (actinolite and clots of epidote are common in the Yellow Aster Complex, but are not generally present in the Chilliwack Group except in rocks which have undergone hydrothermal alteration, which is not in evidence); and presence of a tectonite fabric (which is generally not in evidence in Chilliwack gabbros).

CHERT/BASALT UNIT

Outcrops of the chert/basalt unit are restricted to a small area in the northwestern corner of the map. The portion exposed in the maparea consists of ribbon chert, basalt, and phyllitic siltstone, in descending order of abundance. The chert/basalt unit in this area was distinguished from the Chilliwack Group primarily on the basis of the association of large quantities of ribbon chert with basalt, and by a slightly higher degree of deformation than observed elsewhere in the Chilliwack Group. Blackwell (1983) provides a detailed account of the petrologic relationships in these rocks.

The chert is gray to white, and is made up of ribbons two to five cm. thick, occasionally with phyllitic partings. It is recrystallized, with a sugary texture, and it is frequently disharmonically folded. The basalt is white to buff on weathered surface, and dark green on fresh surface. It is fine-grained and frequently vesicular. Flattened relict pillows were observed in two locations along the forest service road leading to Blue Lake. The phyllitic siltstone is generally highly contorted, and can be distinguished from phyllitic siltstones in the Chilliwack Group by a higher degree of deformation.

TERTIARY DIKES

A leucocratic dike approximately 20 cm. thick is exposed in a roadcut on the Baker Lake Highway in the Baker Dam unit (location 143). The dike was emplaced into phyllitic argillite, and has sheared contacts subparallel to the foliation. Petrographically, the dike is composed of albitized plagioclase crystals displaying a feathery quench texture, with a groundmass of metamorphic (deuteric?) chlorite and calcite (Figure 18). The dike is undeformed, and therefore assigned a Tertiary age.

A series of at least five parallel hornblende diorite dikes crops out in a roadcut on the south side of Grandy ridge (location 151), emplaced into silicified siltstone and tuff. The largest dike is roughly four meters thick, with dark, fine-grained (chilled) margins and a coarse, diabasic center. Flow banding parallel to the margins was observed in this and a few of the smaller dikes. The smaller dikes range from approximately 30 cm. to 2 m. in thickness, and are finer-grained than the largest dike.

Petrographically, the dikes are ophitic to hypidiomorphic in texture, and are composed of abundant elongate, brown, euhedral to spongy textured hornblende crystals in a matrix of euhedral to subhedral plagioclase. apatite and an opaque phase (ilmenite?) are common accessories. The dikes are relatively fresh in appearance, although they have been metamorphosed slightly, with abundant chlorite and lesser amounts of sphene and quartz present in the groundmass (Figure 19).

Although slightly metamorphosed, the dikes are interpreted to be Tertiary in age, based on their relatively fresh appearance and the fact

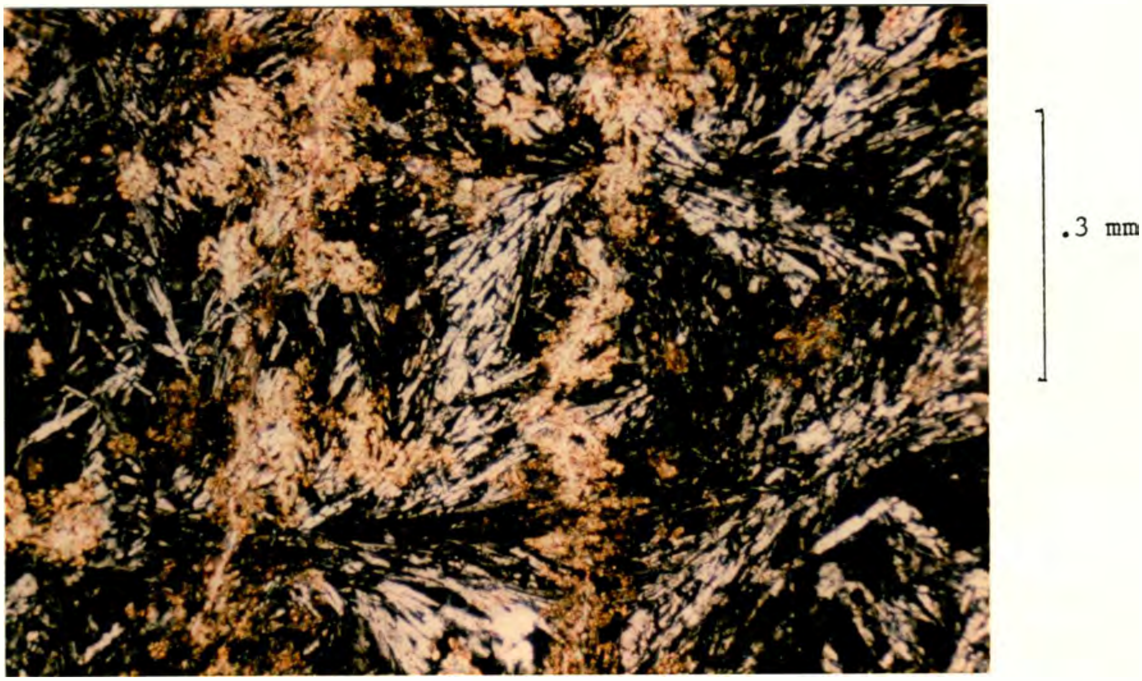


Figure 18: Photomicrograph of feathery quench texture in a leucocratic dike from the Baker Dam unit (crossed polars).

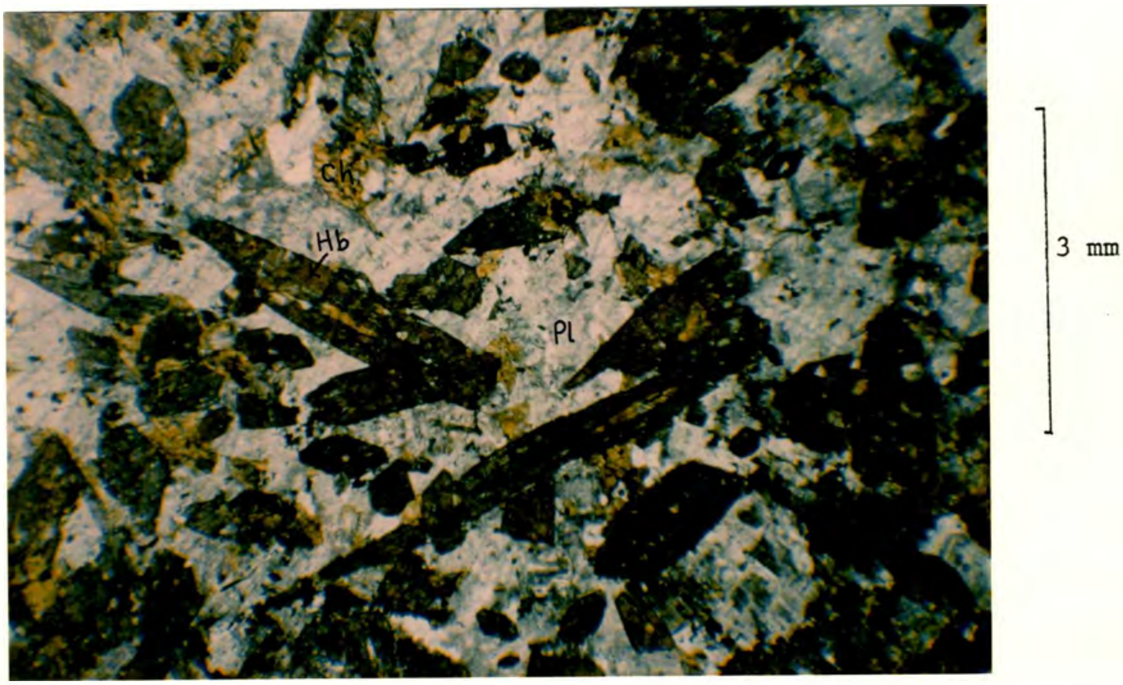


Figure 19: Photomacrograph of a Tertiary hornblende diorite dike intruded into Chilliwack Group siltstones. (Plane polarized light. Hb=hornblende, Pl=plagioclase, Ch=chlorite.)

that they cross-cut features associated with the first deformation.

BAKER VOLCANICS

Tertiary volcanics associated with eruptions of Mount Baker are present along the northern boundary of the area in the Sulphur Creek valley, and capping the prominent knob, elevation 1760, west of Upper Baker Dam.

The Sulphur Creek volcanics are dark gray, porphyritic flow rocks, which crop out in uneven mounds of large blocks. Sections in road cuts exhibit columnar jointing.

Consolidated lahars or pyroclastic rocks and minor flow rocks crop out on the knob, elevation 1760. The contact of this unit with underlying rocks of the Baker dam unit is exposed in a quarry cut, at location 110-47. The lahar deposits are brown- to buff-weathering and heavily fractured. Rare fresh surfaces are dark green. Petrographically, the rocks are composed of rounded andesitic volcanic fragments enclosed in a matrix of feldspar laths and brown grunge, probably altered glass.

METAMORPHISM

Metamorphic mineral assemblages in and the degree of recrystallization of units within the Chilliwack Group in the map area appear to be largely controlled by lithology and by the degree of deformation sustained. All samples examined have undergone relatively low temperature and high pressure metamorphism, based on the presence of characteristic mineral assemblages. Metamorphism in the dacite unit, the Baker Dam unit of the Chilliwack Group, and the rest of the Chilliwack Group will be discussed separately, and related at the end of the section.

Quartz, albite, and chlorite are present in virtually every sample. Quartz is commonly present as vein or amygdule fillings and in a very fine-grained form in the groundmass of fine-grained volcanic and sedimentary rocks. Albite replaces more calcic varieties of plagioclase, and is also found in the groundmass of sedimentary and volcanic rocks. Chorite often completely replaces mafic volcanic grains in tuffs, and it is also found in the groundmass of fine-grained sedimentary and volcanic rocks, partially replacing pyroxene grains, and filling the interstices between plagioclase and pyroxene grains in diabasic rocks. It can be assumed that these minerals are present in all assemblages mentioned in the following discussion.

DACITE UNIT

The dacite unit is characterized by a relatively fresh, unaltered appearance, at least partially due to the lack of mafic minerals and calcic plagioclase. Calcite + Fe-rich pumpellyite is the most common assemblage, with pumpellyite found throughout the groundmass, and calcite present in patches and veins. Sphene and pyrite are common accessories, with the latter present in copious quantities in some areas. Fine mats of lawsonite were observed in a few slides.

BAKER DAM UNIT

The rocks in the Baker Dam unit have sustained considerable deformation and are more fully recrystallized than comparable lithologies elsewhere in the Chilliwack Group. The fine-grained argillites are characterized by the assemblage lawsonite + calcite + white mica. Preferentially oriented lawsonite is very abundant, present both as fine-grained needles throughout the argillite layers and as "clots" in many quartzose layers. Calcite was identified and verified by X-ray diffraction in nearly all samples. It occurs as veins and in patchy areas, which in some instances completely obscure original structures. Euhedral pyrite is a common accessory mineral.

Tuffaceous lithologies commonly contain the assemblage Fe-rich pumpellyite + calcite +/- lawsonite.

CHILLIWACK GROUP

The rest of the Chilliwack Group (excluding the rocks containing Na-amphibole) is generally more recrystallized than the dacite unit, but less so than the Baker Dam unit. The stable assemblages observed include calcite + pumpellyite + lawsonite, pumpellyite + lawsonite, pumpellyite + epidote, pumpellyite + calcite, and pumpellyite + epidote + lawsonite, with partial assemblages also observed. One sample (110-92) contains the assemblage hematite + pumpellyite + epidote.

Relatively unstrained sedimentary rocks have a barely metamorphosed appearance and typically contain calcite, lawsonite, and pumpellyite assemblages. Volcanic rocks range from barely recrystallized (fresh looking feldspars, little replacement of pyroxenes) to ones that are substantially recrystallized. The leucogabbros in particular contain plagioclase grains that are entirely recrystallized to dark, fine-grained mats of epidote, pumpellyite, lawsonite, sphene and albite. Pyroxenes are often 80 - 90% recrystallized to chlorite and pumpellyite. Ilmenite is partially replaced by sphene. A few samples contain irregular, fairly pleochroic grains of actinolite, probably a result of hydrothermal alteration.

Fine-grained flow rocks typically contain a dark, recrystallized matrix of pumpellyite, epidote, chlorite, albite and sphene, with little alteration of phenocrysts.

Common accessories include pyrite, sericite, and white mica, which are abundant in sedimentary rocks, and apatite, commonly found as needles in plagioclase grains.

Several samples, including 59, 59a, 59e, 69, 76, 89, and 2-803, contain abundant, extremely fine-grained needles of Na-amphibole, the presence of which was verified by X-ray diffraction and microprobe analysis. These are the only reported occurrences of Na-amphibole in the Chilliwack Group.

Samples 69, 76, and 89 are coarse diabases with no fabric. The Na-amphibole needles are randomly oriented, but they are restricted primarily to the margins of pyroxene grains, where they appear to "sprout" (Figure 20). The margins of the pyroxenes often show a brownish discoloration or overgrowth resembling aegerine. The presence of sodic amphibole cannot be visually detected in hand specimen, and the rocks resemble other coarse diabases in all other respects.

Samples 59a, 59e, and 59 are from a sheared lapilli tuff located at the 2000 foot level near the boundary of sections 20 and 29. Most of the Na-amphibole needles show a strong preferred orientation parallel to the lineation direction. The Na-amphibole-containing rocks form a blue-green band roughly 2 meters thick which grades into less deformed, non-Na-amphibole-containing tuff on either side. Sample 2-803 is a lapilli tuff collected from near Marblemount by E. H. Brown (1985, personal communication).

Microprobe analyses of the Na-amphibole from these samples were carried out in an effort to characterize the type of Na-amphibole present and to relate this information to pressure and temperature conditions and Na-amphibole occurrences in other units. All samples analysed contain the assemblage albite + quartz + chlorite + Na-amphibole +/- pumpellyite +/- calcite +/- sphene.

Due to the extremely fine-grained nature of the Na-amphibole in these rocks, suitable grains (those over approximately 10 microns wide) are very scarce. Analyses were carried out on two grains from two slides from sample 2-803 (Figure 21) and one grain from sample 69. One pyroxene grain was also analysed.

The samples were analysed using the University of Washington ARL 5-channel microprobe, which necessited the use of two runs for a complete analysis including 8 elements. Several points per grain were analysed. Relocation of points in the second run over points in the first run is necessary for an accurate analysis, but in practice was very difficult to accomplish due to compositional zoning. Many spots were later discarded because of unsuitable match-ups.

The weight percent data were merged and run through the Bence-Albee correction program at University of Washington. The amphibole data were further reduced using the AMPH program at Western Washington University, which translates total iron (reported as ferrous iron) into percent ferrous and ferric iron, and reports formula units in cations per 23

Figure 20: Photomicrograph of Na-amphibole habit in a diabase. Amphibole grains appear to sprout from the pyroxene grain. Pyr=pyroxene, Amp=amphibole. Plane polarized light.

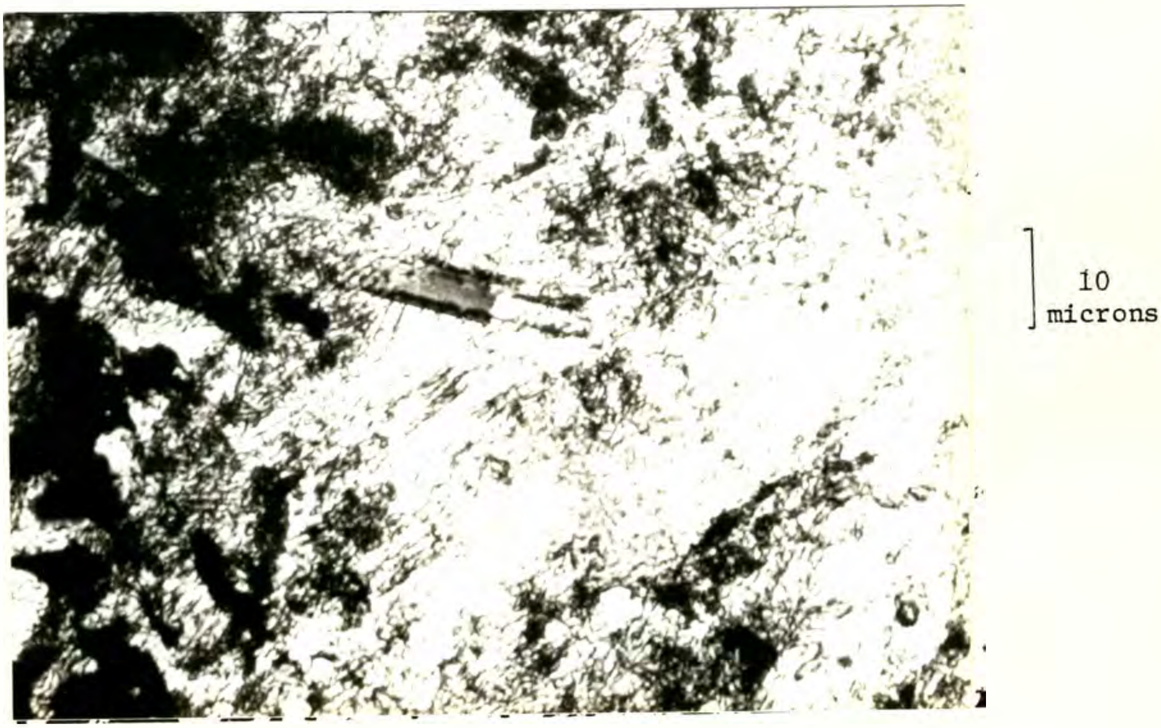


Figure 21: Photomicrograph of amphibole grain 2-803 used for microprobe study (plane polarized light).

oxygens. Bence-Albee corrected data and data generated using the AMPH program are listed in Appendix 2.

The results of this analysis are summarized in Figure 22, a plot of end-member compositions and fields for the common types of Na-amphiboles. The compositions of Na-amphiboles from the Shuksan Suite (Brown, 1974) and the Baker Lake blueschist (Ziegler, 1985) are also plotted on this diagram. The Chilliwack amphiboles plot primarily in the riebeckite field, and are distinctly different compositionally from both the Shuksan and Baker Lake blueschist amphiboles.

The occurrence of Na-amphibole in the tuffs is similar in nature to the occurrence of glaucophane in the Baker Lake blueschist. The Baker Lake blueschist, as described by Ziegler (1985) in the Baker Lake north shore area, is restricted to a sheared tuff, possibly associated with the chert/basalt unit. The contacts appear to be gradational from non-Na-amphibole containing sheared tuff of the chert/basalt unit into the more highly sheared schistose rocks of the blueschist unit.

Occasional incipient Na-amphibole formation has been observed in the chert/basalt unit proper (J. T. Jones, D. A. Silverberg, 1985, personal communication), but the Na-amphibole-containing rocks in the study area are not correlated with the chert/basalt unit (PMcb) because: actinolite is absent from the Chilliwack rocks, while present in the chert/basalt unit; microprobed augites contain only trace amounts of titanium (Appendix 2), while titaniferous augite is a distinguishing feature in the chert/basalt unit; the Na-amphiboles are riebeckite in the Chilliwack group, and glaucophane in the Baker Lake blueschist, which may be related to the chert/basalt unit. In addition, the rocks are interlayered with and are essentially identical to rocks which appear to be part of the

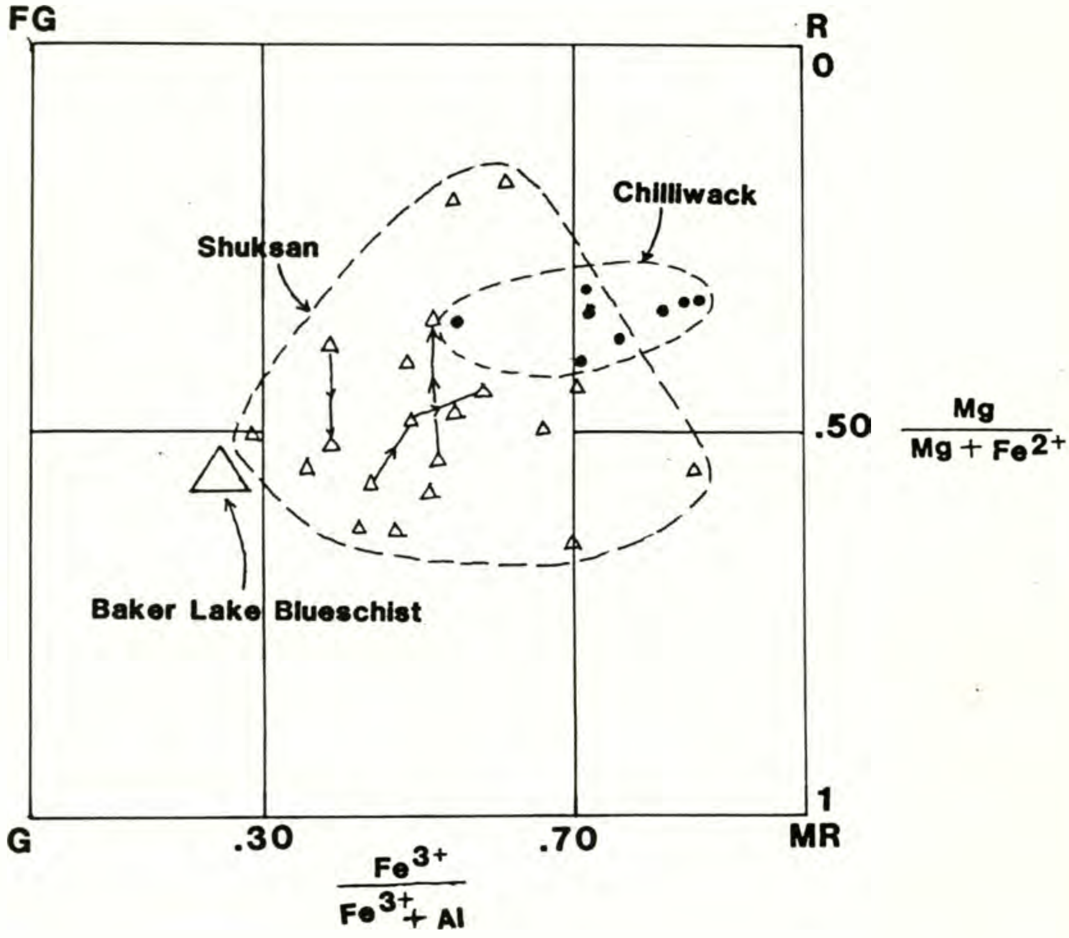


Figure 22: Plot of compositions of Na-amphiboles from the Chilliwack Group (this study), the Shuksan Metamorphic Suite (Brown, 1977), and the Baker Lake blueschist (Ziegler, 1985).

Chilliwack group.

One pyroxene grain was also microprobed, and the data run through the OMPH program at Western Washington University, which calculates pyroxene composition in percentages of the end members jadite, omphacite, and diopside (Appendix 2). The pyroxene grain probed is composed almost entirely of diopsidic augite component, indicating little metamorphic alteration.

Phase relations

The assemblages detailed above can all be represented graphically on a triangular diagram with Al, Ca, and Fe3+ at the apices, with the diagnostic minerals projected from a constant subassemblage of quartz + chlorite + albite + (CO_2, H_2O) (Figure 23b). Locations of the points are approximate, based on theoretical values for mineral composition. The observed mineral assemblages are denoted by x's. Figure 23a is a triangular diagram from Brown and others (1981) illustrating the typical assemblages found elsewhere in the Chilliwack Group. From Figure 23a to Figure 23b, the aragonite-hematite tie line is broken and a new tie line, pumpellyite-Na-amphibole created.

The reaction producing this tie line switch was obtained using the REACT program at Western Washington University, using data from microprobe analysis of Na-amphibole, the composition of Fe-rich pumpellyite from Brown (1974), and theoretical compositions of the other phases. The reaction

$$3.91\ \text{Qtz} + 2.04\ \text{Albite} + .94\ \text{Chl} + 3.57\ \text{Cc} + .82\ \text{Hem} + .14\ H_2O$$
$$= .82\text{Pp} + 3.57CO_2 + 1.0\text{Na-A}$$

relates Figures 23a and 23b. The higher volatile component ($3.57CO_2$ as opposed to $.14H_2O$) is on the right side of the reaction, corresponding to the higher entropy side.

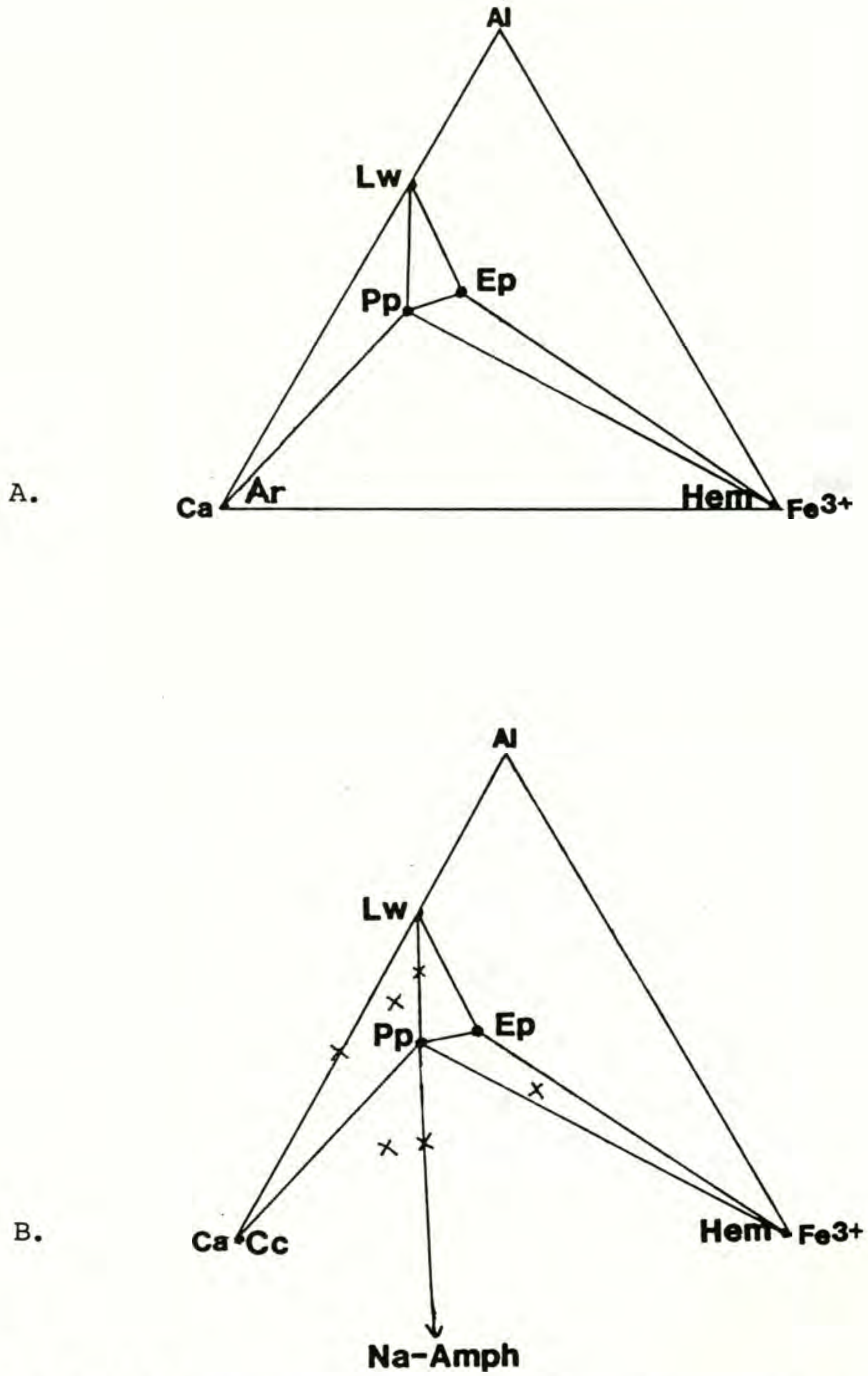


Figure 23: A-C-F diagrams for the Chilliwack Group. All assemblages are projected from a stable subassemblage of quartz + albite + chlorite + H_2O + CO_2. A: A-C-F diagram for the Chilliwack Group in most of the North Cascades region (from Brown and others, 1981). B: A-C-F diagram for the Chilliwack Group volcaniclastic rocks from the southern portion of Grandy ridge and from near Marblemount.

Two curves modified slightly from Kerrick (1974) relating the effect of mole fraction (X) CO_2 and temperature on two types of reactions are reproduced in Figure 24. Curve 1 is the typical shape of a curve for reactions with CO_2 on the higher entropy side and H_2O on the lower entropy side of the reaction. Because the reaction is very water-deficient, curve 2 illustrates a water-free reaction producing only CO_2. The true curve for the reaction probably lies somewhere between these two theoretical curves.

It can be deduced from these curves that the presence of Na-amphibole in the Chilliwack Group could either be due to higher temperatures or lower partial pressure of CO_2 during metamorphism. Evidence for the former might be the presence of calcite, rather than aragonite, in all rocks from the Grandy ridge area, although this could be attributed to the total inversion of all original aragonite to calcite. Evidence for the latter might include the abundance of sphene in the rock, which generally forms under conditions of low pCO_2 (Hunt and Kerrick, 1979). Both curves are quite steep in the low CO_2 half of Figure 24, such that a small drop in CO_2 could account for the presence of Na-amphibole in the rock, whereas a fairly substantial temperature change would be necessary to bring about the same result. Therefore, it is likely that a difference in CO_2 during metamorphism may be the reason for the presense of Na-amphibole in this portion of the Chilliwack Group.

Assemblages in the Chilliwack Group, particularly those containing lawsonite and aragonite, are indicative of high pressure, low temperature conditions of metamorphism. Brown and others (1981) estimate pressures on the order of 6 - 7 kilobars and temperatures of 200 - 250^{o} C for metamorphism of the Chilliwack Group. Blackwell (1983) obtained a

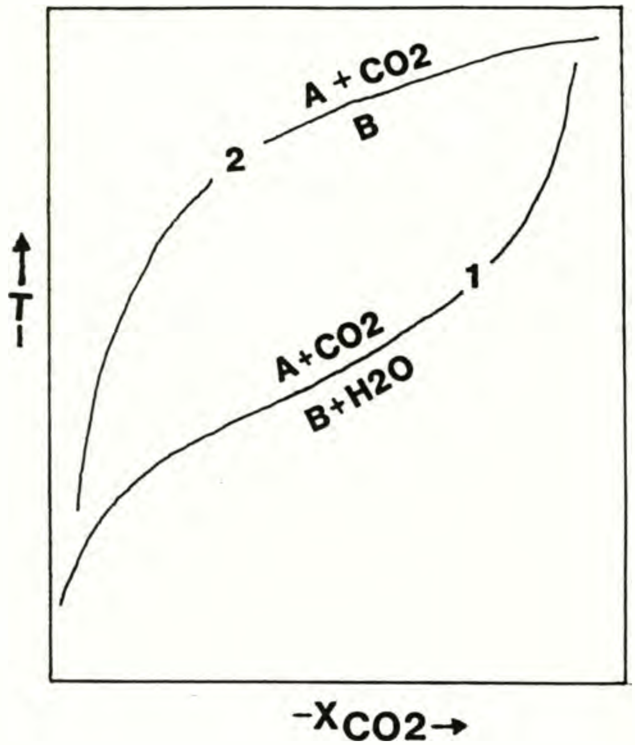


Figure 24: Diagram showing the relationship of temperature and XCO_2 on reactions involving H_2O and CO_2. (Modified from Kerrick, 1974).

vitrinite reflectance temperature of 200^{o}C from an interbedded coal bed in the sedimentary sequence of the Chilliwack Group.

STRUCTURES INTERNAL TO THE CHILLIWACK GROUP

In previous studies, comparatively little emphasis has been placed on internal structures (metamorphic fabrics, etc.) in the Chilliwack Group. It is hoped that this study will contribute to an understanding of deformation within the Chilliwack Group, and that this information will in turn contribute to an understanding of the tectonic history of the western North Cascades region. A large number of topics will be covered in this section, including: descriptions of the metamorphic fabric elements, mylonites, and other strain indicators present in the study area; orientations of the above-mentioned features; interpretation of the L_1 stretching lineations; interpretation of the sense of shear; strain analysis techniques and applications; and timing of the deformation with regard to the metamorphism.

Locations of samples collected in the extended study area for structural analysis are given in Appendix 3. Numbers preceded by the number "2" were collected by E. H. Brown.

STRUCTURAL ELEMENTS: DESCRIPTIONS

Two significant deformations have affected the rocks in the study area, an earlier (D_1) penetrative deformation, which is present in nearly all lithologies except for the diabasic volcanics, and a later (D_2) deformation, which is generally in evidence only in the finer-grained lithologies.

Pre-deformation (S_0) surfaces are readily apparent in bedded rocks (as relict bedding) but rarely in others.

The D_1 deformation is manifested by a penetrative S_1 foliation, found in nearly all lithologies except the coarser volcanic rocks. S_1 is present as a slaty to phyllitic cleavage in argillite and siltstone, as flattened clasts in coarser sedimentary and volcaniclastic rocks, and as flattened amygdules and phenocrysts in volcanic rocks.

A textural classification was developed by Frasse (1981, modified from Bishop, 1972) to classify meta-siltstone and meta-graywacke in his study area along the western margin of the Twin Sisters dunite body (Table 2). This classification is relevent in the present study area as well. Many siltstones along the lower, east-facing slopes of Grandy ridge are in textural zone I. Lithologies in the Baker Dam unit are mostly zone IIB, with some fine-grained samples approaching IIIA. The volcanic arenites and tuffs from the south end of Grandy ridge are largely in zone IIA, with small areas of zone IIB. Textural classifications of appropriate lithologies are included in Appendix 1.

S_1 is nearly always subparallel to parallel to S_0 in areas where a relationship can be observed.

Abundant stretching lineations (L_1) are also associated with the first deformation. L_1 lineations are defined most commonly by stretched clasts in volcaniclastic and sedimentary rocks, stretched amygdules in volcanic flow rocks, parallel alignment of elongate metamorphic mineral grains, and less commonly by boudins or pressure shadows behind resistant grains. Each type is described in more detail below.

<u>Stretched clasts</u> Nearly all sedimentary and volcaniclastic rocks in the map area exhibit stretching to some degree, although this is not always evident in outcrop except in coarser lithologies. Large areas of stretched lapilli tuff and pebbly sandstone are present in sections 20 and 29 on the southeast end of Grandy ridge. Coarse-grained lithologies in the Baker Dam unit also appear well lineated in the field. In many

TABLE 2: A textural classification of meta-siltstone and meta-graywacke in the foothills of northwestern Washington (from Frasse, 1981, modified from Bishop, 1972).

Zone I	No deformation of framework grains.
Zone IIA	Cataclasis and/or flattening of framework grains; foliation present; some original grain boundaries indistinct.
Zone IIB	Cataclasis of framework grains intense; most original grain boundaries indistinct; recrystallization and incipient quartz + feldspar segregation.
Zone IIIA	Original grains obliterated; quartz + feldspar segregated into fine laminations; quartz + feldspar grains less than 0.06 mm in diameter.
Zone IIIB	Quartz + feldpar segregation laminations coarser grained and in well developed lenses; quartz + feldspar grains more than 0.06 mm in diameter.

instances, however, lineations are only evident on cut surfaces.

Clasts in the coarser volcanilithic rocks deform variably depending on composition and grain size. Basic volcanic and argillitic clasts deform readily, whereas dacite clasts are quite resistant (Figure 25). Monocrystalline quartz and feldspar are very resistant, normally deforming by boudinage or by passive rotation, as evidenced by the presence of asymmetric pressure shadows around them.

Sandy beds composed primarily of plagioclase grains occur frequently in the Baker Dam unit. The grains generally deform by boudinage, or, in a few places, appear to be flattened, then further attenuated by the crosscutting of small veins (Figure 26).

<u>Stretched phenocrysts and amygdules</u> Lineations are relatively uncommon in volcanic flow rocks, but at several locations, particularly at the top of Grandy ridge (e.g., location 89), chlorite-filled amygdules define a measurable lineation. A sample(2-683) containing slightly stretched plagioclase phenocrysts was collected from the east side of Lake Shannon by E. H. Brown (1984, oral communication).

<u>Elongate metamorphic mineral grains</u> This type of lineation can only be discerned in thin section. Relatively uncommon in the study area, it is found only in rocks containing abundant white mica, chlorite, lawsonite, and Na-amphibole. This type of lineation will be discussed in more detail in the section on timing of deformation.

<u>Boudins and pressure shadows</u> Boudins associated with sandstone layers and resistant grains and pressure shadows associated with resistant grains are present primarily in the Baker Dam unit, in other fine-grained, highly strained sedimentary rocks, and in highly strained felsic tuffs from the north side of Grandy ridge. Quartz grains (Figure 27), feldspar

Figure 25: Photomacrograph of stretched clasts in a lapilli tuff. Section cut perpendicular to the foliation plane, parallel to the lineation direction (plane polarized light). Dacite clasts (Da) are considerably less deformed than more mafic clasts (Ma). (Plane polarized light.)

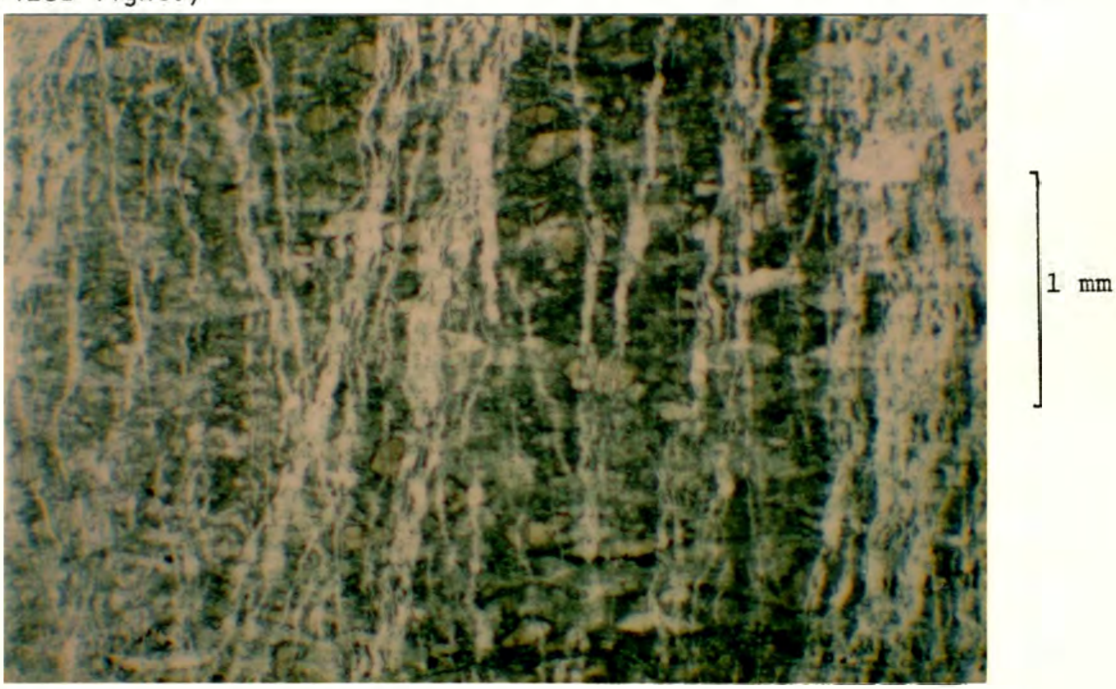
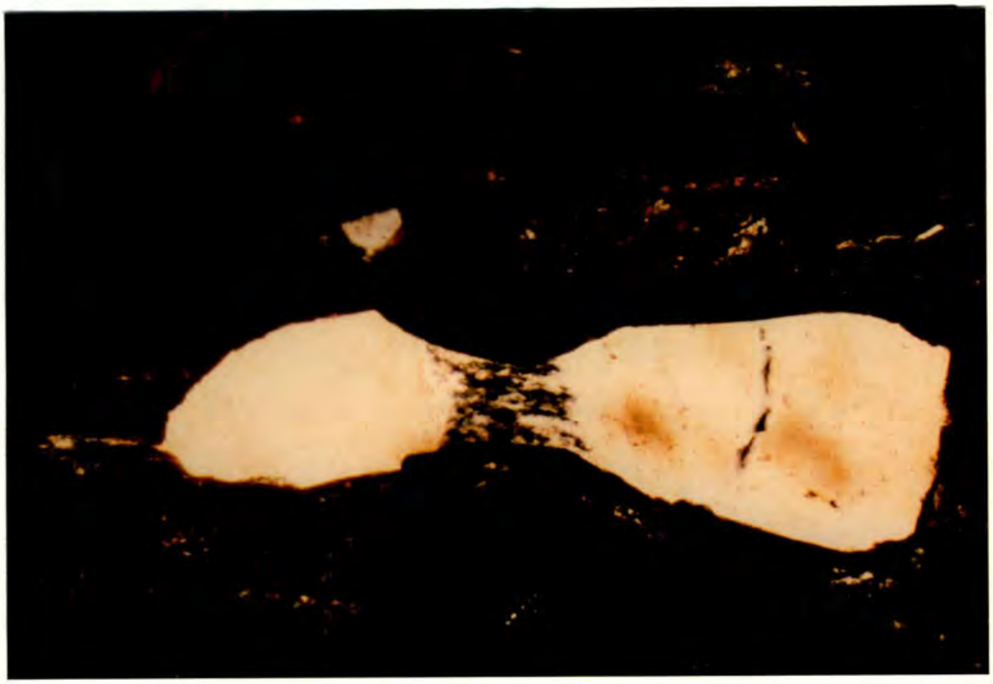


Figure 26: Photomacrograph illustrating another type of deformational style producing elongate clasts. The sand grains have been stretched, then further attenuated by the formation of veins perpendicular to the lineation direction. (Plane polarized light.)

grains, and sandstone beds associated with less competent rocks (Figure 28) frequently deform by boudinage, with the fibers consisting either of quartz or calcite. Euhedral pyrite grains commonly have pressure shadows associated with them. Figure 29 illustrates a pyrite grain with pyrite-type pressure shadows. With this type of pressure shadow, the material comprising the pressure shadow (in this case mostly calcite) is more closely related to the siltstone than the pyrite grain, so the fibers in the pressure shadows initiate growth in the matrix and grow toward the pyrite grain. Therefore, the fibers are younger toward the pyrite grain. The horizontal calcite fibers are associated with the D_1 deformation. The smaller, nearly vertical fibers nearest the pyrite grain are likely associated with a later, non-coaxial deformation.

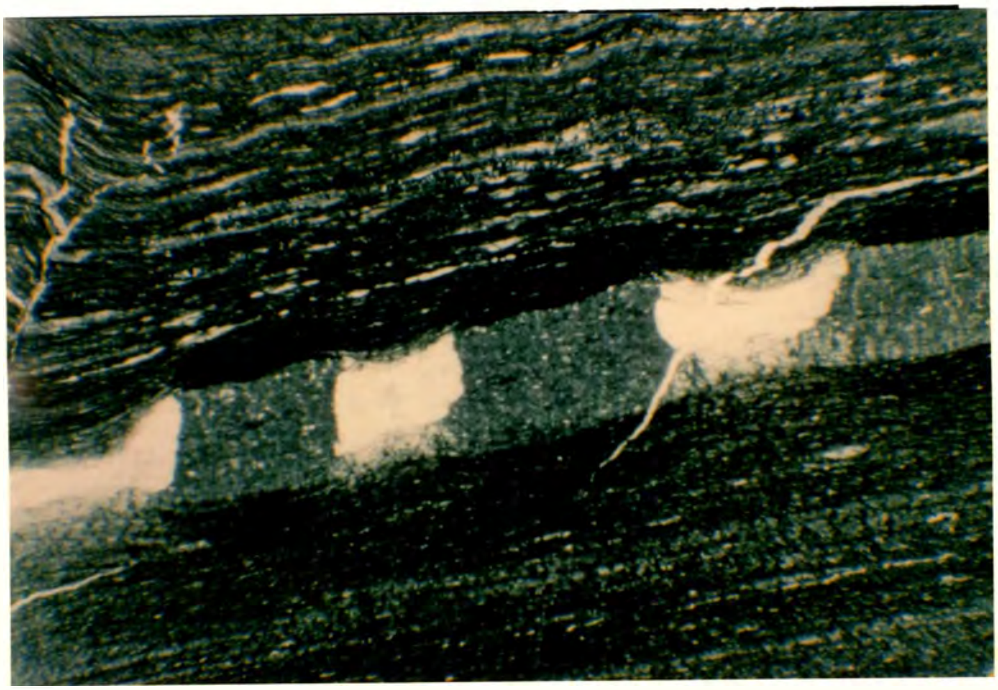
F_1 folds, in the strict sense of folding the S_0 surface but not S_1, were not observed in the map area. Folds associated with D_1 are denoted F_1'. They are most commonly seen as a late kink folding of the S_1 cleavage in more highly deformed (subphyllitic to phyllitic) argillaceous rocks and highly strained tuff. F_1' folds can be distinguished from later F_2 kink folds where the former are seen in association with stretching lineations. F_1' folds have formed with the axes oriented at 90^o to the stretching direction, therefore they exhibit the same sense of shear as the lineations. They probably formed late in the first deformation.

Most of the F_1' features occur on a small scale, but at least one very large fold probably associated with the first deformation was aerially mapped by Blackwell (1983) in the Cultus Formation on Loomis Mountain. While this fold was not located in a subsequent field check for this study, another smaller fold was located south of the location of the first fold (see Plate 2 for location). The aerially-mapped structure was interpreted as an anticline; however field evidence suggests that it is a



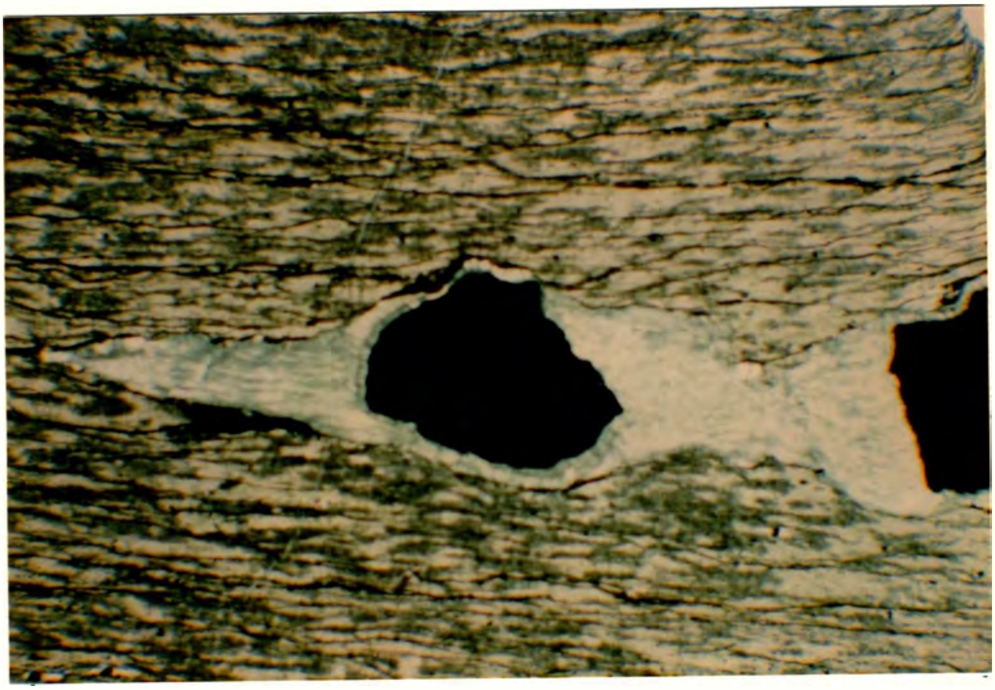
.5 mm

Figure 27: Photomicrograph of a boudinaged quartz grain in the Baker Dam unit (crossed polars).



3 mm

Figure 28: Boudinaged sandstone layer in Baker Dam unit argillite (plane polarized light).



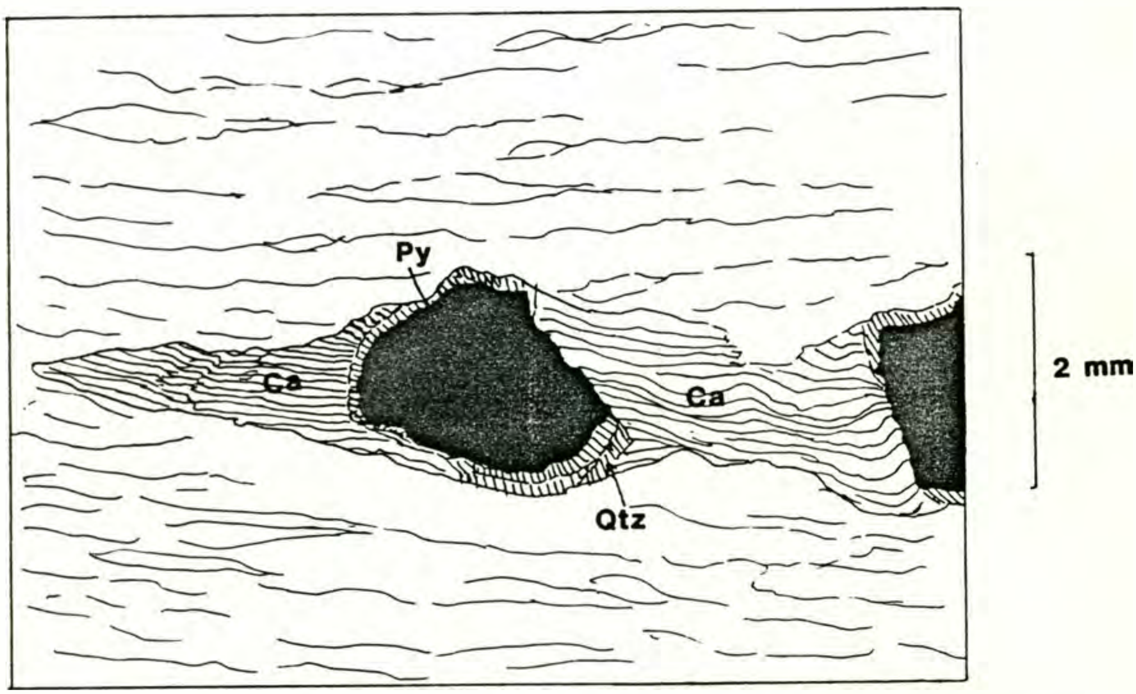


Figure 29: Photomacrograph of a pyrite grain with pyrite-type pressure shadows composed primarily of calcite fibers. Two periods of deformation are suggested by this set of pressure shadows: an earlier, more extensive deformation indicated by the horizontal fibers, and a later deformation indicated by the set of near-vertical fibers. The outermost layer of the second set of fibers is composed of quartz.

synformal structure, as rocks apparently beneath the fold are interpreted as being right-side-up on the basis of sedimentary structures. The S_1 surface is folded, with the formation of an axial planar fracture cleavage (denoted S_1'). The nearly horizontal axis of this fold trends approximately at right angles to the regional trend of stretching lineations, and is therefore interpreted to be associated with the D_1 deformation.

Evidence of a later (D_2) deformation is visible primarily in fine-grained sedimentary rocks and lapilli tuffs in the Baker Dam unit, in sections 20 and 29, and on the lower south end of Grandy ridge.

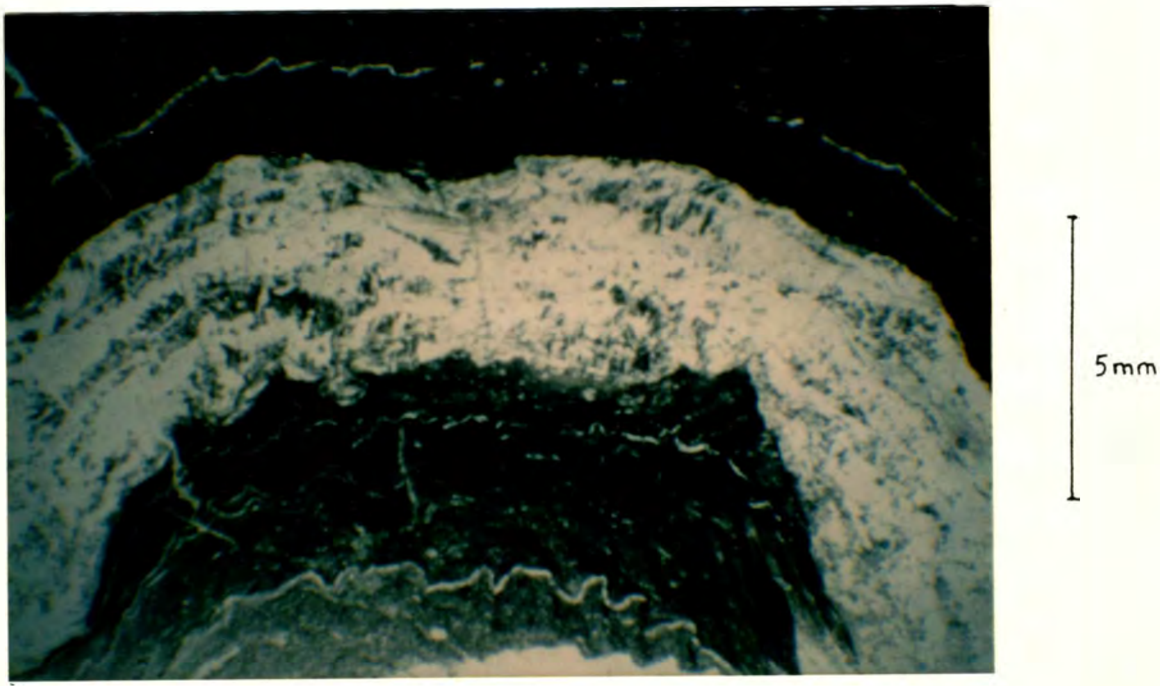
F_2 folding is evident on various scales. Small ptygmatic folds are well developed in siliceous layers in the argillaceous rocks in roadcuts along the Baker Highway west of Upper Baker Dam (Figure 30). Kink folds and conjugate folds are developed on scales ranging from microscopic to conjugate folds with amplitudes of a few feet. Larger open folds are in evidence in a few areas, including locations 43 on a Baker Highway roadcut, and location 109, west of Rocky Creek.

While two sets of kink folds intersecting at roughly 90° angles were observed in phyllites from the vicinity of Upper Baker Dam, the relationship was only observed in float and not observed in rocks tnat were in place. Therefore, F_2 folds are primarily distinguished from F_1' folds on the basis of the relative orientation of the structures relative to stretching lineations, as will be discussed in a later section.

S_2 surfaces are uncommon, and usually found as axial planar cleavages associated with F_2 folds in argillaceous rocks (Figure 31).

<u>Cataclastic rocks</u> Zones of cataclastic rock are most frequently observed in the argillite and siltstone on the north end of Grandy ridge.

Figure 30: Hand sample of F_2 ptygmatic fold in the Baker Dam unit. Ruler is scaled in inches.



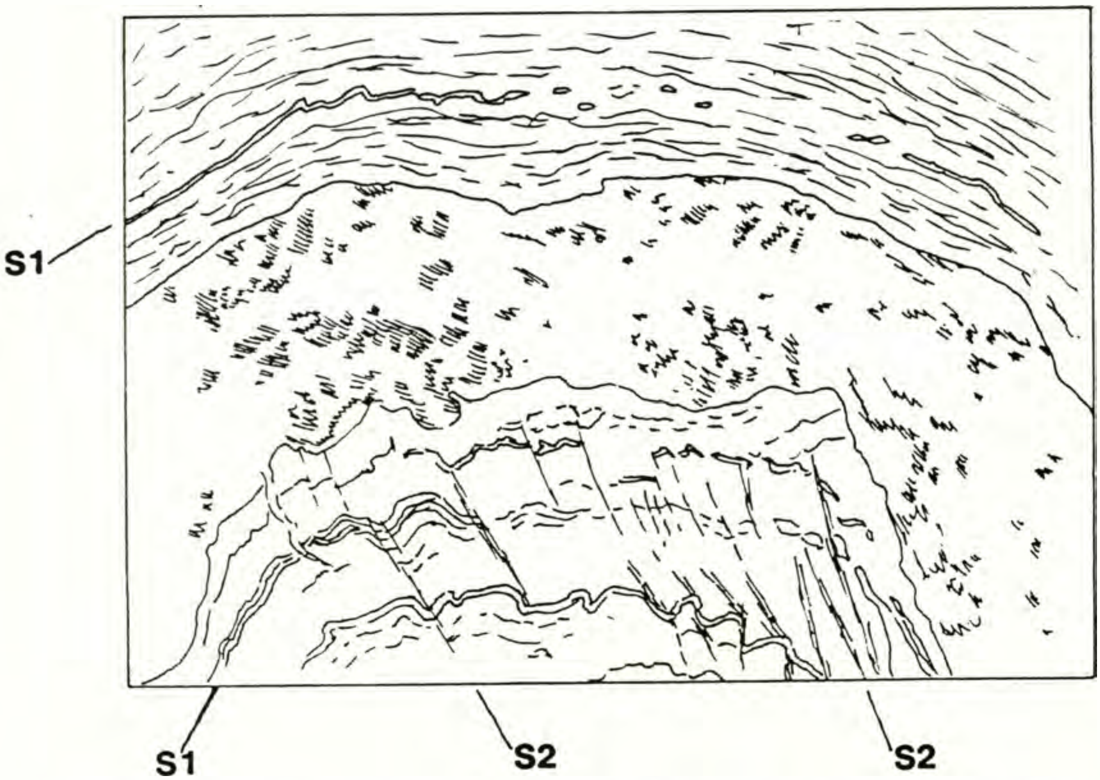


Figure 31: Photomacrograph of S_2 axial planar cleavage associated with small F_2 fold in the Baker Dam unit (plane polarized light).

A commonly observed progression is of coherent, foliated rock grading into disharmonically folded (but still largely coherent) foliated rock grading into completely disrupted cataclastite containing rounded to streaked-out blobs of quartz, calcite, argillite, and sandstone (Figure 32). In areas where this sequence can be observed, the faulting appears largely to postdate the formation of the S_1.

Cataclastic rocks are also common associated with volcanic rocks near the top of the south end of Grandy ridge. They are black to gray, with a well defined, scaly fabric. They are composed of volcanic clasts and segregations of quartz and feldspar in a matrix of chlorite and pseudotachylite.

Small zones in highly strained tuffaceous rocks also exhibit cataclastic deformation (rounding and cataclasis of grains and formation of brown grunge).

DEFORMATION POSTDATING D_1 AND D_2 DEFORMATIONS

A few small Tertiary(?) faults have been noted from the map area, the most prominent being a vertical fault striking approximately N50E, located near the boundary of sections 29 and 30 on the south end of Grandy ridge. It juxtaposes phyllitic siltstone against resistant dacite tuff. The deformation associated with this fault is fairly negligible, except for the presence of drag folds in the phyllite, which indicate that the northwest side moved up relative to the southeast side. Other small, vertical, northeast-trending faults and joints are also present in the vicinity of the larger fault.

Figure 32: Detail of fabric in fault zone immediately below the contact between the Triassic Dacite unit and Chilliwack Group argillite, north side of Grandy ridge. Light colored area is a boudin of sheared dacite tuff.

METAMORPHIC FABRIC: ORIENTATION

The spatial orientation and relationships between S-surfaces, folds, lineations, etc. can be effectively revealed with the use of stereonet plots. The map area was arbitrarily divided into three domains for the purpose of plotting S_1 data: a southwest subarea, including the southern half of Grandy ridge up to Bear Creek; a northwest subarea, including the northern half of Grandy ridge and bounded on the east by Rocky Creek, and a Baker Dam subarea, including outcrops in the northeast portion of the map area.

Contoured data from the southwest subarea (Figure 33), representing 62 poles to S_1, shows a fairly wide spread in S_1 orientations, although most are shallowly dipping. A best-fitting great circle through the points reveals that they have been folded around an axis of N57W trend and a plunge of 7^o to the north. However, the large scatter in points suggests a slightly more complicated deformational history.

Northwest subarea data (Figure 34), representing 36 poles to S_1, reveals a similar, if slightly, clearer picture of open folding about an axis trending N56W and plunging 10^o to the northwest.

Baker Dam subarea data (Figure 35) plots in a relatively tight cluster representing an average S_1 orientation of N29W, 47N. S_1 attitudes in this subarea appear to be little affected by large scale folding.

L_1 data for the map area and for the extended study area are plotted on both a stereonet (Figure 36), and on a regional map (Figure 37) for clarity. L_1 data are remarkably consistent over a wide region, falling in a cluster around a trend of 148^o and a plunge of 10^o , although they diverge from this orientation to the east near the fault between the Chilliwack Group and the chert/basalt unit where the lineations are

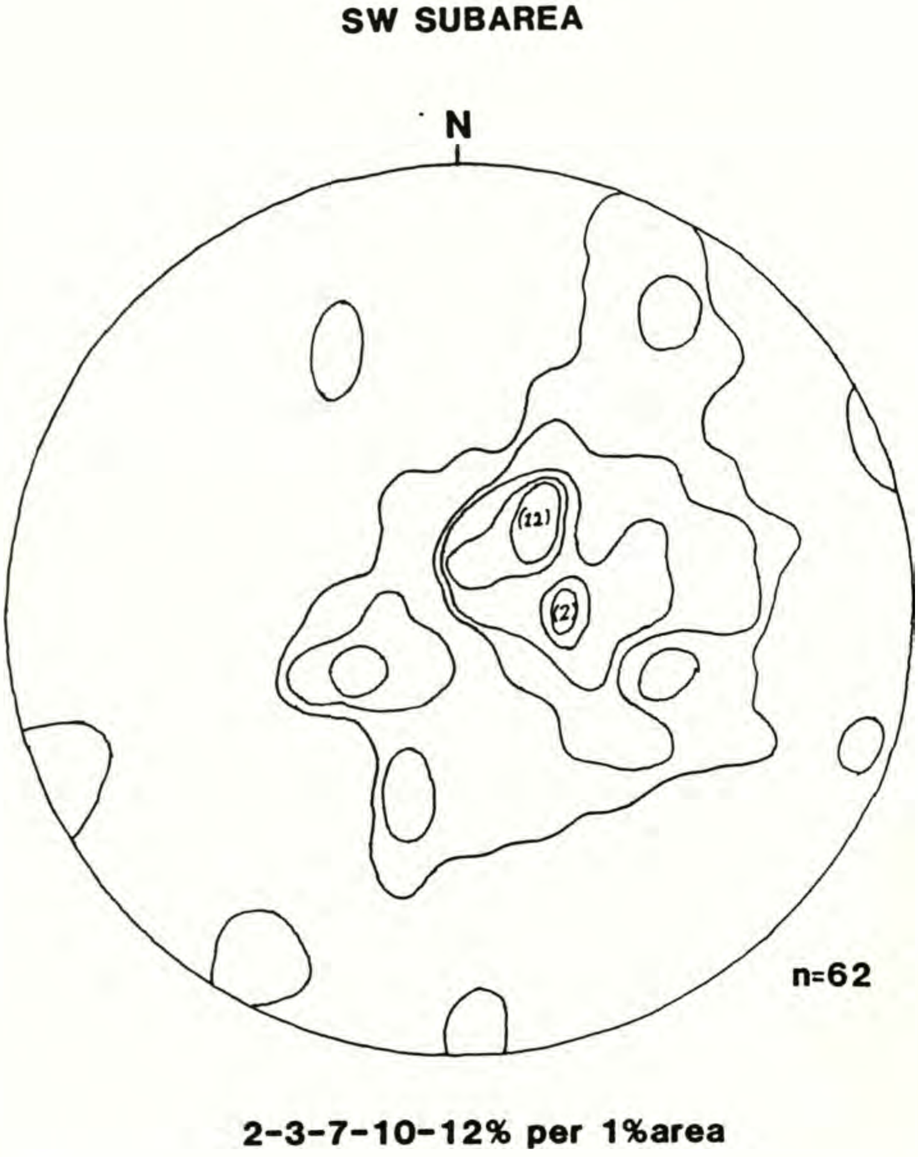


Figure 33: Contoured Pi diagram of poles to S_1 for the southwest subarea.

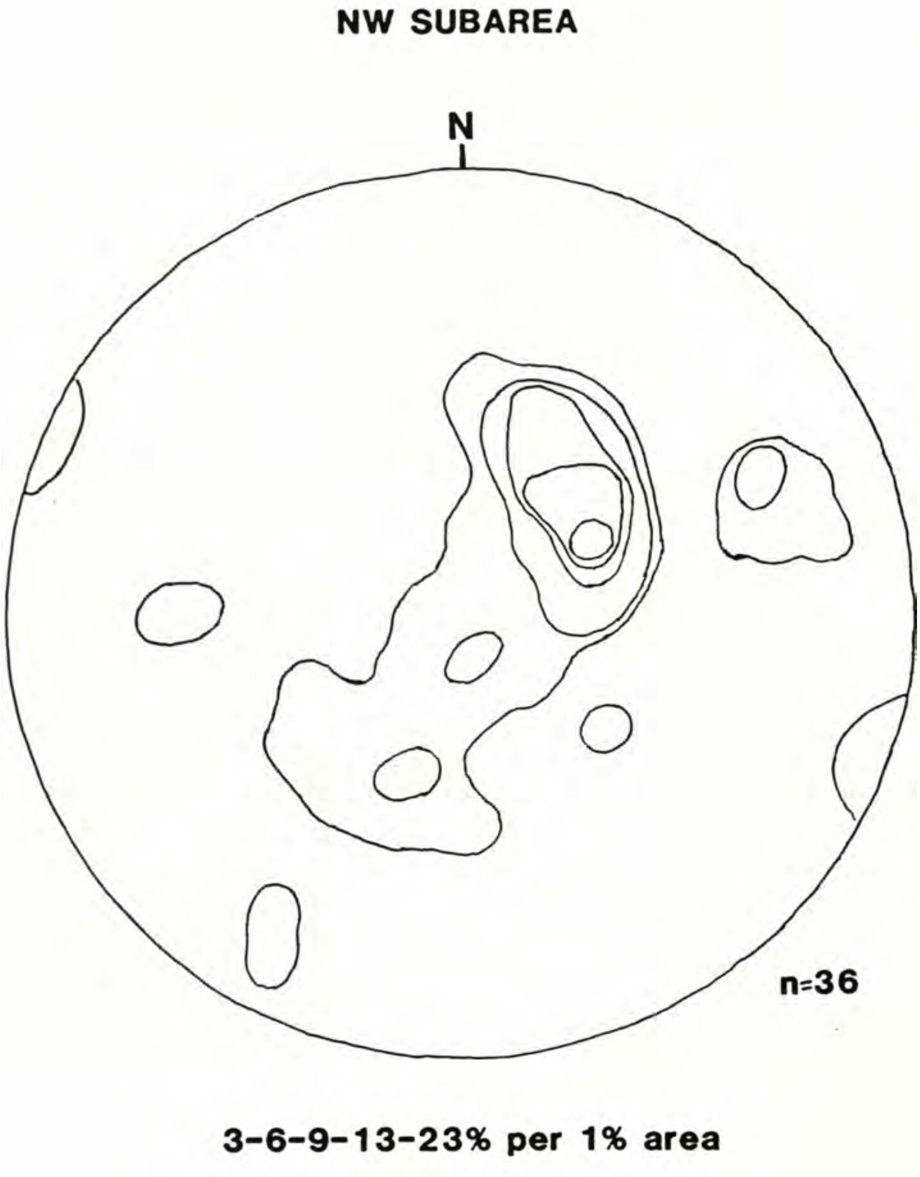


Figure 34: Contoured Pi diagram of poles to S_1 for the northwest subarea.

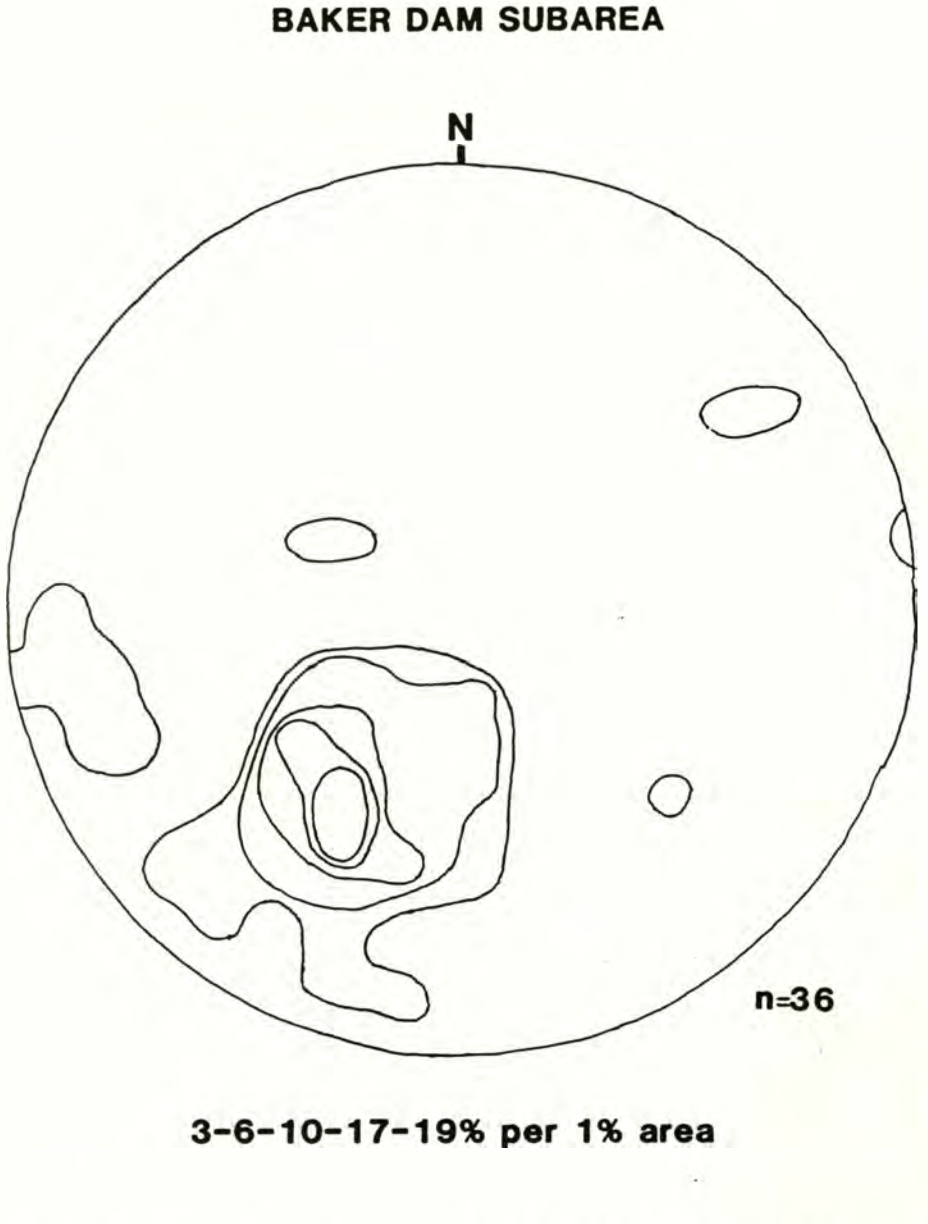


Figure 35: Contoured Pi diagram of poles to S_1 for the Baker Dam area.

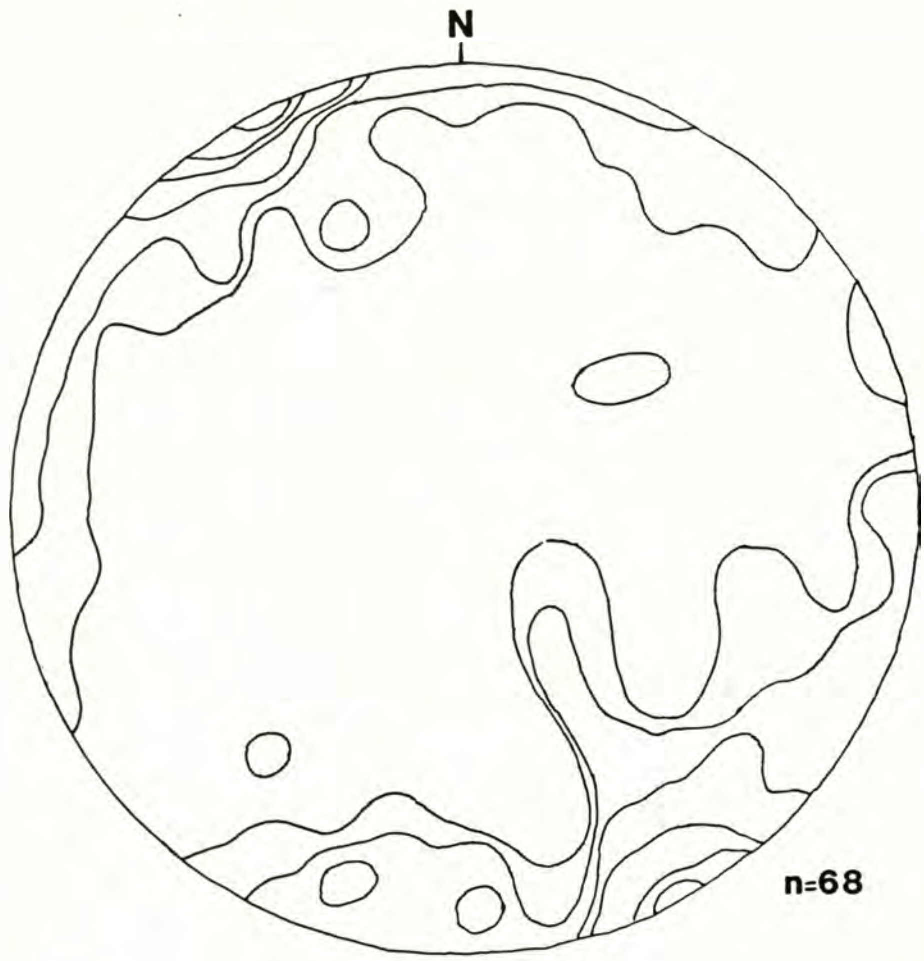


Figure 36: L_1 data for the extended study area.

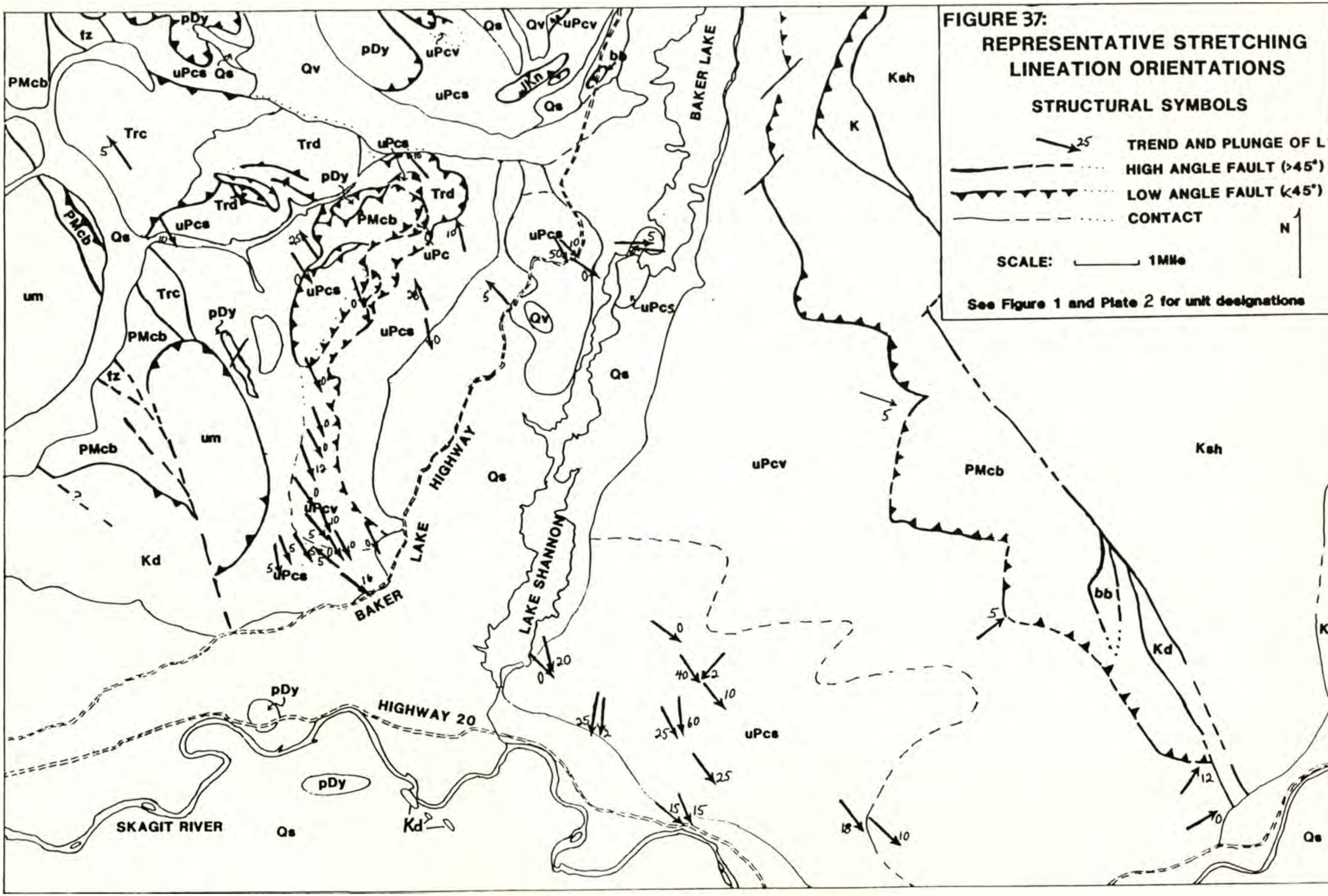


FIGURE 37: REPRESENTATIVE STRETCHING LINEATION ORIENTATIONS

predominantly northeast-trending.

Eleven F_1' fold axes were measured, and are plotted in Figure 38. The points form a cluster around a nearly horizontal line trending N52E. Nine F_2 fold axes were measured, and are plotted on the same figure for comparison. These points loosely cluster around a nearly horizontal axis trending N43W.

A consistent sense of fold vergence was generally not noted in most areas. A few areas showed some consistency in F_1' orientations. F_1' kink folds in phyllitic rock cropping out in a creek bed on the south-facing side of Grandy ridge are generally oriented with short limbs dipping north. The large F_1' folds on Loomis Mountain are recumbant folds overturned to the northwest. Observations of F_1' folds from other areas generally show no consistent sense of asymmetry; nearly as many folds are oriented with the short limbs dipping to the northwest as to the southeast. F_2 folds normally show little sense of asymmetry. The large folds previously mentioned are both overturned to the northeast. At least one set of F_2 kink folds noted in a creek near the Whatcom/Skagit county line are oriented with short limbs dipping to the southwest.

Data from small shear zones and faults are plotted in Figure 39. They show a similar orientation to S_1 data from the northwest subarea, from which most of the measurements were taken.

Discussion

The deflection of S_1 attitudes in the southwest and northwest subareas around the axes of N57W, 7N and N56W, 10N respectively, corresponds fairly well with the average measured F_2 direction of N43W and horizontal, and hence can probably be attributed to F_2 folding.

Comparison of L_1 and F_1 data shows the average F_1 fold axis, at

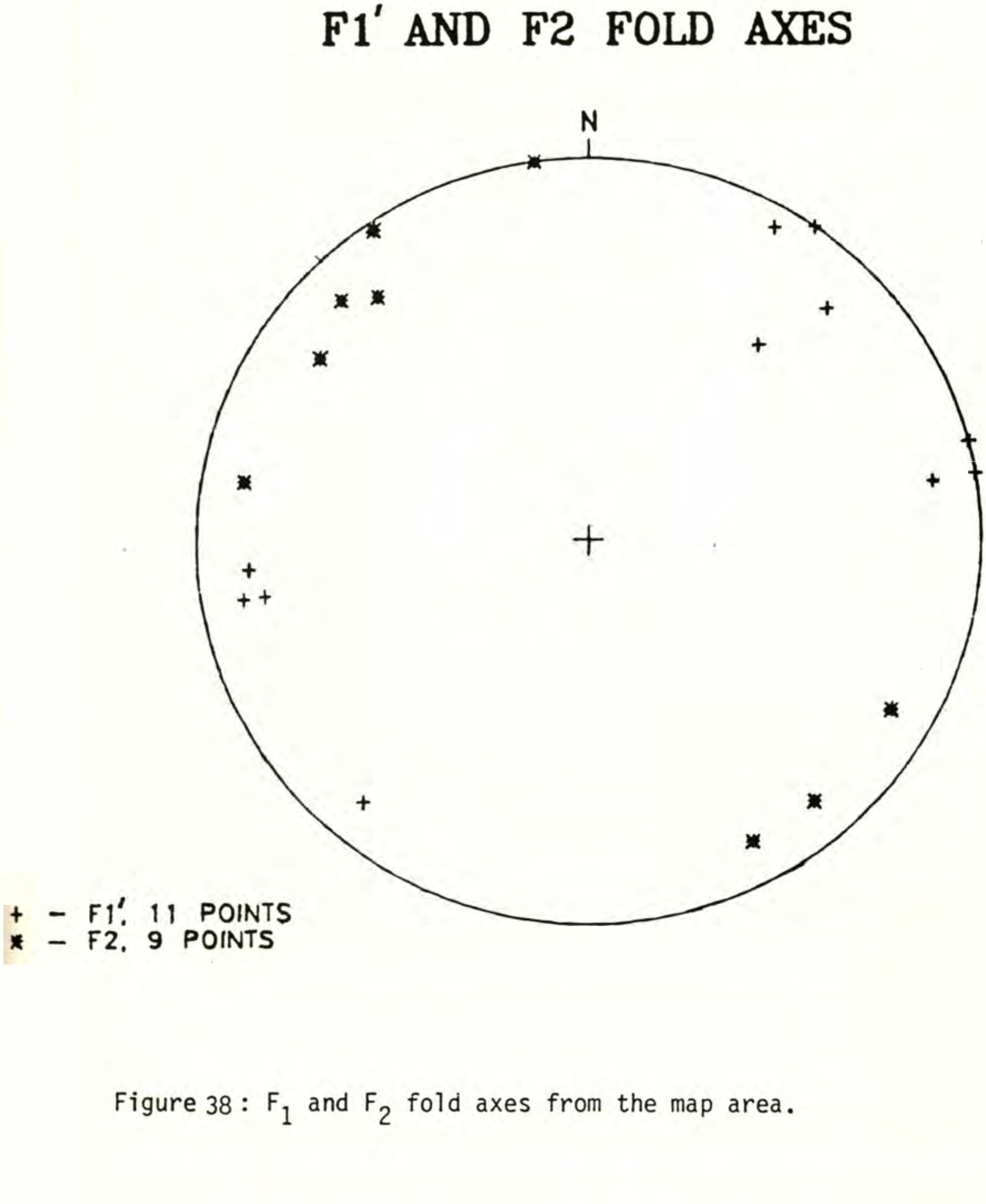


Figure 38 : F_1 and F_2 fold axes from the map area.

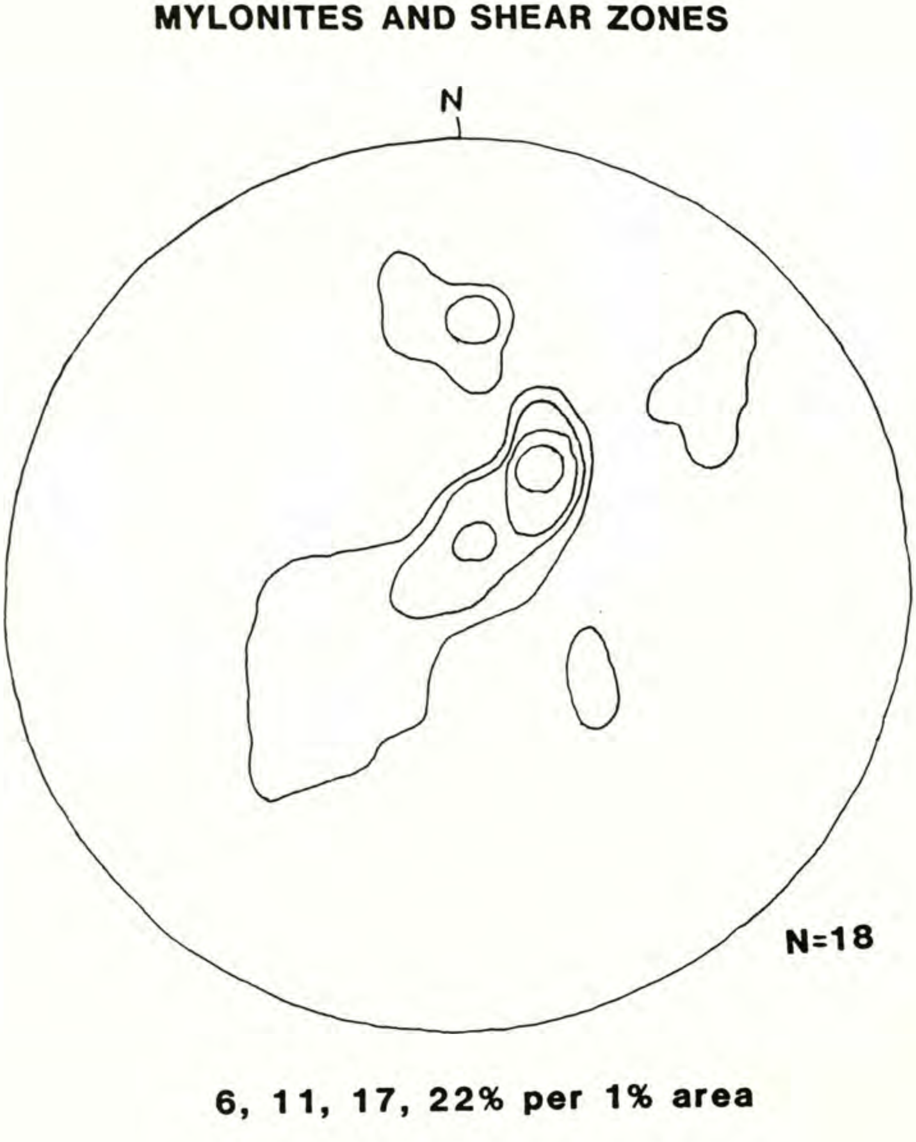


Figure 39: Contoured Pi diagram of poles to mylonites and shear zones.

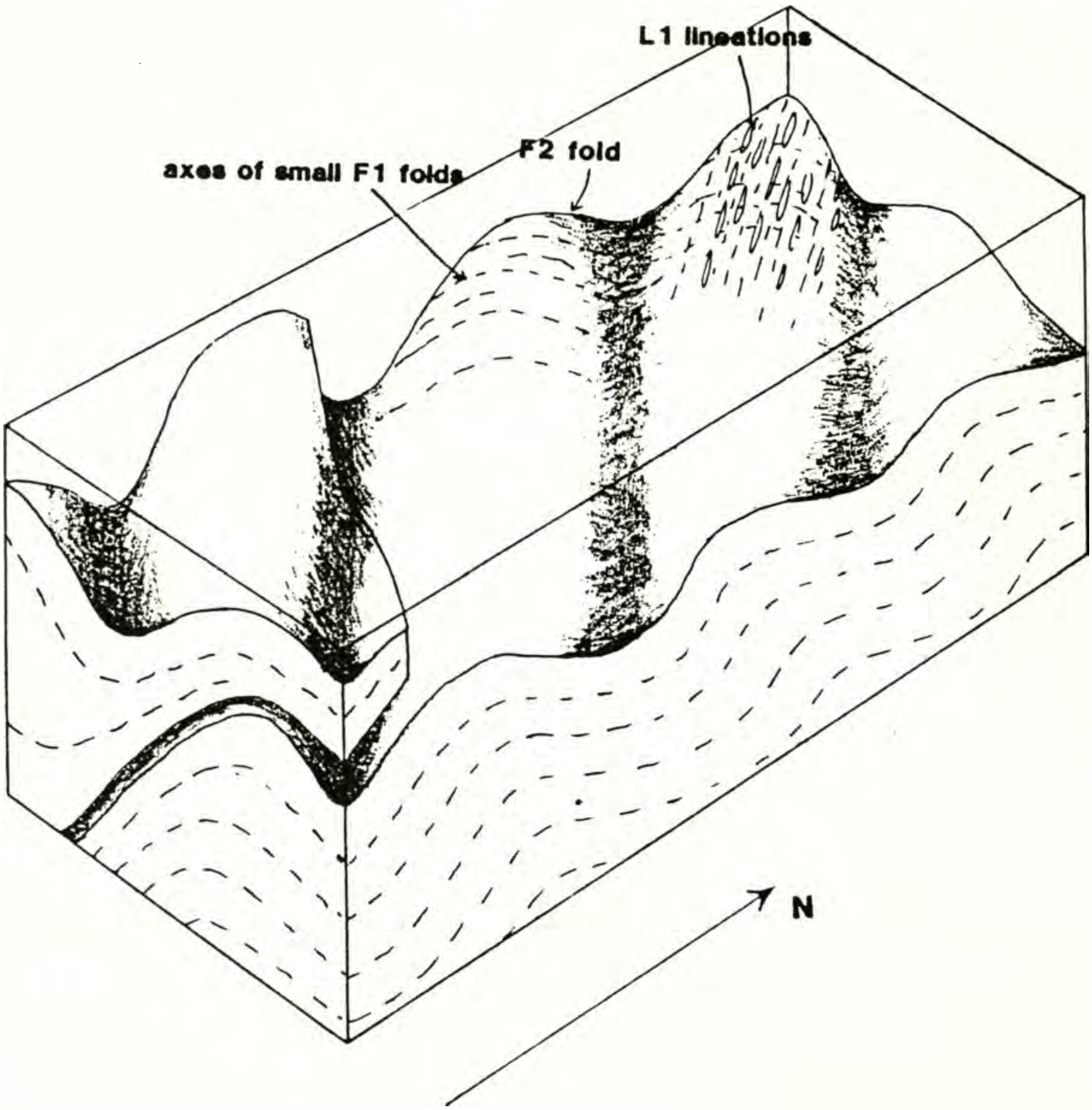


Figure 40: Diagrammatic representation of structural data for Chilliwack Group clastic rocks in the map area.

N52E and horizontal, to be oriented 84^{0} fom the average measured L_1 value (148^{0} trend, 5^{0} plunge) in a slightly south-dipping plane. This is very close to the expected difference of 90^{0} between L_1 and F_1' directions. The large, nearly horizontal fold on Loomis Mountain, with an axis trending N55E, is probably an F_1' fold based on the similarity of its orientation to other F_1' folds. The absence of significant scatter in the L_1 orientations, expected due to later folding, can probably be attributed to the near parallelism of L_1 and F_2 axis orientations.

Figure 40 is a diagrammatic representation of the orientations of the common structural features present in the map area.

The regional map of L_1 lineations (Figure 37) reveals that, while L_1 directions are very consistent in the vicinity of Grandy Ridge, a significant number of northeast-trending lineations are present near the eastern boundary of the regional map, near the fault between the Chilliwack Group and the chert/basalt unit. Also of interest is the concentration of L_1 measurements along Grandy Ridge and to the southeast. This is partially a reflection of the distribution of appropriate lithologies; but, in a number of areas with no or few L_1 orientations plotted, the rocks were only weakly foliated and contained no definite lineation.

KINEMATIC INTERPRETATION OF L1 STRETCHING LINEATIONS

The relationship of the elongation directions in stretched rocks to the kinematic directions is normally a complex one, although it is often possible in a general sense to interpret, for example, relative movement directions between two blocks separated by a shear zone containing stretched clasts or other lineations. This is a subject not without controversy, however, as the significance of stretching lineations has been interpreted in at least three different ways.

Jefferey (1923) placed prolate and oblate ellipsoids in a viscous liquid and subjected the system to simple shear. He found that the prolate forms tended to align in the plane of shear with the long axes perpendicular to the shear direction. Two conditions make this a poor model for most rocks containing ellipsoidal particles. One is that the particles and matrix in the Jefferey study were of vastly different competency, such that no deformation was sustained by the grains, and the second is that the stable configurations were reached only after hundreds of rotations, a condition probably not realized in most rocks.

On a similar note, Blake and others (1981) found lineations in rocks of the Cycladic blueschist belt in Greece and used them as evidence in orienting a paleo-subduction zone parallel to the lineation direction (therefore perpendicular to the subduction or shear direction).

Ave Lallemant (1983) found no apparent relationship between mineral lineations and folding and thrusting in a Mesozoic thrust belt in eastern Oregon, interpreting the lineations to be the result of pressure solution.

A majority of workers, however, favor the idea that stretching lineations are oriented roughly parallel to movement directions, e. g., Bryant and Reed (1969), Escher and Watterson (1974), Rodgers (1984), Shackleton and Ries (1984). These papers address the subject of lineations in association with thrusting or subduction, and conclude that the elongation direction is perpendicular to the overall shortening direction, and approximately parallel to the shear direction.

This concept is illustrated in Figure 41. A passive, spherical marker, when subjected to simple shear, will record the shape of the strain ellipsoid, which is normally represented by the lengths of the long (X), intermediate (Y), and short (Z) axes. The marker in Figure 41, when subjected to simple shear, elongates at an acute angle to the shear plane, with the X-axis orientation approaching the shear direction at high strain magnitudes. The length of the Y-axis remains constant while the Z-axis shortens; the result is that a foliation is formed parallel to the XY plane. Simple shear also produces a characteristic ratio of axial lengths, such that the equation $[(X/Y)-1]/[(Y/Z)-1]$ is numerically equal to one. This value is refered to as the K value (Flinn, 1956). Escher and Watterson (1974) also note the tendency of randomly oriented lines to rotate into parallelism with the shear direction at high strain magnitudes.

This general premise, that the long direction of stretched clasts and elongate objects points in the direction of shear while the foliation forms subparallel to the shear plane, is adopted in this study, based in part on the following observations:

1) Indicators of extension, such as quartz fibers in pressure shadows and boudinaged grains, are oriented parallel to the long axis directions of stretched clasts and elongate mineral grains.

2) Shear directions, indicated by asymmetric pressure shadows, etc. associated with resistant grains that rotate rather than passively deform,

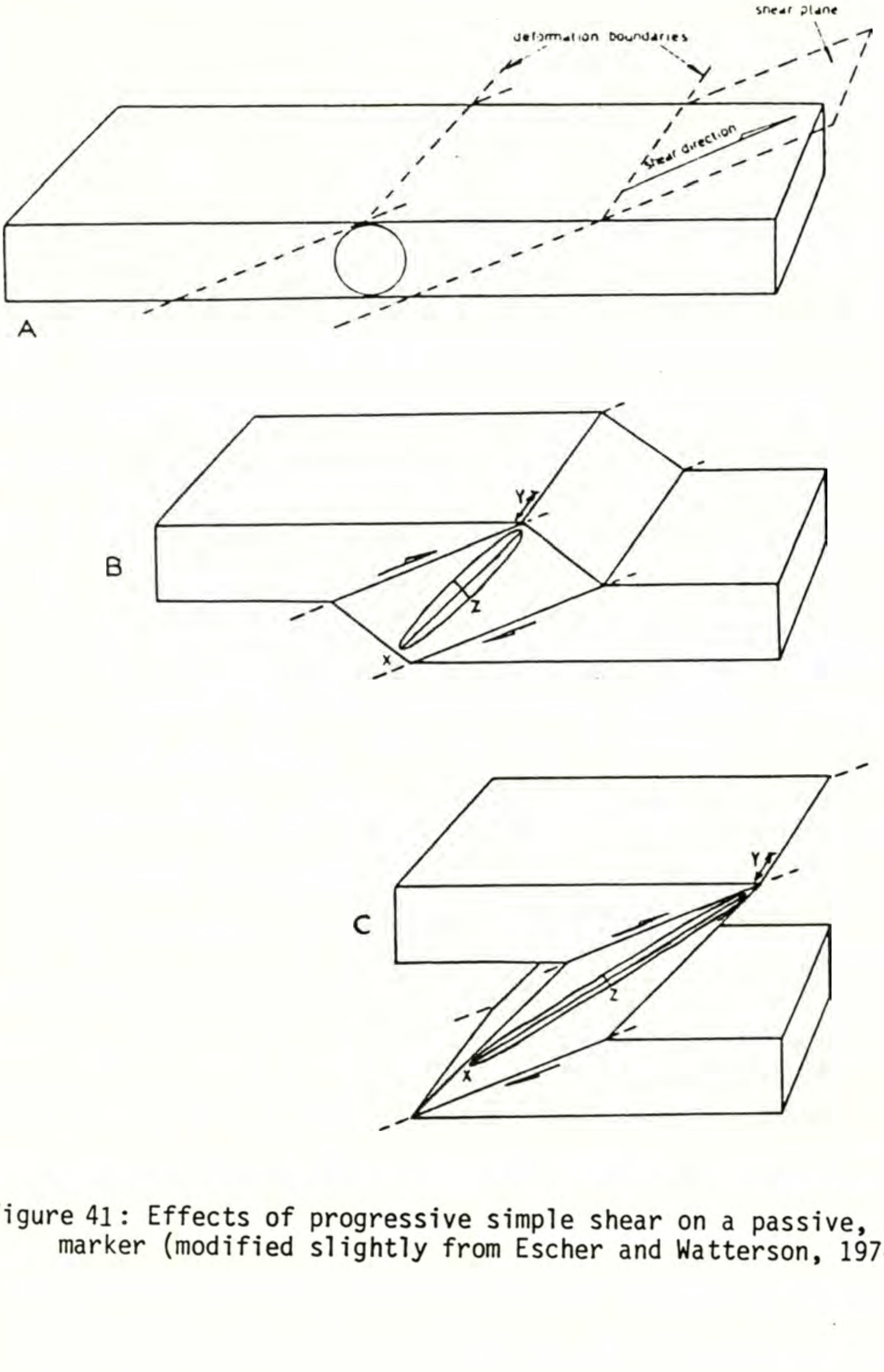


Figure 41: Effects of progressive simple shear on a passive, spherical marker (modified slightly from Escher and Watterson, 1974).

are consistent with the above interpretation.

Unfortunately, it is not often possible to discern whether simple shear, pure shear, or some other mechanism such as pressure solution is responsible for the strain observed in deformed rocks. A model of homogeneous simple shear was used by Escher and Watterson (1974) to explain the occurrence of elongate clasts in rocks from a variety of areas, based on the observed continuity of structures such as bedding planes across deformation boundaries (as Figure 41 illustrates, the size and shape of the boundary planes remain unchanged throughout shearing). Other evidence for strain produced by simple shear might include:

1) K values of 1.

2) The elongation direction in stretched clasts oriented at an angle to slaty cleavage in finer grained rocks, assuming the latter exactly parallels the shear plane.

Evidence for strain induced by pure shear (flattening) might include:

1) K values $<$ 1 (which would indicate flattening).

2) No continuity of structures such as bedding across deformation boundaries.

3) The XY plane in stretched clasts paralleling the slaty cleavage in adjacent finer grained rocks.

K values $>$ 1 may indicate more than one period of deformation.

The above criteria are based on very simple models; inhomogeneities can exist on all scales. Mechanisms such as pressure solution can produce similar relationships. Figure 26, p. 60, illustrates some of the complexities involved in the deduction of a mechanism.

In Figure 26, it can be noted that: grain flattening is roughly parallel to the foliation and that a network of small veins is present, oriented perpendicular to the flattening direction. It is estimated that 43% of the extension in the XZ plane is due to the presense of quartz veins. Veins of this nature normally form parallel to the direction of maximum compression. This and the observation that the elongation and cleavage directions are parallel suggest either pure shear (flattening) or pressure solution as possible mechanisms. However, the influence of these mechanisms does not rule out a component of simple shear. Other samples from the same vicinity contain evidence of rotational shear such as asymmetric pressure shadows around augen; and a computed K value for this rock is approximately 1.2, very close to the expected value for simple shear deformation.

The model proposed by Escher and Watterson (1974) is probably too simple an explanation for the strain in this sample. However, a majority of samples do not exhibit these phenomena, and also have K values near 1 (see strain analysis section). On an outcrop or regional scale, the strain can probably also be considered fairly homogeneous, although clearly it may not be on a smaller scale (as in Figure 25, p.60) The simple shear model, although an oversimplification, will be adopted for analyses and calculations in the rest of this study, because nearly all samples contain evidence of some type of rotational strain, and because it is the easiest model to employ in calculations.

SENSE OF SHEAR IN SANDSTONES AND TUFFS

In rocks which contain a primary stretching lineation, the assumption is often made that the rock underwent shear deformation. The foliation is normally assumed to correspond approximately to the plane of shear, with the lineation direction indicating the direction of maximum elongation. Less obvious are indicators of the sense of shear, particularly in areas where the boundaries of shear deformation and offset marker horizons are absent or not well established, as is the case in the Grandy Ridge area. For this study, an attempt to determine the sense of shear in suitable rocks was carried out primarily using methodology outlined in Simpson and Schmid (1983), by examining structures internal to the rocks. The sense of shear is determined primarily by examination of asymmetrical augen, asymmetric pressure shadows around resistant grains, displacements of broken grains, and intersections of c- (shear) and s- (foliation) surfaces. Other indicators, such as asymmetric kink folds in slates and phyllites, were also examined.

Oriented samples of sandstones and mylonites containing resistant quartz and feldspar grains were collected from within the map area and in the extended study area. Thin sections were made from sections cut parallel to the lineation direction and perpendicular to the foliation and were scrutinized for evidence of shear. A majority of samples proved to be of no use in determining shear sense, apparently because the magnitude of strain was not sufficient to produce the necessary structures. Due to the relatively low grade nature of these rocks, the most abundant and useful structures for determining shear sense are pressure shadows and broken grains (Figure 42). In some rocks, a "cisaillement" or shear fabric (Berthe and others, 1979) has developed at low angles to the

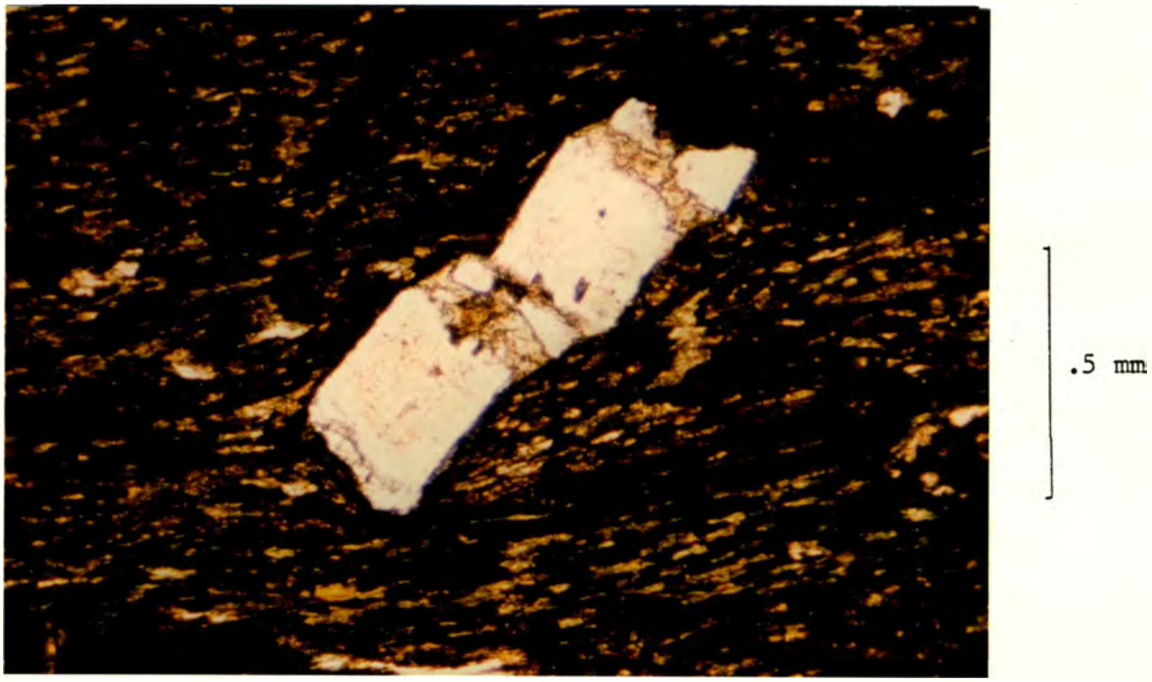


Figure 42: Photomicrograph of a plagioclase grain in a lapilli tuff which has been broken and pulled apart in a manner suggesting dextral shear (crossed polars).

original s-surface, parallel to the boundaries of shear. These so called c-surfaces represent discrete zones of high strain, and can be used to determine shear sense because the original s-surfaces are deflected by the c-surfaces (Figure 43). Grains from the same slides often give conflicting evidence of shear sense, so as many grains as possible were examined in each slide before a determination of shear sense was made. Table 3 summarizes the results of observations of 18 oriented thin sections. The information in Table 3 is also plotted on a regional map (Figure 44).

DISCUSSION

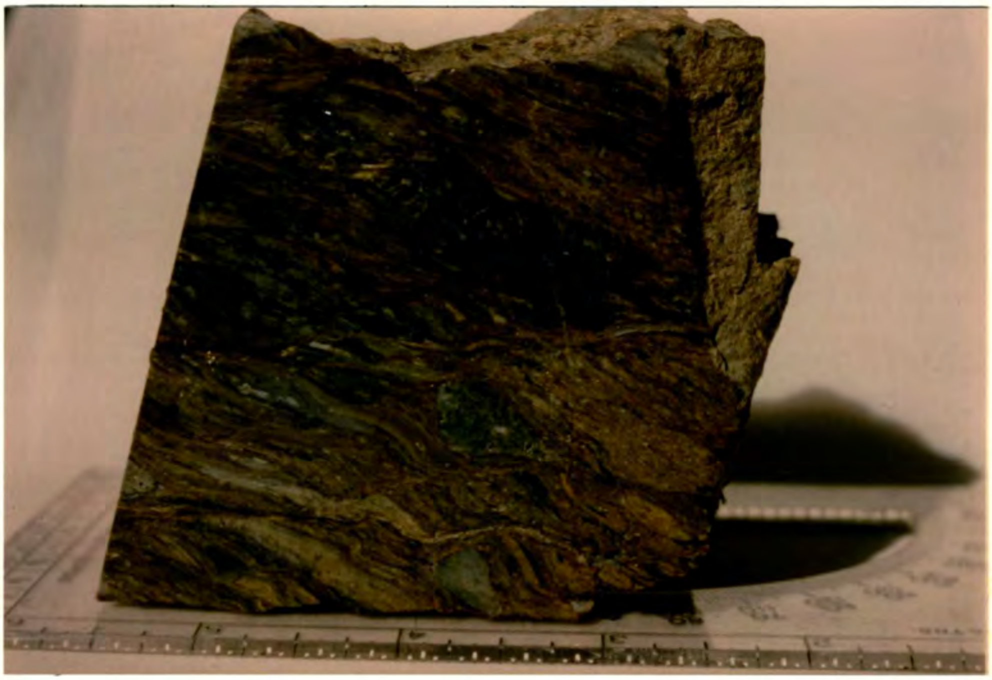
Although the sense of shear in several samples suggests southward translation of the upper plate, a majority of samples contain small scale features that suggest northward translation. In one sample (209) the foliation plane is nearly vertical, such that the relative shear sense is right-lateral.

Fold vergences are another criteria for determination of shear sense in rocks that are not highly contorted. As previously discussed, a number of F_1' features are overturned or have short limbs dipping north, indicating that the upper plate moved north. However, a significant number of folds have an opposite sense of asymmetry.

The shear sense indicated in these samples appears not to be related to either S_1 attitudes (i. e., whether the rocks are dipping northeast or southwest) or the type of indicator used to determine shear sense.

The results of this sense of shear study are not particularly conclusive; however, since more samples show an upper-plate-northward sense of shear, it will be assumed that this is the dominant sense of motion in the Chilliwack group in the study area.

Reasons for the apparent indeterminate nature of the data generated by this study may be several, including: misinterpretation of shear sense;



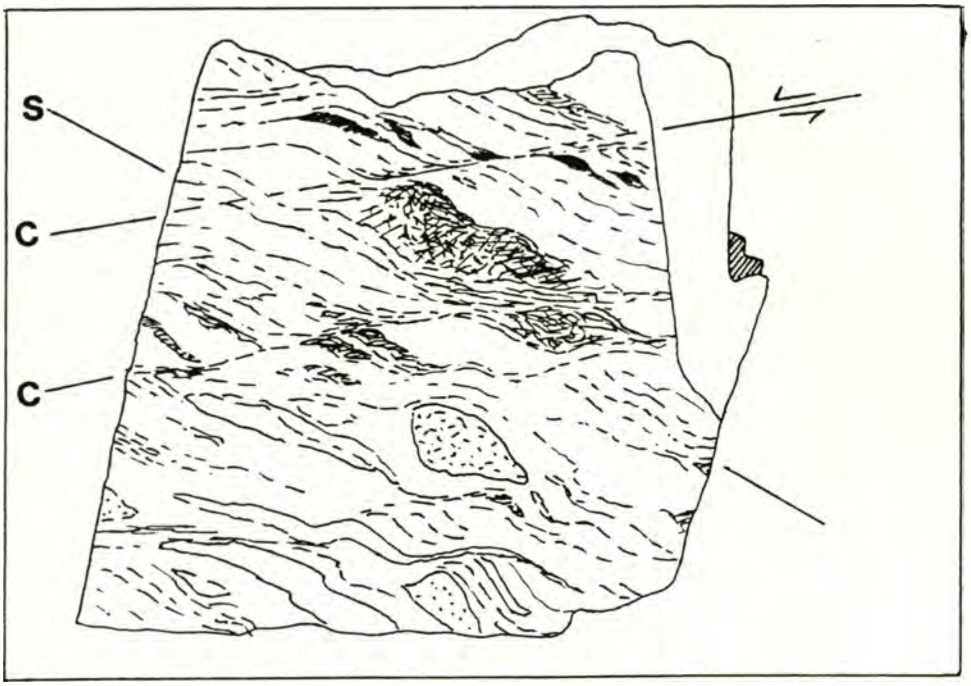


Figure 43: "Cisaillement or shear fabric intersecting existing foliation in a volcanic breccia. S-surfaces curve into shear (C) surfaces in a manner suggesting sinestral shear. Scale at bottom of photo is in inches.

TABLE 3: SHEAR SENSE INDICATORS

SAMPLE #	SHEAR SENSE*
49	S30E
59	N20W
78	N60W
125	N10E
132	N30E
134	N63W
138	S10E
141	N40W
142	N40W
147	S22E
148	N
160	N55W
165	S50E
168	S53E
171B	N85W
209	RT LATERAL
800	N60E
811B	N70W

* in all cases except #209, the foliation (and hence the shear plane) is nearly horizontal, making terms such as dextral and sinestral meaningless. A shear sense designated N50W, for example, indicates that the relative translation of the rocks above that point was in a northwesterly direction.

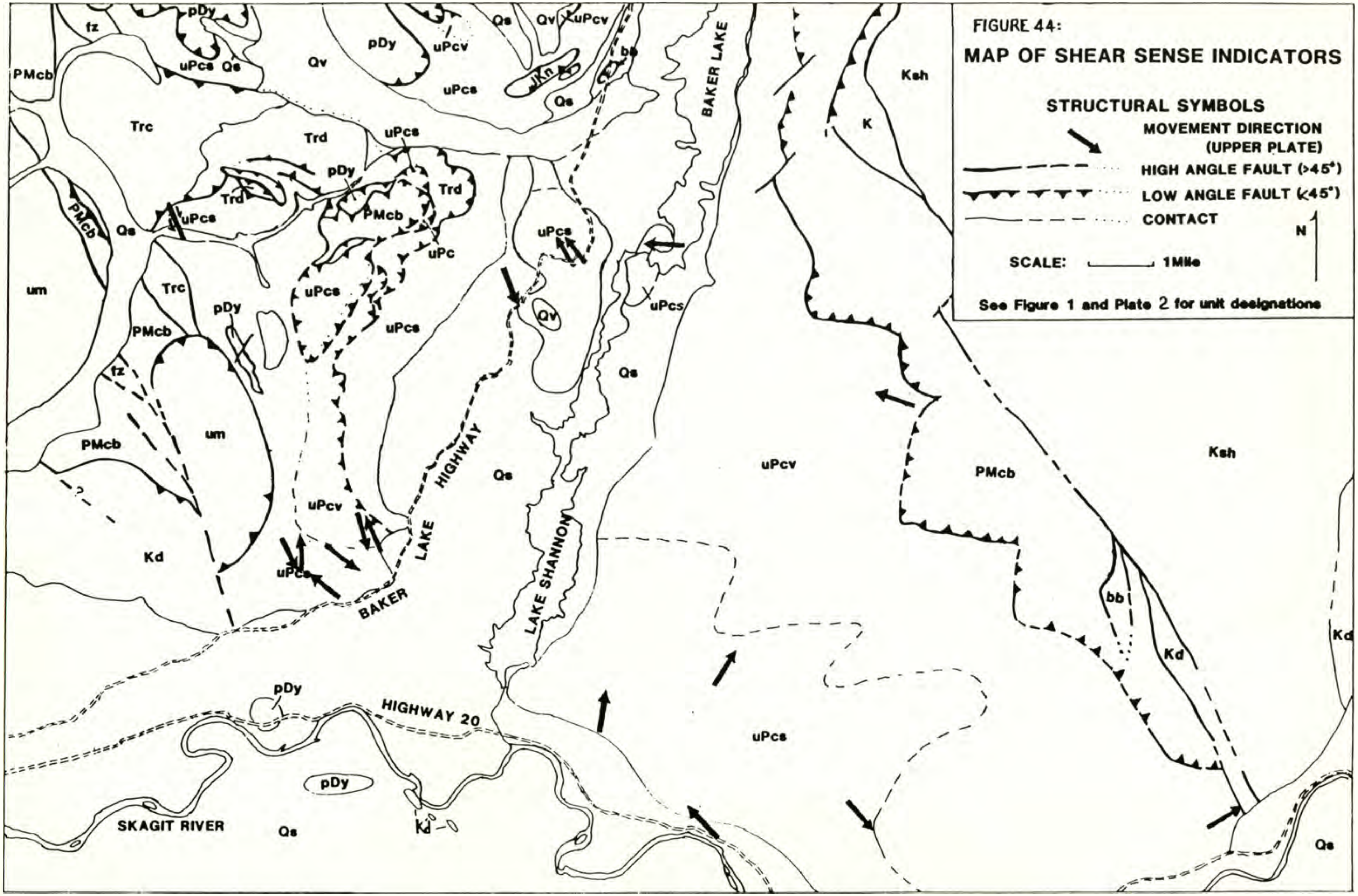


FIGURE 44:
MAP OF SHEAR SENSE INDICATORS

the small number of samples which yielded useful information; or the effects of two periods of deformation. (Notably in samples with c-surfaces intersecting s-surfaces, a slightly later period of deformation is possible.) A fourth possibility is that the deformation is more complex than simple shear, with the development of both thrust and lag faults between units of differing competency accounting for the divergence of shear directions. Monger (1966) identified a fault between two nappes (the McGuire and Liumption nappes) in the type area as a lag fault.

In apparent agreement with the tentative findings of this study, Monger (1966) also interpreted dominantly upper-plate-northwestward movement in the Chilliwack Valley, B. C., based primarily on the geometry of the McGuire nappe. The McGuire nappe is an anticlinal structure overturned to the north, bounded from below by a thrust fault. Although the large, overturned synforms on Loomis Mountain are also overturned to the northwest, the sense of shear is probably indeterminate.

STRAIN MEASUREMENTS ON STRETCHED ROCKS

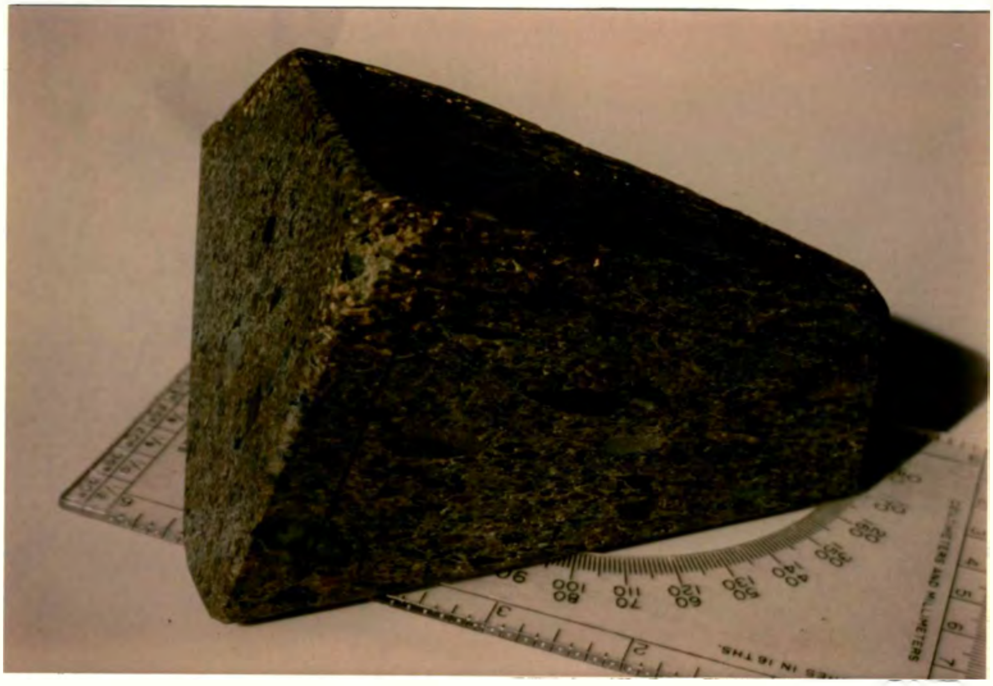
Finite strain measurements were made on 20 samples from localities throughout the region. Coarse-grained lapilli tuff and volcaniclastic conglomerate, finer-grained tuff and sandstone, and a few samples of fine-grained amygdaloidal and porphyritic basalt comprised the majority of rocks used for analysis, because they contain an abundance of originally ellipsoidal objects that are suitable for strain analysis.

As previously discussed, a spherical, passive marker in an isotropic media, when strained, records the shape of the strain ellipsoid, represented by the lengths of the three principal axes (X = long, Y = intermediate, Z = short). The axial lengths of a sample of ellipses are normally measured on three surfaces parallel to the principal planes of strain (the XY, XZ, and YZ planes, corresponding to planes parallel to the foliation, perpendicular to the foliation and containing the lineation, and perpendicular to the lineation (Figure 45). The mean axial ratios R (= long/short) of these ellipses define the shape of the strain ellipsoid. The K value is a useful numerical indicator of shape, with values of $K > 1$ indicating prolate ellipsoids, and values of $K < 1$ indicating oblate ellipsoids (Ramsay, 1983).

Actual strain calculations using real samples can be considerably more involved. Several factors may affect strain calculations using ellipsoidal particles, as described briefly below:

1) Original shape of particles

Most rocks are composed of originally ellipsoidal, rather than originally spherical particles. When strain measurements are made on originally ellipsoidal particles, a simple arithmetic mean of the data will produce strain values considerably higher than actual values (Ramsay



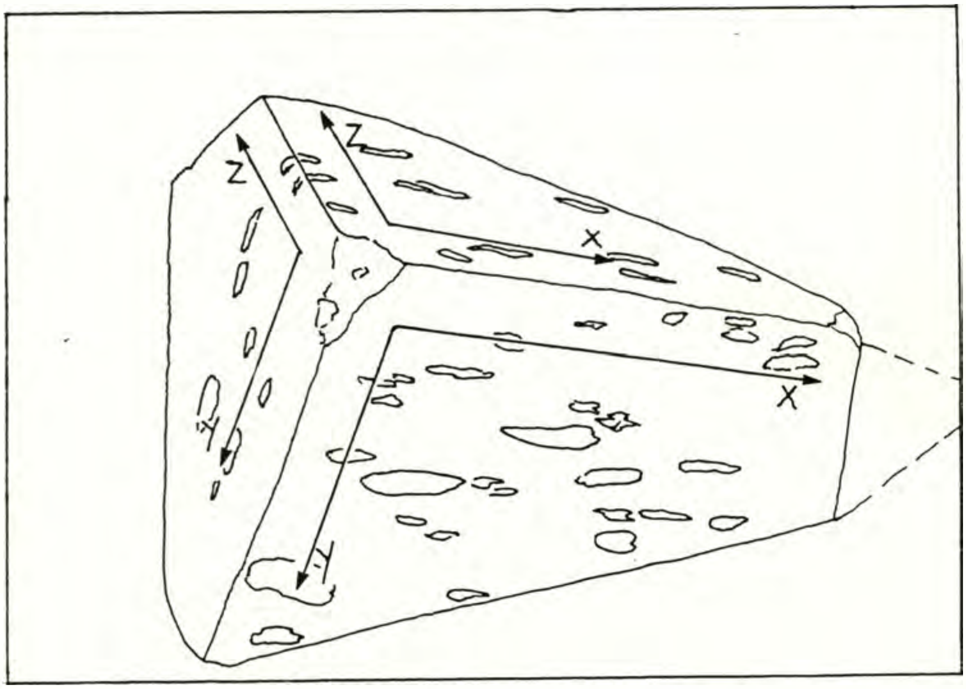


Figure 45: Hand sample of lapilli tuff with cut surfaces parallel to the principal planes of strain. Front surface = XY (foliation) plane; top surface = XZ plane (parallel to the lineation); side surface = YZ plane (perpendicular to the lineation).

and Huber, 1983; Lisle, 1981). In rocks that are not highly strained, the range in orientation of the ellipsoids makes location of the principal planes difficult. The latter difficulty was not a problem in most of the rocks measured for this study, since at high strain magnitudes, such as those present in the rocks studied, the long axes of particles rotate into near-parallel configurations.

2) Competency differences

When the matrix is more easily deformed than the clasts, the clasts may rotate rather than deform, leading to lower than actual strain values if only the clasts are considered. This was not considered to be a significant problem in the rocks measured for this study, as very little matrix was observed, and evidence of rotation was found only in monocrystalline quartz and feldspar grains, which were normally not measured for this reason. A more significant problem in the coarser-grained rocks is the variety of volcanic lithic types present and the corresponding range in strain magnitudes from one type to another.

3) Original preferred orientation of particles

A semi-planar, semi-linear, or imbricate preferred orientation of ellipsoidal particles is common in sedimentary rocks and may significantly affect strain calculations. A few methods have been devised for dealing with this factor (eg., Dunnet and Siddans, 1971, and Elliot, 1970) but these are of limited effectiveness and are difficult to apply, so this problem was ignored in the present study.

4) Volume change

Volume loss, such as that due to compaction, can affect strain calculations by creating a non-random clast spacing or an initial preferred orientation of platy grains prior to shearing. It was assumed that no volume loss took place before or during the strain event because: volume loss is difficult to evaluate, platy grains were not measured, and compactable matrix is at a minimum in these rocks.

5) Type of deformation

Most models assume homogeneous strain, but inhomogeneous strain or mechanisms such as pressure solution can complicate calculations of total strain. These factors are variable and difficult to evaluate. As previously mentioned, the assumption is made that the strain observed in stretched rocks is largely the result of homogeneous simple shear. Therefore, small inhomogeneities, such as more deformation in one clast relative to another, or more deformation in one portion of a thin section relative to another, are simply averaged into the total.

Many methods have been devised to calculate the shape of the strain ellipse in rocks containing originally ellipsoidal particles. Several of these methods were investigated and, where suitable, applied to a suite of four samples so that they could be evaluated for apparent accuracy and for applicability to a large number of samples. Brief descriptions of four of the commonest methods are given below, followed by the results of application and evaluation.

Methods involving grain shape calculations

All methods relying only on grain shape (or orientation) calculations will yield strain values applicable only to the clast fraction, and will underestimate the strain for the rock as a whole. Significant departures from actual strain values will occur in rocks containing significant amounts of matrix or in rocks containing resistant clasts which rotate rather than deform.

A) Arithmetic and Harmonic means

These methods involve computing the lengths of the three principal axes of the strain ellipse from the means of the ellipticities of a sample of grains measured on surfaces cut parallel to the principal planes of strain. Two commonly used calculations are the arithmetic mean,

$$R_f = (R_1 + R_2 + R_3 + \dots + R_n)/n,$$

and the harmonic mean,

$$H = n/(R_1^{-1} + R_2^{-1} + \dots + R_n^{-1}).$$

The harmonic mean was found to yield axial ratios closest to the shape of the strain ellipse in experimentally deformed conglomerates (Lisle, 1979). Hossack (1968) estimated that 30 pebble measurements (per side) were adequate for relatively precise strain determinations using the arithmetic mean. The number of measurements is probably similar for the harmonic mean. Fairly significant departures of mean values from actual strain values occur where the initial ellipticities of the grains are high, or where strain magnitudes are low.

B) $R_f/\emptyset$

This method involves measuring the ellipticity R_f of each clast on a given face and plotting this against $\emptyset$, the angle the long axis makes with an arbitrary line. The resulting curve is then compared to existing theoretically-deduced curves. The closest fit determines the strain magnitude and the average initial ellipticity of the particles. (For a complete treatment of the mathematics and theoretical curves, see Dunnet, 1969). At least 50 clast measurements per side are necessary for a precise analysis (Dunnet, 1969).

This method yields a high degree of precision with a relatively small number of data points, can be used to deduce original preferred orientation of the clasts, and provides one with a value for the original ellipticities of the clasts. It is not, however, appropriate for use in cases where the magnitude of strain is relatively high; in such cases, the fluctuation (the maximum range of Ø values) becomes very small, and it is difficult to measure the angles and compare the experimental to the theoretical curves.

Methods using point separations

Two methods using the relationship of distances between the midpoints of grains are discussed below. These methods, where applicable, probably provide a more reliable measure of strain in the rock as a whole, rather than just the clast fraction, and would be more accurate where large ductility contrasts exist between clasts or between the clasts and matrix.

One constraint on the use of either method involves the distribution pattern of the points. A totally random, or Poisson, distribution of points, where object positions are mutually independent, will retain a random distribution after deformation; hence these methods are not applicable to random point distributions. Homogeneous point distributions of relatively uniform density (anticlustered distributions) are needed to employ these techniques. Employing them on an originally perfectly isotropic, anticlustered point distribution will theoretically produce results that very closely approximate the shape of the strain ellipse. All other configurations will yield results that are lower than true strain values (Fry, 1979). In terms of clastic rocks, a well-sorted and well-rounded sandstone would produce a homogeneous distribution of clast center points on a cut surface, whereas a poorly sorted rock would produce a more random distribution.

A) Nearest neighbor method

For this method, an overlay is used, and the midpoints of all the grains in a sample are plotted. Lines are drawn between points, connecting the "nearest neighbors" to each point. The length of each of these lines is plotted against the angle the line makes with an arbitrary reference line, producing a curve with a maximum corresponding to the angle where the longest lines occur, which is the direction of maximum extension in the rock. The maximum is compared to the minimum for the ellipticity of the strain ellipse, and the proceedure is repeated on another face to obtain the axial length of the third axis of the strain ellipsoid. Ramsay and Huber (1983) suggest that the sample size will probably be determined by the time alloted to analysis, although 50 points appear to be adequate for fairly precise results.

This method is very time consuming, and will only be reliable where it is possible to prove that the nearest neighbors to a point in the strained rock are the same nearest neighbors to the same point in the unstrained rock (i.e., that relative object positions have not changed).

B) Fry method

The Fry method, or "all object - object separations" method (Fry, 1978) also involves plotting the centers of all points in a sample on an overlay. Another overlay is placed on top of the first, and a reference point is chosen near the center of the sample. All other points in the sample are then plotted on the second overlay. The reference point is then moved to an adjacent point on the first overlay, and the new positions of the points are plotted on the second overlay. This process is repeated until enough points are located to define an elliptical girdle and an area containing no points around the reference point, which corresponds approximately to the shape of the strain ellipse. Fry (1978) suggests that at least 300 and up to 1000 points are needed to obtain a high degree of precision using this method.

While application of this method is considerably less time-consuming and exacting than application of the nearest neighbors method, and it does not require that relative object positions stay the same before and after deformation, the large number of data points needed puts a limit on its usefulness.

Four samples were chosen for original analyses using all of the techniques mentioned, to compare difficulty, accuracy, and precision of the methods, in order to determine which would be most suitable to apply to all samples. These samples included three lapilli tuffs, for one of which only the chloritic clasts were measured, since grain boundaries between other lithologies were indistinct, and one porphyritic volcanic rock, for which only the phenocrysts were measured. Samples were cut along the three mutually perpendicular principal planes and polished using #600 grit. The arithmetic and harmonic means were calculated using 30 axial ratio measurements each off the three faces, which were measured using a ruler with 50 divisions to the inch. The $R_f/\emptyset$ method was deemed not applicable to these rocks due to the very small fluctuation in $\emptyset$ values. The nearest neighbor method was applied to 25 points on a single face of one sample and was found to be too laborious and time-consuming for general application. The Fry method was applied using acetate overlays and plotting the center points of roughly 200 grains on each of two principal planes (the XY and XZ). Ellipses approximating the elliptical girdles were traced in, and the axial ratios measured from them.

The results are summarized in Table 4. As expected, values obtained using the arithmetic mean are higher than those using the other methods. Values of the harmonic mean are slightly higher than for the Fry method in two cases, significantly higher in one case (sample 70, where only the chloritic clasts were measured), and lower in one case (sample 683, where

TABLE 4: SUMMARY OF RESULTS OF STRAIN MEASUREMENTS ON SELECTED SAMPLES

SAMPLE#	VALUE	FRY METHOD	HARMONIC	ARITHMETIC	N. NEIGHBOR
49	Rxz	2.7	3.3	4.1	
	Rxy	1.8	1.7	4.1	1.67
	Ryz	1.5*	2.2	2.9	
	K		.6	.4	
	Kder	1.7	.7	.6	
70	Rxz	3.7	6.9	9.1	
	Rxy	2.3	4.1	6.1	
	Ryz	1.6*	1.7*	1.5*	
	K				
	Kder	2.0	4.7	10.6	
218	Rxz	3.5	3.8	5.9	
	Rxy	1.6	2.5	2.9	
	Ryz	2.1*	1.8	2.1	
	K		1.9	1.7	
	Kder	.6	2.9	2.1	
683 (pheno-crysts)	Rxz	2.3	1.9	2.2	
	Rxy	1.6	1.4	1.6	
	Ryz	1.5*	1.4	1.5	
	K		1.1	1.3	
	Kder	1.2	1.2	1.9	

the phenocrysts were measured). The K constants vary considerably from one method to another.

The results show that, as predicted, the arithmetic mean values are erroniously high, so the arithmetic mean method is not valid for use on these rocks. The harmonic mean value for sample 70 is probably considerably higher than the Fry method value, because the shapes of the easily deformed clasts are quite attenuated and not representative of the strain in the rock as a whole; whereas the point spacing has been uneffected by the relative competency of the clasts. Likewise, for sample 683, the relatively resistant phenocrysts may have undergone rotation in addition to being strained, with a resulting low value for the harmonic mean. In both cases, the Fry method may be more accurate.

K values calculated using the harmonic mean appear to resemble visual estimates of K (i.e., whether the rock has undergone significant flattening or not), which appears to indicate that this method is more accurate in an internal sense. In addition to this observation, the harmonic mean method is easier to apply, requires considerably fewer data points, and is easily adapted to use on thin sections using a point count stage for measurements, so it was adopted for all strain calculations.

ADDITIONAL STRAIN CALCULATIONS

Additional strain calculations involved measuring axial ratios only in the XZ plane. The samples were visually evaluated first to insure that the measurement represented significant true stretching in one direction rather than just flattening. Three procedures were used: measurements directly off cut slabs, as in the above descriptions; measurements from projected slides of thin sections cut parallel to the XZ plane; and measurements from thin sections using a point count stage. The latter proved to be the most generally applicable to a wide variety of rocks.

The results are summarized in Table 5, with sample numbers, methods, and apparent Rxz strain ratios indicated. These data are graphically displayed on a regional map (Fiqure 46), with compass directions of the X - axes also shown. The XZ plane is parallel to the lineation, which is roughly horizontal, and perpendicular to the foliation, which is roughly horizontal to gently dipping over much of the region. Therefore, the X axes can be fairly accurately represented in map view, but the Z axes would actually be oriented normal to the plane of the map.

Discussion

Measured XZ-plane strain ratios range from 1.9 to 5.8, with a significant number of samples falling in the 3.5-4.5 range. The highest degree of stretching has occurred in the Baker Dam unit and in the tuffaceous rocks near the south end of Grandy ridge. Rocks from other areas, such as those to the southeast of the map area, record lesser amounts of stretching. The absense of measurements from some areas, such as the Thunder Creek drainage in the northeast quarter of the region and in areas around the north end of Grandy ridge, is partially the result of a lack of appropriate lithologies. More significantly, however, it is a reflection of the fact that appropriate lithologies did not contain evidence of stretching in one direction, but instead showed flattening, with X=Y. To an extent, the distribution pattern and magnitudes of strain shown in Figure 46 probably do represent the true distribution of unidirectional strain in this region, with the most highly deformed rocks found in the Grandy ridge/Upper Baker Dam area, and correspondingly less deformation in other areas.

While the magnitude of deformation recorded in rocks from this region is not exceptionally large, this amount is fairly significant when large

TABLE 5: DATA FROM STRAIN MEASUREMENTS

SAMPLE#	METHOD*	RXZ
12A	PCS	4.4
13	CS	3.4
20	PCS	4.2
45A	PROJ	3.4
47	CS	3.3
59	PCS	5.8
70	PCS	3.3
115	PCS	4.3
120	PCS	4.8
126	PCS	2.0
136	PCS	2.5
138	PCS	5.0
141	PCS	4.4
146B	CS	3.6
160	PCS	5.3
171B	PCS	5.5
207	PCS	2.4
218	CS	3.8
683	CS	1.9

* PCS = point count stage
CS = cut slab
PROJ= projected slide (tansparency)

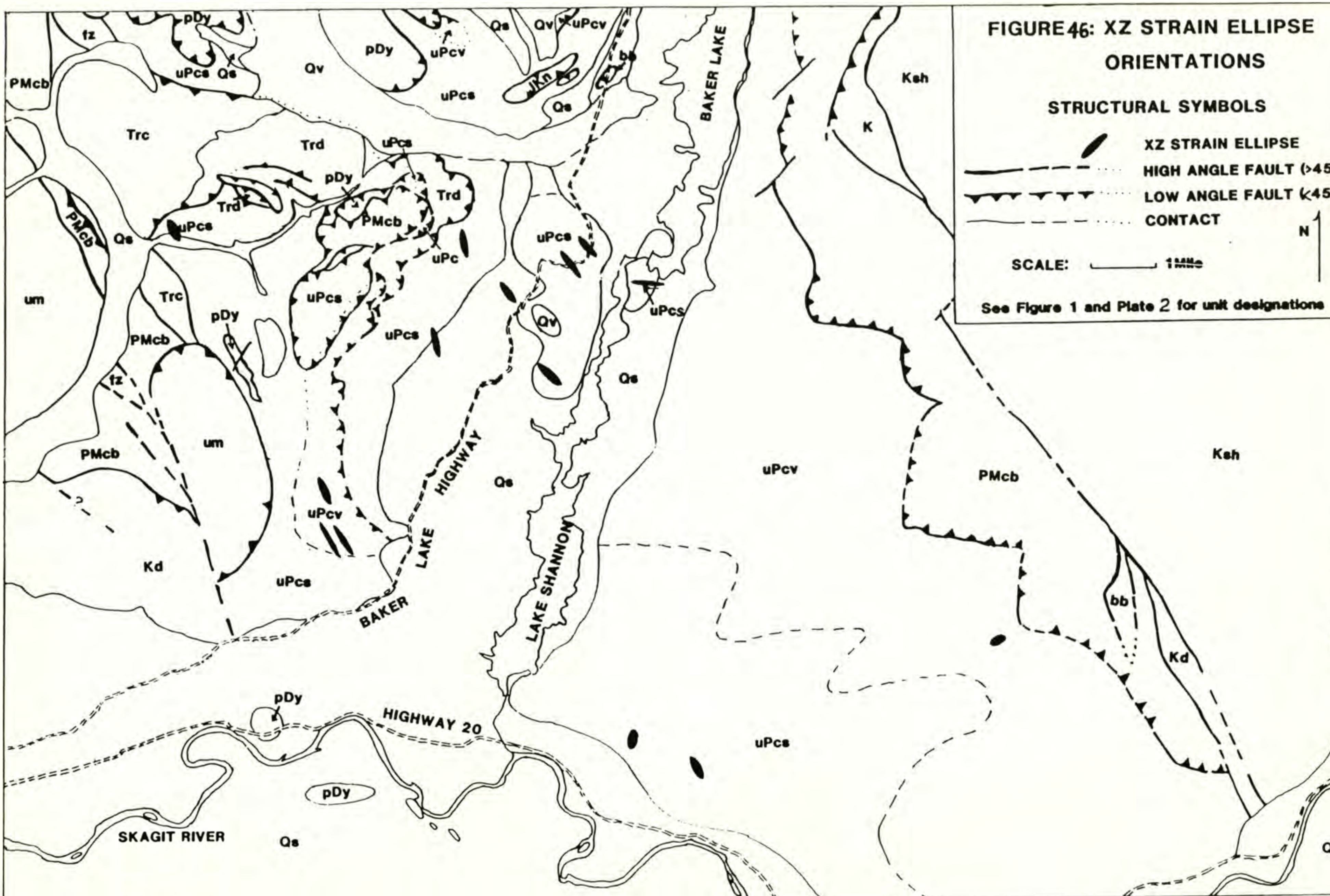


FIGURE 46: XZ STRAIN ELLIPSE ORIENTATIONS

volumes of rock are considered. The ellipticity, R, of the strain ellipse, and y (=tan ψ), the translation of the upper boundary of shear relative to the lower boundary of shear (see Figure 41), are related by the quadratic equation

$$a = [.5(y^2 + 2) +/- y(y^2 + 4)^{.5}],$$

where a is the quadratic extension $(1+e^n)^2$, and $(1+e_1)/(1+e_2) = R$, with e_1 always the larger number (Ramsay, 1984). The largest recorded extension (R=5.8) would, for example, correspond to y=2. If this strain magnitude was consistent over a section one kilometer thick, it would correspond to a translation of two kilometers of a point on one shear boundary relative to a fixed point located on the other boundary.

The strain magnitudes measured represent minimum values. In the Baker Dam unit, strain ratios are probably significantly underestimated, because relatively competent sandstone layers were actually measured; whereas the more voluminous phyllites, which probably sustained considerably more deformation, did not lend themselves well to this type of analysis. In other areas, discrepencies of this type are probably less pronounced. The R value and thickness used in the above computations probably are close to the actual ones, if not slightly underestimated. Therefore, the Chilliwack Group in the Grandy ridge/Upper Baker Dam area (with the exception of the competent volcanics) probably has undergone approximately 2:1 extension, corresponding to several kilometers of northwestward translation of the structurally uppermost rocks relative to the lowermost exposed rocks.

The well developed slaty to phyllitic cleavage present in much of the argillaceous rock in the map area is indicative of shortening perpendicular to cleavage of at least 65-75%, with corresponding elongation (probably mostly in one preferred direction) in the cleavage plane (Wood, 1974).

TIMING OF D1 AND D2 WITH RESPECT TO METAMORPHISM

Although all rocks in the Chilliwack Group are recrystallized to some degree, almost none contain the correct metamorphic minerals in sufficient quantities for a consideration of the relationship between metamorphism and deformation. Evidence for the relationship between deformation and metamorphism is apparently lacking from most other areas as well. Christenson (1981) observed rocks containing a crude lawsonite foliation in the Sauk Mountain area, although most rocks he observed contained no preferred orientation of metamorphic minerals. From this he deduced that the high pressure metamorphism was largely static in nature, slightly overlapping the first deformation but largely postdating it.

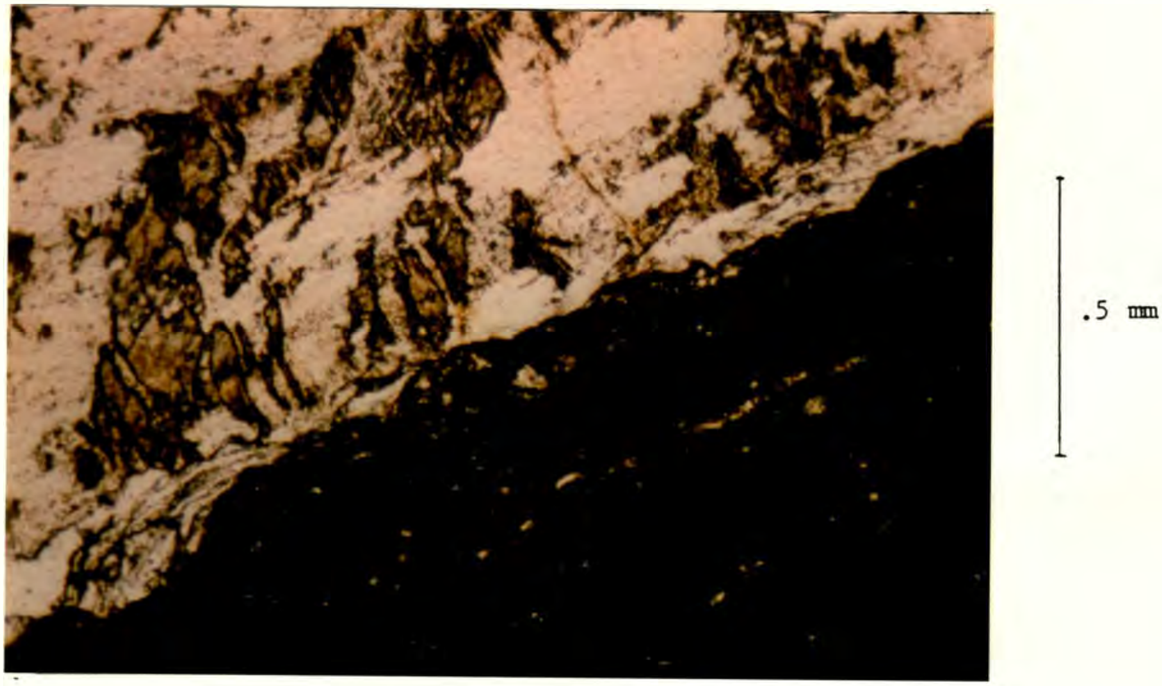
Monger (1966) cited the lack of evidence for a relationship between deformation and metamorphism in the type area in the Chilliwack Valley, British Columbia, but speculated that the metamorphism was a burial type in an area of low geothermal gradient, and preceded the first deformation. Monger (1966) felt that D_1 and D_2 were separated by a significant period of time, based on the lack of new metamorphic minerals associated with D_2 structures. He noted that D_2 predated the Oligocene intrusion of the Chilliwack Composite Batholith in the type area, based on the presense of contact metamorphic minerals growing across D_2 structures.

In the highly deformed argillaceous rocks which comprise most of the Baker Dam unit, the dominant metamorphic minerals are lawsonite, white mica, quartz, chlorite, and calcite. Lawsonite is present as fine-grained needles showing a weak preferred orientation in the foliation plane, and some tendency to align parallel to the L1 direction defined by stretched clasts (and parallel to F2 fold hinges). White mica shows a stronger preferred orientation in the same directions.

In the small white and gray layers, which are oriented subparallel to the sandstone layers, the dominant mineral is quartz, which ranges from being equigranular in form to highly attenuated parallel to the foliation. Lawsonite is present as "clots" scattered throughout the quartzose layers. Larger clots appear to be cracked and pulled apart, with quartz crystallized in the resulting spaces (Figure 47). Although the pulled-apart lawsonite clots appear to be elongated perpendicular to the lawsonite making up the foliation, the signs of elongation are consistent in both occurrences, indicating that the lawsonite crystals were pulled apart, rather than having grown perpendicular to the foliation.

One sandstone layer (Figure 28, p. 62) is composed almost entirely of brownish mats of lawsonite. The layer is strongly boudinaged, with attenuated quartz and calcite grains crystallized in the spaces between boudins. In other slides, lawsonite-replaced sand grains are also boudinaged.

Evidence of the relationship between metamorphism and deformation is also contained in the sheared lapilli tuffs which contain Na-amphibole (sample locations 59 and 2-803). The extremely fine-grained needles of Na-amphibole in theses rocks show a variable tendency toward preferred orientation in the plane of foliation defined by stretched clasts, and are also aligned parallel to the lineation direction. The needles show the strongest preferred orientation in areas which are more highly sheared, such as at clast contacts and in more highly deformed clasts (Figure 48). Although the amphibole needles in these areas are rarely cracked or broken, they are in many cases significantly bent. Where Na-amphibole occurs in small quartzose nodules, the needles exhibit a completely random



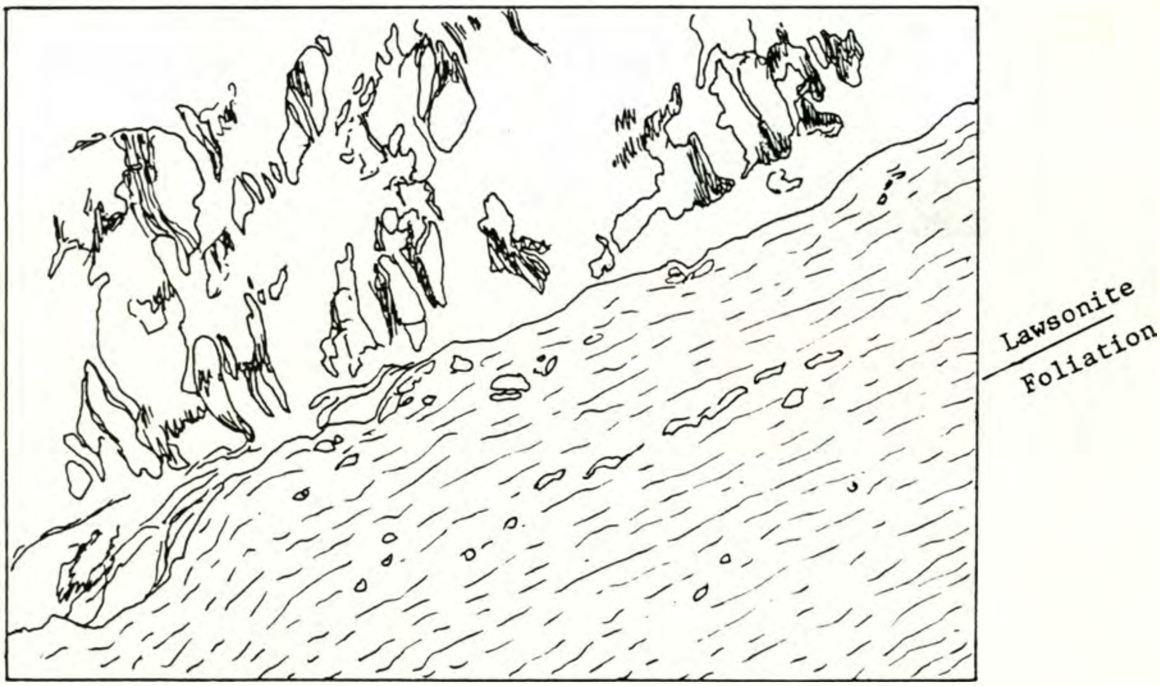


Figure 47: Photomacrograph of a quartose layer in the Baker Dam unit. Lawsonite defines a foliation in the dark colored argillitic layer, and is also present as clots in the quartose layer. See text for discussion.

Figure 48: Na-Amphibole habit in a highly strained area. The amphibole exhibits a preferred orientation in the foliation plane. Plane polarized light.

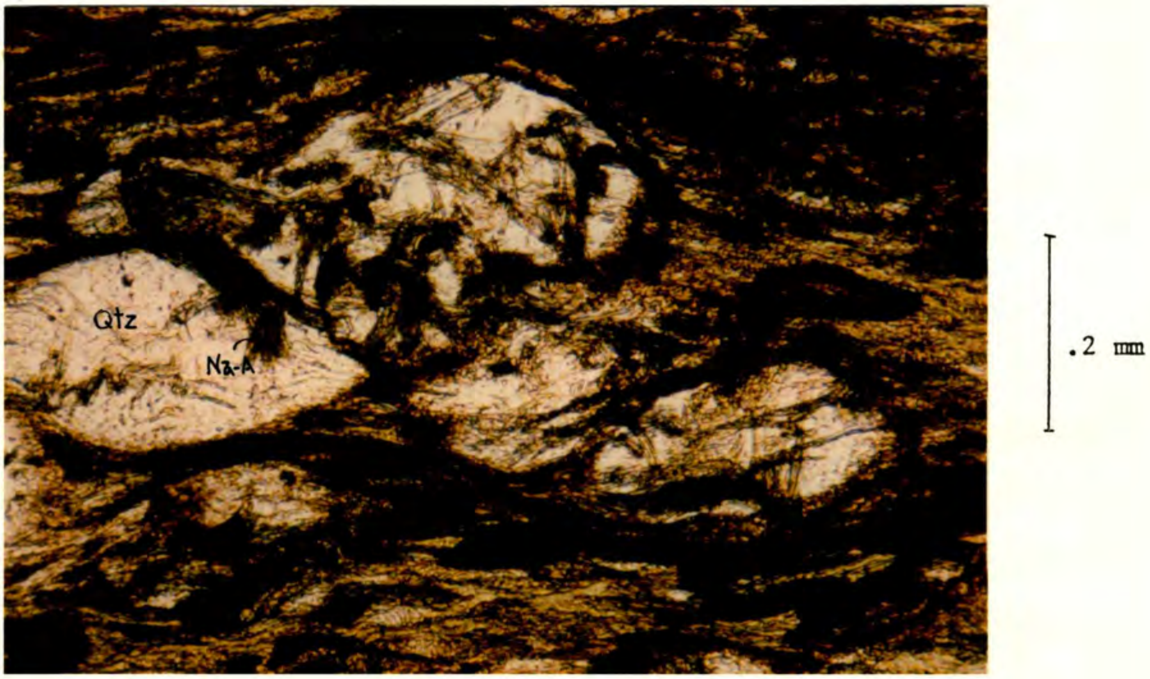
to occasionally radial pattern (Figure 49). The needles were never observed to extend beyond the boundaries of these areas.

Na-amphibole in the diabasic rocks shows no tendency toward preferred alignment, except with reference to the individual pyroxene grains from which they eminate.

Discussion

In both cases described above, the high pressure minerals appear to have crystallized prior to the D_1 deformational event. This suggests that the formation of the high pressure minerals either preceded the deformational event, or may have been partly synkinematic, with the deformation outlasting the high pressure metamorphic event.

No major metamorphic event appears to have accompanied the D2 deformation. The formation of some quartz and calcite veinsappears to coincide with D2, as some are seen to both crosscut and conform with F2 folds. Quartz and calcite anneal cracks in grains bent by F2 kink folds.



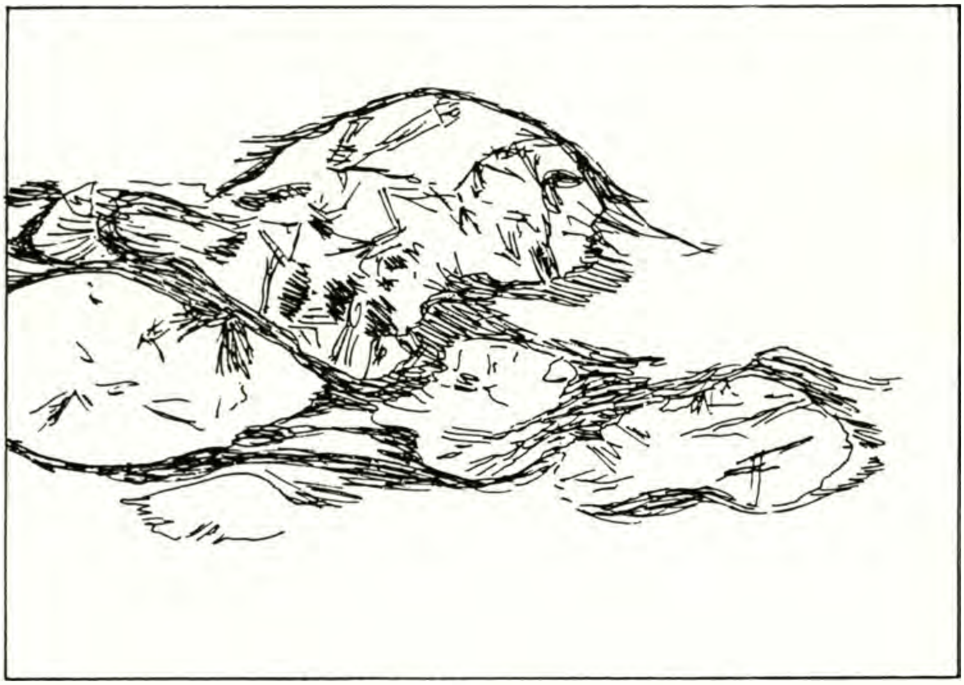


Figure 49: Photomicrograph of a small quartzose nodule containing Na-amphibole growing in an essentially random orientation, in contrast to Na-amphibole present in more highly strained areas which shows a preffered orientation (Figure 48).

EXTRAFORMATIONAL AND LARGE SCALE STRUCTURES

Before a description of the relationships between units, a few comments are in order regarding the mapping and placement of many of the structures. Because of poor exposure due to thick glacial and vegetative cover and the inaccessibility of many outcrops, faulted contacts are invariably either covered or out of reach. Therefore, the the placement of some faults is partly conjectural and based largely on (limited) outcrop patterns; alternative arrangements using the same data certainly exist. Interpretation is also hampered by the fact that much of the faulting is internal to the Chilliwack Group, such that it is often difficult to ascertain whether drastic changes in lithology are the result of fault juxtaposition, or are simply part of a conformable sequence. The structural interpretation given here includes a minimum of faults.

GRANDY RIDGE AREA

A cross section (C - C', Plate 2) was constructed along the crest of Grandy ridge. Three to four major tectonic blocks are present in the northern portion of the map area. The lowermost block, consisting of laminated siltstone and argillite (uPcs), is separated from overlying massive dacite (Trd) belonging to the Triassic dacite unit by a low angle fault contact. The contact is well exposed in a steep stream cut on the middle north side of Grandy ridge. The argillite is pervasively sheared for several tens of meters below the contact, with sheared boudins of limestone and dacite present immediately below the contact (Figure 32, p. 68). Elsewhere, the contact was generally not observed, although its position is fairly well constrained by numerous dacite and siltstone exposures which wrap around the north and east faces of Grandy ridge. The dacite unit appears to be quite variable in thickness, nearly pinching out at location 177 (Plate 1) but in other places exceeding 1000 feet in thickness.

Sporadic exposures of Chilliwack Group are present above the Triassic dacite unit in the northern portion of the map area. They are interpreted to represent blocks associated with a wide fault zone separating the Triassic dacite unit from the overlying chert/basalt unit. The small block of Yellow Aster Complex observed in this area also appears to be associated with this fault zone. Outcrop patterns suggest that this fault is nearly horizontal in the map area.

From Blue Lake south, the Chilliwack Group blocks in the fault zone increase in size and thickness. A thick, relatively coherent section of volcanic rock is exposed in section 5, immediately south of the Whatcom/Skagit County line (Plate 1). The dacite unit pinches out entirely in approximately the same place, about one mile south of Dock Butte. A tectonic block of Chilliwack sedimentary rock was mapped by Blackwell (1983) capping Dock Butte and is included in the cross section, although the existence of this separate tectonic block was not verified in the course of my study.

In the vicinity of Scott Ridge, Chilliwack volcanics are in fault contact with Chilliwack sedimentary rocks. This low angle fault contact is exposed in a roadcut at the bottom of section 8 (Plate 1, location 101). The contact appears to slant down gradually to the south across the east face of Grandy ridge, disappearing under Quaternary morainal deposits in section 28. The irregular nature of the contact suggests that it might be offset by later faulting, particularly in section 20. Substantial thicknesses of limestone are present at the contact in two locations.

The top of the south end of Grandy ridge appears to be a zone of disrupted blocks, characterized by fault juxtaposition of blocks of leucogabbro, vesicular flow rocks, diabase, cherty limestone, tuff, and mylonitized argillite. Beneath these rocks the structure is not well understood. The lower south end of Grandy ridge is comprised of a bewildering array of sedimentary, volcanic, and volcaniclastic rocks with very little apparent stratigraphic order. The reader is referred to Plate 1 for the following discussion, as the small scale of the structures cannot be expressed in cross section. The conglomeratic rocks that crop out in section 30, in the extreme southwest corner of the map area, may represent a single marker bed, based on consideration of bedding attitudes and the similarities of the lithologies. Bedded siltstone and sandstone appear to underly the conglomerate. A fault, which nearly parallels the slope angle, is present in the SE 1/4 of section 30. It separates phyllitic rocks (which are underneath and exposed to the east) from lower grade rocks. It is not known, however, whether this fault is a small shear or whether it actually represents a significant tectonic boundary in the Chilliwack Group. The phyllitic rocks are fairly continously exposed in a steep creek bed in the SW 1/4 of section 29. A Tertiary(?) fault (described on p. 67) juxtaposes tuffaceous siltstone against the phyllite, but the siltstone and phyllite could belong to the same unit. The section appears to be fairly continuous up to the 3500' level. Another problematic feature is the presence of the thick lenses of conglomerate cropping out on the southeast corner of Grandy ridge. Field evidence and bedding attitudes do not suggest that the conglomerates represent a single marker bed, but are instead a thick sequence of interbedded sediments. The relationship between the coarse-grained rocks and the phyllitic and tuffaceous rocks to the west is not well defined.

Approximately in the vicinity of the Skagit River (west end of cross-section C - C'), the predominantly low angle structures associated with the Chilliwack Group and chert/basalt unit are truncated by a high angle fault or faults, with Darrington phyllite present to the southwest. A large block of Yellow Aster Complex that crops out south of the Skagit River appears to be associated with this fault.

UPPER BAKER DAM AREA

A cross section D - D' (Figure 50 and Plate 2) was constructed from the southernmost exposures of the Baker Dam unit near the outlet of Bear Creek (at the extreme south end of the cross section) to the northernmost exposures immediately north of Upper Baker Dam. Tuff and other volcanilithic sedimentary rocks are interbedded with siltstone to the south. Slates and phyllites dominate the middle section, increasing slightly in grade from south to north. The phyllites persist until roughly half way up the north side of Marble Canyon, where drillers reports state that they are "conformably overlain" by greenstone, which crops out north of Upper Baker Dam (Stone and Webster, 1963). Occasional interbedded greenstone layers were also noted below the contact.

Two other locations in the map area not shown on either cross section deserve mention. The rocks tentatively identified as Chilliwack volcanics at sample locations 10 and 54 along the northern border of the map area west of Upper Baker Dam are interpreted as a fault-bounded block. In contrast to the greenstones mentioned in the discussion of cross section D - D', which are bedded and dominantly volcaniclastic in nature, the volcanic rocks at locations 10 and 54 are extremely coarse, lack internal stratigraphic order, are heavily fractured and hydrothermally altered, and are apparently not related to the underlying phyllites.

The small pod of Quaternary Baker Volcanics capping the knob

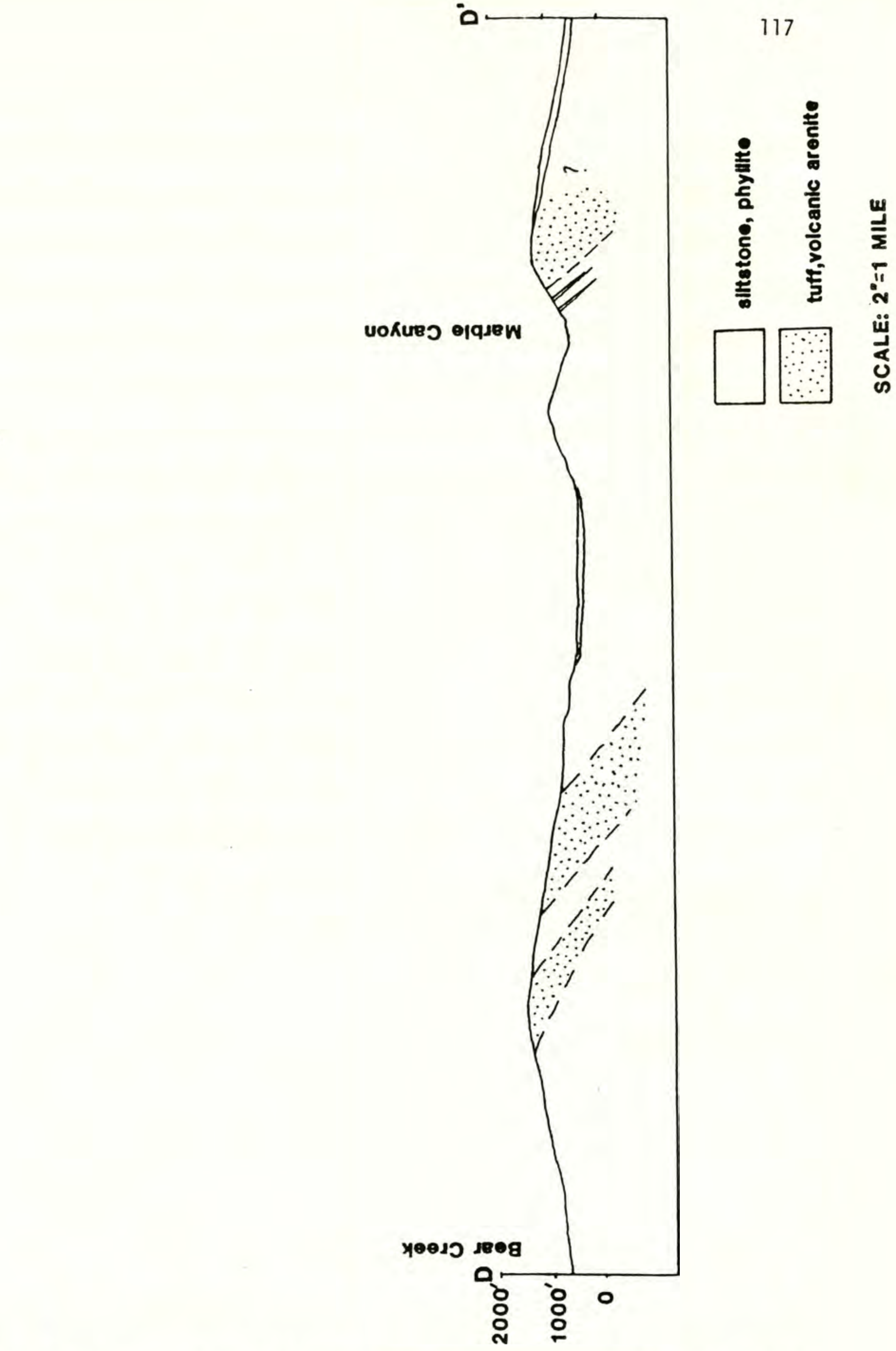


Figure 50: Cross section illustrating structure and stratigraphy in the Baker Dam unit. See Plate 2 for location of cross section.

(elevation 1760) in section 2 is probably an erosional remnant of a more extensive flow issuing from the valley containing Sulfur and Rocky Creeks.

As previously stated, the sedimentary rocks on the west side of Rocky Creek, extending down into Skagit County, are in essence identical to the rocks found on the east side of Rocky Creek. Many rocks as far south as the south end of Grandy ridge are of similar lithology and structural grade. Therefore, the Baker Dam unit is considered to be part of a larger domain which includes all of the siltstones which crop out at the lower elevations along Grandy ridge.

STRUCTURE OF THE EXTENDED STUDY AREA

The nature of the map area as a long ridge of limited width makes consideration of structure in other areas essential to understanding the structure within the map area. A main objective of this study is to tie together structures from the field area of Blackwell (1983) to structures mapped on the east side of Lake Shannon. Two cross sections (A - A' and B - B', Plate 2) illustrate the relationship of structures in the map area to structures to the east and west.

Cross-section A - A' is drawn from the Twin Sisters dunite body through the north end of the map area, to near Anderson Butte on the east side of Baker Lake.

The lowermost structural unit exposed in the cross section is the Chilliwack Group, which is composed of sedimentary rocks to the west and tuffaceous and volcanic rocks to the east. As previously illustrated, the contact appears to be gradational, with numerous interfingerings of tuff and siltstone on the north and west sides of Lake Shannon. The Chilliwack Group is internally tectonized in this area as well.

The Chilliwack Group is in fault contact with the Cultus Formation at the west side of the cross section. The fault is high angle at the point where the line A - A' crosses it, but shallows markedly to the north, suggesting that it shallows at depth in the plane of the cross section. The Chilliwack Group is in fault contact with the Triassic dacite unit on Grandy ridge. As the Triassic dacite unit interfingers with the Cultus Formation, the faults separating these two units are regarded to be equivalent. Likewise, on the east side of Lake Shannon, although the the Triassic dacite unit has not been mapped, significant amounts of pyritized felsic volcanic rock have been noted by E. H. Brown (1985, oral communication) near the top of the Chilliwack Group volcanic sequence and are thought to be equivalent to the Triassic dacite unit.

The Triassic rocks in all areas along the cross section are in fault contact with the overlying chert/basalt unit. Exotic blocks of Yellow Aster Complex, Vedder Complex, and Chilliwack Group are found along the contact in all areas, indicating the presence of a major tectonic boundary.

The chert/basalt unit is in fault contact with the ultramafic Twin Sisters dunite body to the west. The fault appears to shallow at depth, based on its low-angle attitude to the north and south of the cross-section. To the east, the chert/basalt unit is in fault contact with the Shuksan Suite. The sliver of undifferentiated Shuksan Suite has both high- and low-angle contacts along its length, and eventually pinches out, suggesting it shallows at depth. The contact between the chert/basalt unit and the Shuksan greenschist is dominantly a high angle fault which contains numerous exotic blocks.

Cross-section B - B' roughly parallels A - A' but lies a few miles to the south. Structures east of Lake Shannon are a continuation of structures to the north. To the west along Grandy ridge, only the Chilliwack Group is exposed. Structural relationships within the Chilliwack Group could not be confidently ascertained in this area, although it appears that two and possibly three fault-bounded tectonic blocks of Chilliwack Group may be present, with roughly southwesterly-dipping contacts. To the west, the Chilliwack Group is in fault contact with the Goat Mountain Dunite body along a low-angle fault. This fault appears to be truncated at depth by a high angle fault bounding the west side of the ultramafic body.

A structural stratigraphy of the region based on the above cross sections is illustrated in Figure 51. The Nooksack Group, and hence the Mount Baker window of Misch (1966 and Figure 4), appears not to be present in this region, except as small, fault-bounded blocks imbricated with Chilliwack Group sedimentary rocks to the north (Ziegler, 1985). Triassic rocks are found above the Chilliwack Group in this region. The Triassic dacite unit of Blackwell (1983) appears to be extensively present in this area, and is found on both sides of the Baker River Valley. The chert/basalt unit also appears to be regionally extensive, present above the Triassic rocks along a fault containing numerous exotic blocks. The Shuksan Suite is found above the chert/basalt unit. The chert/basalt unit, Triassic dacite unit, and blocks of the Chilliwack Group, Yellow Aster Complex, Vedder Complex, and ultramafic rocks appear to comprise a thick imbricate zone in this area. Although there is no evidence of the northwest-trending anticline associated with the Mount Baker window, there is some evidence for the existence of a broad, north-trending anticline occupying the Baker River Valley, particularly in the vicinity of Lake Shannon.

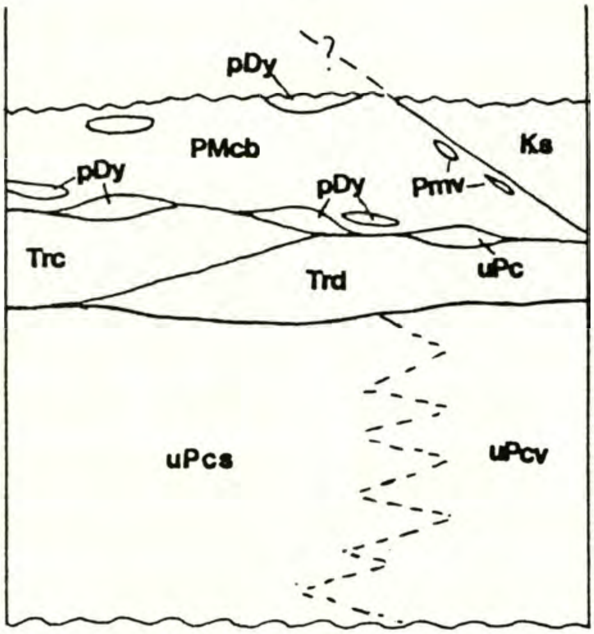


Figure 51: Diagrammatic structural stratigraphy of units in the extended study area. Solid lines = faults; dashed lines = lithologic contacts. See Plate 2 for unit designations.

DISCUSSION

The Chilliwack Group in the extended study area is variably deformed, with the most highly deformed rocks occurring in the southern Grandy ridge and Upper Baker Dam areas. S_1 foliation attitudes are dominantly shallow. There is limited structural evidence for relative north-northwestward transport of the upper plate. Strain measurements suggest a minimum of several kilometers of shear displacement in the exposed thickness of rock, with significant thinning of the units as well.

Table 6 is a compilation of structural data from other locations in the Chilliwack Group. Although the data are rather scant, those available are fairly consistent. S_0 and S_1 are generally of shallow dip and parallel, with a northwest-trending fabric discernible in many areas. Near-vertical S_1 attitudes are present in areas proximal to high-angle segments of the Shuksan Fault (e. g. Sevigney; 1983, and Silverberg, 1985). F_1 folds are nearly horizontal and generally trend northeast. Uncommon F_2 folds are horizontal and trend northwest.

On the basis of this information, it appears that the Chilliwack Group underwent early (D_1) and late (D_2) deformations with fairly consistent orientations of strain throughout the extent of the unit.

Timing of D_1 and D_2 with respect to regional events

Monger (1966) equates D_1 with internal imbrication and nappe emplacement in the Chilliwack Group, and with the imbrication of map units in the western North Cascades. Misch (1966) also equates D_1 with the thrust emplacement of these units in the late Cretaceous. Monger correlates D_2 deformation with a mid-Tertiary Cascades Orogeny.

D_1 and D_2 in this study appear to be correlative with Monger's (1966) D_1 and D_2 based on the similarity of orientations of structural elements, however no direct evidence equates D_1 and D_2 in the present

TABLE 6: CHILLIWACK GROUP STRUCTURAL DATA FROM OTHER STUDIES. ORIENTATIONS ARE REPRESENTATIVE.

STUDY	LOCATION	SO	S1	F1	F2	COMMENTS
Monger (1966)	Chilliwack Valley, B. C.	155,25SW 120,NE 140,25NE		N50E,0		F1 folds are anticlines overturned to northwest SO folded by F1
Christenson (1981)	Sauk Mountain		NW strike			F2 low angle, no consistent trend; regional NNW-SSE fabric in SO; faults strike NW, dip east.
Sevigney (1983)	Tomyhoi Peak		N30W,45NE N10W,90		N-NW S-SE	
Jones (1984)	Canyon Creek/ Church Mtn.			N75E,10NE	N	F1 folds overturn NW Open F2 folds;SO poles define great circle N-S and vertical
Silverberg (1985)	Whitechuck Mt.- Mt. Pugh		N40-50W +/- vert.			S1 parallels shear zones
Smith (this study)	Grandy Ridge		NW-SE, shallow	N80E,0	N47W,0	

study area with other regional deformational events. Two pieces of indirect evidence link D_1 with the regional imbrication of units: The similarity of L_1 directions in the map area with those mapped along the Shuksan Fault; and the similarity of S_1 attitudes in the map area with the attitudes of faults and shears in the map area.

Along the eastern extent of the Shuksan Fault, stretching lineations are dominantly horizontal and trend north to northwest, averaging N20W (Brown, in press; Jewett, 1983; Silverberg, 1985). Most of the stretching lineations measured in the extended study area also trend northwest, although they lie in low-angle foliation planes.

The similarity of S_1 attitudes in the northwest subarea (Figure 34) to fault and shear plane attitudes (both intra- and extraformational), most of which were measured in the northwest subarea (Figure 39), also suggests a genetic relationship between S_1 formation and regional imbrication of units. S_1 and fault plane attitudes in the map area are dominantly low angle. To the south, in the Mount Pugh-Whitechuck Mountain area, S_1 attitudes in the Chilliwack Group are high angle and parallel the plane of the Shuksan Fault (Silverberg, 1985). The same relationship has been observed to the north of the present study area, in the Mount Slesse area (Jewett, 1983).

On the basis of these relationships, it is concluded that S_1 in the present study area was formed during the emplacement of the map units. Exact dating of the deformation producing the stretching lineations along the Shuksan Fault is necessary to pinpoint the actual time of deformation.

The presense of the set of northeast-trending L_1 stretching lineations in the eastern portion of the extended study area and in the type area in the Chilliwack Valley, B. C. (Brown, 1985, personal communication) is enigmatic. Assuming that the trend of L_1 stretching lineations does represent the tectonic transport direction, areas where northeast-trending lineations occur may represent minor regional variations in transport direction. In the type area, however, the northeast-trending lineations are found in association with the McGuire Nappe and other structures indicating a northwestward transport dirction. It is conceivable that the northeast-trending lineations represent a period of deformation that pre- or postdates the event labeled D_1. Deformation associated with D_2 is minor in most areas, usually manifested by folding and faulting, and hence unlikely to produce stretching lineations. A more likely explanation for the northeast-trending lineations is that they predate structures associated with D_1. A similar but more extensive set of stretching lineations averaging N70E are present in the Shuksan Suite (Brown, in press). These lineations are thought to predate the N20W-trending set of lineations associated with the Shuksan Fault.

Assuming the structures associated with D_1 were produced during the regional imbrication of units, the tectonic transport indicated by the orientation of these structures is somewhat different than that proposed by Misch (1966). As Figure 3, p. 9 indicates, west-directed thrusting is postulated during emplacement of the map units, with the direction becoming more northwesterly near the Canadian border, and southwesterly from the present study area south. Evidence from this study suggests northwest-directed (and possibly southeast-directed) tectonic transport throughout the extent of the Chilliwack Group.

Westward-directed thrusting from a root zone might be expected at a strictly convergent plate margin, with the direction of thrusting perpendicular to the plate margin. However, Engebretson and others (in press) have postulated very oblique convergence (transpression) at the Kula or Farallon and Pacific Plate boundaries during the late Cretaceous when imbrication of the units is thought by some workers (e. g., Misch, 1966; Monger, 1966) to have taken place (Figure 52).

The set of structures diagnostic of a transpressive regime has not been well defined, but appears to include such structures as thrust faults, wrench- and strike-slip faults formed nearly parallel to the plate margin, and the presense of exotic material brought up from significant depths in the crust (Sanderson and Marchini, 1984). The tectonic transport direction deduced from structures in the Chilliwack Group, which nearly parallels the present-day plate margin, is suggestive of formation in a transpressive plate tectonic setting (assuming that no significant rotation of the rocks has taken place since the time of deformation).

The structures in the Chilliwack Group do not exactly parallel the more northerly trending present-day plate margin. Crickmay (1930) postulated that the trend to structures in the western North Cascades could have been the result of the "geosynclinal accumulation" being wrapped around the southern end of the "Coast Range Batholith". While this interpretation is problematic in light of recent evidence that none of the rocks present near the present-day plate margin formed in place, none- the-less it is possible that the Coast Plutonic Complex may have served as a buttress during deformation, producing northwest-trending rather than strictly north-trending structures and tectonic transport direction.

The style of deformation exhibited in the extended study area is consistent with that described by Cowan and Miller (1980, Figure 53).

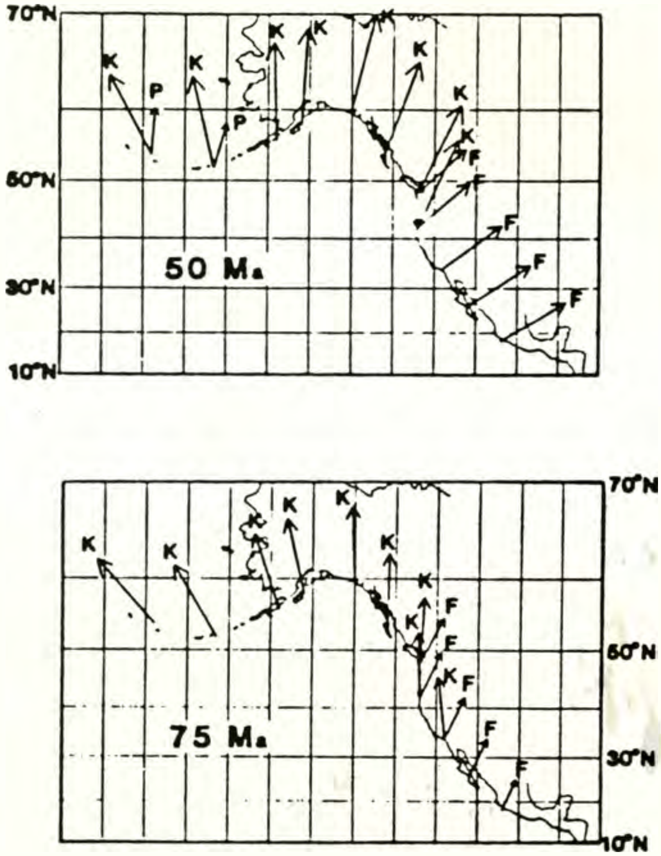


Figure 52:Relative plate motions along the western margin of North America during the late Cretaceous and early Tertiary. (From Engebretson and others, in press).

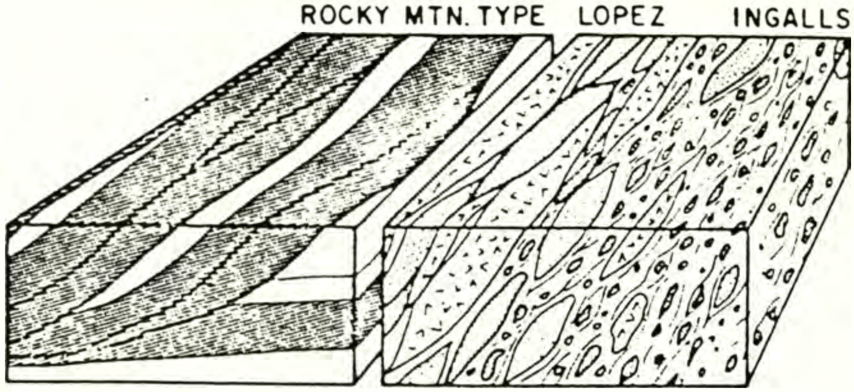


Figure 53: Deformational styles in two Mesozoic fault zones in western Washington (from Cowan and Miller, 1981).

They describe two end-member types of deformation during the Mesozoic in western Washington: the Lopez type, characteristic of the Lopez fault zone on San Juan Island, and the Ingalls type, characteristic of the Navajo Divide fault zone in the Ingalls ophiolite. Both types consist of numerous, heterogeneous tectonic blocks justaposed along anastomosing fault zones containing sheared matrix. The Ingalls type is characterized by smaller tectonic blocks in abundant sheared matrix, whereas the Lopez type is characterized by larger, fault bounded tectonic blocks. These types represent end members in a continuum. The structure present in the map area is in essence a megascopic expression of the Lopez type of deformational style, which has also been noted in other areas where Misch's (1966) imbricate zone is present (e. g. Blackwell, 1983; Jewett, 1984, Ziegler, 1985). Similar deformational styles have been described from the Franciscan Terrane (e. g. Hsu, 1968).

SUMMARY AND CONCLUSIONS

The Grandy ridge/Upper Baker Dam area and the surrounding regionare dominated by lithologies of the Chilliwack Group, the Triassic dacite unit and related Cultus Formation, and the chert/basalt unit, juxtaposed along low angle thrust faults. The Yellow Aster Complex is found as small tectonic blocks emplaced along fault zones. The region studied is bounded on the west by the Twin Sisters and Goat Mountain dunite bodies, and to the east by a high angle fault separating the chert/basalt unit from the Shuksan Suite.

Within the map area, the Chilliwack Group is composed of voluminous sedimentary rocks and lesser amounts of volcanic and volcaniclastic rock. The sedimentary unit is dominantly composed of laminated to thinly bedded siltstone, sandstone, and argillite of the lower clastic sequence. Massive argillite with sparse interbeds of sandstone are more typical in some areas, particularly in the northern portion of the map area. There is a gradation from west to east from fine-grained sedimentary rocks to fine-grained rocks with interbedded sandstone and tuff. The Baker Dam unit, originally mapped by Misch (1966) as part of the Nooksack Group, is assigned to the Chilliwack Group clastic sequence in this study. A thick section of boulder to cobble conglomerate is present on the southeast side of Grandy ridge. Lapilli tuff and fine grained crystal and lithic tuff with interbedded siltstones are common on the upper south- and east-facing sides of the south end of Grandy ridge. Volcanic rocks ranging from fine-grained flows to diabase to plutonic rocks are present above approximately 2700' on the south half of Grandy ridge. Limestone is uncommon in the map area and, where observed, is completely recrystallized.

The Chilliwack Group represents mostly subaqueous deposition on and adjacent to a volcanic arc. The Chilliwack Group has undergone low temperature, high pressure metamorphism characterized by assemblages containing quartz + albite + chlorite +/- pumpellyite +/- epidote +/- calcite +/- lawsonite. In addition, a number of rocks contain Na-amphibole of crossitic to riebikitic composition.

The Triassic dacite unit of Blackwell (1983) is present in the northern part of the map area, and is also present on the east side of Lake Shannon. It consists of massive dacite flows with interbedded crystal and lapilli tuff and rare siltstone. It records a metamorphic history similar to the Chilliwack Group.

The chert/basalt unit is also present in the northern portion of the map area. It consists of fine-grained basalt, ribbon chert, and phyllitic siltstone, and has sustained higher temperature conditions of metamorphism and more deformation than the Chilliwack Group.

One small tectonic block of Yellow Aster Complex was noted from the vicinity of a fault between the Triassic dacite unit and the chert/basalt unit. It appears to be a hornblende diorite.

The Chilliwack Group in the map area and in the surrounding region has undergone two significant deformations, denoted D_1 and D_2, with a few late northeast-trending vertical faults also noted. D_1 is manifested by a pervasive foliation (S_1) which is usually subhorizontal and in places folded around horizontal fold axes. Small kink folds and at least two larger recumbent folds (F_1'), oriented with horizontal axes trending northeast and overturned to the northwest, are also associated with D_1. Stretching lineations (L_1) are present in a number of lithologies and are generally northwest-trending and horizontal. F_2 folds ranging from kink folds to large open folds generally trend northwest. A number of small zones of cataclastic rocks were also noted in the map area, usually with subhorizontal orientations. They appear to be syndeformational with or to slightly postdate S_1, but the exact timing of formation of these structures is not known.

Stretching lineations, formed most notably by stretched clasts, are abundant in the map area. They are interpreted to parallel the movement or shear direction, based on consideration of associated extensional features such as veins and boudinaged layers, and of the model of homogeneous simple shear. While simple shear is not the only mechanism responsible for the deformation in these rocks, it was adopted as a working model.

Shear sense indicators, including asymmetric pressure shadows behind resistant grains, c- and s-surface intersections, and fold asymmetries, mostly suggest relative northwestward translation of overlying rocks. A number of indicators, however, particularly in the southeast part of the region, suggest southeastward translation. This is particularly true of shear sense deduced from c-s surface intersections. It is possible that two periods of shearing are indicated, with the southeast translation associated with the latter period, as the c-surfaces disrupt S_1. Many samples are not sufficiently strained to lend themselves to analysis.

Finite strain measurements yield XZ-plane strain values ranging from 1.9 to 5.8, and represent minimum strain values. Strain magnitudes are highest in rocks from the Baker Dam unit and in rocks from the south end of Grandy ridge. Rocks from other areas are less deformed. Extension and resultant northward translation on the order of several kilometers are postulated for the Chilliwack Group in the map area.

Sheared rocks containing lawsonite and Na-amphibole contain clues to the relationship between the high pressure metamorphism and the deformational events. The presence of cracked and boudinaged mineral grains and evidence of the rotation of grains into the foliation direction suggest that the high pressure metamorphism in part predated the first deformation, but may have been partly synkinematic.

Sedimentary rocks of the Chilliwack Group are found in the structurally lowest levels in the map area and in the surrounding region. They are in fault contact in the map area with the overlying Triassic dacite unit, which may also be present on the east side of Lake Shannon. The Cultus Formation is faulted over the Chilliwack Group to the east. Overlying the Triassic dacite and Cultus formation in most areas is the chert/basalt unit. The fault zone contains fragments of Yellow Aster Complex, Vedder Complex, and Chilliwack volcanics. While anastomosing low angle faults predominate in the map area and in the structural units just described, high angle faults are present between the chert/basalt unit and dunite bodies to the west, and between the chert/ basalt unit and the Shuksan Suite to the east. There is no evidence in the map area for the existence of an area where Nooksack Group lithologies are exposed in the axis of a northwest-trending anticline (the Mount Baker window of Misch, 1966). However, a broad, north-northeast trending anticline appears to be present in the Lake Shannon and lower Baker Lake valley, with Chilliwack group lithologies present in the structurally lowest levels.

The Chilliwack Group in the map area is more highly deformed than it is in most other areas, based in descriptions in the literature. One area of equally highly deformed rocks is in the vicinity of Mount Pugh and Whitechuck Mountain, where both highly lineated and phyllitic rocks have been mapped in association with the Shuksan fault (Silverberg, 1985). Subphyllitic rocks have also been noted to the north, in proximity to the Church Mountain (e. g., Jones, 1984) and Shuksan (e. g., Jewett, 1984) faults. Deformation in other areas is apparently relatively low, suggesting that the rocks in the vicinity of the map area represent a distinct zone of higher deformation internal to the Chilliwack Group.

Orientation of structures associated with the D_1 and D_2 deformations correlate well with evidence from a number of areas, including the type area in the Chilliwack Valley (Monger, 1966), where northeast trending horizontal folds indicating northwestward translation are present along with later, open, northwest trending folds. To the south, northwest-trending, horizontal stretching lineations were observed by Silverberg (1985). Areas containing northeast-trending L_1 stretching lineations may may indicate the presense of an earlier phase of deformation.

The orientation of structures in the study area and postulated late Cretaceous plate motions along the coast of North America indicate that the deformation in the Chilliwack Group may have occurred in a transpressive plate tectonic environment.

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APPENDIX 1: Petrography of selected samples

Key to abbreviations:

Chilliwack Group	uPc
sedimentary sequence	uPcs
siltstone	slt
argillite	arg
volcanic arenite	VAr
conglomerate	cgl
sandstone	ss
limestone	ls
volcanic sequence	uPcv
diabase	dia
gabbro	gab
basalt	ba
andesite	and
lithic tuff	lt
vitric tuff	vt
lapilli tuff	LaT
flow breccia	fb
Triassic dacite unit	Trd
dacite	da
dacite tuff	dat
Cultus Formation	Trc
siltstone	slt
Yellow Aster Complex	pDy
hornblende diorite	HbD
Tertiary dikes	Td
leucocratic dike	Leuc
lamprophyre dike	Lamp
other	
mylonite	myl

sedimentary clasts	s
volcanic clasts	v
monocrystalline clasts	m
mineral identified	x
possibly present	?
trace amount	tr
organic material	o
unidentified grunge	gr
detrital	de
textural zones	IIa,IIb,IIIa

MINERAL	SAMPLE NUMBER 110-1	110-8	110-18	110-24	110-25	110-28	110-35	110-38	110-39a
quartz		x		x	x	x	x		x
albite	x	x	x	x	x	x	x	x	x
chlorite	x	x	x		x	x	x	x	x
pumpellyite	x	x	x	x	x		x	x	x
epidote	?								
calcite		x	x		x				
lawsonite	x	x		x					
white mica						x	x		
clinopyroxene	x								x
plagioclase	x		x						x
actinolite									
hornblende									
sphene		x	x	x				x	x
Na-amphibole									
apatite			x						
ilmenite			x						
pyrite							x	x	
hematite							x		
unident. opaque	x				x				
other				o					
lithic types					v				
textural zone		IIa				IIb			
lithology	LaT	cgl	dia	slt	slt	LaT	da	ba	daT
unit	uPcv	uPcs	uPcv	uPcs	uPcs	uPcv	Trd	uPcv	Trd

MINERAL	SAMPLE NUMBER								
	110-41B	110-42	110-43	110-49D	110-54B	110-59	110-59D	110-61	110-63
quartz	x	x	x	x	x	x	x	x	x
albite	x	x	x	x	x	x	x	x	x
chlorite	x	x	x	x	x	x	x	x	x
pumpellyite				x	x	x	tr		x
epidote				x	x				
calcite	x	x	x	x	x			x	x
lawsonite	x	x	x	x	?				
white mica	x	x	x	x					
clinopyroxene									
plagioclase									
actinolite					x				
hornblende									
sphene				x	x	x			
Na-amphibole						x	tr		
apatite									
ilmenite					?				
pyrite	x	x		x					
hematite									
other opaque	?		x	x		x		x	
other									
lithic types				v	v	v	v		v,m,s
textural zone	IIB	IIB	IIB	IIA		IIB	IIA	IIA	IIA
lithology	arg	arg	arg	LaT	dio	LaT	LaT	lt	slt
unit	uPcs	uPcs	uPcs	uPcs	uPcv?	uPcv	uPcv	uPcv	uPcs

MINERAL	SAMPLE NUMBER								
	110-66A	110-69	110-70B	110-71	110-72B	110-74	110-75	110-76B	110-78
quartz	x	tr			x	x		x	x
albite	x	x	x	x		x	x	x	x
chlorite	x		x	x	x	x	x	x	x
pumpellyite	x	x	x	x			x		x
epidote									?
calcite	x		x	x		x	x	x	
lawsonite				?		x			x
white mica									x
clinopyroxene		x					x	x	
plagioclase	x	x	x				x	x	
actinolite									
hornblende									
sphene		x	x				x	x	
Na-amphibole		x						tr	
apatite	x							x	
ilmenite		x		?			x	x	
pyrite						x			
hematite									
other opaque	x		x						x
other									
lithic types									
textural zone			IIA		IIa				IIA
lithology	and	dia	ba	slt	ch	slt	dia	dia	LaT
unit	uPcv	uPcv	uPcv	uPcv?	uPcs	uPcs	uPcv	uPcv	uPcs

MINERAL	SAMPLE NUMBER								
	110-82	110-84	110-92	110-101	110-103	110-111	110-108	110-120	110-123
quartz	x	x	x	x	x	x	x	x	x
albite	x	x	x	x	x	x	x	x	x
chlorite	x	x	x	x	x	x	x	x	x
pumpellyite	x				?	x		x	x
epidote				x			x		
calcite	x	x	x		x	x	x		
lawsonite								x	?
white mica						x		x	
clinopyroxene									x
plagioclase	x	x		x	x				x
actinolite				?					?
hornblende									
sphene	x		x	x	x		x	x	x
Na-amphibole									
apatite					x				
ilmenite	x				x		x		x
pyrite						x			
hematite			x						
other opaque		x		x				x	
other						o			
lithic types						v,m,s	v	v,s,m	
textural zone						IIA	IIA	IIA	IIA
lithology	gab	and	fb	myl	and	VAr	vt	VAr	gab
unit	uPcv	uPcv	uPcv	uPc	uPcv	uPcs	uPcv	uPcs	uPcv

MINERAL	SAMPLE NUMBER							
	110-125	110-126	110-129	110-130	110-132	110-133	110-134	110-141
quartz	x	x	x	x	x	x	x	x
albite	x	x	x	x	x	x	x	x
chlorite	x	x	x	x	x	x	x	x
pumpellyite		x		x	x			
epidote	de	de	de	de			de	
calcite		x						x
lawsonite			x	x	x	x		x
white mica	x	x		x	x	x	x	x
clinopyroxene								
plagioclase								
actinolite								
hornblende							de	
sphene		x		x				x
Na-amphibole								
apatite				x		x		
ilmenite		x		x				
pyrite					x			x
hematite						?		
other opaque	x		x	x		x	x	
other								
lithic types	m,v,s	m,v,s	s,v,m	v,s	v,m		v,m	m
textural zone	IIA	IIA	IIA	IIA	IIA	IIB-C		IIB
lithology	slt	VAr	VAr	VAr	VAr	myl	VAr	VAR
unit	uPcs	uPcs	uPcs	uPcs	uPcs	uPcs	uPcs	uPcs

MINERAL	SAMPLE NUMBER							
	110-143	110-149	110-151A	110-159	110-160	110-163	110-165	110-171B
quartz	x	x	x	x	x	x	x	x
albite	x	x		x	x	x	x	x
chlorite	x	x	x	x	x	x	x	x
pumpellyite							x	x
epidote								
calcite	x				x		x	
lawsonite					x	x	x	?
white mica				x			x	x
clinopyroxene								
plagioclase			x					
actinolite								
hornblende			x					
sphene			x					x
Na-amphibole								
apatite			x					
ilmenite			x				x	
pyrite				x	x	x		
hematite								
other opaque	x	x					x	x
other					o	o		
lithic types						v	v	
textural zone		IIA		IIB	IIB	IIA	IIB	IIB
lithology	Leuc	slt	Lamp	slt	slt	slt/vt	ss/ls	lt
unit	Td	uPcs	Td	uPcs	uPcs	uPcs	uPcs	uPcv

MINERAL	SAMPLE NUMBER							
	110-184B	110-185	110-192	110-194A	110-195	110-198	110-200	110-203
quartz	x	x	x	x	x	x	x	x
albite	x	x	x	x	x	x	x	x
chlorite	x	x	x	x		x		x
pumpellyite		x					x	
epidote	x			x	x			
calcite						x		
lawsonite						x		
white mica					x	x		x
clinopyroxene					x			
plagioclase		x						
actinolite				x				
hornblende				x				
sphene	x			x		x	x	x
Na-amphibole								
apatite								
ilmenite				x				
pyrite	x	x					x	
hematite								
other opaque			x		x			x
other								
lithic types								
textural zone	IIB					IIA		
lithology	LaT	da	da	HbD	?	LaT	LaT	vt
unit	Trd	Trd	Trd	pDy	pDy?	Trd	Trd	uPcv?

MINERAL	SAMPLE NUMBER 110-213	110-217	110-800	110-803
quartz	x		x	x
albite	x	x	x	x
chlorite	x	x	x	x
pumpellyite			x	x
epidote		x	x	
calcite				
lawsonite	x	x		
white mica	x		x	x
clinopyroxene		x	x	
plagioclase				
actinolite		x		
hornblende		x		
sphene				x
Na-amphibole				x
apatite				
ilmenite				
pyrite			x	x
hematite				
lithics				
other opaque				
other	x			
textural zone				
lithology	arg	HbD	LaT	LaT
unit	Trc	pDy	uPcv	uPcv

APPENDIX II: Microprobe data

1. Selected amphibole analyses with Bence-Albee correction. (Data given in weight percent).

sample number

oxide	803-4	803-7	803-8	803B-1	803B-2	803B-3	69A-1	69A-3
SiO_2	51.026	50.873	51.95	53.295	52.536	51.08	52.533	51.804
Al_2O_3	1.568	1.422	2.63	2.382	1.855	2.419	3.838	3.108
TiO_2	.775	.564	.194	.641	.691	.464	.53	.362
FeO	30.004	30.401	28.697	27.887	29.106	27.437	25.675	25.808
MgO	4.782	4.833	4.84	5.38	4.791	5.378	5.534	5.799
CaO	1.38	1.393	1.868	2.087	1.315	1.65	1.206	1.265
Na_2O	6.723	7.012	6.889	6.715	7.046	6.77	7.903	6.536
total	98.165	98.40	99.0075	100.367	99.2845	97.1073	99.2014	96.5672

2. Selected amphibole compositions in cations per 23 oxygens, calculated using the AMPH program at Western Washington University.

sample number

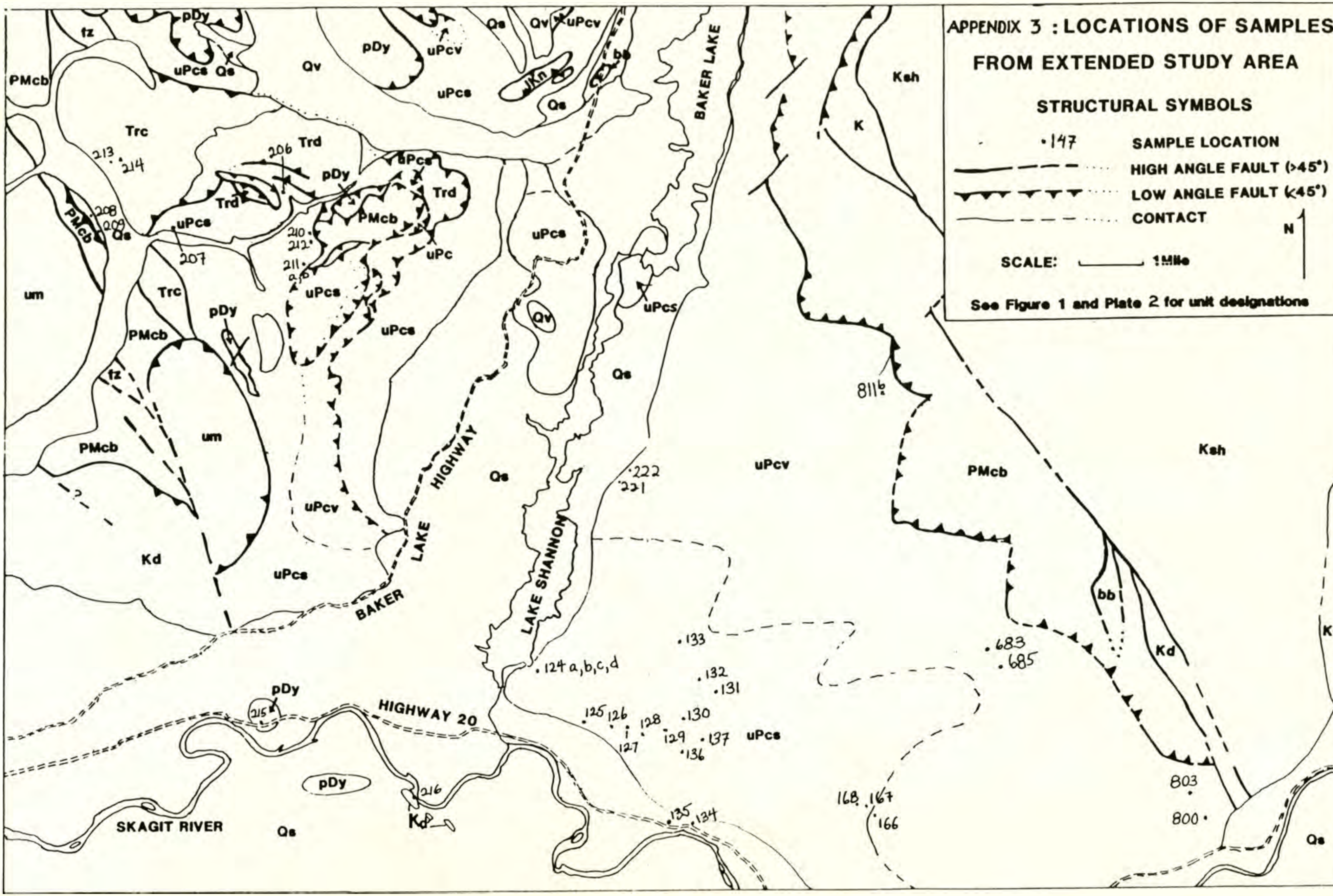
oxide	803-4	803-7	803-8	803B-1	803B-2	803B-3	69A-1	69A-3
SiO_2	7.743	7.726	7.816	7.88	7.876	7.79	7.833	7.834
Al_2O_3	.28	.255	.466	.415	.328	.435	.674	.554
TiO_2	.088	.064	.022	.071	.078	.053	.059	.041
Fe_2O_3	1.631	1.646	1.246	1.096	1.295	1.337	.871	1.382
FeO	2.176	2.215	2.364	2.352	2.353	2.162	2.33	1.882
MgO	1.082	1.094	1.085	1.186	1.07	1.223	1.232	1.307
CaO	.224	.227	.301	.331	.211	.27	.193	.199
Na_2O	1.978	2.065	2.009	1.925	2.048	2.002	2.285	1.916

3. Selected pyroxene analyses with Bence-Albee correction. (Data in weight percent).

oxide	sample number 69C-4	69C-5	69C-6
SiO_2	55.387	55.342	55.508
Al_2O_3	1.423	1.455	1.802
TiO_2	.972	1.07	.85
FeO	13.822	13.89	12.651
MgO	13.813	13.965	14.854
CaO	18.68	18.223	18.409
Na_2O	.24	.382	.293
total	104.337	104.326	104.376

4. Selected pyroxene data reduced using the OMPH program at Western Washington University. Data in cations per 6 oxygens.

oxide	sample number 69C-4	69C-5	69C-6
SiO_2	1.983	1.98	1.975
Al_2O_3	.06	.061	.076
TiO_2	.026	.029	.023
Fe_2O_3	.032	.034	.032
FeO	.382	.381	.344
MgO	.737	.745	.788
CaO	.716	.699	.702
Na_2O	.017	.027	.02
% end member:			
jadite	1.307	2.011	1.703
acmite	.965	1.644	1.097
diopside + hedenbergite	97.728	96.345	97.2


APPENDIX 3 : LOCATIONS OF SAMPLES
FROM EXTENDED STUDY AREA
STRUCTURAL SYMBOLS
•147 SAMPLE LOCATION
HIGH ANGLE FAULT (>45°)
LOW ANGLE FAULT (<45°)
CONTACT
N
SCALE: 1Mile
See Figure 1 and Plate 2 for unit designations
BAKER LAKE
LAKE SHANNON
BAKER LAKE HIGHWAY
HIGHWAY 20
SKAGIT RIVER
PMcb
fz
Trc
um
Kd
Trd
uPcs
uPcv
pDy
Qv
Qs
Ksh
K
bb
uPc
124 a,b,c,d
125
126
127
128
129
130
131
132
133
134
135
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683
685
800
803