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Fabric Study and Structural History of Deformed Plutonic and Metamorphic Rocks in the Holden Area, North Cascades, Washington

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FABRIC STUDY AND STRUCTURAL HISTORY OF DEFORMED PLUTONIC AND METAMORPHIC ROCKS IN THE HOLDEN AREA, NORTH CASCADES, WASHINGTON

by

Gary K. Hurban

Accepted in Partial Completion

of the Requirements for the Degree

Master of Science

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Advisory Committee

Chair

MASTER'S THESIS

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FABRIC STUDY AND STRUCTURAL HISTORY OF DEFORMED PLUTONIC AND METAMORPHIC ROCKS IN THE HOLDEN AREA, NORTH CASCADES, WASHINGTON

A thesis Presented to

The Faculty of

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ABSTRACT

The Holden area, in the Crystalline Core of the North Cascades, contains deformed and undeformed plutons ranging from Triassic to Eocene in age.

Two deformational styles have been identified in the Holden area. Contractional deformation is indicated by steeply-plunging, down-dip, mineral and stretching lineations in the syn-tectonic Seven Fingered Jack pluton (estimated mid-Late Cretaceous), and in the pre-tectonic Dumbell Mountain pluton (220 Ma), associated with apparent flattened fabrics. Strike-slip shear deformation is represented by gently-plunging to subhorizontal, strike-parallel mineral and stretching lineations, which are commonly associated with constricted fabrics. These fabrics occur prominently in the Dumbell Mountain pluton, and crosscut successive intrusive phases in the syn-tectonic root of the Duncan Hill pluton (47-45 Ma emplacement age). Thus, contractional and strike-slip styles of deformation may have been active from mid-Late Cretaceous to early Tertiary in the Holden area. Deformation of uncertain style was active in the mid-Late Cretaceous in the Cardinal Peak pluton (73 Ma), evidenced by: 1) an elongate map pattern; 2) xenoliths aligned parallel to pluton contacts; and 3) a northwest striking foliation defined by recrystallized textures, all of which are aligned parallel to the foliation in the country rock.

Metamorphism reached the amphibolite facies in the Holden area as indicated by the assemblage hornblende + oligoclase + garnet. A few chlorite + albite + epidote assemblages and local alteration of biotite, hornblende, and garnet to chlorite reflect

overprinting by a pervasive low-grade metamorphic event. Steeply-plunging lineation and strike-parallel lineation are defined by amphibolite facies assemblages, indicating that medium-to high-grade metamorphism was coeval with deformation. Strike-parallel lineations defined by both ductile and brittle fabrics with associated chlorite are probably related to deformation associated with later low-grade metamorphic conditions.

Existing models for the structural development of the Cascades include a collisional model resulting in essentially SW-NE directed contraction (Brandon and Cowan, 1985), and a strike-slip or transpressional model resulting in NW-SE lineations with low plunge (Brown and Talbot, 1989). Data for the Holden and surrounding areas indicates that both contraction and strike-slip shear deformation were active at the same time. It is possible that oblique convergence from 80 Ma to 43 Ma was partitioned into orogen-normal and orogen-parallel components to produce coeval contractional and strike-slip shear structures. The development of two structural styles in the Holden area emphasizes the need to incorporate both strike-slip and contractional processes as important deformation mechanisms in the orogenesis of the Crystalline Core of the North Cascades.

ACKNOWLEDGEMENTS

I would like to acknowledge the help of many people who have made this thesis possible.

First, I thank my committee: my main advisor Jim Talbot for his patience and encouragement with me throughout the process and for his dry, Limey sense of humor which often made it quite entertaining; Ned Brown for his helpful suggestions and attainment of microprobe data from University of Washington; and Scott Babcock for his detailed scrutiny and constructive criticisms of my thesis. Thanks go to Kevin Kelly for wrestling with his own computer programs to help me with my plate pushing needs; and to Patty and Vicki for their friendly greetings and seemingly effortless ability to sort through the administrative stuff involved in the graduate school program.

Logistically, the Department of Natural Resources and Western Washington University Department of Geology provided financial support to defray the cost of field expenses. I thank Holden Village for the use of their facility for storage and regrouping; and for the great bread and friendly Norwegian faces as a change of pace from the local camp dogs and slide alder.

You can't say enough about my roommates Tom Flood and Johnny Armstrong (and sometimes Lloyd); without the circular discussions of what is Art?, the spontaneous and late night parties, and random roadtrips, my experience here at Western would have only been partially fulfilled.

I thank Russ Burmester for the summer field experience with the IGS, mapping the ever-changing siltites and argillites of the Belt, flying home from work in a Hughy-500, and drinking bad beer with the folks from Moscow, Idaho.

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INTRODUCTION

The Holden area lies within the Crystalline Core of the North Cascades range of Washington (Figure 1), which is an extension of the Coast Plutonic Complex of British Columbia (Misch, 1966). The Coast Plutonic Complex is one of five major tectonic and physiographic belts (Figure 2) of the Canadian Cordillera (Monger and others, 1982; Armstrong, 1988). The relation of the plutonic and metamorphic Coast Plutonic and Omineca Belts to the largely supracrustal Intermontane and Insular Belts, is problematic. One interpretation is that the Omineca Belt and Coast Plutonic Complex formed in response to collisions of supracrustal terranes; the Intermontane terrane, comprising most of the Intermontane Belt, collided with North America and formed the Omineca Belt; and the Insular terrane, comprising most of Insular belt, collided with the Intermontane terrane and formed the Coast Plutonic Complex (Monger and others, 1982). Alternatively, the Coast Plutonic Complex and Omineca Belt are thought to be the result of continental-margin subduction-related magmatism with the amalgamation of terranes being an earlier, unrelated, event (Dickinson, 1976; Armstrong, 1988).

A further complication is that the Cordillera has experienced oblique convergence between the North American plate and the Kula or Farallon plates, beginning about 84 Ma (Engebretson and others, 1985), when a marked change in the angle of convergence is interpreted to have occurred. Such a change in convergence

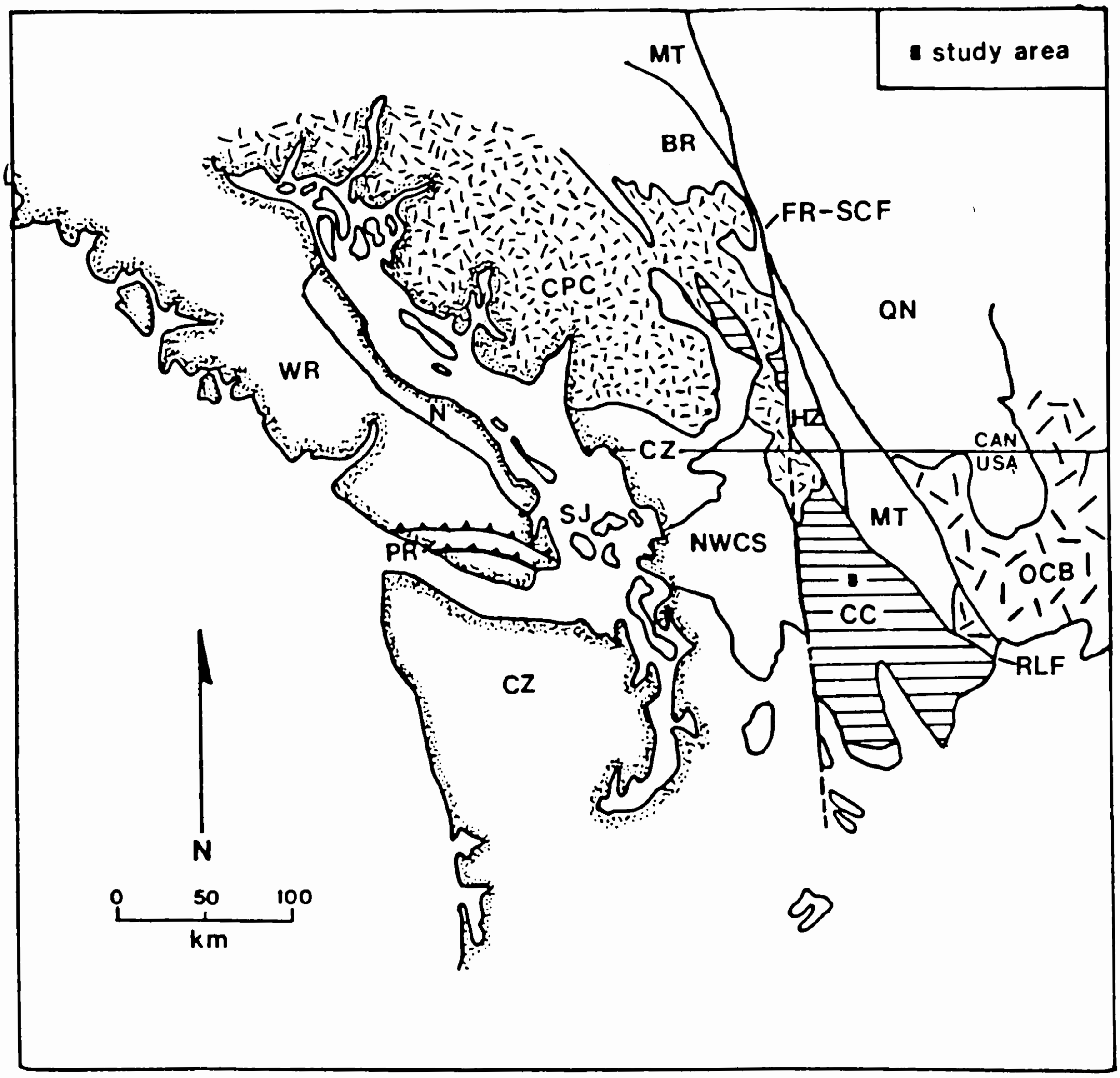


Figure 1. Regional setting of the Crystalline Core (CC), delineated by horizontal ruled pattern. BR = Bridge River terrane, CPC = Coast Plutonic Complex, CZ = Cenozoic, FR-SCF = Fraser River-Straight Creek Fault, HZ = Hozameen terrane, MT = Methow terrane, N = Nanaimo Group, NWCS = Northwest Cascades System, PR = Pacific Rim terrane, RLF = Ross Lake fault, QN = Quesnellia terrane, SJ = San Juan Islands, WR = Wrangellia terrane; Modified from Brown (1987). Holden area is denoted by black square in the Crystalline Core, keyed in inset.

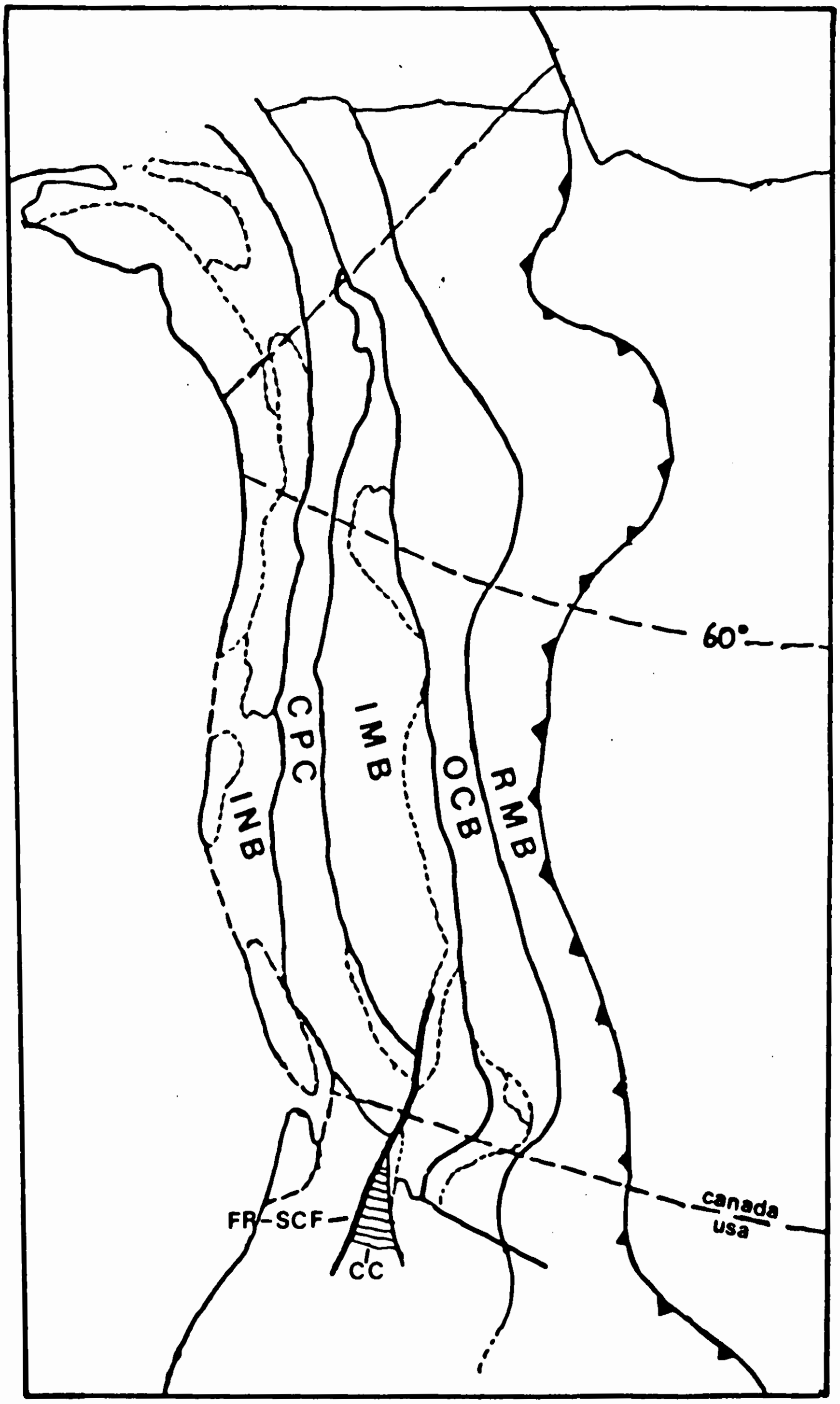


Figure 2. Five geologic and physiographic provinces of the North American Cordillera in British Columbia and northwest Washington. INB = Insular Belt; CPC = Coast Plutonic Complex; IMB = Intermontane Belt; OCB = Omineca Crystalline Belt; RMB = Rocky Mountain Thrust Belt; after Monger and others (1982).

might be reflected in the fabric of the rocks, producing both orogen-normal and orogen-parallel deformation patterns. Most tectonic studies have emphasized the orogen-normal nature of the deformation (Misch, 1966; Brandon and Cowan, 1985; Crawford and others, 1987) though others recognize the importance of orogen-parallel shear (Monger, 1986; Ellis and Watkinson, 1987; Brown and Talbot, 1989).

The Holden area is ideally situated for the study of the relationship between orogen-normal and orogen-parallel deformation as it contains pre, syn, and post-tectonic plutons of varying age (Mattinson, 1972; Cater, 1982; Tabor and others, 1987). A study of the nature, orientations, and relative ages of the fabrics of these plutons was initiated to provide information on the relative importance of orogen-normal and orogen-parallel deformation within the North Cascades.

Regional Geology

The Crystalline Core of the North Cascades (Figure 1) is a complex sequence of schist, gneiss, migmatite, and plutons that range in age from Precambrian to late Cenozoic (Mattinson, 1972). The most significant orogenic activity included coeval metamorphism, deformation, and plutonism from mid-Cretaceous to early Tertiary time (Misch, 1966; Mattinson, 1972).

The Eocene Straight Creek fault has juxtaposed the Crystalline Core against the Northwest Cascade System to the west (Figure 1) (Misch, 1966). To the northeast, the Crystalline Core is bounded by the Ross Lake fault, which separates it from deformed Jura-Cretaceous strata of the Methow Basin. The Crystalline Core can be restored as an extension of the Coast Plutonic Complex of southwest British Columbia, by removal of (80-180 km) mid-Tertiary dextral offset on the Straight Creek fault (Vance, 1957; Misch, 1966). Removal of 110 km of offset (Figure 3) (Tabor and others, 1989) is preferred by Monger (in Price and others, 1985) based on correlation of the Hozameen and Bridge River terranes.

A fundamental problem regarding the nature of the Late Cretaceous orogeny is the relationship between crustal shortening normal to the orogen (Misch, 1966; Brandon and Cowan, 1985; Brandon and others, 1988; McGroder, 1988; McGroder, 1989) and wrench-related deformation parallel to the orogen (Brown, 1987; Brown and Talbot, 1989). In the contractional model, the Crystalline Core is envisioned to be a convergent welt resulting from a Late Cretaceous closure between Wrangellia, the primary terrane comprising the Insular Belt, and Quesnellia, the southernmost of terranes in the Intermontane Belt (Davis and others, 1978; Monger and others, 1982; Brandon and Cowan, 1985). The collision is thought to have produced Barrovian metamorphism in the Crystalline Core, which is inferred to have been the footwall to west-directed thrusts. (Brandon and Cowan, 1985; Brandon and others, 1988; Whitney and McGroder, 1989). Late Cretaceous contractional deformation is evidenced east of the Crystalline Core, in the Methow Basin, by fold belts with northwest trending fold axes and west directed thrust sheets (Tennyson and Cole, 1978; McGroder, 1988). An alternative to the strictly collisional model envisages a regionally transpressive regime during the Late Cretaceous in which oblique strain is partitioned into orogen-normal contraction in the Methow Basin and orogen-parallel extension in the Crystalline Core

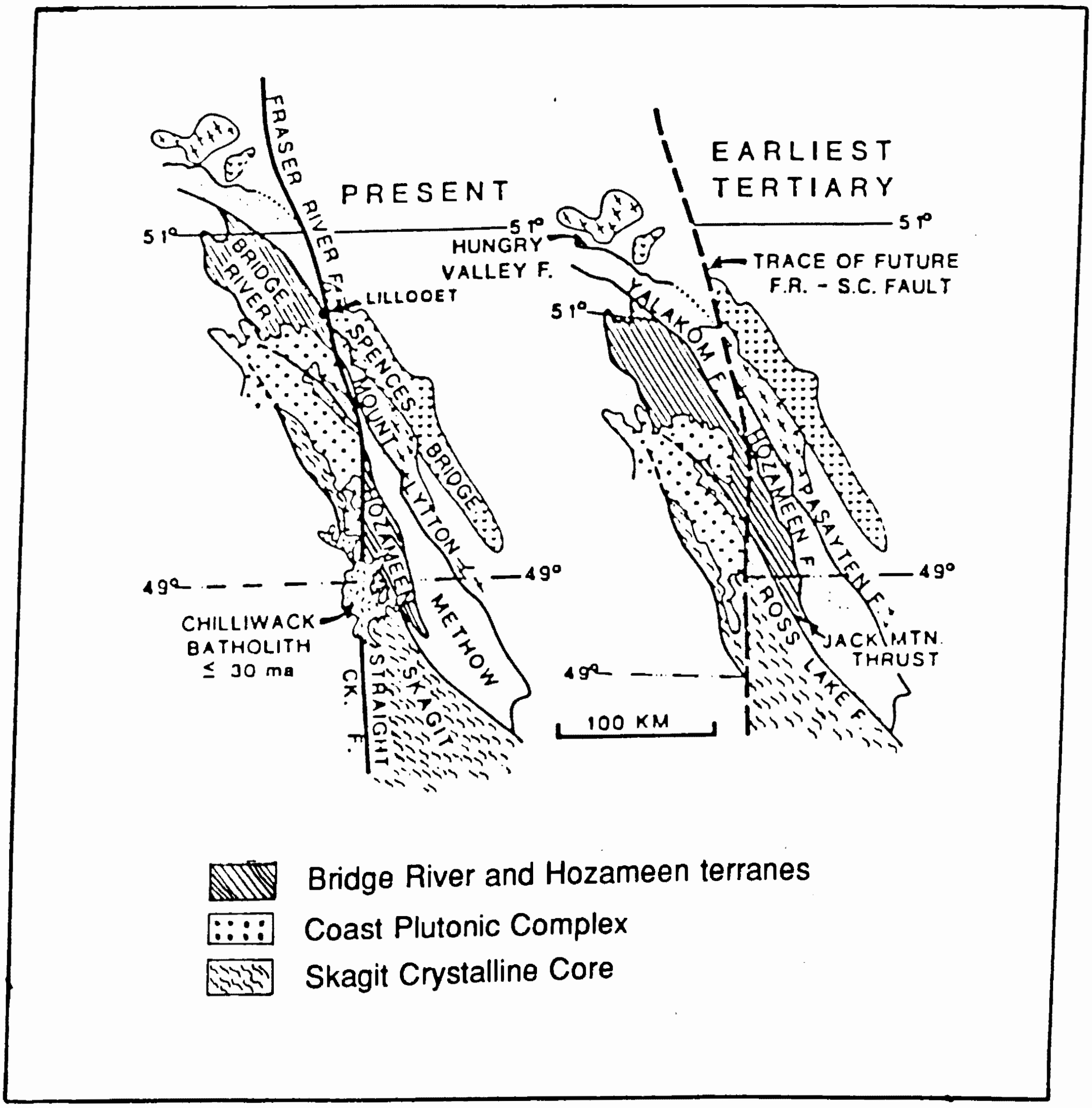


Figure 3. Removal of Tertiary dextral offset on the Straight Creek - Fraser River fault restores igneous rocks of the Coast Plutonic Complex and the Bridge River terrane of southwest British Columbia, with the Skagit Crystalline Core and Hozameen terrane of northwest Washington, respectively (Tabor and others, 1989).

(Brown and Talbot, 1989). Pervasive sub-horizontal northwest-trending stretching lineation, dextrally rotated kinematic indicators, and the presence of Late Cretaceous syn-tectonic plutons are interpreted as evidence for a broad, right-lateral, strike-slip shear zone, active within the Crystalline Core during the Late Cretaceous to Early Tertiary (Brown and Talbot, 1989).

The Holden area is centrally located between the area of Late Cretaceous strike-slip deformation documented in the Skagit and Cascade River areas by Brown and Talbot (1989), and that of Late Cretaceous contractional deformation observed in the Methow Basin (Figure 1) (McGroder, 1988). A compilation of data in the Holden area by Brown and Talbot (1989) indicates the presence of steeply-plunging lineation probably reflecting ductile contractional deformation, and horizontal lineation due to strike-slip shear. Thus, a more detailed structural and chronologic analysis of oriented fabric elements in plutons of known age in the Holden area was initiated to provide new data to elucidate the nature and timing of contractional and transpressional deformation in the Crystalline Core.

Previous Work in the Holden area

A detailed geologic map of the Holden Quadrangle was published by Cater and Crowder (1967). They differentiated the Dumbell Mountain, Riddle Peaks, Seven Fingered Jack, Cardinal Peak, Duncan Hill, Holden Lake, and Copper Peak plutons, and the Younger Gneissic Rocks of Holden (Plate 1) (Figures 4 and 5). Cater (1982)

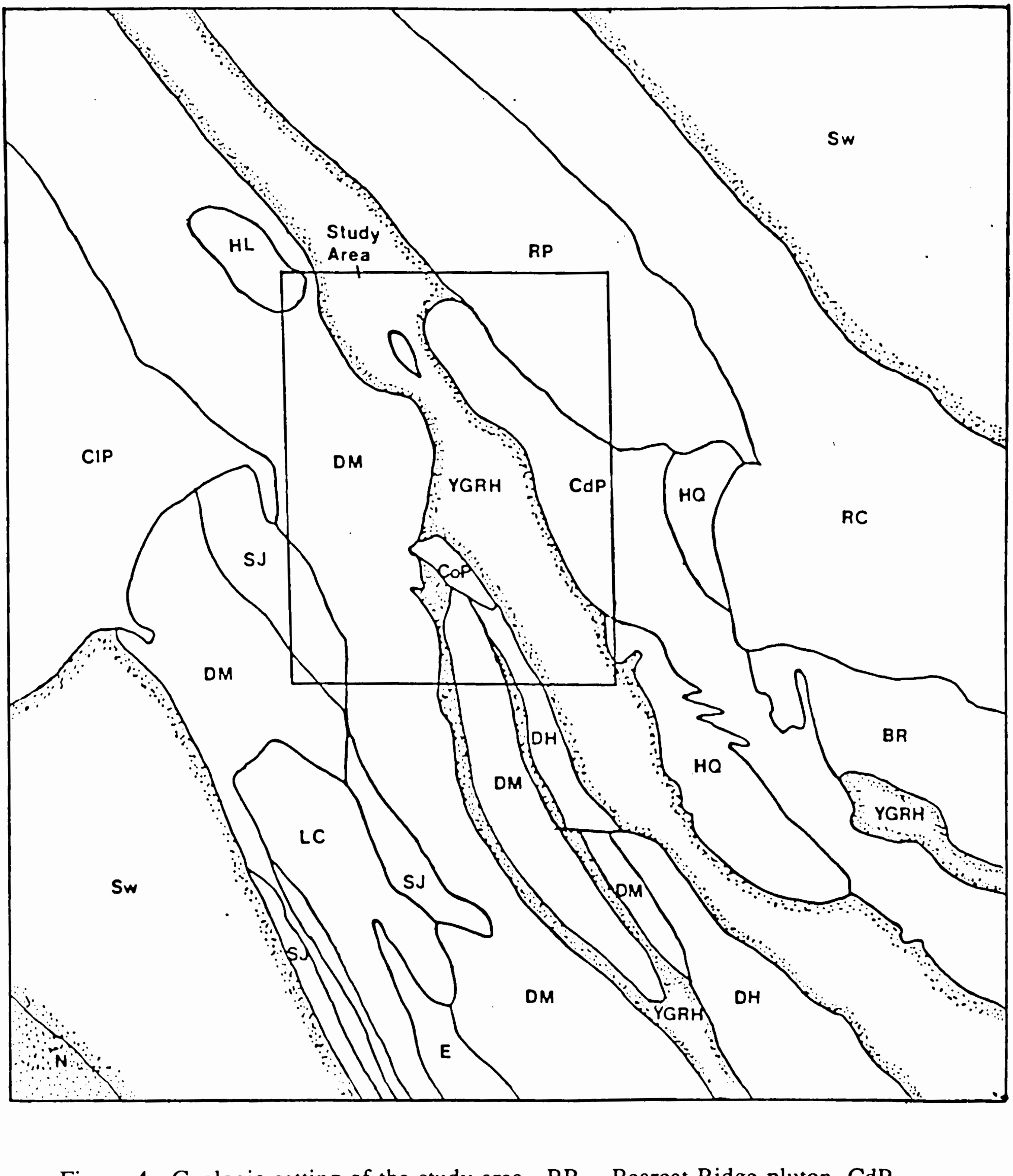
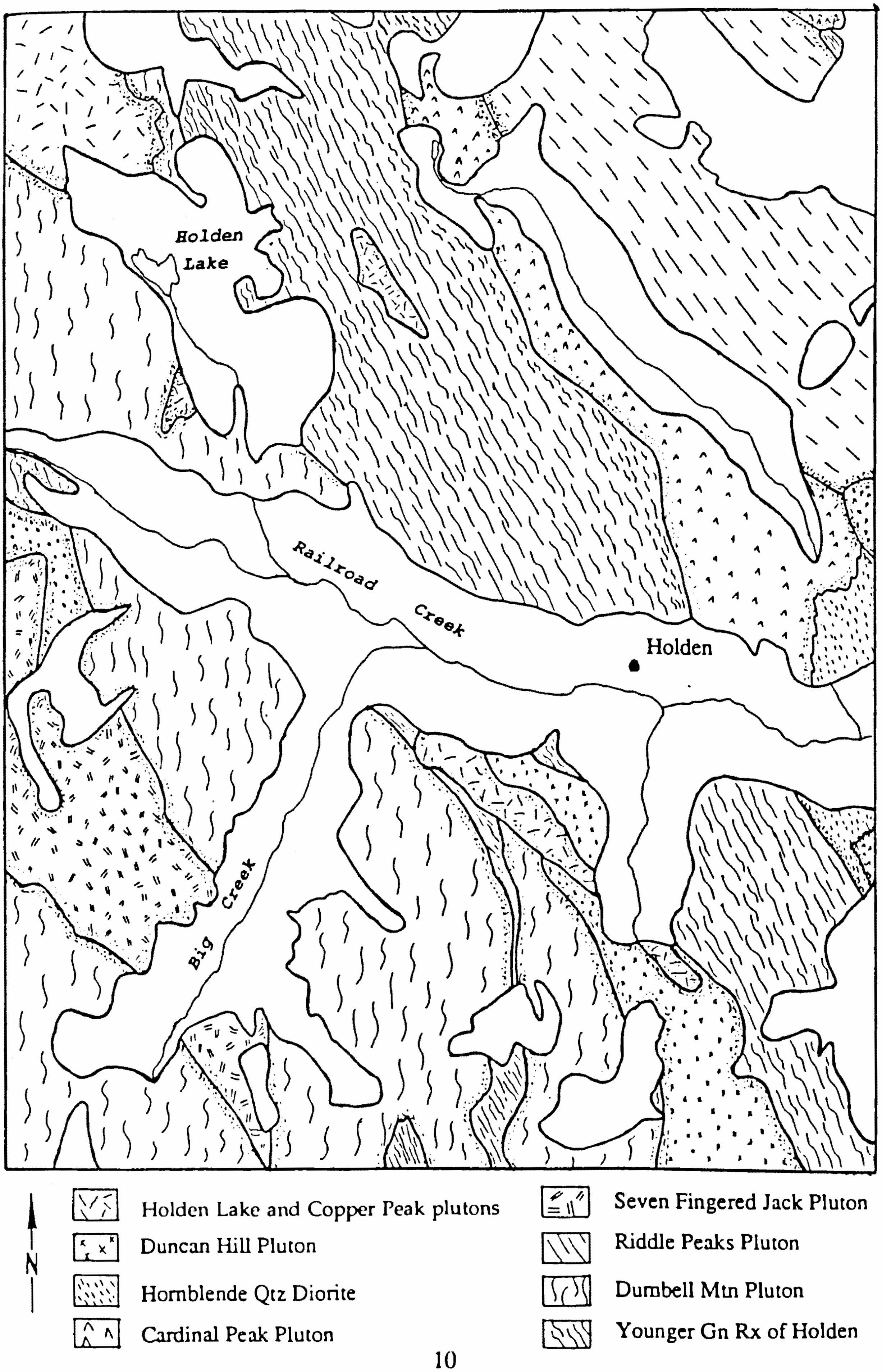


Figure 4. Geologic setting of the study area. BR = Bearcat Ridge pluton, CdP = Cardinal Peak pluton, CoP = Copper Peak pluton, ClP = Cloudy Pass pluton, DM = Dumbell Mountain pluton, DH = Duncan Hill pluton, E = Entiat pluton, HL = Holden Lake pluton, HQ = Hornblende-biotite quartz diorite, LC = Leroy Creek pluton, N = Napeequa, RP = Riddle Peaks pluton, SJ = Seven Fingered Jack pluton, Sw = Swakane Gneiss, YGRH = Younger Gneissic Rocks of Holden; after Cater (1982). Dotted pattern represents meta-sedimentary units. Inner rectangle outlines study area.

Figure 5. Simplified geologic map of the study area. Geology from Cater and Crowder (1967) and this study.


Holden Lake
Railroad Creek
Holden
Big Creek
N
Holden Lake and Copper Peak plutons
Duncan Hill Pluton
Hornblende Qtz Diorite
Cardinal Peak Pluton
Seven Fingered Jack Pluton
Riddle Peaks Pluton
Dumbell Mtn Pluton
Younger Gn Rx of Holden

observed strong foliations in several plutons within the Holden and Lucerne Quadrangles and interpreted the fabrics as "protoclastic", i.e., magmatic in nature formed in response to flow during late stages of emplacement. Cater envisioned plutonism in a deep static orogen where the intrusive bodies acquired gneissose fabrics induced by forceful emplacement and ballooning. He did not consider that the fabrics in the igneous bodies could be the result of mid-Cretaceous to early Tertiary regional metamorphism and deformation, as suggested by Late Cretaceous dates of strongly lineated orthogneisses throughout the Crystalline Core (Mattinson, 1972). Consequently, more work on distinguishing magmatic versus tectonic fabrics in the Holden area is necessary to clarify the relationship of the plutonic fabrics to the regional metamorphism and deformation.

Statement of Problem

To constrain the orogenic models for the North Cascades, we need to characterize the kinematics, timing, and metamorphic P-T conditions of orogenic activity throughout the Crystalline Core. The Holden area contains plutons of known Late Triassic, Late Cretaceous, and Eocene age and of estimated mid-Cretaceous and early Tertiary age. The characteristic fabric orientations and ages of these plutons were intended to help distinguish between the following orogenic models for the Holden area.

1) The regional metamorphic event did not affect the plutons of the Holden area and the fabrics in the plutons are related to "protoclastic" intrusion (Cater, 1982).

2) The main mechanism of orogeny in the Holden area is SW-NE directed contractional deformation active from earliest Jurassic through Late Cretaceous time, as suggested by Brandon and Cowan (1985) and Brandon and others (1988).

3) Contractional deformation occurred early in the deformational history with a shift to strike-parallel northwest-directed shear deformation as the dominant mechanism beginning in the Late Cretaceous (Brown and Talbot, 1989).

4) Contractional and shear deformation were occurring simultaneously as the result of partitioning of oblique strain into contractional and strike-slip components.

To distinguish among these models we must discern whether the fabrics in the plutons are: 1) solely magmatic in nature, 2) largely tectonic in nature reflecting only northwest directed contraction, 3) tectonic with contractional fabrics overprinted by strike-parallel fabrics in older plutons, and strike-parallel fabrics only in younger syn-tectonic plutons; and 4) both down-dip and strike-parallel fabrics formed together but were partitioned differently in plutons of varying age. Previously determined crystallization ages of plutons in the Holden area form the basis for dating syn-tectonic and/or magmatic fabrics and for relative dating of pre- and post-tectonic fabrics.

LITHOLOGIC AND FABRIC DESCRIPTIONS

Introduction

The study area contains dioritic plutons of Triassic to Early Tertiary age and metamorphic rocks of probable Triassic protolith age (Mattinson, 1972; Cater, 1982; Tabor, 1987). The plutons that crop out in the Holden area consist of portions of five large plutons within the Crystalline Core and three smaller plutons (Figure 4). The five large bodies, from oldest to youngest, include: Dumbell Mountain pluton, Seven Fingered Jack pluton, Cardinal Peak pluton, Riddle Peaks pluton, and Duncan Hill pluton. The three smaller bodies have been collectively mapped as the Holden Lake pluton and Copper Peak plutons by Cater and others (1967) (Figure 5). The metamorphic units have been mapped as the younger gneissic rocks of the Holden area (Cater and others, 1967).

Younger Gneissic Rocks of Holden

The metamorphic rocks in the Holden area are interpreted to be silicic to intermediate metavolcanics and rare interbedded metasediments, collectively mapped as the younger gneissic rocks of the Holden area (Cater and Crowder, 1967) (Plate 1). The metamorphic units trend northwest in map pattern and occur as a narrow sliver bounded by numerous plutons (Figure 4). Within the study area, the metamorphic units dip steeply to the southwest; they are bordered to the northeast by the Cardinal Peak pluton and to the southwest by the Dumbell Mountain and Duncan Hill plutons

(Figure 5). Three distinct subunits have been mapped and subdivided by Cater and Crowder (1967) (Plate 1). These subunits include: 1) hornblende schist and gneiss, 2) biotite-quartz schist, and 3) biotite gneiss.

Hornblende Schist and Gneiss

The hornblende schist and gneiss subunit occurs as two elongate strips, one on the northeastern side of the map unit in contact with the Cardinal Peak pluton, and the other on the southwest side in contact with the Dumbell Mountain pluton. Together, these belts comprise approximately 50% of the entire metamorphic package (Plate 1). Ninety percent of the hornblende schist and gneiss subunit is composed of intermediate amphibolite, probably meta-andesite. Two to fifteen meter-thick interbeds of muscovite-quartz schist, meta-basite, and epidote amphibolite, collectively make up approximately the remaining 10%. Two, 2-8m thick layers of marble crop out and comprise less than one percent of the subunit. The intermediate amphibolites have a color index of 25-50 with a distinct compositional layering defined by 1-10mm felsic and mafic layers.

The principal assemblage includes 10-50% hornblende; 40-65% oligoclase; 10-35% quartz; +/- chlorite, biotite, muscovite, and epidote. Accessories include two occurrences of garnet; two of anthophyllite; one of augite; one of calcite; and minor rutile, sphene, apatite, and opaques. The hornblende schist and gneiss commonly contain relict igneous hornblende grains, which are poikiloblastic with plagioclase and quartz forming a fine-grained equigranular granoblastic texture (Figure 6). Locally,

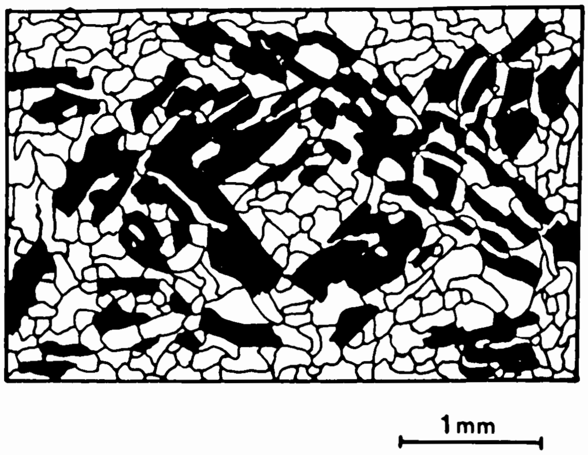


Figure 6. Relict igneous hornblende grains (black) poikiloblastic with plagioclase and quartz (clear) forming a fine-grained equigranular granoblastic texture. Sample #26, from hornblende schist and gneiss subunit of younger gneisses of Holden.

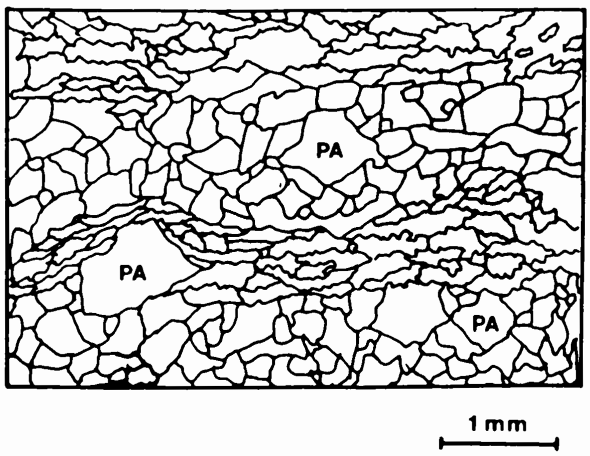


Figure 7. Highly strained ribbons of quartz contain elongate subgrains with sutured grain boundaries and form thin alternating layers with bands of less deformed sub-polygonal grains of plagioclase with curved and embayed grain boundaries; locally plagioclase are deformed into weakly augened shapes - denoted by (PA). Sample # 17, from biotite gneiss subunit of younger gneisses of Holden; fabric is perpendicular to foliation and parallel to lineation.

hornblende occurs in 0.5 to 3mm alternating bands and ribbons with plagioclase and quartz and as medium-size subhedral grains. Plagioclase is medium- to fine-grained and occurs as partially polygonized grains with curved and embayed grain boundaries in a sub-granoblastic texture (Figure 7; texture is from the biotite gneiss subunit). Quartz primarily forms thin ribbons and elongate aggregates of small stretched grains with highly sutured grain boundaries (Figure 7). Epidote is minor but locally forms bands of small, anhedral grains. Biotite, muscovite, and chlorite are minor constituents, occurring as small euhedral grains and as elongate aggregates which wrap around deformed quartz and plagioclase grains. Garnet occurs as altered porphyroblasts in a fine-grained recrystallized matrix of quartz and plagioclase. Augite is medium-grained and shows straight grain boundaries with euhedral plagioclase. Anthophyllite is euhedral and occurs with hornblende locally.

Biotite-Quartz Schist

The biotite-quartz schist subunit trends northwest in map pattern and is in contact with the hornblende schist and gneiss subunit to the southwest and the biotite gneiss subunit to the northeast. The biotite-quartz schist comprises approximately 35% of the metamorphic rocks in the field area (Plate 1). It is a fine-grained, gray (color index, 5-35), quartzo-feldspathic biotite schist with local interbeds of intermediate amphibolite and minor meta-basite.

The principal assemblage includes 0-35% hornblende; 40-70% plagioclase; 10-30% quartz; 5-20% biotite; +/- chlorite, epidote, garnet, sphene; and accessory apatite, rutile and opaques. The biotite-quartz schist subunit contains sulphides and weathers a distinct brownish and orange color in outcrop. It is characteristically fine-grained and has 1-5mm thick alternating light and gray layers of aggregates of plagioclase, epidote, and quartz. Fine-grained biotite occurs as small flakes in a granoblastic texture of quartz and plagioclase and also wrap around medium size aggregates of hornblende (Figure 8). The biotite-quartz schists have hornblende in a granoblastic texture with plagioclase and quartz, compositional layering, and deformed quartz ribbons, as described for the hornblende schist and gneiss unit.

Biotite Gneiss

The biotite gneiss subunit trends northwest in map pattern and is located between the biotite-quartz schist subunit to the southwest and the hornblende schist and gneiss subunit to the northeast. The biotite gneiss is a distinctly light colored (color index, 5-15), fine-grained quartzo-feldspathic gneiss with characteristic large augen of quartz wrapped by biotite; it comprises approximately 15% of the metamorphic rocks in the study area (Plate 1). It contains rare interbeds of biotite-quartz schist and intermediate amphibolite.

The principal assemblage includes 15-40% quartz; 55-70% oligoclase; 0-5% biotite; minor chlorite and epidote; +/- hornblende, muscovite; and accessory sphene, apatite, and opaques. Quartz and plagioclase occur separately in 1-3mm wide bands defining a characteristic layering of the biotite gneiss subunit. The quartz bands contains elongate small grains and trains of subgrains with highly sutured grain

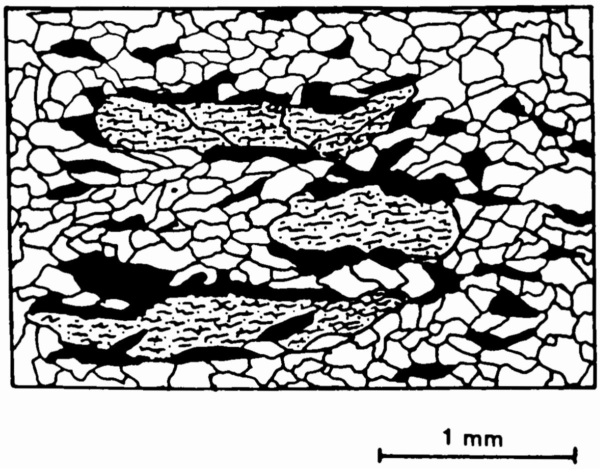


Figure 8. Fine-grained biotite (dark) and elongate aggregates of hornblende (dotted and lined pattern) define a strong fabric. Sample # 16, from biotite-quartz schist subunit of younger gneisses of Holden; fabric is perpendicular to foliation and parallel to lineation.

boundaries (Figure 7). Plagioclase commonly forms .5 to 1.5mm anhedral grains in a partially granoblastic texture and local augen shaped grains (Figure 7). Biotite and

All of the metamorphic units contain a strong layer-parallel foliation. The biotite-quartz schist contains a local, steeply-plunging to down-dip, mineral lineation[1]; which is defined by small, aligned, parallel flakes and clusters of biotite. All three subunits contain pervasive, well developed, and abundant, shallow-plunging to subhorizontal stretching and mineral lineations that strike northwest. Stretching lineation is defined by plagioclase augen wrapped by fine-grained biotite, and by ribbon texture of quartz forming parallel bands (Figure 7). Locally, subhorizontal mineral lineation is defined by parallel small grains of hornblende and biotite parallel to elongate ridges of quartz and plagioclase in outcrop. The steeply-plunging lineation is preserved in local, narrow zones between a dominant shallow-plunging fabric. The foliation is parallel to axial planes of small scale, tight to isoclinal folds.

The protolith of these rocks are interpreted to be andesites and rhyolitic to dacitic tuffs with interbeds of very minor, silt-rich and pelitic sediments, presumably deposited in an arc-type environment.

The Cascade River Schist is interpreted to be an arc volcanic sequence deposited upon or gradational into the Marblemount Meta-quartz Diorite in the Cascade River area (Dragovich and others, 1989). To the southeast, in the Holden

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[1]Mineral lineation (Davis, 1984, p. 426) is defined by the parallel orientation of acicular or prismatic grains, i.e. hornblende and biotite. Stretching lineation (Ramsay and Huber, 1983) has been cited in the literature as defined by: pulled apart grains (Brown and Talbot, 1989); stretched porphyroclasts of plagioclase and quartz (Jain and Anand, 1988); and aligned aggregates of biotite, hornblende, plagioclase, or quartz (Miller and Bowring, 1990).

area, the younger gneisses of Holden and the Dumbell Mountain pluton are on strike with the Cascade River Schist and Marblemount Meta-quartz Diorite, respectively. Mattinson (1972) reported a 265 Ma U-Pb zircon age from the biotite gneiss unit of the younger gneisses of Holden. He interpreted the biotite gneiss to be a quartz keratophyre tuff, with the age (265 Ma) representing the time of deposition (Mattinson, 1972). The 265 Ma depositional age is consistent with Cater's (1982) interpretation that the Dumbell Mountain pluton (220ma) intruded the younger gneisses of Holden. This would impede correlation of the Younger Gneisses of Holden with the Cascade River Schist in the Cascade River area (Misch, 1966). However, a detrital origin of the zircon cannot be ruled out, which could make the younger gneisses of Holden younger than the Dumbell Mountain pluton. In the Holden area, contact relations between the Dumbell Mountain pluton and the younger gneisses of Holden are inconclusive.

Dumbell Mountain pluton

The Dumbell Mountain pluton consists of three elongate phases which trend northwest-southeast and crop out in much of the southwest corner of the study area (Figures 4 and 5). The Dumbell Mountain pluton has been dated at 220 Ma by U-Pb on zircon (Mattinson, 1972). The three distinct phases are: 1) gneissic hornblende-quartz-diorite, which occurs as the southwest portion of the body, 2) quartz-diorite augen gneiss, cropping out to the northeast, and 3) hornblende-quartz-diorite gneiss, which occurs in the center of the body (Plate 1). The hornblende-quartz-diorite gneiss is the oldest of the three phases; the other two intrude it with sharp contact relationships and contain xenoliths of it.

Gneissic Hornblende-Quartz-Diorite

The gneissic hornblende-quartz-diorite is white to medium gray in color (color index, 15-35), fine- to medium-grained, and consists of: 40-65% plagioclase (An 10-30); 15-35% hornblende; 5-15% quartz; minor chlorite; secondary epidote and sericite; one occurrence of garnet; and accessory sphene, apatite, and opaques. Hornblende forms 1 to 5mm subhedral grains, commonly poikiloblastic with plagioclase or quartz (Figure 9). Plagioclase is present as medium-size, subhedral-anhedral grains with curved and recrystallized grain boundaries (Figure 9), and as medium- to small grains in a granoblastic texture with polygonal grains of fine-grained quartz (Figure 10; texture is from the quartz-diorite augen gneiss phase). Locally, quartz forms elongate pods containing subgrains. Garnet occurs as medium-grained porphyroblasts in a matrix of recrystallized plagioclase and contains fractures filled with chlorite. Epidote forms aggregates of small, anhedral grains. Chlorite is euhedral in a few samples and is commonly a retrogression product of hornblende in others.

The dominant fabric in the gneissic hornblende-quartz-diorite is a steeply-dipping, northwest striking foliation, which exhibits shallow-plunging to subhorizontal mineral and stretching lineations and a local, steeply-plunging mineral lineation. The stretching lineation is defined by pulled-apart plagioclase grains (Figure 11) and highly elongate stretched quartz grains (Figure 12; texture is from the quartz-diorite augen

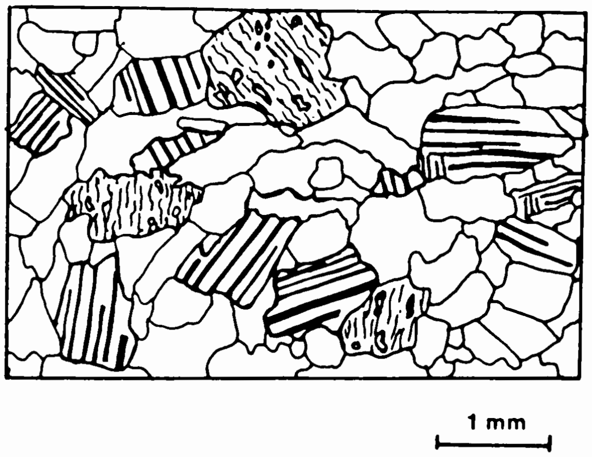


Figure 9. Partially recrystallized texture showing medium-grained subhedral hornblende and relict igneous plagioclase with curved and recrystallized grain boundaries. Fine lined pattern represents hornblende; thick lines represent albite twins in plagioclase; clear grains are anhedral plagioclase. Sample # 198, gneissic-hornblende quartz diorite of Dumbell Mountain pluton.

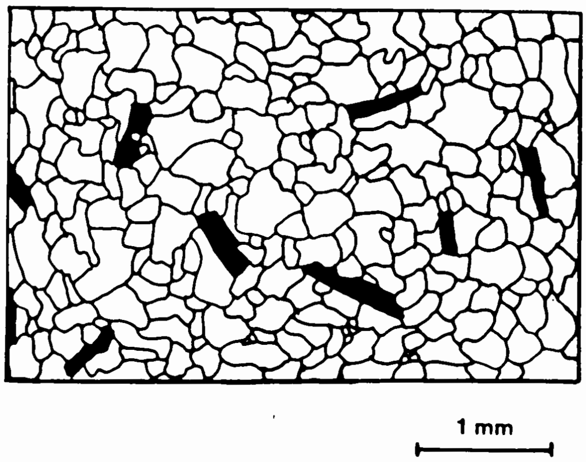


Figure 10. Granoblastic texture with polygonal shaped recrystallized grains of quartz and sparse hornblende grains. Sample # 225, from quartz-diorite augen gneiss of Dumbell Mountain pluton.

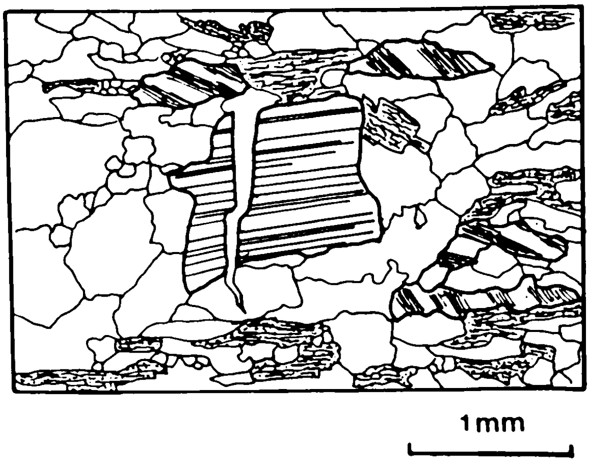


Figure 11. Pulled-apart plagioclase porphyroclasts (with lines denoting pericline twins) and highly elongate stretched grains of quartz (shaded grains), shading denotes similar orientation of extinction of subgrains. Both plagioclase and quartz are extended parallel to small euhedral-subhedral grains of hornblende, defining stretching and mineral lineation. Sample # 196, from gneissic hornblende-quartz-diorite of Dumbell Mountain pluton; fabric is perpendicular to foliation and parallel to lineation.

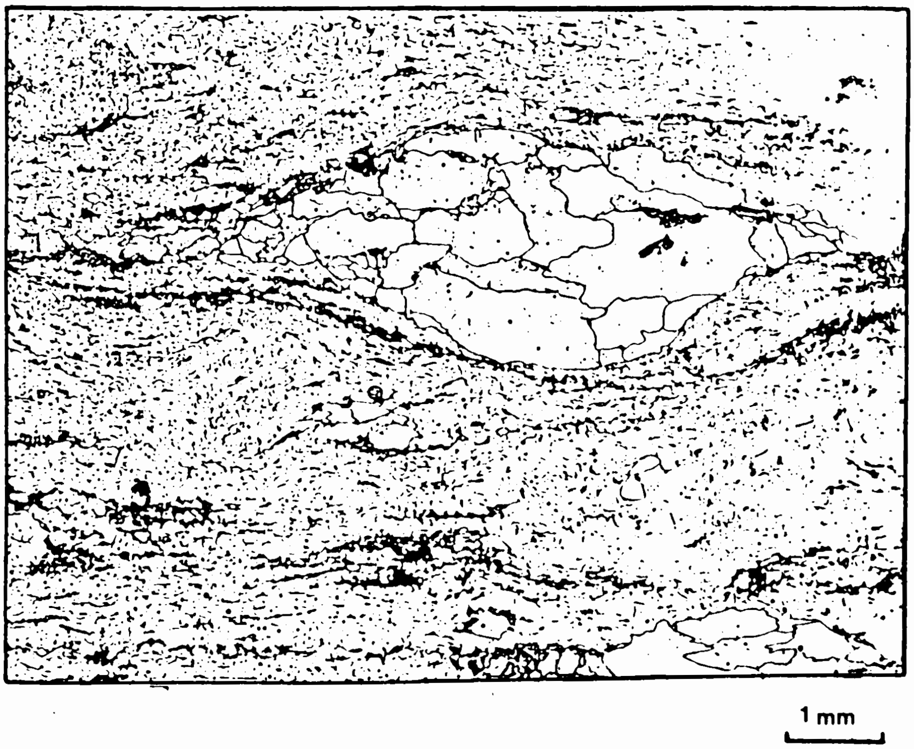


Figure 12. Microfiche copy of a deformed, large, elongate augen of quartz that contains elongate subgrains, and lies within a fine-grained matrix of quartz and plagioclase. Sample # 67, from quartz-diorite augen gneiss of Dumbell Mountain pluton; fabric is perpendicular to foliation and parallel to lineation.

gneiss phase) that have subgrains in the same optical orientation. The mineral lineation is defined by aligned euhedral-subhedral hornblende grains in a mortar texture of granoblastic quartz and plagioclase, and small grains of hornblende with asymmetric tails. Narrow, 2-10mm wide zones of mylonite are defined by strongly aligned pods and bands of fine-grained recrystallized quartz.

Quartz-Diorite Augen Gneiss

The quartz-diorite augen gneiss is light colored (color index, 5-20) and fine- to coarse-grained; it consists of: 30-70% plagioclase (An 20-30); 10-60% quartz; 0-30% hornblende; 1-5% biotite; minor chlorite and muscovite; two occurrences of anthophyllite; and accessory apatite, sphene, zircon, and opaques. Plagioclase and quartz occur as medium to small polygonal grains that form a locally well developed granoblastic texture (Figure 10); plagioclase also occurs as deformed, subhedral, augen-shaped grains (described in the biotite gneiss subunit of the younger gneisses of Holden; Figure 7). Large augen of quartz are composed of highly strained and elongate subgrains that exhibit patchy extinction and sutured grain boundaries (Figure 12). The augen are bounded by small aggregates of biotite and lie in a matrix of fine-grained granoblastic quartz and plagioclase (Figure 12). Biotite and hornblende are medium- to fine-grained, locally euhedral, and commonly altered to chlorite. Chlorite also forms small, aligned, euhedral grains in a granoblastic matrix of quartz and plagioclase. Sericite and epidote are secondary, altering from plagioclase.

The quartz-diorite augen gneiss exhibits a steeply-dipping, west-northwest striking foliation. Many localities show well developed L-S tectonites, with a steeply-plunging to down-dip stretching lineation in some localities and a subhorizontal, northwest-trending stretching lineation in others. Both subhorizontal and down-dip stretching lineations are defined by 1) stretched porphyroclasts of quartz which form elongate augen containing aligned subgrains (Figure 12); 2) small stretched grains of biotite that interfinger with stretched subgrains of plagioclase; and 3) elongate aggregates of small grains of biotite.

Hornblende-Quartz-Diorite Gneiss

The hornblende-quartz-diorite gneiss is a dark green to black (color index, 35-60), fine- to medium-grained diorite. It consists of 30-60% plagioclase (An 20-40); 30-60% hornblende; 10-20% quartz; 0-5% chlorite; minor chlorite, epidote, and secondary sericite. Accessories include sphene, apatite, opaques, and two occurrences of garnet. Hornblende occurs as thin, elongate, prismatic grains .5mm x 2mm long, commonly forming 1-2mm wide bands in a matrix of granoblastic fine-grained quartz and plagioclase (Figure 13). Hornblende also forms mats of medium- to fine-grains with poikiloblastic quartz and plagioclase. Biotite is medium-grained, euhedral, and commonly alters to chlorite. Minor garnet forms euhedral, medium- to fine-grained porphyroblasts with minor fractures filled with chlorite. Chlorite occurs as retrogression products of biotite and hornblende and forms medium-grained euhedral

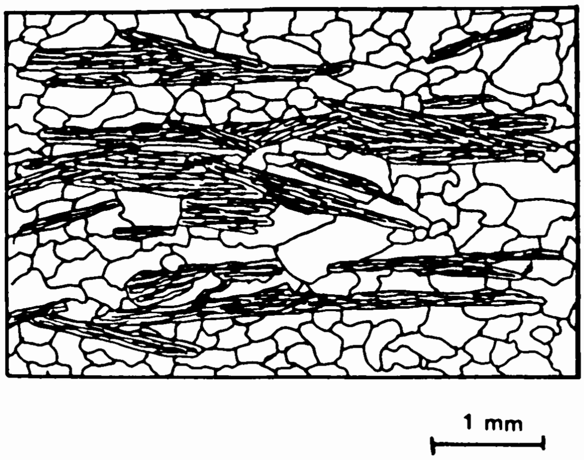


Figure 13. Elongate prismatic grains of hornblende aligned parallel in a fine-grained matrix of granoblastic quartz and plagioclase defining a mineral lineation in rock with an L-tectonite fabric. Sample # 216, from hornblende-quartz-diorite gneiss of Dumbell Mountain pluton; fabric is parallel to lineation.

grains in some samples. Aggregates of fine-grained epidote are present in granoblastic texture and also fill late cross-cutting fractures. Sericite and clay minerals entirely replace plagioclase in some samples.

The hornblende-quartz-diorite gneiss shows a commonly well-developed L-tectonite fabric that defines a west-northwest trending, shallow-plunging mineral lineation. The mineral lineation is formed by the parallel orientation of elongate prismatic hornblende grains (Figure 13). Highly elongate pods of recrystallized quartz and ribbons of small recrystallized grains of plagioclase define a stretching lineation parallel to the mineral lineation.

The Dumbell Mountain pluton contains abundant highly strained fabrics with minor recrystallization. The extensive amount of crystal-plastic strain and lack of coarse-grained recrystallization textures observed in the pluton indicate that deformation occurred primarily in the solid state, and that the pluton was probably intruded before deformation began, and thus is pre-tectonic.

Seven Fingered Jack pluton

The Seven Fingered Jack pluton crops out as a narrow, elongate body intruding the Dumbell Mountain pluton in the southwest corner of the study area (Figures 4 and 5). The pluton has not been dated but has been broadly correlated to the Entiat pluton (Cater, 1982), which has nearly concordant U-Pb ages of 85-75 Ma (Mattinson, 1972). Correlation was based on Cater's (1982) observations of very similar textures and compositions, which were confirmed by recent observations by Dawes (personal communication, 1991). An estimated age of mid-Late Cretaceous for the Seven Fingered Jack pluton is considered speculative for the purposes of this study. The body is an intermediate (color index 15-30), fine- to medium-grained quartz-diorite, with a predominantly massive texture and variable foliation. The pluton contains 60-75% plagioclase (An 10-30); 15-40% hornblende; 5-15% quartz; 1-5% biotite; 1-5% chlorite; minor epidote; two occurrences of hypersthene; two of augite; and accessory apatite and opaques. Medium-grained anhedral plagioclase with embayed grain-boundaries and fine-grained anhedral plagioclase and quartz comprise 75 to 80% of the rock (Figure 14). Hornblende occurs as anhedral-subhedral grains, locally showing lensoidal shapes (Figure 14). Biotite and chlorite form medium- to small euhedral grains; hornblende and biotite have locally altered to chlorite. Epidote occurs as small (.25-.5mm) euhedral grains locally associated with biotite, and as small, anhedral-subhedral interstitial grains. Plagioclase is strongly altered to sericite in some samples.

A variable foliation observable in outcrop is defined by aligned subhedral hornblende and plagioclase grains in thin section and is interpreted as magmatic. The variable foliation is locally crosscut by northwest-striking, steeply-dipping, parallel-sided shear zones that show a moderately- to strongly developed deformational texture. The northern most contact with the Dumbell Mountain pluton, denoted by # 14 in Appendix I (Figure locality map), is characterized by an approximately 100m-wide shear zone. These crosscutting shear zones contain a steep, down-dip lineation. The lineation shows weakly aligned subhedral plagioclase laths with albite twins aligned

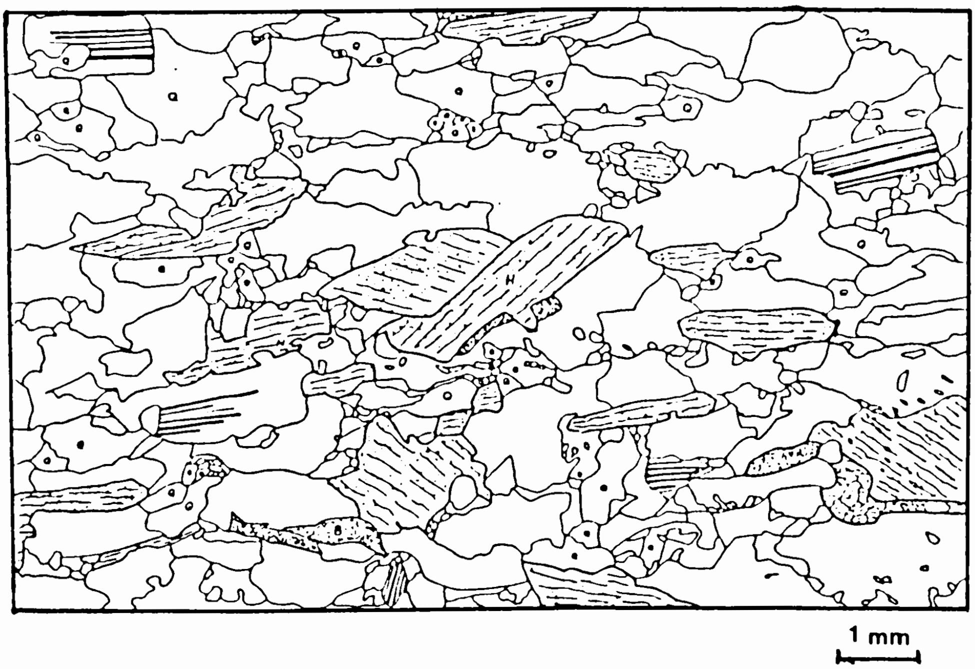


Figure 14. Aligned subhedral, twinned plagioclase grains and lensoidal hornblende grains define a relict magmatic foliation. Relict flow foliation is parallel to elongate plagioclase grains with embayed grain boundaries indicating recrystallization. Sample # 212, from Seven Fingered Jack pluton; at contact with Dumbell Mountain pluton (see Appendix I for locality). Fabric is perpendicular to foliation and parallel to lineation.

parallel to the trend of lensoidal hornblende, together defining a relict magmatic flow alignment (Figure 14). Elongate plagioclase grains with recrystallized and embayed grain boundaries (Figure 14) indicate crystal-plastic strain and recrystallization superposed and parallel to the relict flow fabric. Down-dip tectonic lineations in the Dumbell Mountain pluton are parallel to igneous and tectonic down-dip lineation in contact zone of the Seven Fingered Jack pluton.

The Seven Fingered Jack pluton contains a down-dip lineation defined by coexisting relict magmatic flow fabrics and deformation-recrystallization textures, which is parallel to tectonic down-dip lineation in the Dumbell Mountain pluton. Together, these observations are interpreted to indicate that intrusion occurred prior to and during deformation.

Riddle Peaks pluton

The Riddle Peaks pluton is a large elongate body which trends northwest in map pattern and crops out in the northeast corner of the Holden quadrangle (Figure 4). In the Holden area, the body is bordered by the Cardinal Peak pluton to the southwest and a small isolated patch of younger gneissic rocks of Holden and Cardinal Peak pluton to the northeast (Figure 5). It is of unknown age but has been interpreted to be intruded by and older than the Cardinal Peak pluton, based on its map pattern (Cater and Crowder, 1967). Contact relationships in the Holden area are inconclusive in determining relative age relations for the Riddle Peaks and Cardinal Peak plutons.

Riddle Peaks pluton consists of two distinct phases (Plate 1), 1) a main phase that is a medium- to coarse-grained, layered, hornblende-gabbro, and 2) a lighter, medium- to coarse-grained gabbro which occurs as a narrow, northwest-trending strip along the southwest border of the body. The layered phase of the Riddle Peaks pluton is dark to intermediate in color (color index, 40-95) and consists of 5 to 15cm alternating plagioclase and hornblende rich layers; common 20 to 50cm layers grade from hornblende rich (color index, 90-100) at the base, to plagioclase rich (color index, 0-5) at the top. The lighter gabbroic phase is intermediate in color (color index, 15-50) and is not distinctly layered.

Primary constituents of the main layered phase are 50-100% hornblende; 5-50% plagioclase (An 30-50); +/- chlorite, muscovite, quartz, epidote; and accessory apatite, sphene, and opaques. Both hornblende and plagioclase laths are commonly aligned in a well defined foliation and lack signs of interstitial recrystallization (Figure 15). Hornblende forms medium-size hypidiomorphic grains and locally occurs as large mats of medium- to small grains; both types contain dusty magnetite. Chlorite and epidote are sparse, both occurring in fractures, and chlorite locally altering from hornblende.

The light phase consists of 80-90% plagioclase (An 30-50); 10-20% hornblende; minor chlorite; one occurrence each of hypersthene and augite; and accessory apatite and magnetite. Plagioclase forms medium-size, subhedral grains aligned parallel with medium-grained, hypidiomorphic hornblende, in a well-defined foliation (Figure 15). Hornblende rims both hypersthene and augite.

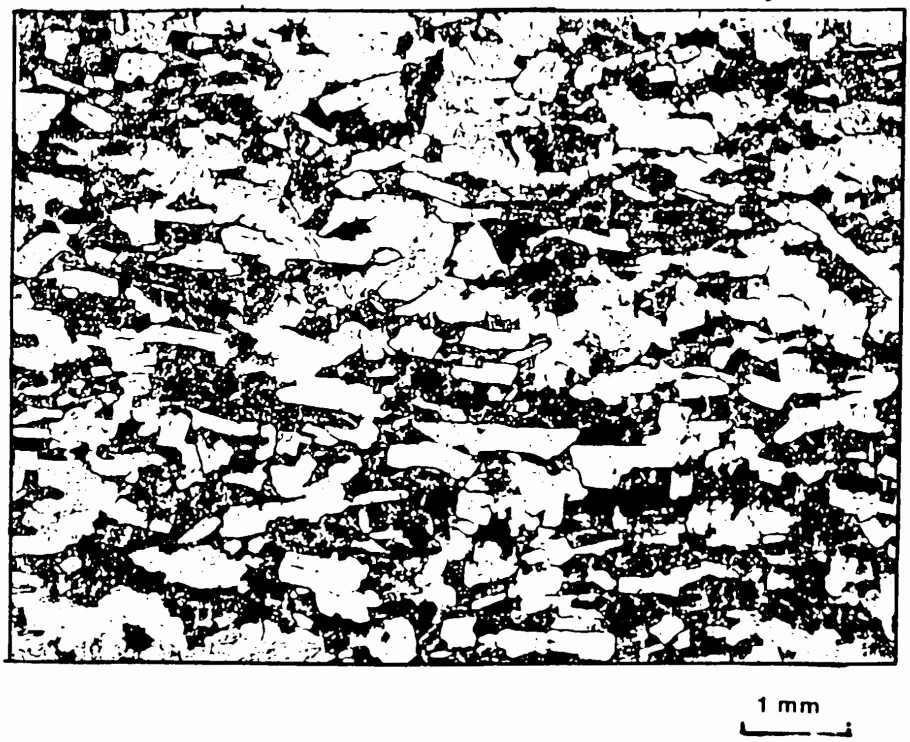


Figure 15. Microfiche copy of aligned euhedral plagioclase and hornblende laths defining a primary magmatic flow fabric. Sample # 186, from Riddle Peaks pluton; fabric is perpendicular to foliation.

A few fine-grained, hypabyssal, felsic dikes crosscut the magmatic layering within the Riddle Peaks pluton and contain a strongly developed mylonitic foliation and gently-plunging stretching lineation. The stretching lineation is defined by fine-grained ribbons of quartz and thin partings of biotite which anastomose around medium-grained rounded plagioclase porphyroclasts (Figure 16).

The Riddle Peaks pluton is pre-tectonic with respect to the lineation formed in brittle-ductile mylonitinized hypabyssal dikes. Cater and Crowder (1967) interpret it to have been intruded by the Cardinal Peak pluton, based on map pattern, which would make it older than 73 Ma (see Cardinal Peak pluton). It was observed to be in sharp contact with the Cardinal Peak pluton, though cross-cutting age relations were inconclusive in determining which was younger.

Cardinal Peak Pluton

The Cardinal Peak pluton is an elongate body which trends northwest in map pattern (Figure 4). The pluton is interpreted to be a tilted diapir (Miller, 1991); with the shallower, larger portion occurring in the Lucerne quadrangle to the southeast, and the deeper, smaller root cropping out in the Holden area to the northwest (Figure 4). It is in sharp contact with the Riddle Peaks pluton to the northeast and the younger gneissic rocks of Holden to the southwest (Figure 5). Zartmann and Tabor of the U.S.G.S. (Tabor, personal communication, 1990) have obtained a concordant, U-Pb zircon age of 73 Ma for the Cardinal Peak pluton.

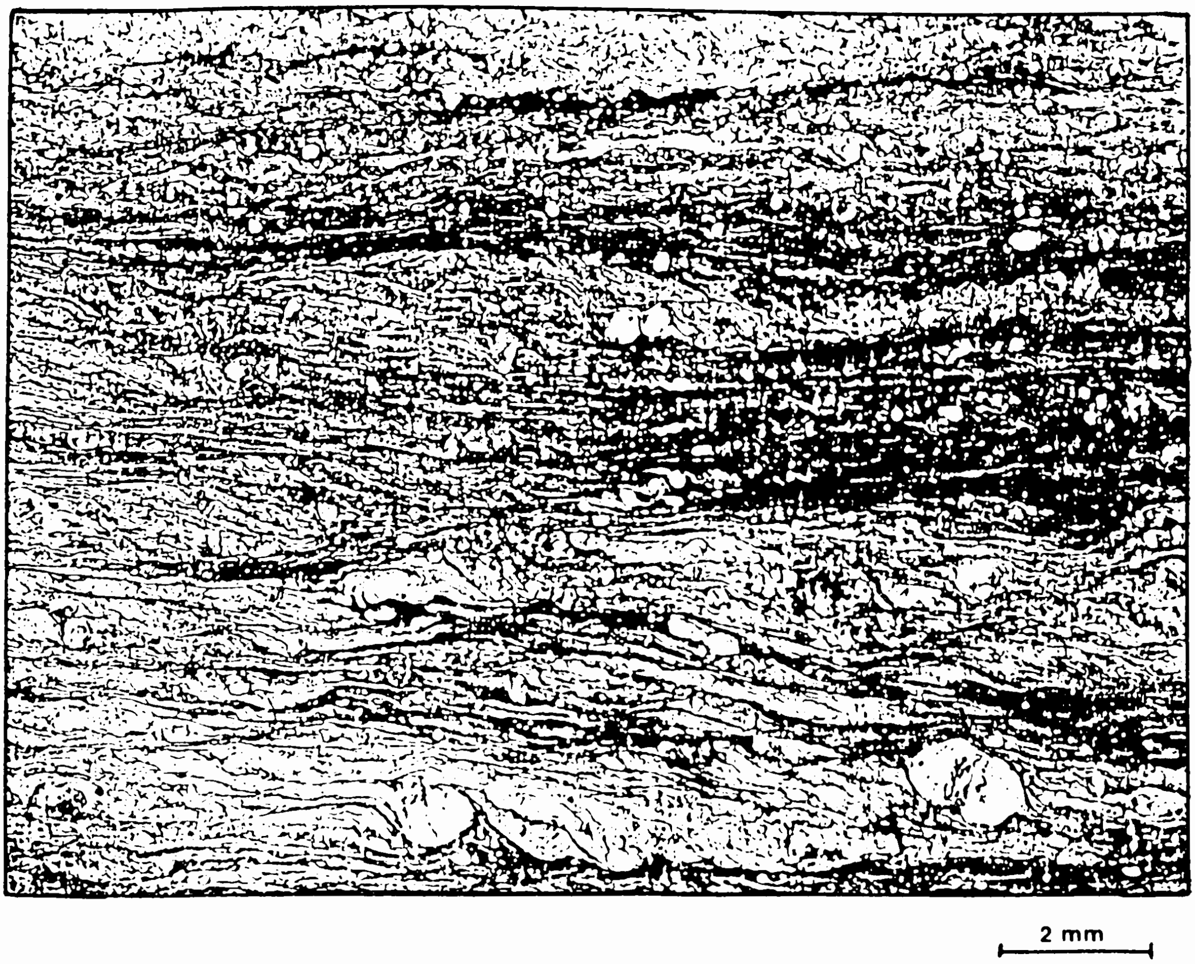


Figure 16. Microfiche copy of highly strained ribbons of quartz that wrap rounded shaped porphyroclasts, defining a mylonitic fabric. Sample # 187, cross-cutting dike in the Riddle Peaks pluton; fabric is perpendicular to foliation and parallel to lineation.

The Cardinal Peak pluton is a coarse- to fine-grained intermediate diorite (color index, 15-35), and contains 60-80% plagioclase (An 20-30); 20-35% hornblende; 1-5% chlorite; 0-2% quartz; +/- epidote and biotite; and accessory apatite, sphene, and opaques. Plagioclase occurs as idiomorphic to subidiomorphic medium-sized grains and laths with albite twins locally aligned parallel, defining a weak magmatic foliation (Figure 17). Plagioclase also occurs as small interstitial pods of recrystallized and deformed grains (Figure 17). Hornblende forms medium size subhedral grains and anhedral aggregates (Figure 17), locally with a poikiloblastic texture. Chlorite replaces biotite and hornblende and occurs as interstitial euhedral grains. Plagioclase is moderately to completely altered to fine-grained white mica in some samples.

The Cardinal Peak pluton is imprinted with a weakly to moderately developed tectonic foliation that is strongly developed at the contacts. Commonly, zones with a weaker fabric preserve magmatic flow fabrics. Figure 17 shows local recrystallized aggregates of fine-grained anhedral plagioclase and minor quartz. These fine-grained aggregates are superposed on moderately aligned euhedral-subhedral plagioclase laths defining the relict magmatic fabric.

The north-northwest striking foliation is strongly developed at the contacts and locally exhibits a subhorizontal stretching lineation. The stretching lineation is defined by augen-shaped plagioclase grains (Figure 18) offset by thin shears and wrapped by thin ribbons of biotite, chlorite, and minor recrystallized aggregates of plagioclase and quartz. The fabric in the pluton is parallel to or at a small angle to the pluton contacts. The pluton contacts are concordant with the regional schistosity in the

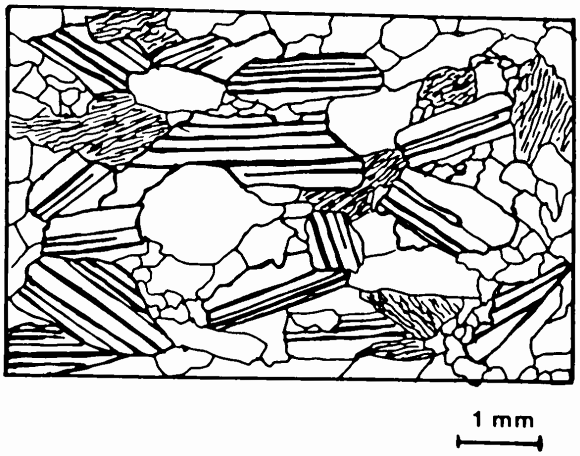


Figure 17. Medium-grained relict igneous plagioclase laths with albite and carlsbad twins moderately aligned showing weak magmatic flow fabric; minor pods of recrystallized quartz are interstitial. Sample # 12, from Cardinal Peak pluton; fabric is perpendicular to foliation.

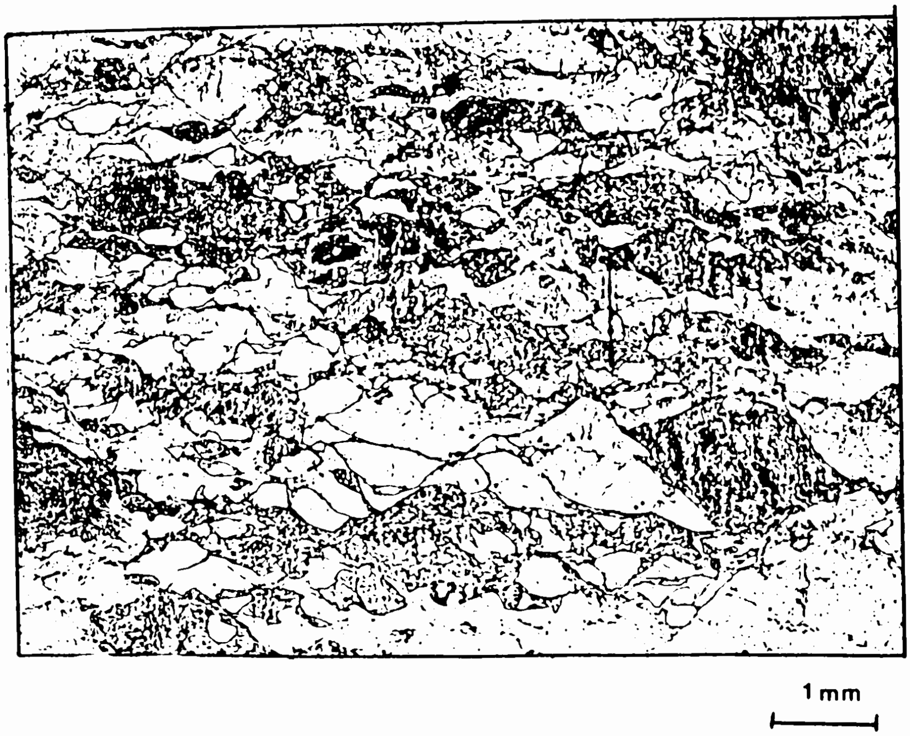


Figure 18. Microfiche copy of augen shaped plagioclase with asymmetric shapes separated by thin shears. Sample # 106, from the Cardinal Peak pluton; at the contact with Riddle Peaks pluton (see Appendix I for locality). Fabric is perpendicular to foliation and parallel to lineation.

country rock. Locally, large elongate screens of country rock within in the pluton are aligned parallel to the regional foliation. Figure 19 shows small xenoliths of country rock, and apophyses of the pluton aligned in a strong tectonic foliation at the contact zone (see Appendix I for locality) with the younger gneisses of Holden. Figure 20 shows large angular blocks of Cardinal Peak pluton which exhibit a well developed north-northwest striking tectonic foliation which is parallel to a moderately developed foliation within a later fine-grained tonalitic host.

The Cardinal Peak pluton shows 1) contacts parallel to the regional schistosity; 2) a foliation within the pluton commonly defined by solid-state recrystallization textures superposed on magmatic flow fabrics; and 3) xenoliths of country rock and which are also aligned parallel to the trend of the regional schistosity in the country rock. These relationships along with the strong fabric which occurs in agmatitic blocks indicate that intrusion of the Cardinal Peak pluton occurred in a ductily deforming environment. The fabric within the phase hosting agmatitic blocks of Cardinal Peak pluton shows that deformation was apparently long lived. Thus, the Cardinal Peak pluton appears to be syn- and pre-tectonic with respect to the deformation producing the regional schistosity.

Duncan Hill pluton-Contact Complex

The Duncan Hill pluton is an elongate northwest trending tadpole shaped body (Figure 4). It is interpreted to be a tilted diapir (Dellinger and Hopson, 1986), with the northwest-side tilted up about a northeast-southwest trending axis, the same as the

Figure 19. Outcrop photograph of strong tectonic foliation in Cardinal Peak pluton concordant with foliation in country rock; at contact zone of Cardinal Peak pluton and younger gneisses of Holden. Locality noted in Appendix I.

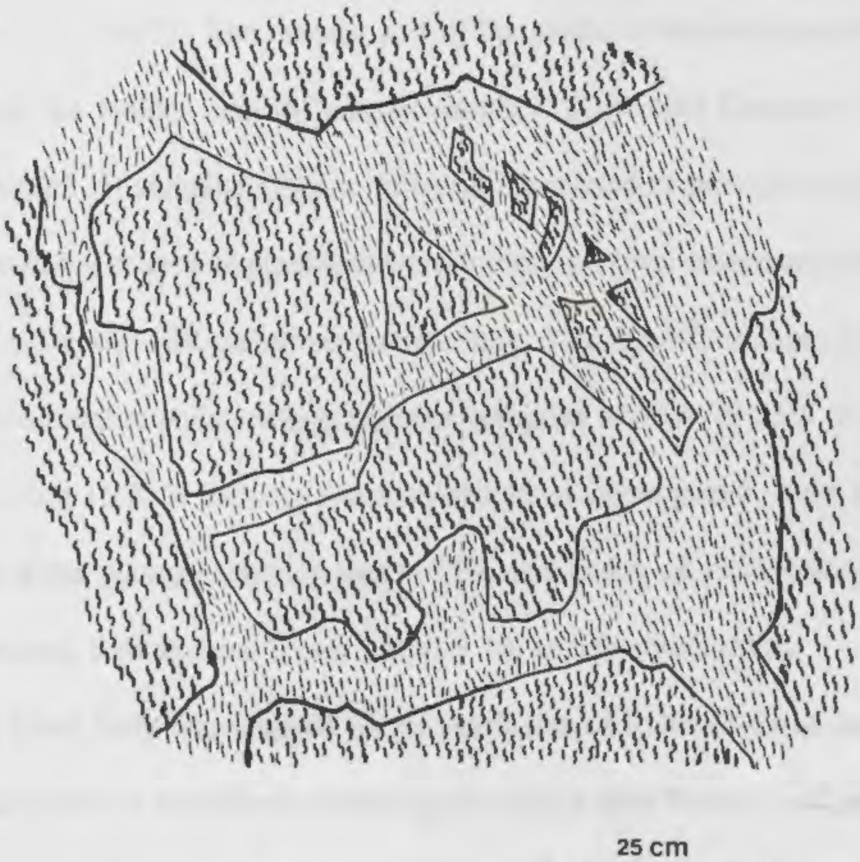


Figure 20. Large angular blocks of Cardinal Peak pluton that contain a strong tectonic fabric are intruded by a later fine-grained phase with a fabric of the same orientation. See Appendix I for locality.

Cardinal Peak pluton. K/Ar ages of 47 Ma from miarolitic granophyre at the top of the pluton which crops out in the Lucerne quadrangle, and 45 Ma from isotropic granodiorite in the middle of the pluton, are interpreted to indicate progressive stages of pluton emplacement (Dellinger and Hopson, 1986; Hopson, personal communication, 1991). The deepest part of the pluton contains migmatitic tonalite and crops out in the Holden area as "contact complex" (Cater and Crowder, 1967) and has not been dated. It contains a strong foliation interpreted as protoclastic by Hopson (1986), probably related to emplacement (Hopson, personal communication, 1991).

The Duncan Hill pluton contact complex (Cater, 1982) consists of two distinct fine-grained tonalite phases which together comprise roughly 75-85% of the map unit. The remaining 15-25% includes Dumbell Mountain augen gneiss, large screens and xenoliths of the younger gneissic rocks of Holden, and local cross-cutting, medium- to coarse-grained, light colored (color index, 5-10) trondhjemitic dikes.

A small body was mapped on the north side of Railroad Creek on the east side of the study area as hornblende-biotite-quartz diorite near Holden by Cater and Crowder (1967) (Plate 1). The composition and fabric of this phase are the same as that of the two main tonalitic phases of the Duncan Hill pluton contact complex and is therefore included in the following description.

The two tonalitic phases are: 1) a light- to medium-gray (color index, 5-15), fine- to medium-grained tonalite; and 2) a lighter gray (color index, 5), fine- to medium-grained tonalite. The darker of the two phases (1) is intruded by the lighter. Both phases have a common mineral assemblage that includes 60-65% plagioclase (An

25-40); 20-30% quartz; 15-20% biotite; minor muscovite, chlorite, hornblende; +/- epidote; and accessory sphene, apatite, and magnetite. In both phases, plagioclase occurs as medium-size subhedral-anhedral grains with normal compositional zoning, which exist in a fine-grained matrix of quartz and plagioclase (Figure 21). Biotite and chlorite occur as small grains within the fine-grained matrix. Epidote and sericite replace plagioclase in some samples.

Weakly to strongly developed foliation and sub-horizontal mineral and stretching lineation are present in both tonalitic phases and in later cross-cutting dikes (Figure 22). Stretching lineation is defined by small, elongate, deformed grains of plagioclase and quartz; mineral lineation is defined by small, aligned, subhedral grains of biotite (Figure 21). The orientation of the fabric is parallel to the regional foliation in the country rock and cuts across irregular contacts of the two tonalitic phases and contacts of cross-cutting dikes (Figure 22). Figure 22 also shows a ptygmatically folded vein with axial planes parallel to the cross-cutting foliation. These relationships indicate that, at the deepest level in the Duncan Hill pluton, protoclastic intrusion was accompanied by pervasive deformation that produced ductile, northwest-trending foliation with a subhorizontal lineation.

Holden Lake and Copper Peak plutons

Holden Lake pluton

The Holden Lake pluton is located in the northwest corner of the study area and intrudes the Triassic Dumbell Mountain pluton (Figure 5). The Holden Lake

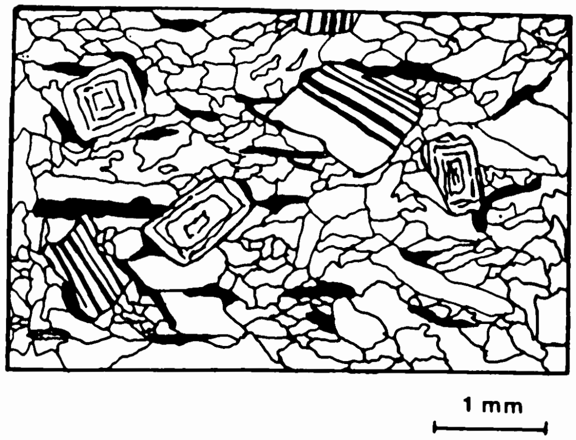


Figure 21. Small elongate grains of quartz and plagioclase in the matrix, along with aligned small grains of biotite (dark) define a strong fabric; relict igneous porphyroclasts show local augen shapes. Sample # 18, from Duncan Hill pluton contact complex; fabric is perpendicular to foliation and parallel to lineation.

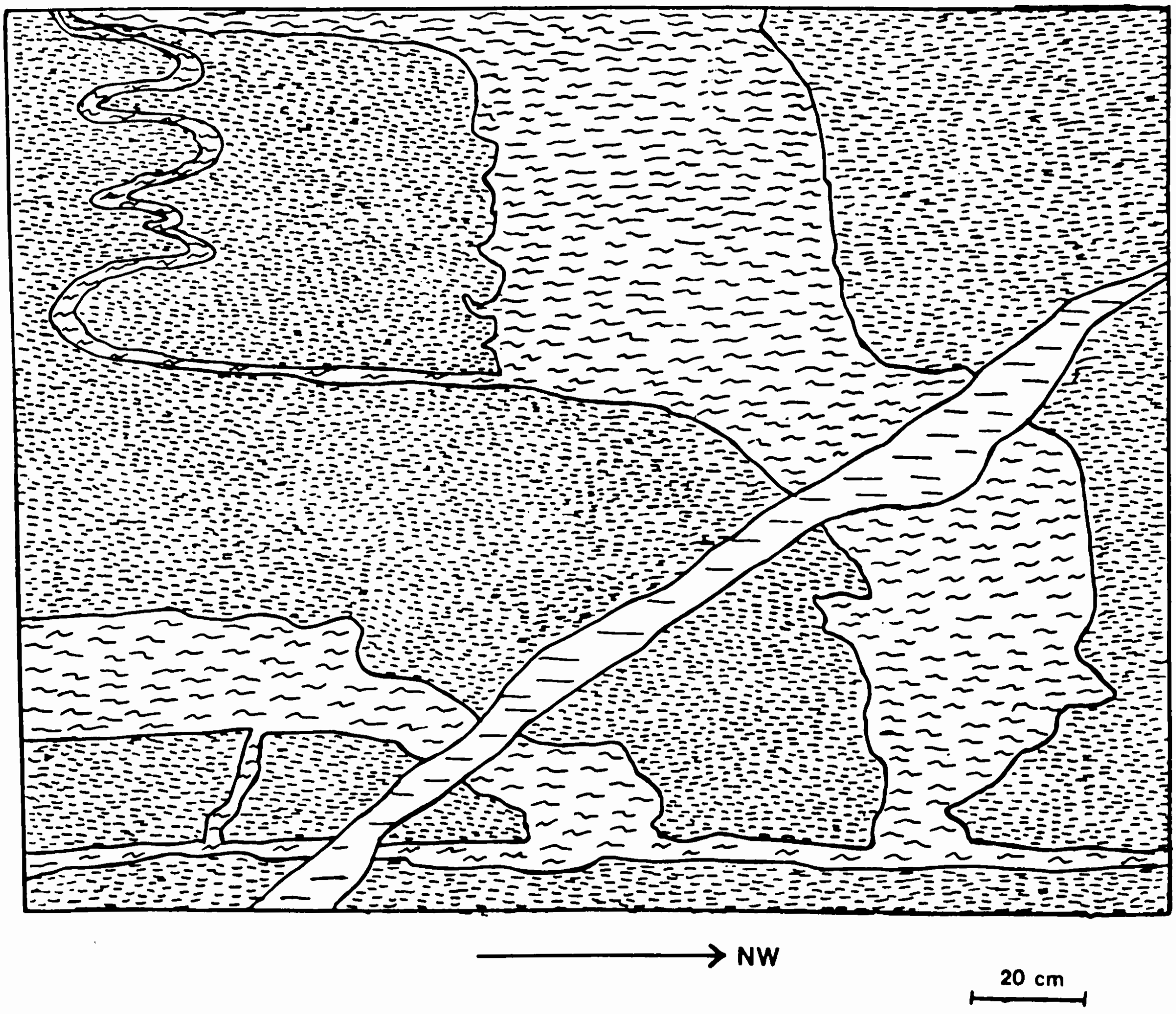


Figure 22. Sketch of cross-cutting tonalitic phases and later cross-cutting dikes in the Duncan Hill pluton Contact Complex (locality noted in Appendix I). All phases contain a weak- to moderately developed northwest trending foliation and lineation defined by fine-grained flakes of biotite. Ptygmatic fold in upper left corner indicates flattening associated with fabric development. Figure shows a plan view; base of figure trends northwest.

pluton is an intermediate color (color index, 15-25), medium-grained diorite. It contains 80-85% plagioclase (An 40-55); 15-25% hornblende; interstitial quartz; minor epidote and chlorite; and accessory magnetite. Hornblende commonly is altered to chlorite, and plagioclase to sericite. Plagioclase and hornblende form equigranular, euhedral-subhedral, medium- to coarse-grains and are predominantly non-aligned showing an igneous texture (Figure 23). Locally, in 3- to 8m-wide zones, long dimensions of hornblende and plagioclase laths are aligned parallel defining a flow foliation. Locally, at contacts of the Holden Lake pluton, xenoliths of country rock occur within massive diorite and contain a schistosity oriented at variable angles to the fabric in the country rock.

The igneous texture and unoriented xenoliths indicate that this pluton is post-tectonic.

Copper Peak pluton

The Copper Peak pluton is a small, northwest trending, elongate mass, which intrudes the younger gneissic rocks of Holden and the Duncan Hill pluton contact complex, just southeast of Railroad Creek (Figure 5).

The body is an unfoliated, medium- to coarse-grained, slightly altered diorite with an intermediate color index of 35-45. The main constituents are: 65% plagioclase (An 30-50); 30% hornblende; 5% quartz; minor cummingtonite, biotite, chlorite, and sericite; and accessory sphene, apatite, and magnetite. Plagioclase and hornblende occur as medium-sized, randomly oriented euhedral-subhedral grains with

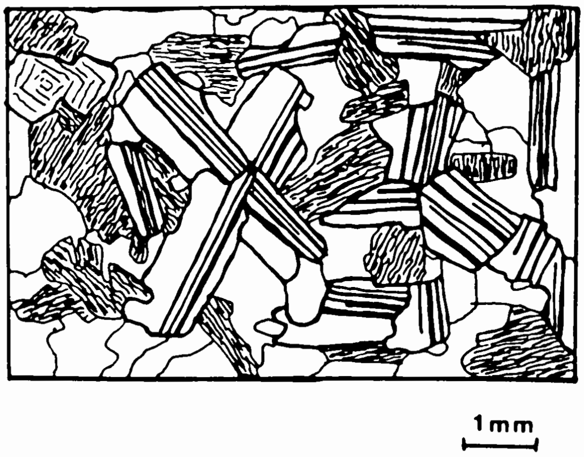


Figure 23. Euhedral plagioclase laths and hornblende grains randomly oriented in a primary igneous texture. Sample # 60, from Holden Lake pluton.

interstitial quartz; they define an undeformed igneous texture, similar to that of the Holden Lake pluton (Figure 23). Sericite strongly replaces plagioclase in all samples, and hornblende locally alters to chlorite.

Igneous textures in the Copper Peak pluton indicate that it is also post-tectonic.

Martin Ridge stock

Cater (1982) included a small elongate body which intrudes the younger gneissic rocks of Holden on Martin Ridge as part of the Holden Lake and Copper Peak plutons (Figure 5). Based on new observations of distinctly different fabrics I have informally separated the body and will refer to it as the Martin Ridge stock.

The body is a light (color index, 5-15), moderately to strongly lineated, fine- to medium-grained quartz diorite. The main phases are: 80% plagioclase (An 20-30); 10% biotite; 10% quartz; 1% cummingtonite; minor hornblende, chlorite, epidote, and sericite; and accessory sphene, apatite, zircon, and magnetite.

Plagioclase is commonly medium-grained and subhedral with normal compositional zoning (see texture in the Duncan Hill pluton; Figure 21). Biotite forms ellipsoidal aggregates of grains within fine-grained ribbon quartz texture and occurs as stringers of small grains that anastomose around plagioclase and hornblende (Figure 24). Chlorite, epidote, and sphene occur locally as small interstitial grains.

The body contains a weak foliation and strong, northwest trending, subhorizontal stretching lineation. The stretching lineation is defined by 1) pulled apart plagioclase laths, hornblende grains, and small acicular epidote grains (Figure

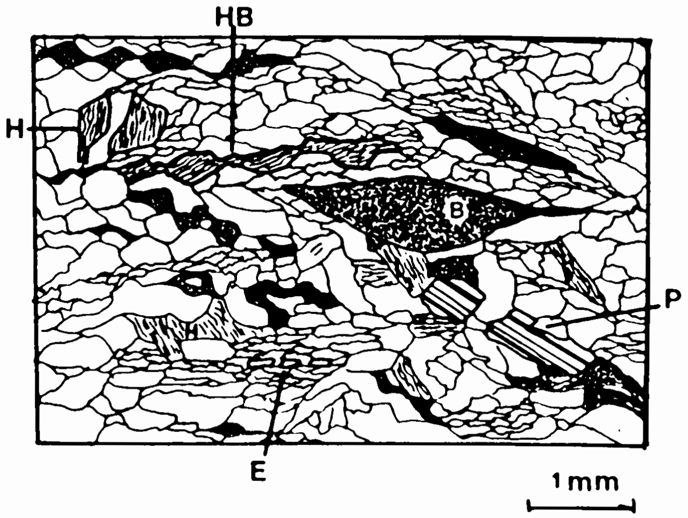


Figure 24. Stretching lineation defined by small epidote grain (E), plagioclase lath (P), and hornblende grain (H) are pulled apart with recrystallized quartz filling in between. Hornblende is also stretched showing small boudined necks (HB). Biotite (solid) is deformed into ellipsoidal aggregates commonly surrounded by small pods of fine-grained quartz with ribbon texture. Sample # 219, from Martin Ridge stock; fabric is perpendicular to foliation and parallel to lineation.

24); 2) deformed ellipsoidal aggregates of biotite (Figure 24); and 3) highly strained ribbons of quartz which wrap around biotite aggregates (Figure 24). The lineation is enhanced in outcrop by elongate xenoliths of country rock which contain a mineral lineation, defined by aligned biotite grains, parallel to the stretching lineation.

The Martin Ridge stock exhibits strong ductile and brittle deformational fabrics which indicate it was intruded before deformation had ended.

Summary of Pluton Age Relative to Deformation

The Dumbell Mountain and Riddle Peaks plutons appear pre-tectonic; Dumbell Mountain pluton (220 Ma) contains pervasive, solid-state recrystallization textures; Riddle Peaks pluton has a characteristic magmatic layering discordant to the regional foliation, and contains strongly lineated dikes that crosscut the magmatic foliation. The Seven Fingered Jack (broadly mid-Late Cretaceous), Cardinal Peak (73 Ma), Duncan Hill (approximately 47-45 Ma), and Martin Ridge (unknown age) plutons are at least in part - syn-tectonic. The Seven Fingered Jack pluton contains parallel magmatic and solid-state down-dip lineations. The Cardinal Peak pluton has field relations and recrystallized textures indicative of syn-tectonic intrusion. The contact complex of the Duncan Hill pluton contains a pervasive, through-going fabric that crosscuts several igneous phases and is parallel to the regional fabric in the country rock. The Martin Ridge stock contains elongate xenoliths of country rock and a well-developed mineral and stretching lineation, both aligned parallel to the regional fabric in the country rock. The Holden Lake and Copper Peak plutons (both of unknown age) are post-tectonic showing undeformed igneous textures, and randomly oriented xenoliths of foliated country rock.

STRUCTURAL ANALYSES AND IMPLICATIONS

Introduction

The structures in the Holden area are dominated by the presence of magmatic and tectonic foliations and mineral and stretching lineations. Orientations of these structures were recorded during detailed field mapping of the study area. Fabric distributions within the plutons and contact relationships were also mapped in detail to assess the nature and significance of lineations and foliations in the plutons. Thin section study was the basis for petrography, detailed fabric analysis, and analysis of microstructures for shear sense criteria. Apparent strain type was determined by finite strain measurements made on elliptical quartz aggregates in hand sample.

Two different styles of ductile deformation are recorded by two distinct orientations of lineation. One of the two styles is characterized by a steeply-plunging to down-dip lineation which occurs on an apparent flattening fabric. The other style is characterized by a shallow-plunging to subhorizontal lineation commonly associated with an apparent constrictional fabric. Locally, the flattened, down-dip fabric is observed in the field to be crosscut by the constrictional, subhorizontal lineation fabric.

Later, thin, mylonitic shears strike northeast and west-northwest cross-cutting the dominant northwest striking fabric. These later shears are presumably related to northeast trending brittle faults which offset map units in the study area. Finally, high-level basaltic dikes crosscut all other structures and trend north-northeast and east-northeast. These are probably related to Tertiary extension late in the structural history.

Significance of Lineation

Nicolas (1987) interprets both mineral and stretching lineations to align parallel with the principal X-axis of the strain ellipsoid during non-coaxial deformation. Escher and Watterson (1974) interpret stretching (and mineral) lineations, which are parallel to the principal X-direction, to be rotated parallel to the shear direction during increasing shear strain. Thus, at high strain, subhorizontal mineral and stretching lineation are interpreted to be nearly parallel to the transport direction of strike-slip shear deformation (Figure 25B). In the Holden area, mineral and stretching lineations are parallel to each other, commonly defining a lineation together. Mineral and stretching lineations occur as both down-dip and strike-parallel lineations within the same foliation plane. Down-dip lineation with a steep plunge is interpreted to have formed by sub-vertical extension associated with horizontal shortening (Figure 25A). The coincidence of both styles of lineation within a single foliation is not easily explained, but may be due to partitioning of oblique strain into simple shear and pure shear components.

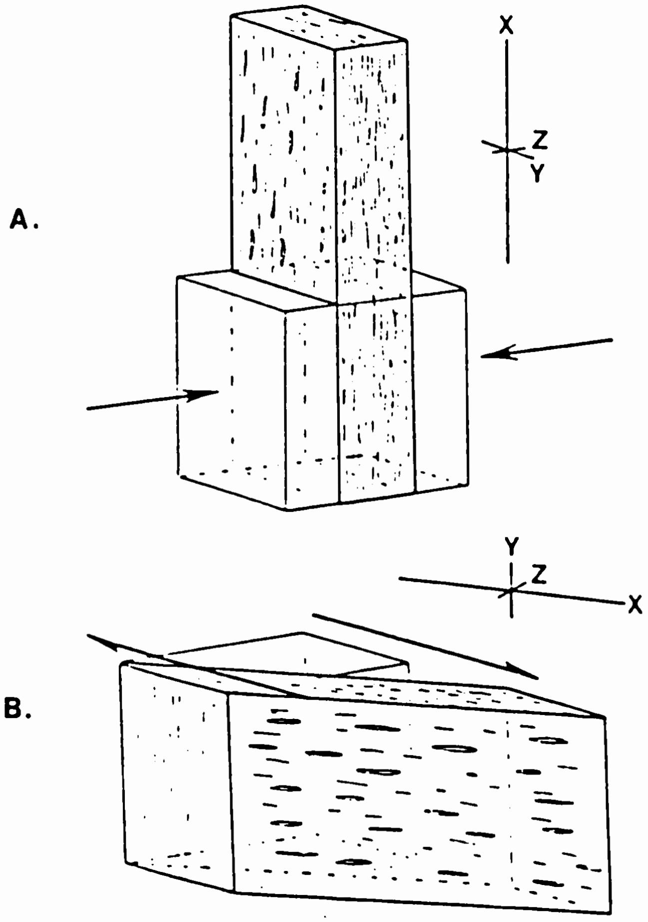


Figure 25. Kinematic models for observed fabrics. A) Pure shear, and B) simple shear. In A, X is vertical, and the lineation and foliation are both vertical. In B, X is horizontal, and the slip direction is at a low angle to X. The foliation is vertical and the lineation is horizontal; from Brown and Talbot (1989).

Geometry of Structures

Foliation and lineation data were subdivided into four subareas (Figures 26 and 27). Subarea one, comprised of the Riddle Peaks pluton and its contact zone with the Cardinal Peak pluton, was distinguished from two, three, and four on the basis of predominantly magmatic foliations observed in the Riddle Peaks pluton. Subarea two, which contains the younger gneisses of Holden and the Cardinal Peak pluton, was distinguished from three and four to isolate the well-defined character of foliation and lineation data in the metamorphic rocks. Subarea three contains the Dumbell Mountain and Seven Fingered Jack plutons; subarea four contains the Dumbell Mountain and Holden Lake plutons. Subarea three was distinguished from four based on the tight clustering of northwest trends of foliation and lineation data in three, and the greater degree of scatter and west-northwest trends of foliation and lineation in subarea four. Foliations that strike north-northwest and dip steeply to the southwest (Figure 26 inset) are the most pronounced fabric element in the study area and predominantly occur in subareas two and three (Figure 26). Subarea four (Figure 26) shows a greater scatter of foliation orientations, which dip roughly south-southwest. Subarea one (Figure 26) shows tectonic foliations within foliated dikes and cross-cutting mylonite zones which dip southwest, and magmatic foliations which dip northeast.

Throughout the study area the steeply-dipping foliation contains pervasive and well developed shallow-plunging to subhorizontal lineations, and steep to down-dip lineations preserved locally. The orientations of these lineations are plotted in Figure

Figure 26. Plots of poles to foliations for four subareas (described in the text) within the study area; inset is total foliations, n = 679; contour interval = 2%.

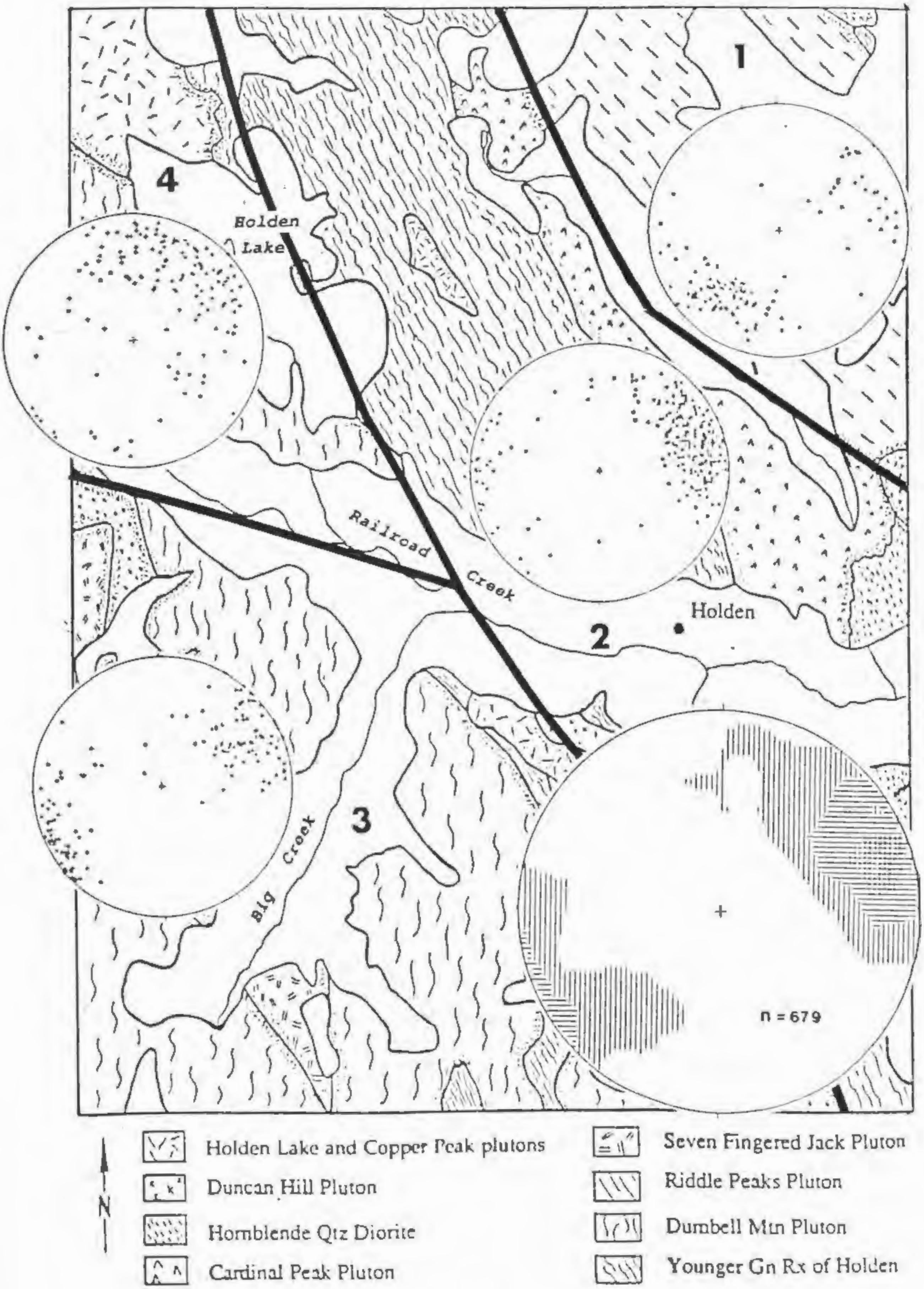
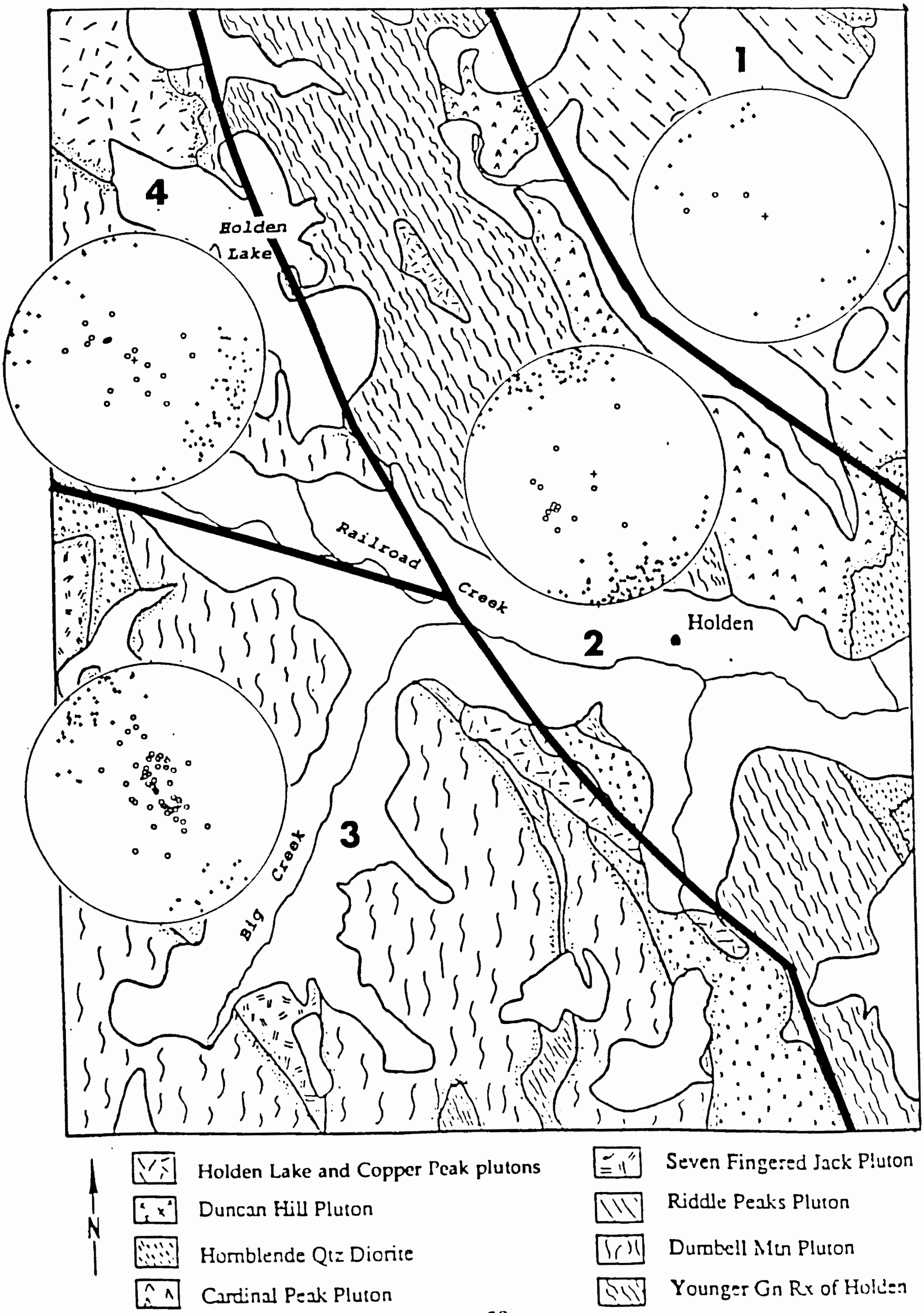

1
4
Holden
Lake
Railroad
Creek
Holden
2
3
Big
Creek
n = 679
N
Holden Lake and Copper Peak plutons
Duncan Hill Pluton
Hornblende Qtz Diorite
Cardinal Peak Pluton
Seven Fingered Jack Pluton
Riddle Peaks Pluton
Dumbell Mtn Pluton
Younger Gn Rx of Holden

Figure 27. Plots of stretching lineations for the four subareas. Lineations with high plunge were associated with a flattening fabric and are denoted by (o); lineations with low plunge were associated a constrictional fabric and are denoted by (+).


1
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Holden
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Creek
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3
Big
Creek
N
Holden Lake and Copper Peak plutons
Duncan Hill Pluton
Hornblende Qtz Diorite
Cardinal Peak Pluton
Seven Fingered Jack Pluton
Riddle Peaks Pluton
Dumbell Mtn Pluton
Younger Gn Rx of Holden

27 for the subareas defined above. Magmatic fabrics were distinguished from tectonic fabrics by field relationships, and confirmed in thin section by observations of igneous versus recrystallized and deformed textures. Rocks which contained a steep lineation were observed in the field to be associated with a flattened fabric and are denoted by circles in Figure 27, and rocks with a gently-plunging lineation were observed in the field to be associated with constricted or elongate fabrics and are denoted by plus signs. Analyses of strain and pitch of both the steep- and shallow-plunging lineations are addressed in following sections to further characterize the different orientations of lineation.

Lineations in subarea one (Figure 27) are minor. They occur primarily in mylonitized porphyritic dikes cross-cutting the Riddle Peaks pluton (Figure 16) and locally in the deformed contact zone of the Riddle Peaks and Cardinal Peak pluton. Subarea two (Figure 27) shows north-northwest trending subhorizontal lineations predominantly from the younger gneissic rocks of Holden and locally from the contact of the Cardinal Peak pluton. Locally, the younger gneissic rocks of Holden preserve steeply-plunging lineations. Subarea three (Figure 27) shows steep- to down-dip lineations, and shallow-plunging lineations trending northwest-southeast from within the Dumbell Mountain pluton. Subarea four (Figure 27) shows abundant east-southeast trending, shallow-plunging lineations with slightly variable northwest to southeast trends, and a moderate number of weakly clustered steep lineations.

Summary of Fabrics Defining Foliation and Lineation

Metamorphic Fabrics

The younger gneissic rocks of Holden are highly metamorphosed and deformed showing a strong layer-parallel foliation and mineral and stretching lineations. Steep and shallow lineations occur in the plane of foliation, parallel to compositional layering. The textures defining the lineations for the metamorphic rocks are described in the lithologic and fabric description section.

Plutonic fabrics

Magmatic flow foliations and tectonic foliations and lineations are observed in the plutons in the Holden area.

Primary magmatic flow fabrics are abundant in the Riddle Peaks pluton and occur locally in the Holden Lake, Seven Fingered Jack, and Cardinal Peak plutons (see Riddle Peaks pluton (Figure 15) for type magmatic flow texture).

Solid-state fabrics overprint magmatic flow fabrics in the Seven Fingered Jack pluton (Figure 14; text description on pages 29-31) and locally in the Cardinal Peak pluton (Figure 17; text description on page 36-37).

Tectonic fabrics resulting from solid-state flow without observable relict igneous flow fabrics are moderately to extremely well developed. These fabrics occur in the Dumbell Mountain pluton, locally in contact zones of the Cardinal Peak pluton, and in mylonitized dikes in the Riddle Peaks and Copper Peak pluton.

Moderately developed tectonic fabrics are characterized by thin zones of high strain between less deformed zones (Figure 28). Ribbons and augen of quartz show subgrain structures with patchy extinction and sutured grain boundaries (Figure 28). The highly strained zones exist within a medium-grained, sub-granoblastic matrix of quartz, plagioclase, and mafics. Quartz and plagioclase have rhombohedral and augen shapes that locally show preferred orientations (Figure 28) and reflect grain-size reduction and minor recrystallization of old grains.

Highly recrystallized and strained fabrics are characteristic in the Dumbell Mountain pluton (Figure 11; text description on pages 21-22).

Kinematic Indicators

Sense of shear indicators show evidence for dextral and sinistral shear for the shallow-plunging lineation. Vertical lineations show both southwest side up and northeast side up shear.

Vertical lineation occurs in the plane of a west-northwest striking, southwest-northeast - steeply-dipping foliation. Sense of shear indicators were observed in five samples which contain a steep stretching lineation; two are northeast-side-up and three are southwest-side-up senses of shear.

Fabrics with northeast-side-up directed shear exhibit S/C fabrics and occur on a flattened fabric within the Dumbell Mountain pluton. They are defined by small grains and aggregates of hornblende which wrap asymmetric deformed pods of quartz and plagioclase. The textures lack brittle microstructures and are ductile in nature.

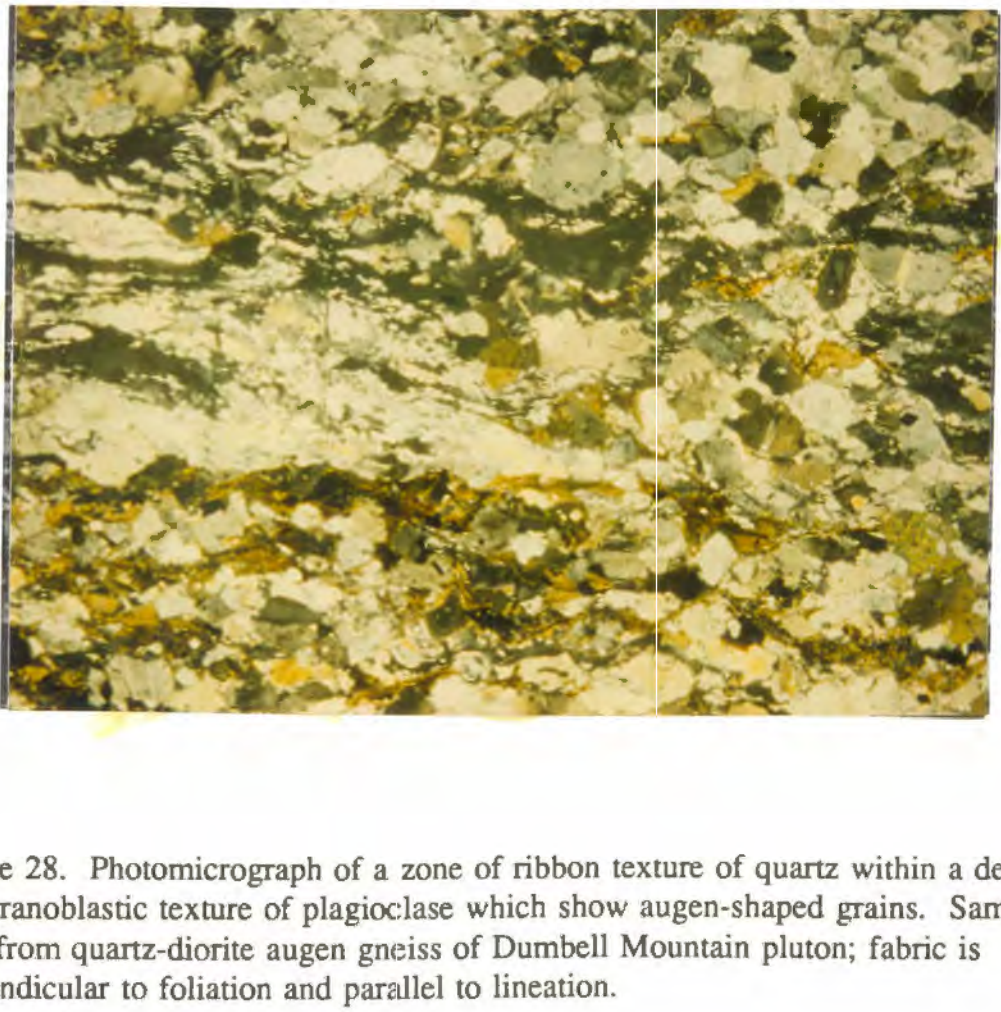


Figure 28. Photomicrograph of a zone of ribbon texture of quartz within a deformed sub-granoblastic texture of plagioclase which show augen-shaped grains. Sample # 227, from quartz-diorite augen gneiss of Dumbell Mountain pluton; fabric is perpendicular to foliation and parallel to lineation.

Features defining the southwest-side-up directed shear occur in rocks without an observable strain fabric. They are distinctly brittle in nature, as they are defined by unstable fractures which propagate randomly across plagioclase grains, and show razor sharp contacts between zones of cataclasite and undeformed igneous texture (Figure 29). These textures reflect deformation at brittle, shallow crustal conditions, probably late in the structural history.

Shallow-plunging to subhorizontal lineation occurs within a northwest striking, steeply southwest dipping foliation. Sense of shear was observed in 15 samples containing the shallow plunging lineation. Nine samples show sinistral shear and six show dextral.

Three of the 15 samples are from the younger gneissic rocks of Holden and show penetrative ductile deformation. Hornblende forms small, asymmetric, recrystallized grains which wrap sheared aggregates and pods of fine-grained quartz and plagioclase, and define S/C fabrics. These samples show dextral shear in two samples and sinistral in one.

The remaining 12 samples are from the Dumbell Mountain, Riddle Peaks, Seven Fingered Jack, Cardinal Peak, and Martin Ridge plutons. These twelve samples are characterized by evidence of ductile deformation close to the brittle-ductile transition (Mitra, 1984). This is evidenced by the presence of stable fracturing of plagioclase grains, where fractures die out in an individual grain (Figures 11, 24, and 30), and dissipate into plastic deformation at the fracture tip (Figure 11). Evidence for ductile deformation coeval with stable fracturing are highly strained quartz ribbons

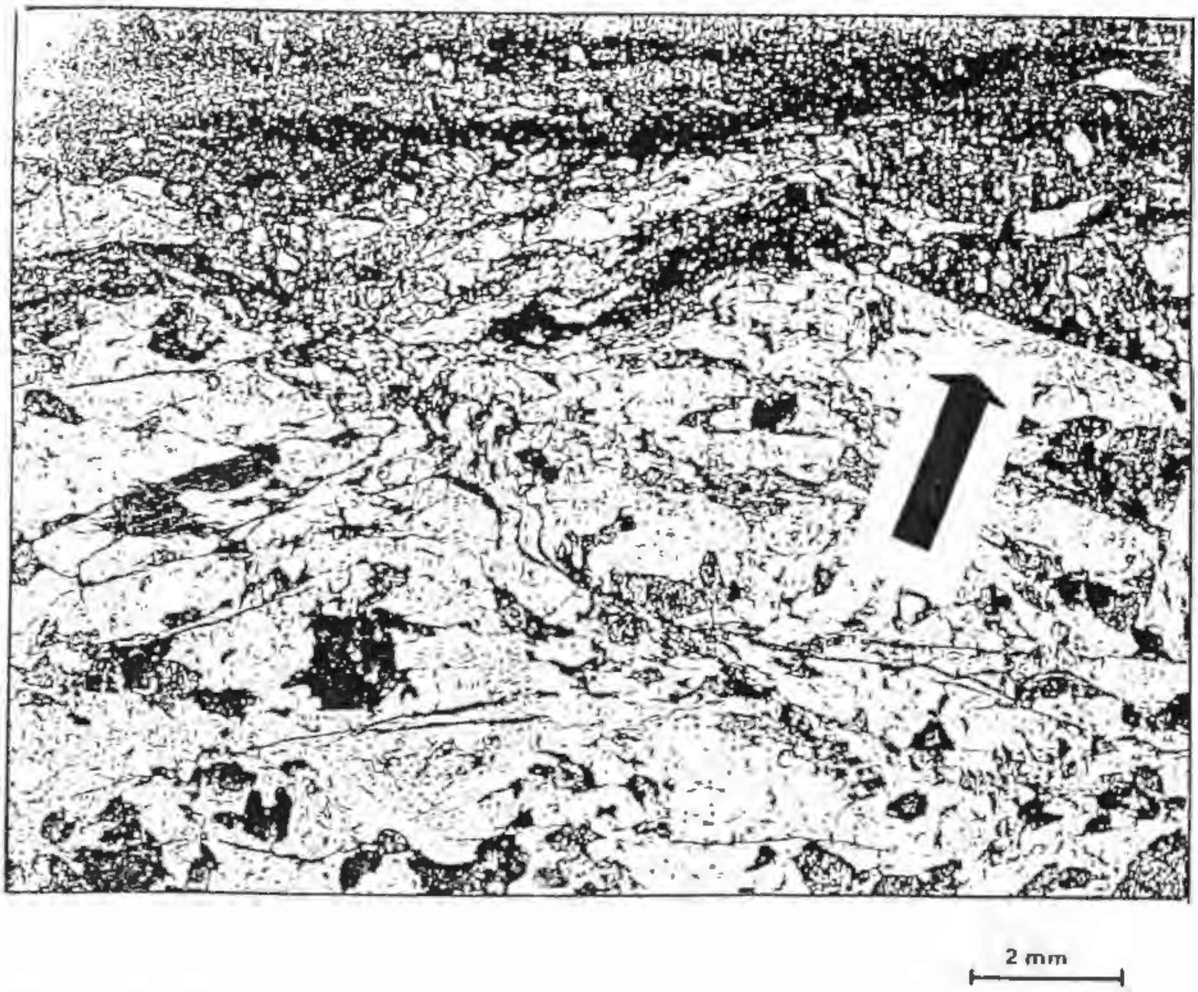


Figure 29. Brittle fractures and sharp contact zone (in front of arrow) of cataclasite in contact with igneous texture. Sample # 210, from Seven Fingered Jack pluton.

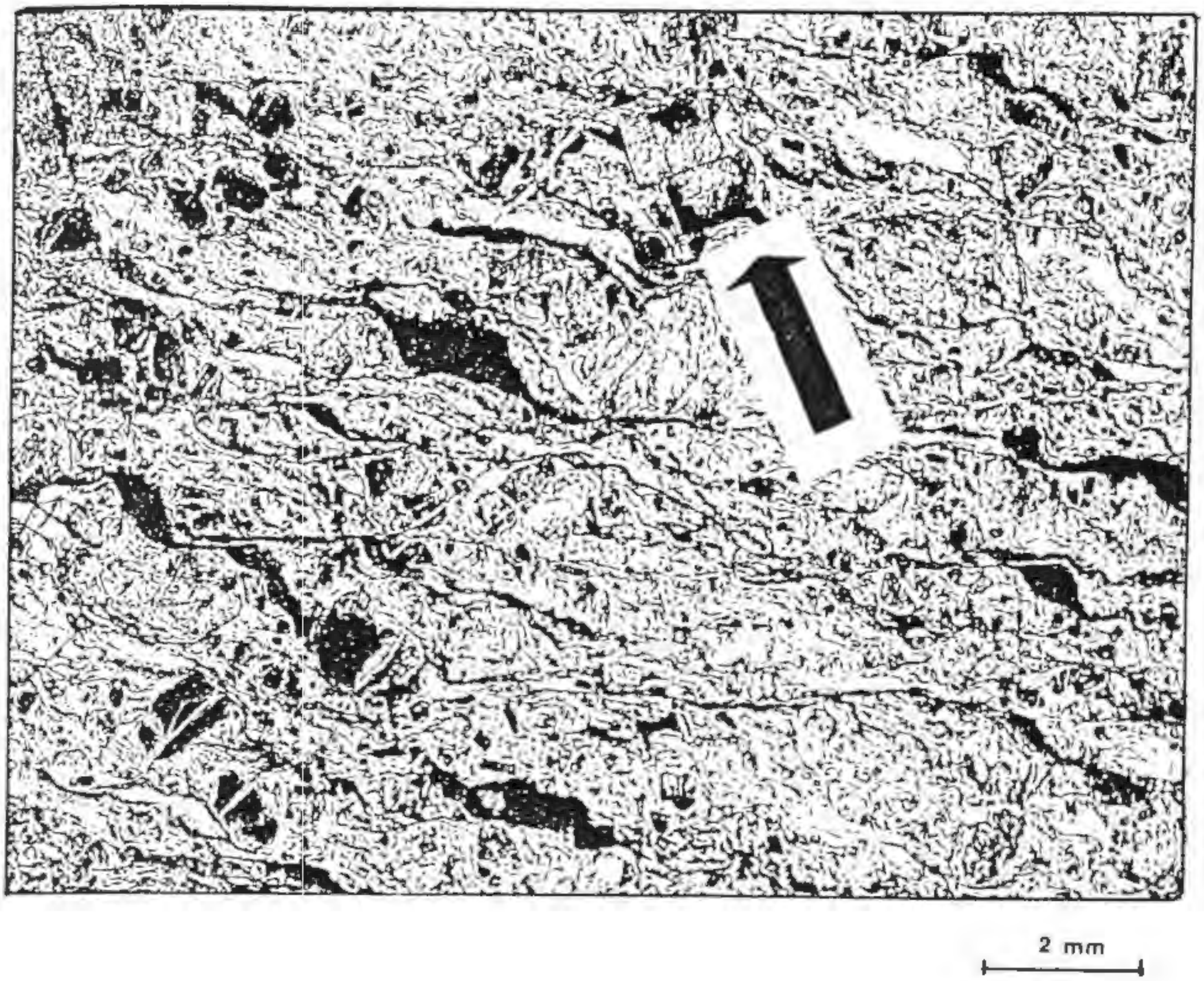


Figure 30. Hornblende forms asymmetric strongly sheared porphyroclasts which show distinct tails defining sinistral shear; locally, plagioclase is brittly fractured (in front of arrow). Sample # 86, from a dike cross-cutting the Riddle Peaks pluton; fabric is perpendicular to foliation and parallel to lineation.

with sutured grain boundaries (Figures 11 and 24), and recrystallized ribbons of hornblende (Figure 30) and biotite (Figure 24) which wrap around plagioclase porphyroclasts. Eight of the twelve samples show sinistral shear and four show dextral.

Thus, samples with a shallow-plunging lineation which lack brittle deformation structures show mixed senses of shear. Samples which show evidence for ductile deformation close to the brittle-ductile transition are dominantly sinistral by a ratio of two to one. Hence, sinistral strike-slip shear, with dextral shear active locally, may have been dominant in the Holden area as the orogen was uplifted to moderately high structural levels near the brittle-ductile transition.

Strain Intensity Patterns

Finite strain measurements were recorded on elliptical quartz aggregates from the Dumbell Mountain pluton (data are tabulated in Appendix II). Low strains can be measured with confidence on elliptical quartz clasts and aggregates from quartzites and quartz rich gneisses (Jain and Anand, 1988). Such analyses assume: 1) original, sub-spherical quartz grains approximated randomly oriented ellipsoids, and 2) original quartz grains had negligible ductility contrasts with the matrix during homogeneous strain. These assumptions are extrapolated to this study for measurement of high strains.

An indirect check of initial ellipticity would be the use of Rf-Phi[2] plots (Ramsay and Huber, 1983; Siddans, 1984). However, high strains in the study area (Rf values range from 6 to 15) make it difficult to distinguish initial spherical from elliptical grains and result in very small Phi angles. These small angles of Phi could not be determined to the degree of accuracy needed to detect an initial ellipticity on samples in the study area. Incorrect strain values could also result from strains measured in rocks with an initial, strong, flow fabric. However, relict magmatic flow fabrics were not observed in the Dumbell Mountain pluton although they may have been present at other localities. Moreover, the only undeformed locality observed in the Dumbell Mountain pluton contains randomly oriented plagioclase laths with aspect ratios of 3:1, and aggregates of fine-grained euhedral plagioclase and minor quartz with aspect ratios of 1:1. In light of the absence of certainty concerning the shape of the initial grains, strain values from the Dumbell Mountain pluton must be considered as maxima.

Figure 31 is a Flinn plot of the data; triangles were measured from rocks with a shallow-plunging to subhorizontal lineation and show fabrics with primarily apparent constrictional strain; squares were measured from rocks with a steeply-plunging lineation and show primarily apparent flattening strain. Figure 32 shows the two types of fabrics as observed in hand sample. At two localities, deformed dikes that contain a shallow-plunging, northwest-trending lineation crosscut a fabric which contains a

[2] Rf is the strain ratio of the grain, and Phi is the angle the long axis makes to the foliation.

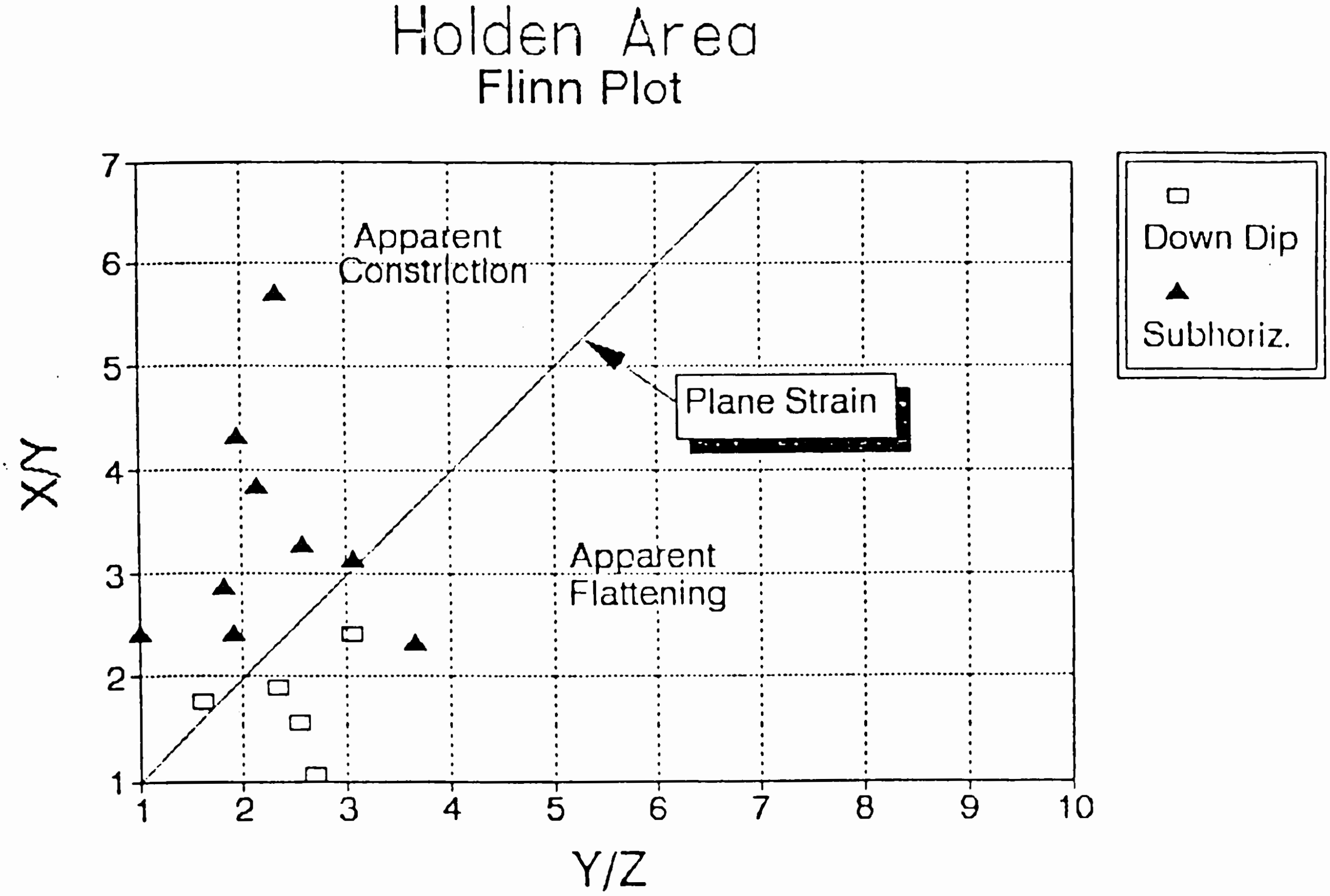


Figure 31. Flinn plot of strain data recorded in the Holden area. Solid triangles represent samples with a subhorizontal lineation; open rectangles represent samples with a down-dip lineation.

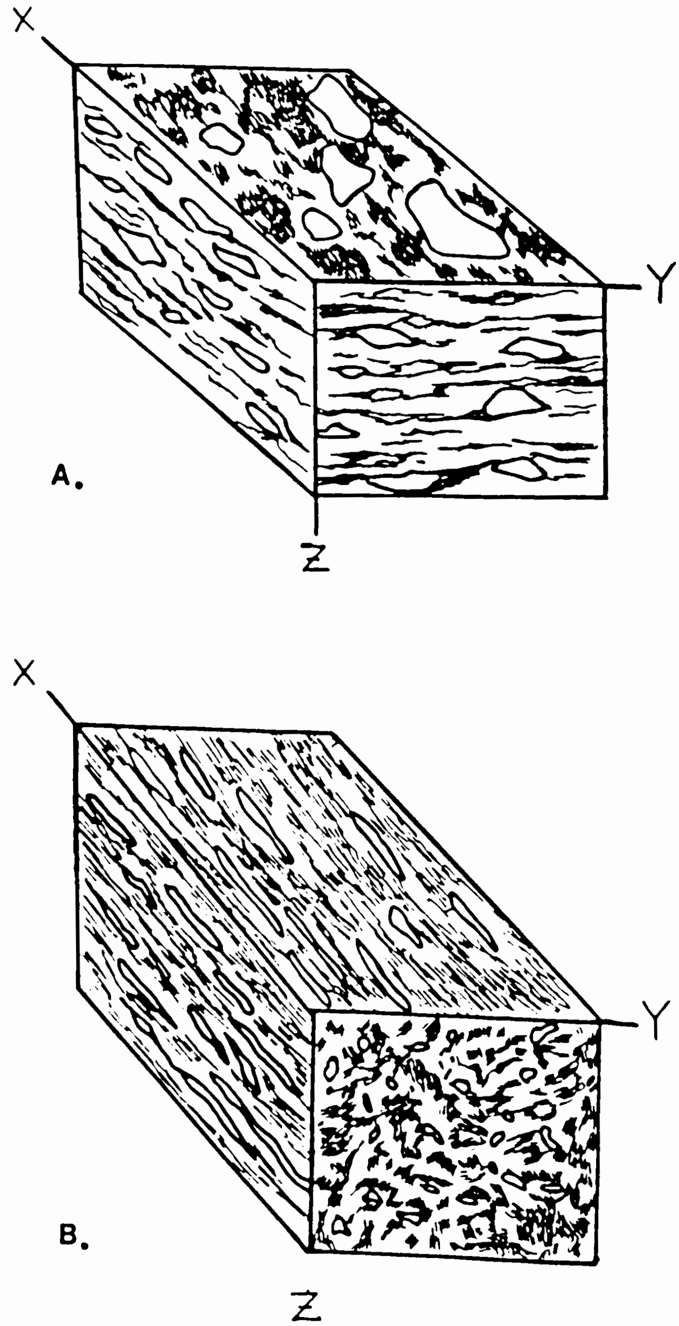


Figure 32. Sketches of: A) flattened fabric in the quartz-diorite augen gneiss showing elongation of 2-4:1 in XZ; 1.5-3:1 in YZ; and 1-2:1 in XY. B) constricted fabric in the hornblende-quartz-diorite gneiss showing elongation of 13:1 in XZ; 2:1 in YZ; and 10:1 in XY.

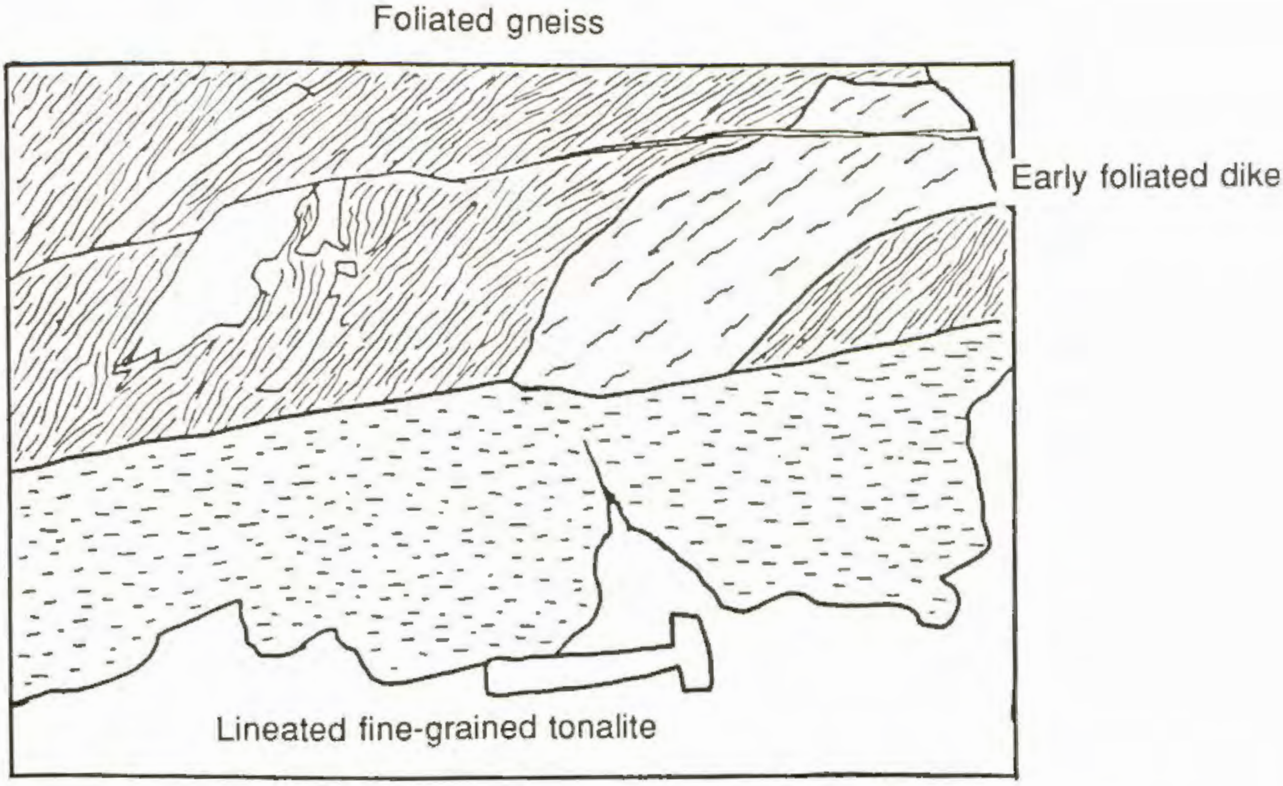


Figure 33. Outcrop photograph and sketch of strongly foliated gneiss that contains a steep lineation and is crosscut by fine-grained tonalite with a shallow-plunging, northwest-trending mineral lineation. Base of figure trends northwest.

steeply-plunging lineation (Figure 33). The steep fabric was not observed to crosscut the gently-plunging fabric in the study area, although this may be the case at other localities as there are no absolute age constraints assignable to the fabrics. Also, both fabrics do occur within the same foliation plane in the Dumbell Mountain pluton, at separate localities.

Analysis of Lineation Pitch

The plunge of a lineation will be affected by later folding of the foliation, so the pitch of the lineation, the orientation of the lineation within the foliation, will give a clearer picture of differences between the lineations which occur with flattened and constricted fabrics. Figure 34 shows the number of occurrences of pitches within a 10° interval, for nine, 10° intervals. The plot shows two distinct orientations of pitch. Lineations with low plunge (stippled) have consistently shallow pitches mainly between 0 and 30°'s. Lineations with a steep plunge (solid) show consistently steep pitches, dominantly between 70 and 90°'s.

Summary

The northwest-striking and steeply-dipping foliation characteristic of the study area is defined by compositional layering in the metamorphic rocks and by weak to strong tectonic and magmatic foliations in the plutons. A local, northeast-dipping foliation is defined by an igneous flow fabric in the Riddle Peaks pluton. Tectonic fabrics weakly to moderately overprint early flow fabrics in some of the plutons.

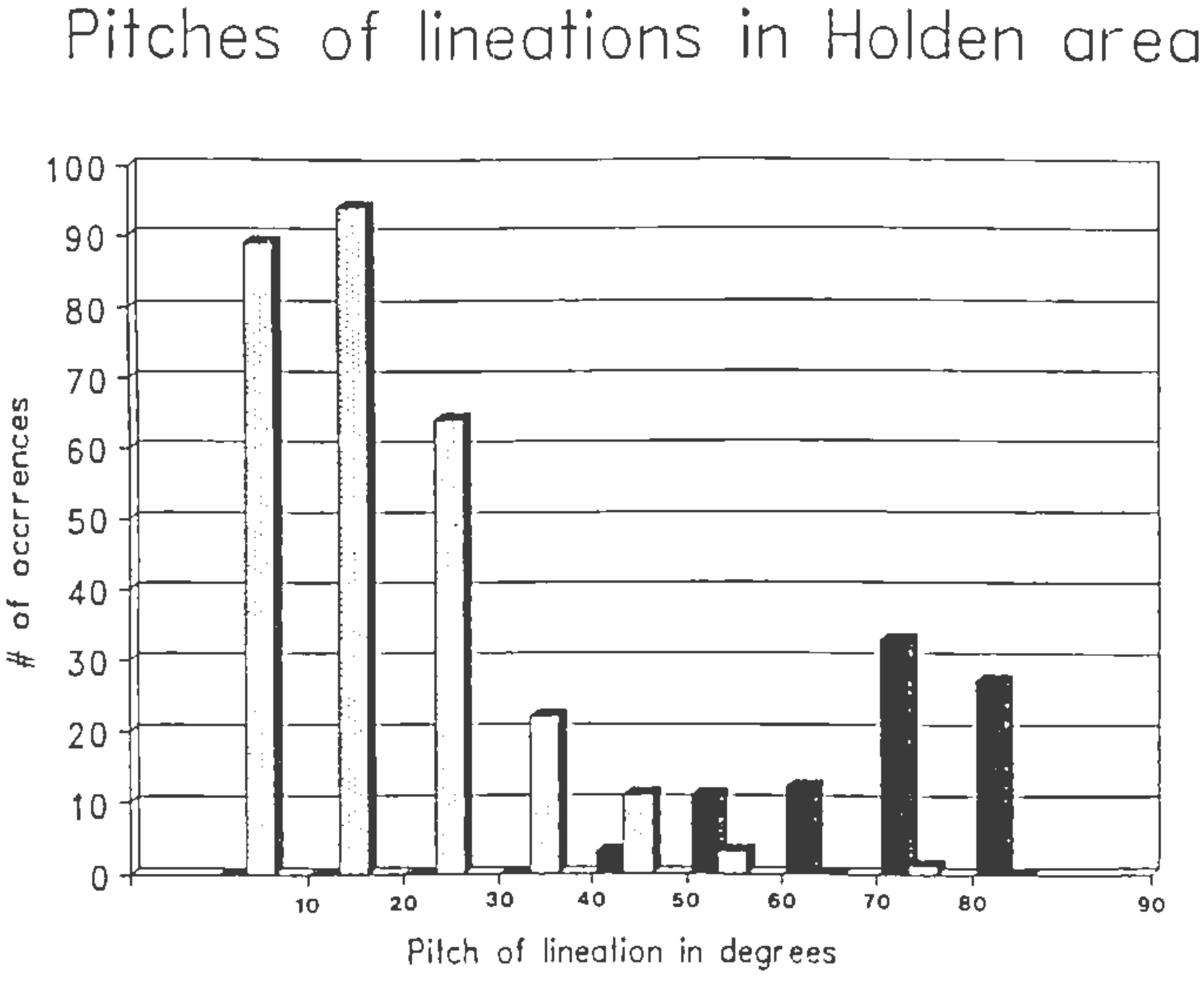


Figure 34. Occurrence plot of pitch of lineation (stippled bars represent lineations with low plunge; solid bars represent lineations with high plunge). Nine 10° intervals are on the X-axis; and the number of lineations with pitches in each of the nine intervals is on the Y-axis.

Tectonic fabrics are pervasive and strongly developed in the Dumbell Mountain pluton and show both flattening and constrictional types of strain. An apparent flattening fabric with steeply-dipping to down-dip mineral and stretching lineations is locally crosscut in the field by the constrictional fabric which contains subhorizontal, strike-parallel mineral and stretching lineations.

The steeply-dipping fabric shows northeast-side-up directed shear, defined by ductile microstructures, and southwest-side-up directed shear, defined by unstable brittle microstructures. The latter were presumably formed after uplift into the brittle zone. Three of the 15 samples with subhorizontal ductile S/C fabrics show mixed senses of shear. The remaining 12 samples are defined by structures evident of ductile deformation near the brittle-ductile transition and dominantly show sinistral shear. The latter suggest shear deformation continued as the orogen was uplifted to structural levels near the brittle-ductile transition (Mitra, 1984).

The different types of strain and distinctly different pitches of the two orientations of lineation plunge, are related to two different deformational styles. One is dominated by apparent flattening which produced steeply-plunging lineations; and the other is associated with constriction, producing subhorizontal strike-parallel lineations.

METAMORPHISM

Introduction

Metamorphic mineral assemblages and geobarometry indicate lower amphibolite facies metamorphic conditions were reached in the Holden area and were later overprinted by a pervasive greenschist facies episode.

Mineral Assemblages

Intermediate amphibolites and orthogneiss are the dominant lithologies in the Holden area. Select samples from the younger gneisses of Holden and the Dumbell Mountain pluton contain diagnostic mineral assemblages. The primary metamorphic assemblage includes 10-40% quartz; 40-70% oligoclase +/- albite; 5-50% hornblende; +/- almandine and biotite, and indicates amphibolite facies metamorphic conditions. The paucity of index minerals in the metamorphic units is due to the bulk composition of protoliths, and limits pressure and temperature constraints for the study area. See Appendix III for complete list of mineral assemblages.

The boundary between the greenschist and amphibolite facies is commonly drawn where actinolite + albite + epidote react to hornblende + oligoclase. This transition is complicated by the existence of a peristerite gap between albite and oligoclase and immiscibility of actinolite and hornblende (Maryuama and others, 1982; Maryuama and others, 1983).

Mineral assemblages containing hornblende and oligoclase indicate amphibolite facies conditions and constrain temperature to approximately 500° C or above (Maryuama and others, 1983) (Figure 35). Pressure cannot be constrained by mineral assemblages in metamorphic rocks within the study area. Metamorphism was in part coeval with both deformational styles, as both steep and shallow lineations are defined by aligned elongate prisms of hornblende in a fine-grained granoblastic matrix of oligoclase and quartz, and by local pre- and syn-tectonic garnet porphyroblasts.

A greenschist facies metamorphic overprint occurs in the study area. A few samples contain euhedral chlorite + epidote +/- albite and suggest temperatures below the albite - oligoclase transition (Figure 35). Deformation was also active during this lower grade episode, as chlorite occurs as fine- to medium- euhedral-subhedral grains commonly defining the shallow-plunging lineation and defining the steeply-plunging lineation locally. Chlorite is also retrogressive in some localities, as it occurs as an alteration product of hornblende, biotite, and garnet, and is commonly associated with sericitization of plagioclase.

Geobarometry

Pressure of crystallization of a pluton of known age, combined with a detailed fabric analysis can help relate the depth of deformational processes in part of an orogen to the age in which the processes were active. However, most plutons in the Holden area are of unknown age, lack the buffering assemblage for hornblende barometry, or lack primary igneous textures. The Seven Fingered Jack pluton was

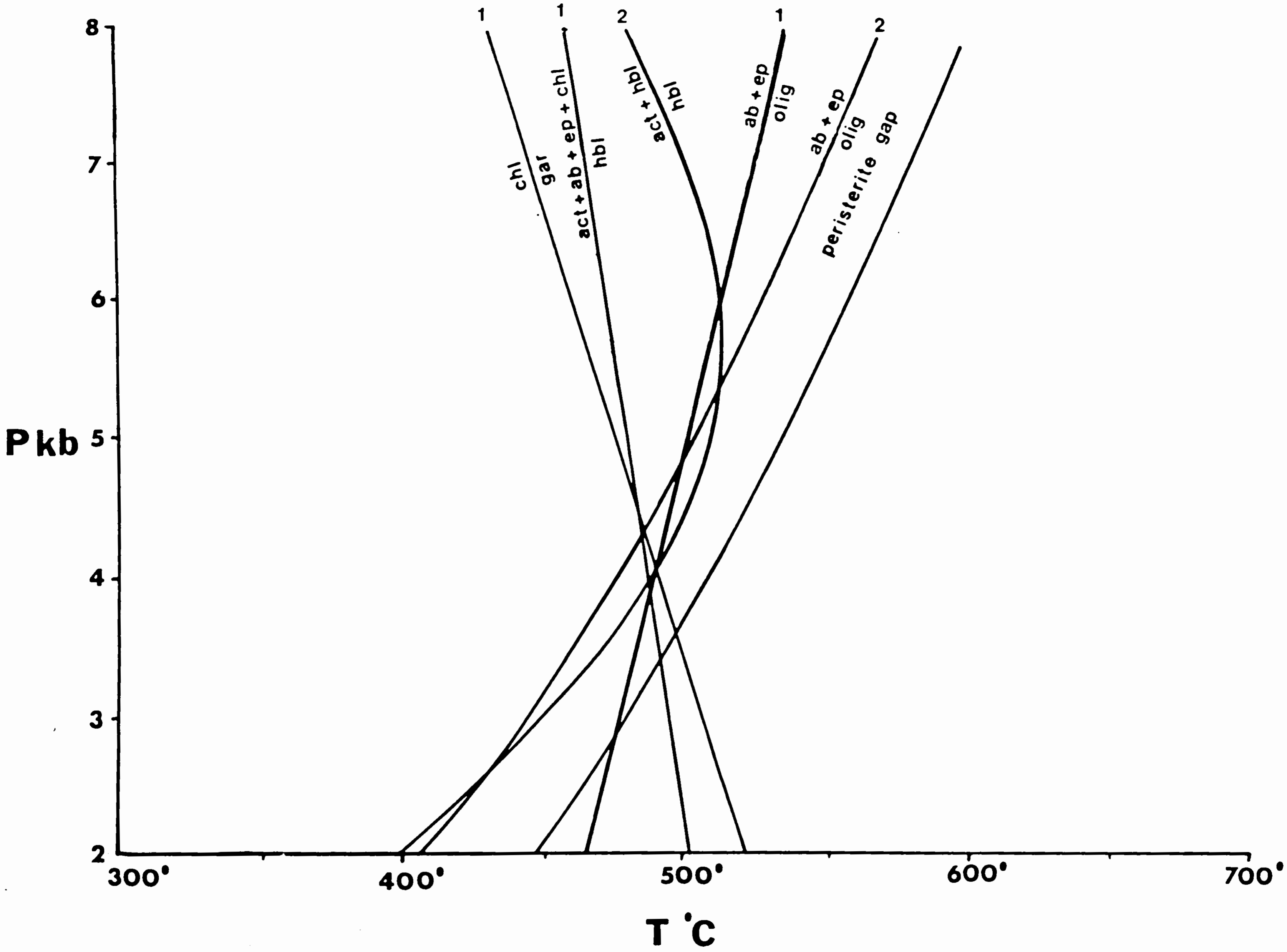


Figure 35. Petrogenetic grid with reaction lines separating the higher grade hornblende + oligoclase field from the lower grade chlorite + albite field; 1 = Brown (1978), 2 = Maryuama and others (1983).

chosen for geobarometric analysis because it is of known age, contains the hornblende buffering assemblage, excluding K-feldspar, and contains important plutonic and metamorphic fabric relationships.

Three samples from the Seven Fingered Jack pluton were analyzed for total Al content of magmatic hornblende. An absence of K-feldspar could result in an increase in the tschermakite (Al) component of hornblende for a given pressure as governed by the pressure sensitive reaction: 2 Quartz + 2 Oligoclase + Biotite = Tschermakite + Orthoclase (Hammarstrom and Zen, 1986). Thus, the aluminum-in-hornblende data shown in Table 1 can only be used to infer a maximum pressure of crystallization. The pressure determined is 4-5 kb maximum. This result is consistent with 5 kb pressures determined on the Seven Fingered Jack pluton from hornblende composition, to the south by Dawes (personal communication, 1991).

Table 1 Summary of pressure estimates from three samples of the Seven Fingered Jack pluton using the hornblende barometer. Refer to Appendix IV for microprobe data.

Sample Number	170-200	170-204	170-211
Avg. Total Aluminum *	1.94	1.82	1.90
Pressure (+\- .5 kb) ++	4.73	4.24	4.58

* E.H. Brown analyst
++ Calibration of Johnson and Rutherford (1989)

Summary

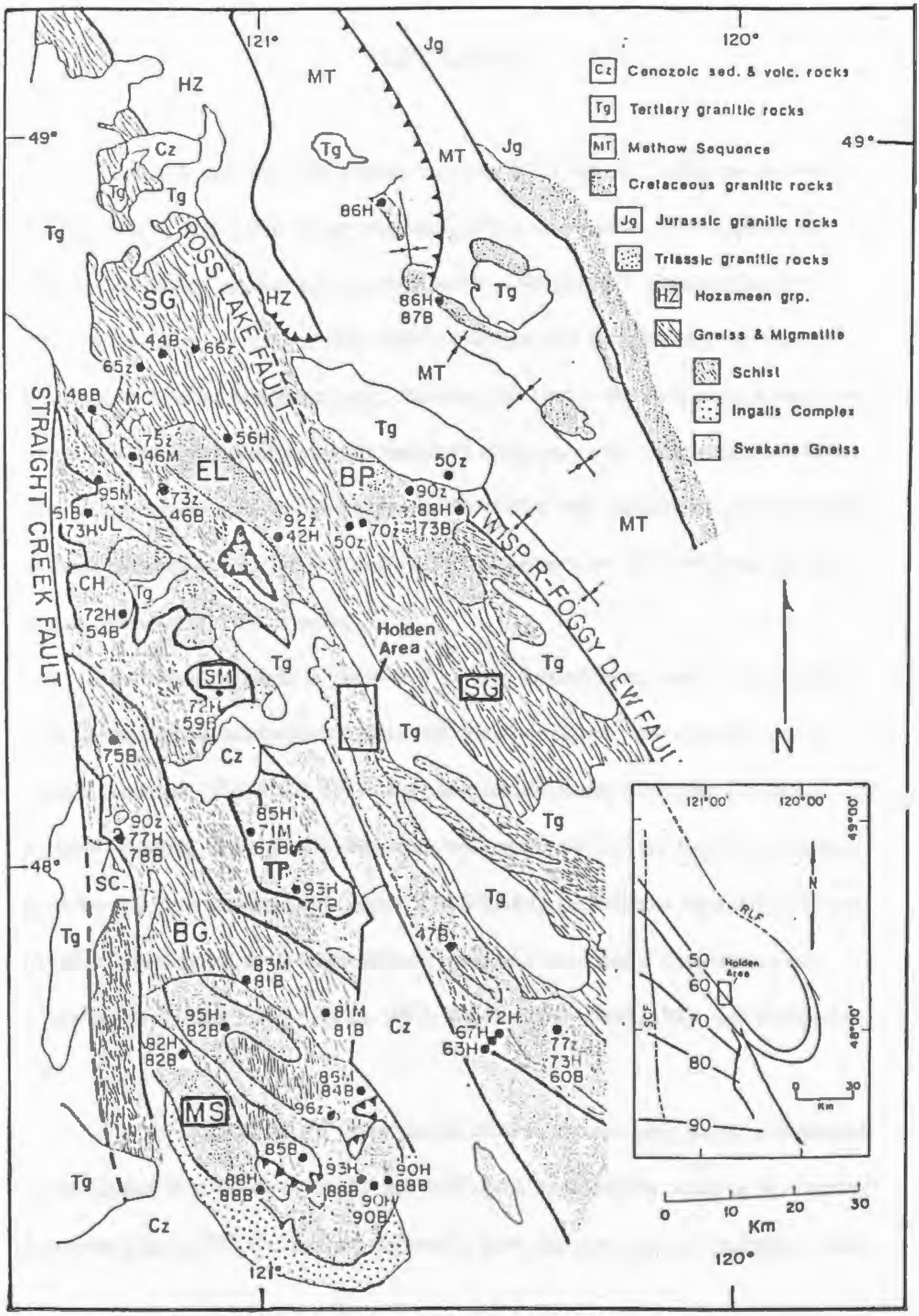
Metamorphic mineral assemblages indicate pressures and temperatures which suggest lower amphibolite facies metamorphic conditions existed in the Holden area. An abundance of alteration textures and greenschist facies phases indicate superposition of a lower grade metamorphic episode.

Age of Metamorphism

Amphibolite facies assemblages define solid-state fabrics in the Dumbell Mountain pluton which are post-intrusive and indicate medium- to high-grade metamorphism after 220 Ma. The Cardinal Peak (73 Ma) pluton contains metamorphic fabrics which define foliation parallel to weak magmatic foliation and indicate metamorphism active at 73 Ma. The Seven Fingered Jack pluton crystallized under pressures of 4-5 Kb and is interpreted as pre- to syn-tectonic. The age of this pluton is unknown although it could be mid-Late Cretaceous, having been broadly correlated to the 85-75 Ma Entiat pluton on strike to the southeast (Cater, 1982; and Dawes, personal communication, 1991). Local greenschist facies assemblages, retrogressive textures, and ductile fabrics formed near the brittle-ductile transition, in the deep portion of the Duncan Hill pluton, indicate lower grade metamorphic conditions probably younger than 45 Ma, as this age is the youngest available date on the Duncan Hill pluton and is a cooling age from the middle of the pluton.

Medium- to high-grade assemblages define Late Cretaceous fabrics, and low grade assemblages define Eocene fabrics, in the plutons of the Holden area. These data are consistent with a gradual younging of K/Ar cooling ages on biotite and hornblende, from 85-90 Ma in the Mt. Stuart area (MS), in the southwest part of the Crystalline Core (Figure 36), to 45-50 Ma in the Skagit Gneiss (SG), to the northeast (Figure 36, inset) (Brown and Talbot, 1989).

Figure 36. Simplified geologic map of the Crystalline Core showing the location of the Holden area with respect to the Sulphur Mountain (SM), Mount Stuart (MS), and the Skagit Gneiss (SG) areas. Inset shows gradual younging of metamorphic cooling ages on biotite and hornblende form the Mount Stuart area northeast to the Skagit Gneiss, taken from data on the above map. Modified from Brown and Talbot (1989).


Cz Cenozoic sed. & volc. rocks
Tg Tertiary granitic rocks
MT Methow Sequence
Cretaceous granitic rocks
Jg Jurassic granitic rocks
Triassic granitic rocks
HZ Hozameen grp.
Gneiss & Migmatite
Schist
Ingalls Complex
Swakane Gneiss
ROSS LAKE FAULT
STRAIGHT CREEK FAULT
TWISP R-FOGGY DEW FAULT
Holden Area
N
Km
121°
120°
49°
48°

DISCUSSION

The study area contains granitoid plutons from Triassic to Eocene age which intrude metavolcanic rocks of the younger gneisses of Holden. These plutons are affected to varying degrees by two main styles of deformation characterized by distinctly different structures. One style is characterized by flattening fabrics with a pronounced foliation and dominantly down-dip lineations; the other style is represented by shallow-plunging, strike-parallel lineations commonly with a constrictional fabric. The two structural styles are developed in the plutons and are parallel to the structures in the metamorphic rocks, thus Cater's (1982) interpretation of the plutonic fabrics as strictly "protoclastic" are incorrect.

The flattening fabric is interpreted to have formed in response to contraction with flattening in a southwest-northeast horizontal direction, with concomitant sub-vertical extension (Figure 25) producing steep foliations and down-dip lineations. The shallow-plunging, strike-parallel lineations are interpreted to have formed in response to strike-slip shear deformation (Figure 25), a finding inconsistent with the collisional model which requires southwest-northeast directed contractional deformation (as interpreted by Brandon and Cowan, 1985; Brandon and others, 1988; and McGroder, 1991).

The age relations of the two styles of deformation are very poorly constrained in the Holden area. Both down-dip and strike-parallel lineations occur in the Dumbell Mountain pluton (220 Ma) and are defined by post-intrusive, syn-metamorphic fabrics.

Hence, contractional and strike-parallel shear styles of deformation were active during medium- to high-grade metamorphism in the Holden area at some time after 220 Ma. The Seven Fingered Jack pluton contains steep, down-dip, magmatic and syn-tectonic lineations interpreted to indicate contractional deformation during late stages of intrusion. The age of the Seven Fingered Jack pluton is unknown, although, it has been correlated with the Entiat pluton (85-75 Ma) by both Cater (1982) and Dawes (personal communication, 1991). Syn-tectonic intrusion for the Cardinal Peak pluton (73 Ma) indicates deformation active at 73 Ma. The style of deformation at this time is inconclusive in the Cardinal Peak pluton as syn-tectonic lineations were not clearly defined. Strike-slip shear deformation is syn-intrusive in the deepest part of the Duncan Hill pluton evidenced by subhorizontal mineral and stretching lineations which crosscut contacts of several intrusive phases. However, the pluton is undeformed in its uppermost shallowest levels, which are interpreted to have been quenched from 47-45 Ma (Dellinger and Hopson, 1986). Detailed interpretation of the evolution of the Duncan Hill pluton is beyond the scope of this study, although it may be that deformation continued in the deeper more ductile reaches of the diapir after primary crystallization of the cooler, more resistant head.

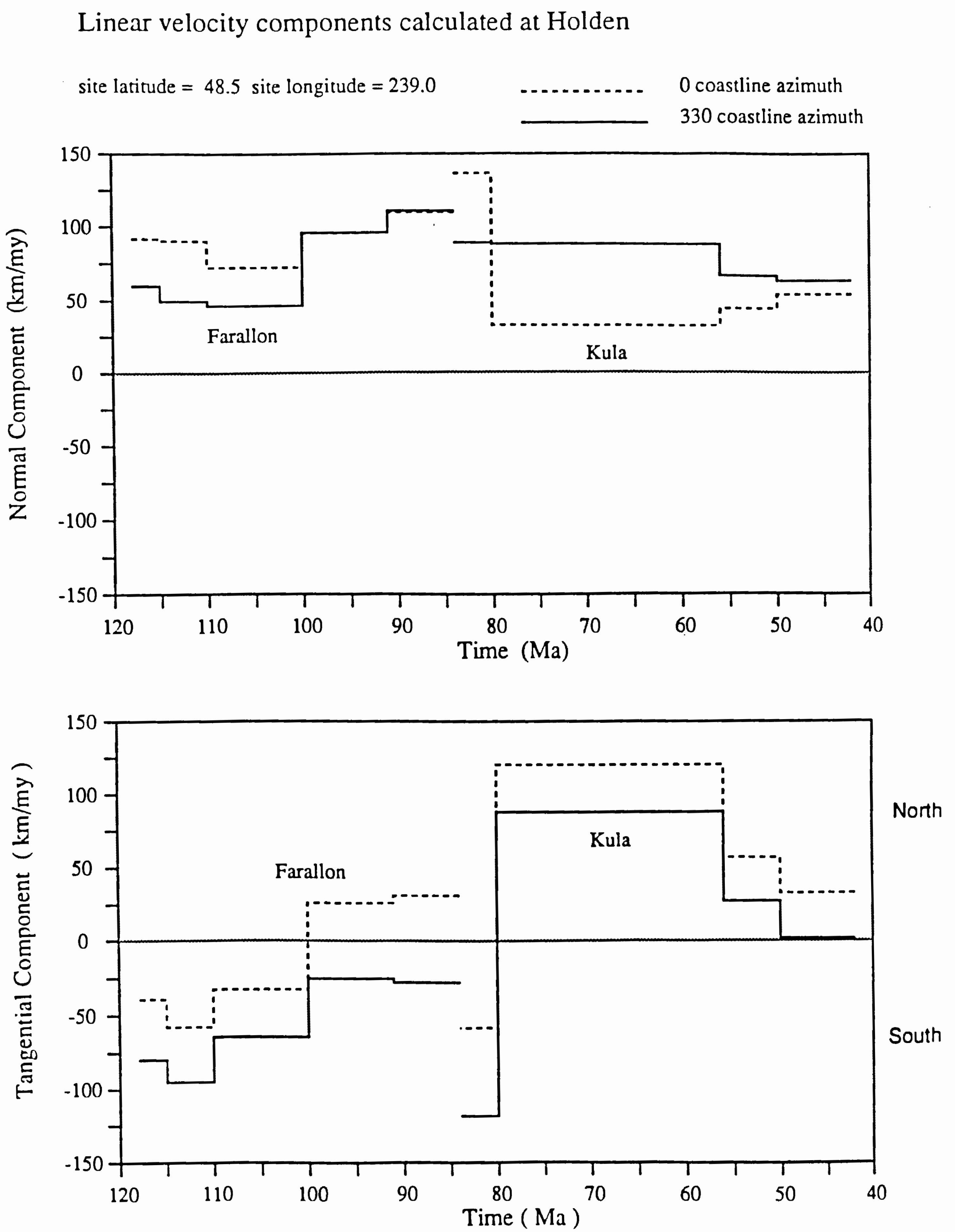
Local, cross-cutting relations of flattened fabrics with steeply-dipping to down-dip lineations by shallow-level dikes with strike-parallel lineations, may be consistent with early contractional deformation followed by a shift to strike-parallel shear as suggested by Brown and Talbot (1989). However, uncertainty of the actual age relations of the two types of fabrics makes timing of the change unconstrainable in the Holden area.

Thus, within the Holden area, the onset of contractional and strike-slip deformation styles are unknown, although they appear to be in part synchronous with medium- to high-grade metamorphism after 220 Ma. Contraction may have been active during mid-Late Cretaceous time in the Seven Fingered Jack pluton. Deformation of uncertain orientation was active at 73 Ma in the Cardinal Peak pluton, and strike-slip shear may have been active during and shortly following crystallization of the middle and upper portions of the Duncan Hill pluton, from 47-45 Ma. Deformation had ended before intrusion of the Holden Lake and Copper Peak plutons, which are of unknown age.

Elsewhere in the Crystalline Core, to the west of the Holden area, strike-parallel shear deformation is active pre- 96 Ma and probably continues through 90 Ma based on: 1) undeformed 96 Ma dikes related to the Sulphur Mountain pluton (Figure 36) that crosscut a strong, shallow-plunging, linear fabric in the Chiwaukum Schist (Walker and Brown, in press); and 2) syn-deformational intrusion of the 90 Ma Sloan Creek pluton (Longtime and Walker, 1990). To the east of the Holden area, Miller and Bowring (1990) observed steeply-plunging, nearly down-dip lineation in the Skagit Gneiss, associated with metamorphism and deformation synchronous with intrusion of the 65 Ma Oval Peak batholith. These lineations are not directly associated with the contact and are interpreted to represent contractional style deformation (Miller and Bowring, 1990). Chocolate tablet boudinage representative of flattening at the contact of the batholith is interpreted to be the result of ballooning during emplacement. Miller (1990) documents the presence of a shallow dipping, northeast directed, reverse-slip shear zone in the vicinity of Mirror Lake, which places 73 Ma Cardinal Peak pluton on top of undated orthogneiss. This shear zone is crosscut by the 45 Ma Railroad Creek pluton and brackets thrusting sometime between 73 Ma and 45 Ma and may imply that contraction was important during the latest Cretaceous and Paleocene. Thus, data from the Holden area and from outside the Holden area, within the Crystalline Core, indicate a period approximately between 85 Ma and 65 Ma when both strike-slip shear and contractional deformation mechanisms were active simultaneously.

The styles of deformation can be roughly related to plate motion reconstructions of Kelly and Engebretson (personal communication, 1991). The reconstructions (Appendix V) provide determinations of azimuths and magnitudes of plate velocities for the Kula and Farallon plates relative to a fixed North America frame of reference. Figure 37 shows the linear components of plate velocities for the Farallon plate, from 120 to 84 Ma, and Kula plate, from 84 to 43 Ma. Kula convergence for the Holden area is interpreted from 84 Ma on, based on a northernmost location of the Kula-Farallon-North America triple Junction in the vicinity of northern California, with the northern option (Engebretson and others, 1985). The trend of the coastline in the Pacific northwest through Late Cretaceous time is poorly constrained. Heller and others (1987) estimate a coastline trend of approximately 327-333° for the Cascade volcanic arc. This estimate is based on

Figure 37. Normal and Tangential plate velocity components calculated at Holden for the Farallon plate (120-84 Ma) and Kula plate (84-43 Ma). Magnitude and azimuth of plate velocities are in Appendix V. The solid line shows linear velocities calculated about a 330° coastline azimuth; the dotted line represents linear velocities calculated about a 0° coastline azimuth. Positive values of the tangential component represent north-directed motion for the 0° coastline azimuth and northwest for 330°. Negative values represent south and southeast-directed motion, respectively. Refer to text for further discussion.


Linear velocity components calculated at Holden
site latitude = 48.5 site longitude = 239.0
0 coastline azimuth
330 coastline azimuth
Normal Component (km/my)
150
100
50
0
-50
-100
-150
Farallon
Kula
120
110
100
90
80
70
60
50
40
Time (Ma)
Tangential Component (km/my)
North
South
Farallon
Kula
Time (Ma)

removal of movement related to faulting, tectonic rotation, and 20% extension at the U.S.-Canada border - interpolated from an estimated 65% extension in the Basin and Range. To represent the uncertainty in coastline trend, the linear components of plate velocity were analyzed for chosen coastline trends of 330° (solid) and 0° (dashed) (Figure 37).

At 100 Ma, the Farallon plate shows an increase in the north (dashed) or northwest (solid) directed component of plate velocity (Figure 37). This increase in the north-northwest directed component of plate convergence is due to a change to more oblique convergence of the Farallon plate (Appendix V), which may be consistent with the appearance of early Late Cretaceous strike-parallel lineations in the Crystalline Core. An even more dramatic increase in the north-northwest directed component of plate velocity occurs at 80 Ma (Figure 37), shortly after the birth of the Kula plate (Engebretson and others, 1985). This change is related to a distinct shift to highly oblique convergence of the Kula plate at 80 Ma (Appendix V) which lasted into the early Tertiary.

Partitioning of strain due to oblique convergence in the Late Cretaceous and early Tertiary into orogen-normal and orogen parallel components is probably the primary mechanism responsible for the irregular distribution of contractional and strike-slip shear fabrics in the Crystalline Core of Late Cretaceous and Paleogene age. In this scenario in the Holden area, the orogen-normal component results in pure shear forming flattened fabrics and steep- to down-dip lineations (Figure 25); and the orogen-parallel component results in simple shear forming strike-parallel lineations

(Figure 25). This is supported by the development of the two structural styles at least in part under the same medium- to high-grade metamorphic conditions, and within the same foliation plane. Moreover, it is consistent with contractional deformation observed in the Methow Basin (McGroder, 1988) and strike-slip shear in the Crystalline Core (Brown and Talbot, 1989), both of Late Cretaceous age.

The distinct development of both contractional and strike-slip structures in the Holden area supports the need to incorporate strike-slip, as well as contraction, as an important deformational mechanism involved in the orogenesis of the Crystalline Core and Coast Plutonic Complex, as introduced by Brown and Talbot (1989). Such simultaneous partitioning of oblique convergence has been reported at higher structural levels in the Sumatra arc (Fitch, 1972), and in New Zealand (Berryman and Beanland, 1991); where orogen-parallel strike-slip faults occur inboard of subduction complexes showing orogen-normal folds and thrusts.

CONCLUSIONS

Two deformational styles are observed in the Holden area. Steeply-plunging to down-dip mineral and stretching lineations commonly occur on apparent flattening fabrics. These are interpreted to represent contractional style deformation. Gently-plunging to subhorizontal, strike-parallel, northwest-trending mineral and stretching lineations, commonly associated with apparent constrictional fabrics. These are interpreted to represent strike-slip shear deformation. The contractional style may have been active in the Holden area during the mid-Late Cretaceous as indicated by deformation patterns in the Seven Fingered Jack pluton. Deformation of unknown style was active at 73 Ma when the Cardinal Peak pluton was intruded, and was dominated by strike-slip shear during or shortly after final emplacement of the Duncan Hill pluton at 45 Ma.

Amphibolite facies metamorphic conditions were synchronous with both contractional and strike-slip styles of deformation, as both steep- and shallow-plunging lineations are defined by amphibolite facies assemblages. Deformation was active at lower grade metamorphic conditions and higher crustal levels, evidenced by deformational fabrics defined by greenschist grade assemblages, and by fractures synchronous with ductile textures suggestive of deformation close to the brittle-ductile transition.

Partitioning of strain due to oblique convergence of the Kula plate from 80 to 43 Ma, into orogen-normal and orogen-parallel components, may explain the irregular distribution of Late Cretaceous and Paleogene age down-dip and strike-slip fabrics within the Crystalline Core. Moreover, strike-slip shear appears to be an important deformation mechanism, along with contraction, in the Coast Plutonic Complex as a whole.

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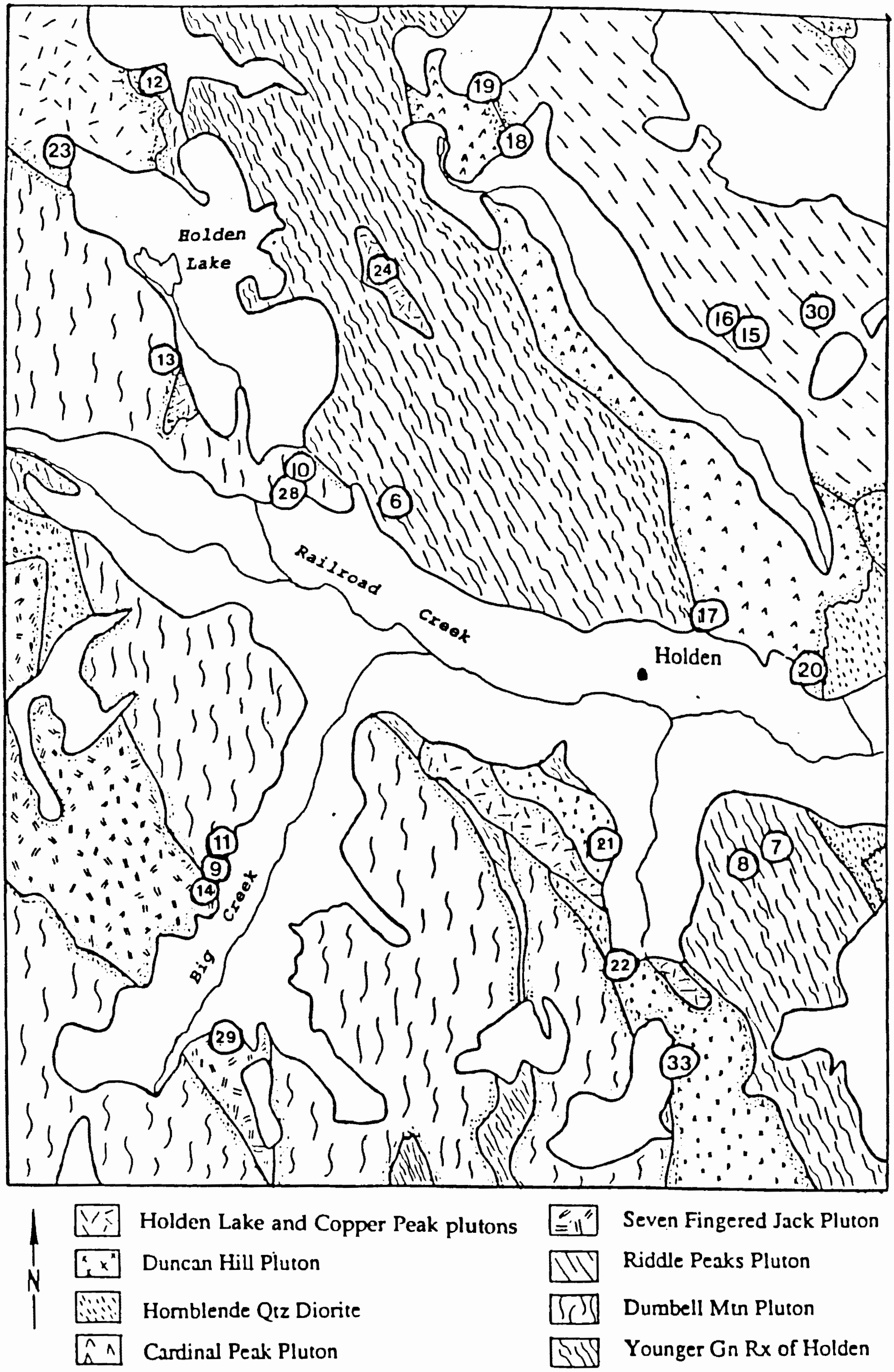
APPENDIX I Figure locality map.

Numbers on the map refers to figure numbers mentioned in the text.



APPENDIX II Strain measurement data.

K = x/y - 1 / x/z - 1

Measurements were taken on two of the three principal planes x/z, y/z, and x/y, from which the third was calculated. Figure 33 shows examples of planes from which measurements were taken for samples with a down-dip lineation (A), and samples with a gently-plunging lineation (B).

A) Samples with down-dip lineation

Sample #	232	44	177	66
x/z	7.36	2.8	3.95	2.84
y/z	3.05	2.69	2.54	1.62
x/y	2.41	1.04	1.56	1.75
K	.68	.02	.36	1.21

B) Samples with gently-plunging lineation

Sample #	215	175	179	225	35	36	227
x/z	13.4	8.44	9.64	8.5	4.59	8.23	8.47
y/z	2.34	2.59	3.06	3.66	4.3	2.14	1.96
x/y	5.7	3.26	3.15	2.32	2.41	3.84	4.32
K	3.51	1.42	1.04	.49	1.9	2.5	3.46

APPENDIX III Thin section mineralogy from the Holden area.

An content was estimated using the Michel-Levy method along with refractive index comparison. qtz = quartz; plg = plagioclase, (An) = approximate anorthite content; amp = amphibole; bio = biotite; whm = white mica; chl = chlorite; epd = epidote; gar = garnet; shp = sphene; ap = apatite; opq = opaque; otr = other. For all letters - upper case = greater than 5%; x = present; t = less than 1%; h = Hornblende; c = cummingtonite; a = anthophyllite; cpx = clinopyroxene; opx = orthopyroxene; r = rutile; z = zircon; cc = calcite; i = ilmenite.

Younger Gneissic Rocks of the Holden area

hornblende schists and gneisses:

#	qtz	plg(An)		amp	bio	whm	chl	epd	gar	sph	ap	opq	otr
9	X	X		H	x	x	x	x		x	x	x	
15	X	X	3-5	H		x		t			x	x	
21	x	X	15	H	X	x	x	x		x	x	x	
24	X					X					x		r
25	X	X	14	Hca			t	x			x	x	
26	X	X	40	H			x			x	x	x	
27	X	X		h			x	X	x	X	x	x	
40	X	X	25	A	X		x				x	x	
71b	X	X	30	h	x	t					x	x	
74b	X	X	25	H						x	x	x	cpx
120	X	X		H		X	x	x		x	x	x	
124	X	x		h	x	x	x	x			x	x	
125	X				x		x				x	x	r
142	X	X	35	H			x	x		x	x	x	r
143	X	X	55	H			x	x		x	x		
144	X	x		Ha			x				x	x	r
145	X	x	30		x		x		x			x	r
146	X			H			x	X		x	x	x	
162		X	35	H			x	x			x	x	
164	x	X		h			X	x		x	x	x	
165	x	X		H			X	x		x	x	x	
218	X	X		H			x	X		x	x	x	
223						x				x		x	CC

biotite gneiss:

#	qtz	plg(An)		amp	bio	whm	chl	epd	gar	sph	ap	opq	otr
8	X	X	30		x	x	x			x		x	
17	X	X	20			x	x					x	z
147	X	X		h			t	t			x	x	
150	X	X	35	H	x			x		x	x	x	

biotite quartz schists:

7	X	X	15		x	x	x				x	x	
29	X	X		H	x		x	x		x	x	x	
148	X	X		H	X			X	x		x	x	r
151	x	X		H	x	x	x	x			x	x	r
160	X	X		H	X			x		x		x	r

Dumbell Mountain pluton:

gneissic biotite quartz diorite:

#	qtz	plg(An)		hbl	bio	whm	chl	epd	gar	sph	ap	opq	otr
95	X	X		H		x	x			x	x		r
110	X	X	22	h	x	x	x	x			x	x	
115	X	X	20	H			x	x		x		x	
168	x	X	15	H			x	x	x	x	x	x	
169	X	X		H			x	x				x	
195	x	X	20	H			x	x		x	x	x	
196	X	X	25	H		x	X	x				x	
197	X	X	35	H	x	x	x	x			x	x	
198	x	X	30	H	x	x	x				x	x	
238		X	1-3	H		x	x	x				x	

biotite quartz augen gneiss:

5	X	X	35	h	x		x	x			x	x	
33	X	X	45	H	x		x					x	
35	X	X	25		X		x	x				x	z
44	X	X	25	h	X		x	x		x	x	x	
61	X	X	22	h	x	x	x	x		x	x	x	
66	X	X	20		X	x	x					x	
67	X	X	25	t	x		x	x		x	x	x	
173	X	X			x	x	x	x					
175	X	X			x	x	x	x			x	x	z
176	X	X		h	x	x	x			x	x	x	
177	X	X	30	h	x						x	x	
178	x	X	25	H	x		x	x		x	x	x	
179	X	X	25	h	x			x			x	x	
225	X	X	40	a	x	x	x					x	
226	X	X		A	x	x	x				x	x	
227	X	X	25	h	x		x	x		x	x		z
228	X	X		h	x		x					x	
232	X	X	45	H	x	x	x					x	

hornblende schist and gneiss:

50	X	X		H	x	x	x	x		x	x	x	i
51	X	X		H		x		x				x	i
52		X	40	H		x	x	x		x	x	x	r
53	X	X		H	x	x	x	x		x	x	x	
54		X	25	Ac			X			x			
170	x	X	25	H	x		x	x	x	x		x	
215		X		H	X	X							
216	X	X	25	H		x	x	x	x			x	i
237		X	50	H			x	X		x		x	

Riddle Peaks pluton

#	qtz	plg(An)		hbl	bio	whm	chl	epd	sph	ap	opq	otr
80		X		H			x				x	
82	X	X		h		x		x				
83		X		H		x	x	x			x	
84		X	40	H						x	x	
86	X	X		h	x		x	x				
87		X	30	H	x	x		x	x		x	
88		X	50	H							x	
90		X	45	H				x			x	
91		X	65	H								
184		X		H			X			x	x	Cpx/opx
186		X		H			x				x	
189	X	X		H						x	x	
190		X	30	H				x		x	x	cpx
191	X	X						X	x	x		

Seven Fingered Jack pluton

#	qtz	plg(An)		hbl	bio	whm	chl	epd	sph	ap	opq	px	otr
199	X	X	15	H	x	x	x	x		x	x	c	
200	X	X	35	H	x			X		x	x	c	
201	X	X		h	x		x	x		x	x	o	
202	X	X	25	H			x	x		x	x	o	
203	x	X	20	H	x	x	X	x		x	x		
204	X	X	30	H	x		x	x		x	x		
205	x	X	25	H	x	x	x	x		x	x		
208	x	X		H		x		x			x		
209a	X				x	X	x	x		x	x	o	cc
209b	X				x	X	x	x		x	x		cc
210	x	X	15	H			x	x				c	
211	x	X		H	X		x	x					

212	X	X	30	H	X			x				
213	X	X	20	H	x		x	x		x	x	

Cardinal Peak pluton

#	qtz	plg(An)		hbl	bio	whm	chl	epd	sph	ap	opq	otr
10	x	X	22	H		s	x	x	x	x	x	
12	x	X	15	H	X	s	x	x			x	
22		X	25	H				x			x	
72		X	22	H	x	s	X	x	x	x	x	
75	x	X		h		s	X	x		x	x	
77	x	X	10	H	t	s	t					
79	x	X	35	H	x		x				x	
106	x	X		H		s	x				x	
107	x	X		H		s	x	t		x	x	
108	X	X		H							x	
128	x	X	25	H	x	s	x	x		x	x	
134	x	X	35	H	x		X	x		x	x	
136		X		H	X						x	

Duncan Hill pluton

#	qtz	plg(An)		hbl	bio	whm	chl	epd	sph	ap	opq	otr
18	t	X	25		x	x	x					
19	X	X	30			x	t					
20	t	X	25		X							
30	X	X	35			X	t					
230	X	X	20		X	x						
233		X	45	X						x	x	
182	X	X	15		X		t			x		
183	X	X	30	t	t	t						
181	X	X	25		X	t						
229	X	X	30		X							

Holden Lake pluton

55		X	20	H			x			x	x	
57	x	X	50	H			x			x	x	
60	x	X	45	H		s	x	x		x	x	
62	x	X	45	H		s	x			x	x	
63	x	X	25	H		s	x			x	x	
64	x	X	25	H	x	x	x			x	x	

Martin Ridge Stock

166	X	X	10	H	x				x			z
219	X	X	10-35	H	x			x	x		x	
221	X	X	10-30	H	x	s	x	x	x		x	
222	x	X	20	H	x		x			x	x	

Copper Peak pluton

31		X	45	C						x	x	
34	X	X		C		s	x			x	x	
234	X	X	40	H		s	X		x	x	x	

APPENDIX IV Microprobe analyses.

Samples from the Seven Fingered Jack pluton.

Sample 170-200 CALC'D WT %

OXIDE	Core	Rim	Rim	Rim	Rim
SIO2	45.76	43.93	44.37	44.34	44.08
TIO2	1.62	1.18	.93	.99	.78
AL2O3	9.94	11.46	11.34	10.99	11.58
FEO	16.88	16.70	16.96	17.02	17.58
MNO	.46	.32	.35	.49	.33
MGO	11.40	10.49	10.32	10.95	9.85
CAO	10.47	11.38	11.40	10.78	11.24
NA2O	1.42	1.36	1.20	1.68	1.53
K2O	.44	.47	.46	.45	.49
Total	98.39	97.29	97.33	97.69	97.46

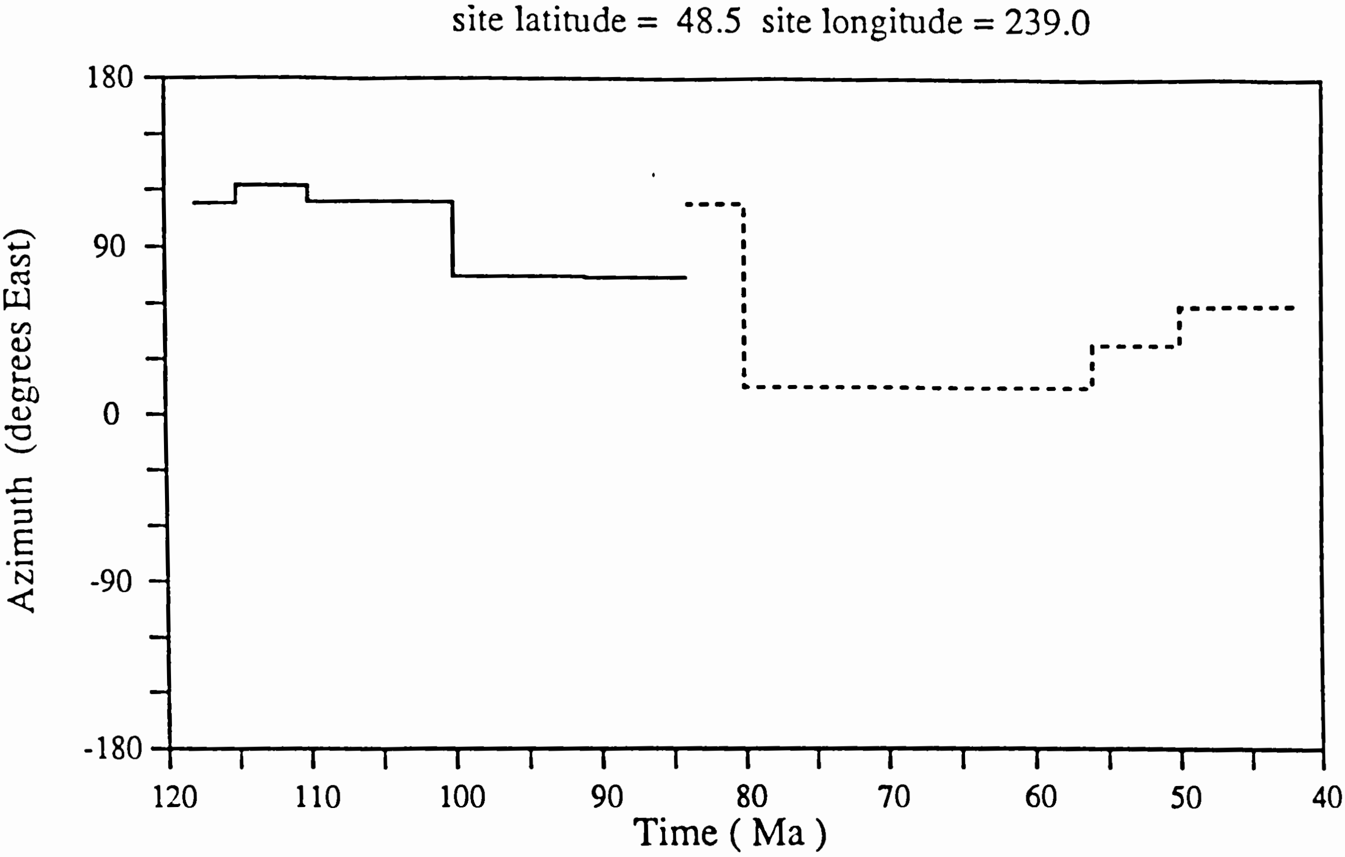
Sample 170-204 CALC'D WT %

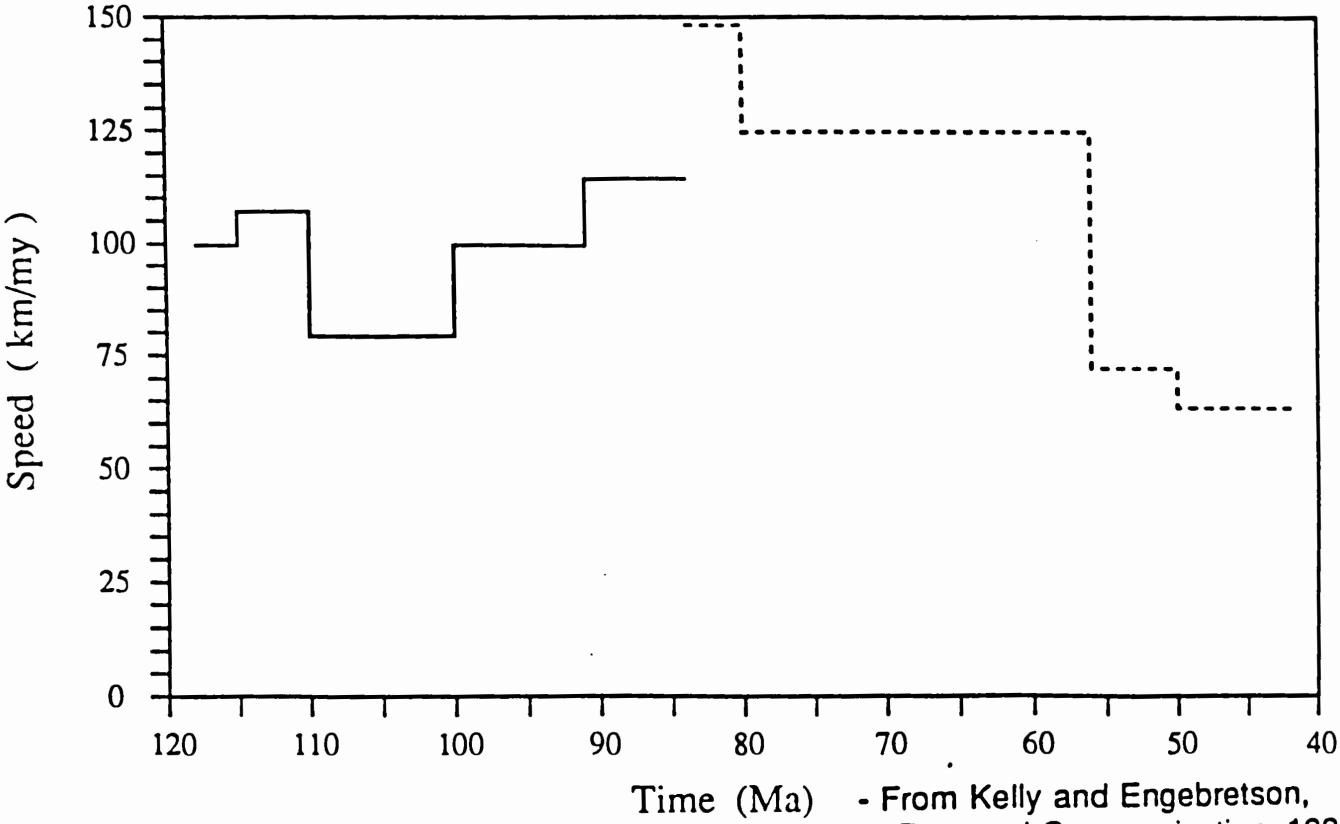
OXIDE	Rim	Rim	Rim
SIO2	45.20	45.60	44.46
TIO2	.97	.91	1.00
AL2O3	10.21	10.22	10.69
FEO	16.19	16.42	16.32
MNO	.55	.53	.47
MGO	11.28	11.06	10.84
CAO	11.33	11.54	11.63
NA2O	1.46	1.14	1.42
K2O	.42	.46	.55
Total	97.61	97.88	97.38

Sample 170-211 CALC'D WT %

OXIDE	Rim	Rim
SIO2	45.20	44.40
TIO2	.92	.89
AL2O3	10.71	10.87
FEO	16.37	16.75
MNO	.34	.44
MGO	10.91	10.60
CAO	11.52	11.33
NA2O	1.24	1.40
K2O	.49	.48
Total	97.70	97.16

APPENDIX V Plate motion reconstructions.





- From Kelly and Engebretson, Personal Communication, 1991