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Stratigraphy, structure, and tectonics of the central Brooks Range, near Dietrich Camp, Alaska

Boler, Kent W., M.A.

Rice University, 1989
RICE UNIVERSITY

STRATIGRAPHY, STRUCTURE, AND TECTONICS
OF THE CENTRAL BROOKS RANGE,
NEAR DIETRICH CAMP, ALASKA

by

KENT W. BOLER

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF ARTS

APPROVED, THESIS COMMITTEE

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May, 1989
ABSTRACT

Stratigraphy, Structure, and Tectonics of the central Brooks Range,

near Dietrich Camp, Alaska

by

Kent W. Boler

The Skagit allochthon consists of an imbricated sequence of heterogeneous Devonian and lower Paleozoic clastic and carbonate rocks which structurally overly the Endicott Mountains allochthon and the Schist belt in the central Brooks Range, Alaska. Three sets of Brookian folds, north directed thrust faults, and a late set of high-angle faults were identified.

Many previously undated imbricates within the Skagit allochthon, which were previously thought to be dominantly Devonian(?) in age, are largely or partially of lower Paleozoic age. Substantial lithologic differences preclude any simple correlation of the lower Paleozoic rocks of the Jesse klippe, as proposed by Brosge and Patton (1982), with rocks in the Doonerak window.

The large scale involvement of lower Paleozoic rocks in Brookian thrusting favors large thrust displacements and high shortening reconstructions. A partial balanced cross section of the Skagit allochthon yields a minimum 100 km of shortening by internal imbrication.
ACKNOWLEDGEMENTS

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Finally, I would like to thank my parents, Harold and Ellen Boler, for their unflagging support.

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CHAPTER 1 - INTRODUCTION

The Brooks Range of northern Alaska is an east-west trending, north vergent, Late Mesozoic - Cenozoic fold and thrust belt. The Brooks Range can be divided into six parallel belts. The most northerly belt, the Endicott Mountains allochthon, consists of middle and upper Paleozoic rocks. The Endicott Mountains allochthon overlies the lower Paleozoic rocks of the Apoon assemblage, which is exposed in the Doonerak Window, and underlies the middle and lower Paleozoic, low-grade metamorphic rocks of the Skagit allochthon (Oldow et al., 1987). The Skagit allochthon structurally overlies the Endicott Mountains allochthon to the north, and the Schist belt to the south. The Schist belt consists of Precambrian(?) to Paleozoic(?) high-grade metamorphic rocks. The Rosie Creek allochthon, which overlies the Schist belt to the south, consists of low-grade metamorphic rocks of middle to upper Paleozoic age (Gottschalk, 1988). The last, and structurally highest tectonic unit is the Ophiolite or Angayucham assemblage, which consists of middle Paleozoic to Mesozoic rocks of ophiolitic affinity.

This study deals with the northern outcrops of the Skagit allochthon in the central Brooks Range, in an area north of Dietrich Camp, and roughly bounded by the Hammond and Dietrich Rivers (Fig. 1.1). The location of the field area relative to previously-published maps is given in Fig. 1.2. This area was originally described in the expeditionary report of Schrader (1904) and in a compilation by Mertie (1923) as part of a 20–35 km wide band of "heavy-bedded crystalline limestone and mica-schist." Reconnaissance mapping by Brosge and Reiser (1964, 1971) and Dillon et al. (1986), at a scale of 1:250,000, shows a series of poorly defined east-west trending lithologic units of presumed Devonian(?) age. The Skagit marble (informal name), is a massive marble which is the most prominently outcropping unit within the Skagit allochthon. The area immediately north of this study area was mapped in detail by Phelps (1987),
Figure 1.1 -- Geographic location map. Patterns: Stippled = Endicott Mountains allochthon, diagonal lines = Apoon assemblage and upper Paleozoic rocks exposed in the Doonerak Window, horizontal lines = Skagit allochthon. Heavy line outlines the study area. Shaded line is the eastern margin of the Gates of the Arctic National Park. The dashed line represents the Dalton Highway and Trans-Alaska Pipeline.
Figure 1.2 — Geologic map sources.
who documented the tectonic contact relationship of the Skagit allochthon with the underlying Endicott Mountains allochthon. Recent work by Dillon et al. (1987) has established the presence of Cambrian, Ordovician, Silurian, and Devonian age fossils in adjacent rocks on strike to the east.

The frontal half of the Skagit allochthon in this area can be grossly characterized as a thin section of Skagit marble which is structurally overlain by a series of south dipping imbricates of Devonian and older (?) metasediments, overthrust in the west by a large (40 x 10 km) klippe of uncertain age. This klippe will be informally referred to here as the Jesse klippe, after Jesse Mountain, the most prominent landmark within it.

The primary purpose of this study was to test the tentative correlation by Brosge and Patton (1982) of argillites within the Jesse klippe with the lower Paleozoic slates of the Apoon assemblage exposed in the Doonerak Window. This interpretation constrains balanced cross sections and paleogeographic reconstructions of the Brooks Range by 1) placing lower Paleozoic rocks over Devonian rocks within the Skagit allochthon, 2) lowering the basal detachment of the Skagit allochthon into the lower Paleozoic section, and 3) making the Skagit allochthon a lateral facies of the Apoon assemblage. The correlation of the lower Paleozoic rocks exposed in the Jesse klippe with those exposed in the Doonerak window implies the structural envelopment of the intervening Devonian rocks of the Endicott Mountains allochthon.

Testing this hypothesis entailed: 1) confirmation of the tectonic nature of the basal contact of the Jesses klippe by detailed mapping of the basal contact and the deformational structures above and below it in the central Hammond River area, 2) definition of the internal stratigraphy of the Jesse klippe and of the subjacent rocks, and 3) collection and identification of macrofossils and microfossils to constrain the age of the rocks in the Jesse klippe and in the subjacent strata.

A second objective was to document the structural evolution and the strain state of
the rocks of the Skagit allochthon in order to constrain their kinematic history. Comparison of the kinematic history of the Skagit allochthon to that of the Schist belt, Endicott Mountains allochthon, and Apoon assemblage could constrain the sequence of deformational events and the regional kinematics of deformation in the central Brooks Range. Fold and fault related deformational structures, including mineral lineations, shear zones, and strain markers, were measured and analyzed to determine the sequential development of structures, the stress and strain axes associated with these structures, and the direction of displacement. Samples were also collected for petrofabric and strain analysis.

The third objective of this study was to carry out the first detailed mapping of the northern Skagit allochthon in the central Brooks Range. An internal stratigraphy was to be defined by mapping of lithologies, lithologic contacts, and faults. Sedimentary structures were analyzed for paleo-environmental significance. Rock units were sampled for structural, micro-paleontologic, and paleo-environmental study. Macrofossils were collected for age determination.

Field investigations were conducted during the summers of 1984 and 1985. Mapping was done at a scale of 1:31,360 on 2x enlargements of the U.S. Geological Survey 1:63,360 topographic sheets of the Wiseman C1 and D1, and Chandalar C6 and D6 quadrangles.

This study forms part of a geological and geophysical transect of the Brooks Range by Rice University and University of Alaska at Fairbanks.
INTRODUCTION

The Late Mesozoic - Cenozoic Brooks Range fold and thrust belt trends east-west across northern Alaska. Precambrian(?), Paleozoic, Mesozoic, and locally, Tertiary rocks crop out in east trending folds and north directed thrust-faulted packages.

The foreland region, the North Slope, consists of a gently south dipping section of Mississippian to Jurassic marginal marine sediments which is overlain by Cretaceous to Tertiary syn- and post-orogenic foredeep deposits (Bird, 1982). A low angle (1°-2°) south dipping basement reflector is observed on North Slope seismic lines and is presumed to continue beneath the Brooks Range (Phelps, 1987; Oldow et al., 1987).

The Brooks Range fold and thrust belt is characterized by the juxtaposition of rock packages of varying degrees of allochthoneity and metamorphic grade. From the exterior portions of the fold and thrust belt, bulk strain and metamorphic grade generally increase southward into the greenschist facies metamorphic rocks of the southern Skagit allochthon. In the interior of the thrust belt, the highest grade metamorphic rocks, high-grade greenschist, amphibolite, and blueschist facies rocks with Precambrian(?) and Paleozoic(?) protoliths, are exposed in the northern portions of the Schist belt (Gottschalk, 1988). The metamorphic grade decreases southward through the Schist belt into the lower greenschist facies rocks of the Rosie Creek allochthon (Gottschalk, 1988). Ophiolitic nappes form the structurally highest thrust sheets (Patton et al., 1977).

BROOKIAN OROGENESIS

Brookian contractional deformation was initiated in the mid- to Late Jurassic, resulting from the obduction of oceanic and island arc material over Arctic Alaska (Patton and Box, 1985; Roeder and Mull, 1978; Patton et al., 1977). Contractional
deformation continued throughout the Early Cretaceous and into the Tertiary (Mayfield et al., 1983). Basement, supracrustal, and syn-orogenic foreland-basin deposits were telescoped in north directed folds and thrusts (Mayfield et al., 1983; Molenaar, 1981). A large number of 130-90 Ma (Cretaceous) K-Ar radiometric ages are thought to represent a Brookian thermal event coincident with the majority of shortening (Turner et al., 1979, Dillon et al., 1980; Mull 1982). Brookian orogenesis is essentially synchronous with the Rocky Mountain Columbian orogeny (Douglas, 1972).

ASSEMBLAGES OF NORTHERN ALASKA

The rocks of the Brooks Range have been variously grouped into laterally extensive, fault bounded terranes, sub-terranes, and lithotectonic assemblages (Figure 2.1) (Churkin and Trexler, 1981; Jones et al., 1981; Silberling and Jones, 1984; Howell et al., 1985; Oldow et al., 1987). Since the relative displacements of these rock packages are unknown, the terms assemblage or allochthon are preferred, and will be used here to describe fault-bound packages of rocks which have a similar stratigraphic and structural history. These assemblages may be internally imbricated, but represent relatively coherent structural packages.

Oldow et al. (1987) divide northern Alaska into seven principal assemblages, known collectively as the Arctic Alaska microplate (Figs. 2.1 and 2.2). These are, from north to south (exterior to interior): 1) the North Slope assemblage; 2) the Endicott Mountains allochthon; 3) the Apoon assemblage; 4) the Skajit allochthon; 5) the Schist belt; 6) the Rosie Creek allochthon; and 7) the Ophiolite assemblage.

North Slope assemblage

The North slope assemblage extends from the Arctic coastline to the frontal mountains of the Brooks Range. It consists of the autochthonous and
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</tr>
<tr>
<td>Ruby</td>
<td>Ruby</td>
<td>Coldfoot</td>
<td>Schist belt</td>
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<tr>
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<td>Ruby</td>
<td></td>
<td>Schist belt</td>
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<tr>
<td>Ophiolite</td>
<td>Angayucham</td>
<td>Angayucham</td>
<td>Yukon-Koyukuk Ophiolites</td>
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Figure 2.1 -- Assemblage nomenclature for north-central Alaska.
Figure 2.2 – Generalized geology of central northern Alaska after Oldow et al. (1987).
para-autochthonous, Devonian to Tertiary rocks of the Brooks Range foreland, which unconformably overlie the pre-Devonian basement of the Arctic continental platform. The North Slope assemblage can be divided into four depositional sequences (Lerand, 1973; Hubbard et al., 1987): 1) Franklinian sequence: strongly deformed, south dipping lower Paleozoic and Precambrian basement rocks of the Arctic continental platform (Kirschner et al., 1983, Mauch, 1985, and Hubbard et al., 1987); 2) Ellesmerian sequence: Devonian clastic rocks deposited in extentional basins (Mauch, 1985) overlain by a sequence of generally northerly transgressive Mississippian clastic rocks (Kekiktkuk Conglomerate and Kayak Shale), Carboniferous platform carbonates (Lisburne Group), and Permian and Triassic clastic and carbonate rocks (Sadlerochit and Shublik Groups) (Brosgé and Dutro, 1973; Bird, 1982); 3) Beaufortian sequence: Jurassic (Kingak) shales and lower Cretaceous mixed clastic rocks (Kuparuk River Formation) (Hubbard et al., 1987; Detterman et al., 1975; Carman and Hardwick, 1983); and 4) Brookian sequence: south sourced Cretaceous and Tertiary flysch and molasse of the Colville foredeep (Mull, 1980). At the surface and toward the north, the post-Devonian rocks are only mildly deformed, although blind thrusts may occur at depth (Mauch, 1985). Bulk strain and the amplitudes of major folds increase southward into the mountain belt (Mull, 1982).

**Endicott Mountains allochthon**

The Endicott Mountains allochthon consists of imbricated Devonian to Jurassic rocks whose exposures form most of the northern half of the Brooks Range, and whose frontal imbricates subcrop below the Cretaceous foredeep sediments of the North Slope (Hawk, 1985; Phelps, 1987). Bulk strain increases southward throughout the allochthon (Handschy, 1987). The Endicott Group comprises most of the Endicott Mountains allochthon and consists of a regressive, north sourced sequence of Middle
and Upper Devonian clastic rocks. The Endicott Group is generally interpreted as a large Upper Devonian deltaic complex (Kanayut Conglomerate and Hunt Fork Shale), which prograded south or southwest over the Middle and Upper? Devonian shelfal sediments of the Beaufort Formation (Dutro et al., 1979; Nilsen and Moore, 1982). A transgressive Carboniferous carbonate platform sequence (Kayak Shale and Lisburne Group carbonates), and minor upper Paleozoic and Mesozoic chert, argillite, and carbonate rocks (Kuna, Siksikpuk, and Otuk Formations) cap the sequence (Mull, 1982; Nilsen and Moore, 1982; Mayfield et al., 1983). Facies studies of the Lisburne Group in the eastern Brooks Range indicate that the Lisburne of the Endicott Mountains allochthon is slightly older and more distal than the autochthonous North Slope Lisburne (Armstrong, 1974; Armstrong and Mamet, 1977).

Apoon assemblage

The Apoon assemblage is an imbricated and structurally complex sequence of lower Paleozoic slates and volcanic rocks which is exposed in the Doonerak window, a tectonic window through the Endicott allochthon in the central Brooks Range. Chemical analyses of the felsic to intermediate Apoon assemblage volcanic rocks are suggestive of island-arc compositions (Dutro et al., 1976; Julian, 1986). The Apoon assemblage is overlain by the Mississippian Kekiktuk Conglomerate, Kayak Shale, and Lisburne Group (Dutro et al., 1976).

The Apoon assemblage was originally interpreted to represent an autochthonous or para-autochthonous sequence of lower Paleozoic basement rocks overlain with angular unconformity by the Mississippian rocks (Armstrong, 1974; Armstrong et al., 1976; Armstrong and Mamet, 1977; Dutro et al., 1976; Nilsen et al., 1981; Mull, 1982). Recent detailed studies by Rice University workers show that the contact between the Apoon assemblage and the Carboniferous is demonstrably a thrust fault over much of its
length, and that angular discordance across the contact is principally tectonic in nature (Julian et al., 1984; Oldow et al., 1984; Seidensticker et al., 1985). The lack of pre-Carboniferous deformational structures in the lower Paleozoic Apoon assemblage and the imbrication geometry of both the Apoon assemblage and the overlying Carboniferous rocks strongly argue that the Doonerak window is a Brookian duplex structure which imbricated below and uplifted the Endicott Mountains allochthon (Julian et al., 1984; Oldow et al., 1984; Seidensticker, 1986; Seidensticker et al., 1987).

Skajit allochthon

The Skajit allochthon, named after the Skajit marble, refers to a poorly understood and structurally complex section of heterogenous low grade metasediments which crop out in a 20 - 50 km wide belt across the northern half of the southern Brooks Range (Schrader, 1902; Oldow et al., 1987). The Skajit marble, the most prominent outcrop unit, is generally thought to represent a carbonate platform of generally Silurian and Devonian age, and locally of Ordovician or Cambrian age (Brosge and Dutro, 1973). Relatively few of the imbricates of the Skajit allochthon are dated. Complex imbricates of calcareous, silicious, and volcaniclastic metasediments have yielded scattered Devonian to Cambrian fossils in the central Brooks Range (Brosge, 1960; Brosge and Reiser, 1964; Brosge and Dutro, 1973; Palmer et al., 1984; Dillon et al., 1987).

Along its northern margin, the Skajit allochthon structurally overlies the Endicott Mountains allochthon (Phelps, 1987). Lower greenschist facies metasediments, exposed in simple, south dipping imbricates in the northern part of the Skajit allochthon, become increasingly deformed and schistose to the south (Brosge and Reiser, 1964; Boler, 1986; Dillon et al., 1986; Oldow et al., 1987; Seidensticker, personal communication, 1987).
Schist belt assemblage

The Schist belt consists of poly-metamorphic and poly-deformed (pelitic) quartz-mica schists with subordinate amounts of intercalated metabasites, metafelsites, and marbles whose metamorphic grade decreases to the south (Nelson and Grybeck, 1980; Gottschalk, 1987; Gottschalk and Oldow, 1987). A belt of Middle or Late Devonian granitic plutons intrudes the schists (Silberman et al., 1979; Turner et al., 1979; Dillon et al., 1980). The protolith of the Schist belt is interpreted to be Devonian and older, possibly as old as Proterozoic, argillaceous and quartzose marine sediments with intercalated basaltic and felsic flows and sills (Turner et al., 1979; Gottschalk, 1986, 1987). An important internal unit is the Ambler volcanics, which consist of Devonian bimodal volcanic and volcanoclastic rocks (Schmidt, 1984, 1987). The volcanic rocks intruding the Schist belt are interpreted by Dillon and Pessel (1979) as forming a laterally extensive Devonian sequence related to ensialic island arc volcanism.

During the Cretaceous, the Schist belt rocks were regionally metamorphosed to upper greenschist facies (Turner et al., 1979; Dillon et al., 1979). Relict high pressure metamorphic facies, including blueschist and eclogite are locally preserved in the northern portions of the Schist belt (Turner et al., 1979; Gottschalk, 1986), but the timing of the metamorphism is controversial. Hitzman and Proffet (1980), Hitzman et al. (1982), and Gottschalk (1987) argue for Mesozoic high-pressure metamorphism related to Brookian orogenesis. Scattered Proterozoic K-Ar and Rb-Sr dates of relict blueschist mineral phases have been used to argue for Precambrian protoliths and metamorphism (Patton et al., 1978; Forbes et al., 1977; Turner et al., 1979).

The Schist belt is observed in structural contact with many of the assemblages (Oldow et al., 1987). The Schist belt overlies the Skagit allochthon west of the Dalton Highway. Eastward the Schist belt is observed underlying the Skagit allochthon, and overlying the Endicott Mountains allochthon. To the south it is overlain by the Rosie
Creek allochthon.

**Rosie Creek allochthon**

The Rosie Creek allochthon is a thin fault-bounded belt of Lower Devonian to Carboniferous(?), low-grade metasedimentary rocks which overlie the Schist belt to the north (Gottschalk, 1987; Gottschalk and Oldow, 1988). The rocks of the Rosie Creek allochthon have yielded rare Devonian spores and Carboniferous radiolarians (Gottschalk, 1987).

The Rosie Creek allochthon occupies the same structural position as the Skagit allochthon, is of similar metamorphic grade, and is at least partially age equivalent (Gottschalk, 1987). But since the Rosie Creek allochthon is substantially thinner than the Skagit allochthon, and is nowhere found in contact, it will be discussed separately.

The rocks of the Rosie Creek allochthon, and of the Ophiolite assemblage, are younger, and of substantially lower metamorphic grade than the rocks of the Schist belt. Geobarometry of the juxtaposed mineral assemblages suggests that at least 10 km of section is missing (Gottschalk, 1987). Gottschalk and Oldow (1988) explain the younger over older, and low-grade over high-grade relationships by structural ommission accomodated by low-angle normal faulting in the Cathedral Mountain fault zone.

**Ophiolite assemblage**

The Ophiolite assemblage, commonly known as the Angayucham terrane, occurs in a narrow band south of the Rosie Creek allochthon and also as klippen in the western Brooks Range (Roeder and Mull, 1978; Silberling and Jones, 1984). The Ophiolite assemblage delineates the southern margin of the central Brooks Range.

These rocks represent the structurally highest thrust sheets of the fold and thrust
belt. The rocks of the Ophiolite assemblage structurally overlie the Rosie Creek allochthon along a complex east-west trending, south dipping fault zone - the Cathedral Mountain fault zone (Gottschalk, 1987) which is a part of the Angayucham fault system interpreted by Dillon et al. (1986) as a thrust fault system. The Ophiolite assemblage terminates to the south against the right lateral Malamute fault zone (Dillon et al., 1986).

The ophiolites consist of an intercalated sequence of pillow basalts, gabbro, diabase, serpentinites, tuff, chert, greywacke, argillite, and limestone which yield scattered dates ranging from Devonian to Jurassic (Patton, 1973, 1984; Roeder and Mull, 1978; Dillon, 1983). The metamorphic grade of the Ophiolite assemblage is the prehnite-pumpellyite facies (Gottschalk, 1987). The Ophiolite assemblage is believed to represent the remnants of a collapsed Paleozoic oceanic terrane whose Cretaceous obduction marks the inception of Brookian orogenesis (Roeder and Mull, 1978; Jones et al., 1983).
CHAPTER 3 - STRATIGRAPHY

INTRODUCTION

The study area is located on the south flank of the central Brooks Range in a belt of heterogenous Devonian and lower Paleozoic rocks called the Skagit allochthon (informal name, after Oldow and Ávé Lallemant, 1986). The Skagit allochthon is roughly equivalent to the Skagit formation (informal) of Schrader (1902; 1904), which includes the Bettles series and the northernmost portion of the Totsen series of Schrader (1900). The rocks of the Skagit allochthon have undergone polyphase folding, thrusting, and lower greenschist facies regional metamorphism during the Brookian (Late Mesozoic to Cenozoic) orogenesis (Dillon et al., 1980).

PREVIOUS WORK

The Skagit allochthon was first described by Schrader (1900; 1902; 1904) in his expeditions up the John and Koyukuk River valleys, as a 20 to 35 km wide band of "heavy-bedded crystalline limestone and mica schist" which forms a prominent east-west trending belt across the southern Endicott Mountains." Smith (1913) and Mertie (1925) characterized it similarly in the Alatna River valley and in the Chandalar district, respectively. They described the Skagit allochthon as a calcareous schist, which becomes more sheared and schistose to the south, and noted the presence of greenstone lenses.

Smith and Mertie (1930) subsequently compiled the early expeditionary results in a summary of the geology of northwest and north-central Alaska. The Skagit formation was divided into the Skagit marble (informal) - the massive crystalline limestone facies with minor intraformational schist, and undifferentiated metamorphic rocks - mica schist, calcareous schist, chloritic schist, phyllite, slate, meta-siltstone,
quartzite, marble, marl, and greenstone. More recent 1:250,000 and 1:500,000 scale
compilations and reconnaissance geologic maps follow this scheme, differing primarily
in the mapping and correlation of the undifferentiated metamorphic rocks (Brosge,
1960; Brosge and Dutro, 1973; Brosge and Reiser, 1964, 1971; Brosge and Patton,
1982; Dillon et al., 1986).

Henning (1982) and Phelps (1987) mapped portions of the Skagit marble in the
Wiseman quadrangle in more detail, at a scale of 1:63,360 and 1:36,630, respectively,
including the first published stratigraphic columns and detailed lithologic descriptions.
Dillon et al. (1987) documented the occurrence of lower Paleozoic fossils and
conodonts in the Skagit allochthon in eastern Chaladar quadrangle.

Recognition of widespread repetition of section by thrust faulting and folding
makes the determination of true stratigraphic thicknesses difficult. The stratigraphic
thickness of the Skagit allochthon is estimated to be about 10 km (Oldow et al., 1987).

There is much debate over the age and correlation of the rocks in the Skagit
allochthon - due to the lack of distinctive and persistent mappable units and to the
paucity and generally poor preservation of fossils. The Skagit marble, which may not
be a single unit, is the most prominent map unit within the Skagit allochthon.

Sparse initial faunas collected from the Skagit marble were originally considered to
be primarily of Silurian age (Schrader, 1904; Mertie, 1925; Smith and Mertie, 1930).
Subsequently collected faunas were found to be of Devonian age. Reexamination of
the earlier collected faunas showed them to be Devonian as well (Brosge, 1960; Brosge
and Reiser, 1964, 1971). Recently collected faunas from the western portion of the
Chaladar quadrangle (Palmer et al., 1984; Dillon et al., 1986, 1987) support a
predominantly Devonian age for the Skagit marble, although it may locally include older
(Silurian?) age strata, and suggest that many of the previously undated undifferentiated
metamorphic rocks are lower Paleozoic in age.
METAMORPHISM

The rocks of the Skagit allochthon have been metamorphosed by a regional Brookian metamorphic event, as evidenced by numerous Cretaceous K-Ar cooling ages from the southern Brooks Range (Turner et al., 1979; Dillon et al., 1980). Conodonts recovered from the Mt. Snowden area have conodont alteration indexes (CAI) of 5.0 to 5.5, which indicate temperatures of 300-520° C (Dillon et al., 1987; Epstein et al., 1977; Harris and Rejebian, 1986). The metamorphic mineral assemblages observed in the study area are indicative of lower greenschist facies metamorphism (Turner, 1981).

The observed metamorphic mineral assemblages are as follows:

Siliciclastics:  
- quartz + sericite + chlorite ± feldspar ± epidote ± calcite
- ± prehnite ± graphite ± illite.

Carbonates:  
calcite + quartz ± dolomite.

Calc-silicates:  
calcite + quartz + sericite + chlorite + tremolite ± dolomite.

PROCEDURE

The study area consists of a number of thrust bound rock packages with unknown displacement histories and poorly constrained ages. Five fault bound, lithotectonic domains were defined by mapping - the North, Kupuk, Central, South, and Klippe domains (Fig. 3.1). The map units defined within each domain are primarily lithologic units and are described from lowest to highest. Correlation of the map units with units on previously published maps is given in Figure 3.2.

Unit thicknesses were estimated by pacing and trigonometric calculations on deformed sections. The observed unit thicknesses have been altered by folding and faulting and thus are not true stratigraphic thicknesses.

Primary sedimentary structures and textures are typically altered or obliterated by metamorphic and deformational fabrics. Recrystallization of calcite, quartz, and phyllosilicates is common, as is microscopic metamorphic differentiation. While
Fig. 3.1 -- Domain map of study area.
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Figure 3.2 - Correlation of map units with units of previous studies.
megascopical, and larger mesoscopic sedimentary features are often readily discernible, smaller sedimentary textures and structures are transposed and frequently obliterated. In meta-conglomerates and meta-sandstones, the original clasts and grains may be recognized although they may be strained or recrystallized. Pelitic and calcareous sedimentary fabrics are usually obliterated by metamorphic and deformational fabrics.
NORTH DOMAIN

The North domain is the structurally lowest lithotectonic domain mapped in the Skajit allochthon. It structurally overlies the Upper Devonian Hunt Fork shale of the Endicott Mountains allochthon (Phelps, 1987). The North domain consists of about 400 m of marble and chloritic calc-schist, overlain by about 850 m of varicolored phyllite (Fig. 3.3 and Plate 1). The described section occurs in the west-central portion of the mapped area - where the least repetition or truncation of the map units by faulting is thought to occur. These rocks crop out in a laterally continuous set of south dipping units which trend roughly east-west across the mapped area. Three map units are broken out (Fig. 3.3): Dsk - Skajit marble and chloritic calc-schist, Dpp - Devonian purple and green phyllite and slate, and Dkp - chloritic phyllite with marble interbeds.

The Skajit marble is considered to be dominantly Devonian in age, but locally it contains Silurian and older (?) age strata (Brosgé, 1960; Brosgé et al., 1962; Brosgé and Reiser, 1964, 1971; Palmer et al. 1984). The phyllites which overlie the Skajit marble have been mapped as of presumed Devonian age and contain rare Devonian brachiopods (Brosgé and Reiser, 1964, 1971; Dillon et al., 1986, 1987; Phelps, 1987)(Fig. 3.2).

Skajit marble (Dsk)

In the central Brooks Range, the Skajit marble has been generally mapped as a south dipping unit of Devonian or Silurian (?) and Devonian marble with intraformational calc-schist (Brosgé and Reiser, 1964, 1971; Henning, 1982; Brosgé and Patton, 1984; Dillon et al., 1986, 1987; Phelps, 1987). Locally, sections of tectonically thickened Skajit marble in excess of 1 km thick have been mapped in the central Brooks Range (Brosgé and Dutro, 1964; Dillon et al., 1986). There is no type section for the Skajit marble (informal unit). Two sections of the Skajit marble have been described: Henning (1982) in the western part of the Wiseman quadrangle, and
North domain

Dkp
PHYLLITE (Devonian(?)). Green phyllite. Upper 50 m of intercalated green phyllite and buff marble.

Dpp
PURPLE & GREEN PHYLLITE (Devonian). Sandy and silty, purple, green, and black phyllite and slate.

Dsk
SKAJIT MARBLE (Silurian(?) and Devonian). Fine crystalline marble (Dski) and chloritic calc-schist (Dskc).

Figure 3.3 – Stratigraphic column for the North domain from the west-central portion of the mapped area.
Phelps (1987) in the eastern part of the Wiseman quadrangle (Fig. 3.4).

Henning's (1982) measured a 400 m section of the Skagit marble. The basal 160 m consist of laminated marble with shallow water carbonate textures including ooid packstones and stromatoporoids. The middle 150 m is characterized by carbonate lithoclastic conglomerate, massive and micaceous marble, and calc-schist. The section is capped by 90 m of massive crystalline marble. Phelps (1987) described a 285 m section consisting of 105 m of calcareous and chloritic phyllite, schist, and marble, overlain by 80 m of calc-schist containing lenses of sheared pebble conglomerate overlain by 100 m consists of massive marble.

In the study area, the Skagit marble is represented by 350-450 m of westward thinning marble with intraformational intervals of calcareous and chloritic schist and phyllite. It crops out in south dipping sheets of massive blue-grey and tan cliff-forming marble, with poorly exposed basal and intraformational intervals of schistose and phyllitic rocks (Fig. 3.5).

**Contacts**

The lower contact of the Skagit marble is a thrust fault, which although generally not exposed, is inferred from 1) the superposition of the Silurian(?) and Devonian Skagit marble on the upper Devonian Hunt Fork Shale of the Endicott Mountains allochthon, 2) the cutting out of the Skagit marble rocks along strike, and 3) from increased strain in the upper and lower plate rocks near the contact (Phelps, 1987).

**Description**

The Skagit marble was mapped (Plate 1) as two lithofacies: massive marble (Dskl), and calcareous and chloritic schist and phyllite (Dske) (Fig. 3.3). The schistose intervals are strongly sheared and foliated mixed siliciclastic and calcareous sediments. The marble intervals are typically massive and homogenous, and consist of layers of crystalline calcite, with phyllitic partings. Abundant quartz and calcite veins and veinlets occur throughout. The described section crops out southeast of the mouth of
Figure 3.4 -- Stratigraphic columns of the Skagit limestone from western Wiseman quadrangle (after Henning, 1982) and eastern Wiseman quadrangle (after Phelps, 1987).
Figure 3.5 -- Eastward view of the northern margin of the Skagit allochthon. The Skagit marble (Dsk) and Devonian purple and green phyllites (Dpp) of the Skagit allochthon structurally overlie the Hunt Fork Shale (Dhf) of the Endicott Mountains allochthon.
Kapoon Creek, where the maximum thickness of non-imbricated section is exposed.

The basal section of the Skagit marble, at least 90 m thick, is typically covered by talus from the marble cliffs above. Infrequent small outcrops show that this section consists of chloritic, graphitic, and slightly calcareous schist and phyllite. The mineral assemblage consists of calcite, chlorite, quartz, sericite, and minor feldspar. A "paper schist" texture is observed. The rocks are increasingly deformed toward the basal contact. Interfolial lenses of stretched chert and quartz pebble conglomerate occur locally.

A prominent lower marble is mapped above the basal schist. It consists of 60 m of fine to medium crystalline, banded marble with rare interbeds of calcareous and chloritic schist. Recrystallization has obscured original sedimentary structures. The marble locally contains quartz, sericite, and feldspar. Rare discontinuous lenses of quartz, chert, shale, and quartzite pebble conglomerate are locally intercalated.

A 110 m thick section of calcareous and chloritic phyllite and schist, with 1-2 m interfolial lenses of sheared chert pebble conglomerate, is largely covered by marble talus. This section is differentiated from the basal schist and phyllite on the basis of lack of graphite, and higher calcite content.

A massive, sparsely fossiliferous, 140 m thick section of crystalline marble caps the sequence and forms the distinctive mottled grey and tan weathering Skagit cliffs in the study area. The marble is typically massive, although indistinct zones of banding and lamination are preserved. The marble varies in composition from pure white crystalline calcite to black argillaceous marbles. Rare calcareous phyllite interbeds occur in the lower 30 m. Sedimentary structures are obliterated by recrystallization which resulted in a granoblastic decussate texture of homogeneous, often twinned calcite with accessory quartz and rare feldspar. Bedding, defined by comositional layering, is variable where observed.

The marbles contain abundant brittle deformational features - veining and
fracturing - in contrast to the ductile deformational features prevalent in the lower schistose section. Calcite and quartz typically fill most of the veins in about equal proportions. Infrequent dolomite veinlets and stylolites were also observed.

Phelps (1987) (Fig. 3.5) and Dillon et al. (1987) suggested that the intraformational schistose and phyllitic intervals may conceal section repeating thrust faults within the Skagit marble. Repetition of map units in the eastern portion of the mapped area suggests that two imbricates exist, although only bedding planar intra-fomational contacts were observed. Multiple imbrications, as well as large asymmetric and recumbent folds, are clearly visible in the Skagit marble east of the Dalton Highway.

Age and interpretation

No age diagnostic fossils for the Skagit marble are known from the study area. Indeterminate poorly preserved colonial branching rugose corals, crinoid columnals, gastropods, and brachiopods were found in one outcrop in the Skagit marble (Station 4-120).

Eight Silurian(?) to early-Late Devonian assemblages are reported for the Skagit marble in the Wiseman and Chandalar quadrangles (Brosgé, 1960; Dutro et al., 1962; Brosgé and Reiser, 1964, 1971)(Figure 3.6). Collections from the uppermost Skagit marbles indicate a Frasnian (early-Late Devonian) age which may serve as an upper age limit (Brosgé et al.,1962). Palmer et al. (1984) reports Cambrian trilobites from a discontinuous marble immediately subjacent to, and reputedly unconformably underlying, the Skagit marble at Mount Snowden, 3 km east of the field area. The Skagit marble is interpreted to be Devonian in age in this area, although it may locally include Silurian, and possibly older strata.

Faunas recovered from the Skagit marble in the central Brooks Range (Oliver, 1955) include tabulate corals, rugose corals, gastropods, brachiopods, cystoids, and crinoids, are indicative of normal shallow marine paleo-environments. In the western
<table>
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<th>Date</th>
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<td>early-Late Devonian</td>
<td>rugose corals</td>
<td>Dutro et al., 1962</td>
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<tr>
<td>early-Late Devonian</td>
<td>rugose corals</td>
<td>Dutro et al., 1962</td>
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Figure 3.6 -- Fossil ages reported from the Skagit marble in the Chandalar and Wiseman quadrangles.
part of the Wiseman quadrangle, shallow water carbonate textures, intertidal sedimentary structures, ooids, and stromatoporoids are observed in less recrystallized outcrops (Henning, 1982).

The protolith of the Skagit marble is interpreted to be massive limestone with shale laminae, with intervals of fine-grained clastics. Rare faunal forms, lithology, and the sedimentary structures of the Skagit marble, along with its widespread distribution, are interpreted to indicate that the Skagit marble was deposited in an extensive Devonian, and locally older, carbonate platform or shelf (see also Brosge and Dutro, 1973; Churkin, 1973b; and Dumoulin and Harris, 1987).

Purple and green phyllite (Dpp)

The Dpp member consists of about 450 m of poorly exposed purple and green phyllite, slate, and meta-siltstone which overlie the Skagit marble. These rocks have been previously mapped as phyllite and slate of probable Devonian age (Brosge and Reiser, 1964; Dillon et al., 1987). The contacts are roughly parallel to observed bedding, although the lower contact is demonstrably sheared in the eastern portion of the mapped area and may locally be a minor thrust fault.

Description

Non-calcareous green, purple, grey, and black phyllite and slate are exposed in low, rubbly outcrops. The lowest and highest thirds of the section are dominated by green phyllite and slate, and the middle third by purple and black slate. Green and grey, graphitic silty phyllite, with accessory quartz silt, and very fine-grained quartz sand is interspersed throughout the unit. Infrequent thin beds of quartzose, sandy meta-siltstone are also observed. The unit is non-calcareous except for rare, tan weathering, fine crystalline marble lenses. Thin (1-10 mm) beds and laminations are typically transposed into a foliation defined by white mica, chlorite, and sericite crystallization.
The thickness of the purple and green phyllite sequence normally varies from about 200 to 250 m, except in the easternmost part of the mapped area where a (structurally?) thickened section in excess of 300 m is observed. No significant lateral lithologic variability was observed.

In thin section, these rocks are classified as silty or sandy phyllite and slate. The dominant lithology is a quartzose, slightly silty phyllite. The coarser grained beds contain up to 15% very-fine to fine-grained subangular quartz, 0-10% silt or sand sized opaque grains, and up to 15% fine sand sized angular and subangular lithic fragments, in a matrix of quartz silt, chlorite, prehnite, and white micas. Veinlets of quartz and calcite are sporadically observed.

**Age and interpretation**

No fossils were observed in the field area. However, one Middle(?). Devonian fossil suite of brachiopods, including *Mucrospirifer* sp., is reported from this unit 15 km to the northeast (Dillon et al., 1987).

The protolith of Dpp was an immature silty and sandy, mudstone. Silicious mudstones occur in a variety of shelfal, pro-delta, basinal, and hemi-pelagic environments which cannot reliably be differentiated without abundant preserved sedimentary structures or diagnostic fossils.

**Phyllite (Dkp)**

The Dkp member is a poorly exposed, upright sequence of interbedded green phyllite, quartz meta-siltstone, and thin buff marble which crops out on the north side of Kupuk Creek. The thickness of Dkp is controlled by the detachment level of the overlying basal Kupuk domain thrust. Dkp is cut out westward from a maximum thickness of 450 m at the eastern margin of the map area, to 150 m at the western margin. The basal contact with Dpp was mapped at the lowest bedded carbonate in the section and appears to be conformable. The upper contact is inferred to be a thrust fault
which cuts out Dkp westward (Plate 2, cross sections A-C). The 450 m thick eastern section is described next.

**Description**

The lower 400 m of Dkp consists of thin to medium-bedded phyllite and sandy meta-siltstone which generally become more calcareous higher in the section. The dominant lithology is a green weathering, silty phyllite. Infrequent dark phyllite interbeds contain pyrite-rich horizons. Interbeds of laminated, buff weathering micritic marble are interspersed throughout the section, but are most common in the uppermost 50 m. Argillaceous, often sandy, quartz siltstone is interspersed throughout, and is often finely intercalated with thin phyllite beds. Fine-grained, graded and crossbedded quartzite interbeds are also present.

In thin section, very thin beds of quartz siltstone alternate with mica-rich or phyllitic layers and lenses. Relict sand size grains are 40-60% subrounded to subangular strained quartz, 40% lithic sandstone and siltstone, and up to 10% opaque grains. Few arenitic meta-sandstone layers were observed; argillaceous material and quartz silt are usually present. Marble intercalations consist of thin bedded to laminated, fine-crystalline silicious marble interbeds along with secondary micritic lenses.

The uppermost 50 m is characterized by a section of thin to medium bedded, dark green weathering, silty and sandy phyllite intercalated with buff weathering, finely crystalline marble. The alternating green and buff color banding is distinctive in the field. Grains are quartz and, with minor calcite and feldspar. Sericite, calcite, illite?, and graphite occur as matrix material.

**Age and interpretation**

Sparse fossils were recovered from Dkp. Several marble lenses containing trilobite fragments were found near the base of the unit. One 5 mm cephalon of post-Cambrian morphology was recovered (Station 5-198), as were indeterminate,
Stauriid rugose corals (Station 5-157) (identifications by L. Gore). The rocks of Dkp must be younger than Early Ordovician because the first appearance of rugose corals occurs in the middle Ordovician (Shimer and Shrock, 1944). Because the Dkp unit seems to overlie the Devonian Dpp unit stratigraphically, Dkp is considered to be Devonian(?) in age.

The sedimentary protolith of Dkp was an alternating sequence of thin bedded quartz silt and mud, with occasional intercalations of carbonate, becoming more calcareous and slightly finer grained upward. The fine intercalations of silt and shale, and silt and carbonate lithologies, and regular sedimentary perturbations of coarser material, along with the observed laminations in the phyllite, and cross-beds and graded bedding in the quartzite, are suggestive of turbidites.
KUPUK DOMAIN

The rocks of the Kupuk domain crop out on the south side of Kupuk Creek, in a laterally continuous set of south dipping units. Previous workers have mapped these rocks as unfossiliferous, fine-grained clastic and carbonate rocks of uncertain correlation but presumed Devonian (Brosge and Reiser, 1964, 1971; Phelps, 1987) or Devonian and older ages (Dillon et al., 1986, 1987)(Fig. 3.6). Three map units are broken out (Fig. 3.7): Pzcp - phyllitic marble, Pzs - olistostromal argillite, and Pzh - black slate. Rare fossils constrain the Pzcp-Pzs-Pzh sequence as pre-Carboniferous and post-Early Ordovician in age. These rocks are interpreted to be of probable Ordovician and Silurian (?) age on the basis of correlation of the Pzcp phyllitic marble with lithologically similar Ordovician conodont bearing marbles, at approximately the same stratigraphic level 5 km on strike to the east (unit Om of Dillon et al., 1987).

Phyllitic marble (Pzcp)

The Pzcp member consists of about 500 m of thin-bedded, phyllitic marble and calcareous phyllite which contain channels filled with sheared quartz and lithic pebble conglomerate. The basal contact is a thrust fault which cuts out lower plate (North domain) rocks westward, but is generally bedding planar to the upper plate (Kupuk domain) rocks. The underlying Dkp phyllite is lithologically similar to the lowermost calcareous phyllites of Pzcp, but does not contain marble beds or intervals thicker than 0.5 m.

Description:

The dominant Pzcp lithology is an argillaceous, very fine to fine-crystalline black marble with phyllitic partings and phyllitic intervals and interbeds. This marble weathers to a mottled light brown color and is thin to medium-bedded. Marble intervals are separated by 1-10 m intervals of calcareous, dark and green phyllite and phyllitic siltstone, and subordinate lithic quartz-wacke. The uppermost 100 meters becomes
Kupuk domain

Pzsh
BLACK SLATE (pre-Carboniferous).

Pzs
ARGILLITE (post-Early Ordovician, pre-Carboniferous). Fining upward sequence of meta-siltstone, argillite, & phyllite. Dolomite olistoliths in carbonate conglomerate flows in the upper third.

Pzep
PHYLLITIC MARBLE (post-Early Ordovician and pre-Carboniferous). Calcereous phyllite grades upward into phyllitic marble. Local conglomerate filled channels.

Figure 3.7 -- Stratigraphic column for the Kupuk domain.
increasingly phyllitic and pyritic toward the top.

Pzcp contains a number of conglomerate lenses and channels. Channels exceeding 7 m in thickness were observed. Matrix and clast support conglomerates show thick, indistinct bedding with no evidence of grading. The dominant clast size is 0.5-1 cm. Matrix composition is approximately equivalent to that of the Pzcp meta-wacke interbeds. Clasts, in order of relative abundance are: rounded to angular quartz pebbles, angular black (Pzcp) marble pebbles and cobbles, sub-rounded quartzite and siltstone pebbles, phyllite pebbles, and rare coral fragments. The marble clasts are lithologically similar to the Pzcp marble and tend to be larger and more angular than the siliciclastic clasts, measuring up to 15x12x6 cm.

The Pzcp marble ranges in composition from a fine crystalline silicious marble, to argillaceous black marbles with up to 30% phyllosilicates, opaque residue, and quartz. Siliciclastic beds range from calcareous and quartzose silty phyllite to calcareous meta-greywacke. Relict sand size grains are 20-40% calcite, 20-30% angular quartz, 7-15% meta-siltstone and phyllite, 2-4% lithic volcanic fragments, and 0-2% feldspar.

Age and interpretation

One fossil suite, containing an indeterminate gastropod mold and several indeterminate rugose corals was observed (Station 5-157). Rugose corals are restricted to the Middle Ordovician to Upper Permian (Shimer and Schrock, 1944). The age of Pzcp is bracketed from Middle Ordovician to Devonian time. Dillon et al. (1987) correlate Pzcp with lithologically similar, late-Early to middle-Late Ordovician marbles 5 km to the east.

The sedimentary protolith of Pzcp was a thin bedded calcareous and terrigenous mud cut by channels filled with silicic and carbonate conglomerate. The regular thin bedding, the frequent occurrence of alternating layers of marble and phyllite, and the presence of siliciclastic conglomerate lenses are strongly suggestive of clastic carbonate deposition, either as argillaceous calci-turbidites or as argillaceous calci-siltites and lime
muds. Two possible environments of deposition are indicated - a prodelta complex, or a carbonate slope or base of slope apron.

Argillite (Pzs)

The Pzs member consists of about 1300 m of a poorly exposed, fining upward sequence of argillaceous quartz meta-siltstone, phyllites, and volcanigenic argillite. Dolomite olistoliths in channelized carbonate conglomerate occur in the upper third. Pzs stratigraphically overlies the Pzcp marble. The contact is mapped at the top of the last marble bed.

Description

Thin to very thin-bedded, black siliceous meta-siltstone becomes increasingly finer-grained and argillaceous upward, eventually grading into black silty phyllite and porcelainous argillite. Relict upright crossbedding, grading upward sequences, and laminations are observed in outcrop and thin section.

Samples from the lower 500 m of Pzs are phyllitic siltstone with a mean composition of 65% quartz silt, 5% very fine-grained quartz sand, 5-10% pyrite, 5% feldspar, and 15% phyllosilicates. Laminations, and upright climbing ripples, tabular crossbed sets, and graded beds were observed. The middle 400 m are silty (5-20% quartz silt), locally pyritiferous, phyllites which exhibit laminar to very thin-bedding and fining-upward sequences. The uppermost 400 m consists of black slatey phyllite which contains distinctive intervals of porcelainous silicious argillite whose constituents - quartz, chlorite, talc, epidote, and magnetite(?) are suggestive of a volcanogenic protolith.

Two large dolomite olistoliths occur in a zone of channelized carbonate lithoclastic conglomerate about 80 m below the top of Pzs. The olistoliths are larger than 25 m, and protrude prominently from the surrounding phyllite. They are composed of laminated, patchily microcrystalline dolomite containing abundant soft sediment
deformation structures. The black, siliceous dolomite weathers mottled orange-brown. Sparse brachiopods and rugose corals were preserved in non-dolomitized, micritic patches. Internal bedding is contorted and discordant to the surrounding phyllites. Channelized carbonate lithoclastic conglomerate flows envelope the olistoliths. These medium to very-thick bedded flows pinch out laterally within 50 m. They contain very poorly sorted subangular dolomite and micritic marble clasts ranging in size from coarse pebbles to boulders. The matrix is irregularly crystalline marble.

**Age and interpretation**

No fossils were found in the argillite. A fossil suite consisting of an indeterminate brachiopod and gastropod, and rugose coral fragments were found in the olistoliths - which limit both the olistoliths and Pzsh to post-Early Ordovician age (Shimer and Schrock, 1944).

The Pzs sequence is interpreted as representing a fining upward turbidite sequence. The carbonate olistostromes represent massive slide deposits which originated at a carbonate shelfbreak, platform, or slope, and slid into the lower slope environment.

**Black slate (Pzsh)**

Pzsh, the uppermost member of the North domain, consists of about 180 m of unfossiliferous black phyllitic slate. The basal contact is gradational with the Pzs; it is mapped at the first true (non-phyllicitic) slate. Pzsh is cut out to the west by the basal Central domain thrust. The generally non-calcareous slate is locally pyritiferous, and infrequently contains up to 15% quartz silt.

No fossils are known from this lithology. Since Pzsh apparently conformably overlies Pzs, the age can be restricted from post-Early Ordovician to Devonian? The protolith of Pzsh was a mudstone which caps the Pzs-Pzsh fining upward sequence.
CENTRAL DOMAIN

The Central domain is a thrust bound sequence of imbricated volcanogenic meta-conglomerate, wacke, and phyllite. The observed structural thickness of the Central domain varies from 2200 m to 3200 m.

These imbricates have been previously mapped as unfossiliferous, volcanic-pebble conglomerate and volcanogenic wacke and phyllite of unknown, but speculated Devonian(?) age (Brosge and Reiser, 1964, 1971; Brosge and Patton, 1982), Devonian(?) or older age (Dillon et al., 1986), or Cambrian(?) - Ordovician(?) age (Dillon et al., 1987) (Fig. 3.2).

Two laterally equivalent facies were mapped in this study: Ovc - volcanic pebble meta-conglomerate and wacke, occurring in the east and central portion of the map area, and Ovs - volcanogenic wacke and phyllite which is best developed in the west. The volcanic pebble conglomerate is generallyly restricted to the area between the Hammond and Dietrich Rivers. The age and interpretation of the Ovc-Ovs facies will be jointly discussed following their lithologic descriptions.

Volcanic pebble conglomerate (Ovc)

The Ovc facies consists of polymictic and monomictic, volcanic and lithic pebble meta-conglomerate interbedded with volcanogenic meta-sandstone, meta-wacke, and phyllite (Fig. 3.8). This facies is exposed in two thrust sheets in the eastern and central portion of the mapped area, and has a tectonic thickness which varies from 900 to 1600 m between the imbricates. The Ovc facies consists of an upright sequence of proximal meta-conglomerate and meta-wacke - which grades laterally into the finer grained Ovs facies.

Description

The Ovc facies is composed of interbedded volcanic pebble meta-conglomerate, lithic meta-sandstone, and meta-wacke, with phyllitic interbeds and partings (Fig. 3.9).
Figure 3.8 - Schematic stratigraphic columns for the Central domain. Ovc and Ovs are age equivalent rock units representing different facies. The fine-grained Ovs facies occurs mostly in the west, and the coarse-grained Ovc facies occurs in the eastern and central parts of the map area. Ovs and Ovc columns taken along Cross Section lines C and A, respectively (Plate 2).
Figure 3.9 — Northwest view of the volcanic pebble conglomerate unit (Ovc). Normally graded and (upright) cross-stratified, 10 - 50 cm thick beds of volcanic-pebble meta-conglomerate and volcanogenic meta-wacke are exposed. These rocks represent proximal alluvial and mass flow fanglomerates.
The meta-conglomerate is medium to very thickly bedded, and contains lenses and interbeds of medium and thinly bedded lithic meta-wacke and phyllite. The Ovc conglomerate and meta-sandstone typically weather mottled green and grey, with the meta-wacke and phyllite weathering dark green. Elongate clasts and grains often exhibit aspect ratios of 3:1 to 10:1, and infrequently, up to 35:1. Cleavage is irregular, with the foliation defined by the preferred orientation of phyllosilicates and elongate clasts.

Both matrix and clast supported conglomerates were observed which grade laterally and vertically into wackes. Most conglomerates were polymictic although several monomictic conglomerates were observed. Abundant cut and scour surfaces, upright cross-stratification and graded, non-graded, and reverse graded sequences were observed. Overlapping subaqueous and subaerial(?) matrix and clast supported debris flows up to 3 m thick are most common. Graded and non-graded matrix and clast supported conglomerates are observed, with % matrix increasing upward. The bases of the flows are generally sharp and erosive, but channels are not well developed. Less common braided stream successions, consisting of repeated fining upward, 1-2 m thick conglomerate-wacke sequences, are locally important. Lenses of silty phyllite are thinly interbedded throughout the section.

The conglomerate clast composition varies between the two Ovc imbricates. The northern Ovc imbricate has a maximum structural thickness of about 1600 m and is characterized by volcanic and quartz pebble meta-conglomerate and meta-wacke. Clasts range in size from coarse sand (1 mm) to medium boulders (30 cm). The average clast size is estimated to be large granule size or small pebbles (3-10 mm). Intermediate composition aphanitic and fine crystalline lithic volcanic pebbles, quartz, and quartzite comprise 50-75% of the observed clasts, with lithic-wacke, quartz-wacke, quartz siltstone, and phyllite clasts comprising almost all of the rest. Carbonate and chert clasts occur locally. Angular phyllite flags commonly form the largest clasts, with the volcanic and silicic lithic clasts being smaller and more rounded. A 6x6x12 cm volcanic, flow-banded, scoriaceous clast
Figure 3.10 — A flow banded, scoriaceous bomb or clast in an Ove fine grained volcanogenic meta-conglomerate. Note the 0.5 cm reaction rim around the scoria.
or bomb was observed (Fig. 3.10). The clast assemblages are, in order of relative abundance: 1) a lithic volcanic clast and quartz pebble assemblage; 2) a quartz and lithic clast assemblage; and 3) and infrequently, a carbonate rich, lithic clast assemblage.

The southern Ovc imbricite has a maximum structural thickness of 1400 m. It has the same gross sedimentology as the northern imbricite, but has more lithic carbonate clasts and fewer volcanic-pebble clasts. The volcanic clasts decrease in number upward in the section, with a concomitant increase in lithic limestone and dolomite clasts. The average clast composition of the southern Ovc imbricite is 20-35% lithic carbonate pebbles and cobbles, 15-25% quartz pebbles and granules, 10-25% volcaniclastic lithic granules, pebbles, and cobbles, and 25-35% silicic lithic granules and pebbles. Intervals of carbonate and quartz pebble conglomerate, containing less than 10% volcanic clasts, crop out in the upper half of the section.

Volcanic clasts show a relict aphanatic texture, and contain relict quartz, twinned feldspar, and amphibole. Identification of the volcanic minerals, even in thin section, is inhibited by the ubiquitous alteration of the volcanic constituents - particularly to chlorite and sericite. Major element ICP analysis of two samples yielded intermediate (dacitic(?)) compositions (Appendix 1).

Matrix is commonly a quartzose and volcanic lithic-wacke which shows extensive alteration of volcanic grains. The volcanic grains are typically highly chloritized and sericitized, although relict plagioclase and amphibole porphyroclasts are often distinguishable in thin section. Matrix sand composition is 20-30% subangular quartz, 15-40% angular lithic sandstone and wacke, siltstone, and phyllite, 20-35% altered volcanic and feldspar grains, and 0-5% opaque grains.

Volcanogenic meta-sandstone, meta-wacke, and phyllite are interbedded within the meta-conglomerate. The meta-sandstone comprise 20-30% of the section. Bedding is variable, but 1-3 cm thick beds are most common. Some upright ripples and normal grading were observed. Sand composition is similar to the matrix composition of the
conglomerates. Original grains are angular and generally poorly sorted. Poorly sorted, 
argillaceous, silty, and sandy meta-wackes occur in thin to medium beds, and are generally 
crudely graded. Thin beds and partings of silty or sandy phyllite occur throughout the 
section, and increase in frequency and thickness westward.

**Volcanogenic phyllite and wacke (Ovs)**

The Ovs facies, which has a tectonic thickness of up to 2250 m, consists of 
volcanogenic meta-wacke, meta-siltstone, and phyllite, with meta-sandstone and 
meta-conglomerate interbeds. An interval containing two discontinuous zones of 
argillaceous, thin-bedded marble (Ovsl) was also mapped.

The Ovs facies becomes coarser grained eastward - where it interfingers with, and 
grades into the Ovc facies. Ovs is the finer grained or more distal equivalent of the Ovc 
facies. The lateral boundary between the Ovc and Ovs facies is mapped where the 
meta-conglomerate comprises less than 10% of the exposed outcrop.

**Description**

The majority of the section is comprised of interbedded, green weathering, 
very-thin to medium bedded meta-siltstone and phyllite which contain relict grading and 
upright crossbeds. In outcrop and thin section, lithic and quartz arenitic meta-sandstone, 
siltstone, and wacke are often rhythmically interbedded with phyllite, and frequently show 
relict cross stratification, grading, and laminations.

Fine-grained meta-conglomerate is present, but decreases in frequency westward. 
Clastic distribution is the same as observed in the Ovc facies, but with quartz clasts 
comprising the largest size fraction. Matrix material is volcanogenic, lithic and quartz, sand 
and silt with lesser amounts of pelitic material. Relict grading is frequently observed.

Two laterally restricted carbonate zones (Ovsl) were mapped at approximately the 
same stratigraphic level in the eastern portion of Ovs. They consist of up to 100 m of 
laterally restricted, orange-brown weathering black marble which is laminated to medium
bedded, argillaceous and fine-crystalline, and has phyllitic partings. No primary or relict primary sedimentary structures or textures other than bedding were observed. The Ovs-Ovsl contact, where exposed, occurs in an apparently conformable interval of dark, calcareous phyllite. No subjacent or marginal conglomerate was observed. No structural discordances were observed.

**Age and interpretation**

No fossils have been found in the Central domain. A correlative interval of polymictic volcanic pebble conglomerate 5 km on strike to the east (OCvc of Dillon et al., 1237), crops out stratigraphically below an Ordovician conodont bearing marble. Dillon et al. (1987) map this volcanic-pebble conglomerate as Cambrian(?) to Ordovician(?), although their map and cross section clearly show OCvc interfingering with Ordovician conodont bearing strata. This relationship was also observed in reconnaissance. An Ordovician(?) age for OCvc, and hence for Ovc and Ovs, is the preferred interpretation of the field relationships.

The Ovc facies represents a thick, but restricted sequence of volcanogenic, dominantly submarine mass flow conglomerate with subordinate braided stream conglomerate. Maximum clast size and the general immaturity of clasts and matrix argue for a proximal source and high sedimentary gradient. Ovc is interpreted to represent a proximal fan or alluvial fan complex.

The protolith of Ovs is thin to very thin bedded intercalations of volcanogenic phyllite, graded beds of lithic silt, sand, silty mud, and thin conglomerate. Ovs is interpreted to represent the more distal facies of Ovc - consisting of finer-grained mass flow deposits. Two pods of argillaceous carbonate (Ovsl) were mapped within Ovs. Active siliciclastic sedimentation inhibits carbonate production, and generally precludes the development of significant biogenic deposits, although organic buildups and active reefs can occur on delta or fan-delta lobes (Santisteban and Taberner, 1988). The thickness (up to 100 m) of the pods of carbonate suggests that a purely biogenic protolith is unlikely.
Tectonic inclusion of the Ovsl carbonate zones within Ovs was initially considered to be the most probable explanation. However, no evidence of faulting was observed. The lack of marginal or subjacent conglomerates, and the concordance with the surrounding bedding would seem to discount the possibility of olistromal emplacement. The thin bedded character of the marbles, the ubiquitous presence of argillaceous material, and the presence of carbonate clasts in the Ovc conglomerates suggests that a calciclastic origin of Ovsl, is not improbable.
SOUTH DOMAIN

The South domain is comprised of about 1200 m of south dipping Devonian calcareous meta-sediments and marble, and Paleozoic quartzite. These rocks crop out in the eastern end of an east-west trending, west plunging syncline which is structurally cored by the Jesse klippe. The Devonian rocks are divided into three map units: a lower member, Dcl, of calcareous phyllite; a middle member, Dcm, of massive marble; and an upper member, Dcu, of calcareous phyllite (Fig. 3.11). Over most of the map area, the rocks of the South domain are not imbricated. However, in the southeasternmost outcrops, a series of small thrusts imbricate Dcl and expose a fourth unit, Pzbs, an imbricate of quartzite of uncertain age. Faunal assemblages and sedimentary structures indicate shelfal carbonate and clastic deposition, with variable fine-grained terrigenous input. The rocks of the South domain are age equivalent to the Beaucoup Formation of the Endicott Mountains allochthon (Dutro et al., 1979).

Lower calcareous phyllite (Dcl)

The lower member, Dcl, is comprised of about 800 m of poorly exposed calc-silicate, phyllite, meta-sandstone, layers and biothermal lenses of fossiliferous argillaceous marble, and meta-igneous sills, dikes, and flows (Fig. 3.11). The age of Dcl is constrained to be post-Siegenian and pre-Frasnian. Dcl structurally overlies Ovc above the basal South domain thrust, and is increasingly cut out from east to west.

Description:

Interbedded calc-silicates and phyllite comprise the bulk of the section, but they are not well exposed. The calc-silicates are schistose and locally contain finely intercalated phyllosilicate-rich layers, quartz-rich layers, and calcite-rich layers. More commonly, a thin to medium bedded, quartzose and calcareous argillite is observed. Calcareous and non-calcareous, silty grey phyllite comprises about 20% of the section.
South domain

**Dcu** UPPER CALCAREOUS PHYLITE (post-Emsian and pre-Famennian). Fossiliferous calcareous phyllite and marble.

**Dcm** MIDDLE MARBLE (Middle Devonian). Massive, fossiliferous marble.

**Dcl** LOWER CALCAREOUS PHYLITE (post-Siegenian and pre-Frasnian). Fossiliferous alcalcareous phyllite, meta-siltstone, and argillaceous, marble. Mafic and intermediate composition greenstones in the lower 250 m.

**Pzbs** QUARTZITE (Devonian or older). Black crossbedded quartzite.

Figure 3.11 — Stratigraphic column for the South domain.
Thin to medium interbeds of cross-beded calcareous quartz meta-sandstone and calc-arenite are interspersed throughout the unit. Quartz sandstone consists of approximately 60% quartz, 15% lithic grains, 10% carbonate, 3% feldspar, 4% opaque grains, and 8% unidentifiable grains. Calci-clastic sandstone consists of 60-70% carbonate, 20% quartz, 7% lithic grains, 2% feldspar, 3% opaque grains. Fossiliferous interlayers and biohermal lenses of argillaceous marbles occur throughout, but are most common in the upper third. Fossiliferous lenses of argillaceous, fine-crystalline marble, contain rugose corals, crinoid columnals, brachiopods, gastropods, and platyceratids, in varying degree of preservation (Fig. 3.12).

A number of bedding parallel layers of meta-volcanic rocks are localized in the lower third of Dcl. These have been previously mapped as Devonian felsic flows, tuffs, lahars and bimodal intrusives (Broségé and Reiser, 1964; Dillon et al., 1986, 1987a, 1987b). These greenstones are exposed in concordant lenses and medium to thick beds. The aphanitic constituents are highly altered by chlorite and sericite. Relict flow banding and possible grading were observed. Chilled margins, the absence of chilled margins, contact aureoles, and the absence of contact aureoles were observed. In thin section, the greenstones are aphanitic porphyritic, with 1-4 mm phenocrysts of relict feldspar, pyrite, and indeterminate mafic grains. The feldspar and mafic grains are largely altered to, and lie in, a matrix of chlorite + sericite + quartz ± epidote ± actinolite(?). ICP analyses of five samples show generally basaltic major-element compositions (Appendix 1).

Age and interpretation

Carbonate interbeds and buildups, are abundantly fossiliferous, but with widely varying degrees of preservation due to recrystallization (Fossil identifications are given in Fig. 3.12). The dated fossils did not appear to be broken or abraded. Resedimented
Unit | Station | Fossils
--- | --- | ---
Dcu (post-Emsian and pre-Famennian)

Identified by R. Blodgett.
4-273 colonial rugose corals
        gyronematid gastropod, n. sp.

Dillon et al., 1987 (Conodonts, identification by A. Harris)
D87-2  *P. cf. P. linguiformis* Hinde
        *Icriodus* sp.
        *Polynathus xylos xylos*
        *Pandorinellina insititia* (Stauffer)

Dcm (Eifelian-Givetian)

Identified by R. Blodgett.
4-114  ribbed atrypid brachiopods, either *Spinatrypa* or *Spinatypina*
        atrypid brachiopods
        exfoliated brachiopods

4-204  brachiopods
        solitary rugose corals

4-238  platerceratid gastropods
        bellerophantacean gastropods
        exfoliated brachiopods
        solitary rugose corals
        crinoid ossicles

Dcl (post-Siegeninan and pre-Frasnian)

Identified by R. Blodgett.
4-178  *Straparollus* (*Serpulospira*) sp
        *Straparollus* (*Euwornallus*) sp.
        *Baylea*?
        subulitid gastropods
        *Yunnania*? sp.
        gypidulinid brachiopods
        indeterminate brachiopods
        naticopsid gastropods
        straparallid gastropods
        platceratid gastropods
        turbiniform gastropod
        colonial rugose corals
        solitary rugose corals
        crinoid ossicles

Brosgé and Reiser, 1964 (identifications by W.A. Oliver Jr.)

BR64-1  stromatoporoids
        *Amphipora* sp.
        *Alveolites* (?) sp.
        rugose corals
        thamnoporoid corals

Dillon et al., 1987 (Conodonts, identification by A. Harris)

D87-1  *Polynathus cf. P. pseudofoliatus* Wittekindt
        panderodontacean (?)

Figure 3.12 -- South domain fossil assemblages. Fossil locations are indicated on Plate 1.
corals were observed in several locations, but were not sampled for dating. Brosge and Reiser (1964) dated the rugose corals in one biohermal lens as of probable Frasnian age. One conodont has been dated by Dillon et al. (1987) as Givetian to early Frasnian. Fossil suites of brachiopods and gastropods constrain the age to post-Siegenian to pre-Frasnian but are strongly indicative of Eifelian to Givetian (Middle Devonian) age (R. Blodgett, written communication, 1985).

The sedimentary protolith of Dcl is shallow marine marl and mud with local carbonate buildups, locally containing coarser calciclastic and siliciclastic material. Faunal assemblages indicate a shallow shelfal environment.

The concordant greenstones could not be unambiguously determined to be intrusive or extrusive. They are interpreted to represent localized volcanism which may be in part contemporaneous with sedimentary deposition and which may be correlative with the Devonian Ambler volcanics (Dillon et al., 1986).

**Middle marble (Dcm)**

The Dcm member forms a prominently exposed, massive gray marble which weathers into mottled gray cliffs with blocky talus slopes. Dcm is mapped as 40-150 m of fossiliferous, Middle Devonian marble. Although the lower contact is covered, it is bedding parallel and is assumed to be conformable.

**Description**

The Dcm marble is a massive, fine to coarsely crystalline fossiliferous marble, argillaceous in part, with phyllitic partings. Bedding is generally thick, but variable and indistinct. Abundant brachiopods, bryozoans, rugose corals, gastropods, and crinoid columnals are observed in less crystalline zones, but are typically poorly preserved. Intercalated thin beds of fossiliferous packstone and wackestone, and crossbedded calc-arenite were recognized. Quartz and calcite filled veins are present throughout the
section in approximately equal proportion. In thin section, Dcm is characterized as a fine to coarse crystalline marble with granoblastic polygonal texture.

**Age and Interpretation**

The fossil suites collected from Dcm, including gastropods, solitary and colonial rugose corals, and brachiopods, indicate a Eifelian to Givetian (Middle Devonian) age (written communication, R. Blodgett, 1985). Devonian and early-Late Devonian corals, brachiopods, and stromatoporoids were observed in four sites west of the study area Brosgé and Reiser (1971). Fossil identifications are listed in Fig. 3.12. Faunas are shallow marine assemblages. The Dcm marble is interpreted to represent a relatively clean, shallow shelfal carbonate buildup.

**Upper Calcareous Phyllite (Dcu)**

The Dcu member consists of Middle to early-Late Devonian calcareous phyllite, meta-wacke, and marble. A maximum of 150 m of section, conformably overlying the massive marbles of Dcm, is exposed on the south side of the Klippe domain, and is cut out above by the basal Klippe domain thrust.

**Description**

Interbedded calcareous and siliceous, silty phyllite comprises the bulk of the observed section of Dcu. Fossiliferous, fine-crystalline, argillaceous marble lenses locally contain coral debris, relict upright burrows, and crossbeds. Carbonate buildups contain colonial and solitary rugose corals and gastropods. Calcareous wacke and rare sandstone have an average sand composition of 60% quartz, 25% lithic grains, 10% carbonate, 1% feldspar, and 4% opaque grains.

**Age and Interpretation**

Conodonts (Dillon et al., 1987) and gyronematid gastropods constrain the age of Dcu to post Emsian and pre-Fammenian (written communication, R. Blodgett, 1985).
Fossil identifications are listed in Figure 3.12. The protolith of Dcu is interpreted to be shallow marine silts and muds, with small localized muddy limestone buildups.

**Quartzite (Pzbs)**

The Pzbs member consists of an estimated 250 m of quartzite and quartz meta-siltstone exposed in a fault-bound horse (Fig. 3.11). Only the upper and lower 50 m was observed. Low quartzite outcrops weather dark grey and form equant black talus blocks and boulders.

Pzbs is characterized by thin-bedded quartzite, sandy meta-siltstone, and quartz wacke, with common cosets of tabular and small-scale trough stratification, laminae, and climbing ripples. Infrequent graded bedding and pinch structures are also observed. In thin section, the quartzite is sucrosic textured quartz arenite with accessory feldspar. The meta-siltstone and quartz wacke contain up to 10% lithic grains, 3% feldspar, and 3% relict mafic grains.

No fossils were observed in Pzbs. The rock age is assumed to be Devonian? or older. The character of the bedding, sediments, and sedimentary structures is consistent with a number of alluvial, fan, and deltaic environments.
KLIPPE DOMAIN

The rocks of the Klippe domain form the structurally highest lithotectonic package in the mapped area. They are exposed in the Jesse klippe, only the eastern end of which was mapped. Approximately 1900 m of section was mapped without encountering the top of the section. The domain is divided into three map units: a basal calc-phyllite (Pzkb), an overlying phyllitic marble (Pzkc), and an upper section of argillite (Pzks) (Fig. 3.13). The rocks which crop out in the klippe are more strongly deformed and folded than the previously described rocks, and primary sedimentary structures are almost entirely transposed by deformational fabrics.

The rocks of the Jesse klippe were previously mapped as Devonian although no fossils have been reported (Brosgé and Reiser, 1964, 1971; Dillon et al., 1986, 1987). The argillaceous klippe rocks, roughly corresponding to Pzks, were suggested to be lithologically similar to the lower Paleozoic slate exposed in the Doonerak window by Brosgé and Patton (1982). Meagre fossil and microfossil data suggest a lower Paleozoic(?) age for the Klippe domain strata.

Basal calc-phyllite (Pzkb)

Pzkb consists of 80-150 m of highly sheared and folded, argillaceous fine crystalline marble, intercalated with schistose calc-wacke, and calcareous phyllite. Pzkb is cut out northward by the basal Klippe domain thrust. The mottled-orange weathering, unfossiliferous marble and phyllite of Pzkb are readily distinguishable from the underlying grey weathering, fossiliferous phyllite and argillaceous carbonate (Dcl) of the South domain. The upper contact with the Pzkc marble is bedding parallel and gradational, and is interpreted to be stratigraphic.

Description

The dominant lithology of Pzkb is argillaceous marble, with subordinate phyllitic
Klippe domain

Pzks
ARGILLITE (Lower Paleozoic?).
Greywacke, quartzite, and silicious argillite with interbeds of argillaceous marble. Becomes more calcareous upward.

Pzkc
PHYLLITIC MARBLE (Lower Paleozoic?).
Orange-brown weathering, thin and medium bedded fine-crystalline argillaceous marble with phyllitic partings.

Pzkb
CALC-PHYLLITE (Lower Paleozoic?)
Calcareous phyllite, argillaceous marble, and calc-schist.

Figure 3.13 – Stratigraphic column of the Klippe domain.
intercalations and intervals of schistose calc-wacke and phyllite. The Pzkb marble is thin to medium bedded, and has phyllitic partings. The marble is dark and fine-crystalline, and weathers a mottled orange-brown. Calcareous, silty phyllite is interspersed throughout the section. Thin and medium interbeds of schistose and quartzose calc-wacke are locally observed.

**Age and interpretation**

No fossils were observed in Pzkb. Since it appears to stratigraphically underlie strata bearing lower Paleozoic conodonts, Pzkb is inferred to be lower Paleozoic in age. The protolith of Pzkb was an argillaceous limestone. There is insufficient data to determine whether it was a shallow water or deep water carbonate.

**Phyllitic marble (Pzkc)**

The Pzkc unit is a 900 m section of highly deformed and recrystallized, orange weathering phyllitic marble of suggested lower Paleozoic age (Fig. 3.13). It crops out as a north dipping sequence on the southern flank of the Jesse klippe, and is cut out northward.

**Description**

Pzkc is a homogenous sequence of dark, finely crystalline argillaceous marble with phyllitic partings. Thin interbeds of calcareous quartz siltstone and calcareous phyllite comprise less than 5% of the section. The unit is very regularly thin bedded, with a maximum observed bed thickness of 10 cm. Dark to black, argillaceous marble weathers into orange-brown, steep and rubbly slopes. Relict, upright graded sequences are very rarely preserved.

In thin section, the Pzkc lithology is a very finely crystalline, argillaceous marble or marl. Calcite, quartz, and phyllosilicates are homogenously distributed in a very fine-grained, granoblastic polygonal texture. Relict bedding and bedding parallel
lithologic bands were the only unequivocal sedimentary structures observed.

**Age and interpretation**

Several conodont forms and fragments of pre-Devonian morphology were recovered from bulk samples of four sites (R. Tipnis, written communication, 1985). The rocks of Pzkc are interpreted to be of probable lower Paleozoic (?) age.

The sedimentary protolith of Pzkc is a muddy limestone. The bedding distribution is strongly suggestive of clastic carbonate deposition. The environment of deposition of Pzkc is consistent with the deposition of calc-turbidites or calcilutites.

**Argillite (Pzks)**

The Pzks member is comprised of more than 800 m of siliceous argillite, quartzite, and marble which crop out above Pzkc, and extend into the interior of the Jesse klippe. The top of the section was not observed in the map area. The lower contact occurs in a 30 m covered interval where the lithologies change from carbonate to siliciclastic rocks. The Pzkc-Pzks contact is bedding parallel, and is interpreted to be stratigraphic in nature.

**Description**

The Pzks lithology is characterized by a heterogeneous sequence of intercalated quartzite, quartz meta-wacke, siliceous argillite, phyllite, and argillaceous marble, which become generally more calcareous upward in the mapped section. Strongly deformed, 20 - 50 m intervals of silty, carbonaceous, and quartzose marble forms mappable horizons (Pzksl) within an otherwise poorly exposed sequence. Bedding, where recognizable, is generally thinner than 5 cm in the lower 600 m of section. The upper 200 m of mapped section is a thick to thinly bedded sequence of calcareous clastics - fine grained quartzite and coarse quartzose meta-siltstone.

The Pzks rocks are characterized by deformational and metamorphic fabrics.
Relict, upright crossbeds were observed in one quartzite bed. Laminations and small-scale cross-stratification are locally distinguishable. Regular thin beds, rhythmic in places, are characteristic. Several brachiopods and coral fragments were collected from an argillaceous quartzite near the base of the unit, comprising the only known macrofossils from the Jesse klippe (Station 5-250).

Tectonite fabrics predominate in thin section. Observed grains were strained and recrystallized. Single and polycrystalline, polygonal quartz comprises 90+% of the sand size grains. Carbonate is present as recrystallized and twinned, very fine-crystalline to microcrystalline calcite.

**Age and interpretation**

Conodont forms and fragments of pre-Devonian morphology were recovered from bulk samples from the Pzks carbonate horizons (written communication, R. Tipnis, 1985, 1986). Poorly preserved atrypid? brachiopods recovered from the basal Pzks rocks constrain Pzks to post-Early Ordovician age (Shrimer and Shrock, 1944). The lower Pzks rocks are therefore interpreted to be Silurian?–Ordovician? in age.

The sedimentary protoliths of Pzks were thin to medium bedded, variably calcareous, fine-grained quartz silts and muds intercalated with fine quartz sand and lime muds. The mixed fine-grained siliciclastic and calcareous lithologies could be generated in a variety of shallow shelf, slope, or hemipelagic environments, but are interpreted to be most consistent with transitional siliciclastic and carbonate shelfal sedimentation.
IGNEOUS ROCKS

Two sets of meta-igneous rocks were observed, hornblende diorite dikes and bedding parallel greenstone layers. The greenstone layers are interpreted to be at least in part volcanioclastic, and are described in detail with the sedimentary rocks in which they occur (principally with Dcl). Major-element compositions of samples was determined by ICP spectrometer analysis - discussed in detail in Appendix 1.

A number of chloritized volcanic greenstones occur in Dcl and Ovs. These rocks have been previously mapped as Devonian felsic flows, tuffs, lahars and bimodal intrusives (Brosge and Reiser, 1964; Dillon et al., 1986, 1987a, 1987b). ICP analyses of five samples show generally basaltic major element compositions (Appendix 1). These concordant meta-volcanic rocks could not be unambiguously determined to be extrusive or intrusive. Chilled margins, non-chilled margins, graded and non-graded sequences, and contact aureoles (?) were observed. They are interpreted to represent localized volcanism which may be in part, contemporaneous with sedimentary deposition.

These volcanic rocks appear to be correlative with a discontinuous belt of volcanic rocks extending from the Ambler volcanic rocks in southwestern Wiseman quadrangle to the northeastern portion of Chandalar quadrangle (Brosge and Reiser, 1964; Dillon et al., 1986, 1987a, 1987b). The Ambler volcanic rocks are bimodal volcanic rocks which contain Devonian fossils and have yielded middle Devonian Pb-Pb zircon ages (Hitzman et al., 1982; Dillon et al., 1980, 1986, 1987b).

A prominent, ridge forming hornblende diorite dike complex, consisting of a large east-west trending central dike with several offshoots occurs in the central portion of the mapped area. These dikes are sub-vertical to steeply south dipping discordant sheets up to 20 m thick, with 1-2 m pyritiferous calc-silicate hornfels aureoles. Porphyritic textures, with up to 2 cm phenocrysts of hornblende, feldspar, quartz, and
accessory clinopyroxene were observed. Chlorite and sericite are the dominant constituents of the matrix, with alteration decreasing inward in the dike rock. ICP analysis of 2 samples yielded basaltic compositions (Appendix 1).
SUMMARY AND INTERPRETATION

The rocks of the northern Skagit allochthon in the central Brooks Range crop out in structurally and stratigraphically complex thrust imbricates. Discontinuous lithologies, due in part to complex internal structure, and poor age control on many units, obscure many facies relationships. These rocks crop out in fault-bound structural and stratigraphic domains with minimally constrained horizontal and vertical displacements. Thus, the rocks in one domain may restore to a depositional position tens of kilometers from the same age rocks in another domain.

Approximately 8 km of section of imbricated meta-carbonate and meta-clastic rocks were observed in the study area. Here, the Skagit allochthon consists of about 7.5 km of undifferentiated metamorphic rocks and about 400 m of Skagit marble (*sensu stricto*).

The mapped area was divided into five thrust-bound domains: the North, Kupuk, Central, South, and Klippe domains. The North domain consists of Silurian(?) and Devonian Skagit marble and fine-grained shelfal meta-sediments. Ordovician(?)-Silurian(?) olistostromal meta-argillite is exposed in the Kupuk domain. The Central domain contains imbricated Ordovician(?) volcanogenic fanglomerate, wacke, and phyllite. The South domain is characterized by abundantly fossiliferous Emsian-Frasnian age carbonate and calc-silicate containing numerous Devonian(?) basaltic and intermediate composition sills, dikes, and flows. The Klippe domain consists of calcareous and siliciclastic rocks of probable Lower Paleozoic age.

North domain

In the North domain, the Skagit mable and the overlying Dpp and Dkp phyllites comprise about 1300 m of sparcely fossiliferous Devonian section. The Skagit marble is a fine to coarsely crystalline marble, with intervals of calc-schist, which contains
shallow shelfal marine faunas, including tabulate and rugose corals, brachiopods, gastropods, and crinoid columnals. The overlying phyllites are thin-bedded, graded or laminated silty mudstones, with occasional sand beds. Shallow marine brachiopods from the Mt. Snowden area (Dillon et al., 1987), imply that the lower (Dpp) phyllites were deposited in a shallow or mid-shelfal environment.

The Skajit marble is widely interpreted to be an extensive Devonian and Silurian(?) carbonate shelf or platform (Brosgé and Dutro, 1973). Data from this study supports this interpretation. The Dpp and Dkp silicious mudstones which overlie the Skajit marble are interpreted to be a fine-grained siliciclastic turbiditic(?) sequence which prograded out over the Skajit carbonate shelf or platform.

Kupuk domain

The Kupuk domain consists of about 2 km of phyllitic marble and calcareous phyllite (Pzcp) overlain by a fining upward sequence of olistostromal argillite (Pzs), and black slate (Pzsh). Although rare indeterminate brachiopods and rugose corals only constrain the rocks of the Kupuk domain to post Early Ordovician, the basal phyllitic carbonate is thought to be correlative with Ordovician conodont bearing marbles 5 km to the east (Shimer and Shrock, 1944; Dillon et al., 1987).

The phyllitic carbonate, Pzcp, is a fine-crystalline marble with phyllitic partings and intercalations, and quartz, silicic-lithic, and lithic carbonate clast conglomerate lenses and channels. Regular thin bedding and the frequent occurrence of alternating marble and phyllite layers, as well as the internal conglomerates, imply clastic carbonate deposition. The environment of deposition is interpreted to be a prodelta or a carbonate slope or base of slope apron.

The depositional environment of the argillites (Pzs) is better constrained. Two 25 m dolomite olistoliths, containing brachiopods and rugose corals and abundant soft
sediment deformation structures, occur in a zone of channelized carbonate conglomerate about 80 m from the top of Pzs. The rugose corals and brachiopods indicate that the olistoliths were derived from a shallow marine environment and that the olistoliths and the surrounding argillite are post Early Ordovician in age (Shimer and Shrock, 1944). The presence of olistostromal deposits constrains the environment of deposition to the lower slope environment, below a carbonate shelfbreak from which the carbonate boulders slid - and implies significant relief. The argillites also form a crude fining upward sequence - meta-siltstone at the base, grading upward into slate - indicating a waning of terrigenous input or an increase in water depth.

Central domain

The Central domain contains three imbricated sections of Ordovician(?) volcanogenic meta-conglomerate, meta-wackes, and phyllite. The total structural thickness ranges from about 2.3 to 3 km. The volcanic pebble conglomeratesrocks of the Central domain are correlated with an Ordovician volcanic pebble conglomerate 5 km to the east.

In the eastern portion of the mapped area, the Central domain consists of imbricated volcanic-pebble and lithic meta-conglomerates and wackes with subordinate volcanogenic phyllites (Ovc facies), which is thrust over a thin imbricate of volcanogenic phyllite (Ovs). The conglomerate clasts are primarily aphanatic and lithic volcanic, silicic-lithic, and quartz pebbles and granules. Lithic carbonate clasts are increasingly abundant upward in the southern Ovc imbricate. Overlapping, proximal mass flows comprise a majority of the section, although braided stream deposits are locally important. Westward, the section interfingers with, and grades into volcanogenic phyllites and wackes (Ovs facies). The Ovs facies is comprised of finer-grained flow deposits, with the average grain size and the number and size of
conglomeratic intervals decreasing westward.

The Central domain is interpreted to represent a thick, but restricted alluvial fan sequence. The Ovc facies, with coarse clastic mass flows and alluvial conglomerates and large immature clasts, represents the proximal upper fan deposits. The Ovs facies represents the more distal, and finer grained, middle and lower fan deposits. The sedimentary provenance, interpreted from the clast composition, contained volcanic, siliciclastic, and carbonate rocks. The volcanic pebbles contain both quartz and feldspar, which along with one questionable dacitic (?) major element ICP analysis, suggests that the volcanics were of intermediate composition. Aphanitic and scoriaceous volcanic clasts imply extrusive volcanism. Whether the volcanism was essentially contemporaneous with sedimentation, or the volcanics were later derived, for example, from an uplifted fault block, cannot be determined at this time.

South domain

The South domain contains about 1200 m of abundantly fossiliferous Emsian to Frasnian (upper-Lower to lower-Upper Devonian) rocks: a lower sequence of calcareous phyllites and marbles (Dcl), a middle massive marble (Dcm), and an upper sequence of calcareous phyllites and marbles. An imbricate (Pzbs) containing about 250 m of unfossiliferous quartzites was also mapped.

Corals, brachiopods, and gastropods indicate a shallow marine (shelfal) environment of deposition. The calcareous phyllites were terrigenous muds which inundated the carbonates.

Klippe domain

The rocks of the Klippe domain are more deformed than the other rocks of the study area. Bedding and lithology were the only sedimentary features that could be
reliably determined. The Klippe domain contains a basal section of 80-150 m of calcareous phyllite and argillaceous marble (Pzkb), about 900 m of thin-bedded argillaceous marble with phyllitic partings (Pzkc), and an upper section of greater than 800 m of silicious argillite, meta-wacke, quartzite, and marble (Pzks). Rare pre-Devonian conodont forms collected from Pzkc and Pzks are interpreted to imply a lower Paleozoic age.

The sedimentary protoliths of Pzkb and Pzkc are calcareous argillite and argillaceous limestone. The regular thin-bedding and phyllitic partings of the marbles are suggestive of clastic carbonate deposition. The protoliths of Pzks were quartzose mudstone, siltstone, and sandstone, with intervals of argillaceous limestone. Siliciclastic, calciclastic, and calcareous sediments are present. The lithologies present could be generated in a variety of shelfal, basinal, slopal, or hemi-pelagic settings. Rare indeterminate brachiopods, if they are not resedimented, imply a shallow marine setting for the basal portions of Pzks and support a generally shelfal or basinal environment for Pzks calciclastic and siliciclastic rocks.

DISCUSSION

Sparse fossils recovered from the Wiseman and Chandalar quadrangles demonstrate that the Skagit allochthon, which until recently was thought to contain primarily Devonian(?) rocks in the central Brooks Range, contains lithologies of Devonian to Cambrian age (Brosge and Reiser, 1964, 1971; Palmer et al., 1984; Dillon et al., 1986, 1987; Oldow et al., 1988). While the Skagit marble appears to be of dominantly of Devonian age in this area, it may locally include basal Silurian age strata. Rocks beneath the Skagit marble have yielded Cambrian to Silurian age fossils (Palmer et al., 1984; Dillon et al., 1987). Many of the sparsely fossiliferous or unfossiliferous undifferentiated metamorphic rocks which were previously correlated as Devonian(?),
now appear to be of lower Paleozoic age. On the basis of sparse fossils and lithologic correlations with adjacent areas, it may be concluded that four of the five domains in the study area may consist partly or completely of lower Paleozoic rocks. The Central and Klippe domains may consist entirely of lower Paleozoic rocks. Fossils in the Kupuk domain are only constrained to be post-Early Ordovician, but the rocks are correlated with lithologically similar Ordovician age rocks on strike to the east. The North domain may include basal lower Paleozoic rocks. Other studies by Dillon et al., (1987) east of the study area, and Dumoulin and Harris (1987) in the western Brooks Range, demonstrate regionally that many Skajit allochthon imbricates involve significant amounts of lower Paleozoic rocks.

The rocks of the Skajit allochthon are characterized by Cambrian to Devonian age heterogeneous shallow marine carbonate, deep water carbonate, and phyllite in the central and western Brooks Range (Fig. 3.14) (Brosge, 1960; Dutro et al., 1962; Brosge and Reiser 1964, 1971; Sainsbury, 1969; Brosge and Dutro, 1973; Palmer et al., 1984; Till et al., 1986; Dumoulin and Harris, 1987; Dillon et al., 1987, Mull et al., 1987). The Skajit allochthon is generally interpreted to have formed an extensive carbonate platform through most of the lower Paleozoic and Devonian (Brosge and Dutro, 1973).

Fossils recovered from the Wiseman, Chandalar, and Philip Smith Mountains quadrangles demonstrate that the Skajit marble is dominantly of Devonian age in the central Brooks Range, although it locally includes Silurian and possibly older strata (Oliver et al., 1955; Brosge, 1960; Dutro et al., 1962; Brosge and Reiser, 1964, 1971; Palmer et al., 1984; and Dillon et al., 1986, 1987).

The portion of the northern Skajit allochthon mapped in this study contains an anomalously thin section of Skajit marble compared to exposures of the Skajit allochthon in the Chandalar quadrangle or in the western portions of the Wiseman
Figure 3.14 -- Stratigraphic correlation chart for the Skajit allochthon. Solid lines = age ranges. Dashed line = age constraints.
quadrangle (Plate 3). This could be due to tectonic and/or stratigraphic factors. The Skagit marble may be tectonically thickened elsewhere, or tectonically thinned in the present study area. Alternatively, the Skagit exposures in the study area may represent equivalent facies deposited inboard or outboard of the Skagit carbonate platform, or increasing terrigenous sedimentation could have inhibited or restricted the formation of massive carbonate in this area. It is suggested that all of the above factors are applicable. Regional map patterns (Plate 3) and field mapping suggest that the Skagit marble is cut out westward along the basal Skagit allochthon thrust in Chandalar and Wiseman quadrangles. Multiple imbricates of the Skagit marble, mapped in the easternmost portion of the study area, are lost westward. Depositional systems from proximal fanglomerate, shelfal carbonate, and slope olistoliths are exposed in the mapped imbricates. The mapped area is characterized as imbricates of mixed clastic and carbonate rocks. Calcareous phyllite, calc-silicate (marl), and phyllitic carbonate comprise the bulk of the mapped rocks. Few marbles are "clean" carbonate. Most contain varying amounts of phyllitic or carbonaceous material in matrix, partings, interbeds, and intervals. The implication is, that in this area, the Skagit allochthon was characterized by a greater degree of fine-grained terrigenous input, and a lower degree of carbonate production than was prevalent to the east and west.

STRATIGRAPHY OF THE SKAJIT ALLOCHTHON

Cambrian trilobites are reported from a thin sandy marble underlying the Skagit marble in the Mt. Snowden area (Palmer et al., 1984). Other Cambrian age rocks have been reported in the Seward Penninsula (Till et al., 1986), the Baird Mountains (Dumoulin and Harris, 1987), the Doonerak Window (Dutro et al., 1984), and the Mt. Michelson and Demarcation Point quadrangles of the eastern Brooks Range, but are not obviously related to the Skagit allochthon rocks.
The Ordovician age rocks exposed in the Skagit allochthon are dominantly shallow and deep water marble and dolostone, with subordinate phyllite (Dumoulin and Harris, 1987; Dillon et al., 1987). Large sections of presumed Ordovician marble and phyllitic marble are also exposed here in the Klippe and North domains. The extensive lower Paleozoic carbonate shelf or platform postulated to accomodate these rocks does not obviously explain the coarse Ordovician volcanogenic rocks documented here (Brosge and Dutro, 1973; Hubbard et al., 1987). Ordovician volcanic rocks are only reported in the Apoorn assemblage exposed in the Doonerak window (Dutro et al., 1976, Moore and Churkin, 1984). Radiometric dating of the volcanic and plutonic rocks of the Brooks range gives Proterozoic, Devonian, and Cretaceous ages (Turner et al., 1979; Dillon et al., 1980; Moore et al., 1987). It appears reasonable to conclude that if Ordovician volcanism occurred, it was of very limited scope. Alternately, Ordovician volcanogenic clastics can be derived from elevated fault blocks exposing older volcanic rocks.

Few exposures of dated Silurian rocks are known from the Skagit allochthon, or elsewhere in the Brooks Range, although the Skagit marble is assumed to locally contain Silurian age strata (Brosge and Dutro, 1973; Churkin, 1973). Three exposures of laminated dolostone are known from the Skagit allochthon in the western Brooks Range (Dumoulin and Harris, 1987), and one exposure of Silurian phyllite is known from the Apoorn assemblage (Moore and Churkin, 1984). Phyllites, argillites from the North and Klippe domains, and possibly the basal Skagit marble, are interpreted to be partially of Silurian(?) age. The simplest assumption of Silurian facies and paleoenvironment is that that generally shallow and deep water carbonate and fine-grained siliciclastic sedimentation continued from the Ordovician.

Shallow shelfal carbonates, including the Skagit marble, deep water carbonate, marl, and phyllite are widely exposed in the present study area, and throughout the
Skagit allochthon (Brosge and Dutro, 1973; Dumoulin and Harris, 1987). Devonian clastic rocks also comprise the bulk of the Endicott assemblage (Nilsen and Moore, 1982), and are locally exposed in the southernmost Schist belt (Gottschalk, 1987). The massive Skagit carbonate shelf or platform postulated for the Skagit allochthon (Brosge and Dutro, 1973; Hubbard et al., 1987) is not as apparent in the present study area. Devonian phyllite and calcareous phyllite, exposed in the North and South domains, comprise a greater volume of section than carbonates. This is either due to the exposure of a deeper water facies, or due to inundation of the carbonate shelf by fine-grained terrigenous material in this area. Some slopeal sedimentation is indicated for the phyllites of the North domain because of carbonate olistostromal deposits, however the phyllite and marl of the South domain contain abundant carbonate buildups containing shallow marine fossils.

MODEL

The facies of the Skagit allochthon exposed in the study area can be explained by a shelf to basin clastic-carbonate depositional system model. In this area, the Skagit allochthon is assumed to essentially be a carbonate shelfal system which has to accommodate large amounts of terrigenous clastic material (Fig. 3.15). Laterally, corresponding to the western and eastern Brooks Range, where lesser amounts of terrigenous clastic material are entering the system, the model reverts to a traditional carbonate shelf system.

Active fan-deltas are presumed to supply fine-grained and some coarser terrigenous sediments to the shelf system. Generally siliciclastic sediment becomes finer grained outboard, but delta and prodelta lobes carry coarser sediments irregularly out onto the shelf. The near ubiquitous presence of pelitic material in the rocks of the study area argues for continuing influx of fine-grained terrigenous material into the
Figure 3.15 -- General model of a shelf to basin clastic-carbonate depositional system from Brown and Fisher (1977). General depositional model of fan-delta, carbonate shelf, and slope systems in a passive pull-apart basin showing schematic representation of relection attitudes and continuity. Active fan-deltas supplied terrigenous clastic sediments to the shelf area where limestone deposition dominated; this sustained episode of clastic-carbonate supply produced a steady progradation of offlap facies I. Alternating with episodes of sustained progradation of shelf/slope environments were episodes of diminished sediment supply with corresponding erosion of shelf edges and onlap of calcareous/clastic slope facies II. The terrigenous influence diminished through time, and slope systems became increasingly calcareous in composition.
outer (dominantly carbonate) shelfal areas. The nearshore to mid-shelf represents a transitional clastic-carbonate domain where competing carbonate and clastic depositional processes result in heterogenous clastic/carbonate sedimentation. Siliciclastic sediments predominate near the deltas, and carbonate sediments toward the shelf margin. The Skagit marble proper, that is the clean massive carbonate facies, occurs near the shelf margin in massive carbonate buildups. Olistoliths are derived from shelfbreak carbonates and are deposited onto the slope. Siliciclastic sediments have either been deposited in the near-shore or mid-shelf areas, or have bypassed the carbonate shelf, through submarine canyons, onto the slope.
CHAPTER 4 - STRUCTURE

INTRODUCTION

The rocks of the study area, have been complexly deformed by Brookian (Late Mesozoic to Cenozoic) polyphase folding, associated contractional low-angle faulting, and by high-angle faulting. Four deformational events were recognized, and are defined by a characteristic set of deformational structures. Three distinct generations of folds, and one generation of high-angle faults were identified based on superpositional and crosscutting relationships. Structural terminology is after Turner and Weiss (1963), Ramsay (1967), and Spry (1969). For simplicity, the various structures will be referred to by the abbreviated nomenclature given in Figure 4.1.

The earliest phase of folding (D1) is characterized by the development of a generally south dipping metamorphic cleavage and foliation which is axial planar to rare, rootless isoclinal folds. The second deformational event (D2) forms most of the mesoscopic and microscopioic folds. These are south-vergent concentric and kink-style folds and crenulations which fold the S1 foliation. The latest set of fold structures (D3), consists of sporadically developed sub-vertical spaced cleavage associated with gentle folding. A late episode of deformation (D4), resulted in a set of east-west trending high-angle faults which dissect the area and offset all folds.

STRUCTURAL DOMAINS

The strain distribution associated with an orogenic event varies in time and space; thus, at one point in time, an area A may undergo a deformation D1 whereas in area B, older D1 structures are refolded by D2, and in a third area C, no structures are (as yet) developed. Also, the style and orientation of folds formed by a given deformational event may vary from one area to another as a function of strain, depth of burial during...
Symbols for fabric elements

D  Deformational event.
F  Fold set.
S  Planar features (bedding plane, foliation, cleavage).
AP  Fold axial planes.
L  Linear feature (intersection and crenulation lineations).
LS  Streching Lineation.
B  Fold axis.

Subscripts of fabric elements

0  Primary sedimentary features.
1  Associated with the earliest set of fold structures.
2  Associated with the second set of fold structures.
3  Associated with the latest set of fold structures.
4  Associated with late high-angle faulting.

Figure 4.1 Table of structural nomenclature. For example: D2 refers to the second deformational event which caused the development of F2 folds which have AP2 axial planes and B2 fold axes.
deformation, the position within large scale structures, or because of differences in the mechanical properties of the rock packages - variations in thickness, lithology, or attitude of the rocks, or due to the presence and distribution of detachment zones or pre-existing zones of weaknesses in the rocks. To get an appreciation of these changes, an area is divided into structural domains.

As used here, a structural domain defines a package of rocks which is statistically homogeneous and which may have experienced a similar structural history. The rocks of the northern Skagit allochthon have experienced the same four deformational phases, but there are systematic differences in the orientation of D1 structures, due to the D2 deformation, and in the style of D2 deformation between the major thrust imbrications. Five structural domains, corresponding to the major thrust-bound rock packages, are defined. These domains are, from north to south, the North, Kupuk, Central, South, and Klippe domains (Fig. 4.2).

The North domain is characterized by a southeast dipping S1 foliation which is crosscut by a well developed north dipping D2 crenulation cleavage. The S1 foliation in the Kupuk domain is similar, but shows less variability in orientation. D2 axial-planes and cleavages strike northeast-southwest. In the imbrications of the Central domain the S1 foliation is steeper and strikes more east-west, and mesoscopic F2 folds are more frequently observed. In the rocks of the South domain the poles to S1 cleavage and AP1 axial planes have a north-northwest to south-southeast trending girdle distribution containing a north-northwest plunging point maximum. Irregularly developed F2 folds have amplitudes and wavelengths of less than 2 m. The rocks in the Klippe domain show the greatest development of D2 folds. Poles to S1 and AP1 foliation and axial planes have a girdle distribution similar to that seen in the South domain, but with two smaller point maxima.
Figure 4.2 -- Domain map of study area. Lower-hemisphere, equal-area plots of poles to S1 define the domains.
FOLDS

Bedding (S0)

Bedding, and other primary sedimentary structures and textures, are sporadically preserved throughout the field area. Megascopically and larger mesoscopic variations, such as average bedding orientations and lithologic contrasts are readily distinguishable in the field. Deformational and metamorphic features, including folds, cleavage, and metamorphic differentiation and recrystallization, overprint and obscure the sedimentary structures and textures. Sedimentary fabrics in calcareous and pelitic lithologies are particularly susceptible to transposition to deformational fabrics. In general, the smaller the feature, the more easily it is obliterated by deformational and metamorphic overprints.

Description

In hand specimen, bedding (S0) is difficult to differentiate from the penetrative S1 foliation - particularly in finer grained lithologies (Fig. 4.3). Due to isoclinal folding, S0 is typically parallel or subparallel to S1. Furthermore, in many outcrops, metamorphic differentiation and recrystallization across bedding planes blurs the lithologic contrasts normally used to define bedding. Bedding was measured only where compositional layering could be distinguished with certainty.

Based on crossbeds, scour surfaces, and graded bedding, bedding was generally found to be upright where observed. Overturned minor folds and small map-scale folds were locally observed.

Measurements

Poles to bedding planes in the domains are plotted on lower-hemisphere, equal-area projections in Fig. 4.4. Rare small F1 isoclinal folds apparently do not significantly reorient bedding. In the North domain, bedding dips 5° to 35° to the southeast; the poles to S0 form a consistent point maximum. Bedding is similarly
Figure 4.3 -- Bedding transposed by S1 foliation in a westward view of an Ovs volcanogenic wacke. The prominent planar surfaces are S1. Lithologic layering parallels S1, but individual bedding surfaces are not distinguishable.
Figure 4.4 -- Lower-hemisphere, equal-area projections of poles to bedding for each domain.
oriented in the Kupuk domain. In the Central domain, bedding strikes east-northeast to west-southwest, and dips steeply to the south in the northern part of the domain, and more shallowly in the southern part of the domain. Bedding planes are more variably oriented in the South and Klippe domains due to more pronounced folding by F2 folds. Poles to bedding in the South domain form a girdle distribution, indicating later folding by F2 folds about a sub-horizontal, east-northeast trending axis. In the Klippe domain, poles to bedding occur in two distinct point maxima. One subgroup of bedding dips moderately to the south-southwest, and the other to the northwest. This distribution is characteristic of the chevron-style (D2) refolding.

First Phase Deformation (D1)

The first recognized deformational event, D1, is characterized by the development of a penetrative metamorphic foliation and cleavage (S1) which is axial planar to rare mesoscopic isoclinal folds. S1 is a strongly penetrative structure which is visible in all rocks, and is commonly the most strongly developed structural element (Figs. 4.3 and 4.5). S1 partially or wholly transposes bedding, particularly in the finer-grained rocks. Where both S0 and S1 are distinguishable, S1 is generally sub-parallel to S0.

Description

S1 cleavage is demonstrably axial planar to rare F1 isoclinal folds (Fig. 4.6). Small isoclinal folds, with amplitudes of less than 1 m, are strongly attenuated to rootless, and have similar fold geometries. The isoclines observed have sub-horizontal fold axes with variable trends. No consistent sense of vergence was found in the few isoclines observed.

S1 is observed in all rocks, and is commonly the most strongly developed fabric element at all scales of observation. The form of the S1 cleavage varies with lithology.

Argillaceous rocks show a fissile slaty cleavage or a very fine schistosity
Figure 4.5 — Thin section of sample 4-002, a quartz meta-wacke from Dpp. Lithologic bands define bedding. S1, the dominant fabric element, is defined by the parallel alignment of micas and the long axes of quartz grains, which form a continuous foliation parallel to S0. Less well developed D2 crenulations fold S0 and S1.
Figure 4.6 — Westward view of S1 foliation which is axial planar to a rare, rootless F1 isoclinal fold of a quartz vein.
characterized by very fine oriented grains of chlorite + sericite ± chloritoid ± prehnite ±
graphite. Small scale metamorphic differentiation often leaves a weak differentiated
zonal cleavage, with quartz- or calcite-rich spaced seams and lenses aligned parallel to
S1 in a mica-rich groundmass. These seams are characterized by quartz or calcite grains
with a granoblastic polygonal texture. Porphyroclasts of quartz, calcite, feldspar,
pyrite, or lithic grains show a shape prefered orientation parallel to the foliation (Fig.
4.5). Weakly asymmetric pressure fringes were observed on several porphyroclasts,
but no consistent sense of asymmetry was determinable. Strained quartz
porphyroclasts show undulose extinction and subgrains, and occasionally have lobate
boundaries decorated with neoblasts. Infrequent parallel seams and whisps of
unidentifiable opaque material, apparently insoluble residues, are also observed.

Meta-sandstones typically show a more continuous cleavage defined by the
dimensional preferred orientation of sand sized grains or by the parallel alignment of
matrix micas. Meta-sandstones typically have granoblastic or granoblastic-elongate
metamorphic textures. Where a dimensional preferred orientation exists, quartz and
calcite grains are oriented with their maximum and intermediate axes in the plane of the
foliation. In many cases, particularly with very-fine grained quartz, the quartz is
present in a uniform, very-fine grained matrix of strain-free, polygonalized grains with
a granoblastic polygonal (annealing) texture. Porphyroclasts of quartz and larger quartz
grains have undulose extinctions. In quartzites, dispersed sub-parallel grains of
chlorite and sericite define the foliation. Where more argillaceous material is present,
the meta-sandstones show a fissility or spaced cleavage defined by differentiated
whisps and seams of oriented mica grains and unidentified opaque material.

Meta-conglomerates tend to retain their sedimentary textures better than the finer
grained rocks. A range of S1 styles is exhibited - from an ill-defined rough cleavage in
the matrix material, to a strongly developed phacoidal cleavage. Thick competent
sections of conglomerate, especially those with larger (>pebble size) clasts, may show a rough cleavage developed in the matrix material, with little preferred orientation or apparent deformation of the clasts. Here S1 is expressed as rough fissility defined by the alignment of elongate grains and micas in interstitial areas and wrapping around clasts. More commonly, stretched-pebble conglomerates exhibit a well developed phacoidal cleavage, with elongate clasts and grains showing a dimensional preferred orientation parallel to the foliation and a "stretching" lineation (see also Fig. 4.24). Most stretched-pebble conglomerates observed had estimated average clast aspect ratios of 5:2:1, although clasts with aspect ratios exceeding 30:4:1 were observed in two outcrops near faults.

In calcareous rocks, S1 is most obviously defined by the preferred orientation of chlorite and sericite, often with unidentified opaque matter, in phyllitic partings and interbeds. Calc-silicate (marly) rocks are characterized by alternating calcite-rich and mica-rich or quartz-rich laminations parallel to S1. Marbles and calcite-rich laminations are characterized by fine to very-fine crystalline calcite, and infrequently, more coarsely crystalline dolomite. Calcite grains are commonly twinned, and often exhibit a weak shape preferred orientation in a granoblastic elongate texture or granoblastic polygonal texture. Solution features are locally observed, including partially dissolved fossils, grains, and clasts along serrate seams of opaque matter parallel to S1.

Measurements

The S1 cleavage is generally parallel to bedding in all domains (Fig. 4.7). In the North, Kupuk, and Central domains, poles to cleavage form diffuse point maxima, indicating relatively uniform south to southeast dipping S1 - with an average dip of 5° to 30° in the North and Kupuk domains, and 10° to 70° in the Central domain. In the South and Klippe domains, poles to cleavage are distributed in a girdle about a
North domain

Kupuk domain

Central domain

South domain

Klippe domain

D1

- Poles to S1 cleavage
- Fold axes
- Intersection lineations

Figure 4.7 -- Lower-hemisphere, equal-area projections of D1 deformational structures for each domain.
sub-horizontal, east-northeast trending axis parallel to F2 fold axes. F1 fold axes and intersection lineations plunge shallowly to the south to southwest in the North and Central domains, but are scattered elsewhere.

**Second Phase Deformation (D2)**

The second deformational phase, D2, is characterized by open to close, south-vergent crenulations, buckle folds, kinkbands, and chevron folds. D2 folds demonstrably refold D1 structures (Fig. 4.8). A cleavage axial planar to these folds is also developed. Most folds seen in outcrop and in thin section are D2 folds.

**Description**

F2 folds range in scale from microscopic crenulations to map scale folds with wavelengths and amplitudes of up to 100 m. However, larger folds occur; the Jesse klippe is lying in a synformal structure believed to be formed during D2. Fold amplitudes of 0.2-20 cm are most common. Both buckle and chevron style folds occur and are characterized by relatively constant orthogonal layer thickness (class 1b folds of Ramsay, 1967).

The second phase cleavage, S2, is commonly developed as a crenulation cleavage in pelitic material. S2 is locally characterized by parallel whips and seams of larger micas and concentrations of opaque matter. In thin section, F2 crenulations show quartz- or calcite-rich hinge areas, and mica-rich (chlorite, sericite) limbs which form a S2 crenulation cleavage which is parallel to the axial planes of F2 folds (Fig. 4.9). Chlorite grains paralleling the S1 foliation are often bent or broken in the hinge regions of F2 microfolds.

The style of D2 folding varies between structural domains. In the North, Kupuk, and Central domains D2 is principally developed as small scale crenulations, and scattered gentle to open folds. D2 is more strongly developed in the South domain
Figure 4.8 — Second phase folding of an F1 isoclinal fold in Pzks calc-silicates. View is to the west with a dime for scale.
Figure 4.9 -- Photomicrograph of well developed S2 crenulation cleavage parallel to the axial-plane of a gentle F2 fold. Sample 4-172 is a Pzkc calc-silicate. The section is about 2 x 1 cm.
where the relatively ductile marly lithologies develop frequent open to close buckle folds. The greatest fold appression by D2 is developed in the Klippe domain, where zones of intense folding frequently exhibit greater than 30% shortening (Fig. 4.8). Kink and chevron style fold morphology is best developed in the Klippe domain.

**Measurements**

The orientations of the south-vergent D2 structures are relatively constant in all domains (Fig. 4.10). S2 cleavage and axial planes dip variably to the north or northwest. Rare conjugate F2 kink folds have axial planes which dip steeply to the south-southeast. Second phase fold axes and lineations are sub-horizontal, and generally trend east to northeast. The axis, about which bedding and D1 structures are rotated, forming great-circle girdle distributions, is parallel to the average F2 fold axis.

**Third Phase of Deformation (D3)**

A third folding event, D3, is expressed as sporadically developed, close- to wide-spaced discrete cleavage sets which crosscut D1 and D2 deformational structures (Fig. 4.11). S3 is axial planar to rare, gentle to open folds and crenulations. In thin section, S3 is visible as a weakly developed crenulation cleavage. More commonly, a weak sub-horizontal intersection or crenulation lineation is present in the cleavage plane. L3 is used to differentiate S3 from similar appearing joints. Phelps et al. (1987) noted that S3 is best developed near the (D4) east-west trending high angle faults which dissect the area.

Third phase cleavage, S3, is a sub-vertical, northwest striking cleavage in all structural domains (Fig. 4.12). L3 crenulation lineations were noted, but were not systematically measured.
Figure 4.10 -- Lower-hemisphere, equal-area projections of D2 deformational structures for each domain.
Figure 4.11 -- Northwest view of S3 spaced cleavage. Rock hammer for scale.
Figure 4.12 — Lower-hemisphere, equal-area projections of D3 deformational structures for each domain.

Poles to S3 cleavage
MAP-SCALE FAULTS

Thrust Faults

Many low-angle to high-angle thrust faults were observed or inferred in the area. Where observed, these faults locally cut out lithologic units both above and below the fault planes. In several cases these faults can be traced for significant distances in a bedding parallel (flat on flat) configuration. In the northeastern portion of the area, thrust faults are inferred from apparent repetition of the Dsk1 marbles although the exposed contacts are bedding parallel (Plate 2, cross section A). Five major thrust faults, are exposed in the mapped area - the basal thrusts of the North, Kupuk, Central, South, and Klippe domains and are designated BNDT, BKuDT, BCDT, BSDT, and BKIDT, respectively. Numerous intra-domainal imbrications were also observed or inferred.

The basal North domain thrust (BNDT), the Kapoon Creek Thrust of Phelps (1987), which is also the basal thrust of the Skagit allochthon, is a south dipping thrust fault which emplaces the Devonian and Silurian (?) rocks of the Skagit limestone over the upper Devonian Hunt Fork shale of the Endicott Mountains allochthon. Although the contact is generally covered, rocks exposed above and below the contact are strongly deformed, and D1 structures are folded by the fault. Following the BNDT from west to east in the upper plate, the lower of the two exposed Dsk1 marble intervals is cut out by the BNDT in the central portion of the mapped area. Lower plate units are also reportedly cut out by the BNDT (Phelps, 1987). In the northeastern portion of the area, several imbricate thrusts which repeat Dsk marble intervals are inferred to be hidden in the intervening phyllites and schists - where strongly deformed outcrops are observed.

A thrust fault (BKuDT) emplaces the pre-Carboniferous and post-Early
Ordovician rocks of the Kupuk domain (correlated as Ordovician(? by Dillon et al., 1987) over the Devonian rocks (Dkp) of the North domain. This fault is bedding planar for most of its length. In the westernmost portion of the mapped area BKuDT is detached about 150 m above the base of Dkp. The detachment level abruptly ramps up eastward to a detachment level about 450 m above the base of Dkp, and remains at that horizon through the central and eastern portions of the mapped area (Plate 2, cross sections A, B, and C).

The basal Central domain thrust (BCDT) emplaces the Ordovician(?) Ovs rocks of the Central domain on top of the Paleozoic (pre-Carboniferous and post-Early Ordovician) rocks of the Kupuk domain. Shallowly south dipping lower plate rocks are cut out by, and are discordant with, the more steeply dipping rocks of the Central domain. The Central domain rocks are strongly reoriented, and are locally overturned by a splay of the BCDT which diverges eastward and emplaces Ovc over Ovs. A third thrust fault, which imbricates Ovc, terminates to the west in a high-angle strike-slip (tear) fault.

The basal South domain thrust (BSDT) emplaces the Middle Devonian rocks of the South domain over the Ordovician? rocks of the Central domain in a younger over older relationship. Both upper and lower plate rocks are observed to be cut out along the BSDT contact. In the eastern portion of the mapped area, the lower rocks of the South domain (Dcl) are imbricated by a rejoining splay of the BSDT. The upper South domain unit, Dcu, is cut out, in the southeastern portion of the South domain, by three internal thrust faults which envelop a Paleozoic horse of quartzite (Pzbs) and repeat Dcl.

The basal Klippe domain thrust (BKDT) emplaces lower Paleozoic rocks over the middle Devonian rocks of the South domain (Plate 1). Dcl in the lower plate, and Pzkc in the upper plate, are progressively cut out northward by the BKDT. The BKDT and
the overlying Klippe domain rocks are folded in a shallow, east-southeast plunging syncline. The BKDT dips shallowly to the south along the northern margin of the Jesse klippe, shallowly westward around the eastern margin, and shallowly to the north along the southern margin of the Jesse klippe. This syncline is probably related to D2 folding. Thus the thrusting occurred before D2 and may have been synchronous with D1 folding.

**High-Angle Faults**

The field area is dissected by a number of prominent high-angle faults which offset map units (Plate 1). The traces of these faults are minimally deflected by topography, indicating sub-vertical fault planes. Late (post-folding) east-west trending high-angle faults crosscut all fold structures and most map units, and are considered to constitute a set of deformational structures associated with a fourth deformational event (D4) (after Phelps *et al.*, 1987). These map-scale faults crosscut, and therefore postdate, all fold and thrust structures. Two sets of map-scale high-angle faults are discussed; east-west trending faults and north-northwest - south-southeast trending faults.

East-west trending high-angle faults constitute the bulk of the observed map-scale faults. Of 34 map-scale high-angle faults, 25 strike between N60°E and S60°E (Plate 1, Fig. 4.13). Clearly visible in the more massive units, these faults are more difficult to trace through phyllitic lithologies (Fig. 4.14). Offsets of map units indicate dominantly down to the south, normal or vertical displacements, with throws of less than 200 m. One reverse fault (or high-angle thrust) in the southernmost portion of the mapped area (97°42') was found to have significant (=150 m) reverse throw. Another fault, in the North domain (97°51'), shows a sub-vertical scissors displacement, downthrown to the north in the central portion of the mapped area, and downthrown to the south in the east. Although these east-west trending faults show apparent normal or reverse offsets
Figure 4.13 — Rose diagram of the strikes of the 34 map-scale high-angle faults observed in the study area, plotted per 10° intervals.
Figure 4.14 — Westward view an east-west trending high-angle fault in the Skagit marble. View is about 15 m across. Fault throw is about 2 m.
of map units, sub-horizontal slickenslide striations are typically seen on fault surfaces. Kinematic analysis of fault structures is discussed later in this chapter.

Two prominent north-south to northeast-southwest trending high-angle faults, with left-lateral strike-slip or oblique-slip offsets of map units, are mapped (Plate 1). The western fault offsets the Central domain rocks and the basal Central domain thrust-fault (BCDT), is offset by the east-west trending high-angle faults. It is interpreted to be a syn-thrusting tear fault because it offsets, with left-lateral strike-slip, the BCDT and does not offset the overlying South domain thrust sheets. The eastern fault, which continues for at least another 8 km southeast of the mapped area, shows oblique-slip offsets of map units and South domain thrust-faults, with displacement increasing to the southeast (Seidensticker, personal communication, 1987). This fault postdates the imbrication of the South domain rocks, and hence, the movement on the western tear fault, but no evidence was found to date displacement relative to the east-west high-angle faulting.
STRUCTURAL ANALYSIS

Mesoscopic and microscopic analysis of ductile structures was performed to study the state of strain and the kinematics of ductile deformation in the area. Structural analysis of ductile fabrics included the study of quartz c-axes preferred orientations, microscopic strain analyses (Fry analysis) of deformed grains, and measurement of the axial ratios of clasts in stretched-pebble conglomerates. Dynamic and kinematic analysis was performed on mesoscopic faults and fractures of the area to ascertain the compatibility of the brittle structures with the overall megascopic deformation. The locations of the stations and samples used for structural analysis are given in Fig. 4.15.

Petrofabric analysis

Deformation and metamorphism commonly causes the development of crystallographic and shape preferred orientations in the rock minerals. In particular, the lattice preferred orientations of quartz, in both naturally and experimentally deformed rocks, have been widely studied. Deformed quartz grains exhibit a range of c-axes microfabrics which, in many cases, can be related to the conditions and kinematics of deformation, and to the state of strain of the rock (Wenk, 1985).

Representative oriented quartz-rich samples, taken from non-folded, mesoscopically homogeneously deformed outcrops, were selected for quartz c-axis analysis. In thin section, these samples are relatively homogenous, recrystallized quartzites showing a shape preferred orientation of elongate quartz grains, with long axes parallel to S1. The metamorphic texture is granoblastic polygonal. Several larger relict strained quartz grains with serrate grain boundaries and contiguous polygonal, strain free quartz grains, are clearly indicative of recrystallization. A four-axis universal-stage was used to determine the optical c-axes of 200 quartz grains for each sample. Only polygonal quartz grains were measured, as there were not enough old
Figure 4.15 -- Location map for structural analysis samples.
quartz grains. The c-axes were plotted on a equal-area, lower-hemisphere stereonet, and then contoured on a 1% unit area Kalsbeek counting net.

Quartz c-axis preferred orientation fabrics are random or near random in the samples analyzed (Fig. 4.16). Since recognizable quartz c-axis fabrics have been shown to develop at relatively low strains, strain rates, and temperatures (Lister and Hobbs, 1980; Wenk, 1985), it is suggested that the random fabrics and granoblastic polygonal textures observed are due to late or post-tectonic annealing.

Fry analysis (Center to Center Method)

With the Fry method, a variation of the center-to-center method, the finite bulk strain of a rock sample is determined by measuring the non-random distribution of the centers of grains or clasts (Fry, 1979; Ramsay and Huber, 1983). In an aggregate of grains, packing considerations dictate that there are characteristic minimum distances between the centers of adjacent grains, and that the centers of the grains form a statistically uniform distribution in space. The homogenous deformation of a uniform distribution of points causes the distribution to be systematically modified in proportion to the strain; e.g. the the centers of grains are closer together in the direction of maximum compression and further apart in the direction of maximum extention, in proportion to the strain magnitudes.

Representative samples with identifiable original grains were chosen from each structural domain, from mesoscopically homogenously deformed, but not folded areas (Fig. 4.15). For each sample, the stretching lineation was located in the plane of the S1 foliation and then two perpendicular principal sections were cut 1) perpendicular to the stretching lineation and 2) parallel to the stretching lineation and perpendicular to S1. Fry analyses were then performed on oriented photographic enlargements of the sections.
Figure 4.16 -- Quartz c-axis petrofabrics. Lower-hemisphere equal-area projections of 200 quartz c-axes with contours at 1% per 1% area. Heavy lines = S1 foliation. Great circles are the horizontal plane with N = north and E = east.

A: Sample 4-002, a quartzite from Dpp in the North domain. In thin section the sample shows a bimodal granoblastic polygonal texture with grains elongate parallel to S1. Most quartz grains are fine sand size with regular polygonal grain boundaries. The larger quartz grains have subgrains, undulose extinctions, and serrate borders, but were too few to yield statistically significant results.

B: Sample 4-035: a lithic quartzite from Pzbs in the South domain. In thin section the sample has a granoblastic polygonal texture with quartz grains elongate to the S1 foliation. Grains are dominantly fine to very-fine sand size with polygonal grain boundaries. Several larger quartz grains have subgrains, undulose extinctions, and serrate grain boundaries.
Consistent strain axes orientation was obtained from all samples (Figs. 4.17, 4.18, 4.19, 4.20). The minimum axis of the strain ellipsoid, corresponding to the maximum compressive strain, plunges moderately to the north. The maximum axis of the strain ellipsoid lies in the plane of the foliation, and trends to the south and southwest.

The finite strains of the samples obtained from the Fry analyses give the bulk strain of the sample, and specifically do not include shortening added by mesoscopic or megascopic folding or faulting. The finite strains measured range from $X : Y : Z = 1.6 : 1 : 0.8$ in the North domain, to $X : Y : Z = 2.4 : 1 : 0.6$ in the Klippe domain.

**Axial ratios of stretched-pebble conglomerate clasts**

Field measurements of the principal axes of elongate clasts in two stretched-pebble conglomerates were also used to estimate the finite strain by the axial ratio method (Ramsay and Huber, 1983). The axial ratio method yields an approximation of the finite strain of the clasts because of the inherent assumption that the pebbles were originally spherical. Furthermore, this strain may not include the strain partitioned in the matrix.

Two stretched-pebble conglomerates with pronounced elongate clasts were analyzed. The maximum ($X$), intermediate ($Y$), and minimum ($Z$) axes of the stretched pebbles were measured and plotted against each other in Figures 4.21 and 4.22. The slope of the lines which best fit the data were determined, and represent the average $X$-$Z$ and $Y$-$Z$ ratios of the measured clasts. In all clasts, the direction of maximum elongation, $X$, is constant, and lies in the plane of the foliation. $Y$ was constructed to be $90^\circ$ from $X$ in the plane of the foliation, and $Z$ is normal to the foliation.

The finite strain cannot be determined exactly because the original shapes and orientations of the clasts are not known. Since the angle between the longest pebble
Figure 4.17 — Fry analysis of sample 5-195, an lithic meta-wage from Pzcp in the Kupuk domain. X, Y, and Z are the maximum, intermediate, and minimum axes, respectively, of the finite strain ellipsoid. A) The YZ section of the strain ellipsoid. B) the XZ section of the strain ellipsoid. The derived strain ratios are X:Y:Z = 1.6 : 1 : 0.8. C) Lower-hemisphere, equal-area projection of the orientation of the strain axes and the S1 foliation.

Figure 4.18 — Fry analysis of sample 4-015, a lithic schistose quartzite from Ovc in the Central domain. X, Y, and Z are the maximum, intermediate, and minimum axes, respectively, of the finite strain ellipsoid. A) The YZ section of the strain ellipsoid. B) the XZ section of the strain ellipsoid. The derived strain ratios are X:Y:Z = 2.4 : 1 : 0.6. C) Lower-hemisphere, equal-area projection of the orientation of the strain axes and the S1 foliation.
Figure 4.19 -- Fry analysis of sample 4-199a, an argillaceous quartzite from Dcl in the South domain. X, Y, and Z are the maximum, intermediate, and minimum axes, respectively, of the finite strain ellipsoid. A) The YZ section of the strain ellipsoid. B) the XZ section of the strain ellipsoid. The derived strain ratios are $X:Y:Z = 2.0 : 1 : 0.7$. C) Lower-hemisphere, equal-area projection of the orientation of the strain axes and the S1 foliation.

Figure 4.20 -- Fry analysis of sample 4-195, a pyritiferous quartzite from Ovc in the meta-wacce from Pzkb in the Klippe domain. X, Y, and Z are the maximum, intermediate, and minimum axes, respectively, of the finite strain ellipsoid. A) The YZ section of the strain ellipsoid. B) the XZ section of the strain ellipsoid. The derived strain ratios are $X:Y:Z = 2.4 : 1 : 0.6$. C) Lower-hemisphere, equal-area projection of the orientation of the strain axes and the S1 foliation.
Figure 4.21 — Strain analysis of a stretched quartzite pebble conglomerate at station 4-001 from the basal part of Dsk in the North domain. X, Y, and Z are the maximum, intermediate, and minimum axes, respectively, of the finite strain ellipsoid. A) Field measurements X-Z ratios of stretched pebbles. B) Field measurements of Y-Z ratios of stretched pebbles. The derived strain ratios are X:Y:Z = 5.3 : 1 : 0.33. C) Lower-hemisphere, equal-area projection of the orientation of the strain axes and S1 foliation.

Figure 4.22 — Strain analysis of a stretched lithic pebble conglomerate from Ovc, station 5-031. X, Y, and Z are the maximum, intermediate, and minimum axes, respectively, of the finite strain ellipsoid. A) Field measurements X-Z ratios of stretched pebbles. B) Field measurements of Y-Z ratios of stretched pebbles. The derived strain ratios are X:Y:Z = 3.5 : 1 : 0.29. C) Lower-hemisphere, equal-area projection of the orientation of the strain axes and the S1 foliation.
axes $X'$ and the foliation is $0^\circ$, the orientation of $X'$ is constant in each outcrop, and the minimum average $X'$-$Z'$ ratios exceed 12:1, it is assumed that the effects of pre-tectonic preferred orientation and non-sphericity of the clasts are minimal compared to the deformational effects. Therefore the strains and strain orientations derived from the axial-ratio estimates are argued to be valid approximations.

The approximate strains derived from the axial-ratio method are $X : Y : Z = 5.3 : 1 : 0.33$ for station 4-001 from the North domain, and $X : Y : Z = 3.5 : 1 : 0.29$ for station 5-031 from the Central domain. $X$ plunges gently south in both cases.

**Strain Results**

When plotted on a Flinn diagram, the measured strains lie in the constriction field (Fig. 4.23). Strains derived from the stretched-pebble conglomerates are higher than those derived from the Fry analysis. This is probably due to a combination of sampling bias and inhomogenous deformation. Samples used for Fry analysis were chosen from representative homogenously deformed sections. In the outcrops where stretched-pebble conglomerates were measured, the conglomerate clasts were conspicuously prominent and elongate, and in one case, were demonstrably proximal to a thrust fault.

Stretching lineations of clasts and grains divide into two groups (Fig. 4.24). Those derived from the Central domain consistently plunge south to south-east. Stretching lineations from the North, South, and Klippe domains plunge shallowly to moderately to the southwest.

**Minor Faults**

Fault planes, poles to fault planes, and slickenside striations are plotted for minor normal faults, reverse faults, and strike-slip faults in Fig. 4.25. Most measured normal
Figure 4.23 -- Flinn diagram representation of homogenous strain. Squares represent strains derived using the Fry analyses and circles represent strains derived from stretched pebble conglomerates. X, Y, and Z represent the maximum, intermediate, and minimum axes, respectively, of the strain ellipsoid.
Mineral and clast stretching lineations

- Field measurements from the Central domain.
- Derived from Fry analysis samples.

N  North domain  C  Central domain
S  South domain  K  Klippe domain

Figure 4.24 -- Lower-hemisphere, equal-area projection of mineral and clast stretching lineations.
faults strike east-west to northwest-southeast, and have steep slickenside displacement
directions to the north and south.

Two groups of generally east-west trending minor reverse faults were observed. One group of three high-angle reverse faults shows steep south over north displacement. Two low-angle reverse faults with north-south slips have nearly conjugate orientations. One fault is a north-south striking thrust fault.

Minor strike-slip faults were observed to occur in two principal orientations. One set of strike-slip faults trend east-west to east-southeast to west-northwest and have sub-horizontal slickenside striations. Several of these faults show dip-slip or oblique-slip offset of beds but have strike-slip last movements. A second set of north-northeast to south-southwest trending strike-slip faults has shallowly north plunging slickenside striations.

Two sets of conjugate faults were observed (Fig. 4.26). For conjugate faults, the direction of maximum compression, sigma1, is the acute bisector of the fault planes, the direction of minimum compression, sigma3, is the obtuse bisector and sigma2 occurs at the intersection of the fault planes (Ramsay and Huber, 1983). Dynamic analysis of the conjugate fault orientations indicates that the conjugate faults formed during east-west directed compression.

While map-scale east-west trending high-angle faults have dominantly down to the south displacements, the measured minor east-west trending high-angle faults show approximately equal numbers of down to the north displacements. Both map-scale and minor east-west trending high-angle faults show evidence of dip-slip offset followed by sub-horizontal last motions. The conjugate faults indicate generally east-west compression, and correspond to the two principal conjugate fault sets recognized by Phelps (1987) in the Endicott Mountains allochthon and in the northernmost portion of the Skagit allochthon.
Figure 4.26 - Equal-area, lower-hemisphere plots of conjugate fault sets. A) Conjugate fractures and calculated stress axes from station 5-240. B) Conjugate fractures and calculated stress axes from station 4-021.
INTERPRETATION OF STRUCTURES

The structural evolution of the Skagit allochthon is reflected in the deformational features in the rocks. The sequential development of deformational structures and fabrics, the orientation of these structures and fabrics, and the state of strain constrain the deformation history of these rocks. These features, and their variation between rock packages, provide clues and constraints to the kinematics of deformation.

First deformational phase (D1)

The earliest recognizable deformational event, D1, is evidenced by a penetrative tectonic cleavage and foliation axial planar to rare rootless, isoclinal folds. D1 is present in all rocks of the study area, including rocks as young as early-Late Devonian. Although there is some evidence of Devonian tectonism in the southern Brooks Range, as well as Devonian plutonism and volcanism (Smith *et al.*, 1987; Dillon *et al.*, 1980, 1987; Hitzman *et al.*, 1982; Schmidt, 1984), no penetrative deformational structures or regional metamorphic fabrics of Devonian age have been described in the central Brooks Range (Turner *et al.*, 1979; Oldow *et al.*, 1984; Julian *et al.*, 1984; Armstrong *et al.*, 1976; Gottschalk, 1987; Phelps, 1987). The reorientation of D1 structures is consistent with their being formed synchronously with the thrust faults. D1 is interpreted to be the first Brookian (Jurassic-Cretaceous) deformational event.

Mineral mobility is associated with D1. Dissolution and precipitation of quartz and calcite from high strain to low strain areas in fold limbs and hinges is common. Pressure solution features are observed in relict quartz grains abutting S1 foliation planes rich in micas and opaque residue. Quartz, and less frequently calcite, are observed in D1 pressure shadows and extention fractures. Small scale metamorphic differentiation is indicated by alternating bands of quartz-rich or calcite-rich layers with mica-rich layers parallel to S1 and oblique to S0. Chlorite, sericite, and white mica are
rotated parallel to the S1 foliation. Mica growth parallel to S1 and oblique to original bedding can be seen in many fine-grained lithic clasts.

The observed cleavage form varies with lithology. Rocks with an increased degree of preferred orientation of mineral grains often also show greater amounts of metamorphic differentiation, closer spacing of disjunctive and differentiated cleavages, and greater fissility. Clasts, porphyroclasts, and platy grains are oblate parallel to the foliation. Low strain areas in competent, matrix supported conglomerate beds show relatively unstrained clasts with little preferred orientation. Here strain is accommodated in the matrix material and S1 is expressed as a rough fissility defined by the alignment of platy grains and secondary minerals around the clasts. High strain areas, often near thrust faults, show pronounced elongation of clasts and matrix grains in the plane of the foliation, defining a stretching lineation.

Although quartz grains have shape preferred orientations, quartz c-axis petrofabrics show random or near-random lattice preferred orientations. Post-D1 recrystallization is inferred from aggregates of unstrained, granoblastic-polygonal quartz grains in D2 fold hinges, and annealing textures (Spry, 1969) in quartzites. The random quartz c-axis petrofabrics are interpreted to be the result of post-kinematic annealing.

Prehnite lathes parallel to the S1 foliation were observed in several samples. The presence of prehnite is a geobarometer which is generally thought to imply metamorphism at less than 3 kb of pressure (Winkler, 1979). This is interpreted to indicate that the rocks of the Skagit allochthon were buried not more than 10 km during D1 deformation.

Strain analyses of deformed meta-conglomerates and meta- sandstones give variable finite strain magnitudes. Two strain estimates, using the axial ratio method on stretched-pebble conglomerates, yield the following average strain ratios X : Y : Z =
4.4 : 1.0 : 0.31. The strain estimates with the Fry analysis in four samples is smaller, averaging \( X : Y : Z = 2.1 : 1.0 : 0.68 \). Sampling bias may account for some of the difference. Samples on which the Fry analysis was applied were chosen from representative, homogeneously deformed sections, whereas the analyses on the stretched-pebble conglomerate analyses was performed on samples with conspicuously elongate clasts. Careful re-examination of the Fry analysis samples shows evidence of pressure solution and recrystallization which may have obliterated the original grain structure. Where recrystallization of strained grains has progressed to the point that it becomes impossible to determine the relict grain shape, or where grains completely disappear due to dissolution, the Fry method becomes unreliable (Ramsay and Huber, 1983). The Fry analyses, in this case, may somewhat underrepresent the total finite strain. Therefore, the Fry analysis and the stretched-pebble conglomerate strain magnitudes are interpreted to represent lower and upper bounding values, respectively, for the average finite strain magnitudes of the study area.

The strain analyses plot in the constriction field on a Flinn diagram. Constrictive regional finite strains appear to be difficult to generate in homogeneously deformed, irrotational tectonites. The strain states of 990 slate samples from the Caladonide fold and thrust belt by Ramsay and Wood (1973) plotted exclusively in the flattening field (oblate strain ellipsoids). Most rocks initially occupy the flattening field of the Flynn diagram due to flattening and volume loss during sedimentary diagenesis and compaction during burial (Fig. 4.27a)(Ramsay and Wood, 1973). During progressive tectonic (contractional) deformation, the initially oblate strain ellipsoid will be deformed into an prolate ellipsoid at low strains; continuing deformation returns the ellipse to the flattening field (Fig. 4.27 b and c).

The rocks of the study area have clearly accumulated finite strains exceeding the requirements of low strain constriction (Fig. 4.27c). There are several ways to enter
a. Pure constriction (Y = Z > X).
b. Plane strain.
c. Pure flattening (Z > Y = X)
   (Commonly by volume loss during burial diagenesis and compaction).

Plots of the strain states of 990 Caladonide slates and theorized deformation path to explain observed flattening field finite strains in tectonites (Ramsay and Wood, 1973).

Burial diagenesis and compaction followed by low strain, contractional deformation.

Burial diagenesis and compaction followed by contractional deformation, and then by inhomogenous deformation.

Figure 4.27 – Strain and deformation paths (after Ramsay and Wood, 1973). A) Flinn diagram with basic deformation paths. B) Strain state of 990 Caladonide slates. C) Constrictive strain by compaction and small strain. D) Constrictive strain by high strains and inhomogenous deformation.
the constriction field during progressive deformation - with high-strain inhomogeneous deformation (Fig. 4.27d), volume gains, or shear strains (rotational deformation). Deformational inhomogeneities are locally observed, but the deformational structures are statistically homogenous within the structural domains. No evidence of significant volume gain was observed. Although mineral mobility is apparent, the ubiquitous cleavage, opaque residues, and rarer solution features instead argue for net volume loss. Asymmetric shear indicators were locally observed, but no consistent sense of shear was determinable. D3 is non-coaxial with D1 and D2, but only generates sporadic, non-penetrative deformational structures. It is difficult to believe that D3 contributed significantly to the finite strain. It is possible that some combination of the above factors, acted to develop a finite constrictional strain; however, D1 rotational strains may have had the most important influence.

The relative strain magnitudes expressed by the Fry analyses agree with the estimated shortening due to folding observed in the structural domains. The rocks of the Klippe domain have been strained the most, the rocks of the Central and South domains somewhat less, and the rocks of the North domain the least.

Several lines of evidence suggest that the direction of shortening (X) is northwest-southeast to north-south. The S1 foliation, which is axial planar to D1 isoclinal folds, strikes east-west to northeast-southwest in all domains, indicating that the direction of maximum shortening, was northwest-southeast to north-south since the axial planes of folds generally form perpendicular to the direction of maximum shortening (Turner and Weiss, 1963; Ramsay, 1967). In fold and thrust belts characterized by strong foliations and lineations, stretching lineations are interpreted to form in the direction of X, with other linear features passively rotating parallel to X during progressive shear (Escher and Watterson, 1974). Stretching lineations from the study area trend north-south. Two-thirds of the measured F1 fold axes and intersection
lineations trend essentially north-south. These lineations consistently trend north-south in the North and Central domains, but show considerable scatter in the Central and Klippe domains. One tear fault in the Central domain also suggests north-south to northwest-southeast directed thrusting (Dahlstrom, 1970).

The shear sense for D1 structures is interpreted to be south over north primarily because of thrust fault morphology. The at least partially syn-D1 thrust faults of the field area are north directed because they cut up section to the north and have north vergent hanging-wall anticlines. D1 deformational structures could not be used to unequivocally determine the shear sense. In the Schist belt, sheath folds, rotated porphyroblasts, and asymmetric quartz c-axis petrofabrics indicate south over north shear (Gottschalk, 1987).

Second deformational phase (D2)

The second deformational phase, D2, is characterized by south vergent buckle folds, chevron folds, kinkbands, and crenulations. The orientations of the D2 structures are relatively constant throughout the study area although the morphology of F2 folds varies between domains. This is interpreted to indicate that Brookian thrusting had largely ceased in this area by the time of D2 deformation. This is interpreted to indicate that D2 is latest- to post thrusting. The North and Central domains are characterized by crenulations, kinkbands, and gentle folds. Mesoscopic buckle folds are better developed in the South domain. The highest strains associated with D2 are developed in the Klippe domain, where and chevron and buckle folds with the greatest degree of fold appression are developed. Locally, zones of intense folding demonstrate greater than 30% shortening by folding. D2 fold axes and lineations are subhorizontal and trend east-west to east-northeast to west-southwest in all domains.

The D2 deformation is probably a low-temperature deformation, as it shows
much less mineral growth and recrystallization than D1. Quartz and calcite recrystallized during D2 as evidenced by a non-penetrative D2 quartz-rich/calcite-rich/mica-rich differentiated crenulation cleavage and by granoblastic polygonal aggregates of quartz and calcite in the hinges of F2 folds. Some chlorite and sericite laths are also observed crosscutting micas parallel to the S1 foliation.

The south vergent D2 deformational structures are in apparent contradiction with north vergent tectonic transport. This is a regional phenomenon also observed in the Endicott Mountains allochthon (Phelps, 1987) and in the Schist belt (D3 of Gottschalk, 1987). Four general hypotheses are given to explain the phenomenon. 1) South vergent structures could be locally formed by backthrusting from thrust ramp folding. As these structures occur regionally, this is viewed as unlikely. 2) South vergent folds could be generated by south vergent thrusting; however all observed thrust faults appear to be north vergent. This idea was popular when two stage north and south directed thrusting was proposed to explain the north and south dipping thrusts on the flanks of the Doonerak window duplex (Dutro et al., 1976). 3) South vergent minor folds would be produced on the lower limb of a large scale north vergent recumbent nappe. However, sedimentary structures are overwhelmingly upright in the study area. 4) Subhorizontal, north-directed shortening of rocks with a penetrative pre-existing south dipping foliation can result in the widespread development of north dipping asymmetric kinkbands and related chevron folds with north dipping axial planes. In several localities in the Klippe domain kinkbands can be traced into chevron folds. Hypothesis 4 is most consistent with the regional character of the south-vergent D2 structures, the generally upright tops indicators, and the north vergence of the observed thrust faults.
Third deformational phase (D3)

The third phase of deformation, D3, is characterized by sporadically developed, close to wide spaced cleavage associated with gentle warps with sub-vertical axial planes. S3 strikes northwest and is subvertical across the field area. D3 crosscuts, and therefore postdates D1 and D2 structures and thrust faults.

The northwest-southeast striking S3 cleavage implies that the principal shortening direction, X, is almost perpendicular to the shortening direction of D3. D3 is interpreted to be either latest Brookian or post-Brookian folding event related to northeast-southwest compression.

Thrust Faults

The stacking sequence of the imbricates of the study area is relatively straightforward. From the relationships of the deformational structures between the thrust imbricates, north directed thrusting is inferred to have initiated during D1 and continued into D2.

The basal North domain thrust (BNDT), which is also the basal thrust of the Skagit allochthon in the field area, emplaces the Devonian and Silurian (?) rocks of the Skagit limestone above the upper Devonian rocks of the Hunt Fork shale of the Endicott Mountains allochthon. Regionally, the BNDT gradually cuts out the Skagit limestone westward (Fig. 3.1).

The basal Kupuk domain thrust (BKuDT) emplaces the pre-Carboniferous to post-Early Ordovician Pzp-Pzsh sequence above the Devonian Dkp phyllites. It is suspected that the Pzp-Pzsh sequence is of probable Ordovician age (Dillon et al., 1987), which would make it an equivalent facies of the Central domain volcanogenic clastic rocks. It is possible that the Kupuk domain contains rocks as young as Devonian, which would imply that it is structurally and stratigraphically related to the
rocks of the North domain.

The Central domain emplaces three imbricates of the Ordovician(?) Ovc-Ovs units above the rocks of the Kupuk domain, which are interpreted to be of the same age. A splay of the BCDT emplaces, and locally overturns Ovc rocks above the basal Ovs facies.

The South domain is exposed in the northern half of a syncline which is structurally cored by the Jesse klippe. The basal South domain thrust (BSDT) places dominantly middle Devonian rocks in fault contact with the Ordovician(?) Central domain rocks. This younger over older relationship is the opposite expected for a thrust fault relationship. Since the contact is dominantly bedding parallel, the preferred interpretation is that the BSDT is essentially a low displacement thrust fault or sheared contact. This relationship can also be explained by duplex development or by low-angle normal faulting. Low angle normal faulting has been proposed in the Schist belt (Gottschalk and Oldow, 1987) to explain anomalous fault bound packages of rocks of low metamorphic grade over older, high-grade metamorphic rocks. In this case, there appears to be no difference in metamorphic grade across the contact, and no overwhelming reason to invoke extentional tectonics in a compressional regime. The relationship could also be explained by making the BSDT the floor thrust of a duplex, or the roof thrust of a passive roof duplex. In this either case, subsidiary thrust faults should be seen merging into the BSDT.

The Klippe domain is exposed in an east-west trending, west plunging, flat bottomed syncline. The basal Klippe domain thrust (BKIDT) and the rocks of the Jesse Klippe are gently folded by late thrusting. The lower Paleozoic rocks of the Klippe domain are thrust over the dominantly middle Devonian rocks of the South domain on the BKIDT. From south to north, the BKIDT ramps rapidly upsection through the Klippe domain rocks, cutting out the Pzkb and Pzke units entirely. Further westward
into the Jesse klippe, a shallow east-west trending syncline-anticline pair becomes more apparent.

High-angle faulting

The field area is dissected by a number of east-west trending high-angle map scale and minor faults which crosscut, and therefore postdate all fold and thrust structures. Phelps (1987) noted that S3 is best developed near the east-west trending high-angle faults, and that many of these faults had left-lateral motions compatible with late stage northeast-southwest compression. Minor fault structures and stress axes calculated from conjugate fractures in the present study area are consistent with late stage northeast-southwest compression.
CHAPTER 5

STRUCTURE OF THE SOUTH-CENTRAL BROOKS RANGE

INTRODUCTION

A cross sections (Plates 3) illustrating the observed structural relationships in the south-central Brooks Range has been prepared along the north-south line given in Fig. 5.1. This line corresponds, in part, to the southern half of the balanced Brooks Range transect II (Atigun Pass transect of Oldow et al. (1987), which incorporated preliminary data from this study. The cross section presented here accepts the interpretation of transect II north of the Skajit allochthon, e.g. in the outer domain and foreland of the Brooks Range fold and thrust belt, and has been reinterpreted from the Skajit allochthon southward.

Five of the major litho-tectonic assemblages of the Brooks Range are represented in this cross section. They are from north to south, the Endicott Mountains allochthon, the Skajit allochthon, the Schist belt, the Rosie Creek allochthon, and the Ophiolite assemblage (Gotschalk, 1987; Oldow et al., 1987).

The stratigraphic thicknesses of these litho-tectonic units are poorly known. The observed sections have been structurally thickened by polyphase folding and faulting to greater or lesser degrees, and undeformed reference sections are not extant. Average observed structural thicknesses have been used.

OBSERVATIONS

Endicott Mountains allochthon

The Endicott Mountains allochthon (EMA) is exposed in the northernmost allochthon of the cross section. Approximately 4 km of upper(?) and middle Devonian Beaucoup Formation and a 1 km thick section of the upper Devonian Hunt Fork shale
Fig. 5.1 -- Generalized geologic map of the central Brooks Range. D = Dietrich Camp; W = Wiseman; C = Coldfoot.
are exposed along the line of section (Phelps, 1987). The structural thicknesses of the Hunt Fork shale is variable, but is estimated to average 4 km (Oldow et al., 1987). The section dips about 25° to the south along the plane of the section (Phelps, 1987).

**Skagit allochthon**

The Skagit allochthon forms an east-northeast - west-southwest trending 300 km long allochthon of Devonian-Cambrian age rocks structurally overlying the EMA and the Schist belt in the central Brooks Range. The northern portions of the Skagit allochthon along the line of section, which were mapped in this study, will be described separately from the less well known southern exposures.

The northern portion of the Skagit allochthon structurally overlies the EMA. These rocks crop out in the central and northern portions of a synclinorium cored by the Jesse klippe (informal name). The mapped thrust sheets expose two stratigraphic sequences, a Devonian or Devonian and Silurian(?) sequence and a lower Paleozoic sequence, which define detachment levels in the middle or upper Devonian, the lower Devonian or upper Silurian(?), and the lower Ordovician or upper Cambrian.

Five major thrust-bound rock packages were mapped in the present study area. These are, from north to south, and from structurally lowest to highest, the North, Kupuk, Central, South, and Klippe domains. The North domain is comprised of about 1.25 km of the Silurian(?) and Devonian Skagit marble and associated phyllite which dip of about 20° to the south. This thrust sheet is gradually cut out westward. Multiple imbrications of the Skagit marble are inserted eastward. The Kupuk domain consists of about 2 km of Ordovician(?!) phyllite and meta-carbonate which are generally bedding parallel to the structurally underlying North domain rocks, but whose dip steepens southward to about 30°. In the line of section, the Central domain is comprised of about 2 km of more steeply dipping Ordovician(?) age volcanogenic phyllite,
meta-wacke, and meta-conglomerate which are locally overturned near the basal thrust. Just to the east, the section is imbricated, and the basal domain thrust is breached by a splay. The South domain is exposed in a west plunging syncline beneath the Jesse klippe. Although only the south dipping northeastern exposures of this unit were mapped in detail, it is clearly persistent on both sides of the Jesse klippe (Fig. 5.1). The South domain is comprised of about 1.25 km of locally imbricated, upper-lower to lower-upper Devonian marble, phyllite, calc-silicate, and quartzite. The Klippe domain crops out in the eastern nose of the east-west trending Jesse klippe. Approximately 1850 m of lower Paleozoic (post-Early Ordovician and pre-Devonian) section were mapped - the top was not observed in the study area. The lower 1 km of section, which consists of north-dipping phyllitic marble exposed and is exposed in the southern portion of the Jesse klippe, is cut out northward by the basal Klippe domain thrust. An overlying section of heterogeneous meta-sediments are flattlying to gently dipping in the plane of the section.

The southern half of the Skagit allochthon is less well known. Heterogeneous, unfossiliferous meta-sediments, which do not obviously correspond to any of the previously defined units, have been mapped in reconnaissance (Brosgé and Reiser, 1964; Dillon et al., 1986, Oldow et al., 1987; Seidensticker and Julian, written communication, 1987). The gross structure of the southern Skagit allochthon is an east-northeast plunging antiform. Along the line of section only one major thrust sheet is apparent - which contains lower Paleozoic conodont bearing strata in the Mt. Snowden area (Dillon et al., 1988). This thrust sheet is structurally(?) overlain by the Devonian rocks of the South domain of the study area. No throughgoing thrust faults have been mapped in an area of poor exposures. A small section of a second thrust sheet is exposed near the Schist belt contact. Devonian(?) rocks, including rocks mapped as the Skagit marble, are exposed in a tectonic window in the antiform 10 km to
to the southwest of the line of section (Dillon et al., 1986).

The nature of the southern contact of the Skagit allochthon with the Schist belt varies. East of the Dalton Highway the Skagit allochthon structurally overlies the Schist belt (Oldow et al., 1987). West of the Dalton highway, however, the Minnie Creek thrust (informal name after Gottschalk, 1987) emplaces the Schist belt over the Skagit allochthon. An inverted metamorphic gradient and increasing deformational complexity is observed in this area, with the metamorphic grade of the Skagit allochthon rapidly increasing from lower greenschist facies to upper greenschist facies and an extra set of deformational structures developed toward the contact (Oldow et al., 1987; Seidensticker and Julian, written communication, 1987). These relationships are interpreted to indicate that the Skagit allochthon is enfolded by the Minnie Creek thrust (Oldow et al., 1987). The base of the Skagit allochthon is inferred to lie shallowly below the surface on the line of section because the basal contact emerges from beneath the envelopment thrust just to east. Elsewhere the depth to the base of the southern Skagit allochthon is unconstrained.

Schist belt

The Schist belt consists of high-grade metamorphic rocks, dominantly schists, of upper greenschist, amphibolite, and blueschist metamorphic facies (Gottschalk, 1987). Along the line of section, a 12 km structural section of the Schist belt is exposed, the northern boundary of which is the Minnie Creek thrust (MCT). From north to south, the rocks of the Schist belt locally dip to the north near the MCT, are essentially flat lying across the Wiseman arch (informal name), and dip about 30° to the south in central and southern Schist belt (Gottschalk, 1987). The MCT is interpreted to be a major envelopment thrust which brings high pressure metamorphic assemblages to the surface, and locally overthrusts the Skagit allochthon (Gottschalk, 1987). East of the
transect the Schist belt structurally underlies the Skajit allochthon and overlies the EMA (Oldow et al., 1987).

Undoubtedly, many unrecognized faults permeate the poorly outcropping and surficially similar schists of the Schist belt. Only two major fault imbricates are illustrated in the cross section. In reality, these represent complexly deformed and imbricated or duplexed structural packages whose internal geometry cannot be estimated with any degree of certainty at this time.

Analyses of the rocks of the Schist belt show an early episode of high pressure metamorphism and ductile, north-directed shear (Gottschalk, 1986, 1987). Geobarometry indicates recrystallization depths of about 23 km for crossite-bearing meta-gabbros, and in excess of 26 km for the highest grade glaucophane-bearing schists (Gottschalk, 1987).

Rosie Creek allochthon

The Rosie Creek allochthon (RCA) (informal name after Oldow et al., 1987) consists of a 1 km sequence of low metamorphic grade meta-sandstone and phyllite which overlies the southern Schist belt. The rocks of the RCA dip moderately (20°-40°) to the south. Early Devonian palynofloral assemblages have been recovered from the meta-sedimentary rocks of the RCA (Gottschalk, 1987). Chert intercalations 15 km to the east contain Mississippian radiolarians (Gottschalk and Oldow, 1988). The RCA is more similar to the Skajit allochthon than to the Schist belt in terms of age, metamorphic grade, and deformational structures, but is substantially thinner than, and is nowhere found in contact with, the Skajit allochthon.

Ophiolite assemblage

The Ophiolite assemblage, which consists of weakly metamorphosed Devonian -
Jurassic basalt, chert, and limestone, represents the structurally highest thrust sheets in the Brooks Range (Roeder and Mull, 1978). The Ophiolite assemblage structurally overlies the Rosie Creek allochthon on the Cathedral Mountain fault zone (CMFZ), a low-angle, south dipping anastamosing fault complex (Gottschalk, 1987). Prehnite-pumpellyite metamorphic facies in Fe2O3 rich basalts indicates a maximum metamorphic depth of 10 km (3 kb) - substantially less than for the Schist belt (Gottschalk, 1987). The contrast in metamorphic grade suggests that at least 10 km of intervening section has been omitted (Gottschalk and Oldow, 1988).

DISCUSSION

In general, the structurally higher allochthons in a thrust belt are more allochthonous than the lower allochthons. For the Brooks Range, the structural stacking order of the assemblages implies that the foreland - the North Slope, is autochthonous or para-autochthonous, and that the Apoon assemblage, EMA, Schist belt, Skagit allochthon, and Ophiolite assemblage probably restore to successively more southerly pre-deformational positions (Fig. 5.2). In this restoration the position of the southernmost (exposed) imbricate of the EMA, is a fixed reference from which the cross section is hung. The relative displacements of the assemblages are essentially unconstrained. In this reconstruction the assemblages are restored to essentially adjacent positions in order to give a minimum displacement estimate. The actual displacements between the assemblages may be, and probably are significantly greater.

The restoration of Ophiolite assemblage is problematic. Ophiolitic klippen, particularly in the western Brooks Range, attest to the once widespread distribution of large oceanic thrust sheets over the Brooks Range (Roeder and Mull, 1978). The ophiolitic remnants preserved could easily have displacements of hundreds of km.

The Rosie Creek allochthon occupies the same structural position as the Skagit
Fig. 5.2 --Structural stacking order of the assemblages of the south-central Brooks Range.
allochthon and contains rocks of similar age, metamorphic grade, and deformational structures. Although they are nowhere contiguous, the rocks of the RCA and the Skagit allochthon are interpreted to be related and to have deformed together above the proto-Schist belt.

Along the southern margin of the Brooks Range, the low metamorphic grade imbricates of the Ophiolite assemblage and RCA structurally overly the high pressure, high-grade metamorphic rocks of the Schist belt in a younger over older relationship. Given that the Schist belt rocks were metamorphosed at greater than 23-26 km depth, while those of the Ophiolite assemblage and RCA at less than 10 or 15 km, at least 10 km of section which originally overlay the Schist belt has been tectonically removed during Brookian orogenesis. Gottschalk and Oldow (1988) have proposed low angle normal faulting, driven by extentional normal faults above the uplifting Schist belt, along the south-dipping faults of the Cathedral Mountain fault zone and the basal RCA fault zone (Fig. 5.3). South vergent minor folds associated with faults with south directed slickenslide striations, and the absence of south-vergent thrust faults, support this interpretation (Gottschalk and Oldow, 1988).

Uplift of the high pressure Schist belt metamorphic rocks was probably accomplished by ductile duplexing followed by ramping and envelopment along the Minnie Creek thrust, which locally overrides the Schist belt - Skagit allochthon contact (Fig. 5.3)(Oldow et al., 1987; Gottschalk and Oldow, 1988).

The Schist belt extends a considerable distance northward beneath the Skagit allochthon. The subsurface leading edge of the Schist belt is assumed to be placed roughly beneath the axis of the frontal Skagit allochthon synclinorium, and on line with the subsurface projection of the Schist belt - EMA contact from eastern Chandalar quadrangle.

The major folds in the Skagit allochthon, the frontal synclinorium and the southern
Fig. 5.3 -- Schematic summary of proposed tectonic evolution for south-central Brooks Range (Gottschalk and Oldow, 1988). Ks = Lower Cretaceous sedimentary rocks of the Koyukuk basin; MzPzv = Paleozoic and Mesozoic mafic volcanic rocks and chert, with associated ultramafic rocks (Ophiolite assemblage); ImPz-Tr(?) = undifferentiated lower Paleozoic to Triassic(?) sedimentary rocks of the Arctic Alaska continental margin; PzPm = Lower Paleozoic and Precambrian rocks of the Schist Belt; pCb = Precambrian continental basement uninvolved in thin-skinned deformation; MCT = Minnie Creek thrust; RCA = Rosie Creek allochthon; CMFZ = Cathedral Mountain fault zone. A) Hypothetical pre-normal fault configuration (Early Cretaceous) based on reconstructions of Oldow et al., (1987). Obducted and structurally dismembered ophiolitic terrane over imbricate stack of lower Paleozoic-Triassic continental margin sediments. Diagramatic thrust faults are not shown in subsequent stages for clarity. B) Inception of movement on MCT during envelopment, and activation of normal faults (Barremian(?)-Albian). C) Unroofing of Schist Belt, and infilling of the Koyukuk Basin (Albian).
anticlinorium, are inferred to be controlled by the subjacent structure of the Schist belt and EMA. The Skagit allochthon is interpreted to have imbricated early in the orogen and then to have been passively folded by the emplacement of the succeeding subjacent allochthons. This is supported by the observation that D1 structures, which formed during the imbrication of the Skagit allochthon, are folded in the major structures.

Complex thrusting relationships are observed in the Skagit allochthon. Significant movement appears to have taken place on three detachment levels - in the middle or upper Devonian, in the lower Devonian or upper Silurian, and in the lower Ordovician or lower Cambrian. These detachments will be referred to as the upper Devonian, lower Devonian, and lower Paleozoic detachments, respectively. Examples of imbrication and duplex development can be seen in the Devonian section at about 67°30'N - 151°W, and in the lower Paleozoic section within the present study area. Along the line of section, lower Paleozoic and Devonian strata are structurally intercalated. In the present study area, Devonian rocks structurally overly and underlie lower Paleozoic imbricates. Minor fold structures, fault geometries, and hangingwall and footwall ramps indicate that displacements occurred on north-directed thrust faults.

No evidence of low-angle normal faults or normal reactivation of thrust fault planes was observed.

**RETRODEFORMATION**

The general restoration of the assemblages of the south-central Brooks Range is relatively straightforward given the depths to the basal detachment (Oldow *et al.*, 1987), the envelopment of the Schist belt on the MCT, and the late low-angle normal faulting of the RCA and Ophiolite assemblage (Gottschalk and Oldow, 1988). The principal question addressed here is the internal imbrication geometry and structural development of the Skagit allochthon.
Each of the imbricates of the cross section are numbered by the interpreted order of emplacement. Thus imbricate 1, the Ophiolite assemblage was emplaced first, and imbricate 9, of the EMA, last. Many of the illustrated imbricates, in particular the two imbricates of the Schist belt, are composite structures containing multiple imbricates unresolvable at this scale or state of knowledge.

The Ophiolite assemblage forms the structurally highest thrust sheets in the Brooks Range and was emplaced first. The RCA, the next highest structural package exposed, was emplaced next. Later low angle normal faulting, probably contemporaneous with the envelopment of the Schist belt along the Minnie Creek thrust, is schematically indicated for the Ophiolite assemblage and the RCA.

The most problematic aspect of the cross section is to explain the presence of the Devonian rocks structurally overlying lower Paleozoic rocks in the core of the southern Skagit allochthon antiform. These heterogeneous Devonian(?!) carbonate and clastic rocks include marbles mapped as the Skagit marble(?) (Dillon et al., 1986) and can either be correlated with the Devonian marl, marble, and phyllite of the South domain, or with the massive Skagit marble.

The preferred interpretation is that the Devonian section coring the southern Skagit allochthon sits on the basal Skagit allochthon thrust and is equivalent to the Skagit marble exposed in the frontal imbricates of the Skagit allochthon (Plate 3). This interpretation implies that the Devonian section is essentially glued to the lower Paleozoic section although the contact is sheared and thrusting is locally significant. This assumption generates the structurally simplest cross sections and correlates rocks mapped as Skagit marble(?) in the southern Skagit allochthon with the Skagit marble. The rocks of the Skagit allochthon are broken out and unfolded in Plate 3-B to illustrate the interpreted stacking sequence. Within the Skagit allochthon, imbricate 3, which includes the lower Paleozoic rocks coring the Jesse klippe, is the structurally highest
imbricate exposed and was emplaced first, followed by the successive emplacement of imbricates 4, 5, and 6. Imbricate 5, which contains the rocks of the Kupuk domain, was emplaced over imbricate 6 next.

Duplexing and uplift of the Schist belt (imbricates 7 and 8) emplaced the overriding Skagit allochthon northward over the EMA. The observed deformational structures and structural relations indicate that the rocks of the Skagit allochthon and the RCA were part of a roof complex above the Schist belt during the duplexing and uplift of the Schist belt (Oldow et al., 1987). The pre-imbrication position of the exposed portions of the Schist belt relative to the Skagit allochthon and the RCA is not known. The Schist belt has been conservatively restored to a position below the Skagit allochthon. The roof complex may have originated further to the south relative to the Schist belt - increasing the total shortening. Alternately, if the Schist belt originated south of the Skagit allochthon then the Schist belt would have moved north relative to the roof complex. This might explain the presence of south-vergent D2 folds in the Skagit allochthon, but would not explain their presence throughout the Schist belt.

Lastly the the Schist belt was enveloped by the MCT, exposing high-pressure metamorphic assemblages (imbricate 8). The MCT overthrusts the southernmost portion of the Skagit allochthon west of the Dalton Highway.

A second class of solutions is generated by correlating the Devonian rocks of the southern Skagit allochthon with the more lithologically similar rocks of the South domain. These solutions generate more structurally complex sections with the Devonian section extensively detached from the lower Paleozoic section. In order to equalize the shortening in the Devonian and the lower Paleozoic sections, the Devonian section must be delaminated from the lower Paleozoic section, translocated forward, and then eroded away.
SHORTENING

Retrodeformation of the allochthons of the cross section implies a conservative estimate of 100 km (50%) shortening of the Skagit allochthon solely by the megascopic imbrication of the major allochthons of the assemblages. This does not include shortening by mesoscopic and microscopic structures unresolvable in the section - conservatively estimated to represent more than another 100 km (50%) shortening for the Skagit allochthon, and substantially greater amounts in the Schist belt (Oldow et al., 1987). This also does not include the shortening represented by the gaps in the reconstruction, most notably between the Ophiolite assemblage and the RCA, and between the Skagit allochthon and the EMA and the RCA. This is consistent with the estimate of shortening in the inner domain of the Brooks Range of Oldow et al. (1987) of 250+ km - exclusive of the shortening represented by the Ophiolite assemblage.

PALEOGEOGRAPHIC IMPLICATIONS

In the Devonian, the rocks of the Skagit allochthon were part of an extensive carbonate shelf or platform system (Brosge and Dutro, 1973). The Devonian marbles, marls, and phyllites, examined in this study are consistent with this interpretation. The restoration of the Devonian rocks of the Skagit allochthon (Plate 3c) shows a southward thinning of the massive marble facies, and a concomitant increase in the proportion of phyllite in the section - from the North domain, to the Devonian rocks of the southern Skagit allochthon, to the South domain.

The lower Paleozoic paleogeography of the rocks of the Skagit allochthon is not well constrained due to the scarcity and imprecision of the lower Paleozoic age dates, and to the paucity of information and the increase in metamorphic grade in the southern portions of the Skagit allochthon. It is generally assumed that a major carbonate shelf or platform system containing shallow and deep water carbonates and slopal sediments,
Fig. 5.4 -- Stratigraphic correlation chart for the assemblages of the south-central Brooks Range.
and locally, coarse clastic rocks and volcanigenic sediments, existed in the lower Paleozoic (Fig. 5.4) (see also Brosge and Dutro, 1973; Dumoulin and Harris, 1987). It can safely be inferred from the heterogeneity of the lithologies exposed, and from the structural juxtaposition of proximal fanglomerates (Ovc-Ovs) and olistromal argillites (Pzs-Pzsh), that there was significant structural relief and probable rapid uplift and basin subsidence during the lower Paleozoic.

The displacements and the facies relationships between the assemblages are poorly constrained. The Skagit allochthon contains rocks which are age equivalent, at least in part, to rocks in the RCA, the EMA, and the Apon assemblages. The ages and lithologies of the assemblages are given in Figure 5.4.

One of the principal objectives of this study was to test the correlation of the lower Paleozoic rocks of the Skagit allochthon exposed in the Jesse klippe with the lower Paleozoic rocks of the Apon assemblage exposed in the Doonerak window (Brosge and Patton, 1982). The Jesse klippe was found to contain lower Paleozoic rocks at least partially time equivalent to the rocks of the Apon assemblage. However, the lithologic differences between the argillites and carbonates mapped in the Jesse klippe and the the volcanic arc sediments and slates of the Apon assemblage were so great as to preclude any simple correlation (Dutro et al., 1984, 1986; Julian, 1989). Reconstructions of the Brooks Range by Oldowet al. (1987) imply a minimum of 150 km of unexposed transitional facies between the Skagit allochthon and the Apon assemblage. Other speculative reconstructions are available in Hubbard et al. (1986) and Julian (1989).

The relationship of the Devonian rocks of the Skagit allochthon to the middle and upper Devonian rocks of the Endicott group exposed in the EMA is less straightforward. Three groups of solutions are possible: 1) vertical facies equivalence; 2) lateral facies equivalence; and 3) no facies equivalence.
A vertical facies transition, with the Skagit allochthon grading upward into the EMA requires deep burial of the Skagit allochthon. Stratigraphically this implies a south-facing lower-middle Devonian carbonate shelf buried beneath a prograding middle and upper Devonian (Endicott group) fan complex (Nilsen, 1981). The Skagit allochthon has an estimated structural thickness of about 8 km. If the Skagit allochthon was brought up by envelopment of the rocks of the EMA, their Mississippian-Cretaceous cover, and ophiolites, then the base of the Skagit allochthon must have been buried at least 30 km, which is contradictory with the observed lower greenschist metamorphic facies (Oldow et al., 1987, Section II B).

Lateral facies equivalence of the Skagit allochthon and the EMA requires the reconciliation of a south-directed silici-clastic fan complex with a north-facing carbonate shelf or platform. This scenario implies that the mixed carbonate and clastic rocks of the middle and upper(?) Devonian Beaucoup Formation of the EMA forms a transitional facies. This is supported by the definition of the Beaucoup Fm., at the type section, by clastic-carbonate cycles, often capped by 25-30 m reefs (Brosge et al., 1979).

Restorations of the Skagit allochthon and the EMA do not constrain their relative displacements. It is entirely possible that the Skagit allochthon and the EMA are not related, and are separated by a transitional basinal facies which is not preserved (Hubbard et al., 1986).

It is also suggested that the Skagit allochthon is related to the RCA. Although they are not found in contact, they have similar lithologies, age, metamorphic grade, and deformational history (Gottschalk, 1987). They occupy the same relative structural position within the roof complex above the Schist belt.

The Schist belt contains the higher metamorphic grade equivalents of many of the lithologies exposed in the Skagit allochthon - some of which may be partially age equivalent (Gottschalk, 1987). Although the Schist belt is shown below the rocks of
the Skagit allochthon in the reconstruction (Plate 3-C), the rocks of the Schist belt may, in fact, restore considerably further to the south. The difference in metamorphic grade also suggests that the rocks of the Schist belt and the Skagit allochthon were probably not in depositional contact. Study of the rocks the northern Schist belt, where exposed in front of the MCT, may shed further light on this topic.

KINEMATICS OF DEFORMATION

The inception of the Brookian orogen is thought to be marked by the imbrication and obduction of ophiolitic material over a south facing continental margin in the late Jurassic (Mayfield et al., 1983). Obduction of the ophiolites was certainly occurring by the early Neocomian, contemporaneous with the inception of synorogenic sedimentation in the western Brooks Range, and imbrication may have occurred as early as Bathonian-Callovian (Mayfield et al., 1983). Imbrication of the subjacent RCA and Skagit allochthon was probably initiated at this time, along with the formation of D1 deformational structures (S1).

By Early Cretaceous time, ductile duplexing and north directed shearing of the high-pressure Schist belt metamorphic rocks was occurring at depth beneath the imbricated Skagit allochthon - RCA - Ophiolite assemblage roof complex. Emplacement of the Schist belt over the EMA probably followed.

Uplift of the Schist belt along the Minnie Creek thrust is dated by retrograde metamorphic 100-130 Ma K-Ar and Rb-Sr cooling ages (Turner et al., 1979; Armstrong et al., 1986) and synorogenic deposition in the Koyukuk basin (Dillon and Smiley, 1984). Gottschalk and Oldow (1988) suggest that extension, possible coupled with subsidence in the Koyukuk basin occurred at this time. Continuing uplift of the Schist belt on the MCT led to loss of overlying rock complex by low angle normal faulting, and the eventual unroofing of the Schist belt. Regional balanced cross
sections by Oldow et al. (1987) suggest that continuing deformation led to the emplacement of the EMA and the subsequent development of the Doonerak duplex beneath the EMA.

South vergent conjugate D2 structure have consistent orientations across the major folds and thrust, implying that they developed after thrusting had ceased in the area. South vergent D2 (or equivalent) structures are observed in the Schist belt, Skagit allochthon, Apon assemblage, and in the EMA south of the Doonerak Window (Avé Lallemant et al., 1983; Gottschalk, 1987; Phelps, 1987), but are not or very poorly developed in the EMA exposed north of the Doonerak window (Handschy, 1988). This suggests that the Doonerak duplex acts as a major structural boundary in the thrust belt, behind which north directed strains were partitioned into north and south vergent conjugate structures - with the south vergent set dominant (Seidensticker et al., 1987).

D3 structures, where developed, have constant orientations. The northwest-southeast striking cleavage implies compression almost perpendicular to the principal shortening direction of the thrust belt. D3 was either a latest Brookian or post-Brookian folding event developed after north-south compression had ceased. A set of east-west trending high-angle faults are the last set of deformational structures developed, and are consistent with northeast-southwest compression.
CHAPTER 6 - CONCLUSIONS

INTRODUCTION

The Skagit allochthon consists of a poly-deformed and imbricated sequence of heterogeneous Devonian and lower Paleozoic meta-sediments. These rocks constitute the northernmost lithotectonic assemblage of the inner domain of the Brooks Range fold and thrust belt (Oldow et al., 1987). The rocks of the Skagit allochthon crop out between the mid-Paleozoic rocks of the Endicott Mountains allochthon to the north, and the Paleozaic to Proterozoic high-grade metamorphic rocks of the Schist belt to the south.

Study and mapping of a portion of the northern Skagit allochthon in the central Brooks Range has yielded data with important implications for Brookian orogenesis and Devonian and lower Paleozoic stratigraphy and paleogeography: 1) Many previously undated imbricates within the Skagit allochthon, which were previously thought to be dominantly Devonian(?) in age, are largely or partially of lower Paleozoic age; 2) The large scale involvement of lower Paleozoic rocks in Brookian thrusting - the emplacement of the Jesse kippe, the envelopment of Devonian rocks by lower Paleozoic rocks in the Skagit allochthon, and the duplexing of the Apon assemblage in the Doonerak window - favor large thrust displacements and high shortening reconstructions; 3) Deformational structures and metamorphic conditions of the Skagit allochthon can constrain restorations of the Skagit allochthon *vis-a-vis* age equivalent strata in the Endicott assemblage, the Doonerak assemblage, and the Rosie Creek allochthon; 4) Although the rocks of the Jesse kippe contain lower Paleozoic conodonts, and are therefore at least partially age equivalent to the rocks of the Apon assemblage, substantial lithologic differences preclude any simple correlation as proposed by Brosge and Patton (1982).
STRATIGRAPHY

The rocks of the northern Skagit allochthon in the central Brooks Range crop out in structurally and stratigraphically complex thrust imbricates. Approximately 8 km of section of imbricated meta-carbonate and meta-clastic rocks were observed in the study area. The age of the Skagit allochthon in the mapped area is Devonian to Ordovician. Shelfal carbonate, calc-silicate, and phyllite, olistromal argillite, and volcanioclastic fanglomerates were observed.

The mapped area was divided into five thrust-bound domains. These are, from north to south - the North, Kupuk, Central, South, and Klippe domains. The North domain consists of about 1.3 km of dominantly Devonian shallow marine to mid-shelfal sediments - about 400 m of Silurian (?) and Devonian Skagit marble stratigraphically overlain by 900 m of phyllite. A 2.0 km fining-upward section of sparcely fossiliferous Ordovician (?) - Silurian (?) olistostromal meta-argillite and marble is exposed in the Kupuk domain. These rocks may have formed in a carbonate slope environment. The Central domain contains up to 2.3 km of imbricated Ordovician (?) volcanogenic meta-conglomerate, meta-wacke, and phyllite deposited in proximal to distal alluvial fans. The South domain is characterized by about 1.0 km of abundantly fossiliferous Emsian - Frasnian age shallow marine marble, phyllite, and marl which contain numerous basaltic and intermediate composition greenstones. The mapped portion of the Klippe domain consists of 1.9 km of calcareous and siliciclastic rocks which contain Lower Paleozoic age conodonts and which may have been deposited in a variety of shelfal or basinal settings.

STRUCTURE

The rocks of the northern Skagit allochthon have been deformed by polyphase folding, associated contractional faulting, and by late stage high-angle faulting. Three
sets of fold structures were identified based on superpositional and cross cutting relationships. Bedding is generally south dipping and upright.

The earliest phase of folding (D1) is characterized by the development of a pervasive penetrative cleavage (S1) which is axial planar to rare, rootless isoclinal folds. This folding is related to the many east-west striking thrust faults along which the imbricates were displaced to the north. The second phase of folding (D2) forms most of the folds seen in outcrop and thin section. D2 forms mostly south-vergent conjugate folds and crenulations of the S1 cleavage. It may have formed as a conjugate to north directed slip on the S1 surfaces. The latest set of fold structures (D3) consists of sporadically developed sub-vertical spaced cleavage associated with gentle folding.

The latest set of deformational structures consists of a number of east-west trending high-angle faults and fractures which crosscut all fold structures. Map offsets typically show normal or reverse displacements while slickenslide striations show sub-horizontal last motions. The D4 deformation is interpreted to be a late or post Brookian faulting event which is compatible with northwest-southeast directed compression.

STRUCTURE OF THE SKAJIT ALLOCHTHON

The Skagit allochthon is a 300 km long allochthon which trends east-northeast - west-southwest in the south-central Brooks Range and structurally overlies the Endicott Mountains allochthon to the north and the Schist belt to the south. The rocks of the Skagit allochthon form a northern synclinorium, which is cored by the Jesse klippe, and a southern anticlinorium - whose axes parallel the axis of the allochthon.

The rocks of the Skjait allochthon can be grossly divided into a Devonian or Silurian(?) and Devonian marble and phyllite section, and a lower Paleozoic section containing heterogeneous clastic, carbonate, and volcaniclastic rocks. Three detachment
levels were observed; in the upper Devonian section, at the base of the Devonian section, and at or near the base of the lower Paleozoic section. Significant displacements are inferred along all detachment levels by imbricates mapped in this study.

A partial balanced cross section was constructed through the south-central Brooks Range. Retrodeformations of the imbricates of the cross section implies a minimum of 100 km of shortening solely by the megascopic imbrication in the Skagit allochthon. This estimate is consistent with the large displacement (250 + km) estimates for the interior of the thrust belt by Oldow et al. (1987).
APPENDIX 1

GEOCHEMICAL ANALYSIS OF IGNEOUS ROCKS

INTRODUCTION

Major-element (ICP) Spectrometer analyses were performed on selected samples of meta-igneous rocks of the northern Skagit allochthon. Whole-rock compositions and major-element ratios and abundances were used to determine the rock classification and the possible tectonic environment of formation of the rocks.

The rocks of the study area have been regionally metamorphosed to lower greenschist facies. Metamorphic differentiation of pelitic material is frequently observed in thin-section, and carbonates are pervasively recrystallized. Original feldspar and mafic minerals have been almost completely altered. Additionally, the rocks of the study area have been highly deformed and exhibit penetrative metamorphic foliations.

Due to the degree of deformation and metamorphism, the concentrations of the more mobile elements may vary substantially from their original values.

SAMPLE PREPARATION AND ANALYSIS

Samples for ICP analysis were chosen from field samples of the meta-igneous rock units. The selection criteria were: 1) representative lithology, 2) minimum deformation, and 3) minimum alteration and weathering. Ten samples were analyzed; seven were chosen from the greenstones and dikes intruding Dcl, two from the volcaniclastic units Ovc and Ovs, and one from a small dike intruding Pzkb. Sample locations are indicated on Plate 2.

The weathered surfaces of the samples were trimmed off with a hydrolic press to expose fresh rock surfaces. These surfaces were then cleaned by immersion in an
ultrasonic bath in a 1% Hydrochloric acid solution. The cleaned samples were kiln
dried overnight and then powdered in a Spex shatterbox. For each sample, 50 mg of
the rock powder was mixed with 250 mg of flux and then fused into a glass bead in a
firing kiln. Solutions for ICP analysis were then prepared by dissolving the beads in
250 ml of Nanopure™ water. The solutions were stored until analysis in clean
polypropylene vials. The samples were analyzed for major-element abundances on the
Rice University ICP Spectrometer. Instrument data were corrected to constant weights
and drift normalized to average rock standards. The ICP data is compiled in Figure
A1.1.

RESULTS

The major-element analyses of the meta-igneous rocks of the central Hammond
River area (Figs. A1.2 and A1.3), show two compositional groups. The greenstones
and dikes which intrude Dcl are of basic composition, 43-48% Si - which are distinctly
different from the acidic, 63-77% Si, compositions of the volcanic rocks associated
with Ovc, Ovs, and Pzkb.

The meta-igneous rocks associated with Dcl show a wide range of basaltic
composition, from sub-alkaline, alkaline, to strongly alkaline (Fig. A1.1). Although
SiO₂ concentrations are uniform, the rest of the major-elements show a wider range of
values (Fig. A1.3). Standard AFM plots do not show a clear tholeiitic vs calc-alkaline
trend (Fig. 'A1.4a).

The remaining 3 samples, from the Ovc, Ovs, and Pzkb units, show similar
subalkaline rhyolitic to dacitic compositions (Fig. A1.2). Although they clearly
represent a different magma composition from the basalts associated with Dcl,
insufficient data exists to discriminate significant compositional differences, if any,.between the volcaniclastics of Ovs/Ovc and the intrusive from Pzkb. The samples vary
### Meta-igneous rocks from Dcl

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>FeₓOᵧ</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
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<tr>
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<td>3.13</td>
<td>33.23</td>
<td>11.55</td>
<td>0.02</td>
<td>3.00</td>
<td>0.74</td>
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<td>KB4-029</td>
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### Meta-volcaniclastic rocks from Ove and Ovs

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<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>FeₓOᵧ</th>
<th>MnO</th>
<th>MgO</th>
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### Meta-igneous rocks from Pzkβ

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<th>Al₂O₃</th>
<th>FeₓOᵧ</th>
<th>MnO</th>
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<td>1.81</td>
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Figure A1.1 -- Major-element ICP analyses of the volcanic rocks of the Skajit assemblage. All analyses are given in weight %. Analyst: F.E. Julian.
Figure A1.2 -- Classification of volcanic rocks associated with the Skagit assemblage (After Cox et al., 1979 and Irvine and Baragar, 1971).
Figure A1.3 — Major element ICP analyses of meta-igneous rocks associated with the Skagit assemblage. All values are given in weight %.
AFM plot of analyses of meta-igneous rocks associated with the Skajit assemblage.

- From Dcl
- From Ovc, Ovs
- From Pzkb

AFM plot of analyses of lower Paleozoic Apoon assemblage (informal) meta-volcanic rocks of the Doonerak window.

- Dutro et al., 1976.

AFM plot of analyses of meta-igneous rocks associated with the Beaucoup Formation of the Endicott allochthon.


\[ A = \text{wt. \% Na}_2\text{O} + \text{K}_2\text{O} \]
\[ F = \text{wt. \% Fe}_{2\text{O}_3} \text{O}_y \]
\[ M = \text{wt. \% MgO} \]

Figure A1.4 -- AFM plots of meta-igneous rocks of the central Brooks Range.
principally in SiO₂ concentration, and little in the other major elements (Fig. A1.3). AFM plots are inconclusive, but also discriminate them from the Dcl basalts (Fig. A1.4a).

INTERPRETATION AND CONCLUSIONS

Two distinct magma compositions are indicated by the major-element data. Further, volcanic compositions vary between, and may be diagnostic of, the different litho-tectonic assemblages.

The meta-igneous rocks associated with Dcl are of basaltic composition. A high degree of elemental mobility during deformation and metamorphism is indicated by the variability of the major element concentrations other than Si. The rocks are strongly depleted of K₂O. In 6 samples, the K₂O content is less than 0.1%; and is 3.34% in one sample (Fig. A1.3). The other major-elements show non-systematic variability that is more consistent with element mobility than with an evolving magma series.

The volcaniclastic sample from Ovc has a dacitic composition. The sample from Ovs, the more distal sedimentologic equivalent, has a higher Si content, but otherwise has the same major-element chemistry, interpreted to be the result of eruptive and depositional winnowing of the denser volcanic crystals (Fisher and Schrimke, 1984).

The intrusive sample taken from Pzkb has the composition of a dacite. Its chemical composition is equivalent to those of the Ovc and Ovs samples.

AFM plots of the analyses of the volcanic rocks associated with the Skagit allochthon are compared with previous analyses of volcanic rocks from the central Brooks Range in Figure A1.4. The lower Paleozoic volcanic rocks of the Apoon assemblage contain slightly higher Mg concentrations and are generally less variable in composition. The volcanic rocks associated with the subjacent Beaufort Formation of the Endicott Mountains allochthon show gross compositional distributions similar to
those of the basalts occurring within Dcl, but show a range of higher alkali contents and have less compositional variability.
REFERENCES


Dillon, J.T., and G.H. Pessell, 1979, Tectonic significance of late Devonian and late Proterozoic U/Pb zircon ages from meta-igneous rocks, Brooks Range, Alaska: G.S.A. Abs. with Prog., v. 11/3, p. 75.


Harris, A.G. and V.A. Rejebian, 1986, Conodont color alteration above 300°C: calibration experiments and geologic applications; G.S.A. abs. with prog., v.18/3, p. 228.


Hubbard, R.J., B.P. Edrich, and R.P. Rattey, 1987, Geologic evolution and hydrocarbon habitat of the "Arctic Alaska microplate": Marine and Pet. Geol., v. 4, p. 2-34.


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UMI
PLATE 1
GEOLOGIC MAP
NORTHERN SKAJIT ASSEMBLAGE
CENTRAL BROOKS RANGE, ALASKA

by
K.W. BOLER
1989

Contacts

--------- Contact
---------- Approximate
----------- Inferred

Faults

--- Thrust fault, barbs on upper plate
----- Dip-slip fault
----- Strike-slip fault
--------- Approximate
---------- Inferred

Attitudes

Bedding (S0)
Overturned S0
S1
S0=S1
S2
S3

Folds

Antiform, arrow in direction of plunge
Overturned antiform
Synform, arrow in direction of plunge
Overturned synform

Fossil locality

Cross section line

Scale 1:31,360
Contour interval = 100 ft.

0 1 2 km.

0 1/2 1 mi.

N

28°
Dskd
Dskc

Massive marble.
Calc-schist.

Black slate [pre-Carb. & post-E. Ord.].
Argillite [pre-Carb. & post-E. Ord.].
Phyllitic marble [pre-Carb. & post-Ord.].

Volcanic pebble conglomerate (Ord).
Volcanogenic phyllite. Grades into Ovc. (Ord)
Argillaceous marble.

Upper calcareous phyllite (post-Em. & pre-Fam)
Middle marble (M. Dev.).
Lower calcareous phyllite (post-Sieg. & pre-Fras)
Quartzite [pre-Carb.].

Argillite (lower Paleozoic?).
Argillaceous marble.
Phyllitic marble (lower Paleozoic?).
Calc-phyllite (lower Paleozoic?).

Hunt Fork Shale (U. Dev.).

Mafic and felsic dikes, flows, & sills (Dev?).

Quaternary deposits, undifferentiated.
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PLATE 2
STRUCTURAL CROSS SECTIONS

NORTHERN SKAJIT ASSEMBLAGE
CENTRAL BROOKS RANGE, ALASKA

by
K.W. BOLER
1989

\[ \text{B' SOUTH} \]
STRATIGRAPHY

Northern Skagit assemblage

- Dkp  Phyllite (Dev.?).
- Dpp  Purple and green phyllite (Dev.).
- Dsk  Skagit marble (Sil?-Dev.).
  - Dskl  Massive marble.
  - Dskc  Calc-schist.

- BNDT  Black slate [pre-Carb. & post-E. Ord.].
- Pzsh  Argillite [pre-Carb. & post-E. Ord.].
- Pzs  Phyllitic marble [pre-Carb. & post-Ord.].
- Pzcp  Volcanic pebble conglomerate (Ord.).
- Ovc  Volcanic/phyllitic. Grades into Ovc. (Ord.).
  - Ovs  Volcanogenic phyllite. Grades into Ovc. (Ord.).
  - Ovsl  Argillaceous marble.

- BCDT  Upper calcareous phyllite (post-Ems. & pre-Fam.).
- Dcu  Middle marble (M. Dev.).
- Dcm  Lower calcareous phyllite (post-Sieg. & pre-Fras.).
- Dcl  Quartzite [pre-Carb.].

- BSD  Calc-phyllite (lower Paleozoic?).
- Pzks  Phyllitic marble (lower Paleozoic?).
  - Pzksl  Argillaceous marble.
- Pzkc  Argilite (lower Paleozoic?).
- Pzkb  Calc-phyllite (lower Paleozoic?).

- BKIDT  Hunt Fork Shale (U. Dev.).
  Dev.)
STRATIGRAPHY
Northern Skagit assemblage

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
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<tbody>
<tr>
<td>Dkp</td>
<td>Phyllite (Dev.?).</td>
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<tr>
<td>Dpp</td>
<td>Purple and green phyllite (Dev.).</td>
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<td>Dsk</td>
<td>Skagit marble (Sil?-Dev.).</td>
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<tr>
<td>Dskl</td>
<td>Massive marble.</td>
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<td>Dskc</td>
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<td>Phyllitic marble [pre-Carb. &amp; post-Ord.].</td>
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<td>Volcanic pebble conglomerate (Ord.).</td>
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<td>Volcanogenic phyllite. Grades into Ovc. (Ord.).</td>
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<td>Ovsl</td>
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<td>Dcu</td>
<td>Upper calcareous phyllite (post-Ems. &amp; pre-Fam.).</td>
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<tr>
<td>Dcm</td>
<td>Middle marble (M. Dev.).</td>
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<tr>
<td>Dci</td>
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Endicott Group

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Igneous rocks

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Surficial deposits

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Endicott Mountains allochthon

Devonian clastic rocks

Skagit allochthon

Devonian

Lower Paleozoic

N  North domain
Ku  Kupuk domain
C  Central domain
S  South domain
Kl  Klippe domain

Schist belt

PC-Pz metamorphic rocks

Rosie Creek allochthon

Dev.-Miss. phyllite

Ophiolite assemblage

tPz-Mz ophiolitic rocks
uPz–Mz ophiolitic rocks