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GENERALIZED GEOLOGIC COMPILATION MAP OF THE HARNEY BASIN

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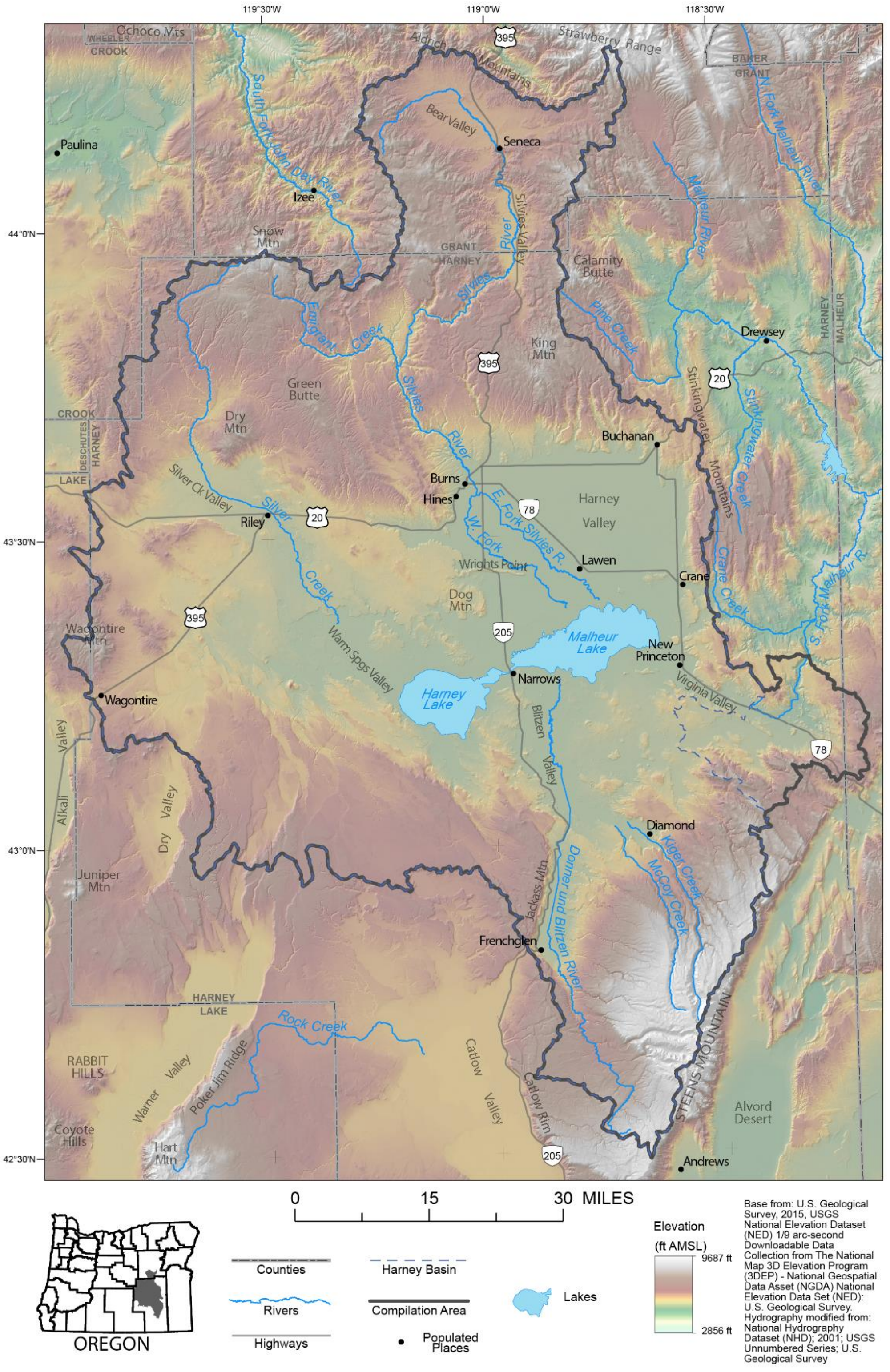
Introduction

The Oregon Water Resources Department (OWRD) in cooperation with the United States Geological Survey (USGS) is conducting a multi-year study of the groundwater flow system in the Harney Basin. In support of this effort OWRD has completed a Geographic Information System (GIS) -based digital compilation of the geology of the Harney Basin at a scale of 1:250,000 (plate 1). This generalized geologic map provides a basin-wide synthesis of the stratigraphic and structural setting of the Harney Basin, and serves as the basin-scale geologic framework for the USGS-OWRD Harney Basin groundwater study. This work, combined with new and existing hydrologic data can additionally be used to define major hydrostratigraphic units for use in the development of a numerical groundwater flow model. The compilation is also designed as an outreach and education tool that informs and engages stakeholders with the basin's geology and hydrogeology.

Existing digital compilations of geologic map data that include the Harney Basin (e.g. Ludington and others, 2005) are of a broader regional scale, and do not include important stratigraphic marker beds that are helpful for addressing questions about the groundwater flow system in the basin. This compilation provides a seamless and stratigraphically consistent digital geologic coverage of the entire Harney Basin. Building upon existing digital data from the Oregon Geologic Data Compilation (OGDC) (Smith and Roe, 2015), this work compiles geologic map data at a variety of scales, and relies on recent published and unpublished 1:24,000 scale geologic mapping, available radiometric ages, new and existing whole-rock X-ray fluorescence (XRF) geochemical analyses, LIDAR elevation data, high resolution aerial imagery, and targeted field reconnaissance to inform map unit designations and resolve map boundary discrepancies. Subsurface interpretations presented as regional cross sections (plate 1) are supported by historic oil and gas well records, recent observation well drilling, and newly acquired whole-rock XRF analyses of subsurface samples.

The Harney Basin as defined for the purposes of this report comprises the four USGS HUC-8 sub-basin (4th level) hydrologic units Harney-Malheur Lakes (17120001), Silvies (17120002), Donner und Blitzen (17120003), and Silver (17120004). This closed drainage basin represents the hydrographic boundary of the contributing surface water drainage area for Malheur and Harney Lakes, which are fed by the watersheds of the Silvies River, Silver Creek, the Donner und Blitzen River and numerous smaller creeks and sloughs. The basin covers approximately 5,240 square miles in southeast Oregon, including most of Harney County and portions of Grant, Lake and Crook Counties. In addition, the compilation area includes the USGS HUC-12 subwatershed (6th level) hydrologic units Standcliff Creek (170501160801), Camp Creek (170501160802), Indian Creek (170501160803), and South Fork Reservoir-South Fork Malheur River (170501160804) from the adjacent Malheur River basin to illustrate the distribution of map units across this portion of the basin divide (figure 1). This area is of special interest to the USGS-OWRD Harney Basin groundwater study because groundwater flows from the Harney Basin to the Malheur River Basin through this surface water divide.

This report describes the contents of the 1:250,000-scale generalized geologic compilation map of the Harney Basin and the methods used to compile geologic map data from publications representing nearly 50 years of geologic field investigations in the basin. Included with this report are digital spatial data files representing the generalized geologic map unit polygons and fault polyline locations provided in ESRI shapefile format. The map plate includes a time-rock chart showing how the generalized geologic map units are related to each other stratigraphically, as well as a tectonic overview map depicting the major structural and volcanic features of the basin. This report is not intended to provide a comprehensive geologic history of the basin. For a more thorough discussion of the basin geology the reader is encouraged to consult the compilation of selected references relevant to the geology of the Harney Basin in Appendix A. The appendices to this report also include summaries of the map unit groupings (Appendix B), and provide additional information used to inform the map compilation process including newly acquired whole-rock XRF geochemical analyses (Appendix C), completion logs of observation wells constructed during the course of the study (Appendix D), and a compilation of available ^{40}Ar/^{39}Ar ages for volcanic rocks in the basin (Appendix E).



Base from: U.S. Geological Survey, 2015, USGS National Elevation Dataset (NED) 1/9 arc-second Downloadable Data Collection from The National Map 3D Elevation Program (3DEP) - National Geospatial Data Asset (NGDA) National Elevation Data Set (NED): U.S. Geological Survey. Hydrography modified from: National Hydrography Dataset (NHD); 2001; USGS Unnumbered Series; U.S. Geological Survey

Figure 1: Geographic overview of the Harney Basin and map compilation area.

Map Compilation and Modifications to Spatial Data

Source Data

The primary data source used for the compilation is the Oregon Geologic Data Compilation (OGDC – release 6) (Smith and Roe, 2015), a statewide digital compilation of geologic data created by the Oregon Department of Geology and Mineral Industries (DOGAMI). Sources of geologic mapping within OGDC include published and unpublished maps at a wide variety of scales from state and federal agencies, university research, and consultant reports. OGDC brings the best available geologic map data for the entire state of Oregon together into a single coverage, using the more detailed or better quality maps where available, while retaining the less detailed or poorer quality maps in areas where no other coverage is available. The OGDC compilation approach has several advantages over the more conventional geologic map compilation process (Ferns and others, 2006), making it a valuable starting point for the compilation. However, it does not provide a seamless coverage of uniform scale, or attempt to reconcile stratigraphic inconsistencies or map boundary discrepancies. This compilation provides the seamless and stratigraphically consistent coverage of the entire Harney Basin as needed for the USGS-OWRD groundwater basin study.

Map boundaries for 24 unique source reference maps from OGDC fall within or partly within the compilation area. Of these, 16 source reference maps representing 14 original publications were selected for inclusion in the compilation (figure 2, table 1). The 8 OGDC source reference maps excluded from the compilation include maps for which very limited extent fell within the compilation area, unpublished university mapping, and 1:24,000 scale mapping for which the linework was far too detailed to compile at 1:250,000. In areas for which an OGDC source map was excluded from the compilation, map unit polygon and fault line data from the underlying, and generally smaller scale publication was digitized directly from the source publication and incorporated into the compilation.

The index map in Figure 2 shows the extent of source publication maps used in the compilation. Several differences exist between the index map in Figure 2 and the source reference maps from OGDC. First, the 8 OGDC source reference maps excluded from the compilation are not depicted. Additionally, OGDC source reference maps that are themselves compilations of previous work (e.g. Evans and Geisler, 2001) are depicted instead showing the extent of the original authors work. A total of 15 geologic maps were used in the compilation, including 1 unpublished 7.5’ quadrangle. Table 1 provides the relationship between the index map in Figure 2 and the source reference maps from OGDC, as well as additional publication details.

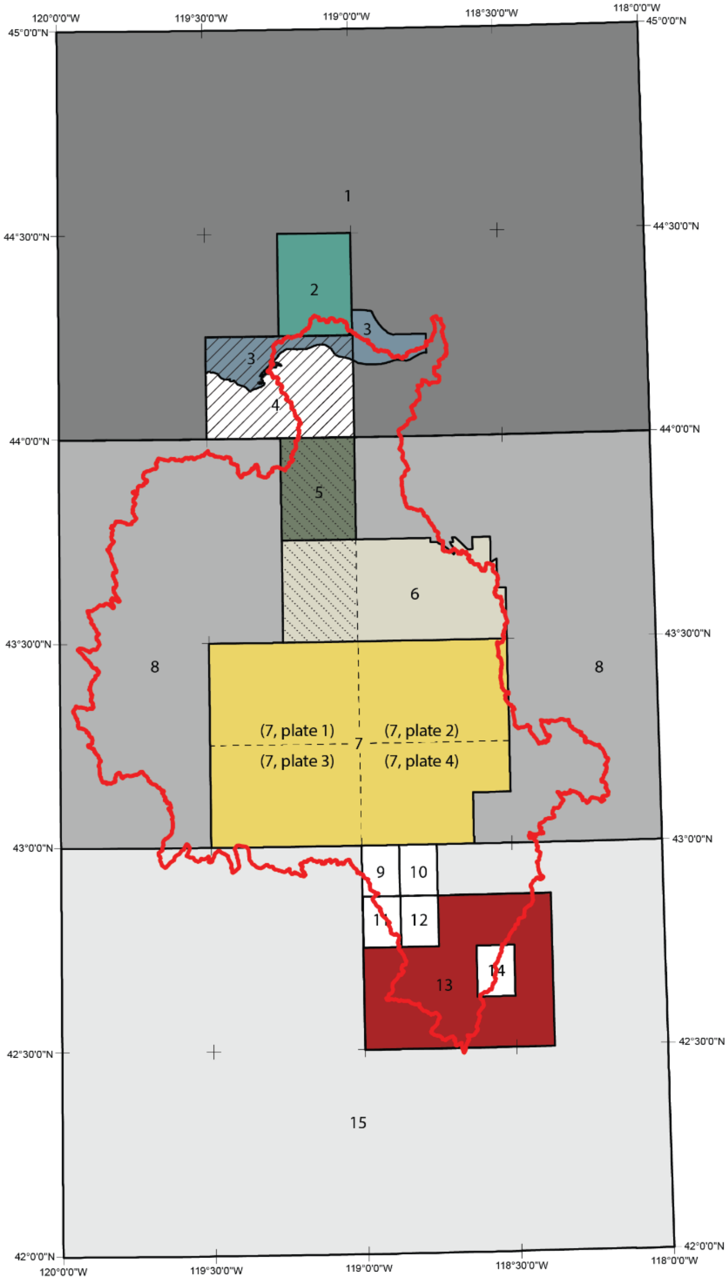


Figure 2: Index map showing the extent of source publication maps. Red line is compilation area. 1 – Brown and Thayer, 1966a; 2- Brown and Thayer, 1966b; 3 – Brown and Thayer, 1977; 4 – Wallace and Calkins, 1956 (full extent of plate hachured); 5 – Greene, 1972 (full extent of plate stippled); 6 – Brown and others, 1980a; 7 – Brown and others, 1980b; 8 – Greene and others, 1972; 9 – Sherrod and Johnson, 1994; 10 – Johnson, 1994; 11 – D.R Sherrod, in Evans and Geisler, 2001; 12 – Johnson, 1996, in Evans and Geisler, 2001; 13 – Evans and Geisler, 2001; 14 – Minor and others, 1987; 15 – Walker and Repenning, 1965. Red line is compilation area. See table 1 for additional publication details.

Table 1: Source publication details

Fig.2 Index	Publication Title	First Author	Year	OGDC Ref ID Code	Originator	Scale
1	Geologic map of the Canyon City quadrangle, northeastern Oregon	Brown, CE	1966	BrowCE1966b	USGS	250,000
2	Geologic map of the Mount Vernon quadrangle, Grant County, Oregon	Brown, CE	1966	BrowCE1966a	USGS	62,500
3	Geologic map of pre-Tertiary rocks in the eastern Aldrich Mountains and adjacent areas to the south, Grant County, Oregon	Brown, CE	1977	BrowCE1977	USGS	62,500
4	Reconnaissance geologic map of the Izee and Logdell quadrangles, Oregon	Wallace, RE	1956	WallRE1956	USGS	62,500
5	Preliminary geologic map of the Burns and West Myrtle Butte 15-minute quadrangles, Oregon	Greene, RC	1972	GreeRC1972b	USGS	62,500
6	Preliminary geology and geothermal resource potential of the northern Harney Basin, Oregon	Brown, DE	1980	BrowDE1980b	DOGAMI	62,500
7	Preliminary geology and geothermal resource potential of the southern Harney Basin, Oregon	Brown, DE	1980	BrowDE1980aplate1	DOGAMI	62,500
7	Preliminary geology and geothermal resource potential of the southern Harney Basin, Oregon	Brown, DE	1980	BrowDE1980aplate2	DOGAMI	62,500
7	Preliminary geology and geothermal resource potential of the southern Harney Basin, Oregon	Brown, DE	1980	BrowDE1980aplate3	DOGAMI	62,500
7	Preliminary geology and geothermal resource potential of the southern Harney Basin, Oregon	Brown, DE	1980	BrowDE1980aplate4	DOGAMI	62,500
8	Geologic map of the Burns quadrangle, Oregon	Greene, RC	1972	GreeRC1972a	USGS	250,000
9	Geologic map of the Irish Lake quadrangle, Harney County, south-central Oregon	Sherrod, DR	1994	SherDR1994	USGS	24,000
10	Geologic map of the Krumbo Reservoir quadrangle, Harney County, southeastern Oregon	Johnson, JA	1994	JohnJA1994	USGS	24,000
*11	Unpublished Frenchglen quadrangle	Sherrod, DR	na	na	na	24,000
*12	Geologic map of the Page Springs quadrangle, Harney County, southeastern Oregon	Johnson, JA	1996	na	USGS	24,000
13	Geologic field-trip guide to Steens Mountain Loop Road, Harney County, Oregon	Evans, JG	2001	EvanJG2001	USGS	100,000
14	Geologic map of the Wildhorse Lake quadrangle, Harney County, Oregon	Minor, SA	1987	MinoSA1987b	USGS	24,000
15	Reconnaissance geologic map of the Adel quadrangle, Lake, Harney, and Malheur Counties, Oregon	Walker, GW	1965	WalkGW1965	USGS	250,000

*in: Evans and Geisler, 2001.

Generalization of Map Units

The stratigraphic nomenclature for Cenozoic rocks in the Harney Basin was updated and formalized in part by Walker (1979), however a comprehensive formalized stratigraphy was not defined at that time due to the reconnaissance nature of available data. As such, many of the stratigraphic units within the basin remain without formalized formation names, and several long-standing stratigraphic issues remain unresolved. The current compilation is not an effort to resolve these long-standing stratigraphic questions or to further formalize the stratigraphic nomenclature in the basin, but is intended to provide a basin-wide framework to support groundwater data analysis that is constrained by existing data and current geologic knowledge.

The compilation of a basin-wide geologic map at 1:250,000 from published maps by different workers at various scales requires some spatial and categorical generalization of geologic units that may have been mapped in greater detail in the available source publications. Compilation of many disparate geologic maps over a large geographic area requires making compromises between the complexity of available geologic knowledge for the area, and the need to keep the resulting compilation relatively simple and applicable for the intended purpose. The original 15 source publication maps included over 100 unique map unit names within the compilation area. In some cases these unique map unit names represent the same geologic unit, and are simply the result of individual source publications using slightly different naming conventions (e.g. Landslide debris; Landslide deposits). In other cases, early workers mapping without the benefit of subsequent regional stratigraphic correlations had given regional units several local informal names which have since been redefined. For example, the now formalized Rattlesnake Ash-flow Tuff (Walker, 1979) had previously been mapped as Welded Tuff of Double O Ranch (Greene, 1972) or included within a generalized map unit including tuffaceous sedimentary rocks, tuffs, and interbedded lava flows (Walker and Repenning, 1965). Elsewhere, existing mapping of individual map units was of insufficient detail or spatial distribution to support inclusion as a separate map unit in the basin-wide compilation – for example the Prater Creek Ash-flow Tuff (Walker, 1979), a widespread unit of regional extent has not been consistently mapped across the compilation area, and by necessity was combined with other strata as a more generalized map unit. Additionally, in order to improve legibility for analysis, minor inliers of thin Quaternary surficial deposits of limited spatial extent as well as several minor exposures of some bedrock units were merged with the underlying or surrounding bedrock map unit.

Map unit polygons from the source publications were grouped into 18 generalized map units that share similar geologic origins, physical properties, and stratigraphic position. The original map units from each source publication that were grouped into each of the 18 generalized map units are listed in Appendix B. Note that in some cases, separate polygons of the same map unit from one source publication have been combined into two or more different generalized units based on stratigraphic or spatial position, subsequent regional correlations, or new correlations based on whole-rock XRF geochemical data and/or available radiometric ages. The process of compiling and generalizing map units endeavored to honor the regional stratigraphic framework of the basin in accord with known constraints, while recognizing the intended application of the compilation as a tool to inform hydrogeological interpretations at the basin scale.

Rectification of Map Boundary Discrepancies

Source publication maps ranging in scale from 1:24,000 to 1:250,000 with publication dates from 1956 to 2001 inevitably have map boundary discrepancies between adjoining maps where scale, nomenclature, or differing interpretations between two authors results in a discontinuity of map units across the map boundary. Efforts to rectify these so called “map-boundary faults” relied on a variety of supporting data including recently published and unpublished 1:24,000 scale mapping (Camp and others, 2003, p. 2003; Houston and others, 2018; McClaughry and others, 2019; Niewendorp and others, 2018; unpublished Portland State University EDMAP mapping; unpublished DOGAMI mapping), available radiometric ages (Appendix E), new and existing whole-rock XRF geochemical analyses (Appendix C), LIDAR elevation data (DOGAMI), high resolution aerial imagery (Oregon Statewide Imagery Program), and targeted field reconnaissance.

Rectification of map boundary discrepancies required making interpretations and compromises based on available constraints, and sought to preserve original published linework where possible while maintaining coherence with established stratigraphic relationships across the map boundary. While best efforts were made to resolve map boundary issues across the entire basin, available data do not allow for resolution of all mapping conflicts, and additional detailed field mapping will be needed to completely resolve all discrepancies. As such, further generalization of map unit geometry was required along some map boundaries, and some map boundary discrepancies remain in the final compilation. No attempt was made to reconcile map boundary discrepancies for the OGDC or directly digitized fault data, and consequently, discontinuities of mapped structures remain across map boundaries.

Description of Generalized Map Units

The descriptions of the 18 map units that follow are generalized from unit descriptions in the source publication maps and reports. Where available and appropriate, additional or updated information was incorporated from supporting data and descriptions in the relevant literature. Analytical uncertainties on the $^{40}Ar/^{39}Ar$ ages are reported at 2 sigma (2σ) confidence level.

Mesozoic rocks—(Mzu): Late Jurassic to Late Triassic

The oldest rocks exposed in the basin are variably deformed and metamorphosed, Upper Jurassic to Upper Triassic marine deposits of the accreted Izee terrane, including interbedded volcanic and tuffaceous mudstone, siltstone, shale, graywacke, calcareous sandstone, conglomerate, limestone, tuff, and minor andesite lavas (Brooks and Vallier, 1978; Brown and Thayer, 1977; Dickinson, 1979; Dickinson and Thayer, 1978; Silberling and Jones, 1984). Minor areas of Miocene intrusive rocks, as well as Permian to pre-Permian(?) metamorphic rocks of limited extent associated with the Canyon Mountain Complex (Brown and Thayer, 1977; Wallace and Calkins, 1956) are also included with this unit. Exposures of Mesozoic rocks in the basin are limited to the northern uplands, however they are presumed to form the basement underlying much of the basin (McClaughry and others, 2019; Streck, 2002). The aggregate thickness of Upper Triassic to Upper Jurassic rocks in the region is estimated at nearly 50,000 feet (Brooks, 1979; Dickinson, 1979).

Older volcanic rocks—(Tov): Miocene and late Oligocene

A thick section of late Oligocene and Miocene volcanic rocks underlies the Devine Canyon Ash-flow Tuff in the northern and eastern uplands. Primarily basalt and andesite lava flows, but also includes rhyolite lava flows and tuffs, rhyodacite and dacite lavas, and interbedded tuffaceous sedimentary deposits. In the northern uplands, this unit includes undifferentiated Columbia River Basalt Group lavas, Strawberry Volcanics, and Dinner Creek Tuff (Brown and Thayer, 1966a; Greene and others, 1972; Houston and others, 2018; Niewendorp and others, 2018). The unit may also include undifferentiated Steens Basalt in some areas (Camp and others, 2013). Age assignment based on stratigraphic position and $^{40}Ar/^{39}Ar$ ages, including an andesite age of 24.75±0.15 Ma (Houston and others, 2018).

Steens Basalt—(Tsb): early Miocene

Dark- to medium-gray, vesicular to massive, aphanitic to coarsely plagioclase –phyric, intergranular to diktytaxitic olivine basalt. The continental flood basalt lavas of the Steens Basalt were erupted from a low, elongate shield volcano centered near the Steens Mountain escarpment where numerous north- and northeast-striking dikes are exposed. The Steens Basalt includes more than 100 individual flows with an average composite thickness of about 2,000 feet and maximum reported thickness of 4,300 feet. The sequence was largely erupted as compound flows ranging in thickness from 30–150 feet, although individual flow lobes rarely exceed 6 feet (Camp and others, 2013; Johnson and others, 1998; Minor and others, 1987). The initial eruption of Steens Basalt occurred by 16.97±0.06 Ma as the earliest pulse of Columbia River Flood Basalt volcanism (Camp and others, 2013; Moore and others, 2018).

Devine Canyon Ash-flow Tuff—(Tdv): late Miocene

Light-gray to greenish-gray, nonwelded to densely welded, crystal-rich (up to 30%) rhyolite tuff that forms a single cooling unit and represents an important stratigraphic marker bed throughout much of the basin. The tuff sheet ranges from a few feet to over 200 feet thick, with an estimated original extent of over 7,000 mi^2 (Greene, 1973; McClaughry and others, 2019; Walker, 1979). Greene (1973) proposed a source caldera in the central Harney Basin near Burns based on unit thickness and crystal content distribution. An $^{40}Ar/^{39}Ar$ age of 9.74±0.04 Ma is reported by Jordan and others (2004).

Andesite—(Ta): late Miocene

Fine grained, dense and commonly flow-banded andesite and basaltic-andesite lava flows occur as multiple thin flows with a total thickness of a few tens to locally over 200 feet. These flows erupted from several vent complexes in the uplands northwest of Burns (Brown and others, 1980a; Brown, 1982; Greene and others, 1972; McClaughry and others, 2019). The age of these lava flows is bracketed by the 8.41 Ma Prater Creek Ash-flow Tuff and 7.1 Ma Rattlesnake Ash-flow Tuff (Jordan and others, 2004; McClaughry and others, 2019).

Basalt and andesite of Dry Mountain—(Tdm): late Miocene

Numerous flows of dark-gray, aphanitic to fine-grained andesite with rare olivine, and high-alumina olivine basalt erupted from a large shield volcano at Dry Mountain at about 7.9 Ma (Greene and others, 1972; Streck and Grunder, 2012). A thickness of 535 feet is penetrated by a well on the flanks of Dry Mountain, and a 700+ foot section is exposed at the summit scarp; the total thickness is unknown.

Basalt of Harney Lake—(Tbh): late Miocene

Black to dark-gray olivine-bearing basaltic rocks with common yellowish devitrified glass and pillow structures. Consists of several flows, each 10–20 feet thick with a total thickness of about 150 feet (Brown and others, 1980b; Greene and others, 1972). The unit is located south and west of Harney Lake where it underlies Rattlesnake Ash-flow Tuff and overlies Devine Canyon Ash-flow Tuff. May intertongue locally with sedimentary rocks of unit Tts. Included in this unit are Basalt of Hog Wallow (Johnson, 1994) and Basalt of Black Rim (Sherrod and Johnson, 1994) on the basis of stratigraphic position. A late Miocene age is based on stratigraphic position and $^{40}Ar/^{39}Ar$ ages of 7.68±0.16 Ma and 7.54±0.26 Ma (Jordan and others, 2004).

Drinkwater Basalt—(Tdw): late Miocene

Medium- to dark gray diktytaxitic basaltic rocks with locally abundant phenocrysts and glomerocrysts of plagioclase and olivine. Forms ridge-capping basalt flows along the eastern margin of the basin near Crane and south and east of Diamond Craters. Commonly one flow, but locally several flows with a total thickness ranging from 20–200 feet (Greene and others, 1972). An $^{40}Ar/^{39}Ar$ age of 7.25±0.09 Ma is reported for exposures of this unit east of the basin near the South Fork Malheur River (Meigs and others, 2009).

Rattlesnake Ash-flow Tuff—(Trt): late Miocene

Light-brown to red-brown to gray, nonwelded to densely welded, pumice-rich rhyolite tuff that forms a single cooling unit and represents an important stratigraphic marker bed throughout much of the basin. The tuff sheet typically ranges from 30–100 feet thick with a maximum reported thickness of about 240 feet and an estimated original extent of 13,500 mi^2 (Brown and others, 1980b; Streck and Grunder, 1995). Streck and Grunder (1995) proposed a source caldera in the western Harney Basin on the basis of outcrop, pumice size, and facies distribution as well as flow-direction indicators. An $^{40}Ar/^{39}Ar$ age of 7.09±0.03 Ma is reported by Jordan and others (2004).

Olivine basalt and andesite of Gum Boot Canyon—(Tobg): late Miocene

Medium- to dark-gray, fine- to medium-grained, aphyric and diktytaxitic basalt with groundmass olivine, and medium-gray aphanitic and nonporous andesite with less than 1 percent plagioclase and olivine phenocrysts. Several flows, each a few feet to a few tens of feet thick with a maximum thickness of about 300 feet are exposed along fault scarps southeast of Dry Mountain (Greene and others, 1972). As mapped by Greene and others (1972), the unit overlies the Rattlesnake Ash-flow Tuff, but an $^{40}Ar/^{39}Ar$ age of 7.60±0.22 Ma from a basalt flow southeast of Dry Mountain (Jordan and others, 2004) indicates part of the unit may be older.

Olivine basalt—(Tob): late Miocene

Dark-gray to black, fine-grained olivine basalt with some andesite. Locally includes thin interbeds of tuffaceous sedimentary rock (Greene and others, 1972) that overlies Rattlesnake Ash-flow Tuff in the southwest part of the basin. A late Miocene age assignment is based on stratigraphic position and a K-Ar age of 6.2±0.8 Ma (Feibelkorn and others, 1982; Parker and Armstrong, 1972).

Silicic lava flows and domes—(Trd): Pliocene and Miocene

Medium- to light-gray, pale-red, and reddish-brown, commonly streaked and flow-banded rhyolite, rhyodacite and dacite with associated vitrophyre and obsidian. The unit occurs as exogenous domes and related flows and plugs (Brown and others, 1980b; Brown and others, 1980a; Greene and others, 1972).

Tuffaceous sedimentary rocks and tuff—(Tts): Pliocene to Miocene

White to buff and pale-brown to yellowish-gray, semi- to well-consolidated lacustrine and fluviatile tuffaceous mudstone, siltstone, sandstone and conglomerate with numerous air-fall ash beds and tuffs, and occasional thin carbonate and chert beds. Commonly consists of a poorly sorted mixture of pumice, scoria, other rock fragments, plagioclase grains, and glass shards in a clay matrix (Brown and others, 1980b; Brown and others, 1980a; Greene and others, 1972). Locally, the tuffaceous sedimentary rocks and tuffs are diagenetically altered to clay minerals, zeolites, and potassium feldspar (Sheppard, 1994; Walker and Nolf, 1981; Walker and Swanson, 1968). This unit includes all tuffaceous sediments and tuff interbedded with the Rattlesnake Ash-flow Tuff and Devine Canyon Ash-flow Tuff, and includes the 8.41±0.32 Ma Prater Creek Ash-flow Tuff (Jordan and others, 2004; Walker, 1979). The upper section of the unit is partially equivalent to the Harney Formation of Walker (1979).

Basalt—(QTb): early Pleistocene and late Pliocene

Medium-gray, fine-grained, diktytaxitic, olivine-bearing vesicular basalt occurring as a series of thin flows locally separated by thin layers of sedimentary rock (Brown and others, 1980b; Brown and others, 1980a; Greene and others, 1972); includes the Wrights Point member of the Harney Formation (Walker, 1979). The Pleistocene–Pliocene age assignment is based on ^{40}Ar/^{39}Ar ages of 2.83±0.89 Ma, 2.54±0.07 Ma, and 2.2±0.08 Ma (Jordan and others, 2004; Streck and Grunder, 2012).

Voltage Basalt—(Qvb): Pleistocene

Medium-gray, vesicular olivine basalt erupted as thin lava flows from numerous vents south and east of Malheur Lake (Brown and others, 1980b; Brown and others, 1980a; Greene and others, 1972). The lava field contains abundant well-preserved tumuli and pressure ridges. The unit is over 300 feet thick in the central part of the Voltage lava field, however elsewhere the thickness is generally less than 200 feet. $^{40}Ar/^{39}Ar$ ages of 1.23±0.10 Ma and 1.47±0.16 Ma are reported by Jordan and others (2004).

Mafic vent complexes—(QTv): Pleistocene to late Miocene

Basaltic to andesitic scoria, cinders, agglomerate, thin flows, and intrusive masses forming lava cones, domes, and small shield volcanoes associated with eruptive centers of mafic and intermediate volcanic units in the basin. Locally this unit includes partly consolidated subaqueous deposits of palagonitized basaltic ejecta occurring as tuff and breccia cones and rings, and reworked volcanic sediments (Brown and others, 1980b; Brown and others, 1980a; Greene and others, 1972).

Diamond Craters basalt and tephra—(Qdc): Holocene

Fine- to medium-grained olivine and plagioclase phyric basalt lava flows and juvenile tephra including agglomerate, cinders and ash. The basalt is medium to dark gray and mostly vesicular, forming thin flows with ropy pahoehoe surfaces (Brown and others, 1980b; Greene and others, 1972; Russell and Nicholls, 1987). Many small craters are rimmed with lava spatter, cinders and bombs. The lava field was emplaced sometime between about 7,320 to 7,790 years ago on the basis of radiocarbon ages and paleomagnetic constraints (Sherrod and others, 2012).

Quaternary sedimentary deposits—(Qs): Holocene and Pleistocene

Unconsolidated to poorly consolidated clay, silt, sand, and gravel of Quaternary age. The deposits originated as alluvium, alluvial fan deposits, colluvium, floodplain deposits, lacustrine deposits, talus, landslide, and other recent sedimentary deposits. This unit includes glacial deposits on Steens Mountain.

Limitations

This map was prepared to provide a basin-wide synthesis of the stratigraphic and structural setting of the Harney Basin to serve as the basin-scale geologic framework for the cooperative USGS-OWRD Harney Basin groundwater study. The intended purpose of the compilation is to aid in hydrogeologic interpretations and analyses. Compilation of many disparate geologic maps over a large geographic area places significant limitations on how these data can be used, and any application beyond the intended purpose may not be appropriate.

Acknowledgments

This work benefited greatly from insightful reviews by current and former staff from OWRD, USGS, and DOGAMI who contributed their time and expertise to improve the manuscript and map plate. We also acknowledge the many current and former DOGAMI staff who have contributed to the OGDC project, without which this work would not have been possible. Ongoing mapping and field data collection by DOGAMI staff and Portland State University students and faculty helped greatly in the compilation process, and continues to further our understanding of the basin geology. And finally, this work would not be possible without the hard work and dedication of the many geologists working in the Harney Basin over the years who contributed to the original source publications used for the compilation.

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Appendix B. Map unit groupings into generalized geologic map units

Qs Quaternary sedimentary deposits (Holocene and Pleistocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
WallRE1956	Alluvium	Qal
WallRE1956	Terrace deposits	Qt
WalkGW1965	Alluvium	Qal
WalkGW1965	Landslide debris	QTls
WalkGW1965	Playa deposits	Qp
BrowCE1966a	Alluvium	Qa
BrowCE1966b	Alluvium	Qa
BrowCE1966b	Landslide debris	Ql
GreeRC1972a	Alluvial-fan deposits	Qf
GreeRC1972a	Alluvium	Qal
GreeRC1972a	Playa deposits	Qp
GreeRC1972a	Sedimentary deposits	Qs
GreeRC1972b	Alluvium	Qal
BrowCE1977	Alluvium	Qa
BrowCE1977	Landslide deposits	Ql
BrowDE1980aplate1	Alluvium and Holocene sedimentary deposits, undifferentiated	Qal/Qs
BrowDE1980aplate1	Alluvial fan deposits	Qf
BrowDE1980aplate1	Playa deposits	Qp
BrowDE1980aplate2	Alluvium and Holocene sedimentary deposits, undifferentiated	Qal/Qs
BrowDE1980aplate2	Alluvial fan deposits	Qf
BrowDE1980aplate3	Alluvium and Holocene sedimentary deposits, undifferentiated	Qal/Qs
BrowDE1980aplate3	Alluvial fan deposits	Qf
BrowDE1980aplate3	Playa deposits	Qp
BrowDE1980aplate4	Alluvium and Holocene sedimentary deposits, undifferentiated	Qal/Qs
BrowDE1980aplate4	Alluvial fan deposits	Qf
BrowDE1980aplate4	Landslide deposits	Ql
BrowDE1980aplate4	Playa deposits	Qp
BrowDE1980b	Alluvium and Holocene sedimentary deposits, undifferentiated	Qs/Qal
BrowDE1980b	Alluvial fan deposits	Qf
BrowDE1980b	Landslide deposits	Qls
MinoSA1987b	Alluvium	Qal
MinoSA1987b	Colluvium	Qc
MinoSA1987b	Glacial deposits	Qg
MinoSA1987b	Talus	Qt
JohnJA1994	Alluvium	Qal
JohnJA1994	Flood-plain deposits	Qfp
JohnJA1994	Landslide deposits	Qls
SherDR1994	Alluvium	Qa
SherDR1994	Landslide deposits	Qls
SherDR1994	Playa deposits	Qp
SherDR1994	Talus and colluvium	Qtc
EvanJG2001	Alluvial fan	Qf
EvanJG2001	Alluvium	Qal
EvanJG2001	Glacial deposits	Qg
EvanJG2001	Landslide deposits	Qls

Appendix B. continued

Qdc Diamond Craters basalt and tephra (Holocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
BrowDE1980aplate4	Ash of Diamond Craters	Qad
BrowDE1980aplate4	Basalt of Diamond Craters	Qbd

QTv Mafic vent complexes (Pleistocene to late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	Mafic vent complexes	QTmv
GreeRC1972a	Pyroclastic rocks of cinder cones	QTp
GreeRC1972a	Subaqueous pyroclastic deposits	QTps
GreeRC1972a	basalt	Tob
BrowDE1980aplate1	Upper Pliocene mafic vent complex	QTmv
BrowDE1980aplate2	Mafic vent complex	Tmbav
BrowDE1980aplate2	Upper Pliocene basalt	QTb
BrowDE1980aplate2	Upper Pliocene mafic vent complexes	QTb
BrowDE1980aplate3	Upper Pliocene mafic vent complexes	QTmv
BrowDE1980aplate4	Upper Pliocene mafic vent complexes	QTmv
BrowDE1980b	Upper Pliocene mafic vent complexes	QTmv

Qvb Voltage Basalt (Pleistocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	Basalt	Qb
BrowDE1980aplate2	Upper Pliocene basalt	QTb
BrowDE1980aplate4	Upper Pliocene basalt	QTb

QTb Basalt (early Pleistocene and late Pliocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	Basalt	Qb
GreeRC1972a	basalt	QTb
BrowDE1980aplate1	Upper Pliocene basalt	QTb
BrowDE1980aplate2	Upper Pliocene basalt	QTb
BrowDE1980b	Upper Pliocene basalt	QTb

Tts Tuffaceous sedimentary rocks and tuff (Pliocene to Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
WalkGW1965	Tuffaceous sedimentary rocks, tuffs and silicic flows	Tts
BrowCE1966b	Volcanic and fluviatile deposits, undivided	QTu
GreeRC1972a	sedimentary rocks	QTs
GreeRC1972a	Tuffaceous sedimentary rocks	Tts
GreeRC1972a	tuffaceous sedimentary rocks	Tst
GreeRC1972a	Welded tuff of Prater Creek	Twtp
GreeRC1972b	Terrace gravels	QTtg
GreeRC1972b	Tuffaceous sedimentary rocks	Tts
GreeRC1972b	Welded tuff of Prater Creek	Twtp
BrowDE1980aplate1	Tuffaceous sedimentary rocks	QTst
BrowDE1980aplate2	Prater Creek ash-flow tuff	Tmtp
BrowDE1980aplate2	Tuffaceous sedimentary rocks	Tmst1/Tmst2/Tmst3
BrowDE1980aplate3	Prater Creek ash-flow tuff	Tmtp

Appendix B. continued

BrowDE1980aplate3	Tuffaceous sedimentary rocks	Tmst1/Tmst2
BrowDE1980aplate4	Prater Creek ash-flow tuff	Tmtp
BrowDE1980aplate4	Tuffaceous sedimentary rocks	Tmst1/Tmst2/Tmst3
BrowDE1980b	Buchanan Ash-flow Tuff	Tmtb
BrowDE1980b	Prater Creek Ash-flow Tuff	Tmtp
BrowDE1980b	Tuffaceous sedimentary rocks	QTst
BrowDE1980b	Tuffaceous sedimentary rocks	Tmst1/Tmst2
JohnJA1994	Tuff and tuffaceous sedimentary rocks	Tts
SherDR1994	Tuff and tuffaceous sedimentary rocks	Tt
SherDR1994	Tuffaceous sedimentary deposits	Tts

Trd Silicic lava flows and domes (Pliocene and Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	Rhyodacite	Trd
GreeRC1972a	Rhyolite and rhyodacite	Trr
GreeRC1972b	Dacite	QTd
BrowDE1980aplate1	Rhyolite of Double O Ranch	Tmro
BrowDE1980aplate1	Rhyolite of Iron Mountain	QTr
BrowDE1980aplate1	Rhyolite of Palamino Butte	Tmrp
BrowDE1980aplate2	Rhyodacite	Tmrd
BrowDE1980aplate3	Rhyolite of Double O Ranch	Tmro
BrowDE1980aplate4	Rhyodacite	Tmrd
BrowDE1980b	Intrusive rhyodacites	Tpri
BrowDE1980b	Rhyodacite	Tmrd
BrowDE1980b	Rhyodacite of Burns Butte	Tmrb

Tob Olivine basalt (Late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	basalt	Tob
BrowDE1980aplate1	Basalt of Iron Mountain	Tmbi

Tobg Olivine basalt and andesite of Gum Boot Canyon (late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	Olivine basalt and andesite of Gum Boot Canyon	Tobg

Trt Rattlesnake Ash-flow Tuff (Late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
WalkGW1965	Tuffaceous sedimentary rocks, tuffs, and interbedded basaltic and andesitic flows	Tst
GreeRC1972a	Welded tuff of Double O Ranch	Tdo
GreeRC1972b	Welded tuff of Double O Ranch	Tdo
BrowDE1980aplate1	Rattlesnake ash-flow tuff	Tmtr
BrowDE1980aplate3	Rattlesnake ash-flow tuff	Tmtr
BrowDE1980aplate4	Rattlesnake ash-flow tuff	Tmtr
BrowDE1980b	Rattlesnake Ash-flow Tuff	Tmtr
JohnJA1994	Rattlesnake Ash-flow Tuff	Tr
JohnJA1994	Devitrified stony tuff	Trd
SherDR1994	Rattlesnake Ash-flow Tuff	Trd/Trl/Trv/Trvt

Appendix B. continued

Tdw Drinkwater Basalt (late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	Drinkwater Basalt	Tdw
BrowDE1980aplate2	Drinkwater Basalt	Tmbd
BrowDE1980aplate4	Drinkwater Basalt	Tmbd

Tbh Basalt of Harney Lake (late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
WalkGW1965	Basalt	Tb?
GreeRC1972a	Basalt	Tb
BrowDE1980aplate3	Basalt of Harney Lake	Tmbh
BrowDE1980aplate4	Basalt of Harney Lake	Tmbh
JohnJA1994	Basalt of Hog Wallow	Tbh
SherDR1994	Basalt of Black Rim	Tbb

Tdm Basalt and andesite of Dry Mountain (late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	Hypersthene andesite	Tha

Ta Andesite (late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
GreeRC1972a	Andesite	Ta
BrowDE1980b	Andesites	Tma

Tdv Devine Canyon Ash-flow Tuff (late Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
WallRE1956	Rhyolitic welded tuff	Tr
WalkGW1965	Tuffaceous sedimentary rocks, tuffs, and interbedded basaltic and andesitic flows	Tst
GreeRC1972a	Welded tuff of Devine Canyon	Tdv
GreeRC1972b	Welded tuff of Devine Canyon	Tdv
BrowDE1980aplate2	Devine Canyon ash-flow tuff	Tmtd
BrowDE1980aplate3	Devine Canyon ash-flow tuff	Tmtd
BrowDE1980aplate4	Devine Canyon ash-flow tuff	Tmtd
BrowDE1980b	Devine Canyon Ash-flow Tuff	Tmtd
JohnJA1994	Devine Canyon Ash-flow Tuff	Td
SherDR1994	Devine Canyon Ash-flow Tuff	Td
EvanJG2001	Welded tuff, tuff, and tuffaceous sedimentary rock	Tts

Tov Older volcanic rocks (Miocene and late Oligocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
WallRE1956	Basalt, undifferentiated	Tbu
WallRE1956	Columbia River basalt	Tcr/Tcrp
WallRE1956	Basalt in valleys	Tvb
BrowCE1966b	Columbia River Group, undivided	Tcu
BrowCE1966b	Strawberry Volcanics	Ts
GreeRC1972a	Basalt	Tb
GreeRC1972a	Basalt and andesite	Tba

Appendix B. continued

GreeRC1972b	Basalt and andesite	Tba
BrowCE1977	Basalt and andesite flows	Tcb
BrowCE1977	Strawberry Volcanics	Ts
BrowDE1980aplate2	Basalt and andesite	Tmba
BrowDE1980plate4	Miocene basalt	Tmb
BrowDE1980b	Basalt and andesite	Tmba

Tsb Steens Basalt (early Miocene)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
WalkGW1965	Flows and flow breccias	Tbf
GreeRC1972a	Basalt and andesite	Tba
BrowDE1980aplate4	Basalt and andesite	Tmba
MinoSA1987b	Dikes	Tsd
MinoSA1987b	Steens Basalt	Ts
JohnJA1994	Steens Basalt	Ts
SherDR1994	Steens Basalt	Ts
EvanJG2001	Steens Basalt	Tsb

Mzu Mesozoic rocks (Late Jurassic to Late Triassic)

OGDC REF_ID_COD	OGDC MAP_UNIT_N	OGDC MAP_UNIT_L
WallRE1956	Basic sills and dikes	pb
WallRE1956	Graywacke, conglomerate, shale, and limestone	TRu
WallRE1956	Graywacke, shale, and limestone	Ju
BrowCE1966a	Ingle Tuff Tongue	Trli
BrowCE1966a	Keller Creek Shale	Jk
BrowCE1966a	Laycock Graywacke	TRl
BrowCE1966a	Murderers Creek Graywacke	TRm
BrowCE1966b	Sedimentary and volcanic rocks	Js/Jtl
GreeRC1972a	Lonesome and Trowbridge Formation of Lupher (1941)	Jlt
GreeRC1972a	Middle member of Snowshoe Formation	Jsn
GreeRC1972a	Sedimentary and volcanic rocks	TRPs/Jsv
GreeRC1972a	Warm Springs and Weberg Formation of Lupher (1941)	Jwsw
GreeRC1972b	Lonesome and Trowbridge Formation of Lupher (1941)	Jlt
GreeRC1972b	Middle member of Snowshoe Formation	Jsn
GreeRC1972b	Sedimentary rocks	TRs/Js
BrowCE1977	Keller Creek Shale	Jk
BrowCE1977	Laycock Graywacke	TRl
BrowCE1977	Mowich Group	Jm
BrowCE1977	Murderers Creek Graywacke	Jmc
BrowCE1977	Permian (?) rocks	Pc
BrowCE1977	Ultramafic and mafic rocks related to Canyon Mountain Complex	PZsp/sp

Appendix C. New X-ray fluorescence (XRF) geochemical analyses for outcrop and subsurface samples

Major element determinations have been normalized to a 100-percent total on a volatile-free basis and recalculated with total iron expressed as FeO*.

Sample	EOARC 520-530	EOARC 540-550	EOARC 540-550-REP	HARN 52743 325-335
gw_logid	HARN0052747	HARN0052747	HARN0052747	HARN0052743
Latitude	43.52580	43.52580	43.52580	43.41623
Longitude	-119.02042	-119.02042	-119.02042	-118.57809
Depth Interval (ft)	520-530	540-550	540-550	325-335
XRF (wt% normalized)				
SiO2	73.31	73.33	73.26	53.58
TiO2	0.39	0.38	0.39	2.12
Al2O3	12.59	12.65	12.66	17.10
FeO*	2.91	2.52	2.54	9.68
MnO	0.12	0.11	0.11	0.18
MgO	0.65	1.14	1.16	3.45
CaO	1.89	2.21	2.23	9.07
Na2O	3.32	3.24	3.24	2.95
K2O	4.70	4.30	4.30	1.29
P2O5	0.13	0.12	0.12	0.59
Loss on ignition %	4.78	6.29	6.49	5.55
XRF (ppm)				
Ni	7	9	9	62
Cr	11	20	20	71
Sc	9	8	10	26
V	28	39	38	241
Ba	853	603	600	487
Rb	83	86	87	36
Sr	71	78	80	332
Zr	299	238	240	160
Y	79	76	77	34
Nb	26.0	25.4	26.3	17.2
Ga	18	19	18	18
Cu	11	15	13	50
Zn	104	95	95	101
Pb	24	16	17	7
La	34	27	28	31
Ce	79	67	66	52
Th	7	7	7	3
Nd	39	36	34	27
U	3	4	4	2

Appendix C. continued

Sample	HARN 52743 365-375	HARN 52743 375-400	HARN 52743 446-465	HARN52235-413
gw_logid	HARN0052743	HARN0052743	HARN0052743	HARN0052235
Latitude	43.41623	43.41623	43.41623	43.44597
Longitude	-118.57809	-118.57809	-118.57809	-118.79498
Depth Interval (ft)	365-375	375-400	446-465	413
XRF (wt% normalized)				
SiO2	53.63	53.66	53.95	83.03
TiO2	2.07	2.07	2.08	0.21
Al2O3	16.68	16.63	16.96	8.28
FeO*	9.94	9.87	9.53	1.59
MnO	0.16	0.16	0.17	0.04
MgO	3.75	3.80	3.49	0.23
CaO	8.82	8.80	8.91	0.41
Na2O	3.07	3.09	3.00	1.59
K2O	1.33	1.36	1.33	4.60
P2O5	0.56	0.56	0.57	0.02
Loss on ignition %	4.49	4.46	4.95	6.15
XRF (ppm)				
Ni	64	61	64	6
Cr	66	68	70	8
Sc	25	25	24	5
V	239	234	236	52
Ba	550	565	523	98
Rb	31	31	34	83
Sr	330	330	328	32
Zr	157	154	156	212
Y	33	33	34	57
Nb	17.7	17.0	16.7	20.4
Ga	18	18	20	15
Cu	45	46	48	10
Zn	98	99	101	51
Pb	6	7	7	14
La	25	22	19	24
Ce	49	57	57	52
Th	2	3	2	5
Nd	27	29	30	24
U	1	2	2	5

Appendix C. continued

Sample	HARN52235-415	HARN52235-429	HARN52235-459	HARN52235-470
gw_logid	HARN0052235	HARN0052235	HARN0052235	HARN0052235
Latitude	43.44597	43.44597	43.44597	43.44597
Longitude	-118.79498	-118.79498	-118.79498	-118.79498
Depth Interval (ft)	415	429	459	470
XRF (wt% normalized)				
SiO2	76.10	75.04	74.78	73.74
TiO2	0.21	0.19	0.21	0.20
Al2O3	13.12	13.65	13.09	13.62
FeO*	1.62	1.61	1.57	1.65
MnO	0.06	0.10	0.08	0.07
MgO	0.33	0.56	1.22	1.25
CaO	0.76	0.76	1.06	1.09
Na2O	5.15	5.37	5.40	5.65
K2O	2.62	2.70	2.57	2.71
P2O5	0.02	0.02	0.02	0.02
Loss on ignition %	12.84	13.81	14.18	14.54
XRF (ppm)				
Ni	2	2	5	5
Cr	5	4	8	6
Sc	5	6	5	4
V	13	10	19	18
Ba	634	866	503	551
Rb	114	131	124	134
Sr	77	95	87	93
Zr	256	267	217	233
Y	67	96	60	60
Nb	30.0	31.8	30.6	27.6
Ga	22	18	16	18
Cu	2	3	5	4
Zn	96	101	93	97
Pb	20	20	19	21
La	34	33	28	28
Ce	73	79	68	65
Th	9	12	6	7
Nd	38	41	34	32
U	11	6	5	4

Appendix C. continued

Sample	HARN52235-UNK1	HARN52235-UNK2	HARN52235-UNK2-REP	HARN52607-70
gw_logid	HARN0052235	HARN0052235	HARN0052235	HARN0052607
Latitude	43.44597	43.44597	43.44597	43.22671
Longitude	-118.79498	-118.79498	-118.79498	-118.48156
Depth Interval (ft)	416-476	416-476	416-476	60-70
XRF (wt% normalized)				
SiO2	75.72	75.71	75.77	48.53
TiO2	0.20	0.19	0.19	0.89
Al2O3	13.26	13.30	13.30	16.83
FeO*	1.56	1.55	1.55	9.80
MnO	0.07	0.07	0.07	0.17
MgO	0.63	0.60	0.59	9.85
CaO	0.72	0.72	0.71	11.06
Na2O	5.26	5.26	5.23	2.55
K2O	2.57	2.58	2.57	0.22
P2O5	0.02	0.02	0.02	0.11
Loss on ignition %	13.53	13.40	13.26	0.79
XRF (ppm)				
Ni	3	3	2	195
Cr	4	4	4	382
Sc	6	6	5	34
V	12	11	11	225
Ba	639	643	640	111
Rb	129	129	129	4
Sr	90	90	91	205
Zr	245	244	245	60
Y	61	60	59	20
Nb	28.9	27.9	28.2	2.2
Ga	20	20	20	15
Cu	2	3	2	66
Zn	97	99	100	66
Pb	20	20	21	2
La	30	31	31	3
Ce	71	71	68	12
Th	8	8	9	1
Nd	36	37	37	7
U	5	3	3	0

Appendix C. continued

Sample	HARN52607-110	HARN52607-140	HARN52607-150	HARN52607-190
gw_logid	HARN0052607	HARN0052607	HARN0052607	HARN0052607
Latitude	43.22671	43.22671	43.22671	43.22671
Longitude	-118.48156	-118.48156	-118.48156	-118.48156
Depth Interval (ft)	100-110	130-140	140-150	180-190
XRF (wt% normalized)				
SiO2	48.41	47.93	48.05	47.99
TiO2	1.12	1.01	1.13	1.08
Al2O3	17.47	17.36	17.39	17.19
FeO*	9.85	10.07	10.77	10.34
MnO	0.17	0.17	0.17	0.18
MgO	9.13	9.31	8.11	9.21
CaO	10.93	11.31	11.37	11.18
Na2O	2.54	2.51	2.67	2.46
K2O	0.24	0.21	0.21	0.25
P2O5	0.14	0.12	0.13	0.12
Loss on ignition %	3.80	2.82	0.86	1.50
XRF (ppm)				
Ni	143	157	150	164
Cr	225	253	242	242
Sc	37	35	36	37
V	239	230	199	239
Ba	142	132	143	120
Rb	3	4	3	4
Sr	200	198	213	221
Zr	68	63	70	69
Y	20	20	22	22
Nb	1.6	2.1	2.2	2.1
Ga	17	15	15	16
Cu	104	90	97	101
Zn	67	65	73	69
Pb	2	2	1	2
La	4	3	6	2
Ce	15	8	15	14
Th	0	0	0	0
Nd	10	8	11	11
U	2	1	0	1

Appendix C. continued

Sample	HARN52607-200	HARN52607-230	HARN52607-250	HARN52607-300
gw_logid	HARN0052607	HARN0052607	HARN0052607	HARN0052607
Latitude	43.22671	43.22671	43.22671	43.22671
Longitude	-118.48156	-118.48156	-118.48156	-118.48156
Depth Interval (ft)	190-200	220-230	240-250	290-300
XRF (wt% normalized)				
SiO2	48.19	48.05	47.86	47.69
TiO2	1.10	1.10	1.08	1.18
Al2O3	17.12	17.23	17.12	17.11
FeO*	10.46	10.45	10.24	10.44
MnO	0.17	0.16	0.18	0.17
MgO	8.59	8.99	8.88	8.66
CaO	11.36	11.07	11.64	11.77
Na2O	2.62	2.58	2.61	2.62
K2O	0.24	0.23	0.24	0.22
P2O5	0.14	0.14	0.13	0.15
Loss on ignition %	0.99	2.10	1.69	2.91
XRF (ppm)				
Ni	151	157	170	155
Cr	247	255	247	234
Sc	36	37	35	35
V	242	232	231	238
Ba	148	143	143	142
Rb	5	5	5	4
Sr	210	205	210	204
Zr	71	70	69	72
Y	22	22	22	23
Nb	2.5	1.7	1.8	1.3
Ga	15	16	17	15
Cu	89	95	86	93
Zn	70	69	68	71
Pb	0	0	0	1
La	7	4	6	5
Ce	13	13	14	6
Th	0	0	0	0
Nd	10	9	9	7
U	1	1	0	0

Appendix C. continued

Sample	HARN52607-320	HARN52607-350	HARN52657-30	HARN52657-100
gw_logid	HARN0052607	HARN0052607	HARN0052657	HARN0052657
Latitude	43.22671	43.22671	43.44737	43.44737
Longitude	-118.48156	-118.48156	-119.23529	-119.23529
Depth Interval (ft)	310-320	340-350	20-30	90-100
XRF (wt% normalized)				
SiO2	47.80	47.77	47.61	47.31
TiO2	1.11	1.14	1.58	2.12
Al2O3	17.15	17.02	17.00	16.70
FeO*	10.34	10.46	10.81	11.60
MnO	0.17	0.18	0.18	0.20
MgO	9.46	8.93	9.02	7.76
CaO	11.14	11.54	10.39	10.44
Na2O	2.51	2.61	2.77	2.90
K2O	0.20	0.21	0.37	0.48
P2O5	0.13	0.15	0.26	0.49
Loss on ignition %	3.20	1.95	0.72	0.20
XRF (ppm)				
Ni	165	168	161	104
Cr	254	248	240	155
Sc	37	35	35	37
V	232	236	245	284
Ba	125	144	195	246
Rb	4	4	7	8
Sr	188	215	263	242
Zr	69	71	107	142
Y	21	23	27	37
Nb	1.8	1.8	7.4	10.6
Ga	15	16	16	18
Cu	95	78	61	66
Zn	67	70	80	86
Pb	1	1	1	2
La	1	5	9	13
Ce	13	10	24	29
Th	0	1	1	0
Nd	9	9	15	20
U	1	0	3	2

Appendix C. continued

Sample	HARN52657-280	HARN52657-430	HARN52657-460	HARN52657-560
gw_logid	HARN0052657	HARN0052657	HARN0052657	HARN0052657
Latitude	43.44737	43.44737	43.44737	43.44737
Longitude	-119.23529	-119.23529	-119.23529	-119.23529
Depth Interval (ft)	270-280	420-430	450-460	550-560
XRF (wt% normalized)				
SiO2	48.17	49.91	50.36	51.79
TiO2	1.87	1.71	1.56	1.58
Al2O3	17.29	16.12	16.29	15.68
FeO*	11.87	9.58	10.82	10.91
MnO	0.19	0.18	0.18	0.24
MgO	8.11	6.39	7.89	7.45
CaO	8.83	10.81	7.18	7.75
Na2O	2.46	2.37	3.31	1.84
K2O	0.88	2.46	2.07	2.43
P2O5	0.32	0.47	0.33	0.34
Loss on ignition %	6.74	19.25	20.29	21.81
XRF (ppm)				
Ni	77	64	80	101
Cr	55	51	111	182
Sc	33	21	25	28
V	252	185	206	191
Ba	513	405	237	346
Rb	21	22	22	35
Sr	784	370	354	451
Zr	148	114	86	88
Y	31	28	25	25
Nb	11.2	7.3	4.5	4.4
Ga	18	14	14	12
Cu	63	43	57	66
Zn	83	69	66	63
Pb	2	4	2	2
La	11	12	8	6
Ce	28	23	22	23
Th	2	2	1	1
Nd	15	16	14	15
U	2	1	1	1

Appendix C. continued

Sample	HARN52657-600	HARN52657-623	HBB17-001	HBB17-002
gw_logid	HARN0052657	HARN0052657	OTCP0023315	OTCP0023316
Latitude	43.44737	43.44737	43.44858	43.43279
Longitude	-119.23529	-119.23529	-119.22327	-119.18697
Depth Interval (ft)	590-600	610-623	outcrop	outcrop
XRF (wt% normalized)				
SiO2	48.63	48.43	48.81	48.05
TiO2	1.96	1.95	2.56	1.43
Al2O3	16.92	16.85	15.59	16.92
FeO*	11.14	11.46	12.38	10.65
MnO	0.19	0.19	0.22	0.19
MgO	7.49	7.19	6.22	8.83
CaO	10.10	10.37	9.36	10.63
Na2O	2.69	2.67	3.25	2.70
K2O	0.48	0.46	0.96	0.34
P2O5	0.42	0.42	0.65	0.27
Loss on ignition %	5.00	5.55	0.86	0.73
XRF (ppm)				
Ni	107	102	66	157
Cr	190	184	120	252
Sc	36	34	38	36
V	273	271	319	262
Ba	301	309	442	229
Rb	6	6	19	5
Sr	220	217	230	231
Zr	123	122	226	88
Y	33	32	46	26
Nb	7.4	6.7	16.3	5.3
Ga	17	18	19	16
Cu	75	73	49	79
Zn	87	86	102	77
Pb	1	2	5	2
La	11	10	19	8
Ce	29	27	44	20
Th	1	1	3	1
Nd	17	19	27	14
U	2	2	2	1

Appendix C. continued

Sample	HBB17-002-REP	HBB17-004	HBB17-005	HBB17-006
gw_logid	OTCP0023316	OTCP0023318	OTCP0023319	OTCP0023311
Latitude	43.43279	43.39347	43.46397	43.56696
Longitude	-119.18697	-119.33786	-119.33081	-119.46143
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	48.08	48.42	47.81	52.92
TiO2	1.42	1.37	1.27	1.35
Al2O3	16.90	17.22	17.85	17.40
FeO*	10.63	10.10	9.92	9.09
MnO	0.19	0.18	0.17	0.16
MgO	8.80	8.94	8.46	5.35
CaO	10.66	10.59	11.43	8.63
Na2O	2.71	2.53	2.52	3.40
K2O	0.35	0.43	0.33	1.25
P2O5	0.27	0.23	0.23	0.45
Loss on ignition %	0.79	1.58	0.65	0.72
XRF (ppm)				
Ni	158	151	153	59
Cr	250	216	220	86
Sc	35	36	38	26
V	258	236	229	214
Ba	226	179	203	686
Rb	5	8	6	15
Sr	232	419	227	467
Zr	87	96	89	151
Y	27	27	25	26
Nb	5.3	7.4	7.0	9.4
Ga	17	15	15	19
Cu	79	83	88	45
Zn	78	71	66	84
Pb	0	0	1	5
La	10	10	8	19
Ce	21	19	21	37
Th	0	1	1	3
Nd	14	11	14	22
U	1	1	2	2

Appendix C. continued

Sample	HBB17-007	HBB17-008	HBB17-009	HBB17-010
gw_logid	OTCP0023312	OTCP0023313	OTCP0023314	OTCP0000001
Latitude	43.56732	43.56783	43.56881	43.52097
Longitude	-119.46153	-119.46163	-119.46202	-119.2791
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	53.81	53.68	54.40	52.55
TiO2	1.32	1.26	1.34	2.01
Al2O3	17.07	17.23	17.03	15.24
FeO*	8.94	8.83	8.47	13.26
MnO	0.16	0.16	0.16	0.34
MgO	5.08	4.96	4.93	2.58
CaO	8.40	8.76	8.27	6.20
Na2O	3.47	3.42	3.50	4.33
K2O	1.28	1.26	1.46	2.15
P2O5	0.45	0.44	0.44	1.33
Loss on ignition %	1.15	1.90	1.26	0.91
XRF (ppm)				
Ni	51	54	49	3
Cr	83	82	78	0
Sc	26	25	27	40
V	204	197	216	42
Ba	749	663	683	1572
Rb	18	17	20	32
Sr	456	459	440	259
Zr	159	155	166	684
Y	27	26	28	123
Nb	9.6	9.3	9.9	51.8
Ga	19	18	18	27
Cu	76	79	67	18
Zn	87	83	86	206
Pb	5	5	6	12
La	18	18	20	67
Ce	45	40	45	156
Th	1	2	2	4
Nd	24	25	24	93
U	1	0	2	2

Appendix C. continued

Sample	HBB17-011	HBB19-001	HBB19-002	HBB19-002-REP
gw_logid	OTCP0000002	OTCP0000102	OTCP0000103	OTCP0000103
Latitude	43.53689	43.13887	43.1466	43.1466
Longitude	-119.58787	-118.83247	-118.82902	-118.82902
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	48.86	47.99	48.41	48.45
TiO2	1.67	1.01	1.22	1.22
Al2O3	16.78	17.39	16.72	16.75
FeO*	11.13	9.91	10.77	10.74
MnO	0.19	0.17	0.19	0.19
MgO	7.77	9.35	8.16	8.15
CaO	10.08	11.23	11.32	11.30
Na2O	2.85	2.56	2.75	2.74
K2O	0.33	0.23	0.27	0.27
P2O5	0.33	0.18	0.19	0.19
Loss on ignition %	0.42	0.43	0.50	0.36
XRF (ppm)				
Ni	139	175	126	126
Cr	247	230	259	258
Sc	33	34	41	41
V	264	225	275	274
Ba	275	146	169	174
Rb	3	4	4	4
Sr	276	230	226	226
Zr	106	65	77	77
Y	33	20	23	24
Nb	5.7	2.9	3.9	3.3
Ga	19	16	17	17
Cu	62	87	35	33
Zn	93	69	76	76
Pb	2	1	1	1
La	10	4	6	6
Ce	19	12	14	13
Th	1	0	0	0
Nd	16	9	10	10
U	1	1	1	1

Appendix C. continued

Sample	HBB19-003	HBB19-004	HBB19-005	HBB19-006
gw_logid	OTCP0000104	OTCP0000105	OTCP0000106	OTCP0000107
Latitude	43.16766	43.2288	43.21053	43.11
Longitude	-118.81663	-118.74051	-118.42707	-118.91247
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	48.62	48.05	49.28	48.07
TiO2	1.05	1.21	0.93	1.55
Al2O3	17.32	17.04	16.68	16.68
FeO*	9.82	10.73	9.88	11.42
MnO	0.17	0.18	0.17	0.20
MgO	8.81	8.84	8.85	7.98
CaO	11.21	10.90	11.10	10.50
Na2O	2.58	2.60	2.64	2.89
K2O	0.22	0.29	0.30	0.39
P2O5	0.18	0.17	0.15	0.31
Loss on ignition %	0.42	0.38	0.55	0.34
XRF (ppm)				
Ni	154	154	156	126
Cr	197	223	348	196
Sc	33	34	35	36
V	229	248	241	282
Ba	187	322	141	261
Rb	4	3	7	5
Sr	229	238	198	307
Zr	67	64	63	101
Y	23	21	21	28
Nb	2.6	2.2	2.0	4.6
Ga	17	16	17	18
Cu	96	50	105	89
Zn	68	75	67	88
Pb	2	2	1	2
La	6	5	4	10
Ce	18	16	16	26
Th	0	0	0	1
Nd	12	9	8	16
U	2	1	1	0

Appendix C. continued

Sample	HBB19-007	HBB19-008	HBB19-009	HBB19-010
gw_logid	OTCP0000108	OTCP0000109	OTCP0000111	OTCP0000113
Latitude	43.13159	43.15961	43.2004	43.02936
Longitude	-118.6597	-118.66857	-118.70815	-118.81994
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	48.82	47.88	48.34	48.31
TiO2	1.89	0.87	1.13	1.43
Al2O3	17.10	17.26	17.24	17.09
FeO*	10.39	9.56	10.28	10.72
MnO	0.17	0.17	0.17	0.20
MgO	7.41	10.10	8.67	7.77
CaO	9.40	11.24	11.11	10.83
Na2O	3.49	2.58	2.70	2.82
K2O	0.89	0.21	0.23	0.47
P2O5	0.44	0.13	0.12	0.36
Loss on ignition %	0.62	0.36	0.34	0.51
XRF (ppm)				
Ni	118	213	152	131
Cr	167	310	211	173
Sc	27	38	33	35
V	202	232	245	272
Ba	288	99	191	321
Rb	15	4	4	6
Sr	391	210	232	325
Zr	200	60	64	91
Y	30	22	21	32
Nb	22.7	2.1	2.5	5.9
Ga	18	14	17	17
Cu	62	102	115	126
Zn	76	60	73	79
Pb	2	2	1	2
La	22	6	4	12
Ce	43	12	14	27
Th	2	0	0	1
Nd	25	9	9	18
U	2	1	1	1

Appendix C. continued

Sample	HBB19-011	HBB19-011-REP	HBB19-012	HBB19-013
gw_logid	OTCP0000114	OTCP0000114	OTCP0000116	OTCP0000117
Latitude	43.07237	43.07237	43.19808	43.17499
Longitude	-118.87274	-118.87274	-118.99953	-118.99898
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	75.93	75.98	76.44	76.64
TiO2	0.16	0.16	0.17	0.15
Al2O3	11.87	11.83	13.17	11.45
FeO*	1.30	1.31	1.54	2.16
MnO	0.06	0.06	0.01	0.03
MgO	0.52	0.51	1.26	0.20
CaO	1.02	1.01	2.95	0.22
Na2O	3.22	3.23	1.69	4.46
K2O	5.63	5.63	2.75	4.67
P2O5	0.28	0.28	0.03	0.02
Loss on ignition %	3.86	3.71	14.95	1.02
XRF (ppm)				
Ni	4	4	0	4
Cr	7	6	7	4
Sc	5	5	4	2
V	13	13	15	14
Ba	421	422	371	56
Rb	98	99	116	107
Sr	38	38	254	12
Zr	250	252	232	511
Y	87	88	60	69
Nb	28.9	29.4	26.6	43.3
Ga	19	19	21	22
Cu	6	5	4	4
Zn	96	96	14	95
Pb	18	19	19	19
La	31	32	27	59
Ce	70	74	58	113
Th	7	8	7	9
Nd	39	38	31	50
U	4	4	3	3

Appendix C. continued

Sample	HBB19-014	HBB19-015	HBB19-016	HBB19-017
gw_logid	OTCP0000118	OTCP0000119	OTCP0000120	OTCP0000121
Latitude	43.16247	43.15774	43.15505	43.14937
Longitude	-118.98279	-118.99081	-118.99226	-118.99037
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	77.58	75.87	47.91	76.46
TiO2	0.14	0.15	1.45	0.16
Al2O3	10.79	11.77	16.57	11.89
FeO*	1.93	2.19	11.22	1.39
MnO	0.04	0.06	0.19	0.08
MgO	0.33	0.15	8.91	0.60
CaO	0.72	0.35	9.18	0.59
Na2O	4.15	3.89	3.81	3.59
K2O	4.30	5.56	0.49	5.21
P2O5	0.02	0.01	0.27	0.03
Loss on ignition %	1.92	3.70	3.52	3.49
XRF (ppm)				
Ni	4	3	147	5
Cr	4	4	222	6
Sc	2	2	33	5
V	13	7	249	23
Ba	56	56	231	450
Rb	94	99	8	99
Sr	14	14	291	26
Zr	469	502	80	252
Y	59	77	26	91
Nb	40.7	43.4	4.6	30.1
Ga	21	21	16	18
Cu	5	6	77	11
Zn	93	100	80	98
Pb	18	19	2	20
La	55	60	9	32
Ce	108	119	21	70
Th	8	9	1	8
Nd	46	54	14	38
U	3	3	2	4

Appendix C. continued

Sample	HBB19-018	HBB19-019	HBB19-020	HBB19-021
gw_logid	OTCP0000122	OTCP0000173	OTCP0000174	OTCP0000175
Latitude	43.57211	42.99414	43.00874	43.02086
Longitude	-119.76306	-118.83371	-118.68439	-118.65763
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	47.55	48.06	56.72	57.57
TiO2	1.90	1.44	1.41	1.14
Al2O3	15.87	17.16	14.71	14.61
FeO*	11.82	10.86	10.42	9.17
MnO	0.20	0.19	0.16	0.17
MgO	8.32	7.67	3.63	4.28
CaO	10.71	11.00	7.23	7.74
Na2O	2.89	2.76	3.57	3.33
K2O	0.35	0.49	1.91	1.84
P2O5	0.39	0.38	0.24	0.17
Loss on ignition %	0.65	0.69	1.18	1.49
XRF (ppm)				
Ni	137	130	24	34
Cr	234	168	28	97
Sc	38	35	35	36
V	308	280	288	264
Ba	197	325	763	727
Rb	6	6	42	30
Sr	258	329	241	196
Zr	122	91	196	181
Y	33	27	40	38
Nb	8.0	5.3	12.0	11.3
Ga	19	16	19	17
Cu	69	96	120	125
Zn	92	79	95	80
Pb	2	2	6	6
La	7	7	20	21
Ce	25	23	38	38
Th	0	1	1	3
Nd	18	17	21	21
U	2	1	3	3

Appendix C. continued

Sample	HBB19-022	HBB19-023	HBB19-024	HBB19-025
gw_logid	OTCP0000176	OTCP0000177	OTCP0000178	OTCP0000179
Latitude	43.07763	43.32552	43.18633	43.16383
Longitude	-118.61017	-118.58957	-118.41462	-118.47323
Depth Interval (ft)	outcrop	outcrop	outcrop	outcrop
XRF (wt% normalized)				
SiO2	50.80	47.92	48.39	48.47
TiO2	1.88	1.47	0.88	0.96
Al2O3	15.71	16.96	17.07	17.02
FeO*	11.71	10.70	10.04	10.21
MnO	0.20	0.18	0.17	0.17
MgO	6.46	8.29	9.21	9.01
CaO	8.36	11.31	11.39	11.23
Na2O	3.14	2.64	2.52	2.61
K2O	1.20	0.33	0.22	0.20
P2O5	0.54	0.20	0.11	0.11
Loss on ignition %	0.46	0.87	0.64	0.50
XRF (ppm)				
Ni	98	147	166	150
Cr	113	199	282	317
Sc	29	36	34	35
V	258	276	232	238
Ba	424	307	188	125
Rb	36	6	4	4
Sr	298	262	184	196
Zr	141	85	62	65
Y	39	26	19	21
Nb	11.1	5.6	2.3	2.8
Ga	18	16	16	16
Cu	63	89	75	93
Zn	99	68	67	72
Pb	6	1	2	1
La	18	7	5	2
Ce	41	16	10	16
Th	2	1	0	0
Nd	26	12	8	10
U	2	1	1	1

Appendix D. Observation well completion logs

Site Name: Chain Lakes Obs Well

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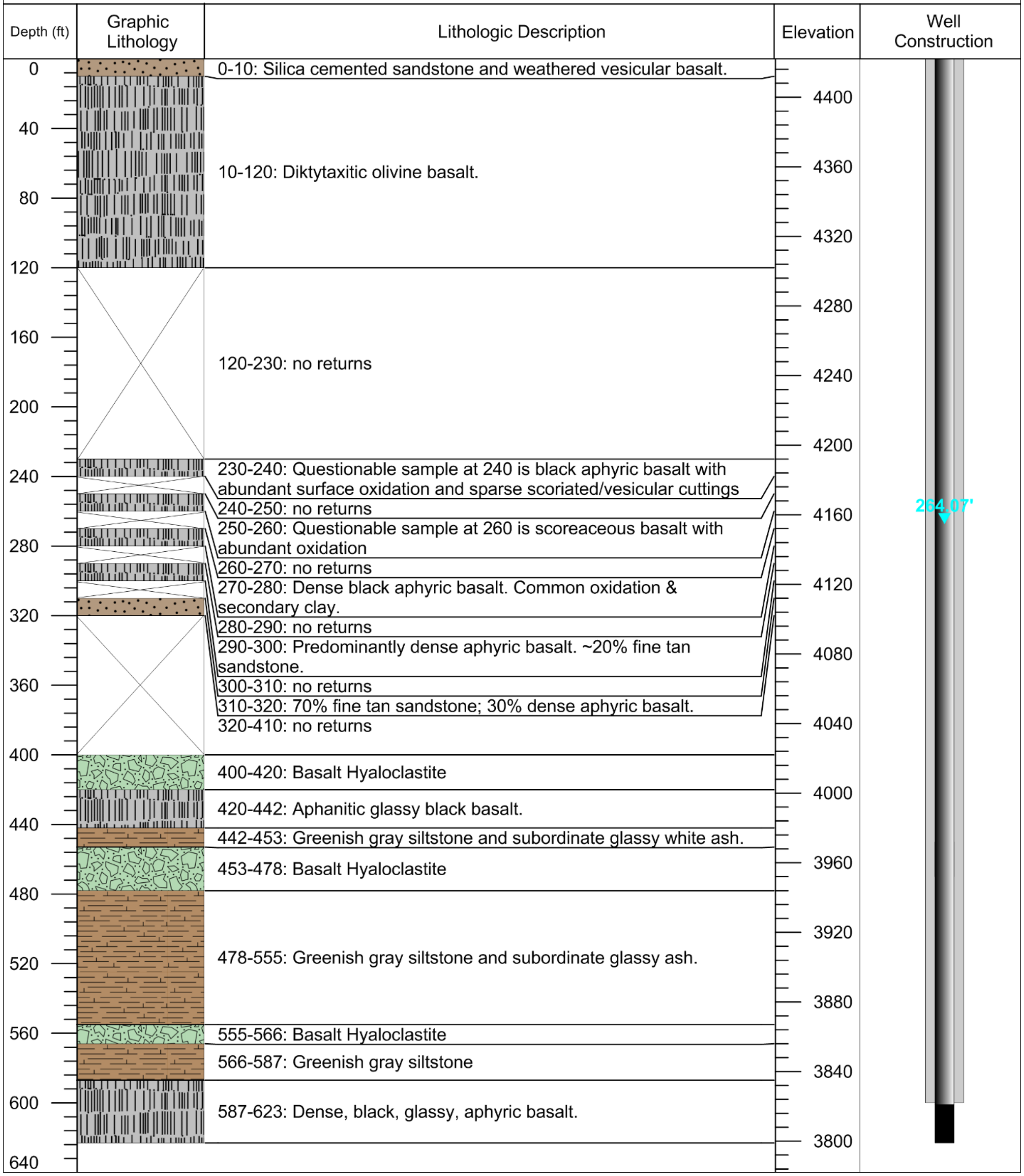
Well Log ID: HARN 52657
Well Tag: L-124977
State Obs Nbr: na
Township/Range-Section: 24S/29E-34 SW-NW
USGS 24k Quad: Weaver Lake
Lat, Long WGS84: 43.44736, -119.23534
County: Harney
Elevation and Datum: 4422
Comments: SWL Date: 8/21/2018
Basin: Malheur Lake
Total Depth: 623 FT
Logged By: D. Boschmann
Drilled: 6/15/2017 - 6/27/2017

OREGON WATER RESOURCES DEPARTMENT



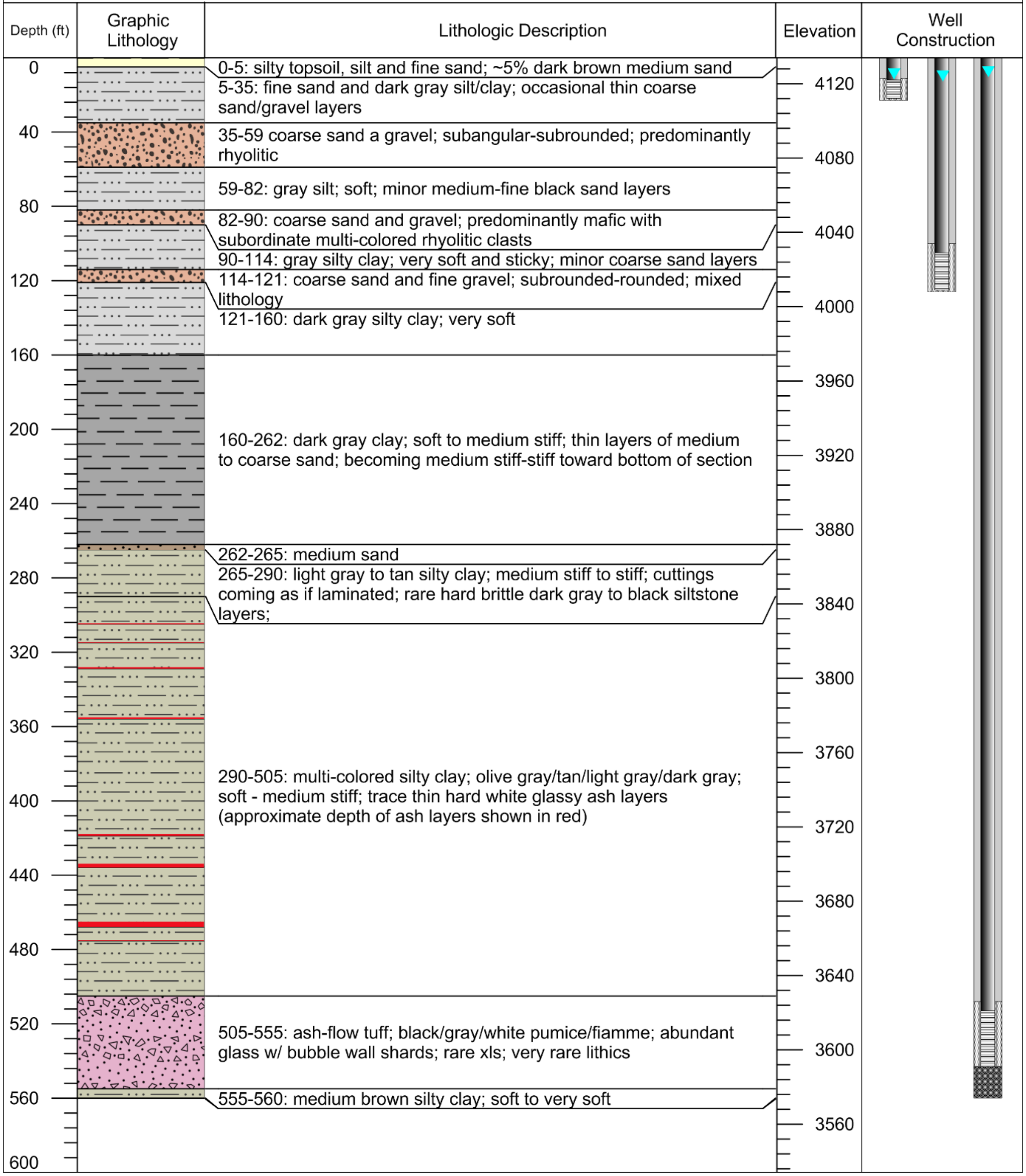
0-10: Silica cemented sandstone and weathered vesicular basalt.
10-120: Diktytaxitic olivine basalt.
120-230: no returns
230-240: Questionable sample at 240 is black aphyric basalt with abundant surface oxidation and sparse scoriated/vesicular cuttings
240-250: no returns
250-260: Questionable sample at 260 is scoreaceous basalt with abundant oxidation
260-270: no returns
270-280: Dense black aphyric basalt. Common oxidation & secondary clay.
280-290: no returns
290-300: Predominantly dense aphyric basalt. ~20% fine tan sandstone.
300-310: no returns
310-320: 70% fine tan sandstone; 30% dense aphyric basalt.
320-410: no returns
400-420: Basalt Hyaloclastite
420-442: Aphanitic glassy black basalt.
442-453: Greenish gray siltstone and subordinate glassy white ash.
453-478: Basalt Hyaloclastite
478-555: Greenish gray siltstone and subordinate glassy ash.
555-566: Basalt Hyaloclastite
566-587: Greenish gray siltstone
587-623: Dense, black, glassy, aphyric basalt.

Appendix D. continued

Site Name: EOARC Obs Wells

Page1 of 1

Well Log ID: HARN 52749/52748/52747
Well Tag: 12158/12517/125156
State Obs Nbr: N.A.
Township/Range-Section: 24S/30E-5 NE-NE
USGS 24k Quad: Burns
Lat, Long WGS84: 43.52586, -119.02049
County: Harney
Elevation and Datum: 4134
Comments: Shallow Well; Intermediate Well; Deep Well
Basin: Malheur Lake
Total Depth: 22'/125'/543'
Logged By: D. Boschmann
Drilled: 09/12/2018 - 09/27/2018



0-5: silty topsoil, silt and fine sand; ~5% dark brown medium sand

5-35: fine sand and dark gray silt/clay; occasional thin coarse sand/gravel layers

35-59 coarse sand a gravel; subangular-subrounded; predominantly rhyolitic

59-82: gray silt; soft; minor medium-fine black sand layers

82-90: coarse sand and gravel; predominantly mafic with subordinate multi-colored rhyolitic clasts

90-114: gray silty clay; very soft and sticky; minor coarse sand layers

114-121: coarse sand and fine gravel; subrounded-rounded; mixed lithology

121-160: dark gray silty clay; very soft

160-262: dark gray clay; soft to medium stiff; thin layers of medium to coarse sand; becoming medium stiff-stiff toward bottom of section

262-265: medium sand

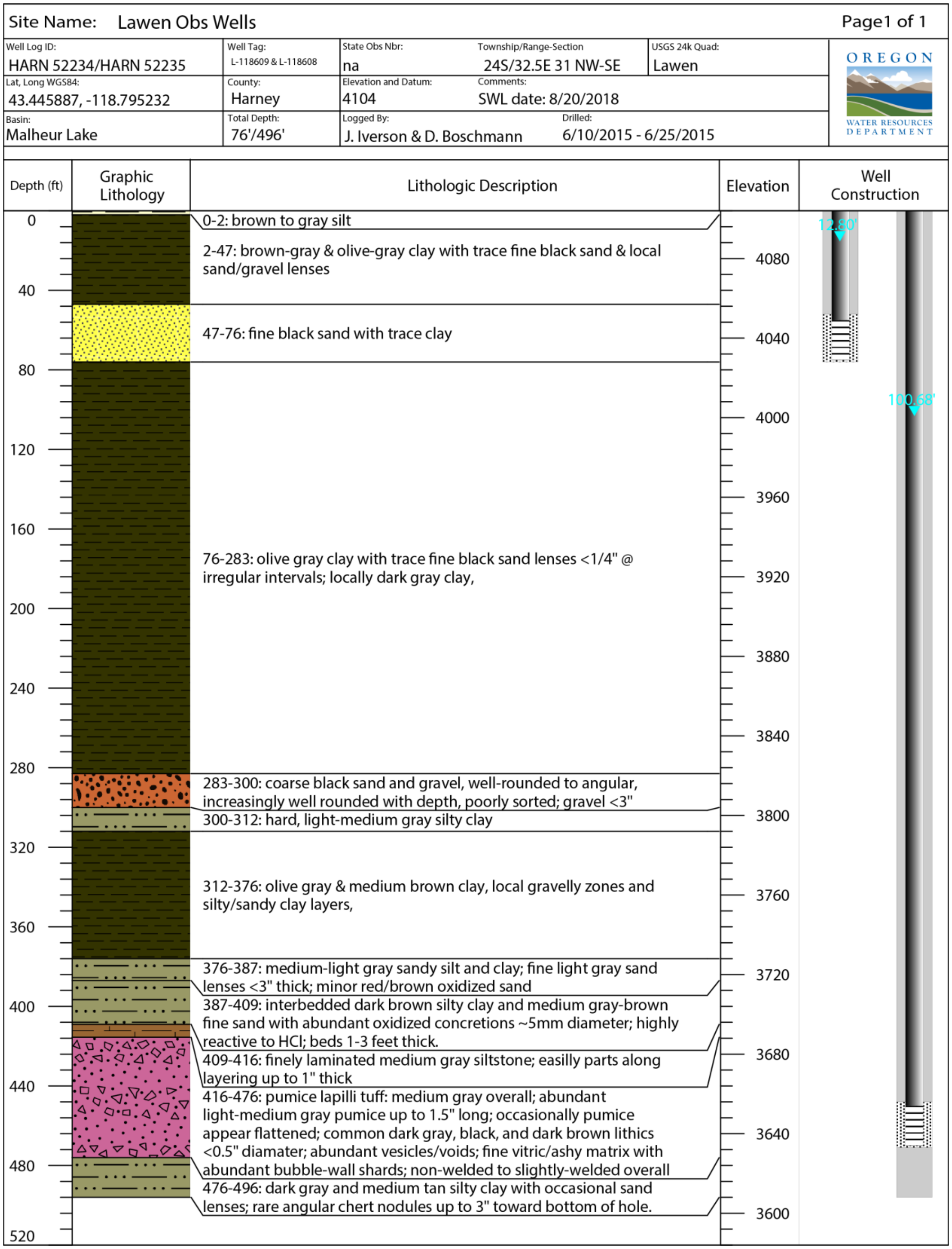
265-290: light gray to tan silty clay; medium stiff to stiff; cuttings coming as if laminated; rare hard brittle dark gray to black siltstone layers;

290-505: multi-colored silty clay; olive gray/tan/light gray/dark gray; soft - medium stiff; trace thin hard white glassy ash layers (approximate depth of ash layers shown in red)

505-555: ash-flow tuff; black/gray/white pumice/fiamme; abundant glass w/ bubble wall shards; rare xls; very rare lithics

555-560: medium brown silty clay; soft to very soft

Appendix D. continued



Site Name: Lawen Obs Wells

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Well Log ID: HARN 52234/HARN 52235

Well Tag: L-118609 & L-118608

State Obs Nbr: na

Township/Range-Section: 24S/32.5E 31 NW-SE

USGS 24k Quad: Lawen

Lat, Long WGS84: 43.445887, -118.795232

County: Harney

Elevation and Datum: 4104

Comments: SWL date: 8/20/2018

Basin: Malheur Lake

Total Depth: 76'/496'

Logged By: J. Iverson & D. Boschmann

Drilled: 6/10/2015 - 6/25/2015

Depth (ft)	Graphic Lithology	Lithologic Description	Elevation	Well Construction

0-2: brown to gray silt

2-47: brown-gray & olive-gray clay with trace fine black sand & local sand/gravel lenses

47-76: fine black sand with trace clay

76-283: olive gray clay with trace fine black sand lenses <1/4" @ irregular intervals; locally dark gray clay,

283-300: coarse black sand and gravel, well-rounded to angular, increasingly well rounded with depth, poorly sorted; gravel <3"

300-312: hard, light-medium gray silty clay

312-376: olive gray & medium brown clay, local gravelly zones and silty/sandy clay layers,

376-387: medium-light gray sandy silt and clay; fine light gray sand lenses <3" thick; minor red/brown oxidized sand

387-409: interbedded dark brown silty clay and medium gray-brown fine sand with abundant oxidized concretions ~5mm diameter; highly reactive to HCl; beds 1-3 feet thick.

409-416: finely laminated medium gray siltstone; easilly parts along layering up to 1" thick

416-476: pumice lapilli tuff: medium gray overall; abundant light-medium gray pumice up to 1.5" long; occasionally pumice appear flattened; common dark gray, black, and dark brown lithics <0.5" diamater; abundant vesicles/voids; fine vitric/ashy matrix with abundant bubble-wall shards; non-welded to slightly-welded overall

476-496: dark gray and medium tan silty clay with occasional sand lenses; rare angular chert nodules up to 3" toward bottom of hole.

Appendix D. continued

Site Name: Sunset Valley Obs Wells

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Well Log ID: HARN 52629/HARN 52606

Well Tag: L-122475/L-95064

State Obs Nbr: 1422/1419

Township/Range-Section 25S/31E-4

USGS 24k Quad: Dog Mountain

Lat, Long WGS84: 43.43585/-119.00109

County: Harney

Elevation and Datum: 4121

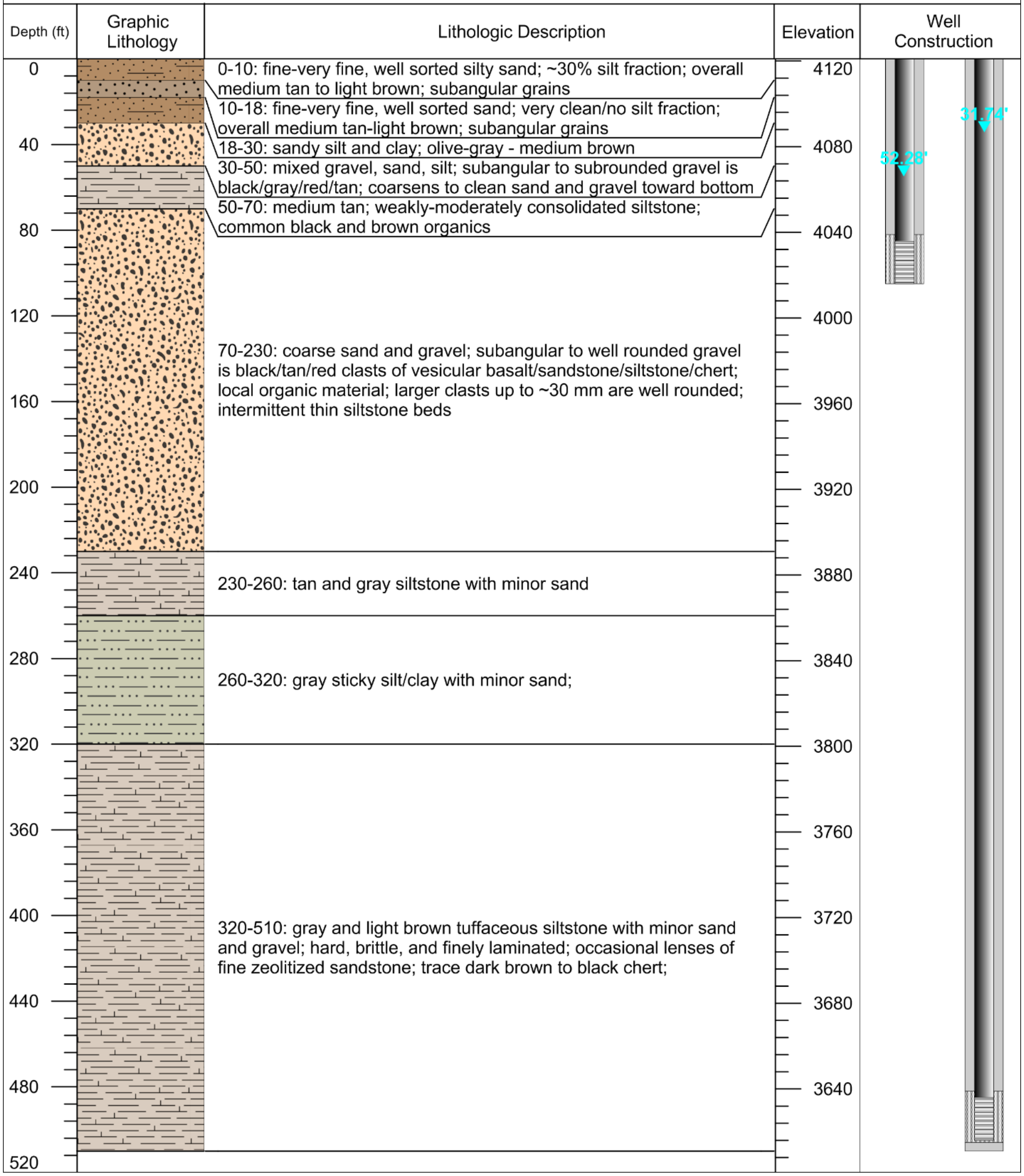
Comments: SWL Date: 8/21/2018

Basin: Malheur Lake

Total Depth: 105/510

Logged By: D. Boschmann/J. Grondin

Drilled: 8/31/2018 - 11/11/2016



0-10: fine-very fine, well sorted silty sand; ~30% silt fraction; overall medium tan to light brown; subangular grains

10-18: fine-very fine, well sorted sand; very clean/no silt fraction; overall medium tan-light brown; subangular grains

18-30: sandy silt and clay; olive-gray - medium brown

30-50: mixed gravel, sand, silt; subangular to subrounded gravel is black/gray/red/tan; coarsens to clean sand and gravel toward bottom

50-70: medium tan; weakly-moderately consolidated siltstone; common black and brown organics

70-230: coarse sand and gravel; subangular to well rounded gravel is black/tan/red clasts of vesicular basalt/sandstone/siltstone/chert; local organic material; larger clasts up to ~30 mm are well rounded; intermittent thin siltstone beds

230-260: tan and gray siltstone with minor sand

260-320: gray sticky silt/clay with minor sand;

320-510: gray and light brown tuffaceous siltstone with minor sand and gravel; hard, brittle, and finely laminated; occasional lenses of fine zeolitized sandstone; trace dark brown to black chert;

Appendix D. continued

Site Name: Virginia Valley Obs Wells

Page1 of 1

Well Log ID: HARN 52608/HARN52607

Well Tag: I-95065/I-95066

State Obs Nbr: 1421/1420

Township/Range-Section: 27S/34E-13

USGS 24k Quad:

Lat, Long WGS84: 43.22673, -118.48157

County: Harney

Elevation and Datum: 4118

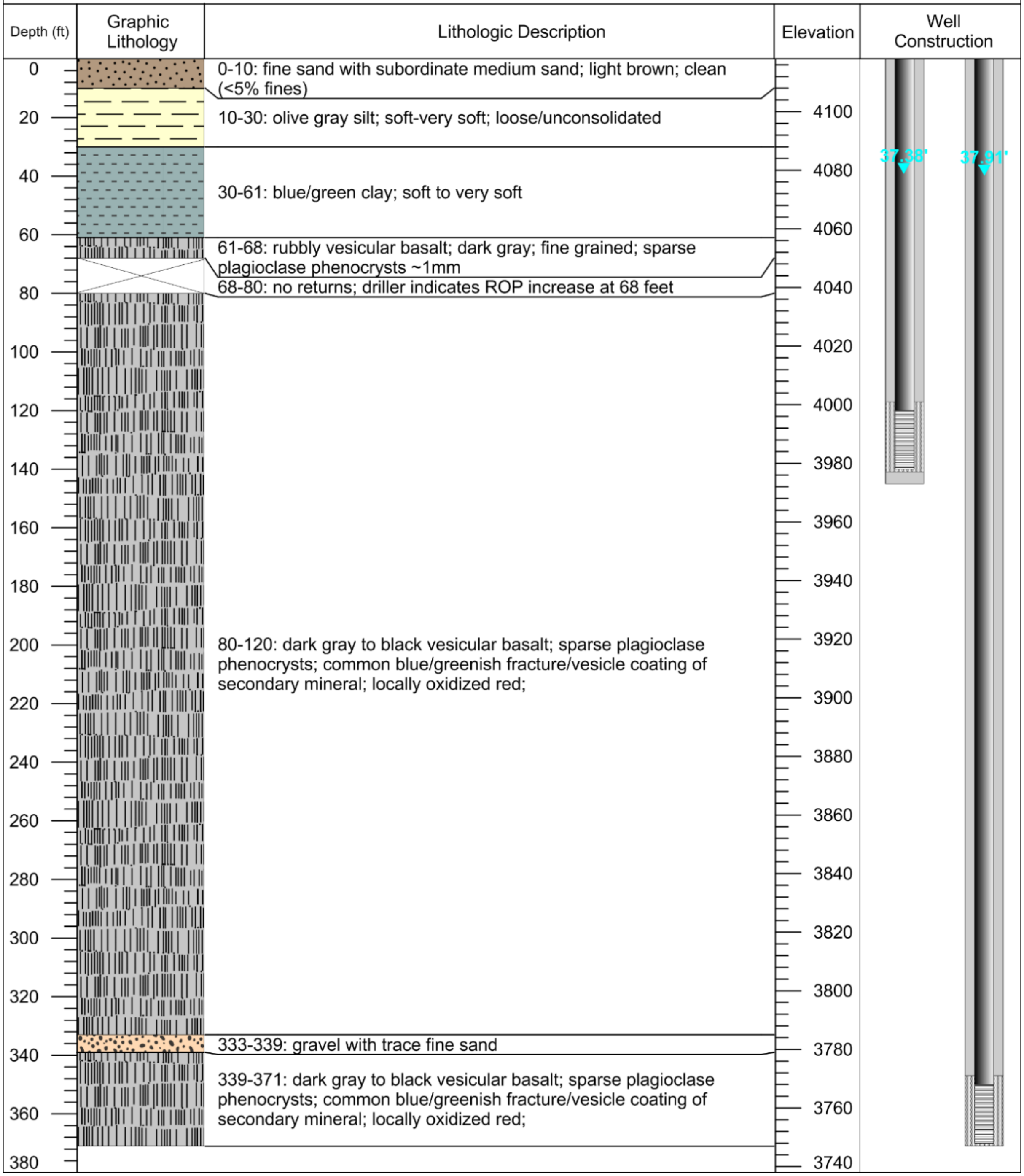
Comments: SWL Date: 8/21/2018

Basin: Malheur Lake

Total Depth: 145/371

Logged By: D. Boschmann

Drilled: 9/22/2018 - 10/22/2016



0-10: fine sand with subordinate medium sand; light brown; clean (<5% fines)

10-30: olive gray silt; soft-very soft; loose/unconsolidated

30-61: blue/green clay; soft to very soft

61-68: rubbly vesicular basalt; dark gray; fine grained; sparse plagioclase phenocrysts ~1mm

68-80: no returns; driller indicates ROP increase at 68 feet

80-120: dark gray to black vesicular basalt; sparse plagioclase phenocrysts; common blue/greenish fracture/vesicle coating of secondary mineral; locally oxidized red;

333-339: gravel with trace fine sand

339-371: dark gray to black vesicular basalt; sparse plagioclase phenocrysts; common blue/greenish fracture/vesicle coating of secondary mineral; locally oxidized red;

Appendix D. continued

Site Name: Weaver Springs Obs Wells

Page1 of 1

Well Log ID: HARN 52631/HARN 52630

Well Tag: L-122476/L-122477

State Obs Nbr: 1424/1423

Township/Range-Section: 25S/30E-28

USGS 24k Quad: Northwest Harney Lake

Lat, Long WGS84: 43.36791, -119.13226

County: Harney

Elevation and Datum: 4147

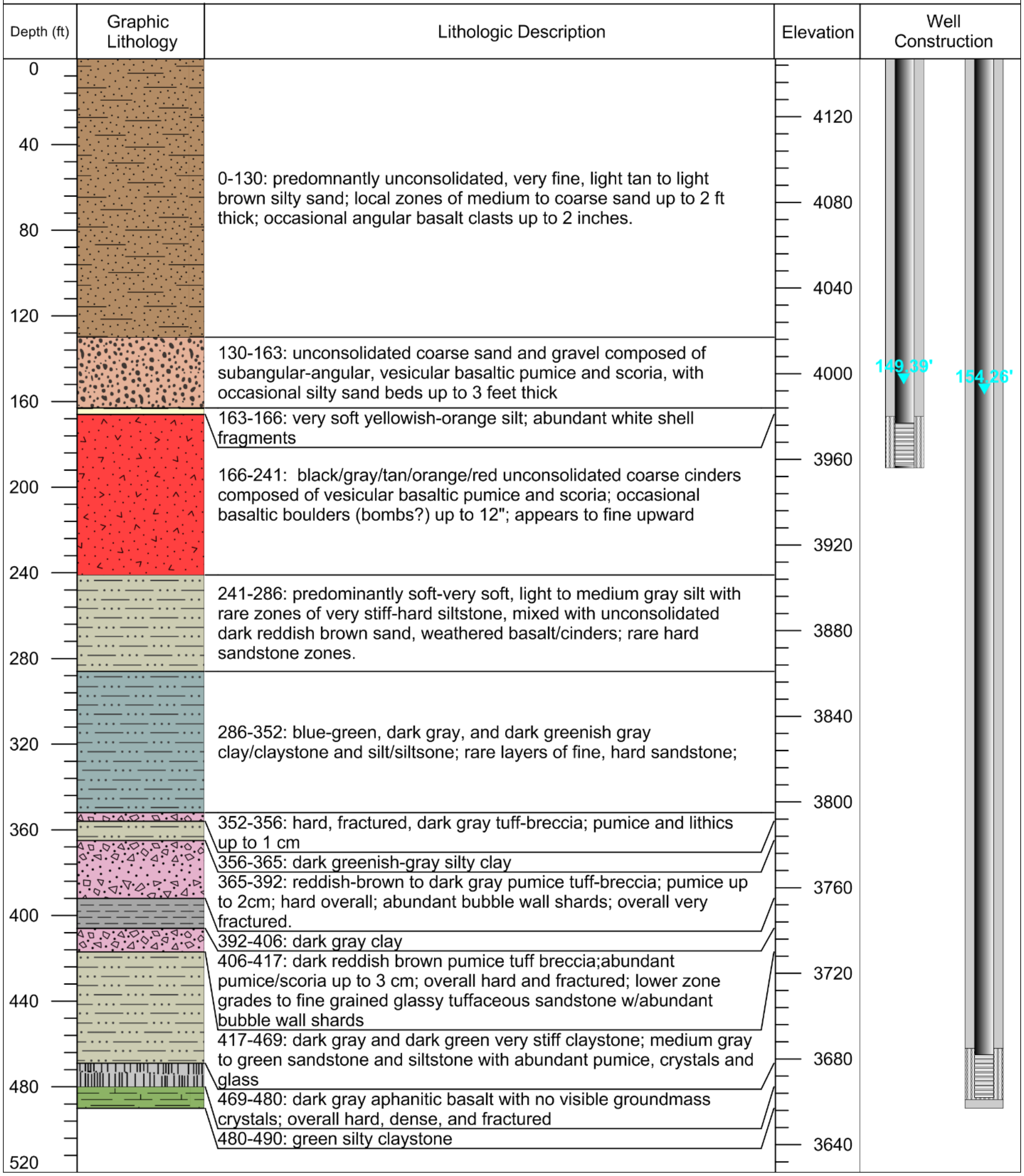
Comments: SWL Date: 9/27/2018

Basin: Malheur Lake

Total Depth: 490/191

Logged By: D. Boschmann

Drilled: 11/11/2016 - 12/7/2016



0-130: predomnantly unconsolidated, very fine, light tan to light brown silty sand; local zones of medium to coarse sand up to 2 ft thick; occasional angular basalt clasts up to 2 inches.

130-163: unconsolidated coarse sand and gravel composed of subangular-angular, vesicular basaltic pumice and scoria, with occasional silty sand beds up to 3 feet thick

163-166: very soft yellowish-orange silt; abundant white shell fragments

166-241: black/gray/tan/orange/red unconsolidated coarse cinders composed of vesicular basaltic pumice and scoria; occasional basaltic boulders (bombs?) up to 12"; appears to fine upward

241-286: predominantly soft-very soft, light to medium gray silt with rare zones of very stiff-hard siltstone, mixed with unconsolidated dark reddish brown sand, weathered basalt/cinders; rare hard sandstone zones.

286-352: blue-green, dark gray, and dark greenish gray clay/claystone and silt/siltsone; rare layers of fine, hard sandstone;

352-356: hard, fractured, dark gray tuff-breccia; pumice and lithics up to 1 cm

356-365: dark greenish-gray silty clay

365-392: reddish-brown to dark gray pumice tuff-breccia; pumice up to 2cm; hard overall; abundant bubble wall shards; overall very fractured.

392-406: dark gray clay

406-417: dark reddish brown pumice tuff breccia;abundant pumice/scoria up to 3 cm; overall hard and fractured; lower zone grades to fine grained glassy tuffaceous sandstone w/abundant bubble wall shards

417-469: dark gray and dark green very stiff claystone; medium gray to green sandstone and siltstone with abundant pumice, crystals and glass

469-480: dark gray aphanitic basalt with no visible groundmass crystals; overall hard, dense, and fractured

480-490: green silty claystone

Appendix E. Compilation of available ^{40}Ar/^{39}Ar ages for volcanic rocks in the Harney Basin

Sample	Latitude	Longitude	Rock Type	Map Unit	Material Dated	Age (Ma)	±2σ	Reference*
HLP-98-59	43.13970	-118.44430	basalt	Qvb	whole rock	0.14	0.16	Jordan and others, 2004
HLP-98-40	43.13160	-118.66010	basalt	Qvb	whole rock	1.23	0.10	Jordan and others, 2004
HLP-98-42	43.19250	-118.81920	basalt	Qvb	whole rock	1.47	0.16	Jordan and others, 2004
HB13	43.40600	-118.28500	basalt	Qvb	groundmass	1.93	0.29	Milliard, 2010
145CHLP98	43.46850	-119.55320	basalt	QTb	whole rock	2.20	0.08	Jordan and others, 2004
JR-91-21	43.48000	-119.72200	basalt	QTv	whole rock	2.37	0.08	Jordan and others, 2004
HLP-98-66	43.44670	-119.00350	basalt	QTb	whole rock	2.54	0.14	Jordan and others, 2004
138CHLP98R	43.46590	-119.82000	basalt	QTb	groundmass	2.83	0.89	Streck and others., 2012
HP-91-5	43.27030	-119.45180	rhyolite	Trd	biotite	2.89	0.16	Jordan and others, 2004
HBA-3	43.55670	-119.42830	basalt	QTv	whole rock	5.44	0.20	Jordan and others, 2004
HP-91-13	43.51236	-119.71173	rhyolite	Trd	sanidine	5.74	0.03	Jordan and others, 2004
JR-91-25	43.48400	-119.75500	rhyolite	Trd	obsidian	5.78	0.04	Jordan and others, 2004
HP-91-4	43.48960	-119.30420	rhyolite	Trd	biotite	6.35	0.06	Jordan and others, 2004
JR-92-56	43.47700	-119.53300	rhyolite	Trd	obsidian	6.90	0.04	Jordan and others, 2004
HP-91-12	43.88860	-120.04540	AFT	Trt	sanidine	7.09	0.03	Jordan and others, 2004
HP-93-4	43.39417	-119.82639	rhyolite	Trd	obsidian	7.13	0.03	Jordan and others, 2004
HP-93-13C	43.35278	-119.85060	rhyolite	Trd	obsidian	7.17	0.04	Jordan and others, 2004
HP-93-2	43.43278	-119.85333	rhyolite	Trd	sanidine	7.18	0.03	Jordan and others, 2004
HB15	43.38450	-118.17080	basalt	Tdw	whole rock	7.25	0.09	Milliard, 2010
148CHLP98	43.24660	-119.52990	basalt	Tbh	whole rock	7.54	0.26	Jordan and others, 2004
HBA-13.5	43.59170	-119.44830	basalt	Tobg	whole rock	7.60	0.22	Jordan and others, 2004
HP-91-2	43.56970	-119.13730	rhyolite	Trd	sanidine	7.68	0.08	Jordan and others, 2004
HLP-98-33	43.05700	-118.95830	basalt	Tbh	whole rock	7.68	0.16	Jordan and others, 2004
DMT-0601	43.67233	-119.56313	basalt	Tdm	whole rock	7.91	0.12	Iademarco, 2009
DO-93-13	43.25083	-119.26111	rhyolite	Trd	plagioclase	8.28	0.10	Jordan and others, 2004
PC-1	43.66564	-119.09773	AFT	Tts**	matrix	8.41	0.32	Jordan and others, 2004
DC-215a	44.16660	118.99310	AFT	Tdv	sanidine	9.74	0.04	Jordan and others, 2004
03SS17A-y	43.10775	-118.25083	AFT	Tdv	sanidine	9.76	0.02	Jarboe and others, 2008
JJ92-5	43.17722	-118.18167	rhyodacite	Trd	sanadine	10.38	0.06	Jordan and others, 2004
HLP-98-54	43.22700	-118.47550	basalt	Tov	groundmass	10.42	0.12	Jordan and others, 2004
HLP-98-32	43.03730	-118.94580	dacite	Trd	plagioclase	15.34	0.38	Jordan and others, 2004
HP-91-7	43.16130	-119.85740	dacite	Trd	sanidine	15.65	0.08	Jordan and others, 2004
EJ-12-03	43.64530	-118.62580	rhyolite	Trd	sanadine	16.13	0.11	Hess, 2014
MF94-63	42.60000	-118.56000	basalt	Tsb	plagioclase	16.60	0.28	Barry and others, 2013
G-41	42.64200	-118.57500	basalt	Tsb	plagioclase	16.61	0.28	Jarboe and others, 2010
HLP-98-35	42.99040	-118.86660	basalt	Tsb	whole rock	16.68	0.26	Jordan and others, 2004
03SS09G-2	43.10919	-118.26141	basalt	Tsb	plagioclase	16.72	0.19	Jarboe and others, 2010
03SS02	43.11234	-118.26997	basalt	Tsb	plagioclase	16.84	0.20	Jarboe and others, 2010
NMSB-55	42.53862	-118.60439	basalt	Tsb	groundmass	16.97	0.06	Moore and others, 2018
HBH295-17	43.76303	-118.89931	andesite	Tov	groundmass	24.75	0.15	Houston and others, 2018

*From Appendix A

**Prater Creek Tuff; AFT=ash-flow tuff