NATURAL RESOURCES

GEOLOGIC MAPPING AND GEOTHERMAL ASSESSMENT OF THE UPPER WIND RIVER VALLEY AND SOUTHEAST FLANK OF MOUNT BAKER, WASHINGTON

by Jessica L. Czajkowski, Jeffrey D. Bowman,
David S. Tucker, and Logan A. Fusso

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Prepared for the U.S. Forest Service
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Publications List:
http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/pubs.aspx

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Published in the United States of America
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Part 1: Geologic Mapping and Geothermal Assessment of the Upper Wind River Valley, Skamania County, Washington

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INTRODUCTION

The Wind River Valley, a northwest-trending valley draining southeastward into the Columbia River Gorge near Washington's southern border (Fig. 1) is a subject of interest in geothermal exploration. There are numerous thermal and mineral springs and seeps along and adjacent to this valley, several of which are now or were previously developed into resorts, such as Bonneville and Carson Hot Springs. Temperature gradients measured in several temperature-gradient boreholes drilled in the early 1980s revealed elevated gradients within this valley. In addition, several water wells at the southern end of the valley, near the town of Carson, contain warm water. Based upon the presence of thermal and mineral springs, relatively young intrusives, and warmer water along the valley's axis, some workers postulate that a structure channels high heat flow from cooling intrusives at depth within and along the length of this valley.

The Washington Department of Natural Resources (WADNR), Division of Geology and Earth Resources (DGER), has recently conducted a geothermal data compilation program within Washington State, including the Upper Wind River valley. This work was funded by federal grants from both the U.S. Department of Energy and U.S. Forest Service and includes geologic mapping, thermal and mineral spring water chemistry analyses, temperature-gradient logging in existing wells, and drilling several temperature gradient holes up to 700 feet deep. One of these boreholes is located in the Upper Wind River valley, near Tyee Springs (Fig. 1, Plate 1). The borehole site was chosen because of its proximity to several springs, postulated faults, earthquakes, and aeromagnetic anomalies. It also is sited where there was previously a lack of gradient data, as higher gradients have already been established in the lower reaches of the valley.

New geologic mapping of the Upper Wind River valley (Fig. 1) was undertaken to better understand the geology, age, and nature of alteration, to obtain structural data, and to improve upon the accuracy of existing mapping in support of the recently drilled borehole. In addition, several thermal and mineral springs in the Wind River Valley (Fig. 1) were re-analyzed for major-element chemistry, as well as helium, oxygen, and deuterium isotopes. An accurate assessment of geologic conditions both at the surface and at depth is critical to future development of geothermal resources and it is the first step in exploration.

PREVIOUS WORK

The Wind River Valley area was first mapped at 1:62,500-scale by William Wise in 1961 and later mapped as part of a reconnaissance-style, geochemistry-based geothermal project at 1:24,000-scale by Berri and Korosec (1983). Mapping was subsequently revised for this area by Korosec (1984) within the Hood River 1:100,000-scale geologic map. Other compilation geologic maps that include this area include Hammond (1980) and Bela (1982).

Spring sampling and/or temperature monitoring was repeatedly conducted over the last half a century at most of the springs in and around the valley, including Government and Little Wind River Mineral Springs, and St. Martin (Carson), Rock Creek, Shiperds (St. Martin on the Wind), and Bonneville hot springs (Fig. 1).

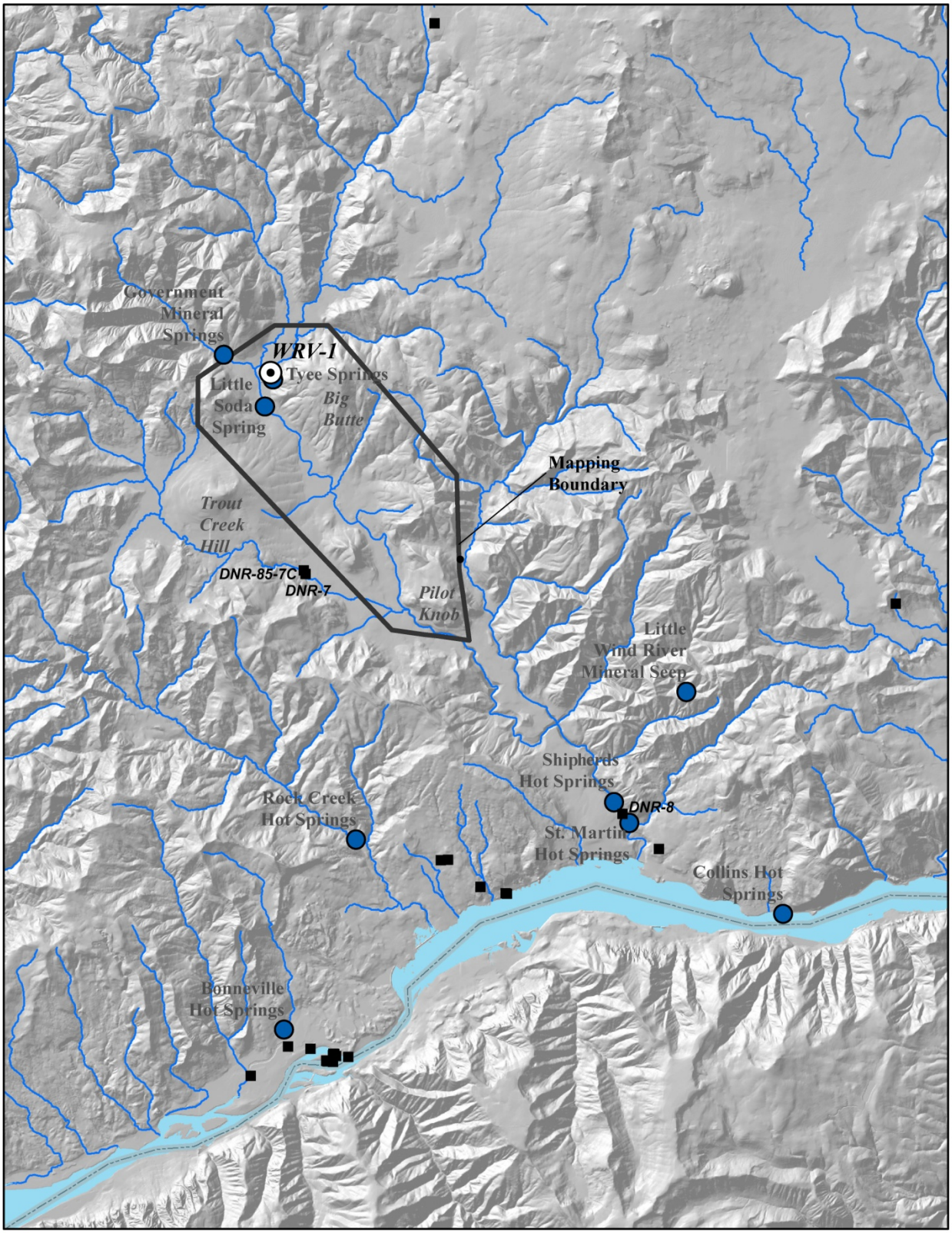

Figure 1. Upper Wind river valley and vicinity showing map area, thermal and mineral springs (blue circles), temperature-gradient boreholes (black squares), and recently drilled temperature-gradient borehole WRV-1 (center left).

In the early 1980s, three temperature gradient boreholes, DNR-85-7C, DNR-7 (DNR-TRCK), and DNR-8 (DNR-CRSN), were drilled by the DGER—two near the Stabler-Hemlock Ranger Station and one near Carson (St. Martin) hot springs, respectively. The two gradient holes near the Stabler-Hemlock Ranger Station yielded gradients between 75 and 79°C/km. The Carson borehole yielded a recalculated gradient of 166°C/km, although earlier reports use a much higher gradient for this well. In addition, elevated temperature gradients were previously measured in several pre-existing local water wells, especially towards the southern end of the Wind River valley.

METHODS

Geologic mapping was primarily performed during the month of June, 2012. A series of U.S. Geological Survey 7.5-minute topographic maps was used as a base map, but contact locations were generally refined by reference to a 10-meter digital elevation model (DEM), aerial photos, and field observations. Access to observation locations was obtained primarily by either largely abandoned or decommissioned Forest Service logging roads, the Pacific Crest Trail, and through off-road terrain traverses. Field samples were collected for comparison and further thin-section analysis. Thin sections were created by Spectrum Petrographics.

Drilling of the temperature-gradient borehole was conducted in early August of 2012 by Schneider Equipment, Inc. & Drilling Co. Drill cuttings were collected every 10 feet for identification. In preparation for drilling, we also performed a small, active seismic survey at the drill site in an attempt to determine depth to bedrock.

Natural gamma and spontaneous potential were measured within the borehole using a Century Geophysical borehole logging tool prior to 2-inch casing installation and well completion. After well completion and a three-to four-week period of equilibration, temperature-gradient logging will be performed using a Hobo temperature logger.

GEOLOGIC SETTING

Geomorphic Setting

The map area (Fig. 1) lies along the Cascade crest, south of Mount St. Helens, at elevations between ~650 and 3400 feet above mean sea level. Valleys are typically steep-sided, and the area is heavily forested with old- and second-growth timber. The northern and eastern portion of the map area consists of a series of sharp ridges and broad crests, including Big Butte, Warren Ridge, and Pilot Knob. The central portion of the map area consists of the Wind River valley, a broad, generally level alluvial channel within the northern portion of the valley, which narrows significantly at the southern portion of the field area, likely controlled by adjacent bedrock and younger, volcanic flows beneath the alluvium there. Much of the western third of the field area consists of broad, gentle slopes covered with dense forest.

Geologic Overview

The upper Wind River valley is predominantly underlain by shallowly west-dipping, intercalated pyroclastics and volcaniclastics of Eocene to Oligocene age; it is possible that the upper portions of the deposit in this area are lower Miocene in age. These rocks were originally called the Skamania Series by Felts (1939a,b) and later the Weigle formation by Wise (1961), but were later associated with the Ohanapecosh Formation (Wise, 1970; Bela, 1982; Hammond, 1980; Berri and Korosec, 1983; Korosec, 1984).

Hypabyssal diorite and gabbro intrusions of late Oligocene to early Miocene age are exposed in numerous locations within the map area, and in many places, were observed to alter the regional layering orientation of the overlying Ohanapecosh Formation. In general, emplacement of these intrusives can be associated with abundant alteration and silicification of the Ohanapecosh Formation, especially in the northwest portion of the map area. Based on field mapping and the amount of alteration and silicification, we speculate that, in general, much of the area is underlain by shallowly buried intrusives.

There are two Miocene basalt/basaltic andesite flows in the northeastern portion of the map area intruded within the Ohanapecosh Formation. In addition, numerous predominantly northeast- and northwest-trending basaltic and andesitic dikes traverse the map area.

The eastern flank of the Quaternary-age Trout Creek Hill volcano is in the western third of the map area. The rubbly flows consist of relatively unweathered, scoriaceous dark gray basalt with abundant labradorite phenocrysts.

In general, exposure of this basalt was poor along the flank of the volcano. Flows from vents were directed east into the Wind River Valley, around Bunker Hill and downvalley to the Columbia River.

Quaternary unconsolidated sediments in the field area include rockfall and talus deposits, landslide deposits, colluvium, alluvial fans, and alluvium. These units are mapped, yet are not differentiated.

DESCRIPTION OF MAP UNITS

We sought to show bedrock units; however, we also attempted to note where Quaternary sediments were especially thick and obscured any evidence of underlying bedrock units. In some areas, due to poor exposure, we relied considerably on geomorphology, field relations, and subsurface records. See Figure 2 for a map of our field observation sites.

Quaternary Unconsolidated Deposits

Qs **Unconsolidated sediment**—Locally derived deposits including talus, rockfall, landslide, colluvium, alluvial fans and alluvium; excludes modified land. These units were not studied in any detail and were mapped to note where bedrock was obscured.

Talus deposits flank most steep ridges, and are especially prominent below areas underlain by intrusive rocks, such as the north flank of Bunker Hill (mapped), the upper portion of the south flank of Big Butte, and the south flanks of both Warren Ridge and Pilot Knob (not mapped).

A large rockfall deposit was noted below a cliff of diorite on the southeast flank of the ridge immediately north of the Trout Creek Hill volcano. Across the Wind River valley to the east, the west flank of Big Butte is blanketed by several large landslide deposits, generally situated within west-dipping, slope-parallel volcaniclastic deposits of the Ohanapecosh Formation. Identification of these slides was in part due to hummocky topography, pistol-butt trees, and an uncharacteristic lack of bedrock exposure.

Thick deposits of loose, poorly sorted, angular colluvium and alluvial fans obscure bedrock exposures on the lower portions of most ridges and peaks, especially along west-facing slopes where the general bedding attitude of the volcaniclastics parallels that of the slope.

Alluvium deposits composed predominantly of sandy gravel line the lowest portions of the Wind River valley north of Bunker Hill. Near Bunker Hill, well records indicate that these deposits are intercalated with the basalt flow from Trout Creek Hill, which flowed upstream, blocking water flow temporarily in this area. No alluvium was observed within the river channel south of the intersection of the Wind River and Trout Creek.

Quaternary Volcanic Rocks

Qvb(tch) **Basalt of Trout Creek Hill**—Scoriaceous, dark blackish-gray basalt with phenocrysts (<1 mm) of subhedral, locally included labradorite and anhedral olivine within a groundmass containing microlitic euhedral albite and granular pyroxene. Outcrop of this basalt is extremely poor along the flanks of the volcano, but the unit is well exposed south of the intersection of Trout Creek within the Wind River channel. Here the river has etched 100- to 200-foot-high cliffs within these flows. K-Ar ages of 0.34 ±0.07 and 0.338 ±0.075 Ma were obtained from this unit south of the map area by Korosec (1984) and Berri and Korosec (1983), respectively.

Qvb(ih) **Basalt of Indian Heaven**—Highly vesicular, dark grayish-black basalt. Outcrop of this basalt is nonexistent within the northeast-trending upper Wind River Valley northeast of the U.S. Forest Service Fish Hatchery. However, this flow was encountered in the newly drilled geothermal borehole WRV-1 (Plate 1) between 6 and 51 feet. Neighboring well logs indicate that this flow does not extend to the Fish Hatchery. No direct age has been obtained from this flow, but its maximum age is constrained by the basaltic andesite flows of Juice Creek; a K-Ar age of this unit obtained outside of the map area by Korosec (1987) and Korosec (1989) yielded an age of 1.4 ±0.06 Ma.

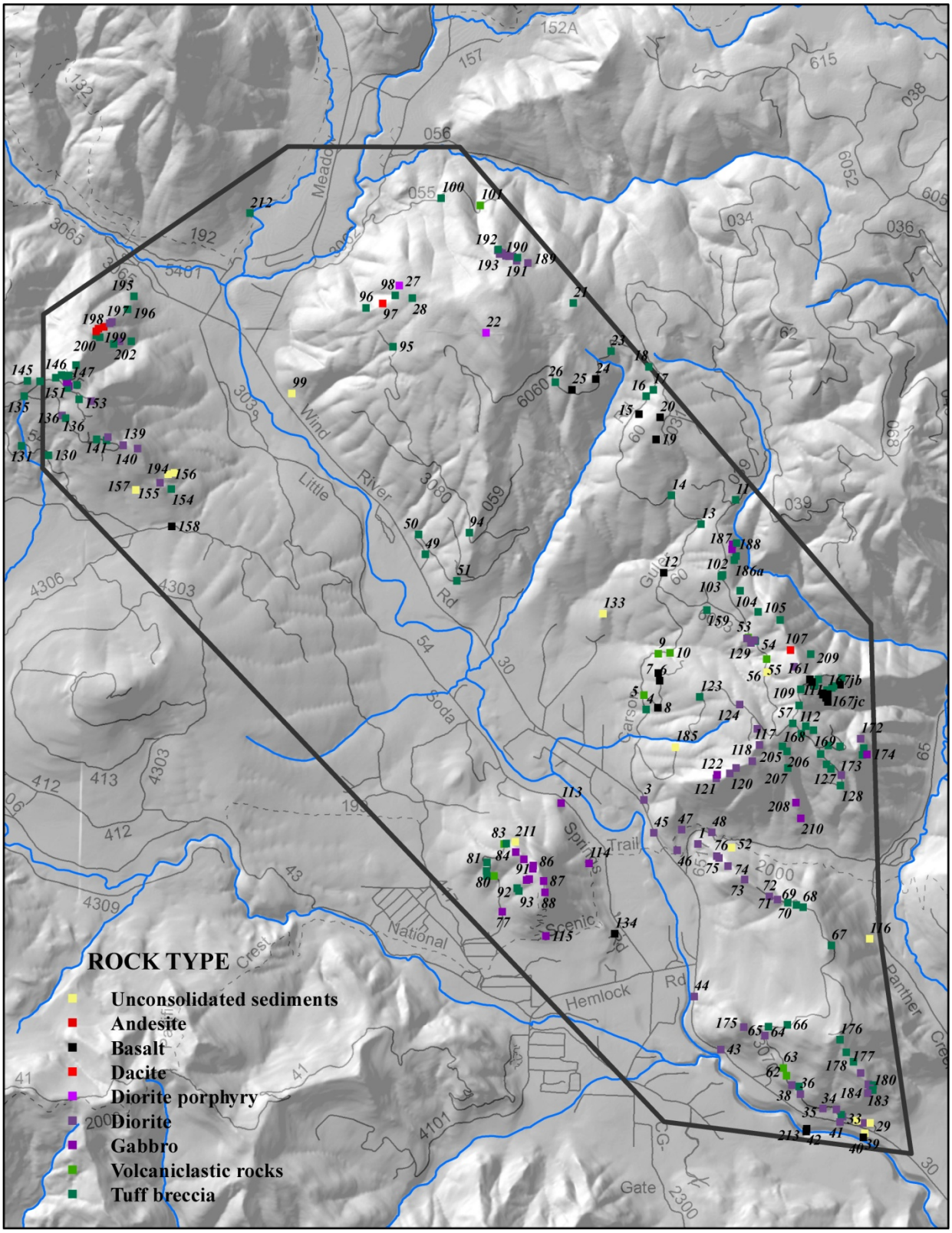

Figure. 2. Upper Wind River valley and vicinity showing field observation sites and corresponding rock types.

Miocene Volcanic Rocks

Mvb **Basalt and basaltic andesite**—Dark grayish-black to dark blackish-gray, seriate to porphyritic basalt to basaltic andesite. These small flows have been quarried extensively in the past. Korosec (1987) obtained a whole-rock K-Ar age of 20.8 ±1.2 Ma from a basaltic andesite sample within this unit southeast of Big Butte. Geochemistry from samples of the basalt and basaltic andesite (map numbers 1, 2, and 7) originally presented in Korosec (1987) is shown on Table 1.

Miocene to Oligocene Intrusive Rocks

OMi **Dikes**—Dark gray to black, predominantly aphanitic to fine- to medium-grained hypabyssal rocks of basaltic and andesitic composition, although textures locally range between intrusive and extrusive; locally composite, scoriaceous, and variably weathered. Additionally, a dacite dike was found west-northwest of Big Butte. These dikes were either previously unmapped or erroneously mapped as either part of dioritic sills and plugs or as interbedded lava flows within the Ohanapecosh Formation (Wise, 1961, 1970; Berri and Korosec, 1983; Korosec, 1987). Dikes generally are geomorphologically distinct, creating narrow, elongate ridges, and at times can be followed for thousands of feet. We suspect that there are additional dikes in the map area, yet time constraints and poor exposure were prohibitive.

Berri and Korosec (1983) obtained an age of 22.7 ±0.9 Ma from a dacite sample taken 0.6 miles to the southwest of the Hemlock Ranger Station (Plate 1, Table 2). The dacite was tentatively interpreted to be an interbedded flow in the Ohanapecosh Formation, and because of its young age, was thought to be thermally reset by heat from nearby diorite emplacement. Berri and Korosec (1983) also noted that the exposures of basalt, basaltic andesite, and dacite flows within the Ohanapecosh Formation could not be traced for any appreciable distances. We suspected that many of these flows are instead dikes or clusters of dikes, as we noted little to no demonstrable instances of observable intercalated flows within the Ohanapecosh Formation in the map area. We visited the dacite sampling location shown in Berri and Korosec (1983), which upon first glance, showed very similar geomorphic surficial expression to dikes mapped in the field area. There, we noted a 50- to 100-foot-wide ridge of light gray, extremely hard dacite traversing northwestward vertically up a hillside, clearly truncating gently northwest-dipping tuff and tuff breccia beds on either side of it. We have tentatively assigned the 22.7 Ma age instead to dike emplacement, based on this field evidence and the abundance of dikes of variable composition in the area.

Geochemistry for several samples previously considered to be flows interbedded within the Ohanapecosh Formation (Berri and Korosec, 1983; Korosec, 1987) that we are interpreting to be dikes are shown on Plate 1 and Table 1; map numbers 11, 12, and 4).

OMid **Diorite**—Dark gray to light brownish-gray, variably weathered, locally altered, fine- to medium-grained aphyric diorite containing equigranular subhedral to anhedral plagioclase, anhedral to recrystallized quartz, pyroxene, sulfide minerals, and abundant clay minerals. All thin section samples of diorite contain a pervasive, regular and closely spaced shear fabric, wherein plagioclase laths are rotated along shear planes and plagioclase laths outside of these zones are randomly oriented. Texture typically becomes cryptocrystalline adjacent to contacts with surrounding rock. Alteration is significant within a small diorite body upon the ridge north of Trout Creek Hill. Diorite locally includes unmapped areas of gabbro, but it is also possible that these areas contain as-yet unidentified dikes. Some exposures of the diorite appear to have cooled at shallow depth, exhibiting columnar jointing. Berri and Korosec (1983) obtained a K-Ar age of 23.2 ±1.0 Ma for the diorite from the southwest flank of Warren Ridge along the Wind River Highway (Plate 1, Table 2). Subdivided into:

OMidp **Diorite porphyry**—Highly weathered, light reddish-brown, pilotaxitic diorite with a fine-grained microlitic matrix with abundant clay mineralization and abundant plagioclase porphyry with secondary quartz intergrowth. This unit was only noted on the crest of Big Butte. Geochemistry for samples of diorites originally published in Berri and Korosec (1983) and Korosec (1987) are shown on Plate 1 and Table 2; map numbers 5, 6, 8, 9, and 10.

Table 1. Normalized major element analysis of igneous rocks in the Wind River map area. Data originally presented in Berri and Korosec (1983) and Korosec (1987).

Map No.	Sample ID	Lithology	Unit Symbol[1]	SiO2	TiO2	Al2O3	Fe2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Total
3	3	Gabbro	Migb	53.60	1.35	19.20	4.34	4.98	0.15	3.01	8.01	4.33	0.78	0.24	99.99
4	4	Andesite/diorite	Mi	56.56	1.78	16.43	5.10	5.84	0.19	2.61	5.42	4.77	1.02	0.29	100.01
5	5	Diorite	Mid	56.91	1.92	15.45	4.85	5.56	0.20	2.81	6.20	4.01	1.61	0.48	100.00
6	6	Diorite	Mid	56.69	1.84	15.86	4.78	5.48	0.19	3.03	5.91	4.15	1.64	0.44	100.01
8	8	Diorite	Mid	61.77	1.44	14.76	4.42	5.06	0.18	1.48	5.57	3.50	1.37	0.46	100.01
9	9	Diorite	Mid	55.10	1.81	15.93	5.49	6.28	0.22	3.20	6.42	4.24	0.99	0.32	100.00
10	10	Diorite	Mid	57.64	1.88	16.40	4.26	4.89	0.17	2.81	5.87	4.29	1.49	0.31	100.01
1	8597	Basalt	Mvb	52.68	2.13	17.03	2.00	9.16	0.18	4.27	8.90	2.50	0.85	0.31	100.01
2	8554	Basalt	Mvb	52.77	2.00	16.78	5.33	6.11	0.17	4.29	8.53	2.73	0.95	0.33	99.99
7	5539	Basaltic andesite	Mi	55.09	2.41	14.96	5.44	6.23	0.18	3.83	7.74	2.53	1.21	0.39	100.01
11	5535	Basaltic andesite	Mi	55.26	1.43	17.97	4.34	4.97	0.16	3.86	6.52	4.12	1.14	0.23	100.00
12	5534	Andesite	Mi	58.16	2.02	15.69	4.62	5.29	0.16	2.99	6.20	3.10	1.32	0.45	100.00

[1] Unit symbols shown from this study and do not always correspond to previous mapping.

OMigb **Gabbro**—Dark brownish-gray, equigranular to porphyritic, medium-grained, composed of embayed and included plagioclase and pyroxene porphyry with minor alteration to hornblende; groundmass composed of plagioclase, clay minerals, and sulfide minerals. This gabbro is predominantly found on Bunker Hill, although this lithology was also noted within the large body of diorite on top of Warren Ridge, as well as in several dikes on the east and southeast flank of Warren Ridge. We suspect the gabbro found within the diorite on Warren Ridge may also be dikes intruding the diorite. In addition, we encountered a small, poorly exposed, yet distinct body of hornblende gabbro porphyry near the top of the ridge north of Trout Creek Hill. Here, hornblende phenocrysts are large (2–3 mm) and subrounded, accompanied by smaller plagioclase in a fine-grained matrix containing plagioclase, minor quartz, and orthopyroxene. The geochemistry for a sample of gabbro on Bunker Hill originally published in Berri and Korosec (1983) is shown on Plate 1 and Table 2; Map number 3.

Eocene to Oligocene Volcaniclastic Rocks

EOvc(o) **Ohanapecosh Formation**—Massive, 1- to 3-meter-thick layers of matrix-supported, coarse-grained crystal-lithic and vitric lapilli tuff breccia, interlayered with a roughly equal amount of thinly bedded tuffs, pebbly diamictites, highly incompetent silty sandstones and siltstones, and other, less abundant, thinly to thickly bedded aquagene-volcaniclastic deposits. Bedding within thinly bedded volcaniclastic units is generally defined by primary ash content, as well as the amount and degree of sorting of larger clasts within clayey, weathered matrices. Tuff breccias are locally vesicular, margins of these layers are frequently baked, and deformed fiamme were noted preferentially oriented parallel to layering, suggesting hot, subaerial deposition. Wise (1961) noted an abundance of logs within the lower portions of many tuff breccias. We also noted abundant woody debris within a relatively thick portion of silty sandstone in borehole WRV-1.

Much of this unit is highly weathered to clay. In addition, alteration of this unit is highly variable and localized; typically, the matrices (and to a lesser degree, clasts) of the unit have been silicified and/or zeolitized, and this alteration generally increases adjacent to intrusive bodies. Silicified tuff breccias and volcaniclastics are typically resistant and outcrop well. We noted minor contact metamorphism to hornfels at intrusive contacts.

Table 2. Whole-rock K-Ar age determinations for the Wind River valley area.

Map Number	Geologic Unit	Age (Ma)	Description	Source	Latitude	Longitude
1*	Qvb(tch)	0.34 +/-0.07	Whole rock analysis performed at Oregon State University	Korosec (1987)	45.75597	-121.83693
2*	Qvb(tch)	0.338 +/- 0.075	Whole rock analysis performed at Oregon State University	Korosec (1987)	45.71777	-121.79962
3	Mvb	20.8+/- 1.2	Whole rock analysis; Average of two analyses	Korosec (1987)	45.86944	-121.92869
4	Mi?	22.7+/- 0.9	Whole rock analysis of dacite performed at Oregon State University; Originally mapped as dacite flow within Ohanapecosh Formation (Berri and Korosec, 1983; Korosec, 1987)	Korosec (1987)	45.79561	-121.93793
5	Mid	23.2+/- 1.0	Whole rock analysis performed at Utah Research Institute	Berri and Korosec (1983)	45.82262	-121.91332
6*	EOvc(o)	32.8+/- 0.8	Whole rock analysis performed at Mobil Research Laboratory; Unit MOvt(3) from Phillips (1987)	Phillips (1987)	45.75512	-122.05249
7*	Mva	23.6+/- 1.2	Whole rock analysis of andesite flow of Three Corner Rock; Average of two analyses	Phillips (1987)	45.79284	-121.99975
8*	PLiq(w)	4.9+/- 0.8	Whole rock analysis on Wind Mountain diorite porphyry	Korosec (1987)	45.71247	-121.76224
9*	PLiq(w)	6.6 +/- 0.7	Whole rock analysis on Wind Mountain diorite porphyry	Korosec (1987)	45.70349	-121.74607

* Not shown on Plate 1

Stratigraphy within the Ohanapecosh Formation in the area did not lend itself to mapping subunits, as exposure was poor enough to prohibit following individual flows or layers for any mappable distance. Nor were general rock types within this unit sufficiently thick to do so. We also chose to not differentiate the upper stratigraphic portions of this unit, previously distinguished by Korosec (1987) as unit Tvt(3). We noted no stratigraphic marker or change, either by lithology or degree of weathering, that defines the contact between the Korosec (1987) reportedly lower Miocene and Eocene–Oligocene volcaniclastics.

The age of this unit is ultimately not clear, and the anomalously young age reported in Berri and Korosec (1983) and Korosec (1984) may be based in part on a radiometric age obtained from a possibly miss-assigned dacitic rock. Fiske and others (1963) assigned an Eocene age to the unit based on fossil leaf evidence. Fossils from an upper portion of the unit near Nelson Creek to the south of the map area near the Columbia River yielded an Oligocene age. A whole rock K-Ar analysis was obtained from tuffs and tuff breccias in this unit ~7 miles to the southwest of the map area at 32.8 ±0.8 Ma (Phillips, 1987). The minimum age of the unit here is limited to the Oligocene by (1) dioritic intrusions that intrude the unit, dated at 23.2 ±1.0 Ma (Korosec, 1987), and (2) ~3 miles to the west of the map area, the unit underlies andesite flows of Three Corner Rock, dated at 23.6 ±1.2 Ma (Phillips, 1987).

Alteration and Structure

Primary layering of tuff breccia and volcaniclastic rocks of the Ohanapecosh Formation dips gently west-southwestward, with a mean orientation of 152/14 (Fig. 3). Exceptions to this orientation occur at or near contacts with dioritic intrusions, where layers are either deflected and upwarped by the intruding mass or deformed into series of poorly developed faults and folds. Deflection of this layering can easily be observed along the Wind River Highway between mile markers seven and eight, where a thinly to thickly interbedded sequence of volcaniclastics is upwarped into an apparent anticline surrounding a well-exposed underlying mass of diorite. The gentle, southwestward regional dip of bedding is likely responsible for the large slope failure of the west flank of Big Butte, where bedding dip is slope-parallel.

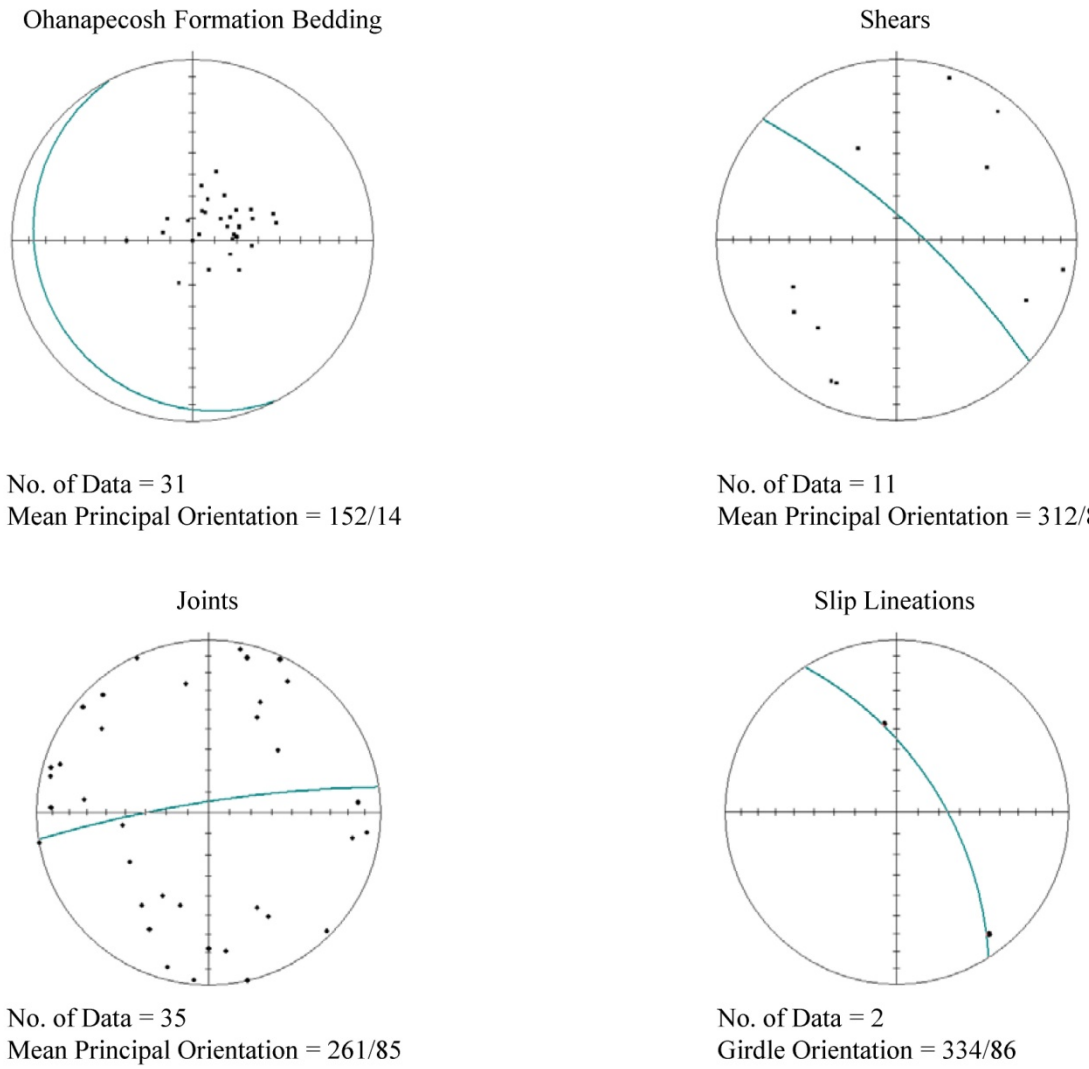

Figure 3. Stereonets showing structural data from the upper Wind River valley.

Several workers have inferred the presence of faults or fault-like lineaments along the length of the Wind River Valley (Bela, 1982; Hammond, 1980; Berri and Korosec, 1983). However, on-the-ground evidence for such features is limited. There is a dearth of bedrock exposure at lower elevations, as well as the large amount of Trout Creek Hill basalt along the valley floor that would obscure evidence for pre-late Quaternary deformation. We agree with the inference that a structure of some kind exists, however, as a high percentage of measured shears possess a valley-axis-parallel trend (Plate 1). The mean shear surface orientation trends 312/81. Although few were encountered, slickenlines upon these surfaces suggest strike-slip to shallow oblique-slip motion (Fig. 3); relative direction of slip could not be determined from these surfaces. We also noted a consistent, pervasive shear fabric within nearly all diorite thin section samples from the field area, with a millimeter-width spacing of subparallel shears defined by rotated and aligned plagioclase laths. While a discrete fault surface along which deformation occurred is possible, the widespread distribution of shearing may suggest that deformation in the northern portion of the valley was distributed among several faults of smaller displacement rather than a narrow, discrete zone of deformation. Berri and Korosec (1983) suggested that activity along this zone is closely tied to dioritic intrusion, which appears to become progressively younger to the southeast. In Oregon, in addition to the Gate Creek and the Blue Ridge faults, workers have recently detected several northwest-trending 1- to 2-meter-high fault scarps that traverse the Oregon rim of the Columbia Gorge from the northern flank of Mount Hood and project toward the Wind River Valley. The

orientation and location of these demonstrably young faults support the hypothesis that deformation gets younger to the southeast along this zone.

There are a few northeast-southwest-oriented faults mapped across the Wind River valley near Carson, including the Little Wind River fault, crossing the valley near Carson Hot Springs, and the Bear Creek fault, crossing the valley ~3 miles to the north, following the trend of Bear Creek (Berri and Korosec, 1983). Similarly, based upon limited evidence including (1) outcrop-scale fault observations on the west flank of Bunker Hill and (2) geomorphic abnormalities on the northwest flank of the southern portion of Warren Ridge, we have tentatively mapped similarly oriented structures to the north within the current study area. Limited exposure along trend of these postulated structures hampered further investigation or characterization. We infer that these structures, if they exist, are likely part of the series of northwest-southeast-trending fold-and-thrust-belt structures, more abundant to the east of the study area.

An oblate area of intense alteration and silicification was noted on the east-west-trending ridge immediately north of the Trout Creek Hill volcano (Plate 1). This zone appears to be concentrated along several northwest-southeast-striking faults that cross the ridge. Abundant granulitic and highly vesicular, locally amygdaloidal silica and aluminum-rich sinter with a locally penetrative crenulation cleavage (4 mm-scale) lies within these zones and lines fractures in adjacent diorite bodies. A thin section of the sinter appears to show secondary quartz mineralization along small microfaults oblique to the crenulation cleavage. The diorite contains abundant blebs of recrystallized quartz. The alteration was likely produced by repeated movement of gas- and silica-rich fluid along faults and fractures within a geothermal system shortly after emplacement and cooling of the diorite. However, the timing of alteration is at this point unclear, and could be younger.

TEMPERATURE-GRADIENT BOREHOLE WRV-1

During August of 2012, a 287-foot-deep geothermal test hole (WRV-1) was drilled using air rotary methods in the northern Wind River valley, at an informal group campsite approximately 1,000 feet northwest of Tyee Springs. Rock cuttings collected during drilling revealed approximately 45 feet of basalt of Indian Heaven overlying a significant thickness of older Wind River alluvium containing significant amounts of water. The alluvium was prone to caving, and as a result, we opted to advance casing through this unit. Bedrock was encountered at a depth of 187 feet, consisting of a thick, poorly cemented, interbedded silty sandstone and siltstone section of the Ohanapecosh Formation. We reached a depth of 341 feet, but due to the tendency of the formation to cave, and the abundance of water, the borehole backfilled from lower, uncased portions of the hole to 287 feet. Because of the extreme difficulty in maintaining an open hole, we ultimately opted to stop drilling and set the 2-inch casing to 287 feet. This hole is currently equilibrating and will be logged for temperature gradient towards the end of September to early October.

CONCLUSION

Geologic mapping of the upper Wind River valley illustrated the presence of a network of Miocene-age dikes which had previously been interpreted as either interbeds within the Ohanapecosh Formation or as part of larger intrusive bodies. These dikes roughly parallel the trend of the valley, suggesting that a northwest-southeast-oriented zone of weakness has existed since Miocene time. While no direct evidence for a through-going fault or faults was found during mapping, other geomorphic, mineralogic, and structural data provides strong evidence for their presence. We found no indication for young geothermal activity, but pervasive fossil hydrothermal alteration suggests this area was a resource at one time.

Further work in this area should be concentrated southward within the lower portion of the valley toward Carson. Higher temperatures in springs and wells, and an abundance of intersecting northwest- and northeast-trending faults suggest higher heat flow and greater permeability. In addition, there appears to be evidence for young deformation in that area. We noted a vegetated, southeast-facing, northeast-trending, scarp-like feature crossing Pleistocene-age Trout Creek Hill basalt approximately 1.6 miles southeast of the high bridge north of the town of Carson. Where this linear feature intersects the Wind River, the river bends sharply 90 degrees to the northeast and the gradient of the river increases visibly. Within the river channel is a dense network of northeast- and northwest-trending fractures in diorite.

Challenges to exploration in the lower Wind River valley include abundant private land ownership, a significant lack of roads in the steep-sloped uplands, the presence of large landslide deposits at the mouth of the river, and the

fact that all of the area adjacent to the Columbia Gorge lies within the highly protected Columbia Gorge National Scenic Area.

Further work, including detailed geologic mapping, would be necessary to delineate the structure crossing the Wind River valley and to accurately characterize bedrock lithology, structure, geomorphology, and alteration of the valley and adjacent uplands. Shallow geophysical surveys, shallow borings, and/or a paleoseismic trench across the structure would provide additional useful subsurface information. In general, the area would also greatly benefit from a lidar survey and from ground- or air-based geophysical surveys. Lidar significantly increases the likelihood of locating geomorphic evidence for active faults in heavily wooded terrain, and geophysical surveys are non-invasive methods for obtaining subsurface information. While several temperature-gradient boreholes exist at the mouth of the Wind River valley, one or more additional deep (>2,000 feet) boreholes at or near fault intersections would likely provide valuable heat-flow information.

ACKNOWLEDGMENTS

This geologic map was funded by the U.S. Forest Service under award no. AG-046W-P-11-0108. Spring sampling and borehole drilling and logging was funded by U.S. Department of Energy grant no. DE-EE0002850.

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Part 2: Geologic Mapping and Geothermal Assessment of the Southeast Flank of Mount Baker, Mount Baker–Snoqualmie National Forest

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INTRODUCTION AND DESCRIPTION OF THE STUDY AREA

A geologic field survey to identify evidence for recent or current hydrothermal activity and related alteration of soil or rocks was made in the Mount Baker Geothermal Nomination Area in June and July of 2012. The Nomination Area is shown on Plate 2 and consists of U.S. Forest Service lands that are either currently part of a geothermal lease or have been nominated for a geothermal lease, subject to auction in less than two years. This mapping project was conducted in support of these lease nominations or lands.

The mapped Nomination Area lies on the east flank of Mount Baker volcano and extends from 135 meter elevation at the mouth of Rocky Creek in the Baker River valley to nearly 1500 meters on the divide between Sulphur and Dillard Creeks. Topography is characterized by deeply incised, subparallel, eastward-flowing valleys of Rocky/Sulphur, Dillard, Sandy, and Park Creeks, radiating from the east and south flanks of Mount Baker, and the intervening steep-sided ridges. The Nomination Area largely omits the drainage of Boulder Creek. Virtually the entire area is covered with dense second-growth forest, although some old growth survives in the western portion of some valleys and on a few ridge crests, notably Forest Divide. Cross-country travel is arduous, visibility due to heavy brush cover is often a few meters or less, and travel is often above the ground on prostrate tree or shrub stems or fallen logs. Thick duff buries the forest floor. Away from roads, the few rock exposures are rarely visible from more than 10 to 20 meters. Road cuts provide the best rock exposures and the most certain place to find and examine the geology. Even along roads, rock exposures are sparse; along 3 kilometers of Road 1131, for example, only three widely separated rock outcrops were observed, two of which were no more than 5 meters across; all three are wholly due to road building. The most likely place to find rock exposures other than road cuts is along the courses of the steepest streams, which have very locally stripped colluvium and till.

GEOLOGY

The lowest elevations in the Baker River valley are dominated by the 8,800-year-old basaltic andesite of Sulphur Creek (Hildreth and others, 2003; Tucker and others, 2007; Tucker and Scott, 2009). This lava flow also fills the upper valley of Sulphur and Rocky Creeks; the two streams are separated by the lava flow. Other rocks are slivers of thrust-faulted metasedimentary and meta-igneous units, generally metamorphosed by Mesozoic and Cenozoic subduction and accretion. These rocks include greenstones (principally of the Chilliwack Group) and argillite and phyllite of the Nooksack Formation. Other rocks include a large dacite unit south of Rocky Creek, the chaotic Bell Pass mélange, and mid-to-late Pleistocene lava of the Mount Baker Volcano Field (Hildreth and others, 2003). Glacial till mantles virtually the entire landscape save the steepest rock faces and cliffs. Alluvium fills the bottoms of all stream valleys. Geology in the isolated sec. PB48, T37N R8E, in the southeast corner of the Nomination Area consists of large amounts of late Pleistocene to early Holocene lacustrine sediment draping Sulphur Creek lava and Nooksack Formation phyllite (Tucker and Scott, 2009).

There are several geologic maps of the area. Three Master of Science students under supervision of Western Washington University Professor Dr. E. H. (Ned) Brown made the original metamorphic basement rock maps in the Nomination Area. Charles Ziegler (1985) mapped much of the western and northern portion of the Nomination Area. Moira Smith (1986) studied the rocks south of Rocky Creek. David Blackwell (1983) mapped the Park Butte–Loomis Mountain area. All three students mapped at 1:63,360 on photo-enlarged 15-minute topographic sheets. Their mapping was later incorporated into a regional reconnaissance compilation by Brown and others (1987).

The map of choice for the region is the 1:100,000 Mount Baker 30 x 60-minute quadrangle by Tabor and others (2003). Disagreements exist between Tabor and the three student maps, some of them significant. We generally prefer the interpretation of Tabor and others (2003) for this area, as it is more modern and the compilers are the foremost geologic mappers in the northern Cascades. Ned Brown, the principal compiler of the 1987 map, is a coauthor of the Tabor and others (2003) map.

Quaternary lava flows and fragmental deposits from a number of vent areas in the Mount Baker volcanic field were mapped by Hildreth and others (2003). That map does not distinguish between basement units or include Quaternary 'overburden', but is state of the art for Quaternary volcanic rocks. The author of this report participated in much of Hildreth's field mapping.

DESCRIPTION OF MAP UNITS

Qs **Unconsolidated surficial deposits**—Till, lahar diamicts, colluvium, alluvium, and lacustrine deposits. These deposits were mapped but not thoroughly described, because hydrothermal activity would not be preserved in these sediments.

Qbsc **Basaltic andesite and basaltic lava of Sulphur Creek**—Black to brownish-black, relatively unweathered, vesicular porphyritic clinopyroxene basalt and basaltic andesite with locally abundant plagioclase phenocrysts that flowed from the Schreibers Meadow scoria cone. Radiocarbon dating of organic material sampled from these rocks yield conventional ages of 7,950 ±90 (age site 3) and 8,420 ±70 years (age site 1)(Kovanen, 2001; Thomas, 1997).

Qafd **Andesite of Forest Divide (~400 ka, K-Ar)**—Grey columnar-jointed porphyritic pyroxene andesite lava flows capping Forest Divide. The age of this unit is constrained by two K-Ar dates from the top and bottom of the flow to be between 366 ±10 (age site 4) and 455 ±9 ka (age site 5)(Hildreth and others, 2003).

KJb **Bell Pass melange (Cretaceous–Jurassic)**—Mélange of deformed argillite, slate, phyllite, sandstone, semischist, ribbon chert, and basalt, with tectonic blocks of marble, gneiss, and ultramafic and other metamorphic rocks (Tabor and others, 2003). Radiolaria within chert-bearing Bell Pass mélange rocks in the southern portion of the map area were tentatively identified as Jurassic (not shown) and late Triassic (age site 6)(Tabor and others, 2003). Locally includes as tectonic blocks:

- bb **Blueschist of Baker Lake (Cretaceous–Jurassic metamorphic age)**—Fine-grained schistose metatuff, meta-basalt, meta-ribbon chert, and marble (Tabor and others, 2003).
- bya **Yellow Aster Complex of Misch (1966)(Paleozoic–Precambrian protolith age)**—Gneissic rocks, marble, and other associated metamorphic rocks (Tabor and others, 2003). A Sm-Nd age of 1.74 by (age site 8) was obtained from metagabbro within this unit and a zircon U-Pb age of 1.379 bya (not shown) was obtained from a pyroxene gneiss (Tabor and others, 2003).

KJna **Nooksack Formation (Cretaceous–Jurassic)**—Predominantly argillite and metasandstone with pronounced cleavage. Argillite is highly oxidized, brownish-grey, very thin to thinly bedded, and fine grained. Metasandstone is highly weathered, blackish-gray, and fine grained. Locally fossiliferous. Radiolarians collected within and outside the map area argillites indicate an early Jurassic to Cretaceous age (age sites 10–12)(Tabor and others, 2003).

JTRcd **Dacite and marine tuffaceous rocks (Jurassic–Triassic)**—Dacite is light green vitreous metadacite (Tabor and others, 2003). Tuffaceous rocks are exotic, subangular to angular, poorly sorted clasts in a blue-grey, fine-grained matrix with locally abundant hematite.

MzPzt **Metatonalite (Mesozoic–Paleozoic)**—Metatonalite intrusives, locally strongly cataclastically deformed (Tabor and others, 2003).

PDcmv **Chilliwack Group, volcaniclastic facies (Permian–Devonian)**—Principally Permian volcanic and sedimentary rocks of Mount Herman (Tabor and others, 2003), consisting of pillow lava and breccia in a fine-grained marine sedimentary host. Coarse crinoidal limestone within metasedimentary rocks was identified as Mississippian in age (age site 13)(Tabor and others, 2003). Also includes Permian–Devonian-age pillow basalts of Tabor and others (2003).

METHODS

Rock outcrops and surface deposits were examined for evidence of recent or current hydrothermal alteration. The full length of all roads and trails in the Nomination Area was walked or driven at slow speed. Pete Stelling (WWU) also accompanied and assisted the mapping team for several days. Previous examination of the Nomination Area was made by the author of this report during extensive cross-country mapping projects with Wes Hildreth and Kevin Scott (USGS), including multi-day traverses far from roads or trails. Any evidence of young hydrothermal activity would have been noted during this earlier work. Based on that prior work, limited additional cross-country investigation was made during the current study due to the remote probability of finding evidence of low-level hydrothermal activity in the forest.

Geologic structures such as faults and high-angle contacts would be expected to provide the best pathways for deep crustal heat and water to reach the surface. However, not one of the few mapped faults in the Nomination Area is located with confidence, nor are any of the contacts between units. Consequently, structures do not provide reasonable targets for investigation in the field in the Mount Baker Geothermal Nomination Area.

OBSERVATIONS

The locations of geologic structures (faults and contacts) in the map area are all conjectural due to discontinuous and poor rock exposures. No map-scale faults were noted anywhere, although pervasive shear was found in many roadside exposures of all metamorphic lithologies.

This mapping project resulted in minor alteration to previous mapping; interpretations from several of the mappers were incorporated from different areas in compilation of this map. We shifted locations of postulated faults based upon lithology changes noted in the field. We did note abundant greenstone where Tabor and others (2003) had previously mapped Yellow Aster Complex, which primarily consists of gneiss and associated metagabbro. This observation generally concurs with Ziegler's mapping in this location, and we adjusted the map accordingly.

Basement rocks are generally highly fractured. Nooksack Formation rocks are bedded and pervasively fractured at centimeter or even millimeter scales. Chilliwack Group rocks are generally more massive, but cut by fractures and joints at close intervals on the centimeter scale. Unfilled vugs suggest that alteration occurred in Chilliwack Group and Nooksack Formation rocks when they were at shallow crustal levels. At documented uplift rates of ~1 km/million years, the fossil systems may have been active within the past 5 million years, which far exceeds the age of any extrusive or intrusive rocks in the Mount Baker volcanic field. The more intensely fractured Nooksack Formation may provide a more likely pathway for a modern hydrothermal system. These rocks form a large proportion of the Nomination Area. We observed no evidence for active hydrothermal activity in any of the map area.

No evidence of recent hydrothermal activity was found or is known from anywhere within the Mount Baker Geothermal Nomination Area. A cross-country traverse southward from Baker Hot Spring to Morovitz Creek failed to locate evidence of recent hydrothermal activity. This is the most promising location within the Nomination Area due to proximity of the springs.

We note that Baker Hot Spring, one of only three known thermal areas in the Mount Baker region, is outside the Nomination Area by less than 100 meters. The other two are at Sherman Crater and the Dorr Fumaroles, far beyond the limits of this study. The hot spring is located within a large area underlain by Chilliwack Group volcanic rocks;

no faults or other structures appear on any geologic map in the vicinity of the springs that could explain their presence at this particular location. This area was also the site of a temperature-gradient borehole (DNR83-3), drilled to a depth of 140 meters in the early 1980s. A gradient constructed from the entire logged depth of the borehole yielded 309°C/kilometer (Southern Methodist University Heat Flow Database). Similarly, a gradient calculated from only the shallow portion of the borehole (between 12 and 25 meters) yielded a gradient of 1,300°C/kilometer.

We visited the hot spring as a point of departure for this investigation and as a model for possible findings; we found the water temperature to be 33°C (90°F). Also, a search was made for two extremely vaguely located 'warm pools' of unknown size or temperature reported by Ziegler (1985) in Swift Creek. The reported location is outside the study area and in the Mount Baker Wilderness Area, but the pools could serve as an example of low-level contemporaneous activity. They were not found despite a concerted search.

Fossil hydrothermal alteration was sporadically observed in metamorphic basement rocks. Evidence included quartz- or calcite-lined vugs and fractures, disseminated pyrite, and iron oxide films in abundant fractures. Lack of alteration in adjacent surface deposits and evident erosion of the rock indicate that this is fossil alteration. Chilliwack Group unit PDcmv was most often altered, though alteration was found in other map units. A single exposure of the JTRcd dacite at 48°39'59.43"N 121°47'10.37"W along abandoned Forest Road 1233 south of Rocky Creek (site 96 on Plate 2) was found, along with abundant sinter along a fracture, but erosion of the rock indicates that this is also fossil alteration.

An occurrence of pale gray clay with hydrothermally altered clasts just below forest duff was found alongside Forest Road 1130, 300 meters north of, and 25 meters above, Park Creek (48°44'41.37"N 121°41'12.75"W)(site 41 on Plate 2). Prevalence of Mount Baker andesite clasts, however, which are not the local lithology, indicated that this is the deposit of the Morovitz lahar (ca. 1845) originating at the east breach of Sherman Crater (Scott and others, *in press*). The lahar traveled down Boulder, Park and lowermost Morovitz Creeks. The gray clay appeared identical to known Morovitz lahar exposures in the banks of Park Creek and Boulder Creek.

DISCUSSION

Barring current hydrothermal activity hidden deep in the forest, there is no evidence of shallow geothermal activity in the Nomination Area. Further work in this area might include utilizing various ground or airborne geophysical surveys, which may aid in locating additional springs or zones of permeability at depth. Given the obvious high heat flow encountered within the temperature-gradient borehole near Baker Hot Springs, and that faults and fractures responsible for higher permeability in that area are not visible at the surface, it seems crucial then to deploy a method that will locate these features at depth. Geophysical surveys such as magnetotellurics, magnetics, gravity, resistivity, spontaneous potential, and other methods, especially when used in tandem, would aid in this search, as would additional temperature-gradient borehole drilling.

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