UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geology of the Wallowa-Seven Devils volcanic
(island) arc terrane between the Snake and
Salmon Rivers near Lucile, Idaho:
Part I - Stratigraphy, structure,
and metamorphism

By

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This report is preliminary and has not been reviewed
for conformity with U.S. Geological
Survey editorial standards and stratigraphic nomenclature.

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INTRODUCTION

Location and access

The study area is located in west-central Idaho, 269 km (164 mi) north of Boise by way of State Highway 55 and U.S. Highway 95, and 16 km (10 mi) north of Riggins on U.S. Highway 95 (fig. 1). The area extends from the town of Lucile on the Salmon River, at an elevation of 1,600 ft, 8 km to the west up Cow Creek to Cow Creek Saddle, at an elevation of 5,220 ft, and then 6 km west, down to an elevation of 1,200 ft at Kirkwood Bar on the Snake River. The Idaho-Oregon border follows the Snake River.

There is good access to much of the field area by gravel road or trail. The land east of Cow Creek Saddle is mostly national forest and is in part privately owned. The ridge along Cow Creek Saddle marks the eastern boundary of the Hells Canyon Recreation Area. With the exception of patented land around the Blue Jacket mine, all of the land between the Saddle and the Snake River is part of the Recreation Area.

Geologic setting

Regional stratigraphy

The Seven Devils Group is one of four groups of rocks that compose middle to late Paleozoic and middle Mesozoic allochthonous terranes in western Idaho and northeastern Oregon (Dickinson, 1979). Using the terminology of Brooks (1979), they are the Wallowa-Seven Devils Volcanic Arc Terrane, Oceanic Crust Terrane, Forearc Basin Terrane, and Huntington Volcanic Arc Terrane (fig. 1).

The Pennsylvanian to Jurassic (Vallier, 1977; Vallier and others, 1977; Walker, 1983) Wallowa-Seven Devils Volcanic Arc Terrane consists of low potassium, predominantly andesitic, or keratophyric, volcanic rocks of the Seven Devils Group. The arc is exposed north of Oxbow, Oregon, in Hells Canyon (Snake River Canyon), Oregon and Idaho (Anderson, 1930; Vallier, 1977; Vallier and others, 1977; and Vallier and Batiza, 1978). The Clover Creek Greenstones in the Wallowa Mountains, northeastern Oregon (Gilluly, 1937; Ross, 1938), are equivalent to the Seven Devils Group.

The Oceanic Crust Terrane (fig. 1) consists of an oceanic assemblage of predominantly ophiolitic suites, including mafic to intermediate intrusions and hornblende pegmatites. These intrusions range from 279 Ma (early Permian) to 210 Ma (middle-late Triassic Norian) (Vallier and others, 1977; Ave Lallement and others, 1980; Walker, 1983; Palmer, 1983). The volcanic rocks were originally low-potassium basalts (Vallier and Batiza, 1978) and alkalic basalts (Mullen, 1979). The terrane extends from approximately Oxbow, Oregon, on the Idaho-Oregon border, to Mitchell, Oregon, 125 mi west of Baker, Oregon (Vallier and others, 1977; Brooks and Vallier, 1978), and may include the Riggins Group near Riggins, Idaho (Hamilton, 1963, 1969; Vallier and others, 1977).

The Huntington Volcanic Arc Terrane, south and east of Huntington, Oregon, consists mainly of Triassic mafic to silicic volcanic rocks. The Huntington and Wallowa-Seven Devils Volcanic Arcs may compose parts of a single arc (Vallier, 1977) that was separated in the late Triassic along the Oxbow-Cuprum shear zone (fig. 1) (Ave Lallement, 1983). Silberling (1983), however, argues against this hypothesis based on differences in lithologies.

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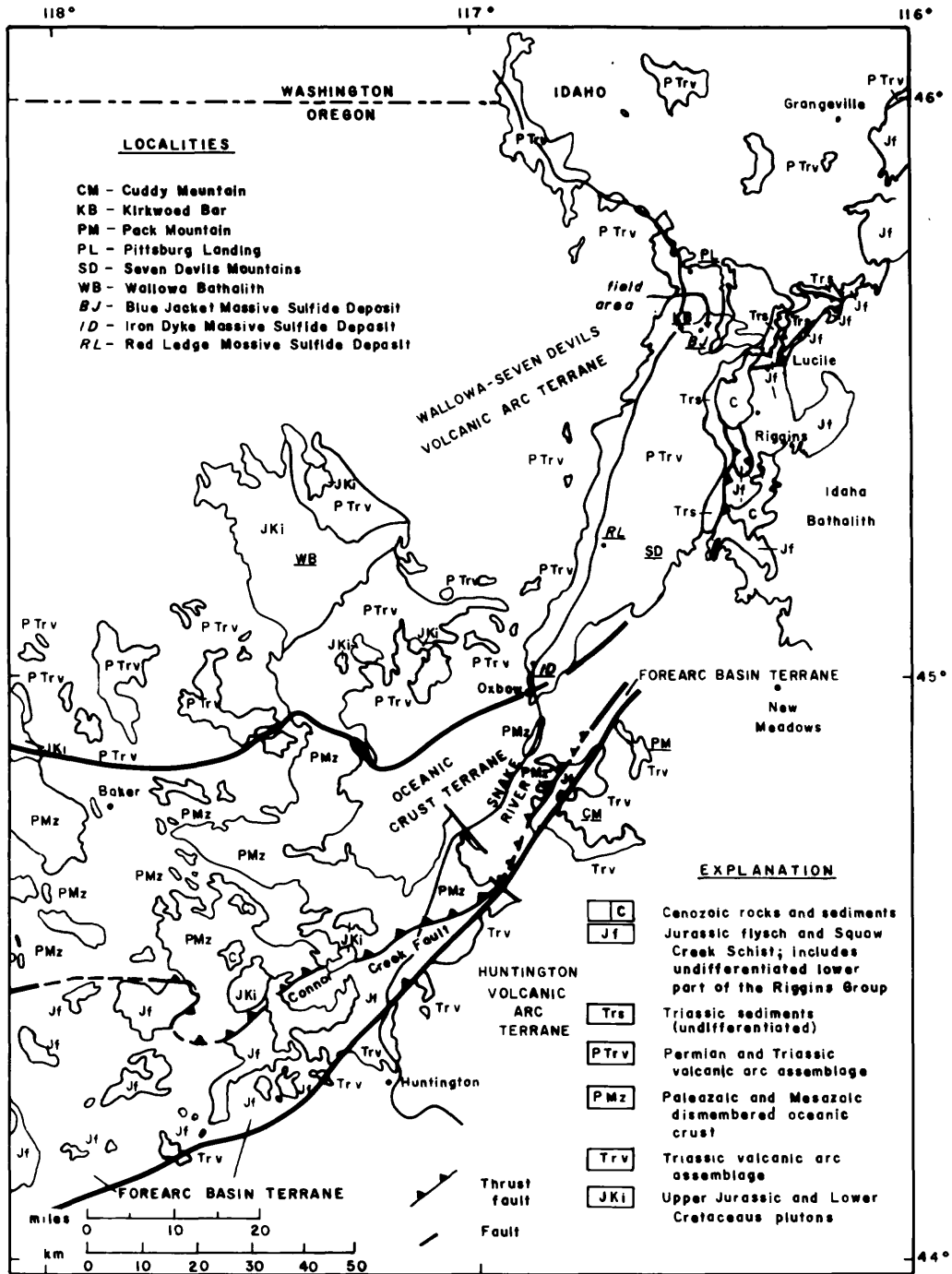Figure 1.—Generalized geologic map of northeastern Oregon and
western Idaho, showing the location of the Wallowa-Seven Devils
Volcanic Arc, the field area, and the Blue Jacket Cu-Zn massive
sulfide deposit. Modified from Hamilton (1969), Bond (1978),
Brooks (1978), Onasch (1977), Swanson and others (1981), Myers
(1982), and Karen Lund (personal communication, 1983)

The Forearc Basin Terrane (fig. 1) includes the Paleozoic-age suite of shelf carbonates and coarse-grained clastic rocks in the Izee-Suplee area south of John Day, Oregon, 107 km (65 mi) southwest of Baker, Oregon (Vallier and others, 1977; Brooks and Vallier, 1978). It includes upper Triassic to Jurassic flysch-like sedimentary rocks that unconformably overlie the Oceanic Crust Terrane (Vallier and others, 1977) and Jurassic clastic sedimentary rocks that unconformably overlie the Huntington Volcanic Arc.

Stratigraphy of the Permian to Triassic Seven Devils Group
and associated Triassic to Jurassic sedimentary rocks

The chiefly metavolcanic sequence in Hells Canyon was named the Seven Devils Volcanics by Anderson (1930) and renamed the Seven Devils Group by Vallier (1977). It consists of basic to felsic volcanic rocks, immature clastic sedimentary rocks, limestone, and intermediate-composition intrusives (Vallier, 1977; Vallier and others, 1977; and Walker, 1983). It is similar in some respects to the accreted island-arc terranes, collectively termed Wrangellia, that extend from Alaska to Vancouver Island (Jones and others, 1977). However, it does not appear to be part of Wrangellia based on the lithologies of both the volcanic and sedimentary rocks (Silberling, 1983) and the composition of the mostly submarine lava flows (Sarewitz, 1983). Nevertheless, both terranes formed within about 18° of the paleoequator.

The Seven Devils Group extends from Lewiston and Orofino, Idaho, on the north, to Oxbow, Oregon, on the south, a distance of approximately 200 km (120 mi). From Hells Canyon along the Idaho-Oregon border, it extends about 98 km (60 mi) to the east into Idaho and 80 km (50 mi) to the west into Oregon, where it was mapped as the Clover Creek Greenstone (Gilluly, 1937; Ross, 1938). To the east, near the Salmon River, it is in contact with the Riggins Group (Hamilton, 1963, 1976). To the south it is in contact with Jurassic sedimentary rocks (Vallier and others, 1977). It is overlain on the north and west, and to a lesser extent on the south, by the Tertiary Columbia River Basalts.

Vallier (1977) subdivided the Wallowa-Seven Devils arc into a basement complex and the Seven Devils Group, which consists of four formations. Vallier and Batiza (1978) considered the lavas in the Seven Devils Group to be principally spilite and keratophyre, using Cann's (1969) definition of spilite and Schermerhorn's (1973) definition of keratophyre and quartz keratophyre, because the lavas are characterized by low potassium and high sodium contents.

The basement complex consists of amphibolite, metagabbro, metaquartz diorite, hornblende schist, mylonite, and gneissic mylonite. It is exposed in the lower elevations of Hells Canyon in the southern part of the arc near Oxbow, Oregon, in the northern part of the arc near Kirkwood Bar and Pittsburg Landing, and, farther to the north, at the mouth of the Imnaha River (Vallier, 1977). The basement complex is mostly older than the Seven Devils Group. A discordant U-Pb age of 310 m.y. (Walker, 1983) dates the complex as Early to Middle Pennsylvanian. However, the basement complex is in part coeval with the Seven Devils Group as dikes in the basement complex locally extend into and cut the lower Seven Devils Group volcanics.

The approximately 500-m-thick Windy Ridge Formation is the lowermost formation of the Seven Devils Group. It is composed mainly of quartz keratophyre lavas and felsic pyroclastics. The best exposures are at the type locality across the Snake River from Oxbow, Oregon, where the lower part of the formation is sheared and tectonically mixed with the underlying metamorphic and plutonic rocks of the Oxbow-Cuprum shear zone (Vallier, 1977).

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The Windy Ridge Formation may be unconformably overlain by the Hunsaker Creek Formation of early Permian Leonardian or Guadalupian age. This age is based on brachiopod faunas (F. G. Stehli, written commun., 1965, reported in Vallier, 1977). Vallier (1977) designated and measured the type section along Hunsaker Creek approximately 1.6 km (1 mi) northwest of Oxbow, Oregon. A reference section is located on the north side of Ballard Creek immediately above the Snake River, approximately 14 km (8.5 mi) north-northeast of Oxbow, Oregon, and approximately 65 km (40 mi) south-southwest of Kirkwood Bar, Idaho. The formation consists of about 2500 m of mainly pyroclastic breccia, agglomerate, tuff, epiclastic volcanic breccia, conglomerate, sandstone, siltstone, and minor limestone, quartz keratophyre, keratophyre, and spilite.

The Wild Sheep Creek Formation unconformably overlies the Hunsaker Creek Formation. Fossil data (H. J. Silberling, personal commun., reported in Vallier, 1977) indicate a latest Middle Triassic (Ladinian) to early-Late Triassic (Carnian) age. Vallier (1977) defined and measured the type section at the junction of Saddle Creek and the Snake River, approximately 54 km (33 mi) north-northeast of Oxbow, Oregon, and approximately 22 km (13.5 mi) south-southwest of Kirkwood Bar, Idaho. A reference section is immediately west of Cherry Creek, in the Deadhorse Ridge 7 1/2´ quadrangle, west of the Snake River approximately 48 km (29 mi) northwest of Kirkwood Bar, Idaho.

Vallier (1977) recognized three units in the Wild Sheep Creek Formation: (1) a lower unit comprised mostly of keratophyric volcaniclastic rock; (2) a thick middle unit predominately of massive and pillowed spilitic lavas, thick beds of coarse breccia, and beds of mafic tuff; and (3) an upper unit of argillite, sandstone, limestone, and spilitic and keratophyric clastic rocks. Conglomerate is present in all three units. Argillite and graywacke are up to about 100 m thick and increase in abundance to the north, as does limestone. The maximum total thickness is approximately 2500 m. The formation appears to thin both to the north and south of the type locality.

The uppermost formation in the Seven Devils Group is the Late Triassic (Carnian, and possibly Norian) Doyle Creek Formation (Vallier, 1977). The age is inferred from the Carnian age of the underlying Wild Sheep Creek Formation and Norian age of the overlying Martin Bridge Formation. The type locality is at Doyle Creek, approximately 23 km (14 mi) north-northeast of Oxbow, Oregon, and approximately 51 km (31 mi) south-southwest of Kirkwood Bar, Idaho. Two reference sections are at McGraw Creek and Ashby Creeks, both close to the Snake River, approximately 16.5 km (10 mi) and 9 km (5.5 mi) north-northeast of Oxbow, Oregon, and approximately 57 km (35 mi) and 48.5 km (29.5 mi) south-southwest of Kirkwood Bar, Idaho, respectively.

The Doyle Creek consists of about 500 m of porphyritic basalt, in part spilite; basaltic andesite and andesite, in part keratophyre; dacite and rhyolite, in part quartz keratophyre; pyroclastic breccia and tuff; and conglomerate, sandstone, siltstone, argillite, arkosic wacke and graywacke. It has been suggested that most of the sequence was deposited in a shallow, well-oxygenated, marine environment (Vallier, 1977), which may have been locally emergent (Morganti, 1972).

The units overlying the Seven Devils Group are almost exclusively clastic and carbonate sedimentary rocks. Due to structural complexity, it is difficult to determine the stratigraphic sequence and to correlate these units from one locality to the next. Hamilton (1969) suggested that the stratigraphic sequence in the Riggins area, 16 km (10 mi) south of Lucile, Idaho, is Seven Devils Volcanics, overlain by the Martin Bridge Formation, and thence by Lucile Slate. However, Lund and others (1983) documented sedimentary intertonguing of the uppermost Seven Devils Group volcanics with

overlying Lucile Slate, and of Lucile Slate, in turn, with overlying Martin
Bridge Limestone in Long Gulch, 9 km (5.5 mi) north-northeast of Lucile. The
Lucile Slate is probably late Carnian to early Norian, based on the Carnian
age of the Wild Sheep Creek Formation in the Seven Devils Group, and the
Norian age of the Martin Bridge Limestone.

In the Pittsburg Landing area, 10 km (6 mi) north of Kirkwood Bar, Idaho,
Vallier (1977) renamed the Pittsburg Formation as the Kurry Creek Member of
the Doyle Creek Formation. The Kurry Creek Member consists mostly of clastic
sedimentary rocks, and probably conformably overlies the Wild Sheep Creek
Formation; it is unconformably overlain by the Jurassic Coon Hollow
Formation. Vallier suggested that the Kurry Creek represents a submarine fan
adjacent to a land mass. Ammonites and Halobia identified by N. J. Silberling
(written commun., reported in Vallier, 1977) from the Kurry Creek indicate a
Late Triassic (late Carnian to early Norian) age--the same age as the Lucile
Slate. The two are probably correlative.

The Early Jurassic Hurwal Formation and Late Jurassic Coon Hollow
Formation overlie Martin Bridge Limestone in the Wallowa Mountains, Oregon.
The Hurwal consists of argillite, limestone, and volcaniclastic rocks; the
Coon Hollow consists of mudstone and sandstone. The Coon Hollow is also
exposed at Pittsburg Landing where it unconformably overlies the Kurry Creek
Member.

Intrusive rocks

Intrusions of intermediate composition are present throughout the
Wallowa-Seven Devils and Huntington volcanic terranes. A 234 m.y.-old
quartz-rich diorite, which is metamorphosed and cut by andesite dikes,
intrudes volcanic rocks of the Huntington Volcanic Arc (H. Brooks, pers.
commun., 1983). A group of intrusions ranging from 169 Ma (Late Jurassic
Oxfordian) to 95 Ma (early Late Cretaceous Cenomanian) (Armstrong and others,
1976, 1977) intrudes the Huntington Arc in the Cuddy Mountain area, Idaho,
about 33 km (20 mi) southeast of Oxbow, Oregon. A group that cuts both the
oceanic and volcanic arc terranes is in the range 159 Ma (Late Jurassic
Oxfordian) to 117 Ma (Early Cretaceous Aptian) (Field and others, 1972).

Intrusive masses in the Black Lake area, Idaho, northeast of Oxbow,
Oregon (White, 1968, 1973), consist of three suites: an older, metamorphosed
suite of gabbro, norite, diorite, and quartz diorite; early post-metamorphic
quartz diorite and granodiorite; and two post-metamorphic quartz diorites.
The Deep Creek Stock, one of the post-metamorphic intrusions, was dated at 121
and 127 m.y. using K-Ar methods on biotite and hornblende, respectively
(White, 1973). These are the only intrusions known by the authors to have
been mapped in detail in the Idaho part of the Seven Devils Group.

Structure and metamorphism

The rocks of the Wallowa-Seven Devils Arc, the Oceanic Crust Terrane, and
the Forearc Basin Terrane west and southwest of Oxbow, Oregon, were deformed
in the Late Triassic and again in Late Jurassic (Ave Lallement and others,
1980) (fig. 1). West of Sparta, Oregon, about halfway between Oxbow and
Baker, Late Triassic folds trend north-south but swing around to a northeast-
southwest to east-west orientation near and immediately northeast of Oxbow,
Oregon. The folds range from open and concentric to tight; they plunge
moderately to steeply both to the north and south and are the only folds
recognized in areas that are mildly deformed.

Late Jurassic folds, west of Sparta, Oregon, vary from west-northwest, to east-west, to east-northeast, and plunge gently both to the east and west. To the east, near Oxbow, Oregon, they swing northeastward and display moderate to steep northerly plunges. Generally, the trends of the Triassic and Jurassic fold sets are perpendicular to one another.

In areas of intense deformation, the structures of both the Late Triassic and Late Jurassic orogenies may be accompanied by later conjugate sets of kink folds and crenulation cleavages that are coaxial with the first sets of folds. Very rarely, a later third set of folds is at a high angle to the first two sets.

The Late Triassic orogeny probably deformed the arc following deposition of most of the volcanic rock units. This orogeny may have been related to blueschist metamorphism in central Oregon between 223 Ma and 213 Ma (Late Triassic Norian) (Hotz and others, 1977; Ave Lallement and others, 1980). Metamorphism and deformation of the Riggins Group at the contact with the continental rocks at 118 Ma is taken as the time of accretion (Lund, 1984; Sutter and others, 1984). Deformation of the Triassic sedimentary rocks at the east side of the Wallowa-Seven Devils Arc took place at this time. The only apparent effect on the Seven Devils Group was development of shear zones.

GEOLOGY OF THE STUDY AREA

Introduction

The study area was mapped in detail on a topographic base except for unit III and the quartz monzonite, which were mapped in reconnaissance (pl. 1). Mapping of unit IIA in the vicinity of the Blue Jacket mine was at a scale of 100 ft to the inch, using a plane table and alidade. The remainder of the area west of Cow Creek Saddle, in the approximate center of the study area, was mapped at 500 ft to the inch, and the area east of the saddle at 1,000 ft to the inch. The structural trend lines on plate 1 represent the orientation of bedding projected to a horizontal surface. Where topography affects the map pattern of rock-unit boundaries, the corrected position and orientation are shown. For example, the upper contact of unit IIA with III crosses the structural trend lines (pl. 1).

Stratigraphy

Introduction

Rocks in the study area include the Pennsylvanian and Permian(?) basement complex, the Permian and Triassic(?) Seven Devils Group, Triassic Lucile Slate and Martin Bridge Formation, Triassic or Jurassic quartz monzonite and quartz diorite intrusions, and Miocene Columbia River Basalt.

Pennsylvanian and Permian(?) systems

Basement complex

The lowermost unit in the field area is the basement complex, also mapped by Vallier (1977). A discordant U/Pb age of 310 m.y. (Walker, 1983) suggests an early to middle Pennsylvanian age. It consists mainly of metamorphosed gabbro and quartz diorite (Vallier, 1977) with an absence of sedimentary and volcanic rocks. In the field area at Kirkwood Bar on the Snake River, it

consists of 30 to 50 percent, 10 cm to 3 m, parallel, fine-grained, possibly basaltic andesite or andesite dikes, and 50 to 70 percent, cumulate-textured plagiogranite. The dikes trend N. 60° E. with an average dip of 80° SE, although they range in strike from N. 25° E. to N. 80° E., and dip from 55° SE to vertical. Although the basement complex is mainly older than the Seven Devils Group, near the northeast end of the complex (pl. 1), several plagiogranite dikes in the basement complex extend upward and intrude the lower part of unit I-1. Vallier (1977) also noted plagiogranite dikes cutting the lower volcanic rocks elsewhere in the canyon.

The complex is present from the canyon bottom to the top of Sumac Gulch for an exposed thickness of approximately 650 m. It is in fault contact with unit I-1; it is not known how much of the complex was removed by faulting. However, the presence of a horizon, adjacent to the study area on the northwest, that consists of approximately 50 percent plagiogranite and andesite(?) dikes and 50 percent lavas and volcaniclastics suggests that as much as 300 m of section may be missing in Sumac Gulch.

A Pennsylvanian age of the complex and Permian age of the lower Seven Devils Group (Vallier, 1977), absence of sedimentary and volcanic rocks, and presence of intrusions indicate that the complex is an intrusive unit and was the basement on which the Seven Devils Group was deposited. Furthermore, if the plagiogranite dikes in unit I-1 had their origin in the complex when the complex formed, then the formation of the complex and the volcanic arc overlapped in time. The similarity of the dike complex and plagiogranite at Kirkwood Bar to sheeted dikes and plagiogranite in ophiolites (Gass, 1980) suggests a similar origin for oceanic crust and the Wallowa-Seven Devils arc basement complex.

Permian and Triassic(?) systems

Seven Devils Group

The Seven Devils Group is the dominant unit in the study area. It consists mainly of intermediate and felsic lavas and volcaniclastics, and subvolcanic rhyolite and dacite intrusions. The Seven Devils Group in the study area does not correspond to the formations defined for the Group by Vallier (1977). Therefore, the Seven Devils Group in the study area has been subdivided into map units. Some of these units are further subdivided based on abundance and distribution of lithologies, e.g., unit I was subdivided into subunits I-1 and I-2.

In order of decreasing abundance, the compositions of the volcanic rocks represented are: calc-alkaline andesite, dacite, rhyolite, and rhyodacite, and tholeiitic andesite, mapped as basaltic andesite; basalt was not recognized. High sodium and low potassium contents are typical of the Seven Devils Group, an indication that the rocks underwent sodium metasomatism (Vallier, 1977; Vallier and Batiza, 1978; and table 1).

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Table 1.—Chemical analyses of unaltered rocks

Sample No.	140	151	68	86	14	278	272	337
SiO_2	56.5	56.3	76.1	66.7	70.1	70.6	61.9	72.4
TiO_2	0.81	0.93	0.22	0.56	0.43	0.41	0.65	0.35
Al_2O_3	16.8	18.6	12.9	15.9	13.9	13.3	15.7	12.5
Fe_2O_3	11.6	6.52	2.25	4.40	4.29	4.08	6.70	3.98
MnO	0.21	0.12	<0.02	0.12	0.08	0.11	0.11	0.09
MgO	2.97	3.46	0.50	2.33	1.75	2.59	2.18	1.24
CaO	1.55	3.61	0.25	0.81	0.88	0.54	7.40	3.57
Na_2O	5.27	3.74	6.53	5.64	5.79	3.48	2.24	4.06
K_2O	1.17	2.96	0.04	1.13	0.41	1.36	0.53	<0.02
P_2O_5	<0.05	0.24	<0.05	0.10	0.09	0.08	0.11	0.07
L.O.I.	2.40	2.83	0.71	1.79	1.35	2.34	2.05	1.15
Total	99.28	99.32	99.50	99.48	99.07	98.89	99.57	99.41

No. 140: Basaltic andesite from unit IIA.

No. 151: Andesite from unit IIA.

No. 68:   Gray rhyolite from unit IIA.

No. 86:   Mottled green and white dacite from unit IIA.

No. 14:   Rhyolite below the Blue Jacket deposit in unit IIA.

No. 278: Dacite-andesite volcaniclastic unit from unit IIA.

No. 272: Volcanic sandstone from unit II.

No. 337: Light-green argillite from unit I-2.

Due to the lack of field criteria that might indicate the degree of sodium metasomatism, the terms andesite, dacite, etc., are used. The basis for distinguishing the various volcanic rock types and assigning names is given in Appendix I together with complete lithologic and petrographic descriptions.

Due to the difficulty of distinguishing between pyroclastic and epiclastic rocks, the term "volcaniclastic" is used for all rocks of this type, except where a pyroclastic or epiclastic origin can be clearly established. Most volcaniclastics are tuffs with lapilli, and lapilli tuffs; tuff breccias are present but are not common. Overall, the relative abundance

of the composition of volcaniclastics is the same as for the lavas. The lithics are usually the same composition as the matrix, but volcaniclastics of variably mixed dacite and andesite components are present and are termed "andesite-dacite" volcaniclastic rocks.

Felsic lavas and volcaniclastics are present throughout but are not evenly distributed. Instead, they are usually found in small clusters that make up less than about 10 to 20 percent of the rocks over distances up to a few hundred meters or more, or, groups comprised of 10 to 90 percent felsic rocks, which range from about 300 m to more than about 1 km in width. In both occurrences, the abundance of felsic rocks decreases abruptly along strike to an average of 5 percent or less. Individual flows continue across the boundaries.

Where felsic rocks make up more than 10 percent of the volcanics over a distance of about 300 m, they have been subdivided into felsic units designated by a letter, e.g., unit IIA. If the strike could be determined, the bottom and top of the felsic unit are placed at the stratigraphically lowest and highest felsic rocks, respectively. The stratigraphic position of the lower and upper boundaries of the felsic unit are used as the boundaries for the entire unit, e.g., units II and IIA (pl. 1).

Volcanic-associated sedimentary rocks consist of chert and fine-grained clastic sediments. The chert may, in part, be of hydrothermal origin. The clastic sediments are graywackes and argillites that are almost always bedded. They are thought to represent locally derived, reworked volcanic material. Epiclastic sedimentary rocks consist of heterolithic breccia and massive to medium-bedded, lithic-poor, argillitic rocks; conglomerate and limestone are lacking.

Unit I is the lowest stratigraphic unit. It has been subdivided into a lower unit, I-1, and an upper unit, I-2, based on relative proportions of rock types. Both units I-1 and I-2 are dominated by andesite lava flows.

Unit I-1 has a maximum strike length of 2625 m and a maximum exposed thickness of 325 m, which is a minimum value due to faulting at the base of the unit. The unit strikes between N. 10° E. and N. 25° E. and dips 20° to 30° SE. It is in fault contact with the basement complex and, apparently, in conformable contact with overlying unit I-2. Unit I-1 is defined by relatively abundant andesite dikes and sills, the presence of plagiogranite dikes, possibly basaltic-andesite (tholeiitic andesite) lavas, dikes, and sills, and the absence of sedimentary rocks.

Minor andesite, dacite, and rhyolite tuff and lapilli tuff are present. Rhyolite lapilli tuff locally contains blocks of flow-banded rhyolite. Aphanitic to fine-grained, dark-green andesite dikes compose 5 percent of the unit. Plagiogranite dikes are thought to have their origin in the basement complex.

Foliation and local shears that parallel the trend of the lavas and the fault contact with the basement complex are thought to be due to movement on the fault. Foliation is better developed in this unit than any other west of Cow Creek Saddle.

Unit I-2 is approximately 1300 m thick, is exposed for a maximum of 3925 m along strike, and strikes N. 25° E. in the lower part to N. 70° E. in the upper part. In order of decreasing abundance the lower, western half contains nearly equal amounts of: andesite, argillite, volcanic graywacke, fine lapilli tuff, epiclastic tuff, and epiclastic lapilli tuff. They are interbedded throughout, more or less equally on all scales. Rhyolite flows are very rare; there are no felsic volcaniclastics.

The upper, eastern half contains the same rock types but much less argillite. Light-green, maroon, red, and rare purple argillite average 2-7 m thick, reaching a maximum of approximately 30 m. Rhyolite flows with quartz phenocrysts up to 1 cm are located below the contact with unit II. A few dacite and rhyolite volcaniclastics are also present near the top of the unit.

Units II and IIA are similar in many ways to unit I. They consist of abundant andesite flows and common, but subordinate, dacite, rhyolite, volcaniclastic rocks, argillite, and all types of volcanic-associated sedimentary rocks in the field area; basaltic andesite (tholeiitic andesite; IIA) and andesite dikes are rare. Unit II, an andesite horizon, is exposed along strike in both directions from the felsic unit IIA. The boundary between the two is based on the abundance of felsic rocks. Both units II and IIA are apparently in conformable contact with units I and III, reach a maximum thickness of approximately 1000 m, and are exposed for approximately 4250 m along strike. They generally strike N. 60° E. and dip 10° to 70° SE, except when folded on northeast axes.

Unit IIA is defined by approximately 10 to 15 percent dacitic and rhyolitic lavas, hypabyssal intrusions, and volcaniclastics. The boundary between units I-2 and IIA is marked by the change from predominately andesite lava in I-2 to predominately rhyolite and dacite lavas and volcaniclastics in lower IIA.

Following initial volcanism in unit IIA, generation of felsic magma migrated about 600 m northeast (pl. 1). It continued from there to the top of the unit at the contact with unit III. Felsic rocks are concentrated along the margins of IIA, a feature not seen in units IIIA-F. As well, felsic rocks in unit IIA are more similar to those in unit I than to those in IIIA-F. Two characteristics unique to the felsic rocks in units I, II, and IIA are the size of the quartz phenocrysts, up to 1 cm, and laterally extensive and thick rhyolite flows.

Unit IIA consists of 25 percent andesitic and felsic volcaniclastics mainly in the center of the unit. Unit IIA has the only occurrence of flow breccia and mixed andesite-dacite volcaniclastics. As well, this unit contains the coarsest volcaniclastics mapped, located near flows or, in the case of dacite, domes of similar composition that could indicate a common source. In general, the volcaniclastics are discontinuous, range in thickness from about one to a few meters, are generally not graded, and are interbedded with flows. The approximate abundance of volcaniclastics in the unit are: 5 percent andesite, 10 percent andesite-dacite, and 10 percent epiclastic andesite-dacite and other compositions.

Less than 5 percent, volcanic-associated, sorted and graded sedimentary rocks are most abundant in the middle part of the unit, where most of the volcaniclastic rocks are located. The two rock types are commonly interbedded.

The top and bottom of unit II is defined by the extension along strike of the top and bottom of unit IIA. The map pattern of the contact of units IIA and II with unit III locally crosscuts the structural trend of bedding shown on plate 1 due to the orientation of bedding with respect to topography.

Unit II to the southwest of IIA has a maximum strike length of about 2300 m and a maximum thickness of about 250 m. It generally strikes N. 55° E. to east-west and dips 10° to 45° southeast (pl. 1). It consists mostly of light-green, siliceous, ash-fall, argillite-like sedimentary rocks, with rare clastic argillite and minor, fine dacite tuff and andesite lapilli tuff; the percentage of andesite lava increases upsection.

Thick, discontinuous, coarse volcaniclastics in the center of IIA, and thick, fine epiclastic and volcaniclastic rocks at the margins of IIA and in unit II, indicate construction of a relatively high-relief volcanic edifice at the center of unit IIA. A probable high heat flow and abundant fractures are interpreted as responsible for the development of convecting seawater, hydrothermal systems, and formation of the Blue Jacket Cu-Zn massive sulfide deposit, located near the center of unit IIA, and a second massive sulfide found near the top of the unit. Hydrothermal alteration is common, especially in and around the two deposits. Analyses of altered rock are given in table 2.

Northeast of unit IIA, unit II generally strikes between N. 50° E. and N. 70° E. and dips between 5° and 25° to either the northwest or southeast depending on location with respect to two northeast-trending folds. There is no apparent change in rock type or abundance across the unit I-2/III boundary. In this area, unit II consists of andesite lavas with minor volcaniclastic rocks, epiclastic tuff, volcanic wacke, and dacite lavas and domes. Dacite is located in the lower part immediately above the felsic rocks in upper unit I-2. It probably marks the continuation of felsic volcanism from unit I-2 into unit II. Hydrothermal alteration is common.

The major element composition of five unaltered lavas from units I and II are given in table 1. The effects of sodium metasomatism are difficult to assess. There was likely a decrease in potassium and a corresponding increase in sodium, possibly accompanied by a decrease in the amount of the other major elements (Vallier and Batiza, 1978). Vallier and Batiza also suggest that there was little change in the FeO*/Mgo ratio. If so, then the position of the samples on figure 2a, with respect to the "A" corner, were probably effected. There may have been little effect with respect to their position on figure 2b. This suggests that both calc-alkaline and tholeiitic composition volcanics are present.

Southwest of unit IIA, a felsic horizon begins at about the center of unit II and continues upsection to a position stratigraphically higher than the extension of the unit II/III boundary (plate 1). This unit consists of a thick sequence of fine epiclastic, sedimentary rocks with thin-bedded felsic flows and volcaniclastics near the top. It was designated unit IIIA because of the similarity of the unit to other felsic rocks in unit III and the dissimilarity to the felsic rocks in units I, II, and IIA. The base of unit IIIA defines the base of unit III in this area. There is no change in the character or abundance of the other rock types across the II/III boundary.

Table 2.--Chemical analyses of altered rocks

[All samples are completely altered except for No. 128, which has 5 percent

relict quartz phenocrysts, and No. 265. All are from the Blue Jacket Cu-Zn

massive sulfide in unit IIA except No. 265 which is from unit I-2]

Sample No.	5	26	128	349	064	356	265
SiO_2	87.7	65.9	60.4	65.8	72.3	52.6	75.6
TiO_2	0.11	0.51	0.89	0.49	0.48	1.35	0.30
Al_2O_3	1.58	16.5	13.9	14.2	11.8	21.4	12.7
Fe_2O_3	3.96	7.29	10.0	5.66	4.32	8.85	1.60
MnO	<0.02	<0.02	0.25	0.11	0.04	<0.02	<0.02
MgO	0.10	0.44	6.72	5.60	2.81	0.89	0.97
CaO	<0.02	0.05	0.12	0.07	0.84	0.03	0.66
Na_2O	<0.15	<0.15	<0.15	<0.15	<0.15	0.25	4.50
K_2O	0.41	0.93	1.75	2.54	2.58	6.39	0.76
P_2O_5	<0.05	0.11	0.13	0.13	0.13	<0.15	<0.05
L.O.I.	1.31	7.71	5.70	4.32	3.65	7.67	1.67
Total	95.17	99.44	99.86	98.92	98.95	99.43	98.76

No. 5:   Silica alteration.

No. 26:   Quartz-sericite-pyrite-clay alteration.

No. 128: Quartz-sericite-chlorite-clay alteration.

No. 349: Quartz-sericite-pyrite-chlorite alteration.

No. 064: Quartz-sericite-pyrite-chlorite alteration.

No. 356: Quartz-sericite-pyrite alteration.

No. 265: Weak quartz-sericite-pyrite alteration.
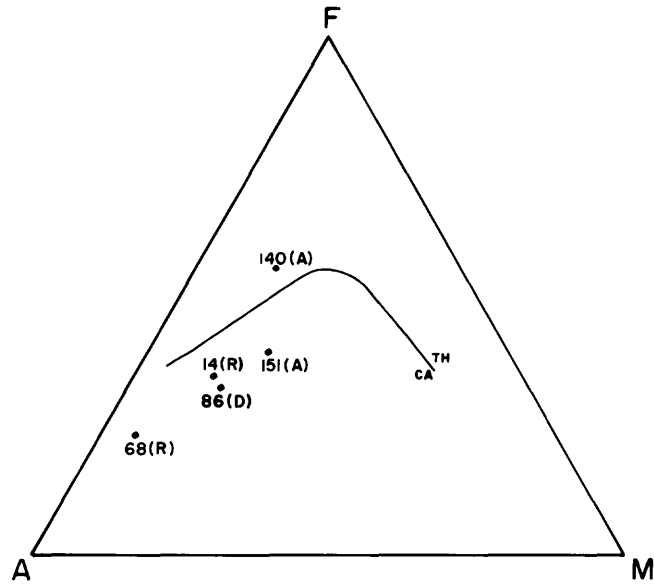
Figure 2a.—AFM plot of unaltered volcanic rocks
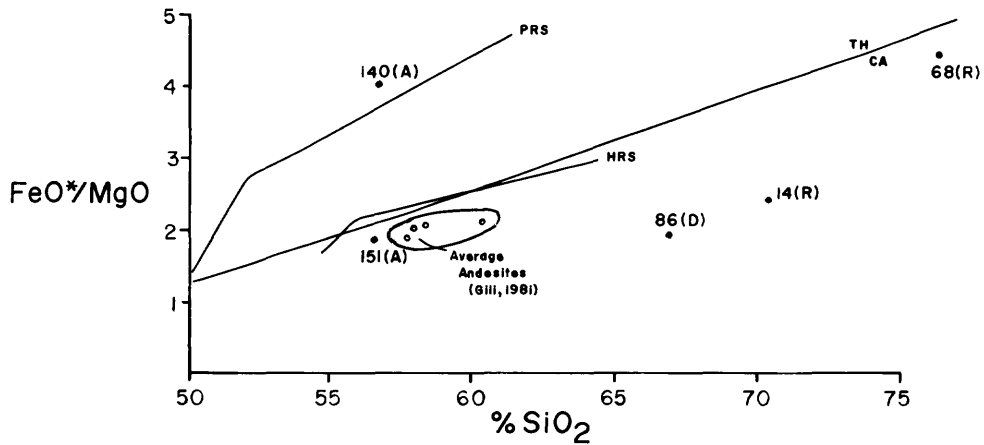

Figure 2b.—FeO*/MgO vs SiO$_2$ plot of volcanic rocks. Sample 140
from unit IIA is an iron-rich andesite, mapped as basaltic
andesite. These plots suggest that basaltic andesite mapped
in the study area is tholeiitic in composition, while the
remaining volcanic rocks are calc-alkaline. (A = andesite,
D = dacite, and R = rhyolite; average andesites (in oval)
are from Gill (1981))

Unit III extends east from the upper contact with units II and IIA, under the Columbia River Basalt on Cow Creek Saddle (pl. 1), almost 6 km to the fault with the Triassic sedimentary rocks. It consists mostly of andesite lavas and volcaniclastics with six felsic units, IIIA-F. Unit III differs from units II and IIA by the scarcity of sedimentary rocks, lack of coarse volcaniclastics, light-green to medium-blue-green color, and in the nature and distribution of the felsic rocks. Due to the general lack of observable contacts, structural trends are poorly known.

Although unit III is shown as a single unit on plate 1, there appears to be basis for subdividing it into three subunits, in addition to six felsic horizons. The first subunit would include all of unit III west of, and most of the unit south of the Columbia River Basalt. The boundary between the second and third subunits would lie between felsic units IIIC and D, 1.6 km east of the Basalt.

The first subunit consists mostly of andesite lavas with a few volcaniclastic rocks and about 1 percent dacite domes. Except for the felsic rocks, the rocks are similar to those in units I and II. The first subunit differs from units II and IIA by the lower amount of sedimentary rocks and absence of coarse volcaniclastics. Argillite and chert occur at the base near the contact with unit II in the southwest part of the area. This subunit is host to felsic horizons IIIA and B. Minor hydrothermal alteration is present throughout. The structure is not well known; there may be one or more folds in the southwestern part. The strike length is approximately 4250 m and the thickness approximately 700 m.

The rocks in the second and third subunits are similar to those in the first. The second subunit is defined by the common occurrence of a light-green color of the rocks. They consist mostly of andesite lavas and lapilli tuff, with minor dacite and rhyolite lavas and volcaniclastics. A few basaltic-andesite (probably tholeiitic andesite) lavas and volcaniclastic rocks may be present. This subunit is host to felsic horizon IIIC.

An apparent shear zone marks the boundary between subunits one and two, immediately south of the basalt. Overall, foliation in the second subunit is more intense and more variable than in any of the other units mapped, taken as a suggestion that the enire second subunit is a shear zone. The contact between the second and third subunits is marked by the gradual decrease in the intensity and variability of the foliation and may also be a structural contact. The strike of the rocks in the second subunit is unknown.

The third subunit is defined by: rare, apparently primary, igneous hornblende in all of the lavas; lithic lapilli that averages 5-15 mm, coarser than in the first two subunits; and a light-green to medium-blue-green color to almost all the rocks.

Andesite lapilli tuff in the southern part is more crystal rich than most of the other tuff. Andesite dikes are not common; they are most abundant about 1.5 km west of the fault contact with the Triassic sedimentary rocks. Dacite and rhyolite are irregularly distributed and consist of lavas and a few volcaniclastics. The third subunit is host to felsic horizons IIID-F.

There are six felsic horizons, units IIIA-F, that consist of 20 to 95 percent dacitic and rhyolitic rocks. The relative ages and stratigraphic positions of these units are not well established. For this reason, units IIIA-F were labeled sequentially from west to east; an age sequence is not implied. However, it appears that unit IIIB is younger than IIIA, that units IIID and E are approximately the same age, and that unit IIIF, the easternmost felsic horizon, is older than IIID and E.

The felsic rocks are very similar throughout the six felsic units, and differ considerably from those in units I, II, and IIA in that: the rhyolite lavas lack large quartz phenocrysts; the percentage of felsic rocks in the felsic horizons is higher; the felsic rocks are commonly thin bedded; and tuffs often have a dark-green matrix, even though they contain up to 10 percent euhedral and broken quartz phenocrysts.

The units mapped in this study differ from the formations mapped by Vallier (1977) which may be due to differences in either the characteristics, age, or both. The greater abundance of volcanic rocks in this area than in most of the area mapped by Vallier (1977) may indicate a greater number of volcanic vents. No fossil evidence was found that would allow the age of the units in the field area to be determined. T. L. Vallier (pers. commun., 1984) believes that, with the exception of the lower part of unit I, the entire sequence mapped in this study is Triassic in age, based on a comparison of these rocks with rocks elsewhere in the canyon.

Triassic system

Two formations are present, the Triassic (late Carnian to early Norian) Lucile Slate and Triassic (Norian) Martin Bridge Formation. The age relationship between the two formations in the field area could not be determined. The stratigraphic sequence is assumed to be Lucile Slate followed by Martin Bridge as determined by Lund and others (1983).

Lucile Slate

The Lucile Slate consists of argillite exposed on the east end of the field area and strikes N. 35° E. to N. 50° E. and dips 35° SE. It is in fault contact with the Seven Devils Group and, apparently, in thrust-fault contact with the Martin Bridge Formation. The slate consists predominantly of fine-grained, thinly laminated to thinly bedded, gray to black argillite and graywacke, and is often interbedded with sandstone, fine conglomerate, and volcanic tuff or compositionally immature volcanic sedimentary rocks. Calcite, gypsum, and pyrite are locally present. Isolated angular blocks of andesite and dacite up to 20 cm are thought to represent blocks that fell into the depositional basin from adjacent steep, subaerial or submarine slopes during deposition of the Lucile Slate.

Martin Bridge Formation

The Martin Bridge Formation is in fault contact with both the Seven Devils Group and Lucile Slate and strikes N. 50° E. to east-west. It is a fine-grained, nonfossiliferous, gray limestone with argillaceous interbeds up to several centimeters thick.

Triassic or Jurassic systems

Quartz diorite

A weakly jointed, light-colored, fine-grained quartz diorite is located in unit III west of the Columbia River Basalt. It contains 60 percent plagioclase, 1 percent K-feldspar, 25 percent quartz, 5-10 percent epidote, 5 percent chlorite, 1 percent magnetite, and trace augite, apatite, and sphene. Plagioclase (An_7) is slightly altered, augite partially altered, and K-feldspar completely altered.

Alteration of the intrusive rock and low anorthite content of plagioclase is taken to indicate that the intrusive was metamorphosed and sodium metasomatized. If so, it may be the same age as the metamorphosed intrusives in the Black Lake area of the Wallowa-Seven Devils Arc (White, 1968, 1973) and (or) the 234 Ma, upper-middle Triassic, metamorphosed, quartz-rich diorite in the Huntington Volcanic Arc (H. Brooks, pers. commun., 1983).

Quartz monzonite

Quartz monzonite is located in unit III east of the Columbia River Basalt and was mapped on a reconnaissance basis only. It is a variable, multiphase, fine- to medium-grained, hypidiomorphic, apparently unmetamorphosed intrusive. It may be similar in age to the unmetamorphosed, 121-127 m.y., middle-early Cretaceous Deep Creek Stock in the Black Lake area (White, 1973).

Miocene system

Columbia River Basalt

Exposures of massive, columnar Columbia River Imnaha Basalt (Swanson and others, 1981) are confined to the central and northwestern parts of the map area. A section of Columbia River Basalt several hundred feet thick is present along the ridge that forms Cow Creek Saddle.

Structure

West of the Columbia River Basalt, the rocks dip gently to moderately, and east of the Basalt, dip moderately to steeply. Two folds in unit II trend approximately north-south to N. 30° E., almost parallel to the foliation, and plunge gently to the south. Minor folds, observed only in units I and II, generally trend northwest to east-west and plunge to the southeast and east, respectively, although a northeast-trending, southwest-plunging anticline was mapped in the northeastern part of unit II. The variation in strike and dip of the units shown in the vicinity of the Blue Jacket mine is due to primary dips on the volcaniclastic rocks rather than to folding.

The general absence of observable bedding contacts east of Cow Creek Saddle made determination of structure difficult. An open, asymmetric, north-northwest trending fold and a northwest-trending fold are located east of the saddle.

Foliation generally parallels the strike of bedding in units I and II, although it is usually somewhat steeper. Foliation is more variable in strike in unit III.

A northeast-trending shear zone marks the boundary between the first and second subunits of unit III, immediately south of the Columbia River Basalt. Throughout the second subunit, foliation is locally very well developed, is commonly refolded on a small scale on variably oriented axes, and varies widely in strike on a large scale. This zone coincides with a north-northeast trending, post-Miocene normal fault, suggested to extend through this area by Swanson and others (1981), based on offsets of Columbia River Basalt both north and south of the study area. It is interpreted here as a pre-Miocene shear zone, reactivated following formation of the Basalt.

Near the eastern end of unit III, within about 1.6 km of the contact with the Triassic sedimentary rocks, foliation, bedding, and dike trends are more or less subparallel and strike approximately north to N. 20° E. About 600 m

west of outcrops of the Martin Bridge Formation there is a large zone of north-trending, intensely foliated rock that is locally folded to an east to northeast orientation. The orientation of the volcanics and folded foliation are thought to be due to deformation associated with accretion of the Wallowa-Seven Devils Volcanic Arc Terrane to the other terranes or to the continent.

Generally, faults were difficult to recognize in volcanic rocks due to the absence of marker horizons. Shears in unit I-1, related to the fault between unit I and the basement complex, cut lavas and volcaniclastics. Numerous small faults, striking both northwest and northeast, were observed underground and around the Blue Jacket mine; they are nearly parallel to the fold axes.

The contact between the volcanic rocks and Martin Bridge Formation is interpreted as a fault because the Martin Bridge is schistose and has flow folds near the contact. The fault between the Lucile Slate and Seven Devils Group, locally obscured by recent landslides, truncates the Seven Devils-Martin Bridge fault. It is interpreted to be in part a thrust fault that displaced the Lucile Slate northward over the Martin Bridge Formation based on the stratigraphy of Lund and others (1983).

Metamorphism

The rocks throughout the area, including the basement complex, have been metamorphosed. The minerals are typical of the greenschist facies, consisting mainly of chlorite, epidote, albite or oligoclase, and quartz. Variations in grade, if present, would be difficult to recognize due to the compositions of the volcanic rocks. Biotite and muscovite were not observed, probably because of composition rather than metamorphic grade.

The high Na_2O and low K_2O content of the volcanic rocks, including rhyolite, is thought to be due in large part to metasomatism during metamorphism as suggested by Vallier and Batiza (1978). However, the volcanic rocks may represent an originally low K_2O (Vallier and Batiza, 1978) and high Na_2O (T. L. Vallier, pers. commun., 1984) suite.

Locally, there are quartz, quartz-epidote, and calcite-epidote veins that crosscut all rocks in the Seven Devils Group. They are thought to be related to metamorphism, although barren milky-quartz veins cut the eastern part of the Miocene Columbia River Basalt in the central part of the area.

Mineralization and alteration

For the most part, mineralization is confined to two syngenetic, stratiform, pyritic Cu-Zn massive sulfide deposits in unit IIA, the largest of which is the Blue Jacket (Richey and LeAnderson, 1984). This deposit is at least 100 m thick and extends for more than 1000 m along strike and to the south from the mine shaft (pl. 1). In order of decreasing abundance, it consists of pyrite, sphalerite, chalcopyrite, tetrahedrite-tennantite, galena, and barite in stratabound stringer mineralization associated mainly with quartz-sericite-clay-pyrite altered rock. The few massive pyrite lenses observed contain base and precious metals, are up to 10 cm thick and 1-2 m in length, and appear to lie at several stratigraphic horizons over a vertical distance of about 10 m. They are capped by microcrystalline quartz, pyrite, and, locally, barite, that is in turn overlain by a 10 cm to 50 cm zone of quartz, clay, and limonite thought to have formed by oxidation of the deposit on the seafloor prior to the deposition of the overlying lavas and volcaniclastic rocks.

The second deposit consists of several blocks, up to 20 cm, of massive, oxidized pyrite in a copper-stained volcaniclastic flow associated with a dacite dome near the top of unit IIA. The dome is intensely altered over an area of approximately 25 m by 40 m.

Apparently unmineralized hydrothermal alteration is commonplace throughout units II and III. It is spatially associated with andesite, rhyolite, and dacite, but is most extensive when associated with the felsic rocks. The mineralogy is similar to alteration associated with the Blue Jacket deposit. Except for isolated mineralized shear zones, all altered rock is thought to be the product of submarine, exhalative systems. The mineral deposits and alteration of the study area will be discussed in more detail in a separate report by Richey and LeAnderson.

SUMMARY AND CONCLUSIONS

The lowermost unit in the field area is the basement complex. It consists mainly of an intrusive suite unit that began to form during the Pennsylvanian Period. The precursor to the intrusives is not exposed and is unknown. Furthermore, dikes that have their origin in the basement complex cut the lower Seven Devils which indicate that formation of the basement complex overlapped in time with deposition of the lowermost Seven Devils Group lavas. The ophiolite-like stratigraphy and rock types of the basement complex suggest that an ophiolite-like oceanic crust of mixed mafic to intermediate composition may form during the initial stages of intra-oceanic arc development, a possibility being investigated by the authors.

The absence of subaerial features, presence of pelagic sedimentary rocks, presence of overlying Triassic marine sedimentary rocks, together with pillow basalt elsewhere in the arc (Vallier, 1977), indicate that the Seven Devils Group formed in a submarine environment. The absence of limestone and coarse clastic rocks in the study area may be an indication of deeper water than elsewhere in the arc where such rocks have been reported. The nature and abundance of volcanics, scarcity of sedimentary rocks, and frequency of altered rocks in the study area indicate that the area was close to volcanic centers throughout its history, unlike areas studied by Vallier (1977). Preliminary chemical analyses indicate that most of the lavas and volcanic-related intrusions are calc-alkaline, although minor tholeiitic andesite, mapped as basaltic andesite, is present.

The Seven Devils Group was subdivided into three map units for this study. Unit I, the lowermost, overlies the basement complex and is in fault contact with it. The unit has been subdivided into units I-1 and I-2 based on amounts of the various rock types. The presence of plagiogranite dikes, identical to plagiogranite in the basement complex, crosscut the flows of unit I-1 indicating that formation of the basement complex and unit I-1 overlapped in time. The abundance of lavas, and scarcity of volcaniclastics in lower unit I-1 indicates that the early stages of arc formation in this area involved relatively quiet volcanic eruptions.

The first appearance of sedimentary rocks in unit I-2 marks the first occurrence of sediment transport and deposition in the area. A decrease in volume of sedimentary rocks towards the top of unit I-2 was probably due to a decrease in erosion rate, an increase in the rate of accumulation of volcanic material, or both. Felsic igneous rocks are minor throughout all of unit I.

Unit IIA represents an abrupt increase in the production and accumulation of felsic volcanic rocks following construction of the arc to a height of approximately 1600 m above the base of unit I. The increase in volume of

felsic rocks, presence of a high proportion of coarse volcaniclastic rocks, character of the volcaniclastics, and presence of sedimentary rocks at the margin of the unit indicate that this is a vent facies unit which formed a topographic high through repeated, local, phreatomagmatic eruption of felsic and andesitic magma. Hydrothermally-altered rock and two massive sulfide deposits were the product of a high heat flow and frequent, seawater-convecting hydrothermal systems. Unit IIA grades along strike into unit II. Andesite lavas, probably in part from more distal sources, are present in both II and IIA.

The distribution of rock types in unit II southwest of IIA indicates that unit II in this area had a volcanic history similar to unit I-2. To the northeast of IIA, however, unit II consists mainly of andesite. Hydrothermal alteration is more common in unit II northeast of IIA than to the southwest, which may indicate a higher heat flow and, possibly, more proximal volcanism.

Unit III is marked by the return to less explosive volcanism, with the exception of the felsic units, and differences of the felsic rocks in comparison to those in units I, II, and IIA. The absence of sedimentary rocks represents a return to erosional and depositional conditions more similar to those that prevailed in unit I-1 than in units I-2, II, and IIA. Commonplace, hydrothermally-altered rock indicates that there was sufficient fracturing and heat flow to lead to hydrothermal alteration, such as seen in units II and IIA.

It appears that unit III consists of three subunits, each with its own unique characteristics. The first subunit is located south and west of the Columbia River Basalt and is similar to units I and II. The second is present at the south end of the Basalt and extends 1.6 km east of it between units IIIC and D. This unit has variably oriented, refolded foliation, thought to be the result of shearing. The third subunit extends east to the contact with the Triassic sedimentary rocks. The lavas in the unit apparently contain primary igneous hornblende that indicates a different origin than for lavas elsewhere in the study area. The contact between the second and third subunits of III may be structural rather than depositional.

The age and thickness of the Seven Devils in this area could not be determined with certainty. T. L. Vallier (pers. commun., 1984) believes that the lowermost rocks of unit I are Permian and the remainder Triassic, based on a comparison with known Permian and Triassic rocks elsewhere in the Hells Canyon. The thickness of the Seven Devils Group in the study area totals approximately 3300 m (10,000 ft) west of the Columbia River Basalt in the central part of the field area. The thickness of unit III east of the Basalt is not known with certainty.

Deposition of Triassic Lucile Slate and Martin Bridge Formation represents termination of volcanic activity and formation of an argillite basin that, in time, progressed to formation of shallow-water carbonates. In the study area, the Lucile Slate is in fault contact with the Seven Devils Group; the fault may be a pre-Lucile Slate fault in the volcanics that formed a steep scarp above the Lucile argillite basin. It is not known if the argillite and Seven Devils Group in this area were in contact at the time of deposition of the Lucile Slate, or if they were juxtaposed through subsequent displacement on the fault. This fault truncates a fault between the Seven Devils and Martin Bridge. East of this intersection, it is interpreted as a thrust fault that displaced Lucile Slate northward and over the Martin Bridge Formation.

In the Triassic, the arc was intruded by dioritic plutons, thought to be represented in the field area by the metamorphosed quartz diorite in the southwestern part of unit III. In the late Triassic, the arc was mildly deformed along northeast- to- east-trending, easterly plunging axes and metamorphosed to the greenschist facies. It was probably at this time that the rocks were sodium metasomatized (Vallier and Batiza, 1978). In the late Jurassic, the area was deformed along north- to- northeast-striking folds that plunge gently to the south. The northeast-trending shear zone in unit III, south and east of the Columbia River Basalt, and northeast-trending folds in the schistosity at the east end of the area represent zones of intense penetrative deformation and shearing. These zones may have formed in the Jurassic or during accretion of the arc to the continent approximately 118 Ma (Lund, 1984; Sutter and others, 1984).

Erosion of the arc continued after accretion. By the Miocene it had reached the approximate level seen today. After deposition of the Columbia River Basalt, there was normal movement on the shear zone in unit III. Recent events consist of continued erosion and landslides near the town of Lucile, Idaho.

REFERENCES CITED

Anderson, A. L., 1930, The geology and mineral resources of the region about Orofino, Idaho: Idaho Bureau of Mines and Geology Pamphlet 34, 63 p.

Armstrong, R. E., Taubeneck, W. H., and Hales, P. O., 1976, Rb-Sr and K-Ar geochronometry of granitic rocks west of the Idaho Batholith in western Idaho and northeast Oregon: Geological Society of America Abstracts with Programs, v. 8, p. 350.

_____1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington, and Idaho: Geological Society of America Bulletin, v. 88, p. 397-411.

Ave Lallement, H. G., 1983, The pre-Tertiary tectonics of the Blue Mountains region, NE Oregon: Geological Society of America Abstracts with Programs, v. 15, no. 15, p. 372.

Ave Lallement, H. G., Phelps, D. W., and Sutter, J. F., 1980, ^{40}Ar-^{39}Ar ages of some pre-Tertiary plutonic and metamorphic rocks of eastern Oregon and their geologic relationships: Geology, v. 8, no. 8, p. 371-374.

Bond, J. G., 1978, Geologic map of Idaho (scale 1:500,000): Idaho Bureau of Mines and Geology.

Brooks, H. C., 1979, Plate tectonic and geologic history of the Blue Mountains: Oregon Geology, v. 41, p. 71-80.

Brooks, H. C., and Vallier, T. L., 1978, Mesozoic rocks and tectonic evolution of eastern Oregon and western Idaho, in Howell, D. G., and McDougall, K. A., eds., Mesozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 2, p. 133-145.

Cann, J. R., 1969, Spilites from the Carlsburg Ridge, Indian Ocean: Journal of Petrology, v. 10, p. 1-19.

Dickinson, W. R., 1979, Mesozoic forearc basin in central Oregon: Geology, v. 7, p. 166-170.

Field, C. W., Bruce, W. R., and Hendrickson, T. A., 1972, Mesozoic plutonism and mineralization of the Snake River boundary area, Idaho-Oregon: Geological Society of America Abstracts with Programs, v. 4, p. 503.

Gass, I. G., 1980, The Troodos Massif--Its role in the unraveling of the ophiolite problem and its significance in the understanding of constructive plate margin processes, in Panayiotou, A., Ophiolites: Proceedings, International Ophiolite Symposium, Cyprus, 1979, p. 23-35.

Gilluly, James, 1937, Geology and mineral resources of the Baker quadrangle, Oregon: U.S. Geological Survey Bulletin 879, 119 p.

Hamilton, Warren, 1963, Metamorphism in the Riggins region, western Idaho: U.S. Geological Survey Professional Paper 436, 95 p.

_____1969, Reconnaissance geologic map of the Riggins quadrangle, west-central Idaho: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-579, scale 1:125,000.

_____1976, Tectonic history of west-central Idaho: Geological Society of America Abstracts with Programs, v. 8, p. 378-379.

Hotz, P. E., Lanphere, M. A., and Swanson, D. A., 1977, Triassic blueschist from northern California and north-central Oregon: Geology, v. 5, p. 659-663.

Jones, D. L., Silberling, N. J., and Hillhouse, J., 1977, Wrangellia--A displaced terrane in northwestern North America: Canadian Journal of Earth Sciences, v. 14, no. 11, p. 2565-2577.

Lund, Karen, 1984, The continent-island arc juncture in west-central Idaho--A missing link in Cordilleran tectonics: Geological Society of America Abstracts with Programs, v. 16, no. 6, p. 580.

Lund, Karen, Scholten, R., and McCollough, W. F., 1983, Consequences of interfingered lithologies in the Seven Devils Island Arc: Geological Society of America Abstracts with Programs, v. 15, no. 15, p. 284.

Middlemost, E. A. K., 1972, A simple classification of volcanic rocks: Bulletin Volcanologique, v. 36, p. 382-397.

Morganti, J. M., 1972, Geology and ore deposits of the Cuprum area, Seven Devils District, Idaho: Pullman, Washington, Washington State University M.S. thesis, 152 p.

Mullen, E. D., 1979, Alkalic pillowed greenstone, Greenhorn Mountains, northeast Oregon: Geological Society of America Abstracts with Programs, v. 11, p. 119.

Myers, P. E., 1982, Geology of the Harpster Area, Idaho County, Idaho: Idaho Bureau of Mines and Geology Bulletin 25, 46 p.

Onasch, C. M., 1977, Structural evolution of the western margin of the Idaho Batholith in the Riggins, Idaho, area: University Park, Pa., Pennsylvania State University Ph.D. thesis, 196 p.

Palmer, A. R., 1983, Decade of North American Geology Geologic Time Scale: Geology, v. 11, no. 9, p. 503-504.

Richey, Scott, and LeAnderson, P. J., 1984, Geology of the Blue Jacket volcanogenic Ar-Zn massive sulfides, west-central Idaho: Geological Society of America Abstracts with Programs, v. 16, no. 4, p. 252.

Ross, C. P., 1938, The geology of part of the Wallowa Mountains, Oregon: Oregon Department of Geology and Mining Industry Bulletin 3, 74 p.

Rupke, N. A., 1978, Deep clastic seas, in Reading, H. G., ed., Sedimentary environments and facies: New York, Elsevier, p. 372-415.

Sarewitz, Daniel, 1983, Seven Devils terrane--Is it really a piece of Wrangellia?: Geology, v. 11, no. 11, p. 634-637.

Schermerhorn, L. J. G., 1973, What is a keratophyre?: Lithos, v. 6, p. 1-11.

Silberling, N. J., 1983, Stratigraphic comparison of the Wallowa and Huntington terranes, northeast Oregon: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 372.

Sutter, R. C., Snee, L. W., and Lund, Karen, 1984, Metamorphic, plutonic, and uplift history of a continent-island arc suture zone, west-central Idaho: Geological Society of America Abstracts with Programs, v. 16, no. 6, p. 670.

Swanson, D. A., Anderson, J. L., Camp, V. E., Hooper, P. R., Taubeneck, W. H., and Wright, T. L., 1981, Reconnaissance geologic map of the Columbia River Basalt Group, northern Oregon and western Idaho: U.S. Geological Survey Open-File Report 81-797, 5 maps, 35 p.

Vallier, T. L., 1977, The Permian and Triassic Seven Devils Group, western Idaho and northeastern Oregon: U.S. Geological Survey Bulletin 1437, 58 p.

Vallier, T. L., and Batiza, R., 1978, Petrogenesis of spillite and keratophyre from a Permian and Triassic volcanic arc terrane, eastern Oregon and western Idaho, U.S.A.: Canadian Journal of Earth Sciences, v. 15, no. 8, p. 1356-1369.

Vallier, T. L., Brooks, H. C., and Thayer, T. P., 1977, Paleozoic rocks of eastern Oregon and western Idaho, in Stewart, J. H., and others, eds., Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 1, p. 455-466.

Walker, N. W., 1983, Pre-Tertiary tectonic evolution of northeastern Oregon and west-central Idaho--Constraints based on U/Pb ages of zircons: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 371.

White, W. H., 1968, Plutonic rocks of the southern Seven Devils Mountains, Idaho: Corvallis, Oregon, Oregon State University Ph.D. thesis, 177 p.

_____1973, Flow structure and form of the Deep Creek Stock, southern Seven Devils Mountains, Idaho: Geological Society of America Bulletin, v. 84, p. 199-210.

APPENDIX

Detailed lithologic and petrographic descriptions

Volcanic rocks and subvolcanic intrusives

Lavas and subvolcanic intrusions are the dominant rock types in, and are confined to, the Seven Devils Group. They consist of basaltic andesite, andesite, dacite, rhyolite, and plagiogranite; basalt was not recognized. Rock types were identified in the field, based on total percentage of quartz phenocrysts and color and hardness of the groundmass. Petrographic and analytical data demonstrate that they are valid indicators of silica content in unaltered rocks, and that alteration is recognizable in the field. Plagioclase is the only feldspar phenocryst which precludes the use of plagioclase/K-feldspar phenocryst ratios in rock type identification.

Rock that is very dark green to green black, has a soft groundmass, and lacks quartz phenocrysts is termed basaltic-andesite; such rock generally has numerous augite phenocrysts. Rock that is light to dark green with a relatively soft groundmass, and also lacks quartz phenocrysts, is termed andesite. Rocks with quartz phenocrysts are subdivided into three groups: those with more than 5 percent quartz phenocrysts are termed rhyolite; those with about 5 percent are termed rhyodacite; and those with less than 5 percent, dacite, unless they have an exceptionally hard, and, therefore, presumably very siliceous groundmass, in which case they are mapped as rhyolite. Rocks with less than 5 percent quartz phenocrysts probably include quartz phenocryst-poor rhyolite. Little rhyodacite was mapped. In the absence of quartz phenocrysts, light-colored, hard, and, therefore, siliceous flows are mapped as either dacite or rhyolite, again depending on hardness of the groundmass.

This mapping scheme is based on the assumption that if silicification is present it can be identified in hand specimen, in thin section, or both. This assumption appears to be warranted. Alteration is common throughout the field area, but recognized alteration assemblages with quartz also contain abundant sericite, clay, or both, with minor pyrite. Silicification in the absence of these minerals was not recognized, which is typical of alteration associated with submarine, exhalative, hydrothermal systems. The effects of alteration on the groundmass of altered rocks were taken into consideration.

This mapping scheme allows for consistent classification of rock types, except that some rocks with low quartz phenocryst content mapped as dacite are probably rhyolite. When chemical analyses are available, the rocks are reclassified, if necessary, based on the scheme of Middlemost (1972). Under this scheme, the silica compositions (in percent) range from: 45 to 53.5 for basalt (not observed in the study area), 53.5 to 62 for andesite, 62 to 70 for dacite, and greater than 70 for rhyolite. Basaltic andesite is not recognized by Middlemost (1972). The composition of the basaltic andesite mapped indicates that it is tholeiitic andesite (table 1 and figures 2a and 2b). Plagioclase compositions were obtained using a U-stage.

The basement complex is the lowest stratigraphic unit and consists of 30 to 50 percent mafic dikes and 50 to 70 percent plagiogranite. Except for a few plagiogranite dikes that extend into the lower part of unit I-1 (pl. 1), plagiogranite is confined to the basement complex. Most plagiogranite has cumulate texture and consists of equigranular quartz and albite crystals as long as 2.5 mm. Near the top of the complex, phenocrysts as long as 5 mm are present; aphanitic plagiogranite occurs locally. Plagiogranite lacks mafic

minerals and ranges in color from off-white with green spots, due to abundant epidote, to very light gray to green, to pinkish gray; epidote is ubiquitous. Medium-grained plagiogranite is typically well foliated.

In thin section, medium-grained plagiogranite from near the base of the exposed section of the basement complex contains (in percent): quartz, 15; albite (An_6), 70-75; epidote, 1; chlorite, 3; opaque minerals, 1-2; and apatite, trace. About 5 percent sericite partially replaces albite, which is in stubby grains.

Mafic dikes, possibly of basaltic andesite and andesite composition, range in width from about 10 cm to 3 m. They are usually aphyric, but may contain rare mafic, possibly augite, phenocrysts as long as 1 mm and occasionally longer, in a groundmass with grain size of 0.1 to 0.5 mm. The mafic dikes are generally medium to dark green gray and locally schistose. They appear to cut the plagiogranite. In thin section, a light-green, relatively felsic sample from the upper part of the complex contains (in percent): epidote, 60; quartz, 30; magnetite and hematite, 1-2; chlorite, 2-3; leucoxene, 3; and sphene, less than 1. One percent apatite is found only in quartz.

A few massive basaltic-andesite lavas and sills with dark-green augite phenocrysts have been tentatively identified in unit I-1 and in unit III east of Cow Creek Saddle. However, these dark lavas are probably iron-rich, tholeiitic andesite, such as sample 140 (table 1 and fig. 2) from unit IIA.

Andesite lavas, dikes, and sills range in thickness from about 0.5 m to several tens of meters and compose approximately 80 percent of the rocks. Relatively light-green basaltic andesite, green aphyric dacite, and very fine-grained andesite tuff may have been mapped as andesite due to the lack of distinguishing characteristics. This is a likely possibility in unit III east of Cow Creek Saddle where light-green to medium blue-green, well-foliated rocks are apparently andesitic in composition.

West of Cow Creek Saddle, it was relatively easy to distinguish dikes and sills from lavas; however, in unit III east of the saddle, contacts were rarely observed. Where only a single contact was observed that could be either an intrusive or lava flow contact, the rock in question was mapped as a dike. East of the saddle, dikes are exposed in greatest number at the east end of unit III immediately west of the Martin Bridge Formation. Here, dikes are about 1 m wide and have epidote halos extending up to 10 cm into the wall rock.

Andesite lava flows are mostly massive, granular textured, fine grained, and weakly foliated. One flow in unit IIA is columnar jointed. The flows are mostly medium to dark green, with medium green the most common. West of Cow Creek Saddle, maroon, green-gray, and occasionally black andesite occurs. Light-green andesite is relatively common only east of the saddle. Grain size is less than 1 mm for most rocks; coarser grained varieties are due to abundant epidote. Some andesite is aphyric, but most contain 0.5 mm to 2 mm plagioclase phenocrysts as long as 10 mm. Minor augite is the most common mafic mineral. Primary, igneous hornblende has been tentatively identified immediately south of Cow Creek Saddle in unit III and east of a line between units IIIC and D. Augite phenocrysts average about 1 mm and hornblende phenocrysts about 3 mm. In hand specimen, phenocrysts of all types are commonly difficult to recognize in green andesite because of the masking green color of epidote. Overall, the phenocryst content ranges from about 2 to 15 percent, rarely reaching several tens of percent.

Vesicles and amygdules are present in andesite but are not common. Both are up to about 5 mm in diameter and may be round, oval, or irregular in

shape. The amygdules are generally filled with epidote and one or more of calcite, quartz, or, less commonly, actinolite and hematite. Rarely, in unit III east of the saddle, lavas contain angular to moderately rounded rock fragments as long as 2 cm in diameter that are apparently the same composition or slightly more mafic than the andesite host. Spherulites, of presumed devitrification origin, are also locally present.

In thin section, green-gray andesite from unit IIA contains (in percent): plagioclase, 65 to 75; opaques, 5 to 20; chlorite, trace to 10; calcite, 0 to 3; leucoxene, trace to 3; epidote, 0 to 3; sericite and clay, trace to 1; and apatite and zircon, trace. There are several percent, 0.5 to 2 mm, glomeroporphyritic, generally subhedral plagioclase phenocrysts; in one thin section, they have inclusions of apatite and zircon. Felty plagioclase microlites are commonly intergrown with other minerals, including, in some samples, quartz. Both plagioclase and mafic phenocrysts are partly altered to sericite, clay, or both, as well as chlorite and calcite; a few are completely altered to calcite.

A sample of green andesite from unit IIA contains (in percent): plagioclase, 45; epidote, 30; augite, 5 to 10; chlorite, 10; actinolite, 5; quartz, 1; and opaque minerals, trace. The green color is due to a high percentage of epidote. The reason for local high epidote content is unknown. Plagioclase phenocrysts include: 1 to 2 percent subhedral to euhedral, square to rectangular grains as long as 1.4 mm; subhedral laths in the groundmass that are 0.1 to 0.5 mm in length; and a few percent, stubby plagioclase grains as long as 0.5 mm in length. The first two types have thin albite twins and a composition of An_7. Plagioclase is commonly partly altered to epidote, chlorite, and actinolite; the phenocrysts are usually less intensely altered than the groundmass grains. Subhedral, 0.3 to 0.5 mm augite phenocrysts are commonly altered to actinolite, epidote, and chlorite.

The composition of an andesite from unit IIA is given in table 1 and figure 2. In comparison with three samples of keratophyre reported by Vallier and Batiza (1978), this andesite has similar silica and sodium, and generally higher potassium, contents.

Dacite lavas, domes, sills, and possibly dikes average about 5 percent by volume, except in felsic horizons where they reach 90 percent. About 10 percent of the felsic rocks lack quartz phenocrysts and textures indicative of a volcaniclastic or sedimentary origin. They have been mapped as dacite if they have a gray to purple color and siliceous groundmass—features typical of dacite. In and around unit IIIE in the eastern third of the field area, there are numerous light-green flows, and possibly tuffs, of apparent dacite composition. They are commonly well foliated, thought to be the result of shearing that destroyed primary textures.

Dacite is present in all units and is irregularly distributed. Most dacite flows, as well as volcaniclastics, are clustered in felsic horizons as are rhyolitic rocks, the basis for mapping these horizons as separate units. Units I-1, I-2, and II average about 1 percent dacite and unit III about 2 percent. The felsic units average (in percent): IIA, 5; IIIA, 90; IIIB, 60; IIIC, 40; IIID, 90; IIIE, 20; and IIIF, 20.

Individual dacite flows appear to be up to several meters thick. The lateral extent could only be determined confidently in unit IIA, where they are apparently up to 300 m in length; they appear to be smaller in the other units. Dikes were not observed, but dacite occurrences less than 1 m wide east of Cow Creek Saddle may be sills or dikes because they are uncharacteristically thin for lavas.

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Endogenous and exogenous domes are present in units II, IIA, and IIIC. They are about 5 m to 250 m in length and up to 100 m in height; in unit IIIC, they often consist of several lava and volcaniclastic flows.

Dacite lavas are usually massive. When well foliated, they were difficult to distinguish from tuff. One dacite, near a small massive sulfide at the top of unit IIA, is columnar jointed. Most dacite is gray, but west of Cow Creek Saddle mottled green and white dacite is also present; east of the saddle rare dark-green dacite occurs. Both gray, and mottled green and white, dacite have 5 to 10 percent opaque minerals, trace epidote, leucoxene, sphene, and chlorite, and rare apatite. The mottled green and white dacite contains more chlorite and fewer opaque minerals, and is commonly sheared.

Most dacite has an aphanitic to fine-grained groundmass of quartz and albite. Ninety percent of dacite west of the saddle is porphyritic with between 1 and 3 percent each quartz and plagioclase (An_{0-3}). East of the saddle, dacite is commonly aphyric, but locally has up to 5 percent quartz and 2 percent feldspar and 2-3 mm hornblende phenocrysts not found west of the saddle. Quartz phenocrysts in both areas are euhedral to subhedral, bipyramidal to anhedral, and as long as 3 mm; feldspar is up to 3 mm. Vesicles and amygdules were not observed except in a few large lithics in volcaniclastic units.

Rhyolite lavas, dikes, and sills are very similar to dacite in appearance and distribution except that they are less abundant. Rhyolite is rare in units I-1, I-2, and II, averages about 5 to 10 percent in unit IIA, up to 5 percent in units IIIA-F, and 0-1 percent in unit III outside of units IIIA-F. Contacts were not commonly observed. Dikes and sills are confined to unit IIA, including one dike that is at least 1000 m in length. Rhyolite lavas appear to be up to several meters thick and long. In unit III they are commonly dome shaped. Three domes in unit IIA are the largest in the field area, ranging from 50 m to 350 m thick. The largest is at least 1000 m in length and is located at the base of unit IIA below the Blue Jacket Cu-Zn massive sulfide deposit. It is columnar jointed in the thickest part which is located in the epidote alteration zone of the deposit.

Rhyolite is usually off-white to dark maroon in units IIA and III, but is occasionally purple-gray in unit IIA, light green in IIA and III, or dark gray in III. Definitive flow banding was observed only in rhyolite blocks in lapilli tuff in units I-1 and II. Rhyolite, similar in texture to dacite, is usually massive, but is well jointed and locally weakly foliated.

The groundmass of rhyolite lavas is usually aphanitic, but may be up to a few tenths of a millimeter. Quartz phenocrysts are anhedral to bipyramidal and usually up to 5 mm, although they reach 10 mm in units I and II. They are generally present in amounts up to about 10 percent but reach 20 percent. Up to 25 percent subhedral to euhedral plagioclase phenocrysts as long as 10 mm are sometimes present; potassium feldspar and mafic phenocrysts, vesicles, and amygdules were not observed. Thin section analysis of two samples from unit IIA shows 15 to 25 percent plagioclase phenocrysts and 30 percent plagioclase in the groundmass, 5 to 10 percent quartz phenocrysts and 15 to 25 percent in the groundmass, 1 to 15 percent chlorite, 5 to 10 percent opaque minerals, 1 percent plagioclase spherulites, and trace epidote, sphene, leucoxene, and sericite.

Volcaniclastic rocks

The most abundant volcaniclastic rocks are andesite tuff with lapilli, fine andesite lapilli tuff with lapilli less than 15 mm, and andesite and

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dacite lapilli tuff. Volcaniclastics of mixed andesite and dacite composition are locally abundant in unit IIA. Andesite tuff and dacite tuff breccia are present locally; other compositions are rare. The relative abundance of the compositions of volcaniclastic rocks are the same as the flows.

Volcaniclastics are often green due to chlorite and minor epidote. Microscopically, the matrix is similar in texture to flows. It consists of fine-grained quartz, plus other minerals, and euhedral and broken crystals of plagioclase and occasional quartz. Broken and unbroken crystals are in greatest abundance in units IIIA-F.

Lithics are usually angular to subangular, may be round, and appear in some cases to have been flattened in, or rotated into, the plane of schistosity. Overall, they range in size from a few tenths of a millimeter to 50 cm in diameter; most are lapilli between 5 and 30 mm. Lithics usually exhibit little range in size in a single unit. They are present in abundance from trace amounts to 85 percent, but are generally less than 60 percent. Volcaniclastic rocks are usually not sorted but may exhibit graded bedding, with the number of lithics decreasing in both abundance and size toward the top of the unit.

Lithics are from lavas, sometimes vesiculated, or tuff. They are often of the same composition as the matrix, especially in tuff with lapilli and lapilli tuff, but may be either more mafic or felsic than the matrix. Occasionally, in units III and IIIA-F, lithics are altered to quartz-sericite-pyrite, cut by quartz veins, or both, while the groundmass is unaltered. Monolithic dacitic or andesitic units are present; in units III and IIIA-F andesitic volcaniclastics are usually finer grained than dacitic ones.

Tuff is not common but is present throughout. It is mostly coarse andesitic tuff that contains angular lithics less than 1 cm in diameter. Fine-grained, lithic-absent ash tuff, if present, was not recognized or could not be distinguished from lava flows.

Volcaniclastic units are often well foliated, especially tuff with lapilli and lapilli tuff. This is also true of most of the volcaniclastic rocks in units III and IIIC-F east of the saddle, where they are commonly very light green and schistose. Where schistose, they are difficult to distinguish from sheared, schistose flows, especially at the east end of the field area where shears are common and well developed within 1.5 km of the fault between the volcanic and Triassic sedimentary rocks.

Basaltic-andesite volcaniclastic rocks were tentatively identified only at a few localities in unit III, approximately 1.5 km east of Cow Creek Saddle. They consist of fine tuff with lapilli.

Andesite volcaniclastic rocks are found in all units. Andesite tuff is most abundant in unit IIA and is minor in units III and IIIC-F. In unit III, the lapilli content of andesite lapilli tuff is highest in the middle geographic third of the unit east of the saddle, including units IIID and E; the crystal content is highest, up to 30 to 40 percent, in the middle one-half of unit III east of the saddle, along the southern limits of the study area. Andesite volcaniclastic rocks are light to dark green and are usually monolithic. They are at least 300-400 m in length and 15-20 m in height.

In unit IIA volcaniclastic rocks consist in part of variably mixed dacite and andesite lithics and matrix and are termed "andesite-dacite." Some are almost 100 percent andesite, but those approaching 100 percent dacite are extremely rare.

The andesite-dacite volcaniclastics often contain twice or more felsic as andesitic lithic fragments. The felsic fragments are identical to dacite lavas. They are aphanitic, purple to gray, and sometimes contain albite

phenocrysts but not quartz phenocrysts. Andesite lithic fragments are green, light green, or greenish gray, softer than the felsic lithic fragments, usually aphanitic, and may be microporphyritic with albite phenocrysts. Both andesite and felsic fragments range from angular to round. The matrix is usually green to light greenish gray, contains albite phenocrysts, and ranges from very hard, siliceous, and nonfoliated, if there is a high felsic component, to usually soft and well foliated, if there is a high andesitic component.

A chemical analysis of a sample from unit IIA (table 1; fig. 2) shows approximately 50 percent each felsic and andesitic components. The clasts are predominantly felsic; the matrix andesitic with broken quartz phenocrysts and with several areas consisting mainly of quartz and albite. Chlorite is in clots along foliation planes and disseminated in the matrix.

Andesite-dacite volcaniclastic rocks are of local extent and appear to consist of several flows. Individual flows range from a few tens of centimeters thick and a few meters long to about 10 m thick and 30-40 m long. Units consisting of several flows are up to about 20-25 m thick and extend at least 270 m.

Andesite-dacite volcaniclastic rocks may be pyroclastics formed by eruptions of felsic magma that incorporated accessory and accidental andesitic material, or vice versa. Alternatively, they may be pyroclastic rocks that subsequently slid downslope due to gravity or submarine currents. These flows may have incorporated material from various other units, producing epiclastics with the cited characteristics. Evidence for a pyroclastic origin includes: lack of sedimentary features, including grading; lack of fragments of a wide range of composition, especially sedimentary; lack of a sedimentary component to the matrix; local concentration near felsic domes; and lack of flows of 100 percent felsic composition that would be expected if both compositions were commonly present on the seafloor and mixed by slumping. The continuum between felsic and andesitic composition may be evidence of a sedimentary origin, because this might not be expected if mixing were the result of incorporation of accessory material. It is the opinion of the authors that they are dominantly pyroclastic flows formed by phreatomagmatic eruptions, and may have been locally remobilized.

Dacite volcaniclastic rocks are found throughout, and are most abundant in unit III and IIIA-F, where they are commonly within a few tens of meters of flows or domes of similar composition. The volcaniclastics are up to 10 m thick and apparently several tens of meters in length. They are usually gray to light green and contain up to 5 percent euhedral, unbroken quartz phenocrysts. Only a few units have a hard, siliceous matrix; high contents of dark-green chlorite are locally abundant.

Rhyolitic volcaniclastics are limited to a few outcrops in unit I-1 and in the southeastern section of unit IIID. They are similar to dacite volcaniclastic rocks except that they contain more than 5 percent quartz phenocrysts in a chloritic matrix. Between Cow Creek Saddle and unit IIID, unit III contains only about 5 percent volcaniclastics, almost all of which are andesite tuff with small lapilli, and lapilli tuff. From the west side of unit IIID to the east side of unit IIIE, unit III contains an average of about 15 percent volcaniclastics, mainly crystal-rich andesite tuff with lapilli, and lapilli tuff in the southern part; both the crystal and lapilli contents are higher here than elsewhere in unit III. East of unit IIIE, unit III contains only a few percent tuff with small lapilli; one area about 1000 m in diameter contains no volcaniclastic rocks.

Unit IIIC contains about 10 percent dacite tuff with small lapilli, and lapilli tuff associated with dacite lavas and domes. Unit IIID contains about 10-15 percent tuff with small lapilli, and lapilli tuff, most of which are felsic in composition, including the only occurrence of rhyolite volcaniclastic rocks in the study area. Unit IIIE appears to contain about 5 percent dacite tuff with small lapilli, but much of the unit is intensely altered and lacks primary textures. No volcaniclastic rocks were recognized in unit IIIF. Overall, unit III east of Cow Creek Saddle contains fewer and finer volcaniclastic rocks than unit IIA, taken to indicate less explosive volcanism, more distal volcanism, or both, especially at the east end of unit III.

The mechanism of formation of andesite, dacite, and rhyolite volcaniclastics is thought to be phreatomagmatic eruption, the result of the interaction of seawater and shallow magma. Gaseous eruption, through expansion of volatiles in a magma, is thought to be unlikely due to the general absence of vesiculated material. The fine-grained, usually equigranular, quench texture of hyaloclastites is absent. Andesite flow breccias in unit IIA that have fragments with little matrix are present in only a few outcrops in unit IIA. They probably form by brecciation of flows, possibly in part through a phreatomagmatic type of process.

Volcanic-associated sedimentary rocks

Volcanic-associated sedimentary rocks consist of several types of fine-grained clastic material, chert, and epiclastic rocks. They are the only sedimentary rocks in the Seven Devils Group in the study area and are found in units I, II, IIA, the lowermost part of III, and in the eastern two-thirds of unit III east of the Columbia River Basalt.

The chert may be in part hydrothermal in origin. The clastic rocks are almost always bedded and are thought to represent locally derived, reworked volcanic material. One variety consists of compositionally immature, low-matrix debris or grain flows such as are found at the base of modern submarine canyons where there is volcanic activity and high relief (Rupke, 1978, p. 394). The clastic rocks in the study area could consist of remobilized hyaloclastites. They make up a body of felsic, epiclastic, sedimentary rocks in the southern part of unit III and IIIA that is at least 400 m thick. Some are interbedded with volcanic rocks in unit IIA where they are thinner and have more matrix than those in unit II. They are rare in unit I-2 and absent in III and IIIA-F.

The clastic sedimentary rocks are slightly greenish gray, coarse grained, 0.5 mm to 25 mm, average 2 mm, and consist of equant, subrounded, moderately sorted to well-sorted grains of quartz, feldspar, and lithics. The quartz content varies from zero to 20 percent in some beds. The beds are generally medium layered to very thickly layered; graded bedding was not observed. The medium-thick layers are often continuous over 30 to 40 m and appear to reach 100 m in length. An analysis of a volcanic sediment from unit II is given in table 1.

Epiclastic breccias have heterolithic, subangular to rounded fragments. They are sorted to poorly sorted and sometimes graded, with a green to maroon and gray tuffaceous matrix that often has an argillite component. Fragments of dacite and andesite lavas are commonly mixed with other types of fragments.

A thin section of a sample from the middle of unit IIA shows several types of subrounded fragments, some of which have been partially replaced by calcite. They are in a matrix of silt-sized, interlocking, probably

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recrystallized quartz, clay, sericite, calcite, and clay-size black and red opaque minerals. Parts of the matrix consist entirely of reddish opaque silt.

Epiclastic tuff, found in units I-1 and IIA, is massive to medium layered and lithic-poor with an argillite component to the matrix. The tuff commonly contains 10-25 percent, 0.5 mm to 4 mm, plagioclase grains, is usually not graded, and is commonly poorly sorted. It therefore represents a transition from tuff to wacke.

Other epiclastic rocks range from andesite-dacite volcaniclastics to those with a mixture of clast types, including occasional sedimentary clasts in a greenish matrix. The extent of development of epiclastic features in the andesite-dacite volcaniclastics is taken to represent the degree of mobilization and mixing of the pyroclastic prototype with other material.

Volcanic graywacke is immature and ranges from thickly laminated to medium layered. They are gray or brown to maroon, and have moderately to poorly sorted, equant, subangular, medium-grained to fine pebble-size lithic fragments, albite, and rare quartz. The matrix is tuffaceous and ranges from 20 to 80 percent. Volcanic graywacke is often slightly graded and exhibits flame and scour structures and rare crossbedding. These units are commonly local in extent and are often interbedded with argillite. They weather rapidly; the best exposures are in road cuts.

Argillite is found in units I-1 and II where it is up to 25 m thick. It consists of light-green, maroon, red, and dark-purple, thinly laminated to thinly layered, very fine grained to silt-size sedimentary rocks. The maroon, red, and dark-purple colors are probably due to variable amounts of hematite. Occasional well-sorted, coarse-sand horizons, up to 10 mm thick, are usually bedded, commonly have scour and soft-sediment deformation features, and are often discontinuous. Petrographic analysis of a light-green sample from unit I-2 has (in percent): quartz, 50; epidote, 15; plagioclase, 30; and chlorite, 5; a chemical analysis of this sample is given in table 1.

Light-green, relatively siliceous argillite is found in units IIA, II, and III east of Cow Creek Saddle. It is less than 1.5 m thick, thinly laminated to thinly layered, occasionally massive, has a conchoidal fracture, and is often similar in appearance to chert. Siliceous argillite differs from other argillite in that it is thinner, very continuous and uniform in thickness, and lacks scour and soft-sediment deformation features. One sample contains interlocking grains of approximately 60 percent quartz and 40 percent plagioclase with trace chlorite, epidote, opaque minerals, and secondary chlorite. Another more siliceous sample contains 2 mm to 10 mm white spots that may be devitrification features.

The origin of the light-green argillite may differ from other varieties. Limited outcrop evidence indicates that one of the 60-cm-thick units may be at least 350 m in length. This, combined with a possible initial glass composition, may indicate that these units formed from a magmatic eruption of siliceous magma that produced a large submarine air-fall deposit.