AN ABSTRACT OF THE THESIS OF

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Signature redacted for privacy.

Abstract approved:___
William H. Taubeneck

Metamorphosed volcanogenic rocks of the Permian and Triassic Seven Devils Group are exposed in the northern part of the Heavens Gate 7.5 minute quadrangle, western Idaho. These rocks originated in a volcanic arc at a destructive plate margin. In the north, rocks that probably belong to the Lower Permian Hunsaker Creek Formation comprise abundant volcaniclastic lithologies and sparse keratophyre and quartz keratophyre flows. To the south, the Middle to Upper Triassic Wild Sheep Creek Formation comprises volcaniclastic rocks interbedded with abundant spilite and keratophyre flows. Trace element analyses of these flow rocks indicate that most are transitional, probably calc-alkaline, island arc volcanic rocks. Some flow rocks may be island arc tholeiites. The lithologic and geochemical character of these rocks is different from that of the Wrangellia terrane, with which they have been correlated.

The Seven Devils Group is overlain along a low angle thrust fault by the lower to middle Norian Martin Bridge Formation.

This unit is composed primarily of sheared marbles, with local occurrence of unsheared micrite. The Martin Bridge Formation is overlain along the Rapid River thrust by the Upper Triassic Lucille Formation and by the Riggins Group (age unknown). The Riggins Group in this area includes metavolcanics of the Lightning Creek Schist and metasediments of the Squaw Creek Schist. They both overlie the Martin Bridge Formation along a single plane of the Rapid River thrust in the southern part of the field area. To the north, the Seven Devils Group, Martin Bridge Formation, Lucille Formation, and Lightning Creek Schist are juxtaposed along imbrications of the Rapid River thrust.

Structural elements of the study area indicate that the Rapid River thrust may have affected rocks significantly farther to the west than had been previously recognized. Bedding-parallel ductile shear fabrics occur in volcaniclastic rocks throughout the field area. The intensity of ductile shearing increases toward the low angle thrust fault that separates the Seven Devils Group from the Martin Bridge Formation. This thrust is interpreted to be an integral part of the Rapid River thrust system. An east-west-trending tear fault that separates Wild Sheep Creek Formation from Hunsaker Creek Formation post-dates low-angle thrusting, and probably indicates the occurrence of structurally lower thrust faults that have not yet been documented.

Tonalites of probable Late Jurassic to Early Cretaceous age postdate ductile shearing and thrust faulting. This may

indicate that deformation of this area occurred during the regionally significant Late Jurassic pulse of the Nevadan orogeny. This event may record the collision of the Seven Devils volcanic arc with North America.

Geology of a Part of the Heavens Gate Quadrangle,
Seven Devils Mountains, Western Idaho

by

Daniel R. Sarewitz

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Signature redacted for privacy.

Professor of Geology in charge of major

Signature redacted for privacy.

Chairman of Department of Geology

Signature redacted for privacy.

Dean of Graduate School

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Typed by Daniel R. Sarewitz

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TABLE OF CONTENTS

Introduction 1
    Description of the Field Area 1
    Previous Work 3
    Stratigraphy and Age Relations 5
    Objectives 10

Rock Units 12
    Seven Devils Group 12
        Hunsaker Creek Formation 12
        Wild Sheep Creek Formation 16
    Martin Bridge Formation 23
    Lucille Formation 26
    Riggins Group 27
        Lightning Creek Schist 28
        Squaw Creek Schist 29
        Ultramafic Rocks 30
        Amphibole Schist 30
    Mesozoic Plutonic Rocks 31
    Late Mesozoic or Tertiary Diorite Porphyry 38
    Columbia River Basalt 39

Geochemical Character of the Wild Sheep Creek Formation 41

Structural Geology 62
    Nature of the Martin Bridge Formation - Seven Devils Group Contact 62
    Shear Textures 68
    Relation Between Brittle and Ductile Shear 78
    Tear Fault 82
    Rapid River Thrust 86
    Timing of Deformation 102

Conclusions 110
    Regional Geologic Relations 110
    The Wrangellia Connection 120
    Summary 130

References Cited 133

LIST OF FIGURES

Figure		Page
1.	Map showing the location of the study area	2
2.	Age relations of rock units within the study area	6
3.	Cliff of Martin Bridge Formation overlying gentler slopes of the Hunsaker Creek Formation above Shingle Creek	24
4.	Micropegmatite in tonalite	35
5.	Alkali-silica plot for rocks of the Wild Sheep Creek Formation	48
6.	Rare earth element patterns for rocks of the Wild Sheep Creek Formation	51
7.	Hafnium-tantalum-thorium tectonomagmatic descrimination diagram	57
8.	Flat rare earth element patterns of three spilites from the Wild Sheep Creek Formation	59
9.	Comparison of La/Yb versus Yb for Wild Sheep Creek Formation and average values from other volcanic arc rocks	61
10.	Fault contact between Martin Bridge Formation and Wild Sheep Creek Formation	66
11.	Fracture cleavage in a keratophyre tuff, Wild Sheep Creek Formation	69
12.	Ductile shear fabric in a keratophyre from the Wild Sheep Creek Formation	72
13.	Quartz pressure solution fringes adjacent to a pyrite cube	74
14.	Clast elongation in sheared volcaniclastic conglomerate, Hunsaker Creek Formation	77
15.	Sheared and recrystallized Pentacrinus stem plate	79
16.	Contact relations near Thorn Gulch	85
17.	Schematic representation of tear fault development	94

18. Schematic cross sections showing development of Rapid River thrust zone and related structures at the northern boundary of the study area 98

19. Generalized map showing distribution of pre-Tertiary terranes of northeast Oregon and west-central Idaho 111

20. Location of the Wrangellia terrane 121

21. Alkali-silica plot for the Wild Sheep Creek Formation and Wrangellia 126

LIST OF TABLES

Table Page

1. Modal analyses of flows from the Wild Sheep Creek Formation 21

2. Modal analyses of tonalites 33

3. Chemical composition of flow rocks of the Wild Sheep Creek Formation 43

4. Comparison of chemical composition of the Wild Sheep Creek Formation with world-wide averages 54

LIST OF PLATES

I. Geologic map of part of the Heavens Gate quadrangle, western Idaho map pocket

II. Geologic cross sections map pocket

THE GEOLOGY OF A PART OF THE HEAVENS GATE QUADRANGLE, SEVEN DEVILS MOUNTAINS, WESTERN IDAHO

INTRODUCTION

A thick sequence of Permian and Triassic volcanogenic rocks is exposed in eastern Oregon and western Idaho. These rocks constitute the Seven Devils Group (Vallier, 1977), and they represent an island arc assemblage formed at a destructive plate margin and accreted to North America after the early Mesozoic. This study attempts to interpret the petrologic character, evolution and sequence of deformation, and structural nature of the eastern margin of the Seven Devils Group. These problems have some bearing not only on the geologic history of the Seven Devils island arc, but on certain aspects of the Mesozoic evolution of the northwest Cordillera of North America.

DESCRIPTION OF THE FIELD AREA

The study area encompasses about 70 square kilometers (25 square miles) of the northern part of the Heavens Gate 7.5 minute quadrangle, Idaho County, Idaho. This area lies on the east flank of the Seven Devils Mountains. The location of the quadrangle is shown in Figure 1. The field area is bounded on the north, east,

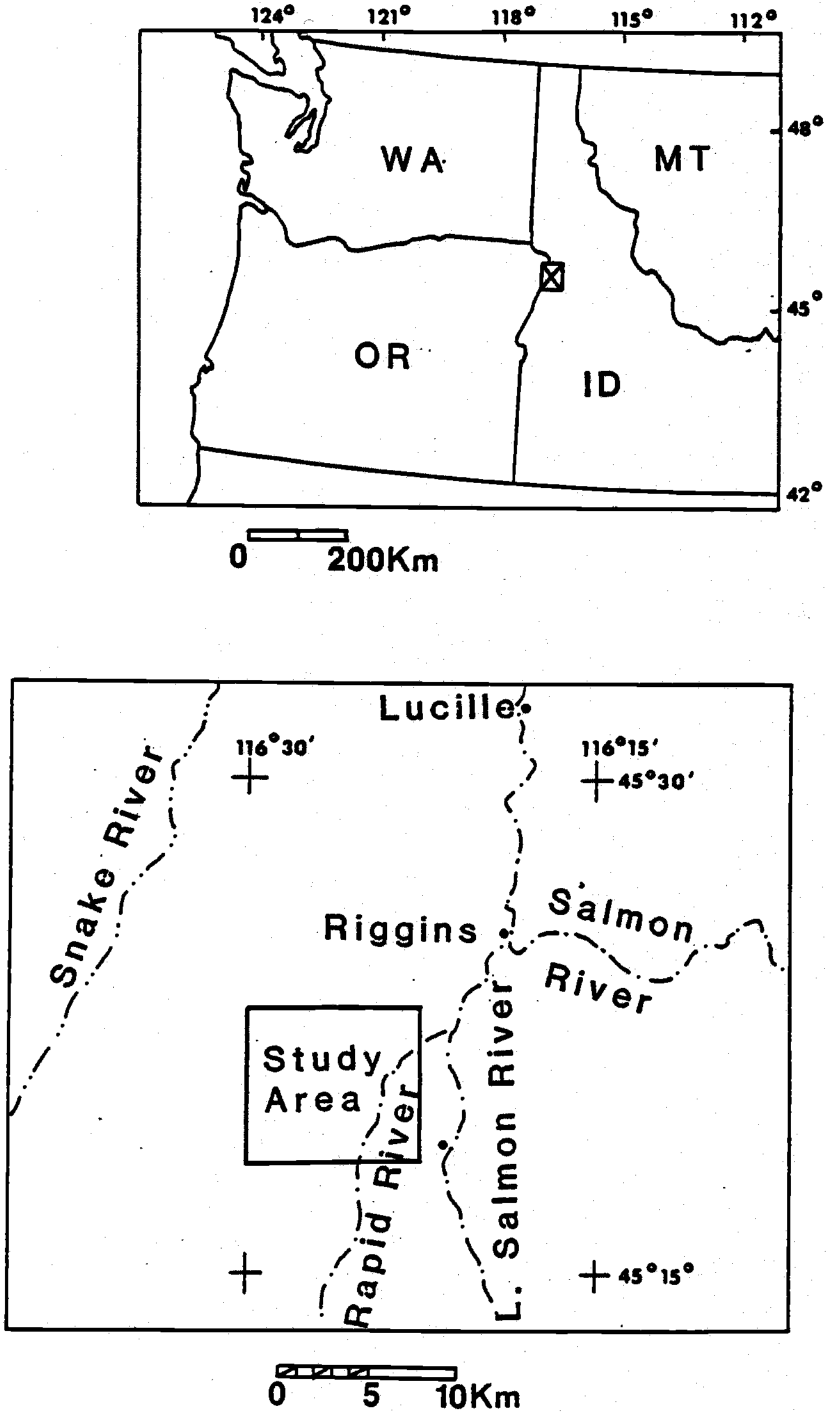

Figure 1. Map showing the location of the study area.

and west by the borders of the quadrangle, and on the south by the West Fork of the Rapid River and by Cannon Creek.

Topography is rugged; overall relief is greater than 1900 meters. In the east, the Rapid River flows northward through a canyon that at some locations exceeds 1000 meters in depth. To the west, Heavens Gate, the highest point in the field area (2570 m; 8429 ft) affords a view of northeast Oregon, central Idaho, and westernmost Montana.

Rock exposure is excellent around Heavens Gate, and in Rapid River Canyon as well, though the quality of outcrop in the canyon is often mediocre because of weathering and lichens, and accessiblity is commonly limited because of steep cliffs. Elsewhere in the field area, outcrop is poor to fair, mostly because of dense coniferous forests in the north, and thick soil in the south and east. Recent logging on Morrison Ridge has exposed some new outcrop.

In late spring and early summer, there is abundant water in all creeks and springs. By mid to late August, only Shingle Creek, Bridge Creek, and Rapid River have appreciable flow. Wildlife is abundant. Deer, elk, bear, coyote, and mountain goat were seen within or near the field area. Over thirty species of birds were seen, including golden and bald eagles.

PREVIOUS WORK

The rocks of the Seven Devils Mountains, as well as associated Permian and Triassic volcanogenic rocks to the east and south, have received rather scanty attention from geologists. Early studies were concerned primarily with ore deposits. Lindgren (1900, 1901) published the first description of the rocks. Livingston and Laney (1920) briefly described the geology of the Seven Devils Mountains, and Anderson (1930) named this thick sequence of volcanogenic rocks the Seven Devils Volcanics. Later studies of ore deposits in the region include Wagner (1945), Cook (1954), Henrickson (1975), and Juhas and others (1980). White (1973) studied some plutonic rocks in the southern Seven Devils Mountains. None of these papers contains more than a cursory description of the general geology of the Seven Devils Mountains.

The only detailed work on pertinent rocks adjacent to the Seven Devils Mountains has been by Vallier (1967, 1974, 1977). who delineated internal stratigraphy and age relations of the Seven Devils Group in and near the Snake River (Hells) Canyon. Vallier and Batiza (1978) studied petrogenesis and major element geochemistry in this area.

Four workers have mapped in areas that included part of the Heavens Gate quadrangle. Hamilton (1963a, 1969) conducted reconnaissance mapping only, and he was primarily concerned with the metamorphic rocks of the Riggins Group, which overlie the Seven Devils Group along the Rapid River thrust fault. Onasch (1977) did some detailed mesoscopic structural analysis in the Seven Devils Group, but he, too, was interested primarily in the Riggins Group. Gualtieri and Simmons (1978) mapped a large area in western Idaho that included much of the Heavens Gate quadrangle. Although their mapping was strictly reconnaissance, they recognized some important relations that are confirmed in this study.

More generally, the Seven Devils Group, recognized as an accreted island arc terrane, is thought to be an important part of the Mesozoic tectonic history of the Pacific Northwest. As such, it has been considered in regional studies by Hamilton (1976, 1978), Vallier and others (1977), Brooks and Vallier (1978), Dickinson (1979), Davis and others (1978), Ave Lallement and others (1980), Jones and others (1977), and Hillhouse and others (1982), to name a few. These studies have been concerned with the Seven Devils island arc as a coherent tectonostratigraphic unit; they have not been concerned with the internal geology of the rocks.

STRATIGRAPHY AND AGE RELATIONS

The Heavens Gate quadrangle contains pre-Tertiary rocks belonging to two important stratigraphic units-- the Seven Devils Group, with associated overlying sedimentary rocks, and the Riggins Group. There are also abundant plutonic rocks of Mesozoic age, and Miocene basalts. The age relations of these units is shown in Figure 2.

The stratigraphy of the Seven Devils Group was defined in Hells Canyon by Vallier (1967, 1974, 1977). He delineated four formations within the thick pile of metavolcanics previously known as the Seven Devils Volcanics (Anderson, 1930). These formations are the Windy Ridge Formation, the Hunsaker Creek Formation, the Wild Sheep Creek Formation, and the Doyle Creek Formation. The Windy Ridge Formation

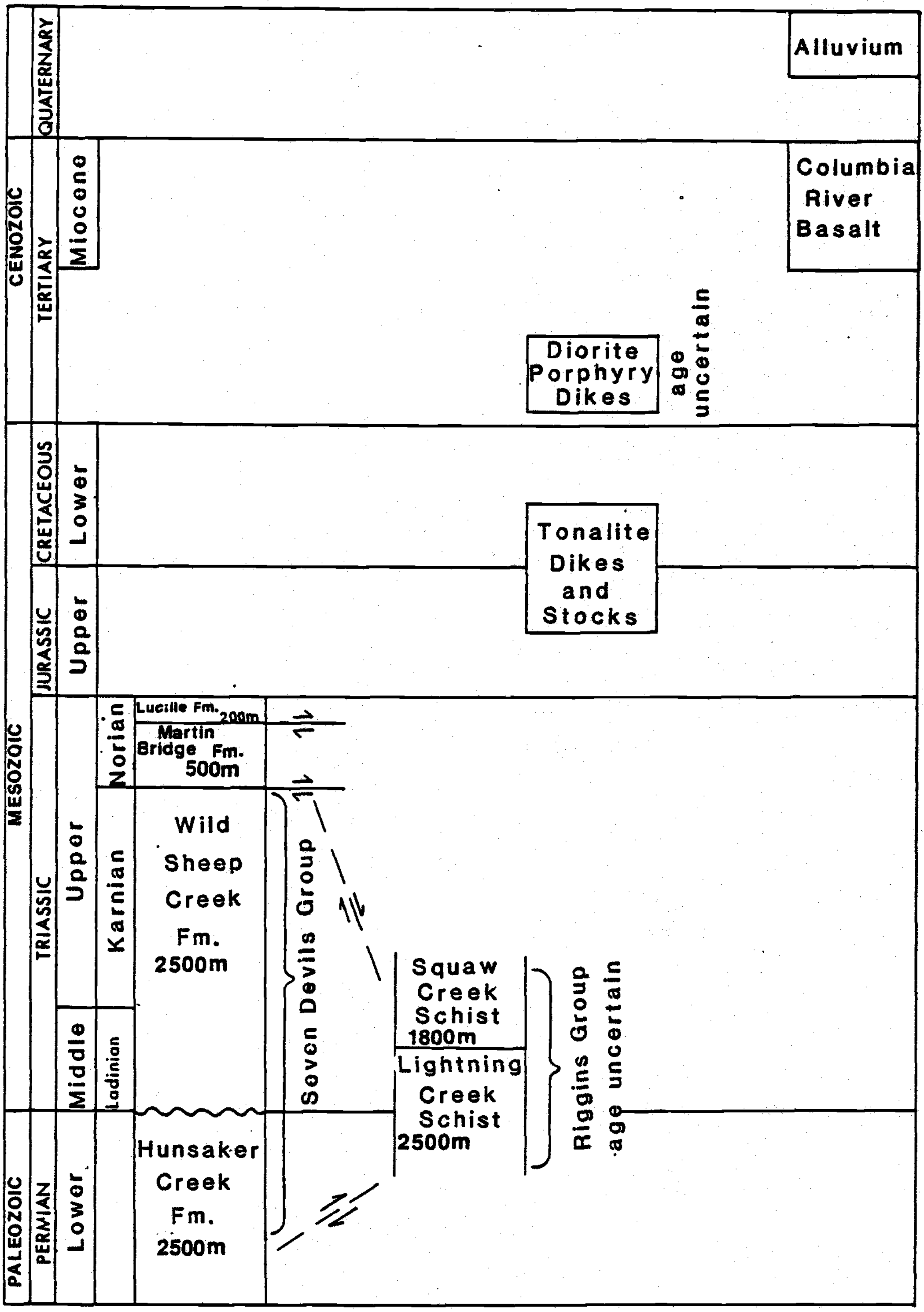

Figure 2. Age relations of rock units within the study area. Thicknesses of the Seven Devils Group from Vallier (1977); other thicknesses from Hamilton (1963a). Arrows denote thrust contacts.

is of probable Early Permian age. It is exposed only locally in Hells Canyon and comprises mostly silicic volcanogenic rocks metamorphosed to greenschist facies. The thickness of the formation is about 500 meters (Vallier, 1977). The Hunsaker Creek Formation is a thick (2500 to 3500 meters) sequence of metamorphosed volcanogenic rocks that is well exposed in Hells Canyon. This unit is dominantly composed of volcaniclastic rocks deposited in a marine environment, with subordinate mafic and felsic flow rocks. The age of this formation is Leonardian or early Guadalupian (Early Permian). These rocks are unconformably overlain by the Wild Sheep Creek Formation, of Ladinian to Karnian (Late Triassic) age. The nature of this unconformity is not well understood (Vallier, 1977). The Wild Sheep Creek Formation is about 2500 meters thick, and has been subdivided by Vallier (1977) into a lower, intermediate volcaniclastic unit, a middle, mafic and intermediate flow and breccia unit, and an upper, volcaniclastic unit. The Wild Sheep Creek Formation grades upward into the distinctive maroon volcaniclastic rocks of the Doyle Creek Formation, which has an estimated thickness of 500 meters in Hells Canyon (Vallier, 1977).

The Permian and Triassic Clover Creek Greenstone (Gilluly, 1937; Nolf, 1966), exposed in the Wallowa Mountains of northeastern Oregon, is probably correlative with the Seven Devils Group (Cook, 1954; Brooks and Vallier, 1978). The Triassic rocks of the Seven Devils Group may also be correlative with metavolcanic rocks of the Huntington Arc sequence, south of Hells Canyon (Vallier, 1977; Brooks and Vallier, 1978).

Application of Vallier's (1977) stratigraphic nomenclature to rocks of the Heavens Gate quadrangle proved difficult. In the south part of the field area, a thick sequence of mafic and intermediate flow rocks and breccias almost certainly belongs to the Wild Sheep Creek Formation. Lowermost Doyle Creek Formation may occur locally. To the north, dominantly volcaniclastic rocks are probably Permian Hunsaker Creek Formation, but this correlation must remain speculative until fossils are found in this area.

The Martin Bridge Formation, of lower Norian age, overlies the Seven Devils Group in Hells Canyon (Vallier, 1967, 1974, 1977) and on the east flank of the Seven Devils Mountains (Hamilton, 1963a 1969). This unit also overlies the Triassic metavolcanics in the Wallowa Mountains (Nolf, 1966). The Martin Bridge Formation comprises mostly shallow water limestones in Hells Canyon (Vallier, 1977) and the Wallowa Mountains (Nolf, 1966), though in the Heavens Gate quadrangle the formation is mostly composed of sheared marbles. Vallier (1977) concluded that basal contacts were probably unconformable in Hells Canyon; in the Heavens Gate quadrangle, contacts are all tectonic. The thickness of the formation is quite variable, but 500 meters seems to be a generally acceptable estimate (Nolf, 1966; Vallier, 1977; Onasch, 1977).

East of the Seven Devils Mountains, the Martin Bridge Formation is overlain by slates, phyllites and schists of the Lucille Formation (Hamilton, 1963a, 1969; Onasch, 1977). This unit occurs as thrust slices in the Heavens Gate quadrangle, but elsewhere it may conformably overlie the Martin Bridge Formation (Hamilton, 1963a). The Lucille Formation is probably correlative with rocks of the Upper Triassic to Lower Jurassic Hurwall Formation of the Wallowa Mountains and Hells Canyon (Vallier, 1977).

The Riggins Group overlies the Seven Devils Group, Martin Bridge Formation, and Lucille Formation along the Rapid River thrust fault (Hamilton, 1963a, 1969; Onasch, 1977). Hamilton (1963a) defined the four formations that compose the Riggins Group. They are the Fiddle Creek Schist, comprising felsic and intermediate metavolcanogenic rocks; the Lightning Creek Schist, comprising mafic, intermediate and felsic metavolcanogenic rocks; the Berg Creek Amphibolite, possibly a product of metamorphism of mafic lithologies; and the Squaw Creek Schist, a thick, complex sequence that comprises mostly metamorphosed volcaniclastic and clastic rocks. In addition to these units, there is also a thick "metaperidotite," or serpentinite unit. Total thickness of the Riggins Group is about 10,000 meters, but this figure reflects structural complications, not original thickness (Hamilton, 1963a). Only the Lightning Creek Schist and Squaw Creek Schist are present in the Heavens Gate quadrangle.

The age of the Riggins Group is unknown, and regional correlations are controversial. Vallier (1977), succinctly presented the viable options for correlation of the Riggins Group:

1. It is not related to any other rocks in the region.
2. It is correlative with the Seven Devils Group.
3. It is correlative with forearc assemblages of eastern Oregon.

The latter interpretation seems to have had the most support (Vallier, 1977; Brooks and Vallier, 1978; Dickinson, 1979) but it presents certain geometric problems that will be discussed later. Correlation of the Riggins Group and the Seven Devils Group has been adopted in this study, as it was by Onasch (1977), because of a great similarity in lithologies, and because this is by far the simplest possible interpretation.

The Seven Devils Group in the Heavens Gate quadrangle is intruded by tonalites that are similar to Late Jurassic and Early Cretaceous plutons in Hells Canyon and the Wallowa Mountains (Armstrong and others, 1977). Miocene flood basalts (Columbia River Basalt) unconformably overlie the Riggins Group in the northeast corner of the field area.

OBJECTIVES

The Seven Devils island arc is an important component of recent models of Mesozoic continental evolution of the western North American Cordillera (Jones and others, 1977; Brooks and Vallier, 1978; Hamilton, 1978; Hietenan, 1981, Hillhouse and others, 1982). However, little is known about the geology of the Seven Devils arc itself. Thus, in a sense, the approach to understanding this terrane has been the reverse of the inductive scientific method. It is not known to what extent the internal features of the Seven Devils arc constrain the various regional models.

The objective of this study has been to examine the structural and petrologic nature of part of the Seven Devils Group, and to determine the extent to which the details of local geology corroborate or contradict regional models. The Heavens Gate quadrangle was originally chosen for study because it was known to display marked evidence of deformation. Structural complications were described, but never mapped in detail, by Hamilton (1963a, 1969) and Onasch (1977). Of particular interest in this study are the nature and age of ductile shearing in the Seven Devils Mountains, the nature and age of the Rapid River thrust fault and associated structures, and the relation between deformation in the Seven Devils Group and evolution of the Rapid River thrust. Also of interest are the criteria for correlation of the Seven Devils Arc and the Wrangellia terrane of British Columbia and Alaska. Of course, a study encompassing only 70 square kilometers cannot delineate the character of an entire terrane. But an understanding of the evolution of a small area may place constraints on models with regional implications.

ROCK UNITS

SEVEN DEVILS GROUP

Rocks of the Seven Devils Group form rugged and steep outcrops along the Rapid River and the West Fork of the Rapid River. To the north, exposure is poor, except in the Heavens Gate area. Throughout the field area, most outcrop is lichen covered, pervasively fractured, and deeply weathered. Poor outcrop quality, combined with rapid lateral and vertical lithologic changes and the homogenizing effects of metamorphism and tectonism, preclude internal subdivision of these rocks beyond the level of formation. Identifiable flows or beds can never be traced beyond an individual outcrop. However, extensive sampling and petrographic analysis give a sense of the distribution and relative abundance of various lithologies. In all, 84 thin sections of Seven Devils Group rocks were studied.

Hunsaker Creek Formation

An east-west trending tear fault through the center of the field area subdivides the Seven Devils Group into two distinct lithologic units. To the north, rocks are tentatively correlated with the lower Permian Hunsaker Creek Formation, defined by Vallier (1967, 1974, 1977) in the Snake River canyon. Correlation is based on the abundance of agglomerates, breccias, and water-laid, bedded volcaniclastic sandstones, and on the relatively uncommon occurrence of keratophyre and quartz keratophyre flow units. Brief reconnaissance in the Snake River canyon north of Oxbow supports this correlation. However, assiduous examination of volcaniclastic beds in the Heavens Gate quadrangle yielded no fossils, so correlation must remain tentative. Correlation with the Upper Triassic Doyle Creek Formation cannot be dismissed absolutely, but characteristic maroon colors are absent.

In the study area, the Hunsaker Creek Formation is composed dominantly of volcaniclastic rocks, with subordinate flow rocks. All lithologies show metamorphism to greenschist facies, and are characterized by mineral assemblages that generally include albite, chlorite, epidote, actinolite, quartz, carbonate, white mica, and opaque, iron-bearing minerals.

Volcaniclastic rocks of the Hunsaker Creek Formation comprise a wide variety of epiclastic and pyroclastic lithologies. Pyroclastic rocks include crystal, lithic, and mixed tuffs, lapilli tuffs, tuff breccias, and agglomerates. Epiclastic rocks include volcanic siltstones, sandstones, conglomerates and breccias. It was difficult to distinguish between epiclastic and volcaniclastic rocks. Strictly speaking, components of both rock types can be transported and deposited by the same processes in similar environments. The differences between them, as Fisher (1966) pointed out, is in the "process of fragmentation." Pyroclastic rocks are direct results of explosive volcanic activity, whereas epiclastic rocks are formed from weathering products of pre-existing rock (le Bas and Sabine, 1979). Definitive criteria for distinguishing these rock types are difficult to formulate. The problem is exacerbated by the metamorphism, tectonism and alteration that obscure primary features. Rocks were usually called epiclastic if they displayed marked sorting, clast diversity, or clast rounding. Rocks were considered pyroclastic if they contained a high proportion of individual crystals, a low diversity of lithic clasts, or distinct evidence of welding. Samples that did not clearly belong to either category were termed volcaniclastic. This system generally follows that used by Vallier (1967, 1977) in similar rocks to the west.

The pyroclastic rocks are variously composed of all the mineral phases and all the flow and volcaniclastic rock types mentioned above. Lithic and mixed tuffs, lapilli tuffs, and tuff breccias are most commonly, but not exclusively, heterolithologic. Agglomerates are always heterolithologic. Altered glass shards and pumice are not recognized in thin section, but this may have been a function of preservation. Epiclastic rocks are compositionally similar to the pyroclastic rocks, differing mostly according to the criteria presented above.

Volcaniclastic rocks of the Hunsaker Creek Formation show some indication of size sorting, but clast diversity is commonly great. The colors of these rocks are distinctive pastel shades of blue, green, and gray. These rocks are best exposed near the western end of Morrison Ridge, where recent logging has created new outcrop. Bedding thickness varies from a few millimeters to greater than outcrop scale. Beds are distinguishable by color as well as grain size and sorting variations. Normally graded beds are common, but other sedimentary structures are rare. Load structures were observed in a few rocks, and flame structures were seen at one outcrop.

These rocks display clast elongation that is always parallel to bedding (where bedding is present). This elongation is due to shearing that affected the entire field area. However, the well developed shear foliation is only displayed conspicuously in these relatively incompetent volcaniclastics, and not in rocks to the south, or even in adjacent flow rocks.

Both keratophyre and quartz keratophyre flows are locally interbedded with the volcaniclastics. These intermediate and felsic metamorphosed flow rocks constitute not more than 15 percent of the rocks in the Hunsaker Creek Formation. Keratophyre makes up about two thirds of the flows. Some keratophyre is characterized by abundant albite phenocrysts that reach three centimeters in length. These rocks are light blue, green, and gray in color. Their characteristically pale color is due to clay alteration of groundmass, and retrograde alteration of albite to paragonite. Quartz keratophyres are of similar appearance, and constitute the remainder of the flow rocks. One spilite, probably a small hypabyssal intrusive, was found in this unit.

Wild Sheep Creek Formation

South of the tear fault, lithologies are conspicuously different than those to the north and are correlated with the Upper Triassic (Ladinian to Karnian) Wild Sheep Creek Formation of the Snake River Canyon (Vallier, 1974, 1977).

Dark colored mafic and intermediate flow rocks and breccias are the most common rock types. Flow rocks constitute up to 40 percent of the lithologies in this area. These rocks display typical "greenstone" mineralogies: ubiquitous and abundant albite and chlorite, plus abundant epidote, actinolite, quartz, carbonate, white mica, and opaque iron-bearing minerals (mostly magnetite). In Rapid River Canyon, green and brown biotite occur sporadically, in quantities of up to five percent. Biotite is not present in the Wild Sheep Creek Formation farther to the west, nor is it found in the Hunsaker Creek Formation to the north. Sphene, leucoxene, and apatite are commonly present in trace quantities throughout the Wild Sheep Creek Formation. Hydrogarnet was found in one rock, as was metamorphic oligoclase (An_{28}), and prehnite was found as a vein filling in one rock.

Relict volcanic textures are commonly preserved in metamorphosed flow rocks at outcrop scale and in thin section. Porphyritic and glomerophyric textures occur in many hand specimens. Plagioclase phenocrysts have been altered to albite, with anorthite content ranging from An_4 to An_8. Much plagioclase shows local alteration to epidote or carbonate, particularly in the cores of large crystals. This may be a reflection of primary normal zoning, and it indicates that some calcium removed from the plagioclase during albitization remained relatively immobile and contributed to the in situ crystallization of epidote or calcite (Winkler, 1974). Albite commonly contains abundant inclusions of chlorite and retrograde paragonite. Much albite has been entirely replaced by paragonite, though crystal shape is usually preserved.

Pseudomorphs of pyroxene and hornblende phenocrysts were recognized in many thin sections. These mafic phenocrysts have altered to chlorite, epidote, actinolite, opaque minerals, and local biotite. Pyroxenes have most commonly altered to either actinolite or epidote, usually with chlorite. Hornblende has altered to various combinations of all of the above mentioned minerals. Altered mafic glomerophenocrysts occur in many samples.

Intergranular and pilotaxitic textures are common, though the latter is more abundant. Vesicles were not seen in the field but are recognizable in thin section. They are filled variously with biotite, albite, actinolite, epidote, chlorite, or quartz.

Groundmass minerals of most flow rocks have been altered and homogenized beyond recognition. Quartz keratophyre commonly contains abundant recrystallized quartz in the groundmass.

Greenschist minerals, particularly albite and chlorite, were identifiable in many thin sections. Some of the more coarse-grained pilotaxitic keratophyres still look fresh, and these rocks display typical greenschist parageneses in their groundmasses.

Relict mineralogy is extremely rare in these rocks. Primary brown biotite, partially altered to chlorite, was observed in one quartz keratophyre, and trace amounts of relict pyroxene, almost entirely altered to actinolite, were seen in a keratophyre. Relict magnetite occurs as phenocrysts or in groundmasses in abundances of up to three percent in some spilites and keratophyres. Near the base of one keratophyre flow, magnetite content approaches 25 percent as a result of density grading. No relict calcic plagioclase was found in the Wild Sheep Creek Formation within the field area. The dearth of relict phases in general contrasts with Vallier's (1967, 1974, 1977) observations in rocks not far to the west. In mapping the Seven Devils Group in Hells Canyon, he noted relict calcic plagioclase and clinopyroxene in many volcanic rocks. It is also significant that Vallier (1967, 1977) did not observe metamorphic biotite in Hells Canyon, whereas metamorphic biotite is commonly present in flow rocks of the Wild Sheep Creek Formation in the Rapid River canyon. This suggests that metamorphic grade increases somewhat to the east in this region, from lower greenschist facies to upper greenschist facies. Further, rocks in the Heavens Gate quadrangle more closely approach equilibrium parageneses than those to the west.

Flow rock lithologies include spilite, keratophyre, and quartz keratophyre. These are greenschist facies equivalents of basalt, andesite, and dacite. Classification was based on appearance in hand specimen, relict textures, and inferred primary mineralogies, but of course this is not unequivocal, even in fresh volcanic rocks. Melanocratic rocks with a high proportion of inferred mafic material in the groundmass, and with small, relatively sparse phenocrysts and intergranular textures were classified as spilites. Spilites are very dark gray or green in color. Keratophyres are characteristically dark blue green, with abundant phenocrysts of albite, altered mafic minerals, or both, in a pilotaxitic or intergranular groundmass composed predominantly of albite with subordinate epidote, actinolite, quartz, and interstitial chlorite. Quartz keratophyres are light blue green, and mineralogically similar to keratophyres, but with recrystallized quartz making up more than twenty percent of the groundmass.

Although this classification scheme is admittedly non-rigorous, it is consistent with recommendations of other workers (Schermerhorn, 1973; Vallance, 1974; Vallier, 1977), and it provides a useful framework for subdividing rocks that are commonly quite homogeneous in hand specimen. Major element data were generally consistent with these qualitative classifications.

Petrography and major element geochemistry indicate a range in compositions from dacite or rhyolite to basalt. Intermediate and mafic lithologies are dominant and constitute the great majority of the flow rocks. Felsic flow rocks are only locally present.

It was impossible to determine modal compositions of most flow rocks because of retrograde metamorphism, clay alteration, and shearing, as well as indistinct grain boundaries and the generally amorphous nature of many metamorphic minerals. Rocks that commonly looked fresh in the field were strongly altered in thin section. Results of four point counts of flow rocks are given in Table 1.

Thick volcaniclastic breccia units are abundant in the Wild Sheep Creek Formation, particularly in Rapid River canyon. These dark green, gray, and blue-gray rocks show little or no evidence of sorting or other sedimentary processes. Clast lithologies are mostly mafic and intermediate flow rocks and pyroclastics. Clast diversity in any individual outcrop is less marked than in rocks to the north. Plutonic clasts of tonalite are commonly present, though never abundant. The distinctly bedded aspect of the northern volcaniclastic is absent in these southern breccias. Though local bedded volcanic siltstone occurs on the east wall of Rapid River canyon, bedding was not observed in the coarser grained volcaniclastics. This is in part a function of outcrop quality, but also indicates that the breccias were quite thick. In Rapid River canyon, where these rocks are best exposed, some breccia units are at least 100 meters thick.

Crystal tuffs are locally abundant in and near Rapid River

Table 1. Modal Analyses of Flows from the Wild Sheep Creek Formation

Sample Number:	D-34a	D-101	D-115	D-127
Plagioclase	63.0 (An_7)	62.5	64.0	68.3 (An_3)
Quartz	0.6	9.7	---	8.3
Chlorite	5.1	14.4	1.3	4.5
Epidote	21.1	1.5	4.3	trace
Actinolite	4.8	6.3	23.6	12.0
Magnetite	1.5	3.7	3.9	4.6
Carbonate	2.1	---	1.0	0.9
Sphene	---	1.9	0.7	1.3
Apatite	---	---	---	0.1
Unknown	1.8	---	1.2	---

1000 points per sample

canyon. Some of these contain high proportions of recrystallized quartz that may be a result of devitrification of silicic glass. Overall, crystal tuffs vary in apparent composition from spilite to quartz keratophyre, but the general absence of phenocrysts makes such classification tentative. In fact, it commonly was not possible to determine if a rock was a crystal tuff or an aphanitic flow rock.

Monolithologic spilitic breccias in the Wild Sheep Creek Formation are probably flow (auto) breccias. One spilite sample from the western part of the field area texturally resembles hyaloclastic basalt.

Light blue silicic volcaniclastic rocks are locally abundant between Thorn Gulch and Blue Gulch, but are otherwise absent south of the tear fault. Maroon and red keratophyre and crystal tuffs crop out near Cannonball Mountain and along parts of Thorn Gulch. Based on Vallier's (1977) nomenclature, these maroon lithologies may be characteristic of uppermost Wild Sheep Creek Formation or lowermost Doyle Creek Formation. Onasch (1977) suggested that rocks throughout this area were correlative with Doyle Creek Formation, based on his observation of widespread maroon lithologies. This correlation is unwarranted in the Heavens Gate quadrangle, however.

MARTIN BRIDGE FORMATION

The Martin Bridge Formation in the Heavens Gate quadrangle comprises light gray to dark gray sheared and unsheared marbles, with subordinate micrites, and rare, thin intercalations of epiclastic siltstone and shale. These rocks overlie the older Seven Devils Group, and locally, younger rocks of the Lucille Formation, along thrust faults. All Martin Bridge Formation contacts within the field area are believed to be tectonic.

In the east, this unit crops out in Rapid River canyon and along Shingle Creek as a continuous, north-trending, fault-bounded band that extends across the length of the study area. This band varies in width from about 200 meters to about 1500 meters. To the west, carbonates overlie isolated portions of the same thrust plane in the north along Morrison Ridge, in the south on and around Mount Sampson, and in the west near Saddle Camp.

The Martin Bridge Formation forms steep cliffs that rise precipitously above the commonly gentler slopes of the Seven Devils Group (Figure 3). From afar, the carbonates can be easily recognized by their dull, gray weathered surface, as well as a characteristic mantle of orange lichen.

Marble constitutes the most abundant lithology. Most marbles have been tectonized and display well developed shear fabrics that are probably parallel to primary bedding. Shear foliation is commonly manifested as fracture cleavage in outcrop.

Figure 3. Cliff of Martin Bridge Formation overlying gentler slopes of the Hunsaker Creek Formation above Shingle Creek; view is to the east.

Where tonalites have intruded the Martin Bridge Formation, marbles near the intrusive contact are fresh looking in outcrop, with sugary texture and no evidence of bedding or cleavage. These marbles are equigranular, with calcite crystals varying from 0.25 mm to 1.0 mm in diameter. Non-calcareous material is generally absent, though very minor quartz was found along some calcite grain boundaries. Some unsheared marbles occur far from intrusive contacts, but these rocks are conspicuously dirty and fractured in outcrop, and contain detrital quartz and sparse white mica in thin section. Stylolites occur in some marbles.

Micrites constitute a small proportion of the formation in this area. They are generally heavily veined with coarse-grained carbonate and, less commonly, quartz. Many micrites display color banding in hand sample manifested by parallel laminations of various shades of gray, but this was not visible in thin section. Stylolites are commonly parallel to color bands.

Light green, light gray, and dark gray volcanogenic siltstone beds are locally intercalated with limestone near Thorn Gulch and on Morrison Ridge. Siltstones are fissile, with parting parallel to bedding. Identifiable minerals include quartz, chlorite, white mica, and carbonate, with minor plagioclase and possibly actinolite. Maximum grain size is about 0.1 mm, but grains are commonly submicroscopic.

Fossil hash is preserved in some marbles. Many shell fragments and crinoid stem plates occur, but they are always recrystallized. *Pentacrinus* crinoid stem plates of probable

Triassic age are present in these rocks, and have been found in the past (Hamilton, 1963a).

Conodonts were found in unsheared, fine-grained marble at Game Warden Saddle between Cannonball Mountain and Mount Sampson (Plate I). Samples from seven other localities were barren. The conodont assemblage was identified by David Clark who recognized two species of _Epigondolella_, probably _E_. _abneptis_ and _E_. _primitia_, of early or middle Norian age. Lower Norian fossils have been identified in the Martin Bridge Formation in Hells Canyon (Vallier, 1977) and the Wallowa Mountains (Nolf, 1966), but this is the first confirmation of similar age in the eastern Seven Devils Mountains.

Conodonts are dark gray to black, and were assigned a color alteration index of five (D. Clark, oral communication, 1981). According to Epstein and others (1977), this indicates that conodonts were exposed to a minimum temperature of 300°C. This is consistent with greenschist facies assemblages of the underlying Seven Devils Group.

LUCILLE FORMATION

The Lucille Formation is exposed as an imbricate thrust slice in the northeast part of the study area. Dark gray quartz-muscovite phyllites are transitional with foliated limy mudstones and muddy limestones. Phyllites, composed of quartz and white mica with minor chlorite, albite, carbonate, and clay, grade into rocks with up to 90 percent carbonate, plus minor quartz, white mica, and clay. Even the most carbonate-rich lithologies are distinguishable from Martin Bridge Formation by their very dark gray color and excellent fissility. Foliations are defined by compositional layering and parallel elongation of quartz, mica and calcite. Quartz shows extreme undulatory extinction in thin section. The Lucille Formation conformably overlies the Martin Bridge Formation at some localities (Hamilton, 1963a), and is therefore of Late Triassic age.

RIGGINS GROUP

Rocks of the Riggins Group are exposed east of the Seven Devils Group and Martin Bridge Formation. These rocks were originally mapped by Hamilton (1963a, 1969) and later by Onasch (1977). The Riggins Group comprises four formations: Fiddle Creek Schist, Lightning Creek Schist, Squaw Creek Schist, and Berg Creek Amphibolite (Hamilton, 1963a). The age of these units is unknown. Only the Lightning Creek Schist and Squaw Creek Schist are exposed in the Heavens Gate area.

Lightning Creek Schist

Within the study area, Lightning Creek Schist overlies the Martin Bridge Limestone, Lucille Formation and Seven Devils Group along an east-dipping thrust fault (Rapid River thrust). Lithologies and metamorphic grade of the schist are indistinguishable from Seven Devils Group greenstones immediately to the west, based on appearance in outcrop and analysis of 13 thin sections. Hamilton (1963a) noted, however, that metamorphic grade of the Lightning Creek Schist increases markedly to the east of the Heavens Gate quadrangle, as a result of metamorphism associated with the intrusion of the Idaho batholith. Higher grade lithologies include hornblende-biotite-oligoclase schists and gneisses. However, it should be emphasized that, within the study area, the schist is identical in most aspects to the Seven Devils Group. Lithologies include keratophyre, quartz keratophyre, and intermediate and felsic volcaniclastic rocks. Mineral parageneses are typical of lower greenschist facies.

The main body of the Lightning Creek Schist within the study area is exposed as a northward broadening band near the eastern margin of the Heavens Gate quadrangle. North of Whitebird Ridge, numerous thrust faults juxtapose slices of greenstone, Martin Bridge Formation, and Lucille Formation. A narrow thrust slice of metavolcanics in this area was mapped by Hamilton (1969) as Seven Devils volcanics, and by Onasch (1977) as Lightning Creek Schist. The presence of distinctive agglomerates that are identical to rocks exposed near Heavens Gate peak, five miles to the west, strongly supports Hamilton's interpretation, but more importantly points out that the distinction between the Lightning Creek Schist and the Seven Devils Group is not precise. In fact, the basal, sheared, mixed-clast agglomerate that is characteristic of the Lightning Creek Schist over much of its extent (Hamilton, 1963a; Onasch, 1977) is, at least within the study area, very similar in appearance to the distinctive agglomerates of the Hunsaker Creek Formation on and near Heavens Gate peak.

It has commonly been suggested that the Lightning Creek Schist and Seven Devils Group might be correlative (for example: Hamilton, 1976; Onasch, 1977; Brooks and Vallier, 1978). This study strongly supports such a correlation. The major objections to this correlation are tectonic slices of altered ultramafic blocks within the schist, and the westward increase in metamorphic grade displayed by the schist. Neither of these arguments addresses the observation that protolithologies of the two units were the same. Based on mapping in the Heavens Gate quadrangle, the Lightning Creek Schist may be equivalent to the Permian Hunsaker Creek Formation.

Squaw Creek Schist

The Squaw Creek Schist lies east of the Lightning Creek Schist on the eastern edge of the field area. Outcrop is poor, and these rocks were not studied in detail. Quartz-muscovite schist is the dominant rock type, with local quartz-chlorite schists and thin marble beds. The nature of the contact between the Squaw Creek Schist and the Lightning Creek Schist could not be determined because of sparse outcrop.

Ultramafic Rocks

Isolated bodies of altered ultramafic rock occur within the Lightning Creek Schist and Squaw Creek Schist. These rocks include talc-serpentine rock, talc-tremolite rock, and talc-chlorite schist. They are best exposed as subdued outcrops on Whitebird Ridge, east of the Rapid River. Outcrop in this area is sparse, though, and it was difficult to satisfactorily delineate the geometry of these bodies. Apparently they are truncated by the north-striking contacts of the Riggins Group.

The presence of altered ultramafic bodies within both the Lightning Creek Schist and the Squaw Creek Schist supports the contention that these are tectonically emplaced blocks. Hamilton (1963a) and Onasch (1977) argued that all ultramafic rocks were emplaced as fault slices within the Riggins Group prior to the development of the Rapid River thrust system.

Amphibole schist

Rocks containing greater than 85 percent actinolite and up to 10 percent sodic plagioclase of indeterminate composition were found adjacent to talc-rich rocks on White Bird Ridge. These rocks probably represent metamorphosed mafic volcanic rocks, but their protolith could not be determined with certainty. Proximity of the amphibole schists and the metamorphosed ultramafic rocks suggests that these two units were both tectonically emplaced. Amphibole schists are considered to be a separate unit because of their distinctive lithology.

MESOZOIC PLUTONIC ROCKS

Probable middle to late Mesozoic leucocratic tonalites have intruded the Seven Devils Group and Martin Bridge Formation at a number of locations. In hand specimen, tonalites are massive, with abundant white feldspar, subordinate quartz, and variably altered mafic minerals. In Rapid River canyon, the largest pluton in the field area intrudes the Wild Sheep Creek Formation and abuts the Martin Bridge Formation on both sides of the canyon. Farther south, a tonalite dike cuts the thrust fault that separates carbonates and metavolcanics on the west side of Rapid River. A small pluton intrudes carbonates south of Mount Sampson, and another intrudes metavolcanics south of Morrison Ridge. Although these are the only plutonic bodies shown on Plate I, countless dikes and small intrusive pods were not mappable because of their small size and irregular exposure. Small bodies which were not mapped are particularly common in Rapid River canyon between the tonalite pluton and the dike to the south. In this area, the Wild Sheep Creek Formation has been thoroughly infiltrated along joints and fractures by intrusion of magma. In much of this area tonalite constitutes more than 50 percent of the rocks.

Within the Seven Devils Group, intrusive contacts are sharp. Contact metamorphism in metavolcanics, and chilled margins in intrusive rocks, were not observed. Intrusive contacts in the Martin Bridge Formation were not exposed, but carbonates adjacent to tonalite have been commonly recrystallized to equigranular, massive, fine-grained marble.

Modal analyses of eight tonalites are shown in Table 2. Classification is based on recommendations of Streckheisen (1973). Tonalites show evidence of metamorphism, but abundant relict minerals indicate that equilibrium parageneses were not attained. Extent of metamorphism is quite variable. Some rocks are completely altered to lower greenschist facies assemblages, whereas others show at most a local replacement of biotite or hornblende by chlorite or actinolite. Changes in the extent of alteration can occur over short distances within the same pluton. These observations are in contrast to Hamilton's (1963a, 1963b) assertion that all tonalites intruding the eastern part of the Seven Devils Group were totally metamorphosed to greenschist assemblages.

Table 2. Modal Analyses of Tonalites

Sample Number:	D-62	D-65	D-82	D-101	D-148a	D-176	D-178	D-178a#	D2-1
Plagioclase	60.2 An_6	61.7 An_4	56.9 An_6	57.8 An_4	68.4 An_4	55.9 An_4	57.3	57.7	66.8 An_{38}
Quartz	29.8	29.5	17.9	29.9	19.3	28.5	34.9	10.4	21.2
Actinolite or Hornblende	3.0	---	16.6	---	2.9	7.3	0.7	21.3	5.3
Biotite	---	---	trace	---	---	4.6	---	---	6.3
Chlorite	6.1	6.4	5.0	4.8	3.3	1.6	4.3	5.7	---
Epidote	0.6	1.2	2.0	5.6	3.0	1.5	2.6	4.7	---
Opaque	trace	0.5	0.6	0.8	2.8	0.6	0.1	trace	0.6
Apatite	trace	trace	0.2	---	trace	---	0.1	trace	trace
Sphene	---	---	0.8	0.8	---	trace	---	---	trace
Zircon	trace	---	---	---	---	trace	---	---	---
Unknown	0.3	0.7	---	0.3	0.3	---	---	---	---

1000 points per sample

#quartz diorite

The dominant mineral is always plagioclase. Most plagioclase is albite (An_2 to An_6), but in the least altered rocks, relict andesine (An_{38}) was observed. Relict oscillatory zoning is commonly preserved. Plagioclase makes up between 55 and 68 percent of these rocks. Polysynthetic twins are commonly wedge shaped, or bent. Retrograde metamorphism to paragonite, with or without carbonate, is universal, though variable in intensity.

Quartz is abundant as anhedral, interstitial crystals, and constitutes between 18 and 35 percent of the tonalites. Crystals commonly are strained, displaying undulatory extinction or deformation lamellae. Many thin sections show micropegmatitic intergrowth of optically continuous quartz and albite (Figure 4).

Hornblende and biotite are present as relict mafic phases in many samples. Biotite may be partially or completely replaced by chlorite. Ten of the 12 samples studied in thin section had some amphibole; five samples had relict biotite. Only one sample had biotite without amphibole. Some biotites show well developed kinks.

Epidote was present in all but one sample. It formed small, subhedral, isolated crystals, and larger, polycrystalline pods. Commonly, epidote and chlorite occur together replacing biotite. Epidote was absent from the sample that had relict andesine. This suggests that liberation of calcium from plagioclase during albitization enabled the formation of the epidote.

Mafic content of 10 tonalites ranges from eight to 25

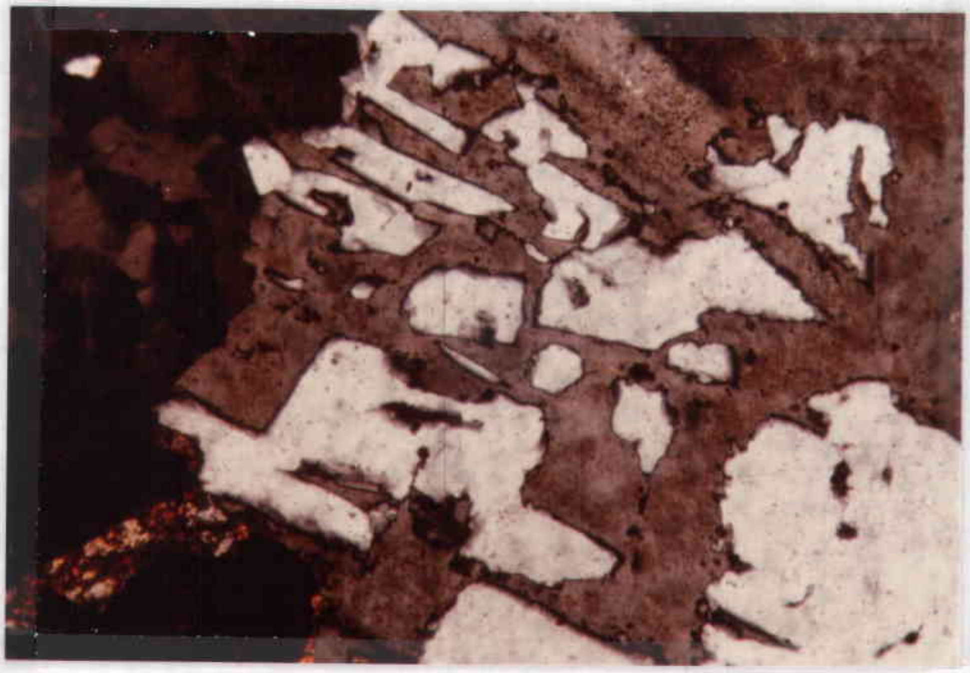

Figure 4. Micropegmatite in tonalite. Intergrowth of optically continuous quartz (white) and albite (gray brown). Crossed polars, X10, field of view 0.8 mm.

percent, but seven of the 10 have mafic content between eight and 12 percent. Streckheisen (1973) recommends that tonalites with less than ten percent mafics be called trondhjemites, so most of the intrusives in the field area approach trondhjemite in modal composition.

Textures are usually hypidiomorphic-granular, except for local eutectic intergrowths described above. Grain size is generally uniform within a given thin section, and variable between thin sections from about 0.5 to 3.0 mm.

The large pluton along the Rapid River canyon is composed of multiple intrusions. Contacts between tonalites of different grain size and mafic content were noted at a few locations. Tonalite and quartz diorite were found together at one outcrop. Modal analysis of the quartz diorite (sample D-178a) is presented in Table 2. This lithology was observed at one locality only.

The age of intrusion was probably Late Jurassic to Early Cretaceous, which was a period of active plutonism throughout the island arc and oceanic assemblages of eastern Oregon and western Idaho (Armstrong and others, 1977). The nearest well dated pluton is the Deep Creek Stock, which intrudes Seven Devils volcanics in Hells Canyon (White, 1973). Armstrong and others (1977) suggest a minimum emplacement age of 133 m.y. (Early Cretaceous).

The possibility that these tonalites are Late Cretaceous satellites of the Idaho batholith (Armstrong and others, 1977) cannot be completely discounted. Trondhjemites that intrude the

Riggins Group (Hamilton, 1962), and quartz diorites to the south in the area of Council Mountain, have been associated with the Idaho Batholith (Taubeneck, 1971). Lack of metamorphism of these trondhjemites probably indicates that they are younger than the tonalites that intrude the Seven Devils Group. Also, mineral contents of the tonalites of the study area are more like those of the Deep Creek Stock to the west (White, 1973) than satellite plutons to the east and south (Taubeneck, 1971).

The relations between the timing of plutonism and the tectonic evolution of the Heavens Gate quadrangle are of course a critically important aspect of the geologic history of this area. Some cross-cutting relations of plutons and faults are straightforward. On the west side of Rapid River canyon, intrusion definitely postdates movement along the thrust that separates Martin Bridge Formation from Seven Devils Group. In this area, the tonalite dike cuts across the thrust, and the large tonalite pluton has caused recrystallization in adjacent carbonates.

To the east, the contact relations are less clear. On Whitebird Ridge, tonalite abuts the Martin Bridge Formation for more than two kilometers, but does not intrude the carbonate or noticeably influence the trace of the basal carbonate contact. Further, carbonates directly overlying the intrusive have not been noticeably recrystallized, as some are to the west. However, some tonalite displays a conspicuous flow structure, defined by parallel alignment of biotite or chlorite flakes.

Such flow structures are typically best developed at or near intrusive contacts (Buddington, 1959; White, 1973). This is probable confirmation that the tonalite-carbonate contact in this area is intrusive. Cataclastic fabrics are not present in the tonalites.

The westernmost pluton in the field area was intruded along a generally east-west striking tear fault. This pluton shows no evidence of brittle shearing, and so probably postdates any significant movement along the tear fault. Bent plagioclase twins, quartz with undulatory extinction and deformation lamellae, and kinked biotite flakes all record deformation of the tonalite. These features are typical of protoclastic deformation that developed as a result of stress directly related to emplacement of the plutons (White, 1973; Taubeneck, 1967; Spry, 1969). Though the possiblity of minor tectonic overprinting cannot be excluded, it need not be invoked to explain the observed deformations. Shear textures such as those displayed by the Seven Devils Group are never seen in intrusives. Contact relations indicate that intrusion took place after the termination of fault motion.

LATE MESOZOIC OR TERTIARY DIORITE PORPHYRY

Throughout the field area there are many small diorite dikes that were intruded after the cessation of metamorphism and tectonism. These dikes are rarely more than two meters wide. They intrude all older rock units, though they seem to be most abundant in the south, within the Wild Sheep Creek Formation and the tonalites.

Diorites throughout the study area are uniform in appearance, with small, white plagioclase phenocrysts and black hornblende needles in an aphanitic, gray groundmass. Plagioclase and hornblende phenocrysts rarely exceed 2.0 mm in length. The plagioclase is labradorite (An_{52}), and it is usually altered to white mica and carbonate. The groundmass appears to be mostly plagioclase, with numerous small honrblende needles and minor opaque crystals. Some secondary quartz is present, but primary quartz was not observed.

COLUMBIA RIVER BASALT

Columbia River Basalt is exposed as a series of thick, columnar-jointed flows in the northeast corner of the study area. The basalt forms vertical cliffs, mantled at their base by basalt talus. In hand sample, basalts are very dark gray or brown, and very sparsely porphyritic. Thin sections of two basalts show intersertal textures, with phenocrysts of plagioclase (An_{50} to An_{54}) and clinopyroxene up to 1.5 mm in length, and tiny magnetite needles up to 0.2 mm in length, in a glassy groundmass dusted with opaque material.

The age of the basalts in this area is middle to late Miocene, based on flora found by Hamilton (1963c) in a tuff bed. Hamilton (1963c) also presented detailed petrography and major element geochemistry of the basalts in this region.

GEOCHEMICAL CHARACTER OF THE WILD SHEEP CREEK FORMATION

Previous workers have recognized that the Seven Devils Group was formed in a late Paleozoic and early Mesozoic island arc that was subsequently accreted to North America, probably in the late Mesozoic (Hamilton, 1976; Vallier, 1977; Onasch, 1977; Hillhouse and others, in press).

The distribution and petrology of various lithologies of the Seven Devils Group indicate formation in an island arc at a destructive plate margin. The great predominance of volcaniclastic rocks over flow rocks has been documented by Vallier (1967, 1977), and is an important criterion for identifying island arc terranes (Garcia, 1978). Flow rocks in the Seven Devils Group display a wide range of silica compositions; protolithologies vary from basalt to rhyolite (Vallier and Batiza, 1978), although intermediate (andesitic) compositions are probably dominant overall. These features serve to distinguish island arc sequences from other volcanic sequences. Strontium isotopic ratios from younger intrusive rocks within and near the Seven Devils Group indicate formation in an oceanic environment--the Seven Devils Group is not underlain by continental crust (Armstrong and others, 1977).

The island arc character of the Seven Devils Group is well accepted, but the petrologic nature of this arc is still not well understood. Because of pervasive metamorphism, a conventional petrographic approach to the petrology of the rocks is not feasible. For the same reason, major element geochemistry is of limited value. Vallier and Batiza (1978) conducted the only detailed petrologic investigation of the Seven Devils Group to date. They discussed ion mobility and spilitization processes in some detail. Because of major element mobility they could not definitively characterize Seven Devils magma types, but the major element data, combined with microprobe analysis of relict pyroxenes, led them to tentatively suggest that the Seven Devils spilites were altered from low potassium, subalkaline (possibly tholeiitic) basalts.

As part of the present study, major and trace element compositions were determined for 13 flow rocks from the Wild Sheep Creek Formation. All but two samples (D-86 and D-151) were collected in Rapid River canyon. Sample D-86 came from Cannonball Mountain, west of the limestone klippe, and D-151 was collected just west of the field area, along the Seven Devils Trail (NE1\4 sec.18, T.23N, R.1W). The analyses of these samples are shown in Table 3. Based on this data, problems that will be addressed include correlation with Hells Canyon flow rocks, confirmation of island arc affinity, nature of the magma(s), and comparison with possibly correlative rocks of the Wrangellia Terrane.

Major element data is marginally useful in the analysis of low grade metamorphic (spilitized) volcanic rocks. Much attention has been focused on spilites and related rocks (keratophyres and

Table 3. Chemical Composition of Flow Rocks of the Wild Sheep Creek Formation

		D-71	D-44	D-18	D-34a	D-41a	D-3	D-142	D-173	D-75	D-41	D-110	D-86	D-151
Major Element Oxides (percent)[1]	SiO_2	48.4	48.6	49.5	51.5	54.7	55.6	55.9	63.0	65.4	70.3	70.8		
	TiO_2	1.36	1.26	1.16	1.56	1.47	1.45	1.59	.80	1.09	.58	.44		
	Al_2O_3	19.5	18.2	17.2	18.5	19.9	18.1	14.4	16.8	14.1	15.4	14.7		
	FeO*	9.5	11.3	10.4	10.9	5.9	9.1	12.3	5.0	7.6	2.7	3.2		
	MgO	6.3	6.0	6.3	3.8	4.5	4.1	4.2	.8	1.4	1.1	1.5		
	CaO	9.5	8.4	9.7	6.7	4.2	4.1	6.5	6.0	2.2	1.3	1.6		
	Na_2O	3.9	4.6	3.7	5.1	8.0	6.6	5.2	6.0	7.0	6.7	6.5		
	K_2O	1.38	.68	2.02	1.00	.50	.79	.14	1.9	.21	.98	1.3		
	Total %	99.84	98.9	99.98	99.3	99.2	99.8	100.2	100.3	98.9	99.1	100.04		
Trace Elements (parts per million)[2]	Sc	37.6 ± .05	34.3 ± .060	37.5 ± .06	25.1 ± .05	26.5 ± .05	32.6 ± .06		17.3 ± .04			5.91 ± .02	40.21 ± .07	38.57 ± .07
	Cr	68.9 ± 2.1	26.7 ± 2.4	62.5 ± 2.5	2.3 ± 1.7	9.7 ± 1.8	47.2 ± .21						102.4 ± 2.5	171 ± 4
	Co	37.62 ± .23	34.4 ± .3	34.1 ± 2.8	25.5 ± .2	22.24 ± .21	16.43 ± .19		10.1 ± .16			3.40 ± .05	43.6 ± .33	41.29 ± .32
	Hf	2.16 ± .14	1.80 ± .17	1.54 ± .16	3.16 ± .16	3.97 ± .20	3.27 ± .20		3.77 ± .14			4.50 ± .16	2.85 ± .21	2.83 ± .18
	Ta	.21 ± .04	.18 ± .07	.19 ± .05	.43 ± .14	.23 ± .06	.15 ± .06		.49 ± .06			.47 ± .05	.21 ± .09	.19 ± .08
	Th	1.24 ± .11	1.19 ± .14	.66 ± .11	1.37 ± .12	1.18 ± .11	.84 ± .09		2.11 ± .16			2.31 ± .06	.44 ± .14	.46 ± .13
	La	11.96 ± .69	11.41 ±.66	8.08 ± .48	14.32 ± .70	12.86 ± .74	8.59 ± .43		19.1 ± 1.1			14.83 ± .76	7.80 ± .92	6.59 ± 1.04
	Sm	5.94 ± .025	5.08 ± .02	4.52 ±.019	7.77 ± .03	6.85 ± .027	5.63 ± .022		6.45 ± .03			5.81 ± .026	5.97 ± .03	5.98 ± .03
	Eu	1.62 ± .060	1.95 ± .03	1.85 ± .033	2.84 ± .037	2.37 ± .032	1.72 ± .030		2.53 ± .03			2.08 ± .03	1.99 ± .032	2.18 ± .03
	Tb	1.12 ± .08	.96 ± .06	.94 ± .08	1.37 ± .06	1.16 ± .06	.84 ± .05		1.10 ± .04			.91 ± .02	1.32 ± .08	1.37 ± .06
	Yb	3.21 ± .09	2.96 ± .08	2.54 ± .064	4.58 ± .079	4.03 ±.10	4.33 ± .087		3.64 ± .10			4.31 ± .14	4.36 ± .11	4.64 ± .10
	Lu	.54 ± .014	.46 ± .01	.40 ± .011	.70 ± .013	.61 ± .013	.89 ± .013		.60 ± .01			.59 ± .01	.76 ± .02	.75 ± .01

1. Maximum analytic error ± 0.5 percent.
2. Error values apply to counting statistics only. Analytic error not available.

Major element oxides analyzed by X-ray fluorescence except Na_2O and K_2O which were analyzed by atomic absorption spectrophotometry. Trace elements analyzed by instrumental neutron activation.

quartz keratophyres) during the past 50 years. Althought most workers since Gilluly (1935) have recognized that spilite is merely a greenschist equivalent of basalt, there has been much study of the mechanisms for spilitization, and in particular the causes and effects of major element mobility (Hamilton, 1963a; Cann, 1969; Battey, 1974; Vallance, 1974; Vallier and Batiza, 1978).

The most notable chemical manifestation of spilitization is high total alkali element content due to secondary addition of sodium, as is apparent from the data in Table 3. This is generally recognized as a characteristic of spilites and related rocks, regardless of the particular alteration process a given author may espouse (Gilluly, 1935; Hamilton, 1963a; Smith, 1968; Cann, 1969; Grenne and Roberts, 1980).

Although high sodium is the most conspicuous chemical feature of spilites, Pearce (1975) notes that virtually all major elements can display some mobility during greenschist facies metamorphism or weathering. In general, one must exercise great care when using major element compositions to draw inferences about spilite source magmas. This is particularly true of the alkali elements, which can undergo profound variation during metamorphism and alteration (Smith, 1968; Pearce, 1975). However, aluminum usually does not show significant mobility (Smith, 1968), and titanium is also relatively immobile (Pearce, 1975). Iron and magnesium can be either stable or mobile. Some workers have used these elements (Fe and Mg) in analysis of spilite petrogenesis (Grenne and Roberts, 1980), but Pearce (1975) warns that such analysis should be accompanied by data from elements that are known to be immobile, particularly titanium, whose behavior in fractionating magmas is similar to that of iron.

"Immobile" trace element distribution has proven to be a powerful method of classifying altered volcanic rocks (Jakes and Gill, 1970; Pearce and Cann, 1973; Winchester and Floyd, 1977; Wood and others, 1979). The effectiveness of such techniques depends on how immobile the relevant elements are during metamorphism. In general, most workers have found that the most diagnostically useful trace elements-- Y, Zr, Hf, Ta, Th, and the rare earth elements (REE)-- are immobile (Jakes and Gill, 1970; Field and Elliot, 1974; Herrmann and others, 1974; Kay and Senechal, 1976; Muecke and others, 1979; Davies and Whitehead, 1980). There is some evidence that light rare earth elements (LREE) may become slightly enriched (Hellmann and Henderson, 1977), or depleted (Sun and Nesbitt, 1978) during metamorphism. However it is likely that the greatest problems with mobility occur during palagonitization of basaltic glass (Ludden and Thompson, 1979), and probably during metasomatism and extensive shearing (Dostal and others, 1980). In light of this last observation, all samples were carefully screened prior to chemical analysis to make certain that they did not display shear fabrics.

Classification of island arc magmas has been fertile ground for petrologists during the past twenty years, but there is still much room for confusion because of the persistence of two different classification schemes that carry genetic as well as semantic implications. It has long been recognized that the character of volcanic rocks changes across well-developed island arcs like Japan (Kuno, 1950). Average silica and alkali contents of magmas generally increase across an arc moving away from the trench, whereas iron and magnesium contents decrease. The end member on the trench side of the arc is generally considered tholeiitic, and the end member on the back arc side is alkalic. The bone of contention is the nature of the transition.

Kuno (1968) describes a tholeiite - high-alumina - alkali volcanic arc sequence. Miyashiro (1973) and Gill (1970), for example, discuss a tholeiite - calc-alkali - alkali sequence. The high-alumina series of Kuno (1968) and the calc-alkaline series of Miyashiro (1974) are different. High-alumina basalts are chemically transitional between tholeiitic and alkali basalts. Kuno (1968) defines them by an empirical intermediate composition field on the alkali - silica variation diagram(Figure 5). Of course, these rocks are also characterized by high values of alumina, generally in the range of 16.5 to 20 percent in basalts (Kuno, 1968).

Whereas high-alumina magmas are distinguished from tholeiites purely by chemical composition, calc-alkaline magmas are distinguished from tholeiites by the absence of iron enrichment during differentiation, and by the overall predominance of andesitic instead of basaltic compositions (Jakes and Gill, 1970; Miyashiro, 1974). Miyashiro (1974) states that high-alumina basalts may be tholeiitic (e.g. Skaergaard intrusion) or calc-alkaline (e.g. Andean volcanics), and that therefore the term is not useful. Kuno (1968) states that calc-alkaline series may be derived from tholeiitic, high-alumina, or alkali series source magmas, but is not a unique series and therefore is not a useful classification. The problem is that all magma series are transitional, even though end members are derived from different sources (Ringwood, 1977).

Tholeiitic, calc-alkaline, and high-alumina series magmas are all subalkaline, based on MacDonald and Katsura's (1964) alkali - silica plot (Figure 5). That is, all three magma series plot below the alkali field. Irvine and Baragar (1971) have shown that most high-alumina series rocks are in fact calc-alkaline (iron-depleted differentiation series, andesite-dominant lithologies), and that high-alumina tholeiites are relatively rare. They divide subalkaline rocks into tholeiitic and calc-alkaline series based on empirical composition fields on an AFM diagram (Irvine and Baragar, 1971, p. 528). Though this diagram is purportedly non-genetic, it does reflect different levels of iron enrichment, and in that sense is consistent with the terminology and intent of Miyashiro (1974). High-alumina series is still used by some workers (Carmichael and others, 1974; Haskin, 1979), but calc-alkaline series is a more widely accepted concept (for example, see Jakes and Gill,

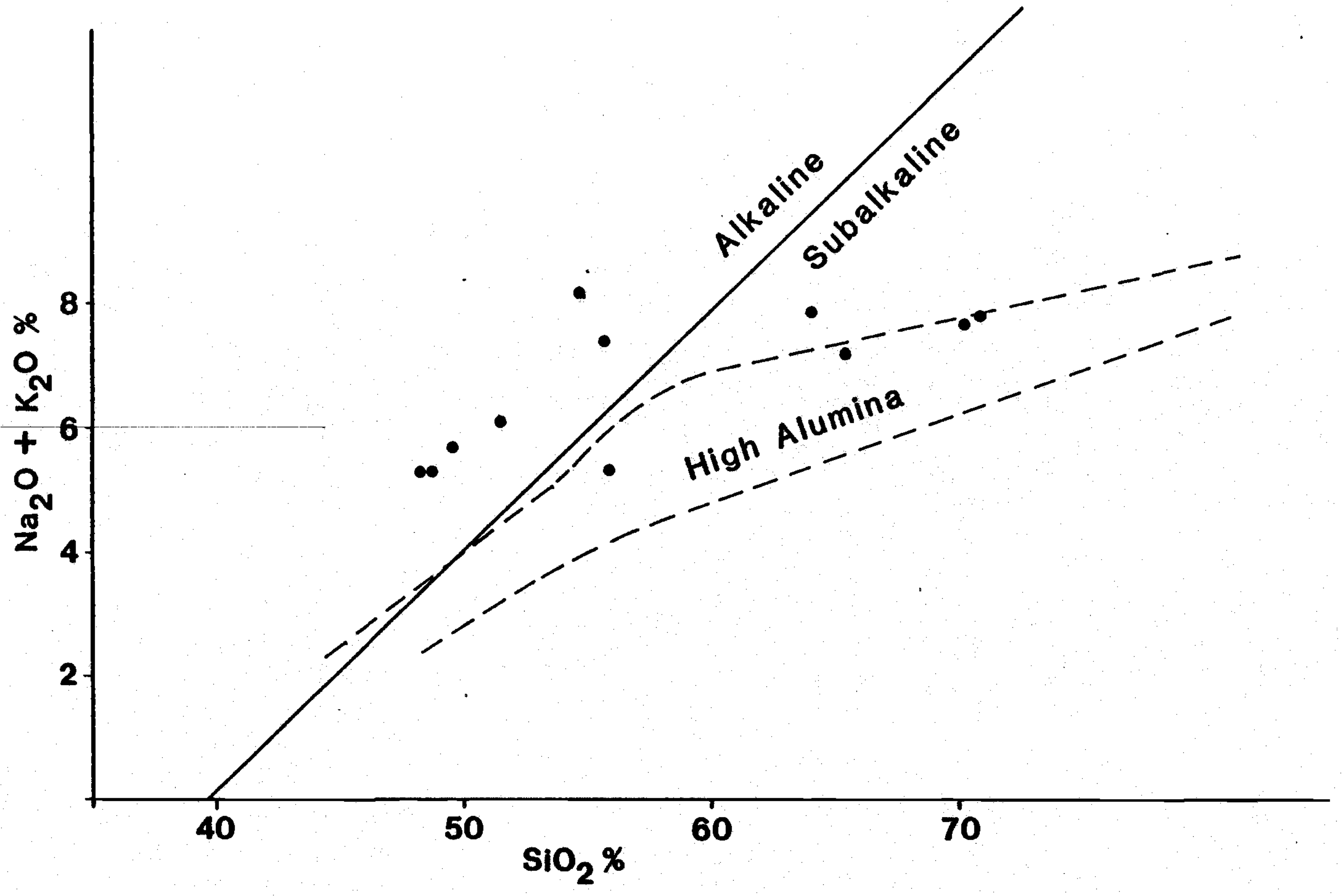

Figure 5. Alkali-silica plot for rocks of the Wild Sheep Creek Formation (after MacDonald and Katsura, 1964, and Kuno, 1968). The subalkaline field encompasses the high-alumina field.

1970; Jakes and White, 1972; Kay, 1977; Garcia, 1978), and it has been adopted in this study.

Total alkalis versus silica for 11 Triassic Seven Devils metavolcanics have been plotted on Figure 5. Similar diagrams are used as the simplest method of separating the alkaline and subalkaline rock series (MacDonald and Katsura, 1968; Irvine and Baragar, 1971). Kuno (1968) modified the field boundaries to distinguish alkaline, high-alumina, and tholeiitic rock series, as discussed above. Data for the Wild Sheep Creek Formation straddle the alkaline - subalkaline and alkaline - high-alumina boundaries. This plot is not particularly useful for classification of spilitized rocks, because sodium and potassium are both highly mobile. Compositions are displaced toward the alkali field. This figure also shows that, in general, increasing silica content is accompanied by increasing alkalis. This is, of course, a predictable relation (Cox and others, 1979), but it suggests that whereas major element concentrations are quantitatively suspect because of metamorphism, the qualitative relations between the various elements are still preserved. The distribution of points on Figure 5 is not useful for classification, but is suggests that the samples may belong to a single magma series. Data from Hells Canyon show a similar distribution on an alkali - silica diagram (Vallier and Batiza, 1978).

Rare earth element patterns can be used to distinguish alkaline and subalkaline rock series. Alkali basalts always show extreme REE fractionation, with LREE greatly enriched relative to chondrites. Lanthanum values are generally 50 to 200 times chondrite abundances (Gast, 1968; Kay and Gast, 1973). Heavy rare earth elements show only slight enrichment relative to chondrites.

Rare earth patterns of subalkaline basalts are usually less fractionated than those of alkali basalts. Abyssal tholeiites and basalts of the island arc tholeiite series (IAT) are characterized by flat (unfractionated) REE curves (Jakes and Gill, 1970; Gast, 1968; Hawkesworth and others, 1977), with abundances around 10 to 20 times greater than chondrites. Calc-alkaline basalts and some tholeiites from island arcs yield moderately fractionated REE patterns that are transitional between flat, tholeiitic patterns and highly differentiated alkaline patterns (Jakes and Gill, 1970; Kay, 1977; Matsuda, 1968).

Chondrite normalized REE data for the Wild Sheep Creek Formation are displayed on Figure 6. The subalkaline nature of these rocks is clearly displayed by the REE curves. Figure 6a shows curves for five spilites. (For purposes of comparison, Figure 6b shows curves for two silicic Triassic Seven Devils rocks.) The spilites show moderate LREE enrichment and moderate overall fractionation. Rare earth patterns and other trace element abundances are similar to calcalkaline island arc basalt data presented by Jakes and Gill (1970) and Jakes and White

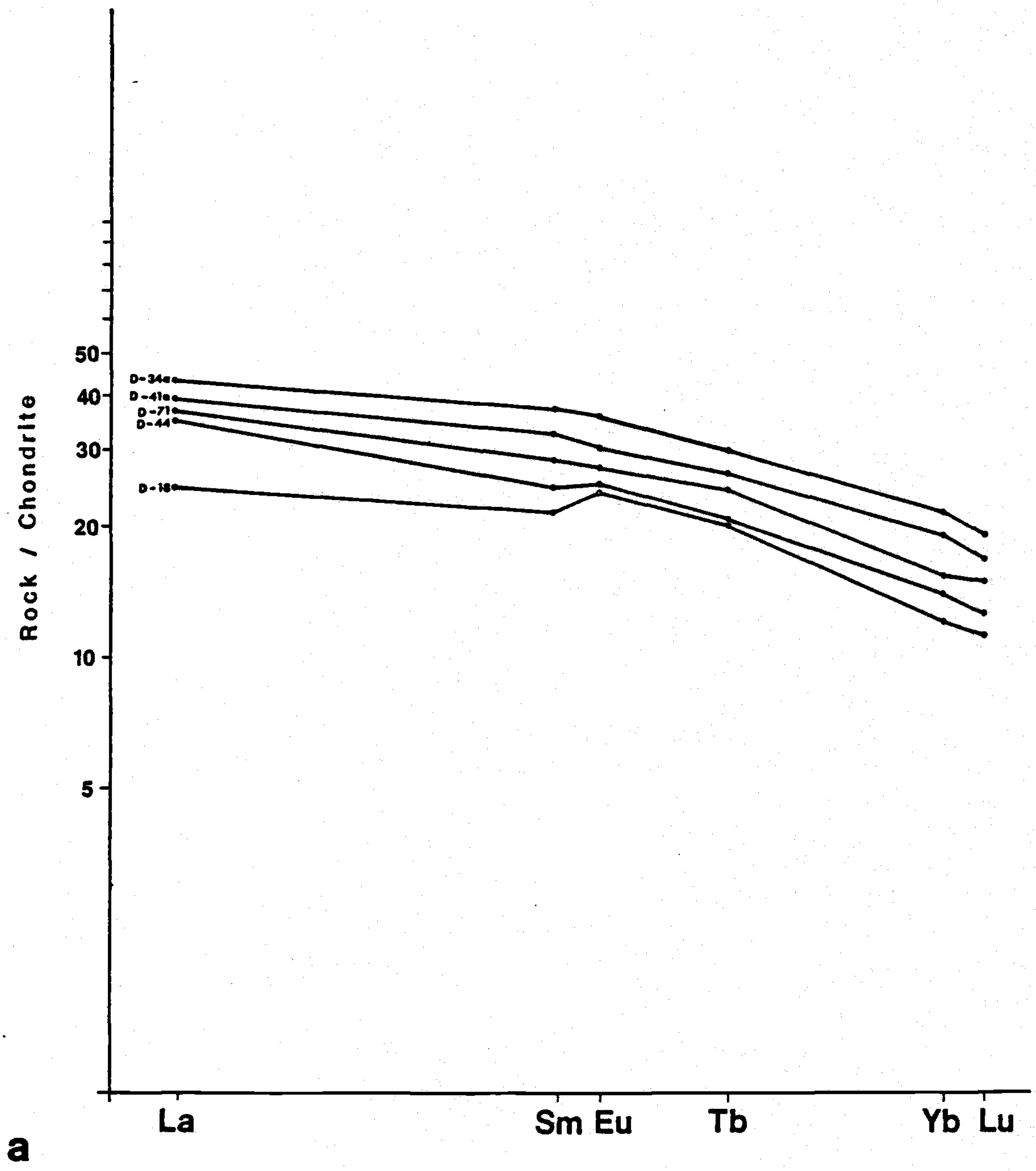

Figure 6. Rare earth element patterns for rocks of the Wild Sheep Creek Formation. 6a shows patterns of five spilites; 6b shows patterns of one keratophyre (D-174) and one quartz keratophyre (D-110).

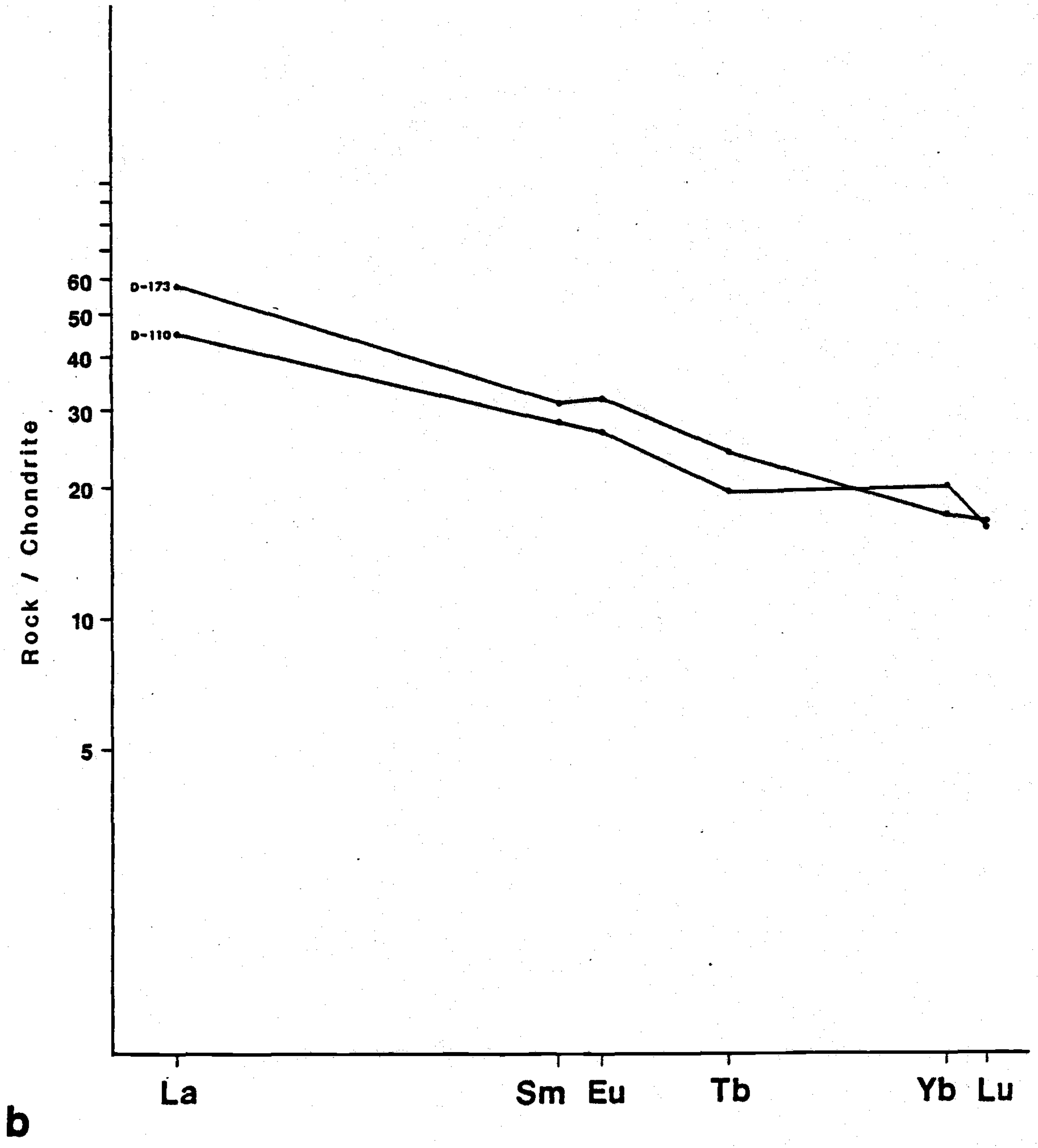

Figure 6., continued.

(1972). These workers recognized two major series of subalkaline rocks in island arcs-- the island arc tholeiite series (IAT), and a calc-alkaline series (CA). Island arc tholeiites are characterized by flat, slightly enriched REE curves. Calc-alkaline island arc rocks are characterized by moderately differentiated REE (Jakes and Gill, 1970).

In Table 4, major and trace element averages for IAT and CA basalts from Jakes and White (1972) are shown with data from this study. Major elements are shown for completeness only, although TiO_2 and Al_2O_3 contents have some comparative value. Comparison of trace element contents shows that spilites of the Wild Creek Sheep Formation are very similar to CA basalts, and quite distinct from IAT basalts. So, based on this classification scheme, these Triassic spilites can be considered calc-alkaline.

Unfortunately, Jakes and Gill's (1970) scheme may be overly simplistic. Kay (1977) notes that Aleutian tholeiitic magmas show fractionated REE trends with enriched LREE values. In fact, these particular tholeiitic rare earth distributions are indistinguishable from calc-alkaline curves from other areas. Kay (1977) calls these magmas tholeiitic because they display iron enrichment trends. What Kay's (1977) work points out is that basalt classification is still imperfect; even with the benefit of trace element data, transitional basalts may be difficult to characterize, particularly for altered rocks. Mobility of iron oxides in the rocks of the Wild Sheep Creek Formation is such that iron depletion or enrichment trends cannot be

Table 4. Comparison of Chemical Composition of the Wild Sheep Creek Formation with World-wide Averages

	C A Basalts (Jakes and White, 1972)	Five C A Spilites (This Study)	I A T Basalts (Jakes and White, 1972)	Three I A T (?) Spilites (This Study$^{\#}$)
SiO_2	50.6%	50.5%	51.6%	55.6%
TiO_2	1.05	1.36	0.8	1.45
Al_2O_3	16.29	18.66	15.91	18.1
FeO*	8.7	9.6	9.74	9.1
MgO	8.96	5.38	6.73	4.1
CaO	9.5	8.78	11.74	4.1
Na_2O	2.89	5.06	2.41	6.6
K_2O	1.07	1.12	0.44	0.79
La	9.6ppm	11.73ppm	1.1ppm	7.66ppm
Yb	2.7	3.46	1.4	4.53
La/Yb	3.5	3.42	1.0	1.70
Th	1.1	1.13	0.5	0.58
Cr	40	34	50	107
Hf	2.6	2.53	1.0	2.98

$^{\#}$IAT major element oxide values from sample D-3 only.

demonstrated.

Additional data are available for consideration of this problem. Most conspicuous is the very high alumina contents of the Triassic Seven Devils spilites. It is not unwarranted to consider these data as reflecting primary alumina, because of the relative immobility of this oxide (Smith, 1968). Irvine and Baragar (1971) state that alumina content is "the most prominent chemical difference" between calc-alkaline and tholeiitic basalts. The average alumina content for seven spilites analyzed in this study is 18.0 percent; the average for Aleutian basalts (Kay, 1977) is 16.5 percent. This is a significant deviation that suggests that Seven Devils magmas may have had calc-alkaline affinities.

Recently, Wood and others (1979) and Wood (1980) presented a hafnium-tantalum-thorium (Hf-Ta-Th) triangular diagram for distinguishing between volcanic rocks from various tectonic environments. Theirs is a standard type of empirical diagram, where compositional and tectonic fields are defined by distribution of points from known tectonic environments. The legitimacy of such a diagram necessarily increases with time, as additional data either corroborate or conflict with the empirical field boundaries. Because the Hf-Ta-Th diagram is rather new, it must be used cautiously. Its most promising application in this study is that it purports to separate calc-alkaline and tholeiitic orogenic magmas.

The Hf-Ta-Th values of ten rocks from the Wild Sheep Creek

Formation have been plotted on Wood's (1980) discrimination diagram (Figure 7). All of the data plot within the field for orogenic (destructive plate margin) magmas. Four of five spilites fall into the calc-alkaline field, and a fifth falls close to the tholeiitic - calc-alkaline field boundary. The two silicic samples also plot within the calc-alkaline field. Three additional spilites fall into the tholeiitic field. These three samples have distinctive (probable IAT) REE distributions that will be discussed below in greater detail.

The consistency with which these data plot in the orogenic magma field is further support for the island arc origin of rocks of the Wild Sheep Creek Formation. The tholeiitic - calc-alkaline fields on this diagram should be viewed with some caution, however. Orogenic magmas are characterized by low Ta values (Wood and others, 1979), so they plot near the Hf-Th boundary of the discrimination diagram. The distinction between orogenic tholeiitic and calc-alkaline magmas is essentially one of relative Hf-Th content (Wood, 1980). Thorium is generally similar in behavior to the light rare earth elements in that it has a very low distribution coefficient (it tends to partition strongly in favor of the liquid phase in a partial melt or fractionating system). Hafnium is less incompatible (it has a higher distribution coefficient), and as such it is similar to the heavier rare earths (Wood and others, 1979). The point is that, in a magma where LREE's are enriched (e.g., the spilites in this study), one might, qualitatively, expect Th enrichment as

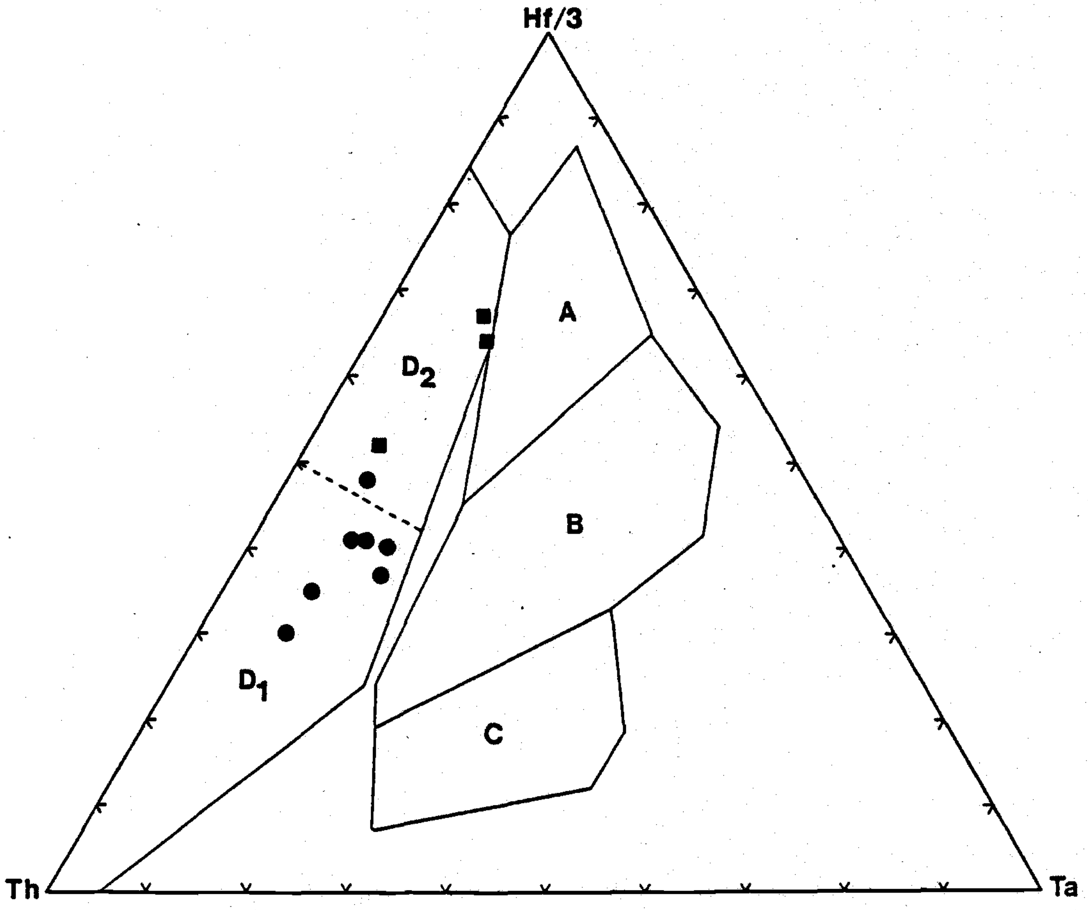

Figure 7. Hafnium-tantalum-thorium tectonomagmatic descrimination diagram (after Wood, 1980). Rocks with LREE enrichment plotted as circles; rocks with flat REE patterns (see below) plotted as squares. Field designations: A- normal mid-ocean ridge basalt; B- enriched mid-ocean ridge basalt; C- alkaline within plate magmas; D- destructive plate margins. Sub-fields D_1 and D_2 may separate tholeiitic and calc-alkaline orogenic magmas, respectively (Wood, 1980).

well. This would displace data points toward the calc-alkaline field in the Hf-Ta-Th diagram. In other words, this diagram may not circumvent the dilemma presented by Kay (1977); it may just restate it. Unfortunately, Kay (1977) did not analyze the Aleutian tholeiites for Hf, Ta, or Th, so this cannot be tested.

The original magmas from which these spilites were derived can be unequivocally characterized as transitional and highly aluminous. They probably are calc-alkaline in nature, but this cannot be determined with complete certainty.

Three Triassic spilites are distinguished by flat rare earth patterns (Figure 8). Two of these rocks (D-86 and D-151) come from the western part of the field area. The third (D-3) comes from Rapid River canyon. These rocks may belong to the island arc tholeiite series. Their island arc affinity is confirmed by the Hf-Ta-Th diagram, and their IAT character is suggested by lack of REE fractionation (Jakes and Gill, 1970). The high alumina content of sample D-3 may be due to abundant plagioclase phenocrysts in the rock, and may not reflect magmatic alumina abundances.

It is unfortunate that only two samples from the western part of the field area were analyzed for trace elements. The IAT character of both of these samples is notable, but may well be coincidental. The possible presence of two magma series in the field area is significant. Further sampling and chemical analysis could serve to delineate the geographic distribution of the two series. A possible consequence of such studies would be

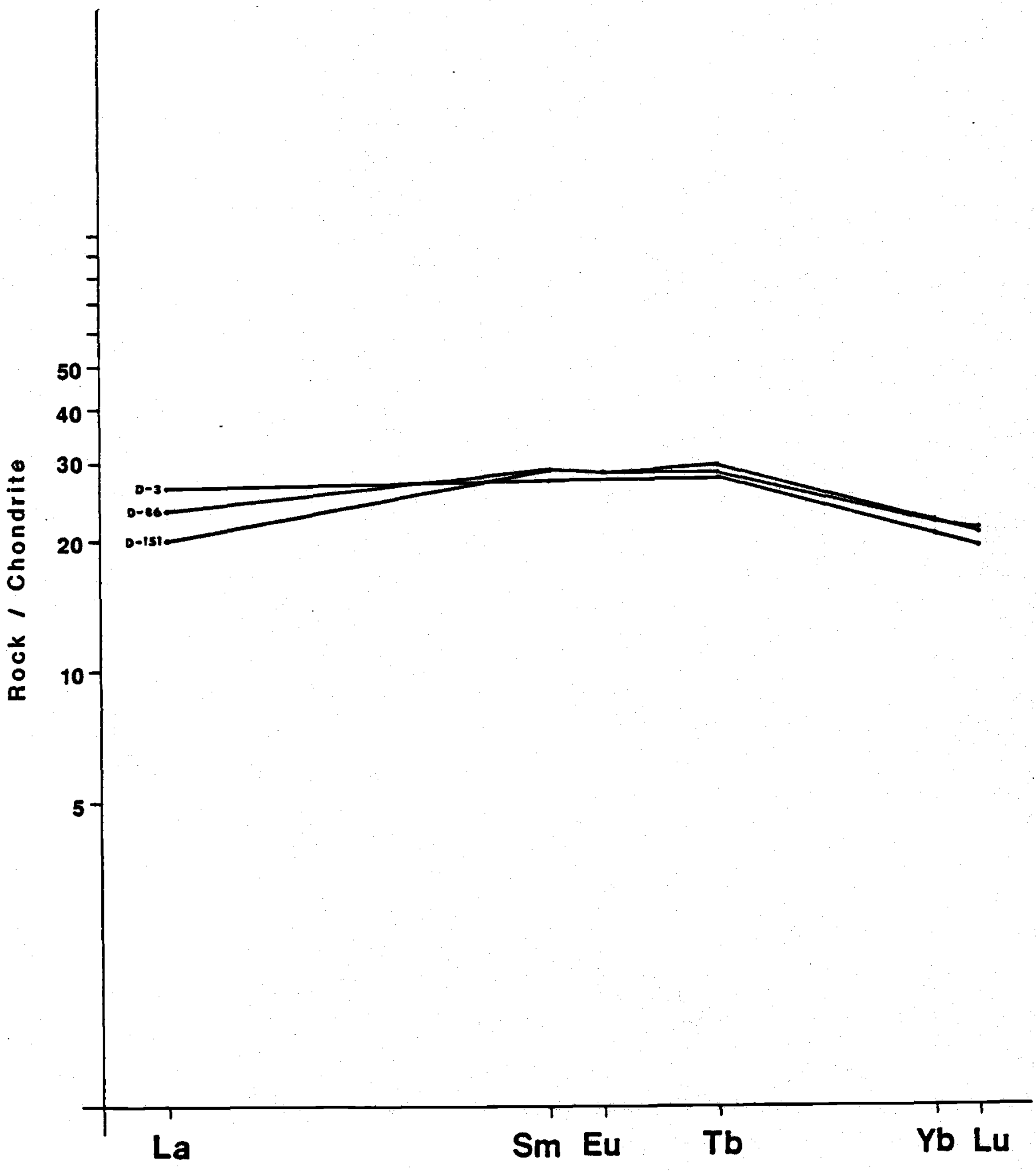

Figure 8. Flat rare earth element patterns of three spilites from the Wild Sheep Creek Formation.

determination of the position of the subduction zone relative to the arc, based on the principle that "primitive" IATs develop on the trench side of an arc (Jakes and White, 1972).

The character of the spilites of the Wild Sheep Creek Formation relative to some other orogenic basalts is shown on Figure 9. The ratio of La to Yb is plotted against Yb content for eight spilites. This is essentially a measure of rare earth element fractionation. Average values of basalts from various destructive plate margins are plotted for comparison with Seven Devils spilites. Predictably, the transitional Seven Devils spilites and the IAT (?) Seven Devils spilites plot in distinct fields. Transitional spilites plot close to average basalts from the Japanese calc-alkaline series, Aleutian tholeiitic series, and overall average island arc calc-alkaline values from Jakes and White (1972). Island arc tholeiite spilites (?) plot near to average basalts of the Japanese IAT series.

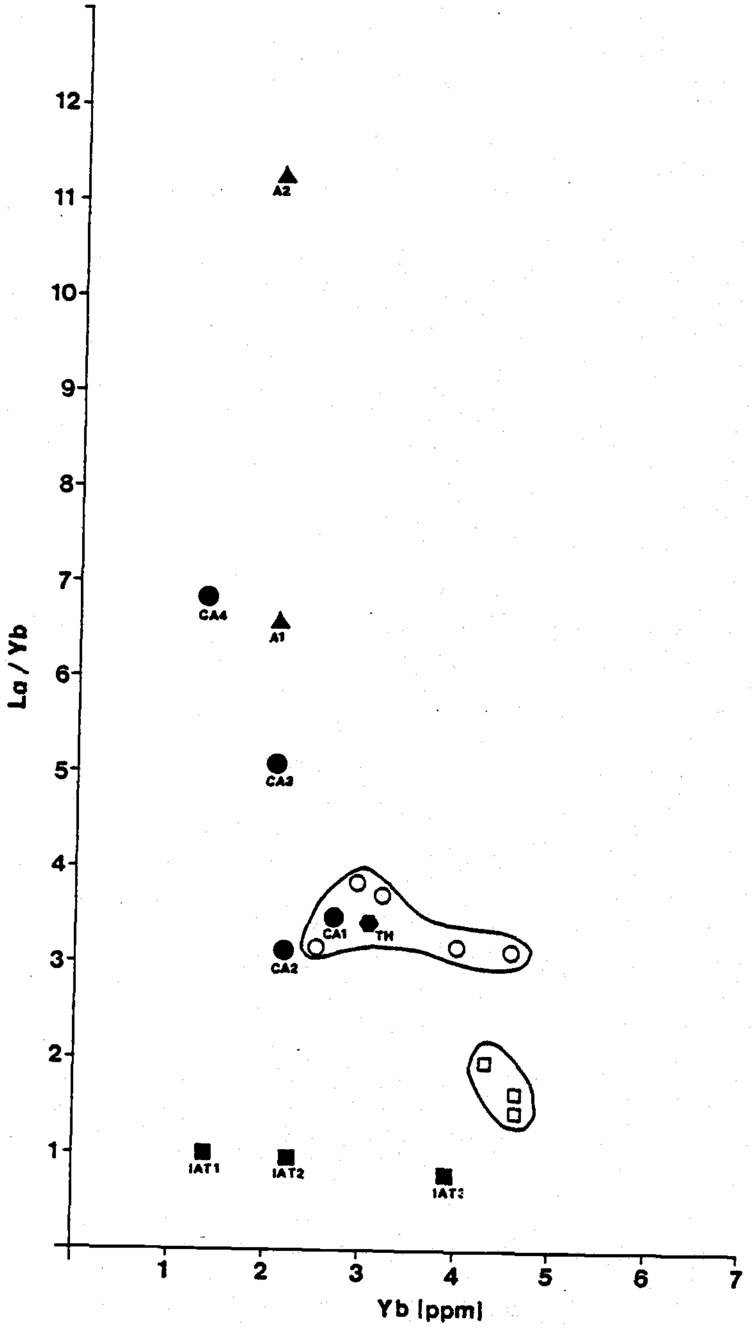

Figure 9. Comparison of La/Yb versus Yb for Wild Sheep Creek Formation and average values from other volcanic arc rocks. Open circles are five spilites from this study with LREE enrichment; open squares are three spilites from this study with flat REE patterns. Island arc tholeiites- IAT1: world-wide (Jakes and White, 1972); IAT2: Scotia Arc (Hawkesworth and others, 1977); IAT3: Japan (Matsuda, 1968). Calc-alkaline basalts- CA1: world-wide (Jakes and White, 1972); CA2: Japan (Matsuda, 1968); CA3: Andes (Lopez-Escobar, 1977); CA4: Aleutians (Kay, 1977). Aleutian tholeiite- TH (Kay, 1977). Alkali basalts- A1: world-wide (Jakes and White, 1972); A2: Japan (Matsuda, 1968).

STRUCTURAL GEOLOGY

NATURE OF THE MARTIN BRIDGE FORMATION - SEVEN DEVILS GROUP CONTACT

The dominant structural features in the Heavens Gate area are thrust faults and related shear-induced fabrics. Near the eastern margin of the field area, rocks of the Seven Devils Group, Martin Bridge Formation, Lucille Formation, and Riggins Group are juxtaposed as imbricate thrust slices, with thrust planes dipping to the north and northeast (Plate I). West of this imbricate sequence, a low angle thrust separates the main body of the Seven Devils Group from the overlying, younger limestone. Slip occurred along the unconformity that separates the limestones and volcanics; initial orientation of the fault was nearly horizontal.

The occurrence of such younger over older faults supposedly violates the "rules" of thrust fault geometry (Elliot and Johnson, 1980); and Dahlstrom (1970), for example, denies their possibility. When considering the entire length of a thrust fault, and assuming that strata were initially horizontal, there must of course be displacement of older strata over younger at some point along the dip length of the thrust. But, if the distance between major thrust ramps is great, and if the slip along the fault is less than the distance between ramps, then there may be significant segments of the fault that displace younger strata over older. Such relations were recently recognized in the fold and thrust belt of southern Idaho (Allmendinger and Platt, in press). Bally and others (1966) implicitly recognized this type of geometry in the southern Canadian Rocky Mountains.

Within the study area, this initially horizontal fault plane has been folded into broad, open folds in the south, and tighter, locally overturned folds in the north. The combination of folding of the thrust plane, near horizontal initial thrust orientation, and extreme local relief, result in repeated exposure of the thrust fault perpendicular to its strike across the field area. Carbonates are exposed above the thrust as a narrow, continuous belt along the east wall of Rapid River canyon, and to the north. Carbonates are also exposed above the thrust farther to the west, where they occur as bodies with irregular geometries in the cores of synclines. The large body of carbonates in the south central portion of the field area is an isolated thrust remnant-- the thrust fault has been entirely breached by erosion of the Rapid River canyon and by movement along a later tear fault. Near the western margin of the map, north of and along the tear fault, a thin carbonate lens about half a mile long is also exposed as a klippe. A third body of carbonate, in the north central part of the field area, is not isolated, but joins with carbonates to the east just beyond the northern edge of the map.

Work by Hamilton (1963a, 1969) in the Riggins Group included reconnaissance mapping of the Seven Devils metavolcanics, but he did not attempt to map their internal structure. However, he did mention "tectonic lenses" of marble within the Seven Devils rocks, and he noted that these marbles were lithologically identical to the Martin Bridge Formation to the east. However, he concluded that the contact of the Seven Devils Group and the Martin Bridge Formation farther to the east (on the east wall of Rapid River canyon) was depositional (Hamilton, 1963a). Onasch (1977) also concentrated his efforts on the Riggins Group, but he did some mapping in the Seven Devils Group as well. He, too, interpreted the eastern carbonate-volcanic contact as depositional. Onasch (1977) recognized and partially mapped the eastern contacts of the "tectonic lenses" to the west, but he felt that the marbles there lay below an east-dipping thrust. Onasch's (1977) work did not extend to the western margin of these "lenses," where volcanic rocks reappear with lithologies identical to those on the east side of the "lenses." Also, as will be discussed below, his interpretation of the contact relations along the eastern margin of the klippe was not supported by this study, which found ample evidence of westward dip at the contact.

Reconnaissance mapping by Gualtieri and Simmons (1978) included a portion of the Heavens Gate quadrangle. Their interpretation of the marble-volcanic contact relations is in general accord with the interpretation that will be presented in this thesis. They mapped the southern carbonate body as lying above a thrust fault, and they consider the eastern carbonate-volcanic contact as a thrust fault as well. It is not clear from their map if they consider these to be the same fault.

Recognition of a thrust fault at the easternmost basal contact of the Seven Devils Group and the Martin Bridge Formation is based on two pieces of evidence. First, the intensity of ductile shear in underlying volcanics increases markedly toward the lithologic contact. Second, although the actual contact was only seen in two localities along the Rapid River canyon, it was distinguished at both locations by a zone of brittle shear, or fault gouge, that ranged from one half to two meters wide. Interpretation of the western limestone bodies as thrust remnants is based on similar evidence: increase in intensity of ductile shear deformation near the contact, and development of brittle shear along the contact (Figure 10). Also, at the southeast edge of the large carbonate klippe (sec.23, T.23N, R.1W) the carbonate-volcanic contact is locally marked by hydrothermal quartz deposits up to five meters thick. Such deposits may typically develop at fault contacts (Billings, 1972, p.203). These veins are well developed near the tonalite dike that cuts the thrust contact; it seems likely that the veins formed during hydrothermal activity associated with tonalite intrusion. In some places the quartz is noticeably stained with iron and copper oxides. Two mine adits, abandoned long ago, were driven into

Figure 10. Fault contact between Martin Bridge Formation (above) and Wild Sheep Creek Formation (below), north of the West Fork of the Rapid River (SW1/4, SW1/4, sec. 23, T.23N., R.1W.). Hammer lies on fault gouge zone.

these hydrothermal zones.

Detailed mapping of the western carbonate-volcanic contact does not support Onasch's (1977) interpretation that volcanics overlie marble along east-dipping fault planes. In the south, where extensive outcrop in the canyons allowed precise mapping of portions of the eastern contact of the klippe, contacts dip to the west beneath the marble, and the marble is exposed as the core of a syncline.

To the north, Onasch (1977) argued at length for an east-dipping depositional marble-volcanic contact in the east, and an east-dipping, discordant thrust contact to the west, based on outcrop exposed along Shingle Creek. In the southern part of sec.35, T.24N, R.1W, traversing west along Shingle Creek, one passes from carbonates to volcanics and back into carbonates (Plate I). Foliation and bedding attitudes are too variable and outcrop is too sparse to demonstrate discordance at the western contact. The map pattern unequivocally supports Onasch's (1977) observation that the contacts dip east at both locations. However, his interpretation of a thrust fault in the west and a depositional contact in the east is not viable. A traverse up Shingle Creek just north of this study area, and beyond the extent of Onasch's (1977) mapping, demonstrates that the eastern and western limestones are a continuous body, locally bisected along the lower reaches of the creek. The contact in this area therefore defines an overturned antiform, verging southwest (Plate II). The trend and plunge of the fold axis are to the northwest. This interpretation is well constrained by the combination of fault trace geometry and topography. There is no direct evidence of overturned bedding based on primary sedimentological features.

SHEAR TEXTURES

Evidence of shearing occurs throughout the study area. Flattening and elongation of clasts in volcaniclastic rocks are commonly visible in outcrop. Conspicuous shear foliations are visible in many thin sections, and are commonly manifested as fracture cleavage at outcrop scale (Figure 11).

The development of shear-induced rock fabrics in the Heavens Gate area seems to be governed by two considerations--proximity to a thrust fault, and rock type. Within approximately 10 meters of the fault contact that separates the Martin Bridge Formation from the Seven Devils Group, ductile shear fabrics are developed in all rocks regardless of lithology. At greater distances below the fault, lithologic character strongly governs the extent to which a given rock shows evidence of shearing.

Discussion of sheared rocks is hampered by a morass of terminology, and a lack of concensus conerning the application of this terminology. Classification schemes presented by Spry

Figure 11. Fracture cleavage in a keratophyre tuff, Wild Sheep Creek Formation.

(1969), Higgins (1971), Hatcher (1978), and Sibson (1977) are all fairly lucid and somewhat complementary. There is general agreement that "fault rocks" (Sibson's (1977) term, admirably unencumbered with historical or genetic baggage) can be divided into non- cohesive and cohesive rocks. Non-cohesive fault rocks include fault gouge, which Higgins (1971) described as an extremely fine-grained, "paste-like" rock with no internal structure or primary cohesion. Non-cohesive fault rocks are generated by brittle shearing (Sibson, 1977).

Cohesive fault rocks may be subdivided into foliated and massive types. Foliated, cohesive fault rocks comprise the mylonite series, and these are products of ductile shearing (White and others, 1980; Sibson, 1977). Non- foliated, cohesive fault rocks comprise the cataclasite series, and are products of brittle shear (Sibson, 1977; Spry, 1969).

Where the thrust contact between the carbonate and volcanic rocks is visible, it is marked by a zone of fault gouge up to two meters thick. In outcrop, the gouge is a dull, earthy brown or blue green, homogeneous in appearance, usually highly veined and fractured, and commonly soft enough to crumble in one's fingers. Where the gouge is apparently cohesive, secondary recrystallization of silica and carbonate has occurred. In thin section, the great proportion of the rock is unidentified clay minerals, but there is generally a surprising abundance (up to about 20 percent) of recognizable minerals, including epidote, chlorite, actinolite, albite, white mica, quartz, and carbonate.

Quartz and carbonate are commonly found as vein filling. The other minerals may be sparsely scattered throughout the matrix, or they may occur in irregular aggregates. Epidote in particular tends to occur in isolated pods several millimeters in diameter.

Fault gouge terminates abruptly against internally cohesive rock. There is no visible transition between the rock types. Volcanic rocks beneath the gouge zone usually look like aphanitic or sparsely porphyritic flow rocks. Thin section analysis shows that these rocks are in fact mylonites. In the mylonites, well developed fluxion structures (shear foliation) are defined by stringers of polycrystalline, fine-grained, strained, elongate quartz, commonly with serrate or lobate grain boundaries. Fluxion bands also can be defined by parallel alignment and stringers of white mica, chlorite, or opaque material. Fluxion structures may be superimposed on a randomly oriented matrix of fine grained, recrystallized albite, with or without epidote, actinolite, quartz, or mica. Porphyroclasts of albite and opaque ore are common, whereas quartz grains are rarely preserved as porphyroclasts in mylonites. Quartz is much less resistant to processes of ductile deformation than feldspar (White and others, 1980; Watts and Williams, 1979). Subparallel alignment and rounding of feldspar porphyroclasts was observed in a few mylonites, and probably indicates physical rotation (Higgins, 1971, p. 60). Fluxion structures are deflected around the porphyroclasts (Figure 12). Pressure shadows were observed between some porphyroclasts and the deflected foliation.

Figure 12. Ductile shear fabric in a keratophyre from the Wild Sheep Creek Formation. Fluxion bands, defined by quartz, white mica, chlorite, and opaques, are deflected around albite porphyroclasts. Plane polarized light, X4, field of view 2.0 mm.

Pressure solution fringes of quartz or chlorite commonly crystallize in these shadows as randomly oriented polycrystalline aggregates, or as crystals elongated parallel to the direction of shear foliation (Figure 13).

The development of mylonite becomes less pronounced and more sporadic as one moves downward from the fault. Lithology becomes the major control on development of shear fabrics. Flow rocks more than a few tens of meters from the fault usually do not display any evidence of shearing, whereas adjacent volcaniclastics may show well developed fluxion structures.

In general, mafic and intermediate flow rocks, and massive, matrix poor breccias, do not show evidence of shearing unless they occur near the thrust fault. Their high shear strength relative to other rock types can be attributed to a more isotropic internal structure, and a comparatively greater proportion of shear-resistant plagioclase. Crystal and lithic tuffs, lapilli-tuffs and tuff-breccias generally show evidence of shearing throughout the field area, although local variations in the intensity of shear development are common even within rocks of a single lithology. In outcrop, shear foliation in these rocks is defined by conspicuously stretched and flattened lithic clasts. Where bedding is visible, it is always parallel to mesoscopic shear foliations. Fluxion structure is generally, but not invariably, well developed in these rocks. Where fluxion bands are poorly developed or absent, quartz crystals always show evidence of strain, manifested as extreme undulatory

Figure 13. Quartz pressure solution fringes adjacent to a pyrite cube. Crossed polars, X4, field of view 2.0 mm.

extinction, with or without deformation lamellae and incipient polycrystallinity.

Shear fabrics are much better developed in rocks of the Hunsaker Creek Formation, north of the tear fault that transects the field area, than in rocks of the Wild Sheep Creek Formation to the south. This is not a result of differing structural histories of the two units. It reflects instead lithologic differences between the formations, and variation in the topographic character of the study area on either side of the tear fault. As discussed, the Wild Sheep Creek Formation contains a high proportion of mafic and intermediate flow rocks, and most volcaniclastic rocks are massive mafic or intermediate breccias or tuff-breccias. Also, local relief in Rapid River canyon is greater than elsewhere in the study area, and the canyon is located approximately beneath the anticlinal axis of the eroded, folded thrust plane. Thus, the rocks on the walls of Rapid River canyon are far below the thrust surface in many areas. It should be emphasized, however, that shear fabrics in the Wild Sheep Creek Formation are generally well developed at high elevations and near the fault contact.

North of the fault, the Hunsaker Creek Formation comprises a large proportion of intermediate and felsic bedded volcaniclastic rocks. Overall relief is great, but local topography is not as extreme as in the south. Further, the thin klippe of limestone near the western perimeter of the field area suggests that the present topographic surface remains close to the eroded thrust surface across the entire northern portion of the field area. The result of these factors is that development of shear fabrics is much more conspicuous and pervasive in the north than in the south. This is not only evident on a microscopic scale, but is commonly visible in the field as well. In outcrop, agglomerates and volcaniclastic breccias and lapilli-tuffs show spectacular evidence of shearing (Figure 14). Clasts in these rocks are commonly markedly flattened, with maximum axial ratios on the order of 1:5:15, where the long dimension is parallel to and helps define the shear foliation.

Ductile shear fabrics are also well displayed in the Martin Bridge Formation throughout the field area. In outcrop, shear foliation is commonly manifested as closely spaced fracture cleavage. In thin section, many carbonates have a distinctive banded appearance defined by alternating layers of coarse- and fine-grained calcite. The coarse grained layers are generally composed of clean, equigranular crystals 1.0 to 2.0 mm in diameter. These layers are always subordinate in number to the finer grained layers, which show variable grain size, from one half millimeter to submicroscopic dimensions, and commonly contain sparse clay material or white mica between carbonate grains. Banding is apparently a shear foliation. Texturally, these rocks look much like the mylonites in the Seven Devils Group. Some large calcite crystals appear to be porphyroclasts--foliation bands diverge around them. If these large crystals predate shearing, then they indicate that carbonates had

Figure 14. Clast elongation in sheared volcaniclastic conglomerate, Hunsaker Creek Formation.

recrystallized to coarse grained marble before shearing began.

Bioclastic fragments are also preserved as porphyroclasts. Shell fragments and Pentacrinus stem plates are sparsely preserved within sheared marbles. The stem plates have recrystallized into polycrystalline aggregates. In one occurrence, the points of a Pentacrinus stem plate have been markedly worn down, and the plate deformed, from rotation due to movement along shear planes (Figure 15).

Evidence of shearing is present in most, but not all, of the carbonates. Intrusion of tonalite after shearing caused local recrystallization of adjacent carbonate and obliterated any shear textures. Elsewhere, primary depositional and diagenetic textures are locally preserved. There does not seem to be a systematic distribution of these unsheared areas.

RELATION BETWEEN BRITTLE AND DUCTILE SHEAR

The relation between degree of ductile shearing and proximity to a brittle thrust fault or lithologic discontinuity, repeatedly observed in this study, has been documented elsewhere. For example, Bell and Etheridge (1976) noted a progressive increase in shear strain, as recorded by increased development of ductile shear fabrics, in approaching the Woodroffe thrust fault, central Australia.

Figure 15. Sheared and recrystallized Pentacrinus stem plate. Crossed polars, X2.5, field of view 3.2 mm.

Watts and Williams (1979), and Grocott (1977) document fault zones that show both brittle and ductile deformation features in the same area. Coward (1980a) suggests that mylonites and thrust faults may have developed together during long periods of time in the eastern part of the Moine thrust zone, northwest Scotland. Hobbs and others (1976) briefly describe a number of areas that display a spatial correlation between mylonite development and brittle faulting along discrete planes.

The nature of the transition from brittle to ductile shear in tectonized rocks has been considered in some detail by a number of workers (for example: Sibson, 1977; Hatcher, 1978; and Orowan, 1961), but field criteria for interpreting the timing of this transition are not always clear cut. Higgins (1971) argues that brittle shear generally postdates development of mylonites because brittle shear ostensibly occurs at lower temperatures and confining pressures than ductile shear. However, in the absence of unambiguous field evidence, such as discordant zones of brittle and ductile shear, temporal relations may not be demonstrable. Further, the controls on the exact conditions of the brittle-ductile transition are complex. Mineralogy, fluid and confining pressures, density and nature of inhomogeneities, and variations in strain rate are all important controls on the nature of shearing (Sibson, 1977; Higgins, 1971; Hatcher, 1978). Sibson (1977) acknowledges that ductile and brittle shearing may occur simultaneously under certain circumstances. On a microscopic scale, it is important to note that typical ductile shear fabrics displayed in mylonites are a combination of both ductile (e.g., elongate, polycrystalline quartz or mica fluxion bands) and brittle (e.g., rounded and fractured or comminuted feldspar porphyroclasts) shear processes.

The point is that both ductile and brittle shear fabrics in the study area are spatially related to the thrust that separates Martin Bridge Formation and Seven Devils Group, but the relative timing of the development of these fabrics cannot be unequivocally determined. However, as Sibson (1977) implies, it is probable that any preserved brittle shear textures within ductile shear zones are late stage features, because persistent ductile deformation would tend to obscure or destroy evidence of earlier brittle deformation. But field relations suggest that brittle and ductile fabrics are both related to deformation along the same zone of strain softening.

Within a single thrust sheet, shearing processes may change along the dip length of a fault (Elliot, 1976; Ramsay, 1980). Both brittle and ductile shear may occur simultaneously, but at different locations along a fault. With increasing depth, slip mechanisms will change from brittle to ductile. Watts and Williams (1979) observed that a complete range of fault rocks, from mylonite to gouge, can occur at one location within a single shear zone. The presence of brittle and ductile fabrics in the same place may be attributed to simultaneous faulting and deroofing. These relations dictate that the locus of shearing was constant over time, although the shear mechanism varied. Decrease in temperature and confining pressure due to unroofing will result in a change of deformation mechanism from ductile to brittle. This transition probably takes place at burial depths of 10 to 15 kilometers (Watts and Williams, 1979). Sibson (1977) notes that the brittle-ductile transition for quartz corresponds generally with the onset greenschist metamorphism, at temperatures of around 250° to 300°C.

TEAR FAULT

The Hunsaker Creek Formation and the Wild Sheep Creek Formation are separated by a fault that strikes east and northeast across the center of the field area, and dips steeply to the north. This fault cuts the marble-volcanic thrust, and is probably truncated in the east by the Rapid River thrust.

Field relations argue for two periods of active slip along this fault. In the first episode, normal(?) faulting uplifted the Permian Hunsaker Creek Formation and juxtaposed it against the Triassic Wild Sheep Creek Formation. The maximum thickness estimated for the latter unit is 2500 meters (Vallier, 1977), and this may be considered a lower limit of throw during this first event, because there probably is uppermost Wild Sheep

Creek Formation within the field area. Later, strike slip (tear) faulting occurred as part of a developing thrust fault system.

Timing of the motion along this fault can be somewhat constrained. The dip-slip event probably occurred in the latest Karnian or earliest Norian, after extrusion and deposition of the Wild Sheep Creek Formation, but before deposition of the Martin Bridge Formation. These relations suggest, of course, that the volcanics in this area were unconformably overlain by limestones. This interpretation is not influenced by later thrusting of carbonates over volcanics, because, within the field area, this thrusting must have occurred along the lithologic contact between these two units. Vallier (1977) observed that the Seven Devils Group-Martin Bridge Formation contact in Hells Canyon was unconformable, though he did not seem to consider the unconformity to be significant.

The fault was reactivated, probably as a right lateral strike-slip (tear) fault, subsequent to ductile shearing and thrusting along the carbonate-volcanic unconformity. The tear fault developed in response to structural complications related to the Rapid River thrust. It cuts the carbonate-volcanic thrust at three locations, and appears to be truncated by the lowermost imbrication of the Rapid River thrust. It is also cut by a tonalite pluton of probable Late Jurassic or Early Createceous age.

The fault plane itself was not observed in the field. Where outcrop is reasonably abundant, abrupt lithologic changes across the fault locate it to within a few meters. The fault strikes eastward along most of its length, and is defined in its eastern portion by a pronounced, linear ravine (Thorn Gulch). Also, the tear fault disrupts the carbonate-volcanic contact along Thorn Gulch. The trend of this contact abruptly changes from north to east and back to north again. The east trending segment of the contact is the tear fault. The north trending segments are the thrust contacts. Also in Thorn Gulch, north-striking volcanic silstone interbeds within the carbonate are clearly truncated by the tear fault (Figure 16).

The easternmost trace of the tear fault is difficult to locate because it has carbonate on both sides of it, but it may be marked by a pronounced notch in limestone cliffs on the east side of the Rapid River. Lack of disruption of Rapid River thrust imbrications farther east indicates that the tear fault was truncated by thrusting along the structurally lowest imbrication.

In the center of the field area, the tear fault truncates the northern end of the large limestone klippe. To the west, the fault strikes east, then abruptly changes to northeast, and then back again to east. Vallier (1977) observed similar geometries along strike-slip faults in Hells Canyon.

Figure 16. Contact relations near Thorn Gulch. Wild Sheep Creek Formation in foreground, Martin Bridge Formation in background, Hunsaker Creek Formation in upper left. The tear fault runs from upper left to lower right, and cuts the low angle thrust fault and a volcanic siltstone interbed in the marble (between the dashed lines). View is to the northwest from Whitebird Ridge.

RAPID RIVER THRUST

The Rapid River thrust is a significant structural discontinuity that strikes generally northward for more than 55 kilometers in west-central Idaho. This fault has been considered in some detail by Hamilton (1963a, 1963b, 1969) and Onasch (1977). Hamilton (1963a) originally recognized that the Riggins Group was displaced by thrusting from east to west over the Seven Devils Group and overlying sediments. In the eastern part of the Heavens Gate quadrangle, the Rapid River thrust is exposed in the south as a single thrust fault that placed Lightning Creek Schist and Squaw Creek Schist over Martin Bridge Formation. To the north, the fault divides into at least three imbricate fault surfaces, and juxtaposes Seven Devils Group, Martin Bridge Formation, Lucille Formation, and Lightning Creek Schist. Thrust planes dip to the east and northeast. They are never well exposed in the study area, but Onasch (1977) reports dips of 10 to 35 degrees elsewhere along the fault.

Estimates of total displacement along the Rapid River thrust have been offered by Hamilton (1963b) and Onasch (1977). Hamilton (1963b) suggested a minimum composite displacement of 24 kilometers (15 miles) along two major imbrications of the thrust. This figure was based on alleged offset of metamorphic isograds to the south of Heavens Gate quadrangle. Onasch (1977) argued that this estimate was excessive, since metamorphic gradients are regionally steep, and because he only recognized one major slip surface (apart from local imbrications) along the length of the fault. He suggests a minimum of five to eight kilometers of total shortening along the fault.

Scrutiny of thrust faults and thrust belts, particularly in North America, has led to the formulation of a number of "rules" governing thrust fault morphology and evolution. Although these rules were developed in and for foreland fold and thrust belts, they may be generally applicable to the development of the Rapid River thrust.

Thrust faults usually develop with a stair-step geometry. In regions of generally flat-lying strata, thrusts propagate parallel to bedding in incompetent rocks, and oblique to bedding in competent rocks (Rich, 1934; Dahlstrom, 1970; Royse and others, 1975). Overall, thrusts have a concave upward shape, and in undeformed strata they cut up section in the direction of slip (Royse and others, 1975; Elliot and Johnson, 1980), although this need not apply to thrusting of folded rocks (Allmendinger, 1981). Structural complexities associated with a given thrust fault occur near steps, or ramps, where the fault cuts across strata (Wiltschko, 1979). These complexities include imbrication of footwall and hanging wall rocks, and folding of hanging wall rocks (Dahlstrom, 1970; Serra, 1977, Elliot and Johnson, 1980; Allmendinger, 1981). Within an imbricate thrust zone, the age of imbrications may decrease (Dahlstrom, 1970; Elliot and Johnson, 1980) or increase (Serra, 1977; Allmendinger,

1981) in the direction of structural transport. Dahlstrom (1970) shows that footwall imbrications decrease in age, and hanging wall imbrications increase in age, in the direction of thrust motion. These observations relate to relatively local imbrications along a single thrust fault. In terms of an entire thrust system, however, the age of thrust faults decreases in the overall direction of thrust transport (Royse and others, 1975).

There are several notable features displayed by the Rapid River thrust within the study area that are applicable to thrust fault rules described above. Conversely, in the context of the rules, most important structural features in the study area can be linked to the progressive development of an imbricate thrust sequence. (For the moment, this discussion excludes the development of older ductile shear fabrics and associated marble-over-volcanic thrusting.)

Briefly, relevant structural features are the following:

1. Within the imbricate stack there is both younger-over-older and older-over-younger juxtapostion of thrust imbrications.
2. Probable strike-slip motion occurred along a tear fault oriented perpendicular to the strike of the thrust faults.
3. The character of the thrust changes along strike from a single slip plane in the south to an imbricate thrust stack in the north.

4. The position of the tear fault approximately corresponds to the transition from single thrust sheet to imbricate stack.
5. Fold axes in the interior of the study area are parallel to nearby thrust faults.

The development of the imbrications in the eastern part of the study area is best explained by progressive hanging wall imbrication of previously folded rocks. The presence of younger-over-older as well as older-over-younger imbricate slices, in combination with commonly observed (but not ubiquitous) subparallel to parallel orientation of foliation on either side of imbricate faults, places stringent constraints on possible fault geometries. These relations can develop during hanging wall imbrication of folded rocks, where imbrications locally propagate approximately parallel to fold limbs. In order to juxtapose younger rocks over older ones along a non-horizontal thrust plane, the rocks must be folded previous to faulting, so that faults can cut down section while propagating upward. This affords a straightforward mechanism for placing slices of Martin Bridge Formation and Lucille Formation over a thrust sheet of Seven Devils volcanics, as seen in the northeast corner of the field area, just east of Shingle Creek (Plate I). Similar geometries have been demonstrated in the fold and thrust belt in Idaho (Allmendinger, 1981).

The relative ages of thrust faults within the imbricate stack cannot be determined unequivocally. The map pattern suggests that the uppermost plate in the stack cuts and post-dates the lower imbrications. Mapping of fault contacts in this area is interpretive, however, because outcrop is sparse.

In the study area, macroscopic folds can be recognized by the map pattern of the carbonate-volcanic thrust trace. Because this thrust places younger rocks over older across a substantial distance, the fault must have propagated along a nearly horizontal surface. The present fault trace must reflect subsequent folding.

Fold axes appear to be parallel to thrust fault trends. Folding probably occurred synchronously with thrusting, as a direct response to compression, or as a response to the space problem created by ramping along a structurally lower thrust fault. Folding of hanging wall rocks above a thrust fault ramp is a geometric requirement (Rich, 1934; Bally and others, 1966; Royse and others, 1975); without folding, a void would be created between the fault and the ramp.

The geometry and style of the folds in the study area cannot be specified with certainty. Macroscopic folds are never visible within the field area, although just north of the Heavens Gate quadrangle, a single macroscopic kink fold, plunging gently to the northeast, is well displayed in carbonates. The map pattern suggests that folds are generally open and upright in the south, and tight and locally overturned in the north. Also, the wavelength of folds appears to be much shorter in the north than in the south (Plates I and II).

Mesoscopic folds with wavelengths on the order of one to two meters were observed in the Martin Bridge Formation and the Lucille Formation at a number of locations near Thorn Gulch and Shingle Creek. These folds were usually tight to isoclinal, plunging gently to the northwest, with upright or inclined axial planes. In the Lucille Formation, a crenulation cleavage was observed on folded foliation surfaces.

Orientation of shear foliations (and bedding) within the field area is variable. Pi diagrams indicate that the highest concentration of foliations is oriented at about N5E, 40E, and most foliations strike between NNE and NNW, but overall patterns are not diagnostic of any particular geometries. Attitudes of foliations are locally quite variable, particularly in the Martin Bridge Formation and Hunsaker Creek Formation, which were presumably more intensely folded than the competent Wild Sheep Creek Formation. Toward the western edge of the map, foliation in the Hunsaker Creek Formation dips almost uniformly to the east, indicating that folding probably dies out in the west. There is no evidence of extensive, macroscopic isoclinal folding in the field area.

The Rapid River thrust has implicitly been considered by past workers as the westernmost exposure of the thrust system that juxtaposed the Riggins Group and the Seven Devils Group. Mapping within the Heavens Gate quadrangle suggests that imbrications of the Rapid River thrust may in fact be splays (back-limb thrusts) off a thrust fault that emerges somewhere west of the field area and has not yet been mapped.

The presence of a tear fault oriented approximately perpendicular to the Rapid River thrust offers compelling evidence for westward continuation of thrust motion. The development of strike-slip faults at high angle to thrust faults is a predictable, though certainly not inevitable, consequence of thrust fault evolution (Dahlstrom, 1970). Tear faults may develop within a single thrust sheet. They indicate that shortening in the thrust sheet was accomodated by different mechanisms on either side of the tear, though overall shortening should, ideally, be the same (Dahlstrom, 1970). In other words, a tear fault may mark a transition between hanging wall rocks of differing mechanical properties. Under compression, these rocks may behave differently, so that local decoupling occurs. It is important to emphasize that this tear develops within a thrust sheet and thus dictates that a thrust fault must emerge somewhere in front of the tear. In fact, Gaultieri and Simmons (1978) do show a north-striking, west-verging thrust fault just beyond the northwest corner of the study area. This may be the predicted thrust.

The origin of the tear fault can be most simply explained by variations in ramp structures along the thrust fault beneath the field area. These variations can be inferred by the nature of folding on either side of the tear, and by the change in lithologies across the the tear. In the Hunsaker Creek

Formation, the presence of competent flow and crystal tuff units alternating with less competent volcaniclastics is an ideal medium for the development of pronounced stair-step morphology in an evolving thrust. Tight, short wavelength folding north of the tear may reflect this morphology.

A thrust propagating through the Wild Sheep Creek Formation would develop a different geometry. The fault would tend to follow the relatively few, thin, incompetent shale and volcanic siltstone beds within the unit (Onasch, 1977). Spacing between ramps would be great if the energy requirements for cutting up through thick, massive flow and breccia units were greater than energy requirments for following incompetent shale layers (Hobbs and others, 1976). At least on the scale of the study area, it is likely that this fault would not climb up section as quickly as a fault with pronounced ramping. The presence of open, long wavelength folds south of the tear may reflect these relations.

This model dictates that, within the field area, there is greater shortening in the hanging wall to the north of the tear than to the south, though shortening may be the same over the entire length of the thrust sheet. This is consistent with right-lateral slip along the tear. This model is shown schematically in Figure 17.

A further interesting geometric relation is that the tear fault intersects the Rapid River thrust very close to the point where the thrust changes from a single plane to an imbricate stack. This may indicate that the development of imbrications is

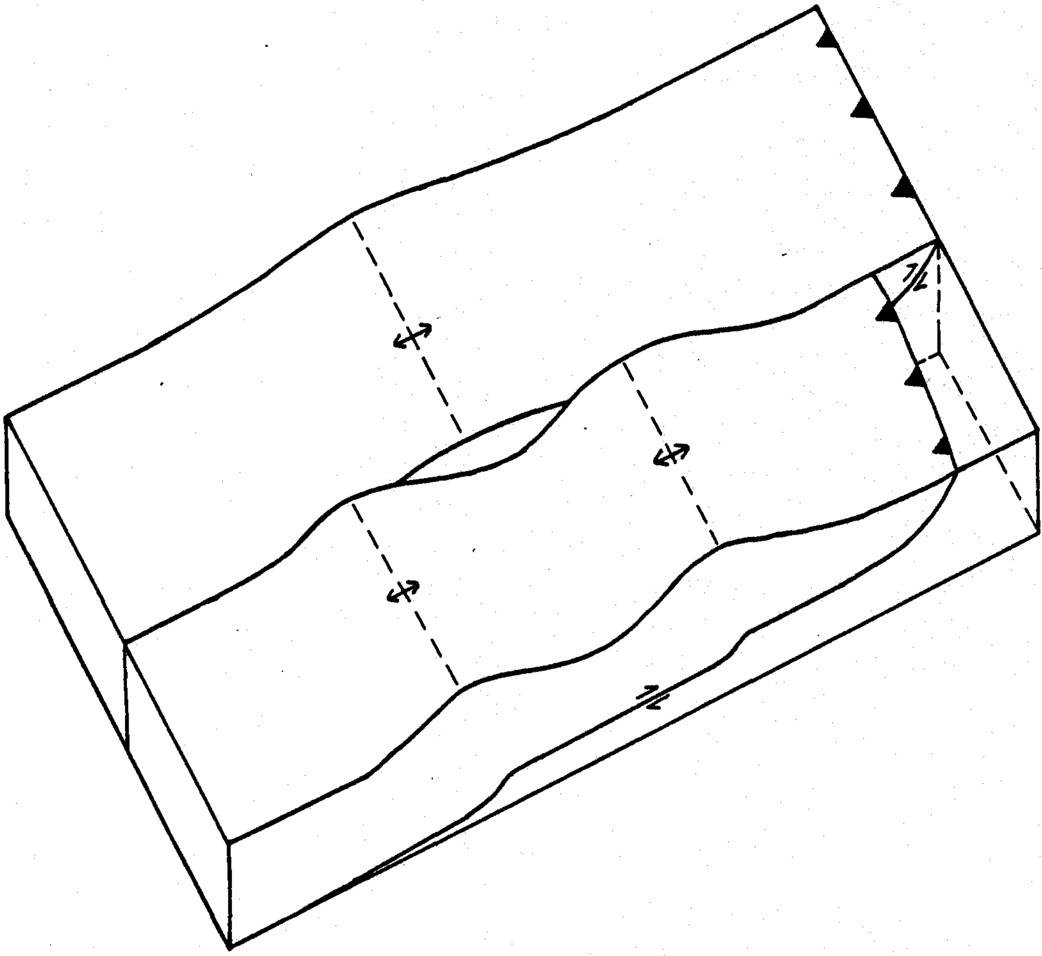

Figure 17. Schematic representation of tear fault development. The tear develops in response to changes in thrust geometry. Where ramping is extensive, shortening in the thrust sheet is greater than where ramping is uncommon. The change in the amount of shortening is accomodated along the tear fault.

related to ramp geometry, or, more fundamentally, to the mechanical properties of the rocks through which the fault is propagating. The more incompetent, anisotropic rocks of the Hunsaker Creek Formation seem to provide a more hospitable environment for imbrication than the massive, competent rocks of the Wild Sheep Creek Formation.

Another possible explanation for the change in the character of the Rapid River thrust is that the youngest fault in the imbricate stack was oriented obliquely to earlier imbrications, and so truncated them in the south. Although there is no explicit evidence in favor of either model, the spatial correlation of change in fault character and change in the nature of footwall rocks indirectly supports the first explanation.

The major structural elements of the northern part of the Heavens Gate quadrangle developed in the following order:

1. Subhorizontal, layer parallel ductile shearing of Martin Bridge Formation and Seven Devils Group.

2. Subhorizontal, west-verging thrust displacement of younger Martin Bridge Formation over older Seven Devils Group.

3a. Folding of limestones and volcanics.

3b. Strike-slip faulting oriented at high angle to, and truncating, the carbonate-volcanic thrust.

4. Single plane and imbricate faulting along the Rapid River thrust.

The relative timing of events 1 and 2 are constrained by inferred relations between ductile and brittle shear processes, discussed above. The timing of events 2, 3 and 4 are constrained by the cutting relations of the tear fault.

Ductile shearing and younger-over-older thrusting are related spatially and probably kinematically as well. Where ductile shear fabrics and bedding are seen together, they are always parallel. Initial orientation of shear foliations was therefore horizontal or subhorizontal. Shear foliations just below the carbonate-volcanic thrust are subparallel to the thrust, and intensity of ductile shearing in volcanic rocks increases near the thrust. Apparently, ductile shear gave way to brittle shear during uplift and unroofing. Such relations are explicitly or implicitly described or predicted by Elliot (1976), Grocott (1977), Watts and Williams (1979) and Coward (1980a).

Temporal and kinematic relations between these early structures and later structures associated with the Rapid River thrust cannot be delineated based on available data. Field relations can be explained most consistently, though, if the carbonate-volcanic thrust and the Rapid River thrust are viewed as part of the same evolving fault system. Thrusting initially occurred along the limestone-volcanic unconformity. This fault became inactive, and a deeper level thrust fault developed. This is in accord with models of thrust evolution profferred by Dahlstrom (1970), Bally and others (1966), Royse and others

(1975), and Coward (1980a). Folding of volcanics and marbles may reflect ramping of the newly evolving thrust. Tear faulting occurred above the thrust fault because of mechanical differences between rocks in the northern part of the study area and rocks to the south. Structural complications, possibly initiating at or near a ramp or ramps (Wiltschko, 1979), led to local development of imbricate, back-limb thrusting that cut up through folded hanging wall strata, truncating the tear fault. The concept of imbrications cutting up from a ramp without rejoining the basal thrust is supported by the work of Bally and others (1966), Coward (1980a), and Allmendinger (1981).

A simplified series of schematic cross sections illustrates how imbrications of the Rapid River thrust developed within the study area (Figure 18). In these cross sections, Lightning Creek Schist is considered to be equivalent to the Seven Devils Group, based on lithologic similarities discussed above. Imbrications are shown to increase in age in the direction of thrust motion, but the opposite sequence of imbrication could yield the same final geometries. The sequence shown is consistent with observations of other workers (Bally and others, 1966; Dahlstrom, 1970; Allmendinger, 1981). Fold geometries were drawn to conform with inferred geometries west of the imbricate stack (Plate II). The cause and effect relations between thrusting and fold geometries are not known. Overturning of folds may have developed in response to additional, subsequent thrusting.

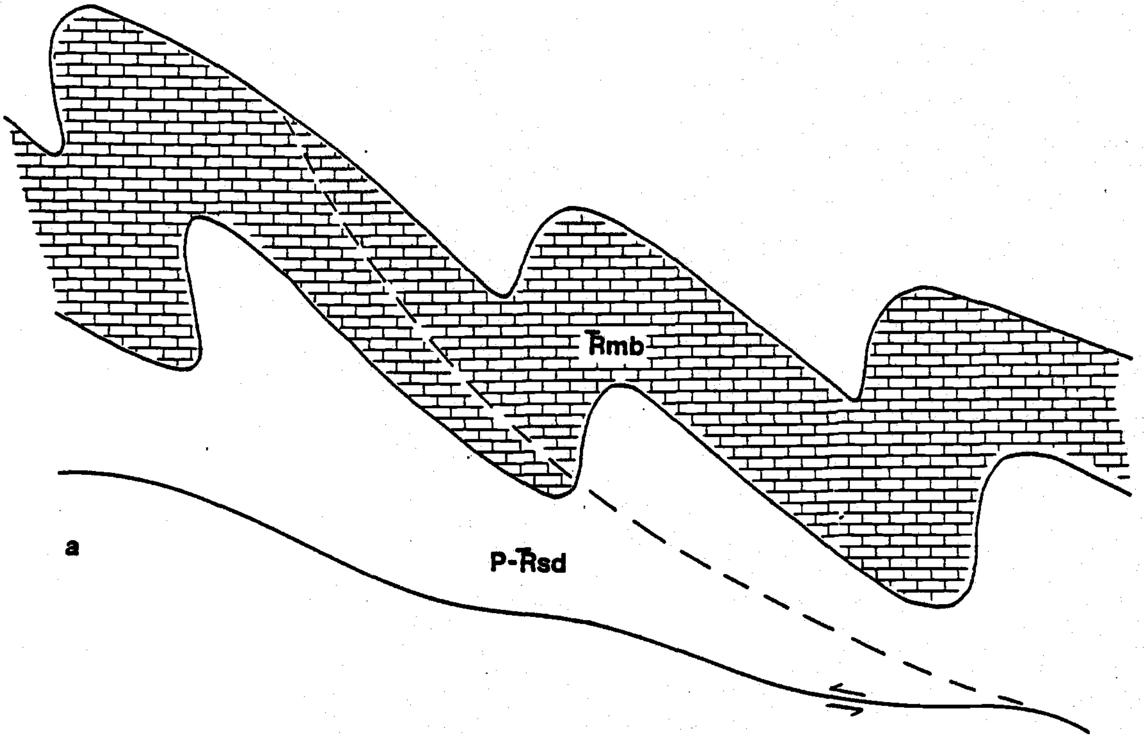

Figure 18. Schematic cross sections showing development of Rapid River thrust zone and related structures at the northern boundary of the study area. Ꞧ mb is Martin Bridge Formation and P-Ꞧ sd encompasses the Seven Devils Group and Lightning Creek Schist. Contact between Ꞧ mb and P-Ꞧ sd is a low angle thrust fault that is no longer active. 18a shows development of inferred basal thrust and folding of overlying rocks. 18b-d show progressive back-limb imbrication above the basal thrust. Present topographic surface shown in 18d without vertical exaggeration. Thickness of Ꞧ mb is 500m.

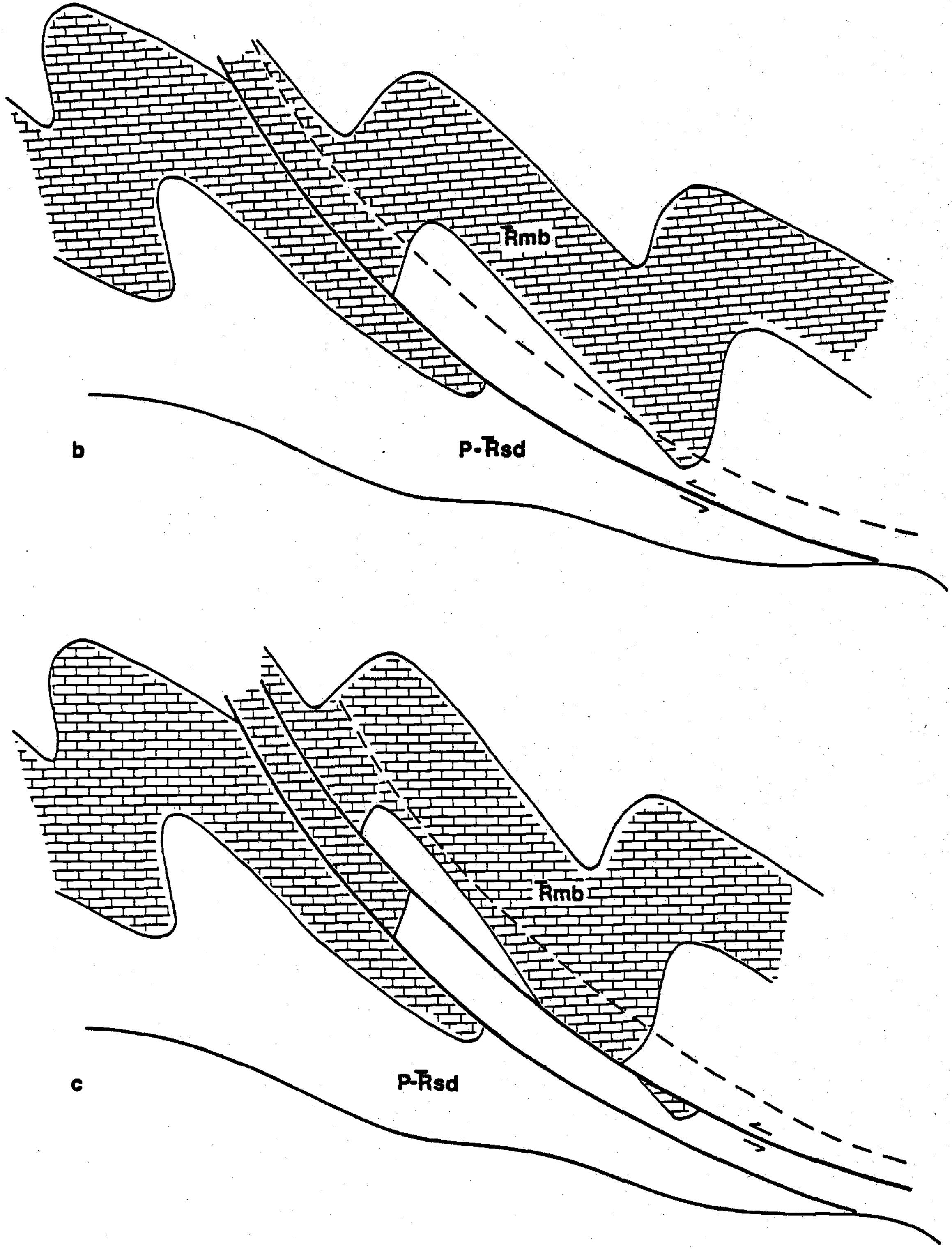

Figure 18., continued.

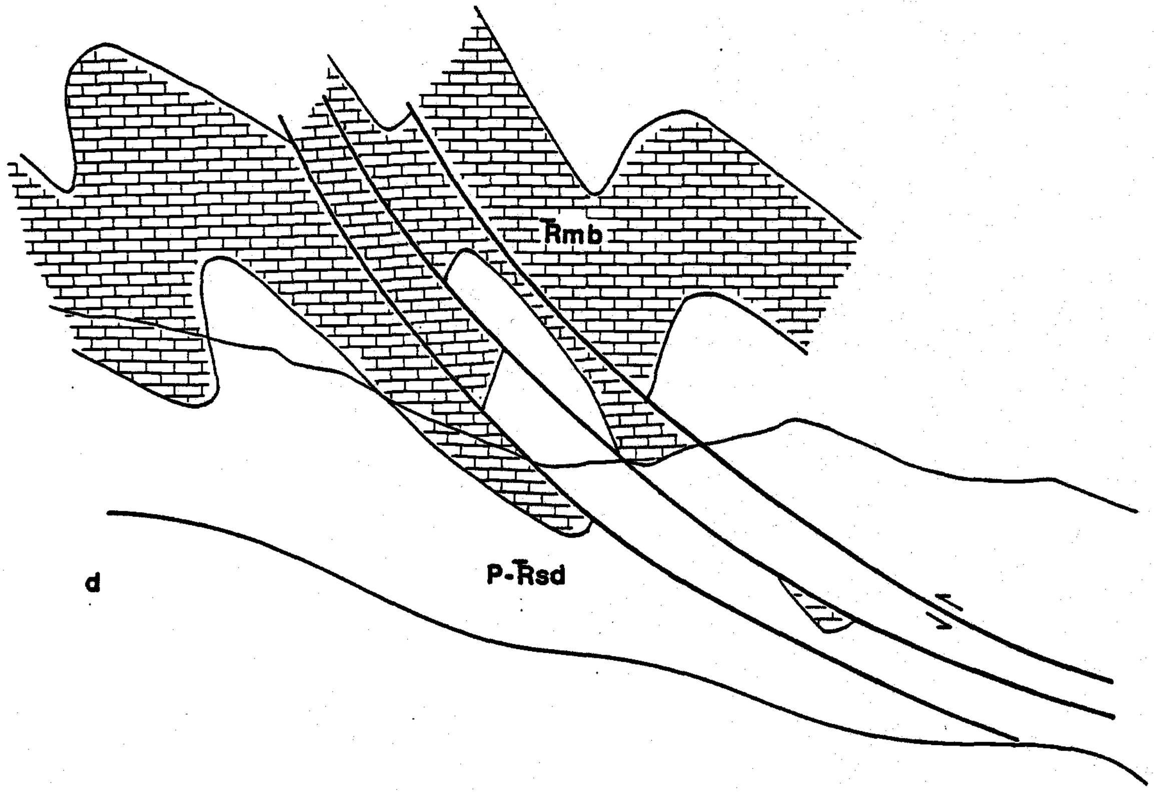

Figure 18., continued.

Evidence for certain aspects of this model is circumstantial. In particular, the presence of the younger, structurally lower thrust, and the existence of ramps along this fault, are inferred and required by the model, but never seen in the field area. Also, because the internal stratigraphy of the Hunsaker Creek Formation is not well constrained, it is not possible to predict the size and geometry of ramps. However, as stated above, generation of strike-slip motion along the tear fault requires thrusting in front of the tear. It is important to recognize that, in spite of somewhat incomplete field evidence, all the significant structural elements within the field area can be encompassed by a single model of thrust fault evolution, and further, that this model is entirely consistent with, and anticipated by, present understanding of the dynamics and geometry of thrust faulting. Bally and others (1966) define four phases in the evolution of thrust systems based on field and seismic data from the Southern Canadian Rocky Mountains:

1. Stair-step, straight, or transitional thrust faulting.
2. Overthrusting, imbrication and emergence at the leading edge of the thrust.
3. Folding of phase 1 and 2 structures by a new thrust fault propagating below the earlier formed thrust(s).
4. "Back-limb" imbricate thrusting at ramps.

This sequence conforms remarkably well with the proposed structural evolution of the Heavens Gate area. The model dictates that the Rapid River thrust is part of a larger thrust system, and that at least one younger, structurally lower thrust fault should emerge to the west of the field area. Although confirmation of this model necessarily awaits further field work west of the study area, the model itself is neither new nor untested. The basic assumption is that the Rapid River thrust developed in a manner similar to that of other, better exposed and more completely understood thrust systems.

TIMING OF DEFORMATION

The significant structural features in the Seven Devils Group and associated sedimentary units of the Heavens Gate quadrangle are layer-parallel shear foliations and a co-planar, younger-over-older thrust fault. These features are cut by unsheared tonalite plutons of probable Late Jurassic to Early Cretaceous age. Thus, shearing of the Seven Devils Group and overlying sediments is probably no younger than Early Cretaceous.

The Rapid River thrust, which juxtaposes the Riggins Group and the Seven Devils Group, is not cut by mappable plutonic bodies (Hamilton, 1969). Therefore, the temporal relations between the shearing of the Seven Devils Group and the development of the Rapid River thrust cannot be rigorously demonstrated. However, macroscopic structural trends in the Riggins Group, above the Rapid River thrust, are broadly parallel to trends in the Seven Devils Group and Martin Bridge Formation, below the thrust, and the strike of the Rapid River thrust is parallel to the strike of the structurally lower younger-over-older thrust that displaced carbonates over volcanics. Some shear foliations are concordant with and across the Rapid River thrust. The model already presented in this thesis regards the major shearing and thrusting of the Seven Devils Group and the Riggins Group as part of the same deformational event.

The nature and origin of the dominant foliation in the Riggins Group was not considered in detail during this study, but it has been discussed more fully by Hamilton (1963a) and Onasch (1977). Hamilton (1963a, p. 83) considered foliations in the Riggins group to be shear induced. Onasch (1977, p. 116) seems to view the foliations as axial planar features that formed during folding. Both workers recognized that foliations are generally parallel to original bedding throughout the Riggins Group. Onasch (1977) regarded this as the oldest foliation in the Riggins group. He also noted folds and foliations from four later deformations, but these are all considered minor, and they do not disrupt regional trends expressed by the pattern of the oldest, bedding-parallel foliation.

Although Hamilton (1963a, p. 83) argued to the contrary, foliations in the Seven Devils Group are almost invariably parallel to bedding. This was observed repeatedly in outcrop and in thin section. Onasch (1977) did not discuss shearing of the Seven Devils Group. He did recognize three mesoscopic folding events in the Martin Bridge Formation and the Lucille Formation. He argued that rocks beneath the Rapid River thrust shared only the latest, minor folding event, with the Riggins Group, and that the structural histories of the rocks above and below the thrust, previous to this folding, were different. This argument is based on mesoscopic structural analysis, that is, analysis of temporal relations between multiple folding events visible at outcrop scale, but not necessarily resolvable at map scale.

Thus, according to Onasch (1977), a total of six separate deformations occurred overall in this area, and only the last of these was shared by the Riggins Group and the Seven Devils Group. Even if one acknowledges the validity of this analysis, the question of the significance of these deformations still remains, because they do not greatly influence regional geologic structure (Hamilton, 1963b, p. 779). Philosophically and geologically, it seems more compelling to compare macroscopic structural character and variations across the fault, because such regionally recognizable features are more likely to reflect regionally significant processes.

Macroscopic structure is reflected by the beds and bedding-parallel foliation in the Seven Devils Group and Riggins Group, and by the attitude of thrust faults. Scrutiny of macroscopic structural trends in the field area (see Plate I, also, Onasch, 1977), does not indicate structural discordance across the Rapid River thrust zone. Overall, the argument for distinguishing the structural history of the eastern Seven Devils Group from that of the western Riggins Group seems unfounded. The most convincing evidence that these units were deformed together is the occurrence of bedding-parallel (and thus originally subhorizontal) shear foliation in both units, and the general NNE to NNW strike of these foliations on either side of the Rapid River thrust zone. These trends are locally disrupted, but this may be attributable to the numerous, subsequent, minor deformations documented by Onasch (1977). Further support of this interpretation is provided by Onasch (1977, p. 163) who implicitly argued that, in the Rapid River area, the thermal metamorphic peak occurred simultaneously above and below the Rapid River thrust, and further, that recrystallization associated with this event defines the oldest foliation surfaces both above and below the thrust. This in fact contradicts his assertion that pre-thrusting deformations of rocks above and below the thrust are not correlative.

The age of deformation is not well constrained. Previously, Hamilton (1963a, 1963b) and Onasch (1977) attributed deformation of the Riggins Group and initiation of the Rapid River thrust to processes related to the intrusion of the Idaho batholith. The age of all deformation from the eastern edge of the Seven Devils Group to the western edge of the batholith has been considered Late Cretaceous. The evidence for this chronology is as follows:

1. Assumed genetic correlation between regional penetrative deformation and thrusting, and intrusion of the batholith.
2. Truncation of metamorphic isograds by the Rapid River thrust in the southern portion of the Heavens Gate quadrangle.
3. Reputed metamorphism and shearing of tonalites (called quartz diorites by previous workers) of Late Jurassic to Early Cretaceous age.

The genetic correlation between intrusion and deformation is highly controversial, and does not in itself constitute evidence (for example, see Hamilton and Meyers, 1967, and Schweikert, 1981, for contrasting views).

The geometric relations between thrusting and metamorphic isograds are complex. Hamilton (1960, 1963a) argued that the Rapid River thrust cut metamorphic isograds in the southern portion of the Heavens Gate quadrangle, within and to the south of this study area. Onasch (1977) mapped isograds that crossed the thrust to the north, near Lucille. He suggested that the thermal peak of metamorphism moved progressively northward with time, and thus predated the fault in the south, but occurred after faulting in the north. Within the study area, there is no change in metamorphic grade across the Rapid River thrust.

Hamilton (1960, 1963a, 1969) shows the biotite isograd truncated by the Rapid River thrust in the southern part of the field area, but in fact the isograd, though difficult to define precisely, crosses the thrust fault on Whitebird Ridge in the vicinity of 45° 20' N. Brown and green metamorphic biotite are both locally abundant in the Wild Sheep Creek Formation in Rapid River canyon. Also, metamorphic garnet (probably hydrogrossular) and metamorphic oligoclase (An_{28}) were each found in one thin section from Rapid River canyon.

Another notable observation is that there is no increase in metamorphic grade within the imbricate stack in the Shingle Creek area. If the region had been metamorphosed prior to west-directed fault displacement, then thrust slices should show higher metamorphic grade than footwall rocks, particularly because the thermal gradient to the east is very steep (Hamilton, 1963a).

Tonalites intruding the eastern margin of the Seven Devils Group are reputedly "thoroughly recrystallized" (Hamilton, 1963b, p. 781) and "variably sheared" (Onasch, 1977, p. 22). In fact, mapping in the Heavens Gate quadrangle indicates that these tonalites are incompletely metamorphosed, containing abundant relict phases. At one outcrop there is no evidence of metamorphism whatsoever. Further, although there is local protoclastic foliation of tonalites near contacts, there is no convincing evidence of penetrative deformation of these rocks within the field area. On the contrary, as discussed above, tonalites cut across thrust contacts and cause recrystallization of sheared marbles in Rapid River canyon. Thus, intrusion of tonalites apparently postdates ductile shearing, thrust faulting, and perhaps the thermal peak of metamorphism of the Seven Devils Group in the study area. If these intrusives are of Late Jurassic or Early Cretaceous age, as seems probable (Armstrong and others, 1977), then shearing and thrusting in the Seven Devils Group are no younger than Early Cretaceous. Further, if ductile shearing and younger-over-older thrusting are related to the Rapid River thrust, then that structure may be older than Early Cretaceous as well. This is at great variance with the interpretations of Hamilton (1963a) and Onasch (1977).

Hamilton (1963a) showed that the eastern margin of the Seven Devils Group was metamorphosed twice. The first metamorphism affected the Seven Devils Group throughout eastern Oregon and western Idaho, and occurred before intrusion of tonalites. The second event affected tonalites near the eastern margin of the Seven Devils Group, but correlative tonalites to the west remained unmetamorphosed. Both Hamilton (1963a) and Onasch (1977) felt that the Rapid River thrust and the second metamorphic event were related to the emplacement of the Idaho batholith. These arguments have led to the general interpretation that the Rapid River thrust is of probable Late

Cretaceous age (Brooks and Vallier, 1978). However, as discussed above, arguments for Late Cretaceous development of the Rapid River thrust are not well constrained.

The results of this study do not directly constrain the age of the Rapid River thrust. Because the tonalites do not occur along the Rapid River thrust *sensu stricto*, relative timing of thrusting and intrusion cannot be determined directly. It is theoretically possible that the Rapid River thrust is Late Cretaceous, even if structurally lower thrust and shear structures, as well as tonalites, are Late Jurassic or Early Cretaceous. However, as discussed previously, geometric relations strongly suggest that all faults in the field area are genetically related to one another.

Another possibility that cannot be discounted is that some tonalites are satellites of the Idaho batholith. If so, they may be as young as Late Cretaceous, which would allow temporal and perhaps genetic correlation between evolution of the Rapid River thrust system and intrusion of the batholith. However, petrographic features of the tonalites are dissimilar to described characteristics of typical satellites, (Taubeneck, 1971; Armstrong and others, 1977).

CONCLUSIONS

REGIONAL GEOLOGIC RELATIONS

The pre-Tertiary rocks of the Blue Mountains tectonic province of eastern Oregon and westernmost Idaho are an incompletely understood, complex assemblage of terranes formed at one or more destructive plate margins. The area has been broadly subdivided into a minimum of three tectonostratigraphic terranes. These are the Seven Devils volcanic arc terrane, the dismembered oceanic crust (or subduction complex) terrane, and the Mesozoic clastic terrane. Possible additional terranes include the Huntington volcanic arc and the Riggins Group. The relative geographic position of these terranes is shown on Figure 19.

A detailed regional geologic synthesis is beyond the scope of this study. A few geologic and philosophic comments are in order, however, based on the results of this study, and some familiarity with the regional geology.

There have been many tectonic models proposed for the Blue Mountains, and the abundance and diversity of these models points to the lack of known constraints on the tectonic evolution of the region. There does seem to be a concensus regarding a number of points, however. Most importantly, the individual

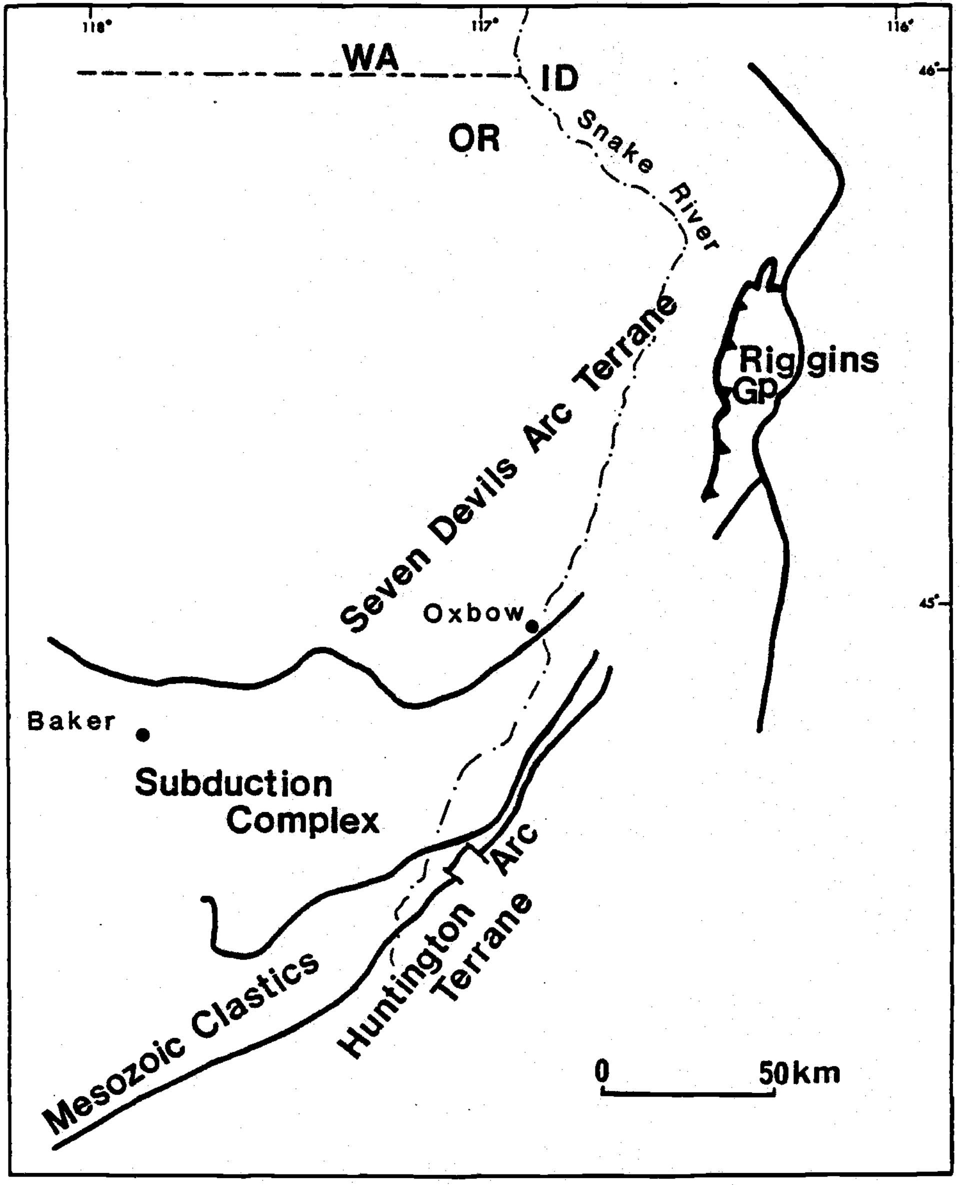

Figure 19. Generalized map showing distribution of pre-Tertiary terranes of northeast Oregon and west-central Idaho.

character of the various terranes does not seem to be a contentious issue. The island arc character of the Seven Devils Group is well accepted (Hamilton, 1963a, 1976; Vallier, 1977; Hillhouse and others, 1982). Volcanic rocks on both sides of the Snake River in the vicinity of Huntington, Oregon, are also understood to have formed in an island arc setting (Brooks and Vallier, 1978). The dismembered oceanic crust terrane is viewed as a subduction complex that includes thick sequences of deformed sediments and volcanic rocks of an accretionary prism (Brooks and Vallier, 1978; Dickinson, 1979; Coward, 1982), as well as large ophiolitic assemblages of controversial affinities (Phelps and Ave Lallement, 1980; Gerlach and others, 1981). The Mesozoic clastic terrane probably represents an evolving forearc basin sequence (Dickinson and Thayer, 1978; Dickinson, 1979).

The ensuing discussion will focus on the relation of the Seven Devils island arc to other terranes in the region. The Seven Devils arc has been variously correlated with rocks of the Huntington arc (Brooks and Vallier, 1978), the Riggins Group (Onasch, 1977; this thesis), and ophiolites of the Canyon Mountain and Sparta areas (Gerlach and others, 1981; Phelps and Ave Lallement, 1980).

Perhaps the most significant problem here is the correlation of the Huntington and Seven Devils arcs. It seems widely accepted that the Huntington arc, Mesozoic clastic terrane, and subduction complex terrane are spatially and temporally consistent with a single, eastward-subducting, arc-forearc sequence (Dickinson, 1979; Ave Lallement and others, 1980; Heitanen, 1981). But the relation between this sequence and the Seven Devils arc is unclear.

A number of pieces of data, some of which are conflicting, bear directly on this problem. For example, the age of Huntington Formation volcanic rocks is late Karnian to early or middle (?) Norian (Brooks and others, 1976), which is correlative with the Doyle Creek Formation of the Seven Devils Group (Vallier, 1977; Brooks and Vallier, 1978), although the Huntington arc may also include volcanic rocks younger than the Doyle Creek Formation. Also, the Huntington Formation is not overlain by Norian carbonates. Volcanic activity may have continued there while the Martin Bridge Formation was deposited over the Seven Devils arc. This fact has been used to distinguish the Huntington and Seven Devils arcs (Dickinson, 1979). However, Brooks and Vallier (1978) note that limestone blocks of unknown affinity occur near the base of the Jurassic clastic sequence that unconformably overlies the Huntington Formation. Also, volcanic siltstone interbeds near the base of the Martin Bridge Formation in Hells Canyon (Vallier, 1977) and higher in the section in the Heavens Gate area, may indicate that some volcanism was occurring simultaneously with the deposition of carbonates. Finally, recent paleomagnetic data from the Seven Devils and Huntington arc terranes indicate that both of these sequences shared common paleolatitudes in the Late Triassic (Hillhouse and others, 1982).

The geometric relations between the Seven Devils arc and the Huntington arc - Mesozoic clastic - subduction complex sequence to the south and southwest are confusing. The Seven Devils arc is apparently adjacent to the subduction complex in eastern Oregon, although the nature of this transition is not known. There is no evidence of an intervening forearc basin, like the one seen to the south. Thus, the present configuration of the Seven Devils arc and adjacent terranes cannot be interpreted as an intact forearc sequence such as those described for modern destructive plate margins by Karig (1974) and Dickinson and Seely (1979).

A model that seems to be widely accepted in its general aspects considers the Seven Devils arc to be part of an exotic island arc terrane that was accreted to the possibly autochthonous Huntington arc - Mesozoic clastic - subduction complex sequence in the Late Jurassic (Dickinson, 1979; Ave Lallement and others, 1980; Heitanen, 1981; Oldow and others, 1982). The proposed collision event is dated by Late Jurassic to Early Cretaceous plutons that intrude all the terranes and do not show paleomagnetic evidence of displacement relative to the North American craton (Wilson and Cox, 1980). An intense, regionally important, Late Jurassic compressional event (Brooks and Vallier, 1978) has been correlated with this arc - arc collison (Heitanen, 1981; Oldow and others, 1982; Coward, 1982).

This model is also appealing because it suggests a correlation with a proposed Late Jurassic arc - arc collision in the western Sierra Nevada (Schweikert and Cowan, 1975; Hietanen, 1981). However, the occurrence and nature of such a collisional event is still controversial (Saleeby, 1981).

There are a number of inconsistencies in any model that considers the Seven Devils arc to be separate from the Huntington arc - forearc sequence. As stated, paleomagnetic data indicate that these two arc sequences were formed at the same paleolatitudes (Hillhouse and others, 1982). Second, known outcrop of the Huntington arc sequence is of limited extent, both aerially and temporally. Thus, the geometry and character of the arc are not well understood, although Brooks and Vallier (1978) considered its character to be similar to the Seven Devils arc. Another objection to considering these terranes as unrelated is the absence of a second forearc basin - subduction complex sequence. If the Seven Devils arc is exotic, then it was somehow isolated from its associated basin and prism sequences. Alternatively, these sequences may be represented in part by the Riggins Group, as Onasch (1977) suggested, or they may be concealed by flood basalts to the north, or destroyed by intrusive magmatism to the east.

Blueschists near Mitchell, Oregon, provide additional constraints on the evolution of this region. The age of these blueschists is 220 m.y. (Hotz and others, 1977). This is consistent with ages of the Sparta ophiolite (Ave Lallement and others, 1980), and the lower Wild Sheep Creek Formation (Vallier, 1977), but it is probably older than the Upper Triassic

Huntington arc. Dickinson and Thayer (1978) argue that the Mitchell blueschists are part of the subduction complex better exposed to the east. If these blueschists were generated at depth in a subduction zone (for example, see Miyashiro, 1973), then the only suitable candidate for coeval arc magmatism is the Seven Devils arc. Coward (1982) reported Late Triassic to Early Jurassic radiolarian cherts in the accretionary prism (Elkhorn Ridge Argillite). Thus, subduction occurred at least from Middle to latest Triassic and possibly into the Jurassic. This brackets the lower age of the Triassic rocks of the Seven Devils arc and the upper age of the Huntington arc, and suggests that they may have formed in response to the same subduction event.

There has been considerable disruption of the Blue Mountains terranes since their creation. Original geometries and juxtapositions may be partially or completely obscured. Saleeby (1981) has pointed out that the Mesozoic tectonics of the Sierra Nevada region of California was dominated by oblique subduction. Ocean floor moved northward and under the California continental margin. Resulting "transpressive" tectonics are characterized not only by subduction related processes, such as collision and accretion, that add material to the continental margin, but by transform faulting that may translate material parallel to the subduction zone and disrupt pre-existing geometries. Saleeby (1981) suggests that such tectonic regimes cannot be explained by standard, one-dimensional tectonic models. He argues that these models do not adequately explain the complexities of the Sierra Nevada region. Oldow and others (1982) suggest that this transpressive regime may also have operated in the Blue Mountains terranes during the Mesozoic.

The overall geology of the Blue Mountains seems to be less complex than that of the Sierra Nevada, although this may be a result of its being less intensively studied. Still, the converse of Saleeby's (1981) argument may be applied. If the present geometry of terranes in eastern Oregon and western Idaho is a result of two-dimensional, transpressive tectonics, then one-dimensional models invoked to explain these geometries may require overly complex or contrived solutions. For example, one-dimensional models generally regard the Seven Devils and Huntington arcs as separate terranes, because they seem to be on opposite sides of the same subduction complex. Such geometries could be explained instead by dissection of a single arc and lateral translation along transform faults. Although direct evidence of significant strike-slip motion in the Blue Mountains has not been documented, the nature of the Seven Devils arc-subduction complex suture is not understood. Further, about 60° of post-Jurassic clockwise rotation of the Blue Mountains has been well documented by Wilson and Cox (1980) and Hillhouse and others (1982). This rotation may be attributable to strike-slip motion associated with oblique subduction. The magnitude of earlier rotations are not yet known.

At this point, there seem to be as many reasons for correlating the Seven Devils and Huntington arcs as there are for considering them as separate terranes. The presence of two island arcs, however, requires as well the presence of two subduction complexes and two forearc basins. There is evidence only for one of each. Tectonic reconstructions that invoke arc-arc collisions to explain present geometries are using one-dimensional models to solve two-dimensional problems.

The simplest model that is consistent with most of the known constraints is that of a single oceanic volcanic arc terrane and associated forearc sequence that was formed during eastward subduction relative to its present geographic position. (The likelihood of substantial pre-Late Jurassic rotation may render meaningless any attempts to ascertain absolute direction of convergence.) Volcanism ended in the Late Triassic. The period between Late Triassic and Late Jurassic is virtually without known constraint, but it may include a substantial amount of northward translation (Hillhouse and others, 1982) as part of a transpressive tectonic regime. Middle and Upper Jurassic volcanogenic sediments of the John Day Inlier probably formed in a forearc basin (Dickinson and Thayer, 1978; Dickinson, 1979), but the location of the associated arc and subduction complex is unknown. Disruption and reorganization of the arc-forearc sequence may have occurred during this period.

Late Jurassic deformation of the Blue Mountains terranes (Brooks and Vallier, 1978) may represent collision of this sequence with the North American continent. Shearing and thrust faulting in the Heavens Gate quadrangle may have occurred during this event. Imporant Late Jurassic thrust faulting has been documented in the Klamath Mountains, to the southwest (Burchfiel and Davis, 1981). Compressional tectonics in the arc during the arc-continent collision has been documented in Taiwan, a modern collision zone, by Chi and others (1981). Taiwan represents a reverse polarity collision zone. Saleeby (1981) has noted that there are no modern examples of normal polarity arc-continent collisions, but Late Jurassic tectonism in the Klamath Mountains and the Sierra Nevada has been correlated with this type of event (Irwin, 1981; Schweikert, 1981).

The mechanism for collision and accretion of the Seven Devils arc sequence is unknown. Eastward subduction (normal polarity), westward subduction (reverse polarity), and transform faulting are all possibilities. The oceanic crust - continental crust suture may be present in the Riggins Group (Hamilton, 1976), where "serpentenite matrix, polymict melange" (Hamilton, 1980, written communication) marks the easternmost occurrence of oceanic rocks in the region. Collision was followed by either a subduction polarity reversal, or by a westward jump in subduction. Renewed subduction generated Late Jurassic and Early Cretaceous granitic plutons that are considered to be autochthonous (Wilson and Cox, 1980). These events can be temporally correlated with a Late Jurassic pulse of the Nevadan orogeny, which has been well documented in the Blue Mountains and throughout much of the western Cordillera of North America.

THE WRANGELLIA CONNECTION

The Seven Devils island arc terrane may represent an exotic terrane that was created far from its present position and transported great distances before its accretion to the Mesozoic continental margin of North America. This island arc terrane is part of a vast collage of allochthonous terranes that characterize the western margin of North America west of the great Cretaceous batholiths (Churkin and Eberlein, 1977; Davis and others, 1978; Hamilton, 1978). The Triassic Seven Devils arc sequence has recently been correlated with rocks of the Wrangellia terrane, farther to the north (Jones and others, 1977; Hillhouse and others, 1982). In this section, a brief assessment of the Wrangellia - Seven Devils correlation will be presented.

Rocks of the Wrangellia terrane crop out on Vancouver Island and the Queen Charlotte Islands, British Columbia, and in the Wrangell Mountains, Alaska (Figure 20; Jones and others, 1977). The terrane is distinguished by its characteristic stratigraphy and paleomagnetism.

On Vancouver Island and in the Wrangell Mountains, Wrangellia comprises a thick sequence of tholeiitic basalts and basaltic breccias of late Ladinian to early or middle Karnian age (Muller and others, 1974) overlain by upper Karnian to middle Norian platform carbonates (Jones and others, 1977). On Vancouver Island, the thickness of the tholeiitic basalt sequence

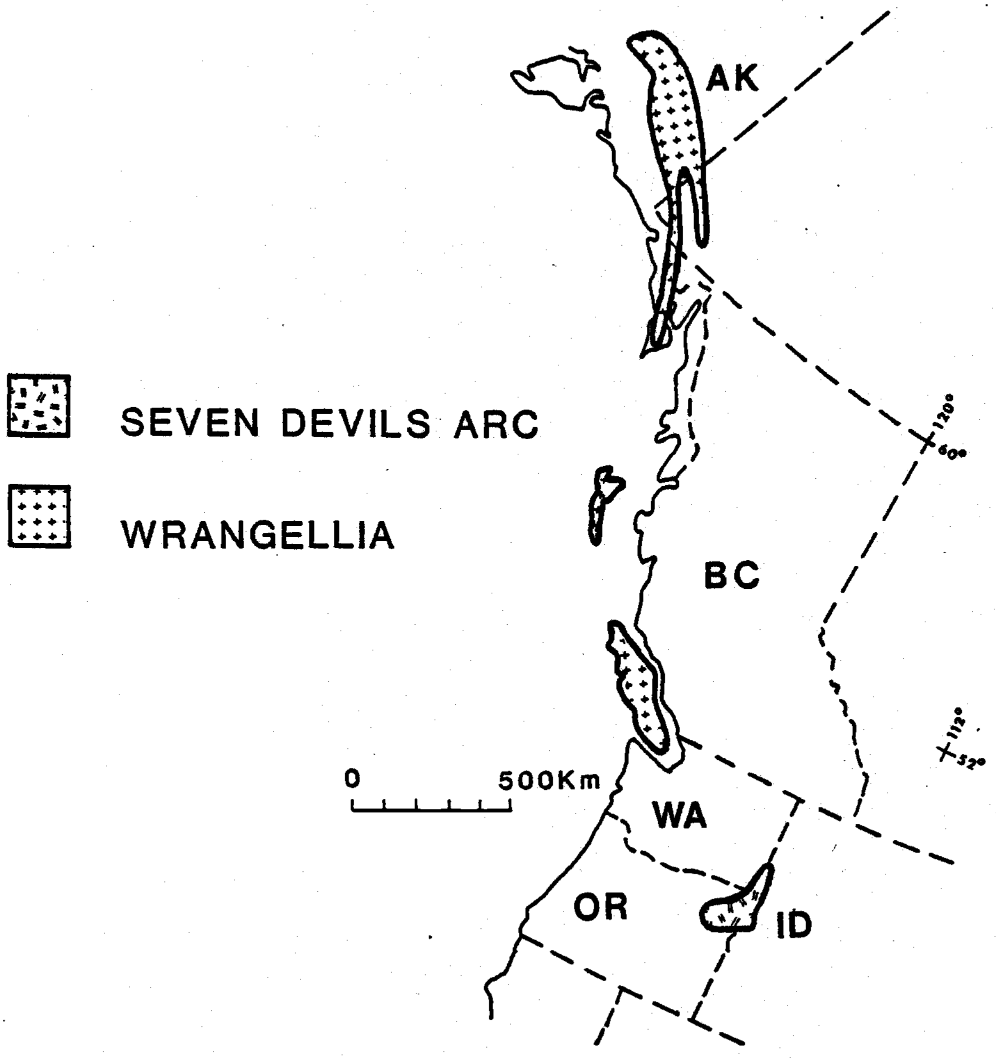

Figure 20. Location of the Wrangellia terrane.

(Karmutsen Formation) is at least 6000 meters (Carlisle and Susuki, 1974). It has been subdivided into a lower sequence of tholeiitic pillow lavas, a middle sequence of pillow breccias and aquagene tuffs, and an upper, massive and amygdaloidal flow unit (Carlisle and Susuki, 1974). This unit has undergone pumpellyite facies metamorphism (Muller and others, 1974). In the Wrangell Mountains, the thickness of the Nikolai Greenstone tholeiitic basalt sequence is at least 3500 meters, and rocks are mostly subaerial basalt flows (Jones and others, 1977).

The paleomagnetism of Wrangellia basalts in the Wrangell Mountains and on Vancouver island has been studied by numerous workers, including Hillhouse (1977), Schwarz and others (1980), and Yole and Irving (1980). Panuska and Stone (1981) studied paleomagnetism of Permian volcanogenic rocks that underlie the Nikolai Greenstone in the Wrangell Mountains. All workers have concluded that the Wrangellia basalts formed at a paleolatitude of about 15° north or south of the equator. This data can only be explained if the Wrangellia terrane has moved northward relative to the continent since the Late Triassic (Hillhouse, 1977; Jones and others, 1977).

Although near equatorial latitudes have been demonstrated for Wrangellia at the time of its inception, the polarity ambiguity for the data has not been satisfactorily resolved. It cannot be determined if the Wrangellia paleopole corresponds to a normal or reverse magnetic interval. Thus, it is not known if the terrane formed at 15°N or 15°S latitude. Both possibilites have been proposed. Yole and Irving (1980) prefer a southerly initial paleolatitude for the Karmutsen formation. This requires a 49° ±6° northward translation accompanied by 22° ± 9° of dextral rotation. The alternative requires 13° ± 6° of northward translation accompanied by 158° of sinistral or 202° of dextral rotation. This northerly option is preferred by Muller (1977), Schwarz and others (1980), and Panuska and Stone (1981). Hillhouse (1977) also favored a northerly initial paleolatitude for the Nikolai Greenstone of the Wrangell Mountains.

Only Panuska and Stone (1981) have attempted to solve the polar ambiguity directly, by sampling Permian rocks from beneath the Nikolai Greenstone. They argue that rocks of this age correspond to a known reversed polarity magnetic interval. Based on this data, the Permian rocks that underlie Wrangellia lie at a paleolatitude similar to that of Triassic Wrangellia only if the latter were created at the northerly paleolatitude option (15°N). As will be shown, this could have great importance in interpreting paleomagnetic data from the Seven Devils Group and Huntington arc.

The tectonic setting and petrologic character of Wrangellia have not been considered in depth. Jones and others (1977) suggest that basaltic volcanism was somehow rift-related. Hillhouse (1977, p. 2590) describes the terrane as a "plateau basalt field." Muller and others (1974) tentatively suggest an inter-arc basin origin. Souther (1977) suggests that Wrangellia basalts may be island arc tholeiites.

The correlation of the Triassic part of the Seven Devils Group with Wrangellia, proposed by Jones and others (1977) and Hillhouse and others (1982) is not straightforward. The significant similarities between these terranes are their age (Ladinian to Karnian), the age (Karnian to Norian) and character of overlying carbonates, and original paleolatitudes. However, the stratigrahy, petrology, and geochemistry of the Seven Devils Group is distinct from Wrangellia. Also, paleomagnetic data from the Seven Devils Group (Hillhouse and others, 1982) does not require substantial northward translation if original paleolatitudes were northerly.

The stratigraphy and lithologic character of the Triassic Seven Devils Group has been cited for its "remarkable similarities" (Jones and others, 1977) with Wrangellia. In fact, these units are lithologically dissimilar. According to Jones and others (1977), the volcanic rocks of Wrangellia are characterized by up to 6000 meters of tholeiitic pillow basalts, pillow breccias, subaerial flood basalts, and aquagene tuffs, with minor carbonate interbeds. Hillhouse and others (1982) describe "nearly identical lithologies" of the Wild Sheep Creek Formation of the Seven Devils Group as comprising "metamorphosed basalt, basaltic andesite, andesite, and dacite flows and volcaniclastic rocks, graywacke, argillite and limestone." Further, the upper Karnian Doyle Creek Formation, composed almost entirely of volcaniclastic rocks in Hells Canyon (Vallier, 1977), has generally been ignored in discussions of

Wrangellia - Seven Devils Group correlation.

The Martin Bridge Formation, which overlies the Seven Devils Group, is similar to carbonate sequences overlying the Wrangellia basalts in terms of its fossil content, depositional history, and diagenetic history, according to Jones and others (1977). Apparently, the Late Triassic sedimentary history of these two terranes was similar.

There is little geochemical data available for rocks of the Wrangellia terrane. Muller and others (1974) have published major element analyses for six basalts of the Karmutsen Formation, and Kuniyoshi (1971) published an average of 71 chemical analyses of basalts from this unit. Jones and others (1977) report the results of the average of 39 basalt analyses originally presented by MacKevett and Richter (1974). Nikolai and Karmutsen major oxide chemistries are identical. They are characterized by silica contents of less than 50 percent, and alumina contents of less than 15 percent. Souther (1977) shows that all published anlayses of Karmutsen basalts are tholeiitic, based on Irvine and Baragar's (1971) AFM descrimination diagram. There is no published evidence of silicic differentiates within the Karmutsen Formation or Nikolai Greenstone.

The chemical character of the Wild Sheep Creek Formation, discussed previously, is not similar to that of Wrangellia. As illustrated on an alkali - silica diagram (Figure 21), rocks from the Heavens Gate area and Hells Canyon show a wide

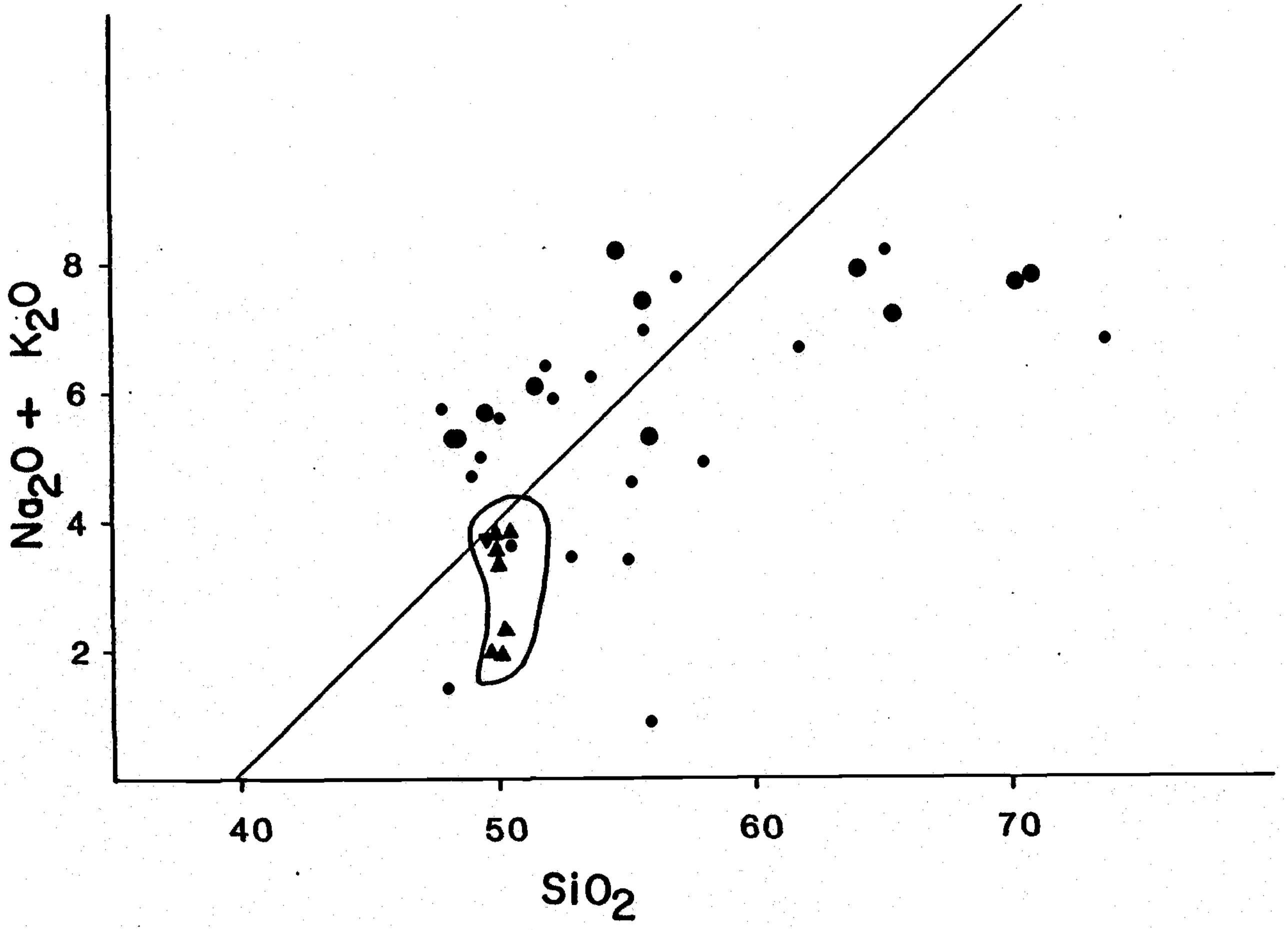

Figure 21. Alkali-silica plot for the Wild Sheep Creek Formation and Wrangellia. Data from the Wild Sheep Creek Formation plotted as large circles (this study) and small circles (Vallier and Batiza, 1978). Wrangellia data from Vancouver Island plotted as upright triangles (Muller and others, 1974; Kuniyoshi, 1971); Wrangellia data from Wrangell Mountains plotted as inverted triangle (average of 39 analyses from MacKevett and Richter, 1974, reported by Jones and others, 1977).

distribution of silica contents, and increasing silica generally corresponds to increasing alkalis. This distribution must be a general reflection of primary variations in composition, although the irregularities in the distribution are probably a result of alkali mobility. In contrast to the volcanic rocks of the Wild Sheep Creek Formation, Wrangellia tholeiites fall within a very small field on the alkali - silica diagram.

The presence of three spilite samples from the Wild Sheep Creek Formation with possible island arc tholeiite affinites may suggest a potential basis for correlation with Wrangellia. Additional trace element data are needed from both areas.

Results of recent paleomagnetic studies in the Seven Devils and Huntington arc terranes provide evidence that the Seven Devils arc did share a Late Triassic paleolatitude with Wrangellia (Hillhouse and others, 1982). This study indicates that the Seven Devils arc was created at $18^{\circ} \pm 4^{\circ}$ north or south of the Triassic equator. These results are comparable to results from Wrangellia, but they also suggest some significant ramifications. Most importantly, within the limits of accuracy for Hillhouse and others' (1982) data, the Seven Devils arc could be considered autochthonous if it formed at northerly paleolatitudes. This is because the predicted paleolatitude for the Seven Devils arc (had it always been in place) is $23^{\circ} \pm 6^{\circ}$ (Hillhouse and others, 1982). Thus there is an overlap in the range of the predicted paleolatitude ($23^{\circ} \pm 6^{\circ}$) and the actual value ($18^{\circ} \pm 4^{\circ}$). Therefore, if the polarity ambiguity solution given by Panuska and Stone (1981) is correct, then the Triassic Seven Devils arc may have formed at or very close to its present latitude relative to the North American craton.

The problem of the Huntington arc is also of relevence here. Hillhouse and others (1982) have stated that the Seven Devils arc and Wrangellia share nearly identical lithologies. They have further argued that the Huntington arc "has a significantly different volcanic and depositional history as compared with any part of Wrangellia." Vallier (1977) and Brooks and Vallier (1977), on the other hand, regard the Huntington arc and the Seven Devils arc as possibly correlative. Further, paleolatitudes obtained by Hillhouse and others (1982) for the Huntington arc are the same as those of the Seven Devils arc. On one level, the problem here is purely logical. According to Hillhouse and others (1982):

1. Wrangellia and the Seven Devils Group are correlative.
2. Wrangellia and the Huntington arc are not correlative.
3. All three terranes share common Triassic paleolatitudes.

In fact, the character of the Huntington arc and the Triassic Seven Devils arc is similar. Brooks and Vallier (1978) state that outcrop pattern, age, lithologic character, metamorphic history, and geochemistry all support correlation of these units. The most satisfactory first order interpretation of Hillhouse and others' (1982) data is that the Huntington arc and Seven Devils arc do indeed represent a single terrane. Further, this terrane may have formed at or close to its present latitude relative to the craton. Both of these sequences apparently shared a common Triassic paleolatitude with Wrangellia.

If the subduction complex terrane and the Mesozoic clastic terrane of the Blue Mountains are genetically related to the adjacent arc terranes (see above; also Dickinson, 1979; Ave Lallement and others, 1980), then the entire Blue Mountains pre-Tertiary sequence can be viewed as representing a single destructive plate margin that formed close to its present position, or perhaps considerably south of its present position, relative to the craton. The more northerly Wrangellia terrane of British Columbia and Alaska may represent a distinct "microplate" that formed at similar paleolatitude, or it may represent a different component of that same complex orogenic sequence. For example, Wrangellia could comprise rocks of a primitive, tholeiitic island arc that was amputated from the Blue Mountains terranes and translated northward to its present location.

SUMMARY

Volcanogenic rocks of the Seven Devils Group, exposed in much of the northern part of the Heavens Gate quadrangle, were formed at an island arc setting in Late Triassic and possibly Early Permian time. Greenstones of the Upper Triassic Wild Sheep Creek Formation, which crop out in the south, comprise metamorphosed basaltic, andesitic and dacitic flow and volcaniclastic rocks. Trace element analysis indicates that these rocks are transitional, probably calc-alkaline in nature, and typical of a mature island arc setting. Other volcanic rocks in the field area may be characteristic of more primitive island arc tholeiite magmatism. To the north, rocks of the Hunsaker Creek Formation (?) are dominantly volcaniclastic in nature. All rocks in the study area have been metamorphosed to greenschist facies.

The Martin Bridge Formation, comprising sheared marble and locally unsheared limestone, contains conodonts of early to middle Norian age. This unit everywhere overlies the Seven Devils Group along a thrust fault. This fault is notable in that it displaces younger rocks of the Martin Bridge Formation over the older rocks of the Seven Devils Group. It is interpreted to have propogated along the carbonate - volcanic unconformity during the early stages of the evolution of the Rapid River thrust system. Later activity in this thrust system juxtaposed rocks of the Riggins Group, Seven Devils Group, Martin Bridge Formation, and Lucille Formation. Continued thrust evolution also may have resulted in the folding of the earlier formed carbonate-over-volcanic thrust fault.

Within the field area, metavolcanic rocks of the Riggins Group (Lightning Creek Schist) are indistinguishable from the Seven Devils Group and may be correlative.

The tectonic history of the field area is characterized by layer-parallel ductile shearing and subsequent thrust faulting. Evidence of shearing is best developed in volcaniclastic rocks in the north, in marbles, and in all lithologies near the carbonate-over-volcanic thrust fault. Probable Late Jurassic to Early Cretaceous tonalite plutons postdate ductile shearing and thrusting, and thus place an upper limit on the age of significant deformation in the area. Deformation may be correlative with Late Jurassic events of the Nevadan orogeny, well documented in eastern Oregon, the Klamath Mountains, and the Sierra Nevada.

Some workers (Jones and others, 1977; Hillhouse and others, 1982) have correlated the Wild Sheep Creek Formation of the Seven Devils Group with the Triassic basalts of the Wrangellia Terrane. This study suggests that the petrologic character of these two units is different, and that such a correlation may not be valid. On the other hand, the Wild Sheep Creek Formation may be correlative with rocks of the Huntington volcanic arc terrane.

Much additional work is needed to more fully understand the evolution of this area. In particular, rocks of the Riggins Group have been conspicuously neglected since the original work by Hamilton (1960, 1963a, 1963b, 1969). Of greatest importance is the age of the Riggins Group, and the nature and distribution of ultramafic rocks within the Riggins Group. This sequence is particularly significant because it marks the boundary between oceanic and continental crust. The nature and age of this boundary is unknown.

The character of the Rapid River thrust needs further scrutiny. The model presented in this study can be tested by looking for additional thrust faults west of the field area, in Hells Canyon. One such fault may have been mapped by Gualtieri and Simmons (1978). Additional thrusts may even be present within the field area, but, if so, homogeneity of lithologies and poor outcrop has obscured them.

Fossils from the eastern Seven Devils Group are needed to confirm lithologic correlations. Radiometric dating of plutons in the Seven Devils Group and the Riggins Group would help constrain tectonic interpretations.

Overall, the region between the Seven Devils Mountains and the Idaho batholith has commanded disproportionately little attention from geologists, in view of its regional geologic significance. Until this area is more fully studied, understanding of the evolution of the pre-Tertiary terranes of western Idaho and eastern Oregon will be incomplete.

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