

State of Oregon  
Department of Geology and Mineral Industries  
Vicki S. McConnell, State Geologist

**GEOLOGIC MAP SERIES  
GMS-118**

**GEOLOGIC MAP OF THE KLAMATH FALLS AREA,  
KLAMATH COUNTY, OREGON**

By

George R. Priest, Frank R. Hladky, and Robert B. Murray,  
Oregon Department of Geology and Mineral Industries



**2008**

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Geologic Map of the Klamath Falls Area, Klamath County, Oregon

## 1.0 INTRODUCTION

The area of the Klamath Falls geologic map lies east of the High Cascades at the south end of Upper Klamath Lake (Figure 1.1). The Klamath River (Figure 1.1) provides the main drainage from the area, flowing from Upper Klamath Lake to the Pacific Ocean. The map boundaries encompass the urban growth boundary for the City of Klamath Falls plus some fringing areas (Figure 1.2). The map covers all of the Klamath Falls and Altamont topographic quadrangles, ~20 percent of the Wocus quadrangle (Figure 1.2), and ~10 percent of the adjacent Whiteline Reservoir quadrangle to the northeast.

Situated in the extreme northwestern part of the Basin and Range province, the quadrangle is dominated by the horst and graben topography resulting from the extensional tectonics that characterize the Basin and Range of south-

east Oregon (Figure 1.1). Elevation in the area ranges from 4,073 feet (1,240 m) at the Lost River to 6,200 feet (1,890 m) at the top of Hogback Mountain. The northwest-trending normal faults that bound Upper Klamath Lake and form the Klamath graben expose up to 480 m of volcanic and sedimentary rocks, ranging in age from late Miocene to Holocene. Upper Klamath Lake and surficial deposits of lake and river sediment cover approximately 25 percent of the map area. Link River flowing out of Upper Klamath Lake and the Klamath River flowing out of Lake Ewauna form the main perennial stream system in the area. The Lost River is a smaller river that flows on the southeastern side of the map area. Figures 1.1 and 1.2 show the location of the main physiographic and cultural features mentioned in the text.

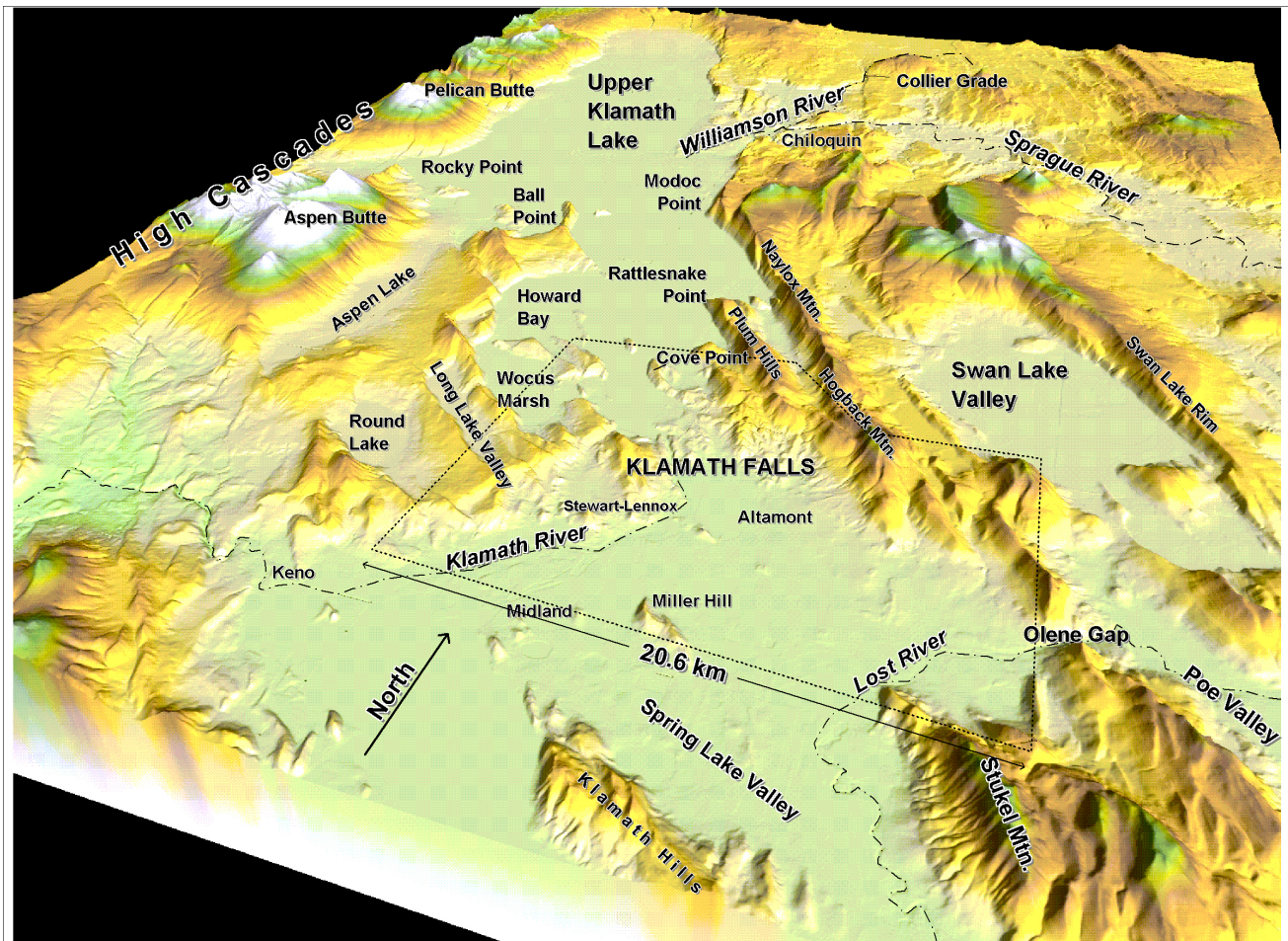
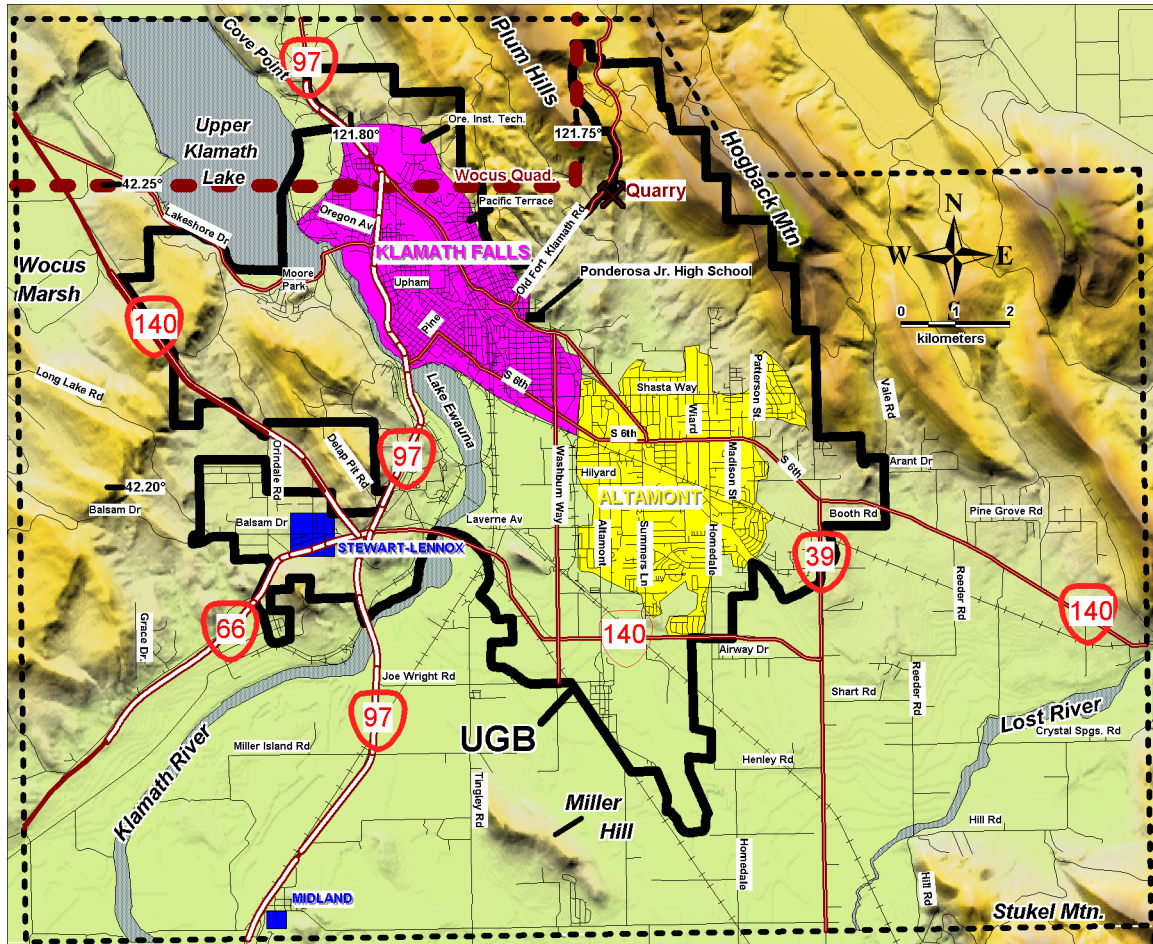


Figure 1.1. Location of mapped area (dotted line).





**Figure 1.2.** Location map of local geographic features. Dotted line is boundary of the geologic map. UGB is urban growth boundary; Ore. Inst. Tech. is Oregon Institute of Technology; Quad. is quadrangle.

Rock in the area is chiefly ~2-7 Ma dark gray lava (basalt and basaltic andesite) and contemporaneous to younger cream-colored diatomaceous mudstone. Local outcrops of sandstone and conglomerate cap a few low hills between Oregon Institute of Technology (OIT) and the Stewart Lennox area. Andesite crops out in a few areas near Link River, Stewart Lennox, and the southeastern tip of Hogback Mountain. Rocks in the area are the product of complex interaction between sedimentation and Cascade volcanism. Composition and extent of the volcanic rocks was modified after ~4 Ma by Basin and Range extension and the decreasing width of Cascade volcanic arc. By the time of the Pleistocene glaciations (by ~1.6 Ma) Cascade volcanic activity had mostly ceased in the area, as Cascade volcanism con-

tinued to narrow toward its present location in the High Cascades. Basin and Range extension continued to pull the area apart, dropping basins lower relative to ridges like Hogback Mountain, while sedimentation, helped along by periodic ash fall from the High Cascades, filled lake basins like Upper Klamath Lake and Round Lake.

The Klamath Falls geologic map covers areas mapped previously by Peterson and McIntyre (1970) and Sherrod and Pickthorn (1992). Geologic maps for adjacent quadrangles recently completed or in preparation include the Keno quadrangle (Hladky and Mertzman, 2000), and the Wocus quadrangle (Murray, in press). Overlapping portions of the Wocus quadrangle were taken directly from Murray (in press) with only minor alterations.

## 1.1 GEOLOGIC MAPPING TECHNIQUE

Geologic mapping was accomplished primarily to supply geologic data for the production of an earthquake hazard map of the Klamath Falls metropolitan area (Black and others, 2000); mapping detail and stratigraphic distinctions were influenced by this focus. In this regard, mapping is most detailed in the metropolitan area, and some surficial units are distinguished more for their engineering characteristics and importance to earthquake ground response than their geologic origins (e.g., see description of unit Qs versus unit Qal).

Fieldwork by Priest and Hladky was conducted during three months in 1997 and five days in 1998. The whole area was mapped in the field on stereo pairs of 1:62,500-scale aerial photos and on paper copies of 1:24,000-scale topographic quadrangles; hence most contacts are located no more accurately than  $\pm 12.2$  m (40 ft) in the horizontal. In areas of soil cover, bedrock contacts are located less accurately than  $\pm 12.2$  m. In many cases contacts observed in the field could be extended using photographic data. Subtle variations in relief are accentuated when viewed stereographically and often indicate changes in rock type beneath thinning soil cover. Field inspections on a case-by-case basis either confirmed or dispelled these indications. Poor exposure, due to colluvium and soil cover that are extensive on most slopes, made contact delineation in many areas difficult, even when the area was traversed on foot.

Detailed mapping by field traverse of critical areas was accomplished throughout the urban growth boundary; other areas were mapped in lesser detail using limited field traverses and interpretation of aerial photography. Mapping at Midland and the eastern part of Stukel Mountain is taken with only minor modification from Sherrod and Pickthorn (1992). In 1999 Robert Murray remapped the portion of the map overlapping the Wocus quadrangle (Figure 1.2) using digital orthophoto quadrangles with 1-m resolution, overlaid with digital line graphs of contour lines and hydrography, and printed out at 1:600 or 1:12,000 scale. These base maps allowed considerably improved location of contacts relative to previous mapping. As a result, Murray was able to map separately some units that were combined in other parts of the map area.

Faults are inferred from offset of rock units. Recognizing deformation required that units crop out and that the outcrops have distinct bedding in sedimentary units or distinct lithology in lavas. Outcrops are rare at Altamont and in the south central part of the map. Even where ditches

or canals penetrated soil cover, the underlying sedimentary rocks generally lack distinct bedding or units that could be correlated. Absence of mapped faults in these areas does not mean that faults are not present, only that compelling evidence was not found. The density of mapped faults in areas of hard rock suggests that many faults are present in areas covered by surficial soil units or extensive outcrops of poorly bedded mudstone of unit Tm or Tms.

The classification of igneous rocks in this report follows the geochemical method of Le Bas and Streckeisen (1991) with one modification: lavas with <53 percent SiO<sub>2</sub> are classified as basalt, while lavas with SiO<sub>2</sub> between 53 and 58 percent are classified as basaltic andesite. Units for which no analytical data were available were assigned rock names based on the following criteria: the name "basalt" was used for rocks having abundant fresh or incipiently altered olivine phenocrysts, typically with granular to felty groundmass; the name "basaltic andesite" was used for rocks containing altered olivine  $\pm$  orthopyroxene phenocrysts with intersertal to intergranular groundmass; the name "andesite" is used for rocks that contain clinopyroxene phenocrysts with orthopyroxene and perhaps a few thoroughly altered olivine phenocrysts in an intersertal intergranular, or devitrified, formerly hyalopilitic (glass plus crystals) groundmass.

## 1.2 RADIOMETRIC DATING

Duncan and others (1997) describe the <sup>40</sup>Ar/<sup>39</sup>Ar methodology used for new isotopic age analyses cited in Table 1.1. Low potassium in the samples limited the accuracy of the ages, particularly for basalt samples less than 2 Ma in age (e.g., Table 1.1; samples K-362 and K-370).

## 1.3 GEOCHEMISTRY

Table 1.2 lists locations, paleomagnetic polarity, and lithology of all samples analyzed for chemical composition (Table 1.3) and includes all isotopic age samples of Table 1.1.

Major and trace element analyses are from the Washington State University geochemical laboratory. Samples were analyzed by Diane Johnson utilizing methods described by Hooper and others (1993). One analysis (Table 1.2; map no. 1, sample 980611-1) was analyzed by S. A. Mertzman of Franklin and Marshall College, Lancaster, Pennsylvania, using standard X-ray fluorescence techniques described by Mertzman (2000). Duplicate analyses on samples with map numbers of 13, 29, and 51 illustrate the precision (repeatability) of the data (Table 1.3).

## 1.4 DIATOM AND TEPHRA DATA

Diatom analyses are from Platt Bradbury of the U.S. Geological Survey (USGS) on samples collected by George Priest (Table 1.4). Andre M. Sarna-Wojcicki of USGS did a tephra analysis and correlation on one sample collected by George Priest from an outcrop on Highway 97 at Collier Grade (43 km north of the map area).

**Table 1.1.**  $^{40}\text{Ar}/^{39}\text{Ar}$  Incremental Heating Ages for Rocks of the Klamath Falls Area

| Map No. | Field No. | Unit | Material   | Total Fusion Age (Ma) | Error | Plateau Age (Ma) | Error | $^{39}\text{Ar}$ Percent of Total | Isochron Age (Ma) | Error | <i>N</i> | $^{40}\text{Ar}/^{39}\text{Ar}$ Intercept $\pm 1\text{s}$ | <i>J</i> |
|---------|-----------|------|------------|-----------------------|-------|------------------|-------|-----------------------------------|-------------------|-------|----------|---|----------|
| 52      | K-29      | Tcba | whole rock | 2.51                  | 0.56  | 2.41             | 0.13  | 97                                | 2.33              | 0.45  | 6        | $302.34 \pm 101.99$                                       | 0.001667 |
| 53      | K-74      | Thb  | whole rock | 2.83                  | 0.70  | 2.67             | 0.21  | 88                                | 3.5               | 1.25  | 6        | $270.01 \pm 88.21$  | 0.001666 |
| 14      | K-90      | Tba  | whole rock | 4.03                  | 0.33  | 4.01             | 0.12  | 100                               | 3.84              | 0.17  | 6        | $299.77 \pm 5.86$   | 0.00164  |
| 7       | K-252     | Tla  | whole rock | 3.60                  | 0.20  | 3.43             | 0.06  | 98                                | 3.48              | 0.21  | 6        | $253.94 \pm 114.43$                                       | 0.00159  |
| —       | K362      | —    | whole rock | 1.14                  | 0.10  | —                | —     | —                                 | —                 | —     | 1        | —   | —        |
| 3       | K-370     | QTwb | whole rock | 0.94                  | 0.64  | —                | —     | —                                 | —                 | —     | 1        | —   | —        |
| 3       | K-370     | QTwb | whole rock | 0.97                  | 0.64  | 0.97             | 0.64  | 100                               | 0.68              | 0.68  | 6        | $313.41 \pm 83.02$  | 0.00144  |
| —       | 980611-1  | QTwb | —          | —                     | —     | 1.80             | 0.39  | —                                 | —                 | —     | —        | —   | —        |

Note: Analyses are by Robert A. Duncan, Oregon State University, Corvallis, Oregon. Table 1.2 lists locations. Sample K-362 is from unit Qsh1 of Wiley (2004), 43 km north of the map area. Sample 980611-1 is from Hladky and Mertzman (2000) in the adjacent Keno quadrangle.

Dash means no data or no map no. because sample is outside the map area; *N* is number of heating increments; *J* is neutron fluence factor; Ma is mega annums (million years ago).

**Table 1.2.** Locations, Paleomagnetic Polarity, and Lithology of All Samples Analyzed for Chemical Composition (see Table 1.3); Includes All Isotopic Age Samples of Table 1.1

| Map No. | Sample No. | Formation | West Longitude | North Latitude | Polarity | Rock Type  |
|---------|------------|-----------|----------------|----------------|----------|--|
| 0       | K-362      | —         | 121.85761      | 42.67179       | n        | Olivine basaltic andesite  |
| 1       | 980611-1   | QTwb      | 121.84714      | 42.23032       | -        | Diktytaxitic olivine basalt  |
| 2       | K-154      | QTwb      | 121.84640      | 42.22175       | -        | Fresh diktytaxitic olivine basalt  |
| 3       | K-370      | QTwb      | 121.83814      | 42.23747       | r        | Diktytaxitic olivine basalt  |
| 4       | K-367      | QTwb?     | 121.83624      | 42.22379       | n        | Olivine basalt   |
| 5       | K-247a     | Ta        | 121.81175      | 42.24281       | r        | Two-pyroxene andesite  |
| 6       | K-300      | Ta        | 121.68700      | 42.20802       | n        | Olivine-two-pyroxene andesite  |
| 7       | K-252      | Tla       | 121.81540      | 42.23390       | (r)      | Two-pyroxene andesite  |
| 8       | K-23       | Tba       | 121.77737      | 42.26132       | l        | Olivine basaltic andesite  |
| 9       | K-24       | Tba       | 121.77692      | 42.26195       | n        | Olivine bearing two-pyroxene andesite  |
| 10      | K-25       | Tba       | 121.77710      | 42.26246       | n        | Olivine basaltic andesite  |
| 11      | K-49       | Tba       | 121.77796      | 42.25303       | (r)      | Glomerocrystic olivine basaltic andesite   |
| 12      | K-88a      | Tba       | 121.70999      | 42.23620       | r        | Sl. glomerocrystic olivine-augite basaltic andesite  |
| 13      | K-89       | Tba       | 121.71072      | 42.23584       | (r)      | Altered sl. glomerocrystic olivine-augite basaltic andesite                                |
| 13      | K-89R      | Tba       | 121.71072      | 42.23584       | (r)      | Altered sl. glomerocrystic olivine-augite basaltic andesite                                |
| 14      | K-90       | Tba       | 121.71111      | 42.23370       | r        | Sl. glomerocrystic olivine-augite basaltic andesite  |
| 15      | K-91       | Tba       | 121.71175      | 42.23517       | (n)      | Vesicular olivine basaltic andesite  |
| 16      | K-91A      | Tba       | 121.71213      | 42.23491       | -        | Altered sl. glomerocrystic olivine-augite basaltic andesite                                |
| 17      | K-92       | Tba       | 121.71247      | 42.23437       | (n)      | Vesicular olivine augite basaltic andesite   |
| 18      | K-157      | Tba       | 121.79976      | 42.21785       | (r)      | Altered olivine basaltic andesite  |
| 19      | K-159      | Tba       | 121.81658      | 42.22360       | r        | Altered olivine basaltic andesite  |
| 20      | K-160      | Tba       | 121.81905      | 42.22593       | (n)      | Altered olivine basaltic andesite  |
| 21      | K-161      | Tba       | 121.81867      | 42.22586       | (n)      | Altered olivine basaltic andesite  |
| 22      | K-162      | Tba       | 121.81837      | 42.22600       | -        | Altered vesicular oxidized olivine basalt  |
| 23      | K-163      | (Tba)     | 121.81817      | 42.22729       | r        | Altered olivine basaltic andesite block probably from unit Tba upslope of the sample point |
| 24      | K-164      | Tba       | 121.80250      | 42.20472       | -        | Fresh basaltic andesite ash and cinder deposit   |
| 25      | K-166A     | Tba       | 121.80630      | 42.20479       | (r)      | Altered olivine basaltic andesite  |
| 26      | K-172      | Tba       | 121.80282      | 42.20920       | r        | Altered olivine basaltic andesite  |
| 27      | K-227      | Tba       | 121.80184      | 42.23788       | r        | Altered olivine basaltic andesite  |
| 28      | K-230      | Tba       | 121.79652      | 42.23233       | r        | Altered olivine basaltic andesite  |
| 29      | K-231      | Tba       | 121.79626      | 42.23242       | r        | Altered olivine basaltic andesite  |
| 29      | K-231R     | Tba       | 121.79626      | 42.23242       | r        | Altered olivine basaltic andesite  |
| 30      | K-236      | Tba       | 121.80681      | 42.24056       | r        | Altered olivine basaltic andesite  |
| 31      | K-238      | Tba       | 121.80678      | 42.24139       | r        | Altered olivine basaltic andesite  |
| 32      | K-248      | Tba       | 121.80565      | 42.23766       | r        | Altered olivine basalt   |
| 33      | K-259      | Tba       | 121.78762      | 42.22749       | n        | Altered glomerocrystic olivine basaltic andesite   |
| 34      | K-313      | Tba       | 121.75695      | 42.26311       | n        | Altered olivine-augite basaltic andesite   |
| 35      | K-316      | Tba       | 121.75794      | 42.26083       | n        | Altered olivine basaltic andesite  |
| 36      | K-318      | Tba       | 121.75656      | 42.25820       | r        | Olivine-augite basaltic andesite autobreccia   |
| 37      | K-319      | Tba       | 121.75542      | 42.25989       | r        | Olivine-augite basaltic andesite autobreccia   |
| 38      | K-320c     | Tba       | 121.75422      | 42.26131       | -        | Glomerocrystic olivine-augite basaltic andesite  |
| 39      | K-328      | Tba       | 121.76900      | 42.26459       | n        | Olivine basalt   |
| 40      | K-329      | Tba       | 121.77203      | 42.26477       | r        | Fresh glomerocrystic hyalopilitic olivine basaltic andesite                                |
| 41      | K-346      | Tba       | 121.84400      | 42.17824       | (n)      | Olivine basalt   |
| 42      | K-355      | Tba       | 121.85551      | 42.18095       | n        | Olivine basalt   |
| 43      | K-357m     | Tba       | 121.77353      | 42.14950       | n        | Altered olivine basaltic andesite  |
| 44      | K-359      | Tba       | 121.73631      | 42.17783       | n        | Altered olivine basaltic andesite  |
| 45      | K-381      | Tba       | 121.78606      | 42.22515       | r        | Fresh olivine basaltic andesite  |
| 46      | K-382      | Tba       | 121.78826      | 42.22232       | r        | Altered glomerocrystic olivine-augite basaltic andesite                                    |
| 47      | K-383      | Tba       | 121.78929      | 42.22298       | r        | Augite basaltic andesite   |
| 48      | K-384      | Tba       | 121.79009      | 42.22340       | (r)      | Fresh glomerocrystic olivine-augite basaltic andesite                                      |
| 49      | K-385      | Tba       | 121.78469      | 42.22204       | n        | Augite basaltic andesite   |
| 50      | K-386      | Tba       | 121.78617      | 42.22068       | r        | Altered glomerocrystic olivine-augite basaltic andesite                                    |
| 51      | K-321      | Tt        | 121.76083      | 42.25086       | -        | Fresh olivine-bearing sideromelane tuff  |
| 51      | K-321R     | Tt        | 121.76083      | 42.25086       | -        | Fresh olivine-bearing sideromelane tuff  |
| 52      | K-29       | Tcba      | 121.81164      | 42.26647       | ?        | Glomerocrystic olivine-augite basaltic andesite  |
| 53      | K-74       | Thb       | 121.70767      | 42.24349       | n        | Glomerocrystic olivine basalt  |
| 54      | K-76       | Thb       | 121.70862      | 42.24363       | n        | Glomerocrystic olivine-augite basalt   |
| 55      | K-80       | Thb       | 121.70623      | 42.23984       | n        | Glomerocrystic olivine basalt  |
| 56      | K-88       | Thb       | 121.70944      | 42.23604       | (n)      | Glomerocrystic olivine basalt  |
| 57      | K-96       | Thb       | 121.71113      | 42.24111       | n        | Olivine augite basalt vitrophyre   |
| 57      | K-96A      | Thb       | 121.71113      | 42.24111       | n        | Olivine augite basalt vitrophyre   |
| 58      | K-111      | Thb       | 121.70719      | 42.23452       | -        | Very fresh olivine basalt  |
| 59      | K-361      | Tpt       | 121.75780      | 42.22807       | -        | Basaltic andesite vitrophyre   |

Note: l is indeterminate polarity; n is normal polarity; r is reversed polarity; () is weak polarity; dash symbol means no measurement; parentheses on formation label indicates that the sample is from a large block of rock that may not be in place.



**Table 1.3.** Major Element Oxide Analyses and Trace Element Analyses

| Map No.<br>Map Unit<br>Sample No.        | 0<br>*<br>K-362   | 1<br>QTwb<br>980611-1 | 2<br>QTwb<br>K-154 | 3<br>QTwb<br>K-370 | 4<br>Tba<br>K-367  | 5<br>Ta<br>K-247A | 6<br>Ta<br>K-300  | 7<br>Tla<br>K-252  | 8<br>Tba<br>K-23  | 9<br>Tba<br>K-24   |
|--|-------------------|-----------------------|--------------------|--------------------|--------------------|-------------------|-------------------|--------------------|-------------------|--------------------|
| Analytical Date                          | 5-Jul-98          | 1998                  | 3-Jul-98           | 5-Jul-98           | 5-Jul-98           | 4-Jul-98          | 4-Jul-98          | 4-Jul-98           | 2-Jul-98          | 2-Jul-98           |
| West Longitude                           | 121.85761         | 121.84714             | 121.84640          | 121.83814          | 121.83624          | 121.81175         | 121.68700         | 121.81540          | 121.77811         | 121.77738          |
| North Latitude                           | 42.67179          | 42.23032              | 42.22175           | 42.23747           | 42.22379           | 42.24281          | 42.20802          | 42.23390           | 42.26067          | 42.26142           |
| <i>Oxides, weight percent</i>            |                   |                       |                    |                    |                    |                   |                   |                    |                   |                    |
| SiO <sub>2</sub>                         | 53.96             | 48.52                 | 49.48              | 48.63              | 49.70              | 57.91             | 58.27             | 58.66              | 52.19             | 58.02              |
| Al <sub>2</sub> O <sub>3</sub>           | 18.93             | 17.54                 | 17.56              | 17.33              | 18.05              | 17.45             | 17.62             | 17.50              | 17.26             | 15.70              |
| TiO <sub>2</sub>                         | 1.061             | 1.080                 | 1.025              | 1.018              | 1.070              | 1.157             | 0.943             | 1.191              | 1.152             | 1.062              |
| FeO*                                     | 7.51              | 9.76                  | 8.23               | 8.51               | 8.00               | 6.72              | 6.24              | 5.25               | 7.98              | 6.46               |
| MnO                                      | 0.128             | 0.17                  | 0.157              | 0.161              | 0.136              | 0.127             | 0.130             | 0.108              | 0.165             | 0.137              |
| CaO                                      | 7.98              | 7.19                  | 11.03              | 11.06              | 11.59              | 6.54              | 6.48              | 6.38               | 8.59              | 6.45               |
| MgO                                      | 4.97              | 11.14                 | 8.99               | 8.96               | 7.35               | 3.26              | 2.37              | 3.09               | 6.48              | 4.71               |
| K <sub>2</sub> O                         | 0.75              | 0.17                  | 0.16               | 0.15               | 0.13               | 1.42              | 2.46              | 1.63               | 1.15              | 2.17               |
| Na <sub>2</sub> O                        | 4.19              | 2.84                  | 2.90               | 2.99               | 3.09               | 4.42              | 3.55              | 4.72               | 3.73              | 4.20               |
| P <sub>2</sub> O <sub>5</sub>            | 0.209             | 0.12                  | 0.104              | 0.104              | 0.112              | 0.343             | 0.488             | 0.360              | 0.424             | 0.413              |
| Total                                    | 99.69             | 98.53                 | 99.64              | 98.91              | 99.23              | 99.35             | 98.55             | 98.89              | 99.12             | 99.32              |
| <i>Trace Elements, parts per million</i> |                   |                       |                    |                    |                    |                   |                   |                    |                   |                    |
| Ni                                       | 76                | 123                   | 160                | 155                | 156                | 22                | 14                | 27                 | 95                | 59                 |
| Cr                                       | 74                | 229                   | 243                | 249                | 251                | 33                | 23                | 36                 | 139               | 152                |
| Sc                                       | 21                | 30                    | 40                 | 35                 | 37                 | 18                | 19                | 22                 | 27                | 20                 |
| V  | 182               | 242                   | 219                | 222                | 227                | 190               | 176               | 202                | 216               | 191                |
| Ba                                       | 320               | 144                   | 79                 | 78                 | 162                | 517               | 1125              | 561                | 529               | 550                |
| Rb                                       | 10                | 3                     | 1                  | 2                  | 1                  | 26                | 31                | 27                 | 14                | 40                 |
| Sr                                       | 697               | 306                   | 295                | 293                | 324                | 611               | 642               | 625                | 761               | 620                |
| Zr                                       | 101               | 66                    | 57                 | 62                 | 64                 | 147               | 203               | 151                | 149               | 171                |
| Y  | 17                | 25                    | 21                 | 24                 | 24                 | 25                | 29                | 26                 | 19                | 21                 |
| Nb                                       | 3.7               | 2                     | 2.6                | 3.1                | 2.1                | 5.4               | 9.0               | 6.4                | 7.0               | 7.2                |
| Ga                                       | 21                | 16                    | 17                 | 16                 | 18                 | 17                | 18                | 20                 | 19                | 18                 |
| Cu                                       | 67                | 91                    | 85                 | 83                 | 116                | 64                | 61                | 79                 | 78                | 76                 |
| Zn                                       | 77                | 71                    | 66                 | 65                 | 77                 | 85                | 80                | 100                | 88                | 82                 |
| Pb                                       | 3                 | 3                     | 4                  | 3                  | 0                  | 8                 | 11                | 6                  | 3                 | 8                  |
| La                                       | 7                 | 3                     | 3                  | 5                  | 14                 | 5                 | 27                | 16                 | 43                | 38                 |
| Ce                                       | 30                | 14                    | 22                 | 16                 | 25                 | 42                | 58                | 54                 | 47                | 57                 |
| Th                                       | 3                 | <0.5                  | 0                  | 1                  | 1                  | 2                 | 1                 | 2                  | 2                 | 3                  |
| Map No.<br>Map Unit<br>Sample No.        | 10<br>Tba<br>K-25 | 11<br>Tba<br>K-49     | 12<br>Tba<br>K-88A | 13<br>Tba<br>K-89  | 13<br>Tba<br>K-89R | 14<br>Tba<br>K-90 | 15<br>Tba<br>K-91 | 15<br>Tba<br>K-91A | 17<br>Tba<br>K-92 | 18<br>Tba<br>K-157 |
| Analytical Date                          | 2-Jul-98          | 2-Jul-98              | 2-Jul-98           | 2-Jul-98           | 6-Jul-98           | 2-Jul-98          | 3-Jul-98          | 3-Jul-98           | 3-Jul-98          | 3-Jul-98           |
| West Longitude                           | 121.77400         | 121.77796             | 121.70999          | 121.71072          | 121.71072          | 121.71111         | 121.71175         | 121.71213          | 121.71247         | 121.79976          |
| North Latitude                           | 42.26192          | 42.25303              | 42.23620           | 42.23584           | 42.23584           | 42.23370          | 42.23517          | 42.23491           | 42.23437          | 42.21785           |
| <i>Oxides, weight percent</i>            |                   |                       |                    |                    |                    |                   |                   |                    |                   |                    |
| SiO <sub>2</sub>                         | 52.54             | 55.11                 | 56.16              | 56.26              | 56.74              | 56.07             | 53.51             | 55.29              | 55.13             | 52.73              |
| Al <sub>2</sub> O <sub>3</sub>           | 18.18             | 17.68                 | 17.86              | 17.77              | 17.92              | 17.78             | 17.50             | 17.48              | 17.32             | 18.09              |
| TiO <sub>2</sub>                         | 0.947             | 1.114                 | 1.122              | 1.093              | 1.101              | 1.093             | 1.063             | 1.108              | 1.058             | 0.939              |
| FeO                                      | 7.80              | 7.10                  | 6.94               | 6.65               | 6.37               | 6.84              | 7.83              | 7.27               | 7.65              | 7.24               |
| MnO                                      | 0.143             | 0.139                 | 0.137              | 0.115              | 0.116              | 0.137             | 0.153             | 0.139              | 0.143             | 0.139              |
| CaO                                      | 8.97              | 7.58                  | 7.58               | 7.46               | 7.49               | 7.57              | 8.26              | 7.64               | 7.70              | 8.88               |
| MgO                                      | 6.30              | 4.39                  | 3.76               | 3.75               | 3.70               | 3.95              | 5.23              | 4.19               | 4.68              | 6.07               |
| K <sub>2</sub> O                         | 0.55              | 1.42                  | 1.60               | 1.55               | 1.55               | 1.50              | 1.25              | 1.55               | 1.48              | 0.69               |
| Na <sub>2</sub> O                        | 3.57              | 4.14                  | 4.05               | 4.20               | 4.19               | 4.29              | 3.53              | 3.68               | 3.55              | 3.60               |
| P <sub>2</sub> O <sub>5</sub>            | 0.273             | 0.493                 | 0.479              | 0.491              | 0.496              | 0.503             | 0.440             | 0.511              | 0.477             | 0.282              |
| Total                                    | 99.27             | 99.17                 | 99.69              | 99.34              | 99.67              | 99.73             | 98.77             | 98.86              | 99.19             | 98.66              |
| <i>Trace Elements, parts per million</i> |                   |                       |                    |                    |                    |                   |                   |                    |                   |                    |
| Ni                                       | 107               | 41                    | 26                 | 29                 | 26                 | 32                | 80                | 44                 | 76                | 120                |
| Cr                                       | 127               | 68                    | 48                 | 50                 | 51                 | 61                | 121               | 63                 | 132               | 153                |
| Sc                                       | 24                | 24                    | 22                 | 21                 | 22                 | 23                | 24                | 22                 | 24                | 31                 |
| V  | 201               | 173                   | 170                | 181                | 181                | 187               | 195               | 171                | 172               | 194                |
| Ba                                       | 385               | 660                   | 737                | 712                | 710                | 708               | 584               | 673                | 658               | 404                |
| Rb                                       | 6                 | 16                    | 22                 | 19                 | 18                 | 18                | 16                | 18                 | 19                | 4                  |
| Sr                                       | 663               | 642                   | 640                | 637                | 632                | 631               | 585               | 654                | 558               | 683                |
| Zr                                       | 96                | 163                   | 180                | 176                | 175                | 178               | 172               | 167                | 193               | 95                 |
| Y  | 17                | 23                    | 25                 | 25                 | 25                 | 24                | 25                | 24                 | 24                | 17                 |
| Nb                                       | 4.8               | 8.8                   | 10.6               | 9.6                | 9.5                | 8.6               | 9.7               | 9.5                | 11.4              | 4.8                |
| Ga                                       | 16                | 21                    | 23                 | 18                 | 21                 | 21                | 17                | 20                 | 19                | 20                 |
| Cu                                       | 70                | 65                    | 71                 | 50                 | 50                 | 65                | 60                | 68                 | 22                | 78                 |
| Zn                                       | 78                | 85                    | 85                 | 83                 | 83                 | 84                | 85                | 87                 | 97                | 75                 |
| Pb                                       | 7                 | 5                     | 7                  | 9                  | 8                  | 9                 | 8                 | 8                  | 7                 | 4                  |
| La                                       | 16                | 22                    | 33                 | 6                  | 21                 | 30                | 26                | 27                 | 18                | 25                 |
| Ce                                       | 31                | 60                    | 61                 | 55                 | 60                 | 47                | 65                | 59                 | 60                | 34                 |
| Th                                       | 3                 | 0                     | 1                  | 5                  | 2                  | 5                 | 0                 | 2                  | 2                 | 0                  |

Note: File "K\_Falls\_Original\_Chemistry.xls" in the accompanying digital database shows recalculated analyses used to assign rock names. FeO\* means all iron oxide is shown as FeO. Map no. 1 is from Hladky and Mertzman (2000).

\*- = outside mapped area.



Table 1.3. — continued

| Map No.<br>Map Unit<br>Sample No.        | 19<br>Tba<br>K-159 | 20<br>Tba<br>K-160  | 21<br>Tba<br>K-161 | 22<br>Tba<br>K-162 | 23<br>Tba<br>K-163 | 24<br>Tba+<br>K-164 | 25<br>Tba<br>K-166A | 26<br>Tba<br>K-172 | 27<br>Tba<br>K-227 | 28<br>Tba<br>K-230 |
|--|--------------------|---------------------|--------------------|--------------------|--------------------|---------------------|---------------------|--------------------|--------------------|--------------------|
| Analytical Date                          | 3-Jul-98           | 3-Jul-98            | 3-Jul-98           | 3-Jul-98           | 3-Jul-98           | 3-Jul-98            | 3-Jul-98            | 4-Jul-98           | 4-Jul-98           | 4-Jul-98           |
| West Longitude                           | 121.81658          | 121.81905           | 121.81867          | 121.81837          | 121.81817          | 121.80250           | 121.80545           | 121.80282          | 121.80184          | 121.79652          |
| North Latitude                           | 42.22360           | 42.22593            | 42.22586           | 42.22600           | 42.22729           | 42.20472            | 42.04793            | 42.20920           | 42.23788           | 42.23233           |
| <i>Oxides, weight percent</i>            |                    |                     |                    |                    |                    |                     |                     |                    |                    |                    |
| SiO <sub>2</sub>                         | 52.10              | 52.51               | 52.19              | 50.97              | 52.98              | 51.28               | 52.59               | 51.91              | 53.37              | 52.65              |
| Al <sub>2</sub> O <sub>3</sub>           | 17.95              | 17.90               | 17.94              | 18.80              | 18.27              | 16.02               | 17.92               | 17.83              | 18.58              | 18.04              |
| TiO <sub>2</sub>                         | 0.950              | 0.937               | 0.926              | 0.988              | 0.954              | 1.183               | 0.918               | 0.945              | 0.957              | 0.931              |
| FeO*                                     | 7.36               | 7.37                | 7.42               | 7.93               | 7.35               | 8.29                | 7.52                | 7.73               | 7.24               | 7.06               |
| MnO                                      | 0.147              | 0.147               | 0.124              | 0.192              | 0.155              | 0.183               | 0.138               | 0.141              | 0.123              | 0.137              |
| CaO                                      | 9.06               | 8.89                | 8.95               | 8.98               | 8.93               | 8.30                | 9.04                | 8.96               | 8.88               | 8.74               |
| MgO                                      | 6.47               | 7.01                | 6.47               | 6.69               | 5.79               | 8.41                | 6.53                | 6.64               | 4.58               | 6.67               |
| K <sub>2</sub> O                         | 0.62               | 0.69                | 0.64               | 0.52               | 0.70               | 0.40                | 0.67                | 0.60               | 1.05               | 0.81               |
| Na <sub>2</sub> O                        | 3.40               | 3.57                | 3.54               | 3.43               | 3.47               | 2.30                | 3.42                | 3.39               | 3.89               | 3.55               |
| P <sub>2</sub> O <sub>5</sub>            | 0.288              | 0.290               | 0.270              | 0.301              | 0.277              | 0.198               | 0.279               | 0.287              | 0.274              | 0.272              |
| Total                                    | 98.34              | 99.31               | 98.47              | 98.80              | 98.88              | 96.56               | 99.03               | 98.43              | 98.94              | 98.86              |
| <i>Trace Elements, parts per million</i> |                    |                     |                    |                    |                    |                     |                     |                    |                    |                    |
| Ni                                       | 115                | 123                 | 107                | 130                | 99                 | 155                 | 116                 | 112                | 36                 | 99                 |
| Cr                                       | 154                | 165                 | 153                | 161                | 129                | 306                 | 151                 | 158                | 74                 | 142                |
| Sc                                       | 22                 | 25                  | 29                 | 25                 | 21                 | 23                  | 25                  | 29                 | 27                 | 25                 |
| V  | 201                | 198                 | 197                | 151                | 196                | 194                 | 192                 | 204                | 207                | 207                |
| Ba                                       | 440                | 410                 | 377                | 423                | 381                | 159                 | 348                 | 342                | 406                | 372                |
| Rb                                       | 7                  | 3                   | 4                  | 5                  | 11                 | 5                   | 9                   | 8                  | 15                 | 10                 |
| Sr                                       | 712                | 689                 | 693                | 692                | 688                | 331                 | 699                 | 713                | 706                | 682                |
| Zr                                       | 102                | 100                 | 93                 | 101                | 100                | 89                  | 93                  | 101                | 105                | 90                 |
| Y  | 16                 | 17                  | 16                 | 21                 | 16                 | 20                  | 16                  | 16                 | 19                 | 15                 |
| Nb                                       | 4.9                | 5.0                 | 4.4                | 5.8                | 5.5                | 5.6                 | 5.0                 | 4.7                | 6.1                | 5.0                |
| Ga                                       | 20                 | 19                  | 19                 | 20                 | 20                 | 17                  | 21                  | 18                 | 20                 | 20                 |
| Cu                                       | 68                 | 45                  | 72                 | 122                | 73                 | 71                  | 75                  | 63                 | 67                 | 80                 |
| Zn                                       | 82                 | 76                  | 77                 | 77                 | 77                 | 74                  | 76                  | 78                 | 67                 | 77                 |
| Pb                                       | 1                  | 4                   | 6                  | 8                  | 4                  | 0                   | 4                   | 6                  | 5                  | 1                  |
| La                                       | 11                 | 7                   | 12                 | 14                 | 8                  | 6                   | 22                  | 16                 | 18                 | 7                  |
| Ce                                       | 34                 | 32                  | 30                 | 24                 | 26                 | 24                  | 17                  | 34                 | 33                 | 46                 |
| Th                                       | 3                  | 2                   | 1                  | 0                  | 2                  | 1                   | 1                   | 0                  | 2                  | 2                  |
| Map No.<br>Map Unit<br>Sample No.        | 29<br>Tba<br>K-231 | 29<br>Tba<br>K-231R | 30<br>Tba<br>K-236 | 31<br>Tba<br>K-238 | 32<br>Tba<br>K-248 | 33<br>Tba<br>K-259  | 34<br>Tba<br>K-313  | 35<br>Tba<br>K-316 | 36<br>Tba<br>K-318 | 37<br>Tba<br>K-319 |
| Analytical Date                          | 4-Jul-98           | 6-Jul-98            | 4-Jul-98           | 4-Jul-98           | 4-Jul-98           | 4-Jul-98            | 4-Jul-98            | 4-Jul-98           | 5-Jul-98           | 5-Jul-98           |
| West Longitude                           | 121.79626          | 121.79626           | 121.80681          | 121.80678          | 121.80400          | 121.78762           | 121.75695           | 121.75794          | 121.75656          | 121.75542          |
| North Latitude                           | 42.23242           | 42.23242            | 42.24056           | 42.24139           | 42.23680           | 42.22749            | 42.26311            | 42.26083           | 42.25820           | 42.25989           |
| <i>Oxides, weight percent</i>            |                    |                     |                    |                    |                    |                     |                     |                    |                    |                    |
| SiO <sub>2</sub>                         | 52.20              | 52.31               | 53.79              | 54.02              | 52.32              | 55.54               | 55.59               | 51.89              | 52.22              | 52.00              |
| Al <sub>2</sub> O <sub>3</sub>           | 18.09              | 18.08               | 17.73              | 17.93              | 17.74              | 17.86               | 16.77               | 17.70              | 17.80              | 18.06              |
| TiO <sub>2</sub>                         | 0.937              | 0.944               | 0.954              | 0.932              | 0.939              | 1.146               | 0.938               | 1.313              | 1.069              | 1.373              |
| FeO*                                     | 7.74               | 8.14                | 6.63               | 6.78               | 7.68               | 6.74                | 7.06                | 8.50               | 7.29               | 8.44               |
| MnO                                      | 0.116              | 0.115               | 0.143              | 0.108              | 0.144              | 0.129               | 0.112               | 0.154              | 0.175              | 0.122              |
| CaO                                      | 8.68               | 8.70                | 9.27               | 9.34               | 8.85               | 7.72                | 7.33                | 8.65               | 8.94               | 8.92               |
| MgO                                      | 5.05               | 5.06                | 5.16               | 4.75               | 6.19               | 4.04                | 4.79                | 5.19               | 5.39               | 4.20               |
| K <sub>2</sub> O                         | 0.75               | 0.75                | 0.73               | 0.48               | 0.72               | 1.29                | 1.52                | 1.17               | 0.58               | 0.69               |
| Na <sub>2</sub> O                        | 3.51               | 3.51                | 3.48               | 3.51               | 3.67               | 4.11                | 3.67                | 3.30               | 3.13               | 3.59               |
| P <sub>2</sub> O <sub>5</sub>            | 0.382              | 0.385               | 0.243              | 0.277              | 0.272              | 0.507               | 0.269               | 0.452              | 0.428              | 0.473              |
| Total                                    | 97.45              | 97.99               | 98.13              | 98.13              | 98.53              | 99.08               | 98.05               | 98.32              | 97.02              | 97.87              |
| <i>Trace Elements, parts per million</i> |                    |                     |                    |                    |                    |                     |                     |                    |                    |                    |
| Ni                                       | 102                | 100                 | 133                | 169                | 142                | 46                  | 90                  | 86                 | 50                 | 66                 |
| Cr                                       | 141                | 141                 | 175                | 193                | 143                | 73                  | 115                 | 128                | 73                 | 122                |
| Sc                                       | 28                 | 30                  | 28                 | 30                 | 25                 | 25                  | 23                  | 27                 | 27                 | 29                 |
| V  | 155                | 146                 | 206                | 186                | 197                | 181                 | 176                 | 232                | 211                | 246                |
| Ba                                       | 396                | 399                 | 272                | 307                | 429                | 674                 | 456                 | 403                | 333                | 452                |
| Rb                                       | 8                  | 9                   | 9                  | 5                  | 6                  | 11                  | 23                  | 13                 | 6                  | 5                  |
| Sr                                       | 706                | 710                 | 608                | 625                | 697                | 650                 | 765                 | 640                | 720                | 659                |
| Zr                                       | 95                 | 96                  | 107                | 106                | 93                 | 165                 | 141                 | 129                | 108                | 134                |
| Y  | 18                 | 16                  | 20                 | 20                 | 19                 | 25                  | 24                  | 23                 | 18                 | 30                 |
| Nb                                       | 3.2                | 3.3                 | 4.6                | 5.3                | 4.2                | 9.3                 | 5.5                 | 8.1                | 6.1                | 8.6                |
| Ga                                       | 23                 | 21                  | 20                 | 21                 | 18                 | 21                  | 20                  | 19                 | 18                 | 20                 |
| Cu                                       | 69                 | 73                  | 77                 | 76                 | 86                 | 68                  | 88                  | 74                 | 70                 | 73                 |
| Zn                                       | 78                 | 82                  | 68                 | 74                 | 94                 | 87                  | 75                  | 83                 | 80                 | 88                 |
| Pb                                       | 5                  | 5                   | 3                  | 3                  | 4                  | 6                   | 7                   | 6                  | 2                  | 5                  |
| La                                       | 26                 | 0                   | 14                 | 1                  | 1                  | 15                  | 8                   | 23                 | 31                 | 0                  |
| Ce                                       | 37                 | 38                  | 22                 | 21                 | 28                 | 33                  | 40                  | 46                 | 55                 | 35                 |
| Th                                       | 0                  | 2                   | 1                  | 1                  | 0                  | 3                   | 2                   | 4                  | 1                  | 1                  |

\* Single small basaltic ash and cinder layer within unit Tms but composed of rock unit Tba; too small to map separately from Tms diatomaceous mudstone and lithic sandstone.

Table 1.3. — continued

| Map No.<br>Map Unit<br>Sample No.        | 38<br>Tba<br>K-320C | 39<br>Tba<br>K-328 | 40<br>Tba<br>K-329 | 41<br>Tba<br>K-346  | 42<br>Tba<br>K-355   | 43<br>Tba<br>K-357M | 44<br>Tba<br>K-359 | 45<br>Tba<br>K-381 | 46<br>Tba<br>K-382 | 47<br>Tba<br>K-383 |
|--|---------------------|--------------------|--------------------|---------------------|----------------------|---------------------|--------------------|--------------------|--------------------|--------------------|
| Analytical Date                          | 5-Jul-98            | 5-Jul-98           | 5-Jul-98           | 5-Jul-98            | 5-Jul-98             | 5-Jul-98            | 5-Jul-98           | 5-Jul-98           | 6-Jul-98           | 6-Jul-98           |
| West Longitude                           | 121.75422           | 121.76900          | 121.77203          | 121.84400           | 121.85551            | 121.77353           | 121.73631          | 121.78606          | 121.78826          | 121.78929          |
| North Latitude                           | 42.26131            | 42.26459           | 42.26477           | 42.17824            | 42.18095             | 42.14950            | 42.17783           | 42.22515           | 42.22232           | 42.22298           |
| <i>Oxides, weight percent</i>            |                     |                    |                    |                     |                      |                     |                    |                    |                    |                    |
| SiO <sub>2</sub>                         | 55.95               | 48.46              | 53.22              | 52.57               | 53.50                | 52.89               | 54.04              | 55.77              | 55.62              | 55.88              |
| Al <sub>2</sub> O <sub>3</sub>           | 17.80               | 17.58              | 17.76              | 17.51               | 18.37                | 19.00               | 18.41              | 19.12              | 18.11              | 18.57              |
| TiO <sub>2</sub>                         | 0.977               | 1.043              | 1.121              | 0.769               | 1.093                | 1.068               | 1.058              | 1.209              | 1.098              | 1.131              |
| FeO*                                     | 6.61                | 8.63               | 7.50               | 7.16                | 7.58                 | 6.55                | 6.94               | 5.89               | 6.85               | 6.30               |
| MnO                                      | 0.129               | 0.167              | 0.133              | 0.145               | 0.151                | 0.119               | 0.115              | 0.114              | 0.137              | 0.116              |
| CaO                                      | 7.72                | 11.40              | 8.60               | 9.93                | 8.14                 | 9.91                | 7.79               | 7.86               | 7.73               | 7.96               |
| MgO                                      | 3.79                | 8.79               | 4.48               | 6.33                | 4.17                 | 4.40                | 3.69               | 3.32               | 3.61               | 3.10               |
| K <sub>2</sub> O                         | 1.61                | 0.14               | 1.23               | 0.61                | 1.09                 | 0.67                | 1.60               | 1.01               | 1.39               | 1.19               |
| Na <sub>2</sub> O                        | 3.86                | 2.78               | 3.65               | 3.14                | 3.99                 | 3.56                | 4.20               | 4.00               | 3.99               | 3.94               |
| P <sub>2</sub> O <sub>5</sub>            | 0.417               | 0.121              | 0.359              | 0.224               | 0.671                | 0.269               | 0.515              | 0.439              | 0.525              | 0.522              |
| Total                                    | 98.86               | 99.11              | 98.05              | 98.39               | 98.75                | 98.44               | 98.36              | 98.73              | 99.06              | 98.71              |
| <i>Trace Elements, parts per million</i> |                     |                    |                    |                     |                      |                     |                    |                    |                    |                    |
| Ni                                       | 33                  | 149                | 30                 | 90                  | 56                   | 73                  | 29                 | 28                 | 34                 | 23                 |
| Cr                                       | 60                  | 205                | 77                 | 177                 | 61                   | 103                 | 48                 | 72                 | 61                 | 63                 |
| Sc                                       | 25                  | 37                 | 27                 | 28                  | 22                   | 29                  | 23                 | 26                 | 23                 | 22                 |
| V  | 185                 | 234                | 198                | 198                 | 164                  | 227                 | 188                | 168                | 184                | 181                |
| Ba                                       | 765                 | 92                 | 418                | 330                 | 671                  | 305                 | 656                | 847                | 751                | 689                |
| Rb                                       | 20                  | 3                  | 14                 | 9                   | 9                    | 8                   | 20                 | 12                 | 20                 | 19                 |
| Sr                                       | 661                 | 264                | 733                | 742                 | 795                  | 718                 | 887                | 706                | 652                | 673                |
| Zr                                       | 169                 | 57                 | 130                | 89                  | 185                  | 96                  | 160                | 174                | 177                | 186                |
| Y  | 22                  | 23                 | 21                 | 13                  | 25                   | 16                  | 22                 | 31                 | 24                 | 27                 |
| Nb                                       | 7.7                 | 2.3                | 6.6                | 3.0                 | 10.0                 | 5.3                 | 8.6                | 9.7                | 8.8                | 10.9               |
| Ga                                       | 21                  | 16                 | 19                 | 21                  | 20                   | 21                  | 21                 | 20                 | 22                 | 22                 |
| Cu                                       | 78                  | 99                 | 68                 | 71                  | 38                   | 83                  | 65                 | 46                 | 54                 | 62                 |
| Zn                                       | 81                  | 64                 | 76                 | 71                  | 97                   | 77                  | 84                 | 78                 | 94                 | 88                 |
| Pb                                       | 9                   | 3                  | 6                  | 2                   | 4                    | 3                   | 9                  | 9                  | 9                  | 9                  |
| La                                       | 23                  | 0                  | 7                  | 2                   | 29                   | 22                  | 31                 | 27                 | 41                 | 38                 |
| Ce                                       | 54                  | 14                 | 46                 | 31                  | 57                   | 24                  | 51                 | 50                 | 52                 | 57                 |
| Th                                       | 2                   | 1                  | 2                  | 2                   | 2                    | 1                   | 0                  | 2                  | 3                  | 2                  |
| Map No.<br>Map Unit<br>Sample No.        | 48<br>Tba<br>K-384  | 49<br>Tba<br>K-385 | 50<br>Tba<br>K-386 | 51<br>Tbtv<br>K-321 | 51<br>Tbtv<br>K-321R | 52<br>Tcb<br>K-29   | 53<br>Thb<br>K-74  | 54<br>Thb<br>K-76  | 55<br>Thb<br>K-80  | 56<br>Thb<br>K-88  |
| Analytical Date                          | 6-Jul-98            | 6-Jul-98           | 6-Jul-98           | 5-Jul-98            | 6-Jul-98             | 2-Jul-98            | 2-Jul-98           | 2-Jul-98           | 2-Jul-98           | 2-Jul-98           |
| West Longitude                           | 121.79009           | 121.78469          | 121.78617          | 121.76083           | 121.76083            | 121.81164           | 121.70767          | 121.70862          | 121.70623          | 121.70944          |
| North Latitude                           | 42.22340            | 42.22204           | 42.22068           | 42.25086            | 42.25086             | 42.26647            | 43.24349           | 42.24363           | 42.23984           | 42.23604           |
| <i>Oxides, weight percent</i>            |                     |                    |                    |                     |                      |                     |                    |                    |                    |                    |
| SiO <sub>2</sub>                         | 55.73               | 55.88              | 55.37              | 45.54               | 45.53                | 53.94               | 51.62              | 51.53              | 51.27              | 50.51              |
| Al <sub>2</sub> O <sub>3</sub>           | 17.87               | 18.55              | 18.00              | 15.21               | 15.22                | 18.31               | 17.81              | 17.32              | 16.95              | 16.66              |
| TiO <sub>2</sub>                         | 1.104               | 1.141              | 1.107              | 1.184               | 1.187                | 0.973               | 1.503              | 1.591              | 1.551              | 1.597              |
| FeO*                                     | 6.98                | 6.34               | 7.23               | 9.12                | 9.14                 | 7.42                | 9.46               | 9.40               | 9.41               | 9.72               |
| MnO                                      | 0.146               | 0.120              | 0.128              | 0.153               | 0.155                | 0.133               | 0.176              | 0.176              | 0.175              | 0.178              |
| CaO                                      | 7.71                | 7.77               | 7.59               | 7.82                | 7.83                 | 8.56                | 9.26               | 9.19               | 9.24               | 9.20               |
| MgO                                      | 3.45                | 3.28               | 3.60               | 8.67                | 8.55                 | 4.93                | 5.03               | 5.50               | 5.96               | 6.99               |
| K <sub>2</sub> O                         | 1.36                | 1.24               | 1.30               | 0.47                | 0.47                 | 0.92                | 0.80               | 0.74               | 0.76               | 0.71               |
| Na <sub>2</sub> O                        | 4.05                | 4.10               | 3.96               | 0.63                | 0.66                 | 3.85                | 3.60               | 3.44               | 3.53               | 3.36               |
| P <sub>2</sub> O <sub>5</sub>            | 0.505               | 0.511              | 0.484              | 0.296               | 0.295                | 0.281               | 0.385              | 0.396              | 0.387              | 0.389              |
| Total                                    | 98.91               | 98.93              | 98.77              | 89.09               | 89.04                | 99.32               | 99.64              | 99.28              | 99.23              | 99.31              |
| <i>Trace Elements, parts per million</i> |                     |                    |                    |                     |                      |                     |                    |                    |                    |                    |
| Ni                                       | 28                  | 25                 | 45                 | 170                 | 170                  | 47                  | 41                 | 57                 | 63                 | 97                 |
| Cr                                       | 64                  | 62                 | 60                 | 324                 | 319                  | 70                  | 78                 | 104                | 127                | 158                |
| Sc                                       | 25                  | 22                 | 25                 | 28                  | 28                   | 29                  | 30                 | 35                 | 31                 | 29                 |
| V  | 183                 | 179                | 176                | 211                 | 207                  | 196                 | 246                | 261                | 254                | 242                |
| Ba                                       | 723                 | 753                | 703                | 155                 | 171                  | 397                 | 351                | 302                | 300                | 307                |
| Rb                                       | 21                  | 17                 | 19                 | 6                   | 4                    | 12                  | 7                  | 9                  | 10                 | 9                  |
| Sr                                       | 648                 | 669                | 651                | 321                 | 323                  | 707                 | 536                | 456                | 432                | 450                |
| Zr                                       | 180                 | 183                | 182                | 87                  | 86                   | 114                 | 124                | 127                | 127                | 130                |
| Y  | 24                  | 26                 | 25                 | 24                  | 26                   | 18                  | 29                 | 29                 | 28                 | 28                 |
| Nb                                       | 11.0                | 10.6               | 10.5               | 6.9                 | 6.0                  | 4.8                 | 6.3                | 7.7                | 7.5                | 8.5                |
| Ga                                       | 22                  | 19                 | 22                 | 16                  | 19                   | 21                  | 19                 | 20                 | 19                 | 21                 |
| Cu                                       | 50                  | 50                 | 59                 | 78                  | 73                   | 74                  | 56                 | 64                 | 46                 | 61                 |
| Zn                                       | 84                  | 87                 | 82                 | 80                  | 83                   | 78                  | 91                 | 88                 | 88                 | 93                 |
| Pb                                       | 3                   | 9                  | 8                  | 2                   | 0                    | 5                   | 3                  | 3                  | 2                  | 2                  |
| La                                       | 27                  | 22                 | 15                 | 9                   | 15                   | 26                  | 15                 | 16                 | 12                 | 4                  |
| Ce                                       | 58                  | 61                 | 64                 | 19                  | 40                   | 24                  | 27                 | 29                 | 41                 | 33                 |
| Th                                       | 0                   | 3                  | 1                  | 0                   | 0                    | 3                   | 1                  | 3                  | 0                  | 3                  |

Table 1.3. — continued

| Map No.<br>Map Unit<br>Sample No.        | 57<br>Thb<br>K-96 | 57<br>Thb<br>K-96A | 58<br>Thb<br>K-111 | 59<br>Tpt<br>K-361 |
|--|-------------------|--------------------|--------------------|--------------------|
| Analytical Date                          | 3-Jul-98          | 3-Jul-98           | 3-Jul-98           | 5-Jul-98           |
| West Longitude                           | 121.71113         | 121.71113          | 121.70719          | 121.75780          |
| North Latitude                           | 42.24111          | 42.24111           | 42.23452           | 42.22807           |
| <i>Oxides, weight percent</i>            |                   |                    |                    |                    |
| SiO <sub>2</sub>                         | 49.67             | 51.18              | 50.28              | 52.20              |
| Al <sub>2</sub> O <sub>3</sub>           | 16.38             | 17.23              | 16.64              | 23.85              |
| TiO <sub>2</sub>                         | 1.645             | 1.481              | 1.608              | 1.368              |
| FeO*                                     | 9.76              | 9.44               | 9.91               | 3.78               |
| MnO                                      | 0.179             | 0.166              | 0.177              | 0.039              |
| CaO                                      | 9.25              | 9.50               | 9.17               | 12.05              |
| MgO                                      | 7.82              | 5.84               | 6.92               | 1.22               |
| K <sub>2</sub> O                         | 0.68              | 0.56               | 0.78               | 0.12               |
| Na <sub>2</sub> O                        | 3.14              | 3.51               | 3.27               | 3.25               |
| P <sub>2</sub> O <sub>5</sub>            | 0.422             | 0.363              | 0.385              | 0.443              |
| Total                                    | 98.95             | 99.27              | 99.14              | 98.32              |
| <i>Trace Elements, parts per million</i> |                   |                    |                    |                    |
| Ni                                       | 128               | 72                 | 92                 | 43                 |
| Cr                                       | 192               | 133                | 156                | 218                |
| Sc                                       | 32                | 33                 | 26                 | 42                 |
| V  | 269               | 254                | 255                | 206                |
| Ba                                       | 336               | 295                | 312                | 162                |
| Rb                                       | 8                 | 3                  | 9                  | 4                  |
| Sr                                       | 468               | 446                | 453                | 379                |
| Zr                                       | 135               | 124                | 134                | 72                 |
| Y  | 28                | 27                 | 29                 | 27                 |
| Nb                                       | 8.9               | 8.1                | 9.0                | 3.2                |
| Ga                                       | 17                | 20                 | 18                 | 20                 |
| Cu                                       | 62                | 63                 | 61                 | 94                 |
| Zn                                       | 94                | 85                 | 92                 | 48                 |
| Pb                                       | 4                 | 3                  | 4                  | 0                  |
| La                                       | 36                | 1                  | 8                  | 5                  |
| Ce                                       | 58                | 39                 | 38                 | 14                 |
| Th                                       | 3                 | 1                  | 1                  | 0                  |

**Table 1.4.** Diatom Analyses (by J. Platt Bradbury, U.S. Geological Survey)

| Map No. | Sample No. | Unit | West Longitude | North Latitude | Geographic Location  | Lithology  | Estimated Age                 | Depositional Environment                         | Species   |
|---------|------------|------|----------------|----------------|--|--|-------------------------------|--|---|
| 60      | K-424      | QTfs | 121.85932      | 42.15817       | Keno Hwy in unit QTfs  | Cream colored tuffaceous diatomaceous mudstone almost barren of diatoms                  | indeterminate                 | indeterminate                                    | A few corroded fragments of pennate species but are too small to identify.  |
| 61      | K-429A     | QTfs | 121.72615      | 42.22455       | Foothills Drive: NW end at first big cut at bottom of section of QTfs            | Cream colored tuffaceous diatomaceous mudstone with poorly preserved, uncommon diatoms   | Diatoms resemble modern forms | Slightly acidic plant-rich marsh of local extent | <i>Fragilaria virescens</i> is most common and chrysophyte cysts are abundant.  |
| 62      | K-430C     | QTfs | 121.71723      | 42.22660       | Foothills Drive: 0.5 km N. of Homedale Rd. at top of section of QTfs             | Cream colored tuffaceous mudstone with rare diatoms, poorly preserved                    | < 1 Ma?                       | Shallow, alkaline slightly saline pond or marsh  | <i>Fragilaria</i> species, <i>Anomoeoneis costata</i> , <i>Campylodiscus clypeus</i> , <i>Epithemia</i> . Nothing age diagnostic. In Tule Lake core this assemblage is sporadically present after 1 Ma, but that may not prove anything about sample age — the types live today.  |
| -*      | K-387      | QTfs | 121.86046      | 42.66692       | Hwy 97 cut N. of Collier Park at 4415 ft elevation ~145 ft above base of section | White 1 cm air-fall ash layer correlative to several tephra at 48-m depth in Wocus Marsh |                               | not given  | <i>Stephanodiscus rhombus</i> suggests correlation to Tule Lake core ~1.8–2 Ma. This diatom is present in Lake Britton-Pit River deposits in N. Calif. but these are not dated. An ash in the Lake Britton seq. is close to Tule Lake ash at 226 m with tephra age of 2.3 Ma.     |
| -*      | K-387A     | QTfs | 121.86046      | 42.66692       | Hwy 97 cut N. of Collier Park at 4415 ft elevation ~145 ft above base of section | White 1 cm air-fall ash layer correlative to several tephra at 48 m depth in Wocus Marsh |                               | not given  | <i>Stephanodiscus rhombus</i> suggests correlation to Tule Lake core ~1.8–2 Ma. This diatom is present in Lake Britton-Pit River deposits in N. Calif. but these are not dated. An ash in the Lake Britton sequence is close to Tule Lake ash at 226 m with tephra age of 2.3 Ma. |
| -*      | K-432      | QTfs | 121.8705       | 42.66516       | Hwy 97 cut N. of Collier Park at base of section                                 | Lignite with a few diatoms   | indeterminate                 | peaty marsh                                      | A few scrappy diatoms.  |
| 63      | K-399      | Ths  | 121.73807      | 42.25850       | NW scissor fault ridge: new house cut SE of K-398                                | Cream colored diatomaceous tuffaceous mudstone   | indeterminate                 | not given  | Large, wide-fascicled <i>Stephanodiscus</i> sp.— like <i>St. Carconensis</i> , but perhaps not the same thing; probably not the same assemblage as the Tule Lake core; similar to samples at North Ridge estates on Old Fort Rd. and the landfill.                                |

Table 1.4. — continued

| Map No. | Sample No. | Unit | West Longitude | North Latitude | Geographic Location   | Lithology                                      | Estimated Age   | Depositional Environment | Species  |
|---------|------------|------|----------------|----------------|---|--|---|--------------------------|--|
| 64      | K-411C     | Ths  | 121.72581      | 42.26219       | Hogback Rd: at 5330 ft on side road at sharp turn; N. of turn | Cream colored diatomaceous tuffaceous mudstone | indeterminate   | not given                | Large, wide-fascicled <i>Stephanodiscus</i> sp.— like <i>St. Carconensis</i> , but perhaps not the same thing; probably not the same assemblage as the Tule Lake core; similar to samples at North Ridge estates on Old Fort Rd and Klamath Falls landfill.  |
| 65      | K-336A     | Tm   | 121.85095      | 42.19178       | Balsam Rd.: SE quarry   | Cream colored diatomaceous mudstone            | > 2–3 Ma<br><i>Stephanodiscus</i> is not in the Tule Lake core (bottom at 3 Ma), this may argue for an age >3 Ma. | not given                | Large, flat <i>Stephanodiscus</i> sp. similar to <i>S. subtransylvanicus</i> , <i>Cyclotella servant-vildary</i> (r), <i>Aulacoseira</i> spp. <i>C. servant-vildary</i> is rare & thus possibly reworked but suggesting >2 Ma (from Tule Lake strata where it is found in low numbers before 2 Ma).                    |
| 66      | K-395      | Tm   | 121.75057      | 42.23548       | Klamath Landfill at crop in middle                            | Cream colored diatomaceous tuffaceous mudstone | indeterminate   | not given                | Large, wide-fascicled <i>Stephanodiscus</i> sp.— like <i>St. Carconensis</i> , but perhaps not the same thing; probably not the same assemblage as the Tule Lake core; similar to samples at North Ridge estates on Old Fort Rd. and the landfill.   |
| 67      | K-427A     | Tm   | 121.84626      | 42.20629       | Long Lake Rd. at gate to private property                     | Cream colored diatomaceous tuffaceous mudstone | > 2.8–3 Ma (could be Pliocene)  | not given                | <i>Cyclotella elgeri</i> dominates. It is common in Sheepy Ridge and Chalk Bank Landing in Lower Klamath Lake. Abundant near base of Tule Lake core and should be 2.8–3 Ma or older; also in Glenns Ferry Formation of Snake River Plain that is Pliocene in part.   |
| 68      | K-428      | Tm   | 121.74511      | 42.22256       | Foothills Dr. at Detention Center below unit Tpt              | Cream colored diatomaceous tuffaceous mudstone | > 3 Ma  | not given                | <i>Aulacoseira paucistriata</i> (d), <i>Stephanodiscus</i> sp. (kinked or sinuous costae) (c), <i>Cyclotella</i> sp. aff. <i>C. servant-vildary</i> (r). <i>Au. paucistriata</i> present in low numbers throughout; probably because it is easily reworked. Similar to samples from Poverty Flat, NE of Klamath Falls. |
| 69      | K-431      | Tm   | 121.80499      | 42.26095       | Hwy 97 cut S. of weigh station near Pelican City              | White diatomite                                | indeterminate   | not given                | <i>Aulacoseira paucistriata</i> (d), <i>Stephanodiscus</i> sp. (kinked or sinuous costae) similar to assemblage of K-428.  |

## 2.0 EXPLANATION OF MAP UNITS

### 2.1 FILL

- Mef Engineered fill (Modern)**—Well graded (poorly sorted) stiff to very stiff mixed clay, sand, silt to small pebble size material; 2-3 m thick; has been mechanically compacted to form a semi-indurated deposit suitable for building foundations. Mapped in only one place in north Klamath Falls, but probably present in other areas beneath structures.
- Mf Fill (Modern)**—Mixed clay to gravel-sized material with unknown degree of compaction, but probably not highly compacted. Includes landfill on north side of Klamath Falls where it consists of refuse mixed with disaggregated tuffaceous mudstone. Generally well graded (poorly sorted) and 2–6 m thick. Mapped in extensive areas around the margins of Klamath Lake and a few areas adjacent to major roads. No attempt was made to map every fill area; only large areas of fill are shown.

### 2.2 SEDIMENTARY UNITS

- Qc Colluvium (Holocene)**—Poorly consolidated unit mantling bedrock slopes undergoing active mass movement by creep; includes talus deposits. Mostly cohesionless poorly sorted sandy, silty gravels. Generally 1–3 m thick.
- Qac Alluvium and colluvium undifferentiated (Holocene)**—Poorly consolidated unit mantling bedrock slopes undergoing active mass movement by creep or intermittent stream runoff. Poorly to moderately sorted cohesionless sands and gravels. Generally 1–3 m thick.
- Qal Coarse-grained alluvium (Quaternary)**—Poorly consolidated coarse- to medium-grained sand and gravel fringing and underlying rivers. Forms low slopes except where undercut by recent river erosion. Mostly cohesionless fluvial sands and gravels. Thickness generally 1–3 m but locally up to 30 m in the Link River area where boulder-size gravel is common; chiefly Holocene in age but lower part may be Pleistocene at Link River. Restricted to coarse-grained alluvium for the purposes of this map in order to distinguish unit Qal from fine-grained deposits of unit Qs that contain lacustrine and fluvial deposits of fine-grained sand and silt with coherent engineering properties, regardless of sedimentary facies. Probably underlies at shallow depth silt and sand of unit Qs in the Lake Ewauna-Klamath River area. Unit Qs there was probably deposited after installation of downstream dams near Keno.
- Qs Lacustrine and alluvial clay, silt, fine-grained sand, and peat (Quaternary)**—Unconsolidated unit that forms flat slopes except at recently eroded, steeply sloping river banks. Thickness probably more than 50 m at Lower Klamath Lake (Sherrod and Pickthorn, 1992), Wocus Marsh (Adam and others, 1994), and Round Lake (Adam and others, 1995), 6 m in the Klamath River area, and <3 m elsewhere. Varies from fine-grained sandy or silty units with low plasticity at the Klamath River and Altamont area to highly plastic organic clay at Upper Klamath Lake. Includes interbedded fine-grained fluvial sand and silt in and near the Klamath River. Fine-grained fluvial facies mapped separately from coarser sand and gravel of unit Qal in order to emphasize contrasting engineering properties. No data was available to constrain location of contact between fine-grained and gravelly facies at Link River where it runs into Lake Ewauna, so contact is inferred. Chiefly Holocene in age but lower part at deep sedimentary basins is Pleistocene; examples are Round Lake (Adam and others, 1995), Wocus Marsh (Adam and others, 1994), and probably Upper Klamath Lake and Lower Klamath Lake. A core at Wocus Marsh had sediment with ages of  $31,720 \pm 860$  radiocarbon years at 11.21–11.25 m depth,  $27,550 \pm 780$  radiocarbon years at 14.47–14.52 m depth, >48,000–49,000 radiocarbon years at 20.42–21.02 m depth, 400–470 ka at 26.58–28.11 m depth, and < 1.45 Ma at 49.38–49.42 m depth (Adam and others, 1994). At Round Lake a core had ages of 160–180 ka at 6.78–6.85 m depth, 1.36 Ma at 49.51–49.55 m, and <1.45 Ma at 49.94–49.95 m (Adam and others, 1995). Age <1.45 Ma to Holocene.



- Qls** **Landslide deposits (Quaternary)**—Unconsolidated to slightly consolidated landslide debris (poorly sorted mixtures of boulders, cobbles, sand, silt, and clay), and local blocks of bedrock. Forms low to moderate slopes. Highly variable thickness and engineering characteristics; chiefly Holocene in age.
- Qoc** **Older colluvium and alluvium (Pleistocene)**—Moderately indurated colluvium and alluvium. Forms low to moderate slopes with little evidence of extensive mass movements. Generally a stiff soil with fair to poor sorting. Sorting and induration distinguish the unit from unit QTfs, which is much better sorted and better indurated. Moderate induration distinguishes the unit from younger colluvium and alluvium. Generally 1–5 m thick. Age uncertain; inferred to be Pleistocene from degree of induration; could be similar in age to unit QTfs (i.e., a colluvial facies of unit QTfs), but lack of such a facies at a steep, well-exposed depositional contact of QTfs on the flank of Hogback Mountain casts doubt on the hypothesis.
- QTfs** **Sedimentary rocks of Foothills Drive (lower Quaternary or upper Pliocene)**—Upper part consists of poorly indurated pebble to cobble conglomerate underlain by and interbedded with poorly indurated, well-sorted sandstone; lower part consists of poorly indurated well-sorted, fine-grained sandstone interbedded and overlying lesser amounts of tuffaceous diatomaceous sandy and silty mudstone. In the Foothills Drive area the lower part is well exposed and consists mostly of very well sorted, poorly indurated sandstone interbedded with tuffaceous diatomaceous mudstone and minor silty sandstone; lower part may, in part, be lacustrine shallow lake and beach (strand-line) deposits. Unit appears conformable on parts of unit Tm in the Altamont area, where unit Tm reaches a thickness of up to 400 m. Thickness is up to 150 m but generally no more than 50 m in most areas due to erosion. Lies in steep depositional contact with major fault blocks below 1,430 m (4,700 feet) elevation. At these steep contacts in the lower part of the unit fine-grained sandstone has only rare clasts larger than sand size, generally as a few sub-angular cobbles from underlying rocks; coarse-grained facies in upper part of unit have abundant lithic clasts, including many rounded cobbles, of underlying older rocks. Generally lacks significant chemical cement. Sandstone facies may be distinguished from unit Ts by much better sorting, rounding of clasts, poor induration and more mature composition (quartz clasts in some samples, dominance of hypersthene in mafic minerals in many samples, and less clay matrix). Sandstone closely resembles unit Ths but has more common occurrence of well-rounded amber volcanic glass clasts and lacks significant chemical cement. Unit Ths is locally uplifted on fault blocks to high elevations, whereas unit QTfs is not exposed above 1,430 m (4,700 feet) elevation; below that elevation unit QTfs lies unconformably on these same fault blocks. Tuffaceous mudstone is similar to unit Tm but is generally less well indurated, better bedded, and contains more silt and fine sand. Locally deformed by normal and oblique slip faulting and contains internal angular unconformities in upper part indicative of ongoing tectonic deformation during deposition. Younger than unit QTwb with radiometric age of 1.8 Ma (Hladky and Mertzman, 2000); older than unit Qs. Lower part of unit QTfs is lithologically similar and possibly correlative to sedimentary rocks exposed in outcrops along Highway 97 at Collier Grade ~43 km north of the map area (Figure 1.1), but has less olivine than those rocks. Preliminary correlation of a tephra layer in the uppermost part of the Collier grade sequence suggests an age >0.614 Ma and probably >1.45 Ma (unpublished interpretation and data of Andre M. Sarna-Wojcicki, 1998); diatoms at Collier grade suggest an age of 1.8–2 Ma. (Table 1.4; unpublished interpretation and data of J. Platt Bradbury). The Collier grade rocks are capped by basaltic andesite with a radiometric age of  $1.14 \pm 0.10$  Ma (age reported here for unit Qsh1 of Wiley [2004]). Unit QTfs lies at base of fault blocks capped by unit QTwb with age of ~1.8 Ma, so younger than age inferred for Collier Grade tephra and diatoms, but these data are preliminary and not highly quantitative. If the 1.14 Ma age of the capping flow at Collier Grade is closer to the age of the underlying sequence, then the lower part of unit QTfs could be contemporaneous with Collier Grade sedimentary rocks. Late Pliocene fossils have been reported from the Wilson quarry at the north end of Stukel Mountain (Peterson and McIntyre, 1970), but this quarry contains both unit QTfs and Tm, so it is difficult to evaluate the significance of the information; nevertheless, locality and host rock descriptions by a local resident familiar with the fossil find match unit QTfs exposed at Stukel Mountain. Age is thus late Pliocene to Pleistocene, but less than ~1.8 Ma; lower part may be older than 1.14 Ma, if correlative to Collier Grade sedimentary rocks, but this is a highly speculative hypothesis.

## 2.3 VOLCANIC AND INTRUSIVE UNITS

**QTwb Basalt of Wocus Marsh (lower Quaternary or upper Pliocene)**—Olivine basalt with fresh appearance and slight development of diktytaxitic texture in most flows, although a few basal flows are compact. One flow has elevated (1.6 percent)  $\text{TiO}_2$  similar to unit Thb; all others sampled have  $\text{TiO}_2$  near 1 percent. Appears confined to the central west part of the area where it is 24–30 m thick. Unit pinches out to the southeast and northwest against highlands of the underlying Tertiary units. Extends southwestward out of the map area toward possible High Cascade source areas. Has irregular blocky fracture on a 1–2 m scale and forms cliffs. Age is uncertain. Radiometric age of  $0.94 \pm 0.64$  Ma and  $0.97 \pm 0.64$  Ma on uppermost flow in Lakeshore Drive area has potassium too low to yield an accurate age. Hladky and Mertzman (2000) obtained an age of  $1.8 \pm 0.39$  Ma in the adjacent Keno quadrangle where they found the unit overlain by rocks with a 1.4 Ma age. Older than unit QTfs, which laps onto fault blocks capped by unit QTwb. Most probable age is  $\sim 1.8$  Ma.

**Tcba Basaltic andesite of Cove Point (Pliocene)**—Glomerocrystic, slightly diktytaxitic olivine-augite basaltic andesite. Cliff forming unit with blocky fracture. About 90 m thick at Cove Point but complexly interbedded and invasive into unit Tm there. Minerologically, texturally, and chronologically similar to unit Thb but does not have the high  $\text{TiO}_2$  and  $\text{FeO}^*$  characteristic of unit Thb; chemical composition similar to unit Tba. Radiometric age of  $2.41 \pm 0.13$  Ma.

**Thb Basalt of Hogback Mountain (Pliocene)**—Glomerocrystic high-titanium olivine basalt capping Hogback Mountain. High titanium tholeiitic composition with  $\text{TiO}_2 > 1.4$  percent and  $\text{FeO}^* > 9.4$  percent is distinctive; most lava flows have abundant glomerocrysts of fresh olivine and plagioclase; basal lava flow locally has smaller glomerocrysts than overlying flows, has some clinopyroxene phenocrysts, and is vitrophyric where interbedded with sedimentary rock of unit Ths or hyaloclastic units. Approximately 330 m thick at Hogback Mountain, where unit unconformably overlies older Tertiary units; the contact at Hogback Mountain dips  $\sim 5^\circ$ – $6^\circ$  NE, whereas underlying sedimentary units dip  $\sim 15^\circ$ – $22^\circ$  NE. Generally overlies and is locally interbedded with palagonitic sandstone and unit Ths. Characterized by irregular blocky fracture on a scale of 1–2 m, which gives rise to distinctive talus forming narrow dark bands (basalt streamers). These basalt streamers are uncommon in older rocks in the area. Forms cliffs. Uppermost flow has a radiometric age of  $2.67 \pm 0.21$  Ma. Roughly contemporaneous to basaltic rocks with similar texture dated at  $2.80 \pm 0.06$  Ma at an outcrop on the north end of Naylox Mountain north of the map area (sample S5-1, Pickthorn and Sherrod, 1990). Overlies unit Tba with a radiometric age of  $4.01 \pm 0.22$  Ma. Older than unit QTfs, which lies unconformably around the base of Hogback Mountain.

**Tba2 Basaltic andesite (Pleistocene and upper Pliocene)**—Relatively unaltered, glomerocrystic basaltic andesite with minor basalt and andesite. Locally includes minor thin or poorly exposed pyroclastic and sedimentary interbeds not mapped separately. Individual lava flows vary in thickness from approximately 1 to 20 m; total thickness is at least 240 m in the Plum Hills. Unit is cliff forming; blocky fracture is typical, platy fracture is well developed locally. Commonly crops out as rim-rock exposures; caps all major fault blocks, although is locally overlain by erosional remnants of pyroclastic or sedimentary rock on dip slopes. Typical lava is gray with conspicuous plagioclase and olivine phenocrysts; dark green clinopyroxene phenocrysts are smaller and less conspicuous. Phenocrysts commonly form glomerocrysts, some as large as 5 mm. Plagioclase is invariably subhedral and seriate; larger grains are zoned and commonly have abundant groundmass inclusions. Olivine is typically glassy green with tiny opaque inclusions but may be altered to glassy brown iddingsite. Some flows have small orthopyroxene phenocrysts. Flows are variably vesicular, locally grading to scoriaceous clinker, especially at flow margins; a few are slightly diktytaxitic. Most have a glassy groundmass with mixed intersertal/intergranular textures; trachytic and subophitic textures are rare. All samples of unit Tba2 analyzed from the map area can be classified as calc-alkaline using the criteria of Irvine and Baragar (1971). One sample, a basalt collected from the unit north of Whiteline Reservoir, fits the criteria of Hart and others (1984) for classification as a low potassium-low titanium tholeiite, although it plots as a calc-alkaline basalt otherwise. No sample from the unit can be classified as high alumina olivine tholeiite, which is common



elsewhere in the northern Basin and Range (Malin and Hart, 1991). Differentiated from unit Tba by fresh appearance, especially of the olivine phenocrysts, common occurrence of conspicuous glomerocrysts, and the general lack of interbedded sedimentary rocks that are common in unit Tba. Age based on stratigraphic correlation with ~2.4 Ma basaltic andesite of Cove Point; offset by faults that pass through ~1.9 Ma and 0.86 Ma basaltic andesite vent deposits at Bald Hill and Algoma but offset more by these faults than are the ~1.9 to 0.86 Ma rocks.

**Ths Sedimentary rocks of Hogback Mountain (Pliocene)**—Poorly indurated tuffaceous mudstone and poorly sorted to well sorted volcanic lithic sandstone. May be, in part, lacustrine shallow water to beach (strandline) deposit. Sandstone is generally cemented by zeolitic? minerals or mineraloids but is still highly porous and permeable. Up to 24 m thick at northwest end of Hogback Mountain. May be distinguished from unit Ts by poorer induration and more mature composition (lack of olivine clasts, presence of quartz clasts in some samples, dominance of hypersthene in mafic minerals, less clay matrix, and better rounding of clasts). Difficult to distinguish from lower part of unit QTfs, which has similar fine-grained mudstone and sandstone. Distinguished from lower part of unit QTfs by rarity or absence of well-rounded, unaltered amber volcanic glass clasts, the presence of significant chemical cement in most samples, and the relationship as an interbed between units Tba and Thb, locally above 1,470 m (4,820 ft) elevation in the map area. Older than unit Thb with a radiometric age of  $2.67 \pm 0.21$  Ma. Overlies unit Tba which has a radiometric age of  $4.01 \pm 0.22$  Ma in lower part. Most probable age is close to 2.7 Ma; age is highly uncertain, so older age equivalent to unit Tm is possible.

**Tpt Tuff of Ponderosa Junior High School (upper Pliocene or upper Miocene)**—Very poorly sorted, nonwelded lapilli tuff with distinctive clasts of hydrated nearly aphyric basaltic andesite glass and prismatically jointed lapilli of fresh vitrophyric lithic fragments in a matrix of mostly cream colored diatomaceous mudstone with lesser amounts of Tertiary basaltic andesite clasts up to a decimeter across. Probably a subaqueous hyaloclastic flow deposit. Up to 50 m thick. Irregular dikes of the unit complexly intrude or are invasive into underlying Tertiary mudstone at the Ponderosa Junior High School, suggesting that unit Tm may not have been well consolidated at the time of eruption. Overlies unit Tm on a highly irregular surface of erosional unconformity possibly eroded in part by the flow emplacement process; upper contact is obscure owing to erosion and colluvial cover, so could be interbedded in unit Tm. Generally forms steep slopes with rare, small-scale landslides. Appears to be stratigraphically below unit QTfs, so pre-Pleistocene. Possibly similar in age to the thick sequence of unit Tm deposited in the Lake Ewauna-Altamont area, so possibly younger than unit Thb (see discussion of the age of the basin in the Altamont area below). Most probable age is upper Pliocene but less than ~2.7 Ma; age is highly uncertain so older age equivalent to unit Tm is possible.

**Tt Tuff, lapilli tuff, and tuffaceous breccia (Pliocene)**—Massive to well-bedded pyroclastic deposits. Predominantly well-indurated ash and lapilli tuff, with lesser amounts of volcanic breccia, formed where unit Tba was erupted through surface water or water saturated sediments. Includes minor lava, autobreccia, mudstone, and epiclastic tuffaceous sandstone and conglomerate (similar or equivalent to units Tm, Ts, and Tg, respectively) not mapped separately. Commonly exposed in fault escarpments throughout the area; excellent exposures crop out in the Highway 97 road cut south of Rattlesnake Point and east of Shady Pine. Coarser-grained lapilli tuff and breccia are cliff-forming; ash and finer-grained lapilli tuff typically crop out in low relief or hollowed-out zones with little or no vegetation. Tuff and breccia are composed of black, scoriaceous clasts in a tan or yellow weathering palagonitic matrix. Bedding, defined by the ash-to-lapilli ratio, has normal and reverse grading and gradational contacts. Initial dips locally up to  $30^\circ$  suggest some deposits were emplaced as tuff cones. A sample collected from NE $\frac{1}{4}$  sec. 21, T. 38 E., R. 9 S. is basalt with major oxides totaling 89 percent, indicating ~11 percent volatile components, probably from hydration (Table 1.3; Map no. 51, sample K-321). Unit Tt locally includes beds of well-sorted, poorly indurated, olive-gray or light-brown ash and black, scoriaceous lapilli. These beds are planar, 0.5–4 m thick, with wavy, locally cross-bedded internal stratification 2–3 cm thick that drapes underlying high spots. Distinguished from tuffaceous beds in underlying units Tms, Ts, and Tg by lack of multi-lithic clasts and fluvial structures. Thickness is about 110 m, increasing to 175 m five kilometers north in the Plum Hills, to greater than 245 m east of Shady Pine (3 km north of map); and to 425 m at Naylox Mountain (5 km north).

- Tbv Basalt or basaltic andesite vent complex (Pliocene and upper Miocene)**—Autobreccia, hyaloclastic breccia, palagonitic sandstone, cinders, and interbedded thin flows, generally with high initial dips. Occurs as highly dissected tuff cones and composite cones of unit Tba in the Stewart Lennox area, where it is up to 100 m thick at a possible vent area. Forms moderate to steep slopes with little tendency to form landslides. Probably similar in age to unit Tba.
- Tbtv Mafic diatreme vent complex (Pliocene and upper Miocene)**—Olivine-bearing (mafic) nonwelded lithic crystal, vitric lapilli tuff in diatreme dikes of tachylite sandstone cutting unit Tm at such close spacing (centimeters) that the dikes appear to be bedded. Probable hyaloclastic vent complex. Forms moderate to steep slopes with little tendency to form landslides. Unknown age but cuts uppermost unit Tm; is below an outcrop of unit tentatively correlated to unit QTfs; probably similar in age to adjacent unit Tpt, which was also locally vented and cuts uppermost unit Tm.
- Ta Andesite (Pliocene and upper Miocene)**—Highly phyric two-pyroxene andesite characterized by large (up to 1 cm) plagioclase phenocrysts and smaller orthopyroxene and clinopyroxene and, in a few cases, olivine reacting to other minerals; phenocrysts are set in a very fine-grained groundmass generally showing signs of devitrification. One thin flow of hornblende andesite occurs in the Plum Ridge area but is too small to depict at the map scale. Generally interbedded in lowermost part or at base of unit Tba and in unit Tm. Up to 115 m thick near Stewart Lennox, where distinctive flow can be correlated across some major faults. Thick platy to blocky joints are common. Forms cliffs. Similar in age to units Tba and Tla. May be roughly contemporaneous with the Klamath Gorge Two Pyroxene Andesite dated at 4.4 Ma (Hall, 1996) and the lower part of unit Tba with ages of 4–4.5 Ma.
- Tla Andesite of Link River (Pliocene or upper Miocene)**—Highly phyric two-pyroxene andesite characterized by 0.2–6 mm euhedral to subhedral sieved to clear plagioclase (8 percent) with 0.2–1 mm orthopyroxene (0.5 percent) and clinopyroxene (1 percent) set in a very fine grained, nearly opaque groundmass of the same minerals with iron-titanium oxides; contains very minor (0.1 percent) phenocrystic olivine altered to smectite. Occurs between olivine basaltic andesite of unit Tba and diatomaceous mudstone of Unit Tm in the Link River and Moore Park area, where it is 66–88 m thick. Unit is a blocky to platy jointed cliff former. Radiometric age is  $3.43 \pm 0.06$  Ma but  $^{40}\text{Ar}/^{39}\text{Ar}$  spectra on this whole rock sample are somewhat irregular, possibly indicating loss of radiogenic argon from alteration of the devitrified groundmass. Alteration of olivine to smectite suggests that unit has undergone significant alteration, which may have led to argon loss. Overlain by basaltic andesite with age of  $4.47 \pm 0.28$  Ma (sample S5-12, Pickthorn and Sherrod, 1990), so probably somewhat older than about 4.5 Ma.
- Tba Tertiary basaltic andesite (Pliocene and upper Miocene)**—Compact olivine- and plagioclase-phyric basaltic andesite with minor andesite, olivine basalt, and locally thick interbeds of palagonitic sandstone and breccia. Holocrystalline units generally have seriate texture (complete gradation from phenocrystic to groundmass sizes); phenocrysts are generally plagioclase and olivine  $\pm$  clinopyroxene. Most samples have some glomerocrysts. Olivine is generally altered to iddingsite or green minerals. Spherical blue-green amygdules of smectite occur in many outcrops. Commonly interbedded with units Ta, Tm, Tms, Ts, and Tg; 117 m thick south of Moore Park; 213 m thick at Hogback Mountain; up to 67 m thick in and around the Plum Hills; 450 m of dark lava intercepted in geothermal wells near OIT may be unit Tba, but there are no samples to prove this. Platy fracture in basaltic andesite units is a distinguishing characteristic from younger basaltic units in the area; basalt in the unit has blocky to columnar fracture. Forms cliffs. Radiometric age of  $4.47 \pm 0.28$  Ma from a flow interbedded in unit Ts at prominent outcrop on Highway 97 near Lake Ewauna (sample S5-12, Pickthorn and Sherrod, 1990); age of  $4.01 \pm 0.22$  Ma from a flow near the base of a thick section at Hogback Mountain, where it overlies units Ts and Tm; age of  $4.08 \pm 0.12$  Ma from a flow near the top of the section at Indian Springs Ridge, 5.8 km east of Klamath Falls quadrangle (Hladky and Mertzman, 2000). The sequence containing the flow dated at 4.47 Ma appears to overlie unit Tla with an age of  $3.43 \pm 0.06$  Ma, so accuracy of unit Tla age is doubtful. Unit Tba underlying thick sections of unit Tm at Lake Ewauna-

Altamont is not dated. Regionally the oldest age from the unit is 6.88 Ma (Sherrod and Pickthorn, 1992). Overlain by unit Thb with a radiometric age of about 2.7–2.8 Ma. Most of the unit is 4–7 Ma in age.

- Tbas Mixed volcanic and sedimentary rocks (Pliocene or upper Miocene)**—Subequal abundance of volcanic flows (unit Tba) and lacustrine and fluvial sedimentary rocks (lower unit Tms) interbedded at a scale too small to map separately. Crops out in the fault scarp east of the OIT campus and Wocus. Lava flows are typically water affected, with the groundmass variably altered to palagonite, locally to the point of disintegration. A red “baked” zone commonly marks contacts between lava and the underlying sediments. Outcrop patterns, palagonitic alteration, and abundance of interbedded conglomerate suggest that the lava flows were deposited within existing stream channels. Base not exposed; top mapped at the base of the first overlying lava flow or sedimentary bed thick enough to map as a distinct unit. Up to 270 m thick near OIT. Age equivalent to oldest part of unit Tm in quadrangle.
- Tm Lacustrine mudstone (Pliocene and upper Miocene)**—Tuffaceous diatomaceous mudstone with cream color and fair induration except in upper part of section in basins. In basin areas, the unit may be only weakly indurated, locally forming a plastic silty clay with loose silty or fine sand interbeds that may be difficult to distinguish from Holocene sediments of similar composition. However, if sandstone interbeds can be found, they are generally well indurated, unlike sand layers in younger units. Nearly always massive and poorly bedded unless interbedded with coarser-grained sedimentary rocks. Generally highly fractured weak material that forms low slopes and valley floors throughout the area. Locally fails in small landslides and slumps. About 260 m of unit is overlain by unit Tba dated at about 4 Ma at Hogback Mountain; overlain by unit Tba dated at 4.47 Ma by Pickthorn and Sherrod (1990) on the west side of Lake Ewauna. Diatoms from samples in fault blocks indicate an age >2.8–3 Ma (unpublished data of Platt Bradbury, 1998, Table 5). Water well logs (Table A1) indicate that unit Tm is 400 m thick in the Lake Ewauna-Altamont basin area, where the unit overlies lava flows of unknown age; underlies unit QTfs. Lava flows of the basaltic andesite of Cove Point with an age of 2.4 Ma are invasive into unit Tm and thus contemporaneous with part of it. In local subsiding basins like Round Lake and probably Wocus Marsh and Upper Klamath Lake, where continuous deposition of lake mud has occurred, uppermost unit Tm is probably indistinguishable from lowermost unit Qs at a gradational boundary. A similar gradational contact separates unit Tm in the Altamont area from unit QTfs, so there may not be significant age separation at the contact; upward change from essentially sand-free mudstone to sandy mudstone and well-sorted sandstone of unit QTfs may reflect a change from deeper to shallower water (strandline or deltaic) conditions of lowermost unit QTfs. Outside the map area the unit is underlain by volcanic rocks ranging in age from 5.52 to 6.88 Ma and overlain by a flow dated at 3.68 Ma (Sherrod and Pickthorn, 1992). Middle to late Pliocene vertebrate fossils were reported from various localities (Peterson and McIntyre, 1970). It is possible that some of these localities were actually in unit QTfs, as explained above (description of unit QTfs). Unit is between ~2.4 and ~5.5 Ma but is probably younger in the Altamont area and in other subsiding basins.
- Tms Mudstone and sandstone (Pliocene and upper Miocene)**—Diatomaceous mudstone of unit Tm but with lesser amounts of fine-grained sandstone, siltstone, and very minor conglomerate interbedded at a scale too small to map; as the unit is essentially a facies change and laterally contemporaneous with unit Tm, contacts are laterally gradational. Forms moderate- to low-angle slopes with only minor mass movement. Same age and general thickness as unit Tm.
- Tg Conglomerate (Pliocene and upper Miocene)**—Moderately indurated volcanoclastic conglomerate with well rounded pebble- to cobble-size clasts in a moderately sorted sandstone matrix. Forms low, rolling hills and moderate slopes in the northwest and northeast part of the area; locally mined for gravel aggregate. Up to 85 m thick near Stewart Lennox. Locally interbedded with unit Tba. Most probable age is between 2.4 and 4.5 Ma.
- Ts Sandstone (Pliocene and upper Miocene)**—Well-indurated, moderately sorted to very poorly sorted volcanoclastic sandstone. Generally medium-grained angular to subangular sand of olivine, clinopyroxene, hypersthene and >85 percent volcanic lithic clasts; contains local pebbly layers and minor hyperconcentrated flood flow deposits. Up to 60 m thick near Stewart Lennox but mostly 10–20 m thick and enclosed in unit Tm. Extensive smectite and zeolite

cement causes the unit to be resistant to weathering and slope instability; forms very steep slopes and ridge crests. Interbedded with unit Tba and unit Tm. Most probable age is between 2.4 and 4.5 Ma.

**Ti Intrusion (Pliocene)**—Fine- to medium-grained, green-black, amygdaloidal diorite. Crops out in the southeast part of the quadrangle as a thick sill but also crosscuts the enclosing sedimentary rocks of units Tba, Tbas, and lower part of unit Tms; small outliers crop out in T. 38 S. R. 9 E., sec. 21. Plagioclase is subhedral, seriate up to 1 mm (rarely 2 mm). Olivine is anhedral or subhedral, less than 0.5 mm, variably altered to iddingsite or bowlingite. Clinopyroxene up to 4 mm ophitically or subophitically encloses plagioclase. Amygdules filled by radiating needles of white zeolite (probably natrolite) and milky, blue-white chert. Interstitial glass nearly completely altered to brown or green fine-grained, fibrous minerals. Slightly younger than unit Tba and lower unit Tms; uplifted on range front faults, so older than basin filling units like uppermost unit Tm and unit QTfs.

**Hydrothermal alteration (Holocene? to Pliocene)**—Areas of silicification and argillization affecting rock units. Varies from hydrothermally bleached and slightly argillized sedimentary rock to complete replacement of host rock by masses of chalcedonic quartz. Highly variable on a meter scale from soft, poorly indurated argillized rock to highly resistant silicified units. Forms moderate to steep slopes with little evidence of extensive mass movements. Alteration is of unknown age; hydrothermal systems are still active below the water table, where alteration is most intense.

### 3.0 STRUCTURAL GEOLOGY

#### 3.1 INTRODUCTION

The following text is included with the geologic map to provide an overview of the geologic hazards, resources, and geologic history of the area. The importance of geologic structure (faults and folds) to understanding resources, hazards, and geologic processes is such that this discussion is best begun with an overview of the structural geology. An attempt is made to make the information understandable to a lay audience, while still being useful to a geoscientist. This attempt was more successful in the geologic history, resources, and hazards sections; less so in the geologic structure section, which is necessarily a more technical discussion.

#### 3.2 GEOLOGIC STRUCTURE

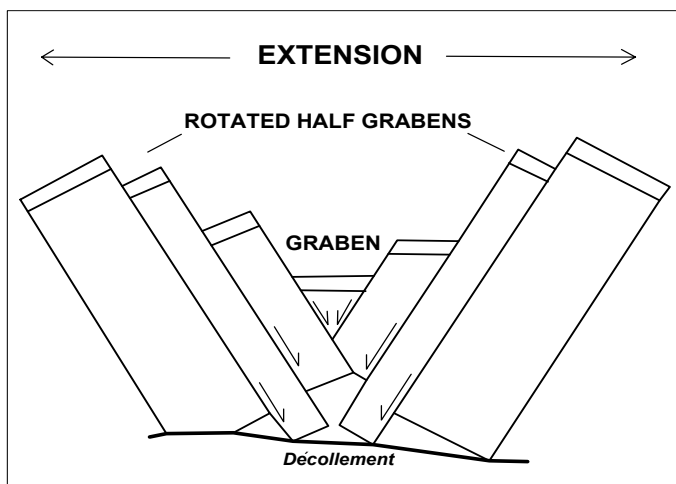
##### 3.2.1 Northwest-Striking Normal Faults

The dominant structures in the quadrangle are N30-40°W-striking normal faults (Figures 3.1, 3.2, and 3.3) that rotate fault blocks northeastward on the northeast side of the area and southwestward on the southwest side (see cross section A-A' on the geologic map). These faults are the result of N. 50°–60° E. extension in response to a minimum stress

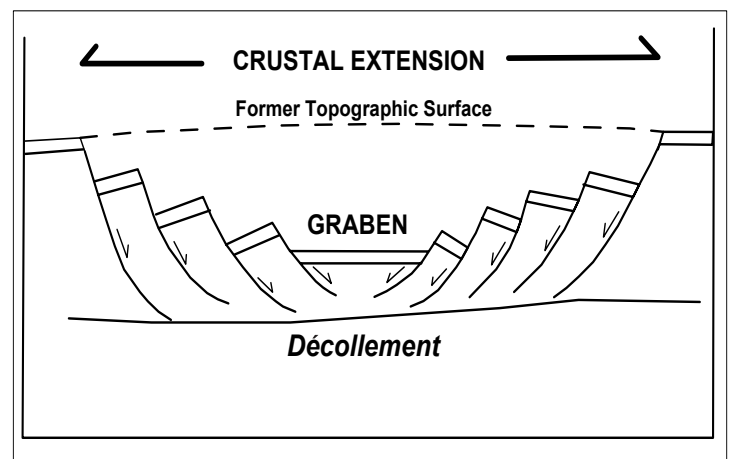
axis in this direction with maximum principle compressive stress probably N. 0°–10° W. to vertical (i.e., gravity).

One of the ways of achieving the fault block rotation is by development of a series of half graben detached at depth from deeper basement rocks by a *décollement* (Figure 3.1). Another way is by listric faulting (Figure 3.2). A key difference between the two rotations is the planar faults bounding the half graben versus the curving listric faults. Exposures and subsurface data were inadequate to distinguish which of these rotation models applies to the Klamath Falls area. Slightly curved fault planes are inferred on cross sections (see geologic map).

Areas of northeast- and southwest-tilted fault blocks are separated from one another by either the Klamath Graben (Figure 3.3), or by single faults within complex zones of normal and high angle reverse faulting, as in the ridges west of Link River (see geologic map and Figures 3.4 and 3.5). The Klamath Graben is bounded by the West Klamath Lake fault zone (Hawkins and others, 1989) and the East Klamath Lake fault zone (Figure 3.3; Bacon and others, 1999). The East Klamath Lake fault zone enters the map area as the normal faults at OIT, the Plum Hills, and Hogback Mountain (Figure 3.4). Structural relief on the Klamath graben is inferred to be about 450 m in the vicinity of Klamath Falls (Sherrod and Pickthorn, 1992) but probably increases

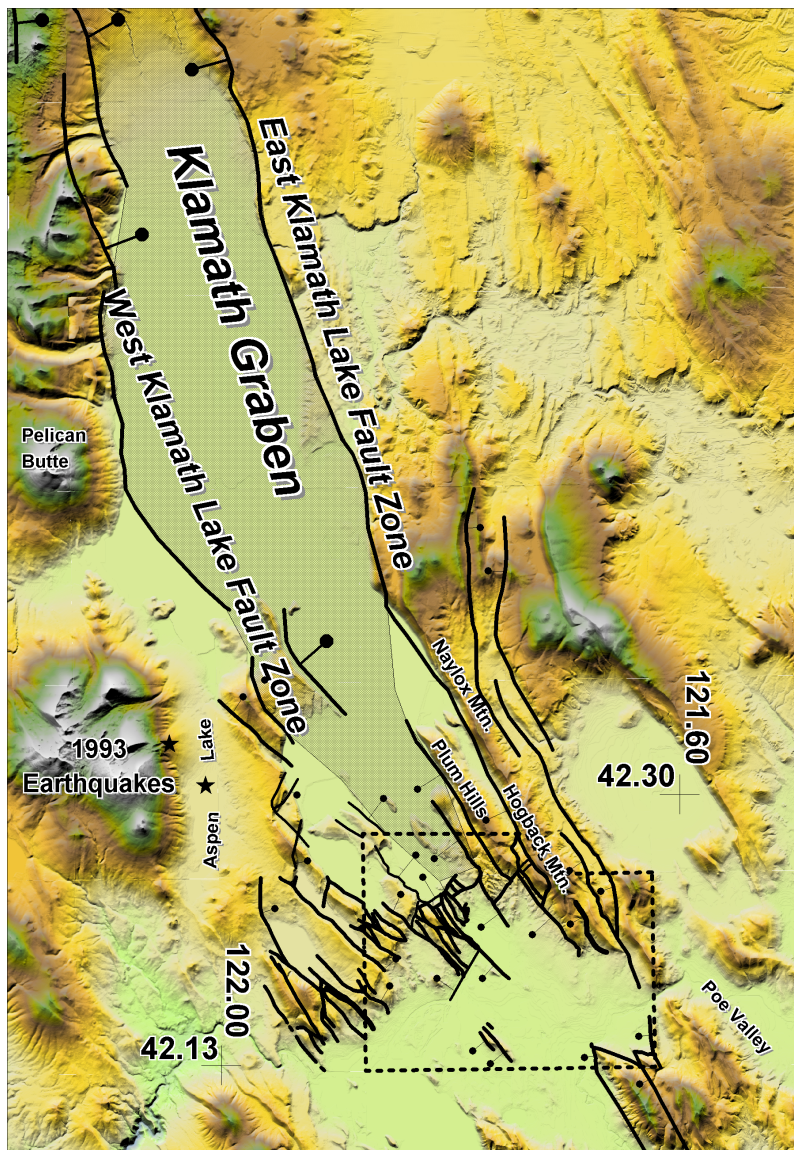


**Figure 3.1.** Illustration of how block rotation occurs during the development of half graben (modified from an illustration on the cover of the Ninth Keck Research Symposium in Geology [1996]).



**Figure 3.2.** Illustration of how listric normal faulting can rotate fault blocks.





**Figure 3.3.** Location of the Klamath Falls geologic map (dotted line) with respect to regional faults and the 1993 Klamath Falls earthquakes. The Klamath Graben and East and West Klamath Lake fault zones are taken from Bacon and others (1999) supplemented by the map of Sherrod and Pickthorn (1992) and Smith and others (1982). Only faults adjacent to the graben and in the map area are shown. Downthrown side of each fault is marked by a bar and ball. Thinner lines are faults with somewhat less offset. See Figure 1.1 for a three-dimensional view of the topographic base map.

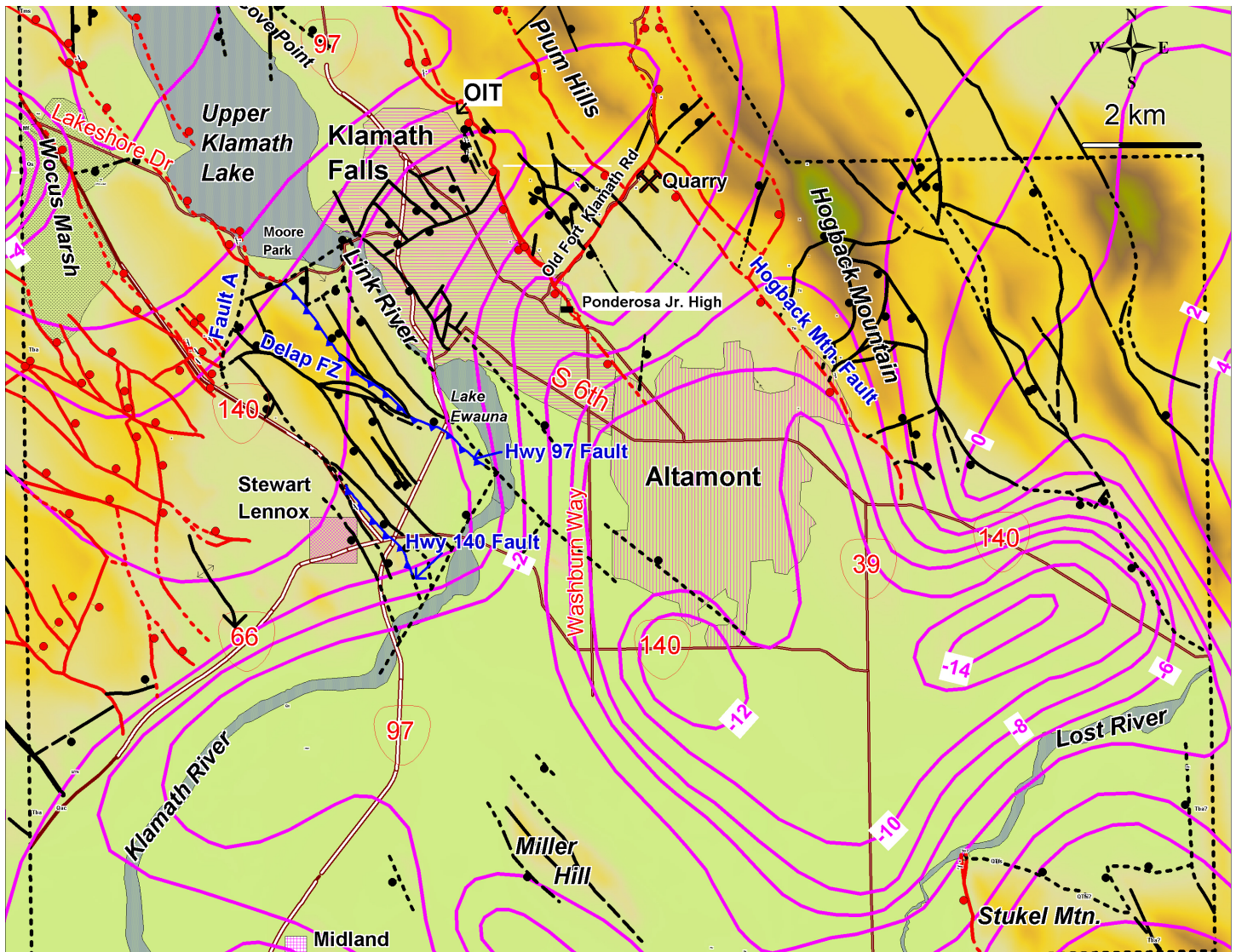
in structural relief to the north where large negative gravity anomalies are consistent with up to 1.2 km of basin fill (Couch and others, 1982a and 1982b). Structural relief on the Hogback Mountain fault could be as much as 1.4 km, if dark lava found in water wells under 400 m of mudstone in the Altamont area is the downdropped basalt of Hogback Mountain. Evidence for a subsiding basin at Altamont is discussed later in the text.

The dominant northwest-striking faults generally terminate along strike at zones of decreasing displacement or at northeast-striking faults. The ends of tilted fault blocks at Moore Park (Figures 3.4 and 3.5) and the southeast end of Hogback Mountain (geologic map) are marked by 600- to 700-m-long blocks of rock rotated at high angles to the direction of rotation of the main block. The one at Hogback

Mountain is rotated in the opposite direction from the main block and exposes a capping andesite unit not seen in the main block. Because andesite in other areas, like Link River, tends to underlie unit Tba, this rotated block probably has a large amount of displacement, enough to bring up a unit older than the rest of the exposed stratigraphic section.

Large slump blocks along range front faults can in some cases resemble normal faults. One northwest-striking normal fault 1 km northwest of Moore Park on Lakeshore Drive may be such a block. The short length (0.8 km) and arcuate shape argue for a large slide block, but the northeast dip of underlying diatomaceous mudstone in the block argues against any large amount of backward rotation that would normally be associated with a slump. Offset on this structure is ~50 m down toward Upper Klamath Lake.





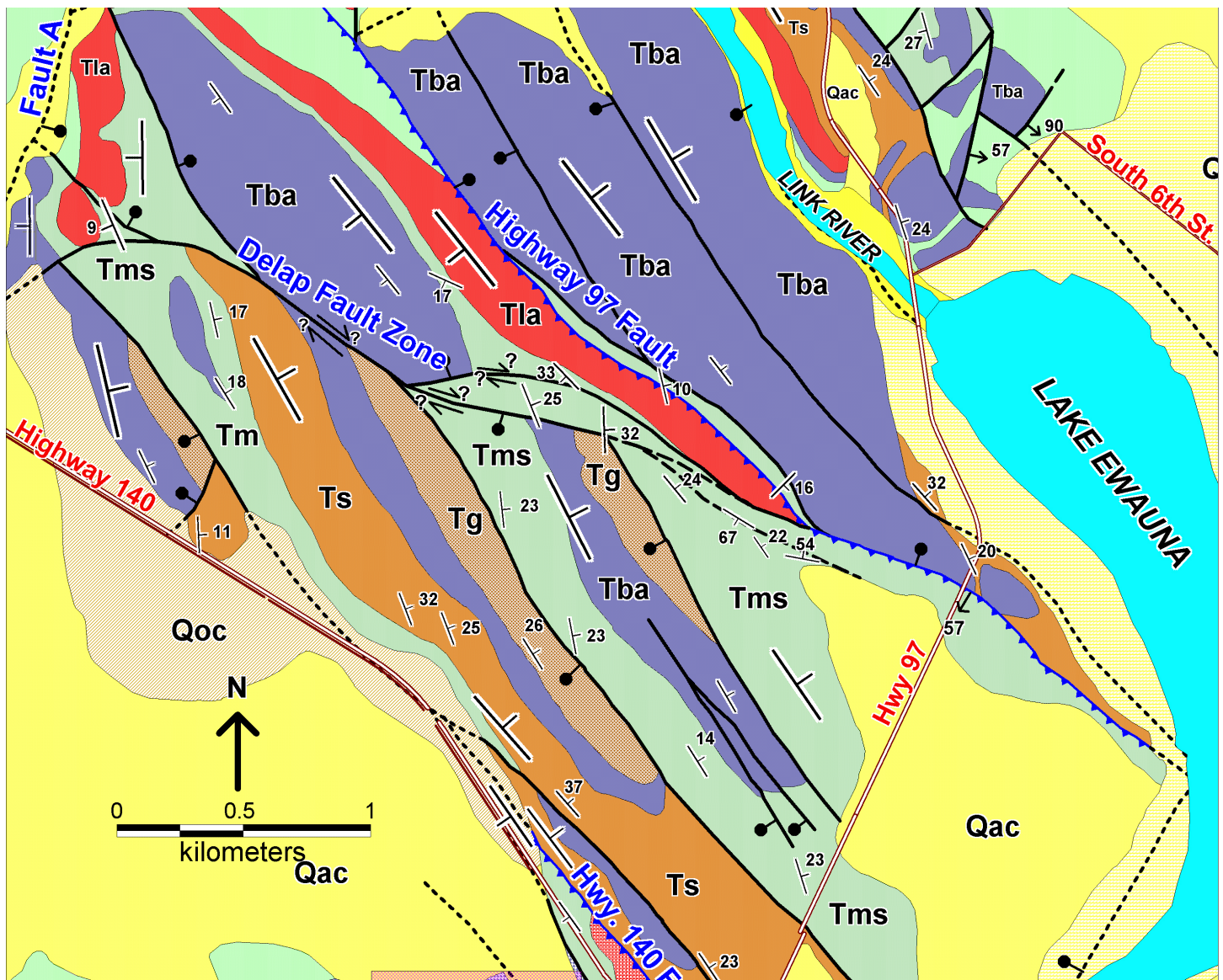
**Figure 3.4.** Faults and folds in the area of the Klamath Falls geologic map. Dotted line is geologic map boundary. Faults outside the map boundary are from Sherrod and Pickthorn (1992), Murray (in press), and Hladky and Mertzman (2000). Dots are on the downward displaced side of each fault. Lines with triangular teeth are high angle reverse faults with teeth toward upthrust side; others are normal faults. Red faults have evidence of more recent activity (post-1.8 Ma). Black and blue faults cut rocks older than 1.8 Ma. Dotted lines indicate cover by surficial deposits. Arrows on fold lines point in direction of plunge; opposed arrows pointing away from the fold axis indicate an anticline (upwarped rocks). Purple lines are residual gravity contours of Couch and others (1982b) in milligals. FZ is fault zone; OIT is Oregon Institute of Technology.

### 3.2.2 Northwest-Striking Lateral Faults, Reverse Faults, and Folds

The northeast- and southwest-tilted blocks west of Link River generally come together at zones of complex reverse and possible northwest-striking, oblique-slip faulting. A northwest-striking reverse fault with a dip of 57° SW is exposed along Highway 97 southeast of Link River (Highway 97 Fault, Figure 3.5). This fault extends to the northwest where it separates northeast- and southwest-rotated fault

blocks (Figure 3.5). On the northwest end of what appears to be the extension of this fault the distinctive andesite of Link River (unit T1a) is offset about 240 m, with the southwest side (hanging wall) up (cross section A-A'). An interpretation of reverse movement is based on the assumption that unit Tms exposed on the hanging wall at Highway 97 is older than unit Tba on the footwall and that the southwest fault dip persists to the northwest. Similarity of diatomaceous, tuffaceous mudstone of unit Tms in the hanging wall to unit Tms and contemporaneous unit Tm underlying





**Figure 3.5.** Map of complex faulting near Link River. Faults with triangular teeth are high-angle reverse faults with teeth in direction of the upthrust side. The Highway 97 Fault is exposed in a prominent road cut on Highway 97 (see 57° dip). Note how fault blocks tilt away from the Highway 140 Fault and the Highway 97 Fault (see also cross sections A-A' and C-C' on the geologic map). Note how fault blocks tilt toward the Delap Fault Zone on its northwest end; this fault is inferred to have a component of right-lateral offset. Symbols are defined in geologic map explanation. Pink square at the bottom marks the Stewart Lennox area shown in Figure 3.4.

ing both unit Tba and unit Tla at the base of adjacent fault blocks support this interpretation. Note that the northwest end of the Highway 97 Fault separates fault blocks that dip away from the fault, effectively forming a broken anticline. This is further evidence that it is probably a compressional structure.

The Delap Fault Zone separates southwest-tilted from northeast-tilted groups of fault blocks (Figure 3.5). This fault zone extends west-northwest from the Highway 97 Fault and separates somewhat different stratigraphic se-

quences. The sequence on the north side of the Delap Fault Zone is unit Tba underlain by a thin layer of unit Tms, then unit Tla, and a thick section of unit Tms. The sequence on south side is unit Tg, underlain by unit Tba, which is underlain by a thick section of unit Tms in the eastern tilted block and unit Ts in the western blocks. Lava flows in unit Tba on both sides of the fault zone are mineralogically and chemically similar (see Table 1.2; samples 19 and 20 compared to 25 and 26), so the difference in sequence could be from juxtaposition of laterally distant parts of correlative lava in unit



Tba by lateral faulting. This fault zone could also be a zone of accommodation between these two areas of tilted blocks with no significant lateral movement. Another possibility is some kind of oblique-slip movement. Lateral motion is consistent with the mismatch of the stratigraphic sequence across the fault. Right lateral motion is compatible with the clockwise rotation of the strike of unit Tms (from northwest to north-south) in the small elliptical fault block that occurs in the central part of the fault zone; queried arrows there show the possible direction of lateral motion (Figure 3.5). Right lateral motion in the general region of Klamath Falls is also consistent with interpretations of regional gravity data by Blakely and others (1997). It is possible that some portion of the west-northwest trending right-lateral faulting inferred by Lawrence (1976) occurs in this area. More detailed mapping, chemical analysis, and paleomagnetic measurement may resolve this problem.

The Highway 140 Fault is 1.6 km south of the Delap Fault Zone (Figure 3.5). Northeast- and southwest-rotated blocks come together at a shear zone tens of meters wide in this area. The exposed fractured, sheared, and weathered rocks in this zone reveal no well-defined fault plane dip. Because the fault blocks rotate away from the shear zone, a broken anticlinal structure is inferred, as at the Highway 97 Fault. This would make the fault a high-angle reverse fault. No rock units correlate across this shear zone, so it may have large reverse offset. Without a dip on the fault plane, it is not possible to infer which side is up. It is possible that the same forces that caused the Highway 97 Fault caused the Highway 140 Fault; hence it may have a similar dip and sense of movement (southwest dip and southwest side up). That is what is shown on cross section C-C'. Once again, this inferential evidence does not prove that this is a reverse fault.

Two kilometers west of Stewart Lennox, a reversal in dip occurs across a gentle, northwest trending anticline with only minor faulting (less than 2 m offset) along the anticlinal axis (Figure 3.5; cross section C-C'). This anticline is consistent with a component of northeast compression in the Stewart Lennox area. This inferred northeast-southwest compression is in the correct direction to cause the inferred reverse movement on the Highway 97 and 140 faults, although one might wonder why this compression is manifested here as such a gentle fold rather than a more heavily deformed broken anticline. If all these structures are caused by the same general stress regime, then, for some reason, the resulting deformation (strain) varies over relatively small (3 km) distances.

Regional northeast-southwest compression is not compatible with the overall northeast-southwest extension that

causes tilting of fault blocks bounded by northwest-trending faults throughout the area unless (1) the reverse faulting is of a different age or (2) there is some local stress regime at work. A component of lateral motion can produce local areas of compression, especially where the trend of the lateral fault takes a sharp bend. Judging from the evidence at the Delap Fault Zone, faulting with a right-lateral component of motion could be present in the area, so local regions of compression are possible. A similar, but highly speculative right-lateral or right-lateral oblique-slip fault appears to be present on the northeast side of the gentle anticline west of Stewart Lennox (geologic map). Both this inferred lateral fault and the Delap Fault Zone appear to have undulating trends compatible with development of local regions of compression.

If the N. 55°–75° W. strike (averaging ~N. 65° W.) of the possible right-lateral or right-lateral oblique-slip faults is at 30° to the principal compressive stress, as is usually the case, then one might infer a principal compressive stress axis oriented ~N. 35° W., virtually parallel to the overall strike of normal faults in the area. Clearly this is not consistent with overall north-south to vertical orientation of the principal compressive stress inferred from the north northwest trending normal faults that dominate the area. Another possibility is that the possible lateral faults are actually related to parallel west-northwest-trending transform faults that bound varying amounts of extension in the Basin and Range (Lawrence, 1976; Davis, 1980). Lawrence (1976) summarizes evidence for a number of major west-northwest-trending right-lateral transform fault zones that appear to take up the decrease in extension of the Basin and Range Province from southeastern Oregon to the Blue Mountains. The closest right-lateral fault zone identified by Lawrence is his McLoughlin zone, which on his maps has a measured trend of N. 58° W. and causes an apparent 15–20 km of right-lateral offset of “the High Cascade trend” (term from Lawrence, 1976). The possible right-lateral or right-lateral oblique-slip faults mapped here are subparallel to this trend and could be related. All this is speculative, as the potential lateral and reverse faults could just as easily be local zones of accommodation between groups of tilted fault blocks with differing directions of tilting.

Because the hypothesis of reverse faulting at the Highway 97 Fault hinges in part on the assumption that outcrops of unit Tms in the hanging wall are older than unit Tba in the footwall, it is important to understand that, although this is the simplest interpretation, it is not proven. The uppermost parts of units Tm and Tms in the adjacent Lake Ewauna and Altamont areas are lithologically similar to the mudstone in the hanging wall of the Highway 97 Fault but

probably younger than unit Tba. If this younger part of unit Tms is what is in the hanging wall, then the fault is a normal fault. The younger part of units Tm and Tms in Altamont-Lake Ewauna area is worth farther exploration.

### 3.2.3 Altamont-Lake Ewauna Area and Displacement on the Hogback Mountain Fault

The Altamont-Lake Ewauna area is mostly covered by surficial units, so the geologic structure shown on cross sections is based on water well data (Table A1) and observations in a few exposures. At Altamont this relatively flat basin is bounded on the east by Hogback Mountain which rises 640 m above the valley floor. As much as 400 m of moderately to well consolidated tuffaceous and diatomaceous mudstone of unit Tm overlies what is described in water well logs as hard, dark-colored rock that could be any dark-colored hard rock unit in the area (units Tba, Ta, Thb, etc.). Couch and others (1982b) show a negative (–6 to –14 milligal) residual gravity anomaly in the Altamont area that roughly defines the basin area (Figure 3.4). Couch and others (1982a) infer about 1.2 km of sediment fill in the northernmost part of the Klamath Graben based on modeling of a –20–22 milligal residual anomaly there; because the negative anomaly at Altamont is 30–60 percent of the one at Upper Klamath Lake, one might expect about 360–760 m of fill. Considering the errors inherent in geophysical modeling (see Veen, 1982, for discussion of the gravity data), this is reasonably close to the ~300–400 m of low density mudstone intercepted in several deep drill holes in and near Altamont (see well data, Table A1).

Without chemical, mineralogical, and age data from rocks in the wells there is no way to tell which hard rock unit or units underlie the thick section of mudstone. Likewise, the age of the mudstone in the Altamont-Lake Ewauna area is unknown. If the mudstone is relatively young, there could be very large displacement on the Hogback Mountain fault (i.e. the basalt of Hogback Mountain, unit Thb, would be displaced beneath the mudstone). If unit Tm is relatively old, say, older than the rock capping Hogback Mountain, then the displacement on the Hogback Mountain fault could be much less.

Some insight into the possible age of unit Tm can be gleaned from observations of lava flows that are interbedded in it. At Cove Point the basaltic andesite of Cove Point (unit Tcba), age ~2.4 Ma, is invasive into the upper part of unit Tm and has a lower contact at about the same elevation as the surface of Upper Klamath Lake (1280 m). About 100 m of mixed unit Tcba and unit Tm crop out there, indicating eruption of the basaltic andesite into a persistent lake.

The age of the upper part of unit Tm is therefore roughly 2.4 Ma at Cove Point.

Basalt of unit Thb, with an age of ~2.7 Ma caps Hogback Mountain. At its lower contact (1615 m elevation), unit Thb is interbedded with a minor amount of mudstone and fine-grained, well-sorted sandstone and has hyaloclastic texture and mineralogy indicative of eruption into water. Below that is a thick sequence of basaltic andesite of unit Tba. The lower contact of unit Thb is therefore 335 m above the lower contact of unit Tcba and both were interacting with water at the time of initial eruption. The upper part of unit Thb, however, is subaerial, whereas the upper part of unit Tcba is still interbedded with unit Tm. There is clearly not much geologic time between emplacement of units Thb and Tcba; in fact the ages are the same within 1–2 standard deviations of the error (Table 1.1; 0.13–0.21 Ma). The two units, while differing in chemical composition, share enough mineralogical and textural similarities that they are difficult to tell apart in outcrop. One might conclude that at 2.4–2.7 Ma unit Thb filled a valley that was a shallow arm of the lake where unit Tcba was erupting. If so, then there was probably not much elevation difference between them at this time. The current 335 m of elevation difference is probably caused by faulting after 2.4 Ma.

This reasoning is fine for Cove Point, but what about Altamont? Because there is no basaltic andesite of Cove Point or basalt of Hogback Mountain at Altamont, just tuffaceous mudstone and some sandstone, these basalt and basaltic andesites were either eroded away, making the mudstone older, or they lie beneath the mudstone. If the basalt of Hogback Mountain or contemporaneous lava was eroded away, then this occurred sometime after 2.7 Ma (age of Thb) but before the start of deposition of unit QTfs (i.e., sometime after ~1.8 but before ~1.1 Ma?). There is no evidence of a major erosional episode in this interval. All evidence seems to point to gradually decreasing eruption of lava flows with time at Altamont, and progressively more opportunity for uninterrupted deposition of thick lacustrine mudstone of unit Tm. The weight of the evidence is therefore on the side of a youthful (<2.7 Ma) age for the Altamont mudstone that accumulated atop downward offset unit Thb. The down-to-the-west offset on the Hogback Mountain Fault would then have to be on the order of 1.4 km (cross section D-D').

One problem with the above hypothesis is that one would expect to see some exposures of units Thb, Tba2 or Tcba in tilted fault blocks that emerge from this cover of lacustrine mudstone in downtown Klamath Falls. Instead, lava of unit Tba chemically and mineralogically identical to basaltic andesite underlying units Thb and Tba2 caps many of these fault blocks. Other fault blocks in the downtown

area are capped by unit Ts lithologically similar to sandstone underlying unit Tba at Hogback Mountain. Did units Thb, Tba2, or Tcba ever reach this area? Were they eroded off during progressive uplift and fault block rotation? Did the tilted fault blocks in downtown Klamath Falls form after eruption of unit Tba but before unit Thb and contemporaneous lavas? If bedrock exposed in downtown Klamath Falls is representative of the basement of older rock beneath the Altamont and Lake Ewauna area, then there may not be much or any basalt of Hogback Mountain there. The lateral extent of unit Thb shown in cross section D-D' is thus highly speculative. Units Tba and Thb are shown queried in cross sections B-B', C-C', and D-D' and in data fields of the water well table (Table A1) to emphasize the uncertainty of the stratigraphic interpretations.

It is also not known whether the older basaltic andesite flows of unit Tba in the downtown area pinch out to the southeast into the Lake Ewauna area, interfingering with the thick mudstone sequence under the basin. If so, then at least part of the mudstone sequence at Altamont could be older than unit Thb.

The structure under Altamont and Lake Ewauna is probably just as complex as that exposed in downtown Klamath Falls. Without extensive geophysical and drilling data it is not possible to accurately represent this complex structure in the cross sections. The cross sections are thus highly simplified compared to the real situation.

### 3.2.4 Northeast-Striking Faults

Northeast-striking faults are not as common as northwest-striking faults, but a number are interpreted mainly from abrupt termination along northeast trends of groups of northeast- or southwest-tilted fault blocks. A northeast-striking fault at the Klamath River south of Stewart Lennox appears to offset a sequence of andesite and interbedded sedimentary rock downward to the northwest by about 440 m (Figure 3.4; cross section C-C'). The northeast strike is inferred from the trend of the river and the residual gravity anomaly in this locality (Figure 3.4). Another northeast-striking fault occurs southwest of Moore Park, separating a series of southwest-tilted fault blocks to the northwest from an east-rotated fault block (fault A on Figure 3.4; see strike and dips on the geologic map). Northeast tilted fault blocks north of Link River are inferred to terminate against inferred northeast-striking faults that also appear to show up in the residual gravity data (Figure 3.4; geologic map). A major northeast-striking fault approximately follows Old Fort Klamath Road (Figure 3.4). As discussed below, this

fault at Old Fort Klamath Road has some of the best evidence in the area for geologically recent activity.

### 3.2.5 Age of Faulting

The age of deformation in the Klamath Falls area appears to be chiefly less than 4 million years. Petrographic and chemical correlation of the rocks from single lava flows of unit Tba from the Link River area to the Plum Hills and Hogback Mountain demonstrate that some basaltic lava flows spread at least several kilometers east-west across areas now occupied by prominent northwest-trending, fault-bounded ridges. The age on these flows is approximately 4 to 4.5 Ma (Table 1.1; sample K-90, 4.47 Ma date by Sherrod and Pickthorn, 1992). Progressive tilting and deposition has occurred since that time. For example, at Hogback Mountain an age of  $4.01 \pm 0.12$  Ma (Table 1.1; sample K-90) was obtained near the base of basaltic andesite unit Tba. There the underlying sandstone dips  $20^\circ$  to  $30^\circ$  NE. Flows near the top of the basaltic andesite dip about  $11^\circ$  NE, and the capping basalt of Hogback Mountain (unit Thb, age about 2.7 Ma) lies on a surface dipping  $5^\circ$ - $6^\circ$  NE. Thus approximately  $16^\circ$  of tilting apparently occurred between about 4 and 2.7 Ma. Many of the tilted fault blocks capped by units Tba and Ts northwest of Old Fort Klamath Road and in downtown Klamath Falls may have formed in this interval. This might explain why they lack capping lava flows of unit Tba2 or Thb. One caveat about this observation is that the dips in the older rocks at Hogback Mountain are taken from exposures of sedimentary rock near the Hogback Mountain Fault (Figure 3.4); it is quite possible that those dips are created by highly localized deformation rather than tilting of large parts of the fault block.

On the basis of the dip of its lower contact, the basalt of Wocus Marsh appears to be tilted  $4$ - $5^\circ$  southwest in the fault blocks surrounding Wocus Marsh, but underlying rocks of unit Tm have southwest dips up to  $18^\circ$ . Diatoms indicate an age  $>2.8$ - $3$  Ma for unit Tm (Table 1.4; unpublished data of J. Platt Bradbury). The age of the basalt of Wocus Marsh is probably about 1.8 Ma. Thus tilting of as much as  $14^\circ$  could have occurred between 1.8 Ma and sometime before  $\sim 3$  Ma, but the same caveat applies. Local faulting can cause dip measurements unrepresentative of overall structure in a sedimentary sequence, whereas the dip of a formation contact can give a much more accurate picture of fault block tilt.

Possible right-lateral faults and reverse faults north and northwest of Stewart Lennox cannot be traced northwest into the faulted basalt of Wocus Marsh. Faults cutting the basalt of Wocus Marsh northwest of Stewart Lennox ap-



pear to be northwest-striking normal faults with no evidence of reverse or lateral faulting. Sherrod and Pickthorn (1992) note that most slickensides and mullions in the west half of the Klamath Falls 1° by 2° quadrangle plunge directly down dip, consistent with normal slip. Some of the best-exposed slickensides of this type are on the northwest-striking Holocene faults cutting colluvial deposits in the East Klamath Lake fault zone (Figure 3.3). The only place where there may be some small lateral offset on basalt of Wocus Marsh is 3.3 km west of Stewart Lennox at the extension of a small fault with highly speculative inferred right-lateral oblique-slip (see geologic map). Even there, the major offset on the basalt is obviously normal, and no lateral offset is needed to explain the outcrop pattern. The stress regime that gave rise the possible reverse and lateral faults either changes to the north and northwest of Stewart Lennox (the stress regimes are highly localized) or ceased after 1.8 Ma (age of unit QTwb)—or the reverse and lateral faults are really normal faults that have been misinterpreted. Rocks involved in the possible reverse and lateral faults north and northwest of Stewart Lennox are some of the oldest units in the area; the youngest is unit Tba with an age of about 4–4.5 Ma in this area; hence it is possible that these complex faults represent an older episode of deformation characterized by west-northwest right-lateral transform faulting that has either ceased or slowed since 1.8 Ma.

Where faults cut the youngest rock units, one can infer that those faults are potentially active. The late Pliocene (?) and early Pleistocene sedimentary rocks of Foothills Drive (unit QTfs) are locally highly deformed; examples are the gravel quarry on Old Fort Klamath Road and the quarry at the northwest tip of Stukel Mountain (Figure 1.1; geologic map). The gravel quarry at Old Fort Klamath Road is noteworthy because a northeast-striking fault passes through the west side of the quarry, tilting poorly consolidated sedimentary rocks of unit QTfs to near-vertical dip. Exposures ~100–200 feet east of the fault show decreasing dip upward and eastward in section, suggesting ongoing deformation during deposition of unit QTfs. In other areas, measured dips in unit QTfs are on the order of 10°–12° E. to NE. Some of this dip may be original depositional dip in the coarser grained sedimentary beds, but the dip persists in tuffaceous mudstone beds, so some tilting has occurred even in areas relatively far removed from mapped faults. This tilt suggests the presence of unmapped normal faults in the Altamont area.

North of the map area at Upper Klamath Lake there is abundant evidence of Holocene and Pleistocene faulting. Volcanic rock with an age of  $1.9 \pm 0.5$  Ma is cut by gra-

ben bounding faults on the east side of Upper Klamath Lake at Rattlesnake Point (Sherrod and Pickthorn, 1992; M. O'Brien and S. Benson, in Fiebelkorn and others, 1983). The structural relief on the Klamath Graben has therefore developed chiefly after 1.9 Ma (Sherrod and Pickthorn, 1992) and created topographic escarpments rising up to 1.3 km above Upper Klamath Lake (e.g. southeast of Rattlesnake Point). Veen (1982) infers from gravity data 0.4–1.2 km of sediment fill in the Klamath Graben at Upper Klamath Lake. Couch and others (1982a) infer sediment fill of 1.2 km, based on modeling residual gravity anomalies. In the map area at least 110 m of structural relief was developed on the west side of Upper Klamath Lake where northwest-striking faults cut the basalt of Wocus Marsh (age ~1.8 Ma). Geophysical surveys of Upper Klamath Lake revealed that numerous northwest-striking faults offset the Mazama ash bed by 1–2 m (Colman and others, 2000). One fault cutting Upper Klamath Lake sediment has had at least three episodes of movement since deposition of the Mazama ash 7,540 calendar years ago (Colman and others, 2000).

Bacon and others (1999) have demonstrated similar youthful faulting and potential for future fault movement on the West Klamath Lake fault zone. The September 20, 1993, Richter magnitude 5.9 and 6.0 earthquakes (Wiley and others, 1993) occurred at the southernmost end of the West Klamath Lake fault zone (Figure 3.2). Although the number of aftershocks related to the 1993 earthquakes has decreased every year since 1993, future earthquakes with magnitudes as high as Mw 7.25 are possible on the West Klamath Lake fault zone (Bacon and others, 1999). The faults on the east side of the Klamath graben at Upper Klamath Lake probably have similar potential for large earthquakes. The West and East Klamath Lake fault zones extend into the Klamath Falls urban area but have less obvious youthful displacement than outside the urban area. However, preservation of youthful fault scarps in the urban area is difficult owing to the dominance in many areas of easily eroded tuffaceous mudstone and diatomite.

The Hogback Mountain and Plum Hills faults are part of the East Klamath Lake fault zone that extends into the map area (Figures 3.3 and 3.4). Deformation rates on these fault zones at Upper Klamath Lake are so high that range front faults appear as sheared colluvium-bedrock contacts that are preserved high on the slopes (Sherrod and Pickthorn, 1992). Similar sheared colluvial-bedrock contacts have not been found on the southeast extension of these faults into the map area, but this may be due in part to poorer exposures and to the less competent nature of the sedimentary rocks forming the base of the Plum Hills and

Hogback Mountain. Escarpments bounding the Klamath Graben in Upper Klamath Lake are composed chiefly of basaltic lava that is much more likely to preserve fault scarps for long periods of time. Nevertheless, there are no areas in the Klamath urban area where Holocene alluvial fans are clearly cut by fault scarps, so it is possible that overall deformation rate is less than to the north. The only alluvial fan that appears to be cut by a major northwest-striking range front fault is probably Pleistocene in age (uppermost unit QTfs) on the southeast side of Old Fort Klamath Road (Figure 3.4; geologic map).

### 3.2.6 Recent Faulting at Ponderosa Junior High School

Over the last few decades cracks and small graben have formed along a northwest-trending zone up to 70 m wide at Ponderosa Junior High School and surrounding school grounds (Figure 3.6). Subsidence in this zone is as much as 45 cm in the asphalt track around the playing field southeast of the school; numerous small vertical offsets of the school parking lot are on the order of 3–10 cm (Figure 3.7). The scarp cutting the running track on its southeast margin trends N. 15° W. with ~36 cm of pure dip-slip motion down to the west (Figure 3.6). This scarp trends N. 17° W. at the playing field but turns to a trend of N. 8° W. where it passes through the bus shelter and the chain link fence to the southeast (Figure 3.8). The scarp could not be followed northwest of the playing field owing either to a lack of deformation or lack of easily recognized features that could be offset. A historical photo taken during construction of the canal to the southeast shows a hot spring at the projected extension of this feature (Figure 3.9).

A small shear cuts through a slightly uplifted part of the running track at its north end. The shear has ~6 cm of left-lateral offset across a cement curb on the inside of the track (Figure 3.10). It strikes N. 17° W. toward a similar but much smaller left-lateral offset of a curb on the southeast side of the school parking lot (Figure 3.11). Overall, deformation in this area and at the school parking lot is, however, a series of small irregular, generally northwest trending graben (Figure 3.12). Most of these features either have pure dip-slip or small (~1 cm) component of right-lateral oblique offset.

Deformation of the school building (Figure 3.13) is being quantitatively monitored, so data exist on how deformation has varied with time (data and interpretations from Mark Dew, Dew Engineering, 1998, oral comm.). The conclusion from this monitoring is that recent deformation was caused by ground-water withdrawal from the active geothermal system. This interpretation is supported by observed dramatic decrease of deformation of the school

building after geothermal wells in the area began to reinject water. Furthermore, minor, ongoing deformation of the school building appears to correlate with seasonal changes in the ground-water table. Similarly deformed areas of the school grounds to the southeast of the parking lot were reportedly sites of active hot springs prior to development.

Ponderosa Junior High School lies at the southwest end of a large zone of active geothermal circulation tapped by numerous wells at Pacific Terrace and OIT. Because hydrothermal minerals commonly seal up such systems unless fractured by episodic deformation, this system is probably cut by active faults. A number of major northwest-striking faults are mapped in the same area, one inferred through the Ponderosa Junior High School site (Figure 3.4; geologic map). It is recommended that detailed analysis of the deformation and seismicity near and at Ponderosa Junior High School be conducted to determine if some movement could be from active fault creep.

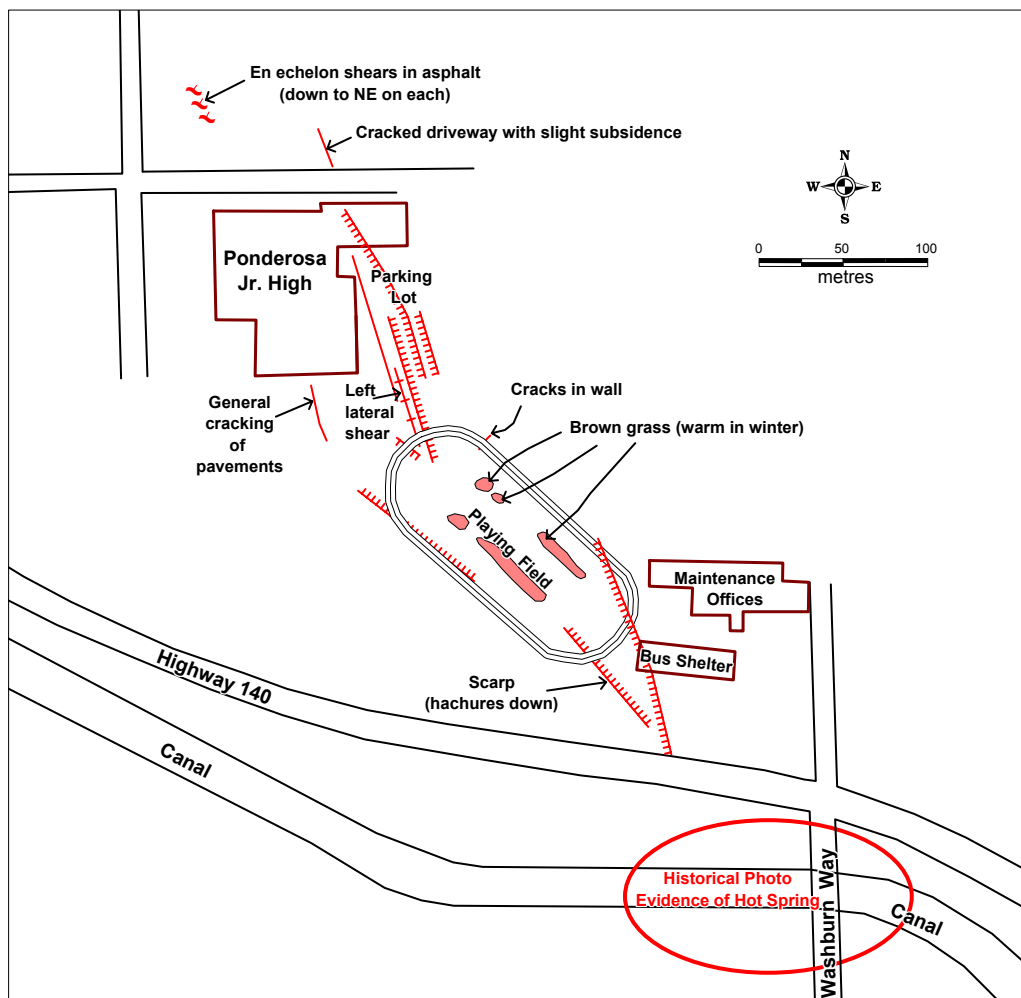
### 3.2.7 Summary

To summarize, northeast-southwest extension that has caused northeast and southwest tilting of fault blocks over the last 4 million years probably continues today. Structural relief on the northwest-trending fault bounding the northeast-tilted block at Hogback Mountain could be up to 1.4 km. All of this structural relief developed after ~2.7 Ma, the age of lava capping Hogback Mountain. A west-northwest fault zone at the Delap Pit Road area near Stewart Lennox could be part of a right-lateral transform fault zone or simply a zone of accommodation between groups of tilted fault blocks with differing tilt.

Probable high-angle reverse motion on the Highway 140 and Highway 97 Faults may be related to local northeast-southwest-directed transpressive forces on a regional right-lateral transform fault or similar forces accommodating the reversal in tilt of fault blocks. The evidence for the reverse and lateral faulting is highly speculative and needs to be confirmed by more detailed investigations.

Faults bounding the Klamath graben extend into the map area and are probably still active and capable of producing local large (~magnitude 7) earthquakes. Faults that are considered most likely to experience further movement are colored red on the geologic map. These faults are either extensions of fault zones known to have Holocene movement northwest of the map area, or they are closely related to faults that cut rocks less than 1.8 Ma in age (age of unit QTwb). These youthful faults, where the fault planes are well exposed north of the map area, appear to be normal faults with pure dip slip.

**Figure 3.6.** Structural geologic map of the area around the Ponderosa Junior High School. Hachures are on the down thrown side of scarps. Areas depicted as brown grass were taken (by inspection) from unpublished, undated engineering geology map of CH2M Hill and provided by Oregon Institute of Technology. The circled area refers to Figure 3.9.



**Figure 3.7.** Looking northwest at down-to-the-west offset of school parking lot.







**Figure 3.8.** Northwest-trending scarp offsets the bus shelter.



**Figure 3.9.** Historical photo of hot spring in canal when the canal was constructed. See Figure 3.6 for approximate location. Photograph is courtesy of James K. Bryant, Chief of the Water and Lands Division of the U.S. Bureau of Reclamation in Klamath Falls.





**Figure 3.10.** Left-lateral shear at north end of running track.



**Figure 3.11.** Left-lateral offset in curb at parking lot northwest of shear in Figure 3.10. The two shears are connected by a small, northwest-trending notch cut by erosion of apparently sheared soil.





**Figure 3.12.** Approximately 7-m-wide graben in school parking lot. Backpack is shown for scale.



**Figure 3.13.** Slightly deformed roof line on Ponderosa Junior High School where down-to-the-west (left) ground deformation crosses the building.

## 4.0 GEOLOGIC HISTORY

**6–4 Ma.** Between 6 and 4 million years ago the Klamath falls area looked very different from today. It was much more volcanically active and probably had much lower topographic relief. Volcanoes periodically erupted basaltic andesite and andesite lava with calc-alkaline chemical composition similar to lavas from subduction zone volcanoes worldwide. As basaltic andesite magma rose through the Earth's crust, it cooled faster and faster, culminating in very rapid crystallization during eruption at the surface. This process gave nearly all of these flows a distinctive seriate texture characterized by all sizes of crystals from a millimeter or two down to microscopic sizes. Many of the magmas intruded into the lake sediment and flashed the ground water and lake water to steam. The resulting violent steam explosions blasted out fragments of the lava and underlying country rock. Slurries of steam-blasted ash built up palagonite tuff cones. An example is the hill of unit Tbv immediately south of Stewart Lennox. Erupting lavas flowed into the extensive lakes, intruding upward from below at vents and invading downward from above into the soft lake mud as they flowed out and sank into it.

Local streams were flooded with sand and gravel from the abundant volcanic activity, so the deposits were rapidly accumulated with little time for rounding or sorting of clasts. Many of these same streams funneled lava flows, so there is often a close association between lava outcrops of unit Tba and outcrops of sandstone (unit Ts) and conglomerate (unit Tg) in the area (e.g. hills north of Stewart Lennox).

Volcanic ash carried by westerly winds from Cascade volcanoes rained down on the lakes. Silica from weathering of these ash fall deposits and local volcanic rocks nourished blooms of microscopic plants called diatoms. The result was extensive deposits of cream-colored diatomaceous, ash-rich mud similar to modern lake mud of Upper Klamath Lake.

**4–2.7 Ma.** After ~4 Ma, andesite eruptions ceased, and volcanic activity consisted mainly of basaltic andesite eruptions. Between 4 and 2.7 Ma earthquake activity probably increased as the area began to be slowly pulled apart (extended) in a northeast-southwest direction. This crustal extension caused normal faulting and tilting of rocks and lake sediments toward the southwest and northeast away from Upper Klamath Lake and Altamont-Lake Ewauna. Figures 3.1 and 3.2 show ways in which this may have occurred. Keystone-like blocks (graben) started to drop, forming depressions similar to the current basin at Upper

Klamath Lake. Additional blocks formed on each side of these basins, rotating backward toward the northeast on the northeast side and southwest on the southwest side. A west northwest trending fault located where the Delap Pit Road is now began taking up the offset between groups of these southwest- and northeast-tilted blocks.

**2.7–2.4 Ma.** About 2.7-2.4 million years ago the basalt of Hogback Mountain (unit Thb) and basaltic andesite of Cove Point (unit Tcba) poured out across a landscape that was probably similar to the present topography but with much less relief. The extensional faulting allowed magma from deep in the Earth's mantle to rise more quickly toward the surface than in earlier times, so there was not as much time for magma to exsolve volatiles or mix with melted crustal rocks. Many of these lava flows have small angular vesicles indicative of exsolution of volatiles after the flows reached the surface and began to crystallize. The basalt of Hogback Mountain also has a high titanium (TiO<sub>2</sub>) content similar to other basalt erupted during crustal extension in the Basin and Range province (e.g. Hart and others, 1984) and Cascades (Priest and others, 1983; Priest, 1989). When these flows spread out on the surface, the ones around Cove Point sank into the soft unconsolidated sediment of a lake, while flows at Hogback Mountain mainly flowed onto stream or deltaic sediments and quickly built up a shield volcano of subaerial flows. Magmatic processes that led to eruption of these two units and contemporaneous unit Tba2 favored entrainment of clumps of partially crystallized magma (olivine and plagioclase feldspar), giving most of the flows a distinctive glomeroporphyritic texture. Magma probably paused within the Earth's crust long enough to form mats of crystals that were continually disrupted by fresh intrusions of magma.

**2.4–1.8 Ma.** Between 2.4 and 1.8 million years ago, the faulted topography began to look more like the current landscape as volcanic activity decreased, forming by 1.8 Ma a belt of basalt vents located immediately west of the area and in the High Cascades. Overall extension of the Earth's crust at this time allowed erupting magma to rise through the crust even faster than before. Transit time was so fast that very little dissolved water was able to exsolve out of the basalt flows, so when they erupted, they were highly fluid, rapidly spreading out in thin layers that puffed up when the dissolved water was finally driven out of solution by cooling and crystallization. This process causes the numerous angular vesicles and large crystals termed diktytaxitic texture characteristic of the basalt of Wocus Marsh. The flows cov-



ered a surface of consolidated mudstone on the southwest side of the area, flowing over a surface that was mainly free of lakes, the area having already undergone normal faulting, uplift, and erosion. The basalt of Wocus Marsh appears to thin out toward the east along a north-northeast trending line that was probably an old valley wall; the wall was controlled in part by a north-northeast-striking fault (fault A, Figure 3.4).

Basins subsided at Upper Klamath Lake and probably in the Altamont area, allowing persistent lakes to collect hundreds of meters of tuffaceous, diatomaceous mud. The lower part of this stack of mud compacted and lost water, converting the material to mudstone.

A unique volcanic eruption at the area now occupied by the Ponderosa Junior High School formed a 50-m-thick mound of broken rock and still-hot lava fragments that spread out over the lake bottom; the resulting deposit is the tuff of Ponderosa Junior High School. The soft cream-colored mud of the lake allowed the hot, steaming mound of broken material to sink into the lake bottom. The age of this eruption is not known. It could have been as early as 4–6 Ma, but the association with thick sections of diatomaceous mudstone in the Altamont area is consistent with a eruption in the 2.4–1.8 Ma time interval, while a fairly deep lake still persisted in the sedimentary basin at Altamont.

The eruption near the Ponderosa Junior High School was roughly contemporaneous with violent venting of steam and basaltic glass shards (ash-size tachylite glass) from N. 20° W.-trending fissures 1 km east of the present site of the school.

Both the tuff of Ponderosa Junior High School and the diatreme dikes left behind by the fissure eruptions are evidence of basaltic magma intruding into the lake sediments, flashing ground water to steam, and blasting out mixtures of country rock, lake sediment, and quenched, broken fragments of the magma itself. The phreatic (steam) eruptions were probably the last gasp of volcanic activity within the map area.

**1.8–1.1 Ma.** Between 1.1 and 1.8 Ma volcanic activity ceased in the map area but continued in adjacent areas to the north and west. The Upper Klamath Lake and Altamont basins continued to subside even as sediment from lakes and streams filled the basins. The lower parts of these deposits are chiefly lake and deltaic sediments that accumulated in the latest Pliocene, whereas the upper part is characterized in some areas by alluvial fan gravels that spread out at the base of the largest ridges like Hogback Mountain. These sediments are the sedimentary rocks of Foothills Drive (unit QTfs). Owing to the cessation of local

volcanic activity, sediment accumulated much less rapidly, and the resulting sandstone in the lower part of unit QTfs is much better sorted, rounded, and generally finer-grained than sandstone deposited earlier (unit Ts). Minerals (for example, orthopyroxene and phenocrystic quartz) in these fine-grained sandstone beds are not common in volcanic rocks of the local area, suggesting sources outside the map area brought in by either streams or air fall ash. Gravels in the uppermost part of unit QTfs appear to be derived from erosion of local volcanic rocks. The upward change from fine-grained sediment to locally derived gravels and sands may have been caused by a change in climate from the Pliocene to the colder, wetter glacial climates of the Pleistocene. Increased rainfall probably led to greater discharge from streams during glacial times, so coarser sediment could be mobilized from local highlands.

At Hogback Mountain the top of sedimentary rocks of Foothills Drive is at elevations as high as 1,420 m (4,700 feet), while the base is at ~1,270 m (4,180 feet), suggesting that 150 m of the unit accumulated on top of the ~400 m of lake deposits (diatomaceous mudstone) of unit Tm in the Altamont basin. This 150 m is a maximum thickness, since these rocks have been cut and uplifted an unknown amount on the Hogback Mountain Fault (Figure 3.4). Nevertheless, it is clear that the sedimentary basin at Altamont was at one time filled to higher elevations than at present and that this fill helped consolidate unit Tpt and the underlying ~400 m of mudstone in unit Tm.

**After 1.1 Ma.** Sometime after 1.1 Ma, a radical change occurred; instead of the basin at Altamont filling with sediment, sediment was flushed out of the area, probably down some newly opened river outlet. How and where this occurred is not clear. One possibility is that an ancestral Klamath River eroded its headwall back through the High Cascades and into the Klamath Basin at this time, so sediment could for the first time escape to the sea. Indeed, a lava flow at the top of the Klamath River gorge in the Topsy Grade area of the High Cascades has an age of 1.1 Ma, suggesting that headward erosion of the river crossed the High Cascades sometime after 1.1 Ma (Gravley, 1996). In areas of uplift or with low rates of subsidence, like the Altamont area, the sedimentary rocks of Foothills Drive were exposed to erosion. Increased river discharge possibly caused by climate changes, episodically bursting ice dams in the High Cascades, and glacial melting at the end of each ice age stripped away from the map area most of the sedimentary rocks of Foothills Drive. Boulder deposits up to 30 m thick beneath Link River could be deposits left behind by these Pleistocene rivers.

Basins like the Klamath graben in Upper Klamath Lake, Wocus Marsh, and Round Lake probably subsided and trapped sediment even as sediment was being stripped out of other areas after 1.1 Ma. For example, at Round Lake and Wocus Marsh, the upper 50 m of sediment was deposited in the last 1.4 million years (Adam and others, 1994, 1995). From gravity data, Veen (1982) infers that 0.4–1.2 km of sedimentary deposits probably fill the Klamath Graben north of Modoc Point in Upper Klamath Lake.

About 0.9 Ma, renewed volcanic activity occurred immediately north of the map area at Bald Hill. This volcano appears to be on the extension of the northwest-trending normal fault that passes through the OIT and the Ponderosa Junior High School. This fault is probably still active, as it cuts the Bald Hill rocks and appears to conduct upwelling

geothermal water through its fracture systems (see discussion of geothermal resources below).

As explained above, crustal deformation is ongoing, so Klamath Falls is still affected by the same forces that started 3–4 million years ago. The 1993 earthquakes are a harbinger of possibly larger earthquakes that may occur in the future on faults within the city (see Wiley and others [1993] and Bacon and others [1999] for more information).

Extensive glaciers of the last Pleistocene ice age are now gone from the High Cascades, so rivers have only modest flow—much less than during melting of the last glaciers. The low flow of the streams coupled with the dry climate and growing needs of the local population has led to water quality and quantity problems.



## 5.0 GEOLOGIC HAZARDS

### 5.1 MINERAL RESOURCES

**Aggregate.** All of the lava flow units in the area (units Tba, Ta, Tla, Thb, and Thb) can be or have been used as sources for crushed aggregate. The conglomerate of unit Tg has also been excavated for aggregate, as have similar rocks within the uppermost part of unit QTfs in the Old Fort Klamath Road area. Units Qal, Qac, and Qc have been used locally as fill. Gravel within unit Qal can be used for aggregate.

**Diatomite.** Diatomite deposits occur throughout unit Tm and locally in unit Qs and QTfs, but none have been exploited for commercial production. Peterson and McIntyre (1970) identified four surface exposures that may have commercial potential (see geologic map).

**Mercury.** Ancient hot springs deposits surround OIT and are mapped as hydrothermal alteration (see geologic map). Mercury in the form of the red mineral cinnabar is commonly deposited in such rocks by hot springs. Peterson and McIntyre (1970) show one such occurrence in the OIT area (see geologic map).

### 5.2 WATER RESOURCES

#### 5.2.1 Overview of Geologic and Hydrologic Resources

For a more detailed discussion of geologic and hydrologic resources, see Peterson and McIntyre (1970). An in-depth analysis of the hydrologic and hydrothermal systems is given by Sammel (1980); the following is a brief summary.

**Groundwater.** The water table (top of the zone of ground-water saturation) may be pictured as forming a gently undulating surface that looks like the local topography but with lower relief. The surface of the Earth intersects the water table at lakes and perennial streams. Excessive withdrawal of ground water can lower the water table over large areas, causing shallow water wells to dry up. In some cases a lowered water table can cause perennial streams to lose rather than gain water from stretches of a stream where the water table has been lowered. A high water table does just the opposite, adding water to the stream channel.

Finding the water table in a well does not mean that the well produces adequate water. A permeable zone of water-saturated rock or soil (an aquifer) must be present as well. Local aquifers are mainly in stream sand and gravel, the equivalent rocks (sandstone and conglomerate), or in lava flows. Highly fractured zones at the base or top of lava flows

generally produce large amounts of water. Mudstone of unit Tm is nearly impermeable to water and confines aquifers contained within it. In some cases these confined aquifers have water pressure high enough to produce artesian wells. Much of the Altamont area is underlain by a thick section of mudstone, which makes it necessary to drill over 400 m to reach confined lava flow aquifers adequate for large-scale municipal or commercial uses. Total depths of wells listed in Table A1 and on the geologic map give a good indication of how deep to drill for productive aquifers in a given area. Table A1 also lists rock types intercepted at various depths. These rock types are interpreted from well logs filed with the Oregon Water Resources Department (OWRD) by water well drillers who are not generally trained in geology, so there is considerable uncertainty about the actual rocks penetrated; nevertheless, it may be inferred that parts of wells interpreted to intercept units Qal, QTfs, QTwb, Tcba, Thb, Tba2, Ths, Tbv, Tla, Ta, Tba, Tbas, Tg, and Ts may contain adequate flows of ground water, if located below the water table. Fracturing of rock can greatly increase its permeability, hence fault zones are often desirable targets for water wells. Wells should be sited to penetrate fault zones in one or more of the above units below the water table, taking into account the possible inclination (dip) of the fault zone. The cross sections on the geologic map give an approximation of what inclination faults typically have, but detailed, site-specific geologic and geophysical investigations can give a much better estimate. Keep in mind that the geologic map shows only the fault zones that could be easily recognized from mapping outcrops or interpreting water well data. There are many more faults that remain undiscovered. These faults may be found with appropriate geological and geophysical investigations of individual sites.

#### 5.2.2 Water and Geothermal Well Data

**Water Well Database.** Depths, temperatures, and hydrologic information for water wells are taken from files of the OWRD. No well location was plotted unless there was some corroborating evidence that the listed location was at least approximately correct (e.g., listed address matching the plotted location, similarity of data to adjacent wells, etc.). Wells are plotted with different symbols depending on accuracy of the location. In some instances the locations are from field surveys; in others, the location is from the in-

formation supplied in the water well registration information, which locates the well to the quarter-quarter section level. In a few cases, even though the location is given at the quarter-quarter section level, other information on the registration form (e.g., address) allowed a better approximation (generally within about 50 m) of the actual well location. As OWRD field-locates wells, the locations are modified in their database. New wells are also regularly added to the database at OWRD. Check their web site at <http://egov.oregon.gov/OWRD/> for the most recent information on water wells. Water well logs can be directly downloaded from submenus within this web site. The well number field in Table A1 corresponds to the OWRD log identification number. All well logs in Table A1 are in Klamath County.

Geologic unit assignments in Table A1 are derived from interpretations of lithologic descriptions in OWRD records. These descriptions are often ambiguous with respect to actual lithology, because water well drillers are not trained geologists. Unit assignments and parts of the cross sections based on well data must therefore be considered speculative. Wells shown in cross sections are projected along the inferred northwest strike of the rocks to the section; only surveyed, field-located wells are shown in cross sections.

### 5.3 GEOTHERMAL RESOURCES

**Geothermal Well Spreadsheet.** A geothermal well database consisting of two data sets, one for the City of Klamath Falls and one for Klamath County, were provided by OIT. These data were used for the data points in Figure 5.1. No attempt was made to merge or correlate this data set with Table A1 OWRD data. Accuracy and precision of these well locations and listed temperatures is not known. The raw data sets are included on the CD-ROM as spreadsheet and GIS files.

Geothermal systems are still active in an elongate area parallel to the northwest striking fault from OIT to Ponderosa Junior High School (Figure 5.1). Warm (63–71°C) aquifers have been intersected at Miller Hill and Stukel Mountain (Figure 5.1). Many wells in and near OIT, Pacific Terrace, and Ponderosa Junior High School have water at or near boiling temperatures and are used for direct heat applications, including a municipal district heating system. Homeowners generally extract heat from wells by use of heat exchangers, whereas the municipal system pumps and reinjects hot water. Wells deep enough to test for electric generation potential (150–200°C) have not been drilled, but fluids of this temperature could be present (Peterson and McIntyre, 1970; Mariner and others, 1980). For example, one of the OIT geothermal wells (well 6) has a reser-

voir temperature of 185°C estimated by the sulfate-water method (Mariner and others, 1980).

Figure 5.2 illustrates how rapidly temperature increases with depth in the map area. Figure 5.2 is based on the assumption that all temperatures in the two well spreadsheets represent approximate bottom-hole temperatures and that the ambient ground temperature is about 10°C (Gerald Black, personal communication, 2002), so gradients are calculated by dividing temperature minus 10°C by total depth. Obviously, temperatures are actually measured water temperatures, which represent a mixture of all water flows encountered, so this is not a true representation of the actual gradient. Nevertheless, this calculation gives some crude indication of temperature gradient, as most wells stop drilling shortly after they penetrate into a significant aquifer that contributes much of the water to the well.

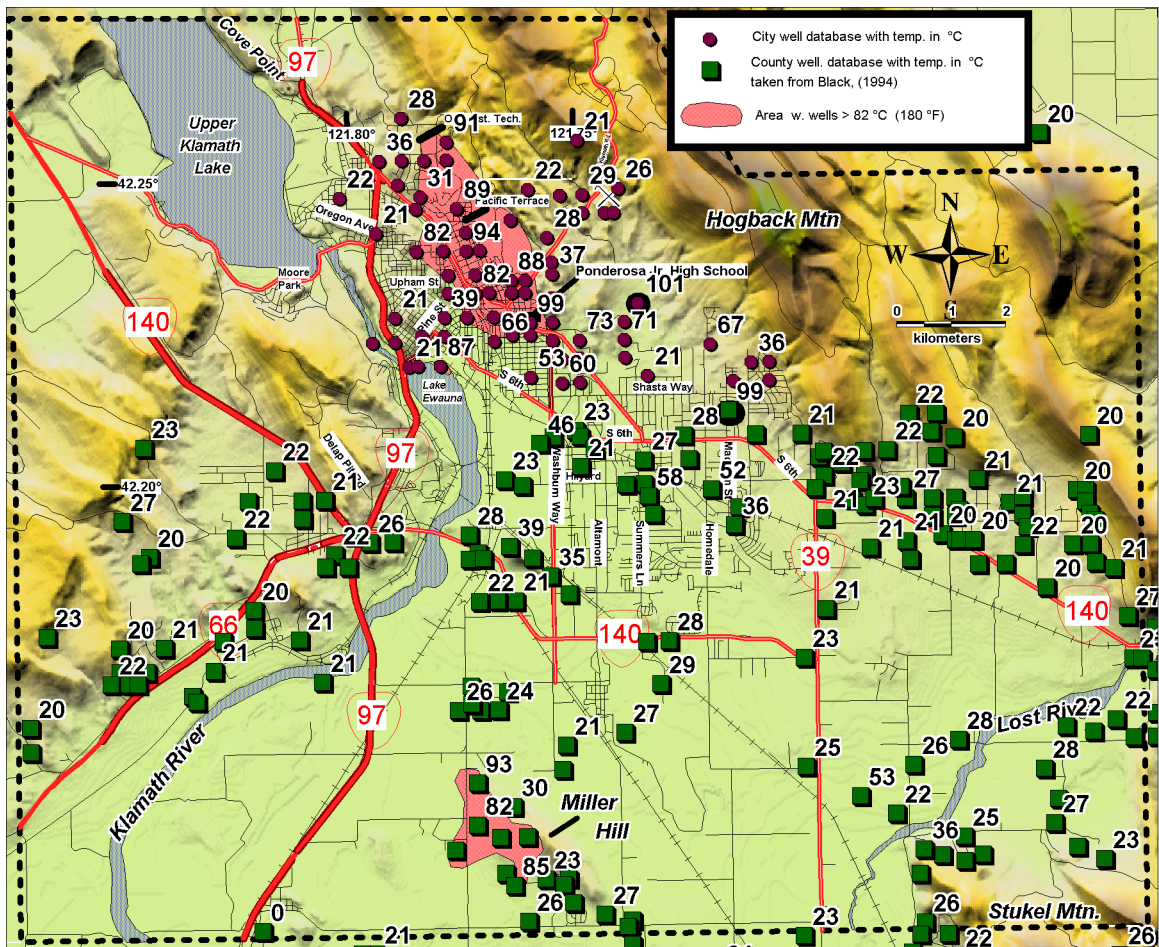
The natural background temperature gradient is approximately 30–60°C/km in this area, on the basis of some of the deeper water wells. Areas of background gradient are shown approximately by the blue colors in Figure 5.2. In these areas one would need to drill to depths of 2–3 km to get temperatures high enough to be of interest for direct use heating. Anomalously high gradients occur in much of downtown Klamath Falls to Link River, from OIT to Ponderosa Junior High School, several areas of Altamont, at Miller Hill, and at Stukel Mountain. Many of these high gradients are based on temperatures measured in shallow wells, so they may not persist at depth. High gradients from shallow wells in mudstone of units Tm or Tms are particularly hard to project to greater depth, because these rocks have low thermal conductivity (they are insulators that store heat) relative to hard rocks like lavas, sandstone, conglomerate, or altered, vein-quartz flooded rocks that may lie at depth. If these more thermally conductive rocks lie below, then temperature gradient will be lower than in the overlying mudstone. Nevertheless, it is possible that deeper drilling in areas with high gradients may yield significant hot water at relatively shallow depths.

Targeting areas at depth that have potentially high fracture permeability is the best way to improve the chances of getting geothermal resources. Good targets include fault zones and lava flows. Parts of fault zones cutting brittle rocks like sandstone, conglomerate, lava flows, or silicified rock units are particularly likely to be permeable. Areas of combined high gradient and faulting are apparent on Figure 5.3. Predicting where these fault zones cut brittle rocks deep enough to be hot requires detailed geological exploration and analysis.

## 5.4 EARTHQUAKE AND MASS WASTING HAZARDS

**Earthquakes.** The main geologic hazard is earthquake shaking and associated slope instabilities. A map showing areas most vulnerable to earthquake shaking was produced by Black and others (2000) and is available from the Oregon Department of Geology and Mineral Industries (web site: <http://www.oregongeology.com>). Youthful faulting on long (~70 km) fault zones and the two ~Mw 6.0 earthquakes on

September 21, 1993, (Figure 3.3) clearly argue for the possibility of large (~magnitude 7) earthquakes in the future (e.g., Bacon and others, 1999). Any area with soft soil will tend to amplify ground shaking, particularly if the soft soil is underlain by hard rock. Areas with loose silty or sandy soil and high ground-water table, as around Upper Klamath Lake, Lake Ewauna, and the Klamath River, could experience liquefaction during an earthquake. Soil turns to the consistency of quicksand when liquefied by ground shak-



**Figure 5.1.** Well temperatures for the mapped area (in degrees Centigrade); red areas indicate where wells have intercepted rock at temperatures greater than 82°C (180°F), a temperature useful for direct-use geothermal heating applications. The fact that a well has a relatively low temperature does not mean that the area lacks higher temperatures. The well may be a shallow well that never reached deep enough to be hot. Consult the digital spreadsheet Geoth\_KlamCounty\_FINAL2.xls and OITcitywells\_FINAL.xls files directly and see Figure 5.2 for a map of how quickly temperature increases with depth in the area. Some of the data points have more than one well in a small area, but a temperature label for only one of the wells will show in this map view of the data; that temperature may or may not be the highest one in that area. The areas highlighted in red take into account the highest temperature wells for each such area of closely spaced wells. Warmer colors on the base map indicate higher elevations; Ore. Inst. Tech. is Oregon Institute of Technology.

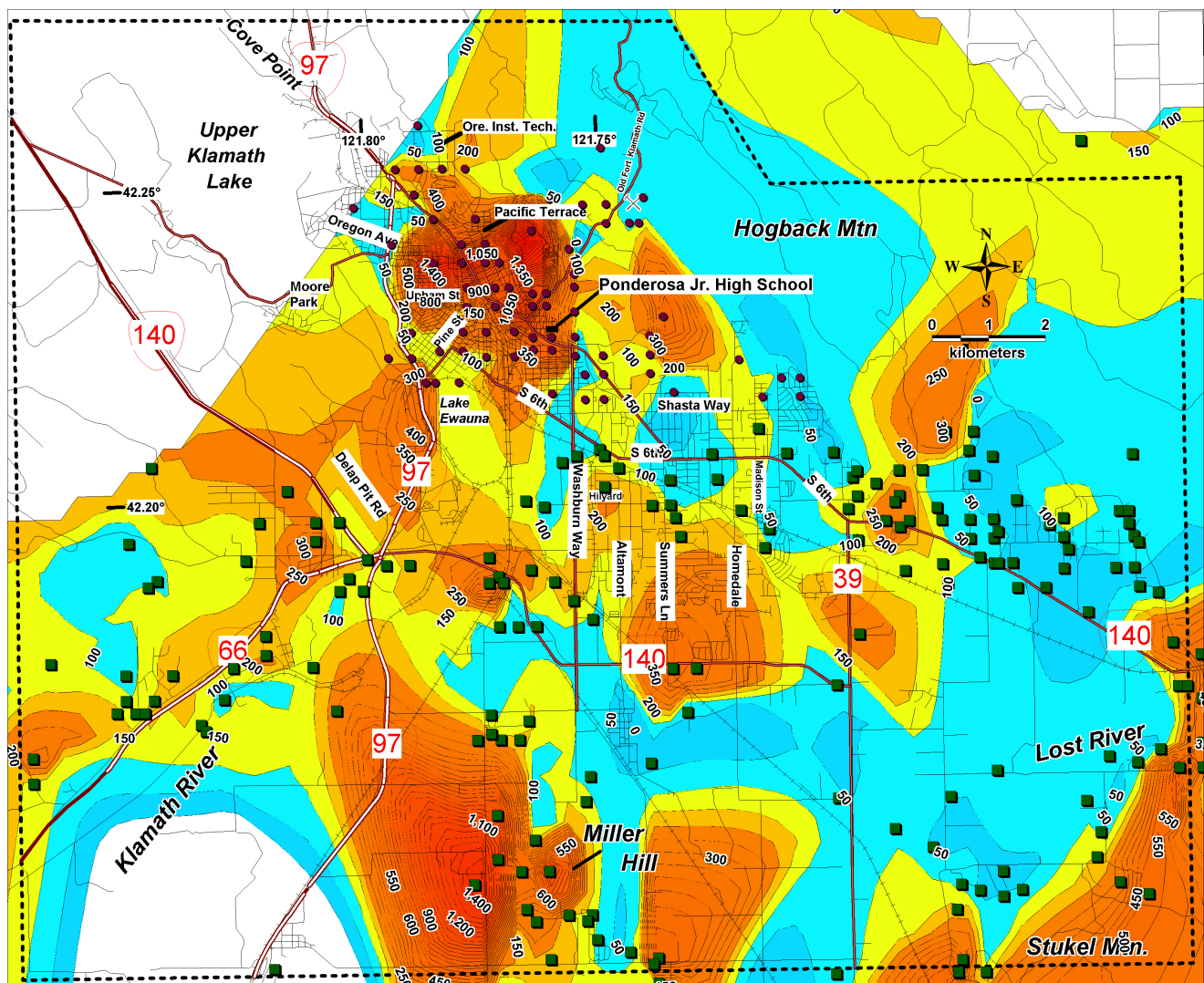


ing. In liquefied material dense, heavy things like buildings sink; buoyant, light things like buried fuel tanks rise; and very gentle slopes can slide, particularly if there is a cut like a riverbank at the end of the slope. This sliding of liquefied material is called lateral spreading and can tear buildings, roads, and bridges apart.

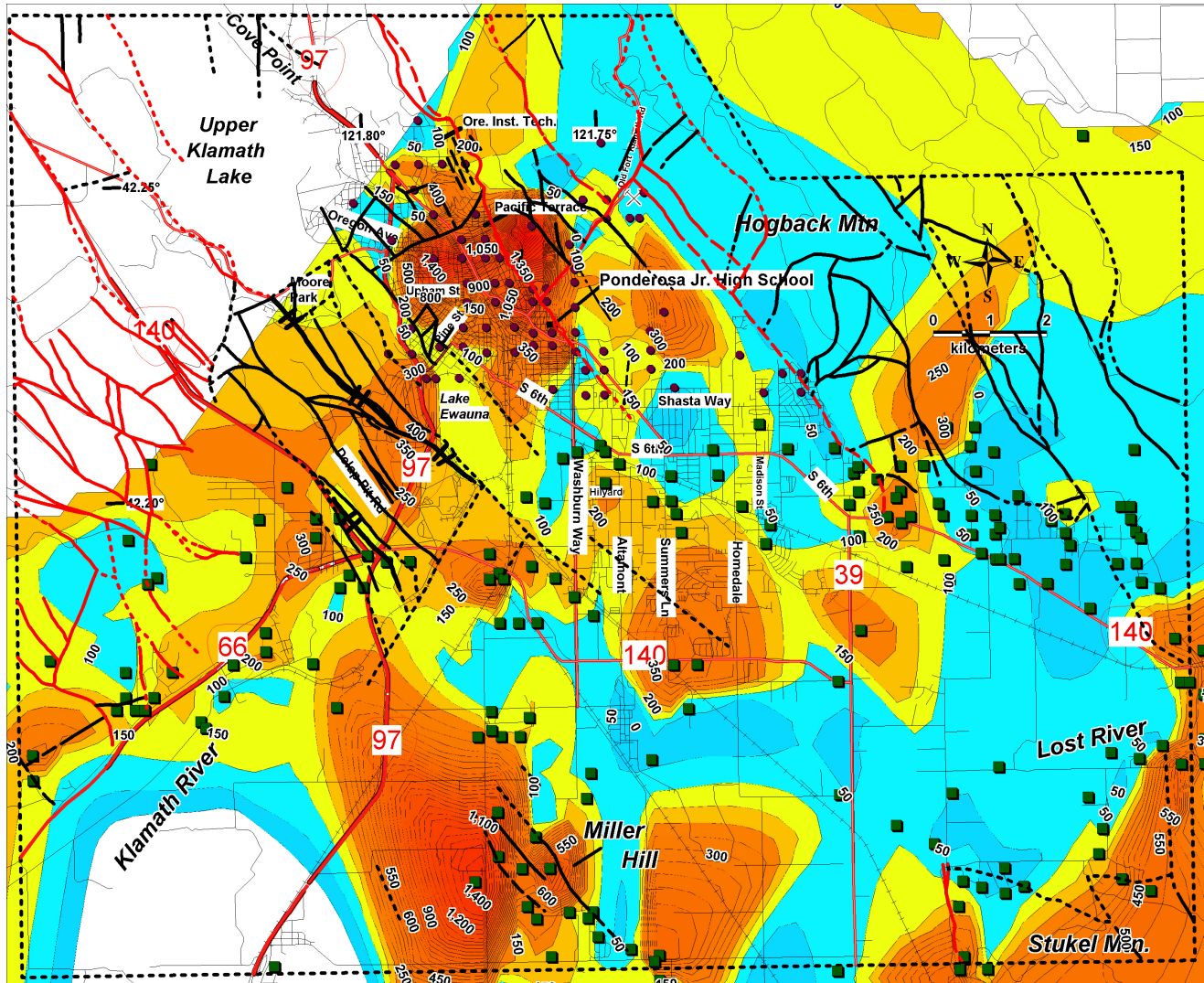
The other major slope stability hazard is from rock falls on steep slopes. Rock falls can be a problem wherever rock units composed of lava form a substantial part of a steep

slope. Road cuts create particularly steep slopes, so vehicle traffic is inevitably located next to some of the most dangerous rock fall hazards. Rock falls could be severe during an earthquake. The only fatality from the 1993 earthquakes resulted from a rock fall striking a moving vehicle.

**Active Fault Displacement.** If fault rupture during an earthquake is large enough, it can propagate to the surface, displacing roads and buildings. Any mapped fault in the area might produce such displacement, as fault activity was



**Figure 5.2.** Contour map of geothermal gradients in the map area at intervals of 50°C/km. Areas with widely spaced well data do not have accurate contours and should be disregarded. Examples are the areas east and west of Miller Hill, the Delap Pit Road-Moore Park area, and Hogback Mountain. White areas have data spaced at such wide intervals that the contouring program did not produce contours. Gradients shown are crude estimates at best; they are calculated by subtracting the regional ambient surface temperature of 10°C (Gerald Black, personal communication, 2002) from the well temperature and dividing by the total depth of the well. Accurate temperature gradients can only be calculated by measuring temperatures at intervals throughout the length of a well.



**Figure 5.3.** Geothermal gradients and faults in the map area. Gradients are contoured at intervals of 50°C/km. Faults may be areas of higher fracturing of rock units, leading to higher permeability and more likelihood of good flow of geothermal fluid. Brittle rock units like lava flows, sandstone, conglomerate, and silicified (quartz-flooded) rocks are more likely to have open fractures that carry water. Hot water is more likely to be found at shallow depth in areas where temperature gradients are high. Good geologic reasoning based on detailed, site-specific geological and geophysical data should be used to infer where and at what depth faults intercept brittle rocks.

hard to determine in most cases. The faults marked in red on the map probably have somewhat higher potential for damaging offsets. In some cases, active faults can displace the surface gradually with little or no earthquake shaking; this process is called fault creep. It is possible that some portion of the ground deformation at Ponderosa Junior High School could be from active fault creep. A review of existing seismic data for microseismicity on the fault projected through the school would be a low-cost first step in

evaluating whether fault creep is occurring. A detailed tectonic analysis of the pattern of ground displacement would also be very useful and relatively inexpensive. If resources are available, active monitoring of seismicity with a local seismograph array could yield valuable information. Monitoring of displacement of the ground (strain measurements) would be a useful addition to monitoring of displacements of the school buildings currently being done by the school district.

**Landslides.** Relatively few landslides were mapped, so landslides are not a major hazard. The few that were mapped are in weathered sedimentary beds of units Tm and Tpt. The small number of landslides is probably a function of the dry climate, but should an earthquake occur during an unusually wet winter when ground water tables are high, landslides could pose a threat. Indeed, there are a few large landslides immediately outside the map area (see Sherrod and Pickthorn, 1992). The small number of landslides in the study area probably indicates that the coincidence of an earthquake with an extremely high water table is a rare event.

**Expansive Soils.** Clay-rich soil derived mainly from sedimentary units Tm, Tms, or Tpt is composed of minerals that swell when wet but shrink when dried. These soils, unless removed or stabilized by engineering techniques, can crack pavement and foundations. Some of the cracking of pavement in the parking lot of the Ponderosa Junior High School could be from expansive soils.

**Subsidence.** Damage can occur when ground water is withdrawn on a large enough scale to cause subsidence. Previously discussed correlation of ground-water changes with deformation of buildings at Ponderosa Junior High School is an example. Reinjection of water such as the hot water used for geothermal heating can reduce or eliminate subsidence.

## 5.5 VOLCANIC HAZARDS

Volcanic activity is concentrated tens of kilometers to the west and northwest in the High Cascades. It is possible that some ash could fall on the area from High Cascades eruptions, but this would likely not be a devastating hazard unless coming from the large volcanic centers at Crater Lake or, possibly, Mount Shasta. Eruption from Crater Lake could cause the caldera lake to be ejected. Should this occur, hot volcanic mudflows of large volume would flow down the sides of the volcano, probably reaching Upper Klamath Lake. Influx of these flows and associated hot air fall ash could degrade the quality of lake and stream water. The shallow depth of the lake would probably render insignificant any tsunami hazard to Klamath Falls from large-scale influx of volcanic mudflows, although temporary flooding of low-lying areas might occur due to displacement of lake water.



## 6.0 ACKNOWLEDGEMENTS

Platt Bradbury of the USGS provided diatom analyses that helped greatly in age assignments of mudstone. Andre M. Sarna-Wojcicki of the USGS provided an important analysis and interpretation of a tephra collected 43 km north of the map area at Collier Grade. Tanya Boyd and John Lund of OIT provided an extensive digital database of geothermal well data for the City of Klamath Falls and Klamath County. The Oregon Department of Transportation allowed use of their facilities in Klamath Falls as a temporary field office and facilitated access to some fenced areas. Mark Dew of Dew Engineering provided valuable information on the ground deformation at the Ponderosa Junior High School. The Klamath County School District allowed access to the Ponderosa Junior High School grounds for geologic mapping. James K. Bryant, Chief of the Water and Lands Division of the U.S. Bureau of Reclamation, Department of the Interior, Klamath Basin Area Office, kindly provided historical photos of the construction of the canal near the Ponderosa Junior High School. Jeld-Wen, Inc. allowed access to their extensive lands in the western part of the area. Numerous other residents and businesses too numerous to mention were also very helpful in providing access to their properties. John D. Beaulieu, Ian P. Madin, Gerald L. Black, and Tomas J. Wiley of the Oregon Department of

Geology and Mineral Industries (DOGAMI) offered review and advice. Mr. Black also helped with some field sampling and offered valuable advice on interpretation of geothermal data. Margaret D. Jenks of DOGAMI facilitated entry into the Ponderosa Junior High School grounds and offered valuable interpretations of the depositional environment of the well-sorted sandstones that characterize the sedimentary rocks of Hogback Mountain and sedimentary rocks of Foothills Drive; she suggested a shallow water lake or lake-shore environment. Neil M. Woller of EVREN Northwest assisted with field mapping for one week. David R. Sherrod of USGS did a very detailed and immensely helpful review of the map and data. Dr. Sherrod also kindly provided copies of his field maps from earlier reconnaissance mapping of the area. Michael Cummings of Portland State University provided valuable discussion of possible depositional regimes for the tuff of Ponderosa Junior High School and suggested a subaqueous mode of eruption. Thomas L.T. Grose of the Department of Geology and Geological Engineering at the Colorado School of Mines provided valuable advice and discussion about the complex faulting in the Link River-Stewart Lennox area. Bill Thompson of Klamath County Emergency Services was helpful at all stages of the project by serving as coordinator with local government.

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## 8.0 APPENDIX A: WATER WELL DATA

Table A1. Water Well Data\*

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)                                | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|--|----------------|----------------|
| 1       | 2214     | 965             | 4                      | 130       | 88          | Qs, 0-12, Tm, 12-951, Tba? or Th   | 121.760214     | 42.200148      |
| 2       | 2491     | 415             | 319                    | 50        | 72          | Qc, 0-3, Tm?, 3-11, Tcba, 11-141, Tm +Tcba, 141-283, Tm, 283-327, Tba?, 327-415            | 121.821261     | 42.269887      |
| 3       | 2502     | 154             | 40                     | 60        | 49          | Tm, 0-17, Tba, 17-19, Tm, 19-54, Ts, 54-130, Tm, 130-153, Tba, 153-154                     | 121.843174     | 42.244447      |
| 4       | 2505     | 240             | 8                      | 30        | 54          | Qs? w. sand + Qc boulders, 0-80, Tm? brown clay, 80-240                                    | 121.833646     | 42.240084      |
| 5       | 2506     | 214             | 12                     | 30        | 53          | Qs organic silt, 0-9, Tm? clay, 9-198, Ts? cem. gravel, 198-214                            | 121.819563     | 42.233082      |
| 6       | 2508     | 235             | 7                      | 30        | 60          | Qs clay + gravel, 0-3, Tm, 3-200, Tba, 200-235   | 121.837086     | 42.241098      |
| 7       | 10014    | 62              | 12                     | 10        | 54          | QTfs?, 0-33, Tms, 33-62  | 121.695993     | 42.186007      |
| 8       | 10019    | 166             | 19                     | 30        | 59          | QTfs, 0-11, Ts, 11-51, Tms, 51-73, Ts, 73-114, Tm, 114-148                                 | 121.688137     | 42.188635      |
| 9       | 10139    | 360             | 65                     | 800       | 80          | QTfs, 0-29, Tms, 29-290, Tba, 290-360  | 121.67398      | 42.196415      |
| 10      | 10179    | 219             | 2                      | 1700      | 68          | Qal, 0-23, Tm, 23-59, Tba, 59--219   | 121.7918       | 42.221796      |
| 11      | 10187    | 501             | 315                    | 30        | 89          | Tm, 0-304, Tba, 304-501  | 121.753877     | 42.242802      |
| 12      | 10200    | 684             | 8                      | 25        | 80          | Qs, 0-2, Tms, 2-13, Tm, 13-118, Tms, 118-147, Tm, 147-550, Tm?, 550-684                    | 121.750174     | 42.200381      |
| 13      | 10232    | 500             | 144                    | 14        | 65          | Tms, 0-208, Tba, 208-249, Tm, 249-500  | 121.749925     | 42.24795       |
| 14      | 10264    | 309             | 125                    | 200       | 70          | Tm, 0-278, Tba, 278-309  | 121.809237     | 42.200126      |
| 15      | 10274    | 59              | 4                      | 12        | 56          | Qs, 0-12, Ts, 12-59  | 121.735395     | 42.134791      |
| 16      | 10302    | 286             | 118                    | 30        | 54          | Tba?, 0-46, Tm, 46-92, Tba?, 92-103, Tms, 103-206, Tba, 206-225, Tm, 225-243, Tba, 243-286 | 121.862835     | 42.163758      |
| 17      | 10350    | 545             | 25                     | 25        | 151         | Qs, 0-.5, Tba? or Thb?, .5-15, Tms, 15-67, Tm, 67-511, Tms, 511-545                        | 121.76664      | 42.222906      |
| 18      | 10367    | 196             | 13                     | 18        | 78          | Qs, 0-3, Tms, 3-118, Ts, 118-124, Tm, 124-168, Ts, 168-181, Tms, 181-196                   | 121.779414     | 42.16366       |
| 19      | 10380    | 430             | 341                    | 0         | 0           | Tms, 0-331, Tba?, 331-341  | 121.754861     | 42.244416      |
| 20      | 10390    | 1675            | 173                    | 1000      | 109         | Tms, 0-210, Hard silicified? Tms?, 210-518, Tba?, 518-995, Tms?, 995-1078, Tba?, 1078-1675 | 121.789173     | 42.254971      |
| 21      | 10419    | 832             | 28                     | 2         | 66          | Qs, 0-3, Tm, 3-568, Ts, 568-576, Tm, 576-832   | 121.706061     | 42.152514      |
| 22      | 10476    | 335             | 296                    | 30        | 63          | Tm, 0-77, Tba, 77-182, Ts, 182-296, Tba, 296-308, Tm, 308-335                              | 121.842946     | 42.196442      |
| 23      | 10581    | 250             | 54                     | 1500      | 64          | Tm, 0-97, Tba, 97-250  | 121.833205     | 42.211261      |
| 24      | 10600    | 225             | 94                     | 60        | 64          | Tm, 0-87, Tba?, 87-225   | 121.823537     | 42.207618      |
| 25      | 10718    | 862             | 25                     | 15        | 60          | QTfs, 0-11, Tms, 11-862  | 121.686056     | 42.17848       |
| 26      | 10719    | 90              | 5                      | 40        | 55          | Qs, 0-3, Tm, 3-8, Ts, 8-42, Tm, 42, 78, Ts, 78-90  | 121.681593     | 42.15649       |
| 27      | 10747    | 781             | 7                      | 900       | 92          | Qs, 0-12, Tm, 12-530, Tba? or Thb?, 530-781  | 121.774589     | 42.215936      |
| 28      | 10750    | 233             | 13                     | 400       | 62          | Tm, 0-63, Ts, 63-90, Tba, 63-233   | 121.779663     | 42.20016       |
| 29      | 10766    | 103             | 25                     | 25        | 58          | Tm, 0-24, Ts, 24-90, Tm, 90-103  | 121.681523     | 42.16723       |
| 30      | 10768    | 850             | 50                     | 220       | 80          | QTfs, 0-24, Tms, 24-730, Tba, 730-850  | 121.666874     | 42.189156      |

Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)   | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|---|----------------|----------------|
| 31      | 10770    | 402             | 36                     | 25        | 64          | QTfs, 0-23; Tm, 23-370, Tg, 370-402   | 121.686131     | 42.193094      |
| 32      | 10782    | 685             | 446                    | 20        | 82          | QTfs, 0-49, Tba?, 49-79, Tm?, 79-89, Ts?, 89-96, Tm?, 96-112, Ts?, 117-129, Tba, 129-190, Tm?, 190-222, Ts?, 222-234, Tm, 234-264, Tba, 264-271, Tm?, 271-322, Ts?, 322-363, Ts?, 363-373, Tm, 373-439, Ts?, 438-462, Tm, 462-572, Tba, 572-633, Tms, 633-685 | 121.721097     | 42.231903      |
| 33      | 10802    | 319             | 89                     | 20        | 66          | Tm, 0-74, Tms?, 74-319  | 121.813807     | 42.193141      |
| 34      | 10809    | 104             | 15                     | 40        | 62          | Qs, 0-3, Tm, 3-69, Ts, 69-83, Tba, 83-104   | 121.814607     | 42.133564      |
| 35      | 10822    | 488             | 80                     | 700       | 79          | Tm, 0-271, Ts, 271-303, Tba, 303-488  | 121.837485     | 42.205592      |
| 36      | 10921    | 575             | 92                     | 750       | 70          | Tms, 0-374, Tba, 374-575  | 121.677549     | 42.200408      |
| 37      | 10961    | 449             | 30                     | 450       | 68          | Mf, 0-5, Tm, 5-193, Ts or Tba?, 193-449   | 121.798473     | 42.183832      |
| 38      | 10966    | 134             | 13                     | 10        | 50          | Qs, 0-4, Tms, 4-134   | 121.784244     | 42.174901      |
| 39      | 11001    | 455             | 335                    | 24        | 77          | Tg, 0-3, Tba, 3-455   | 121.845453     | 42.191015      |
| 40      | 11135    | 555             | 14                     | 20        | 87          | Soil of Ts varying hardness with depth 0-3, Ts, 3-18, Tm, 18-152, Tms, 152-540  | 121.686424     | 42.141949      |
| 41      | 11159    | 454             | 138                    | 250       | 65          | Ts, 0-6, Tba?, 6-8, Ts?, 8-10, Tba?, 10-12, Tms, 12-454   | 121.785486     | 42.206084      |
| 42      | 11223    | 200             | 79                     | 29        | 52          | Tm?, 0-24, Tba, 24-118, Tm, 118-194, Ts, 194-200  | 121.847648     | 42.248036      |
| 43      | 11251    | 150             | 11                     | 300       | 56          | Qc + Qs, 0-8, Tba, 8-150  | 121.84368      | 42.254327      |
| 44      | 11258    | 743             | 390                    | 20        | 74          | QTfs, 0-57, Tm?, 57-79, Ts?, 79-86, Tm?, 86-95, Ts?, 95-147, Tm, 147-166, Ts?, 166-171, Tm, 171-312, Tba, 312-743   | 121.748655     | 42.251627      |
| 45      | 11260    | 70              | 14                     | 20        | 57          | Qac, 0-56, Tm, 56-59, Ts, 59-70   | 121.688911     | 42.169118      |
| 46      | 11266    | 411             | 189                    | 25        | 69          | QTfs, 0-57, Tm, 57-203, Ts, 203-205, Tm, 205-384, Tms, 384-409, Tm, 409-411   | 121.745081     | 42.247918      |
| 47      | 11474    | 964             | 18                     | 30        | 79          | Qs, 0-4, Ts, 4-17, Tm (clay), 17-125, Ts, 125-126, Tm (clay), 126-934, Ts, 934-944, Tm (shale), 944-964   | 121.696076     | 42.163852      |
| 48      | 11544    | 309             | 33                     | 1300      | 59          | Qs, 0-27; QTwb, 27-309  | 121.857944     | 42.239218      |
| 49      | 11630    | 120             | 14                     | 20        | 52          | Qs, 0-6, Tm?, 6-82, Tm? + Tg?, 82-94, Tba?, 94-120  | 121.809015     | 42.273345      |
| 50      | 11631    | 88              | 12                     | 25        | 55          | Qac, 0-3, Tm? + Tg?, 3-50, Tba?, 50-88  | 121.801766     | 42.275056      |
| 51      | 11643    | 610             | 106                    | 1000      | 58          | Tm, 0-12, Tba, 12-610   | 121.7745       | 42.273566      |
| 52      | 11655    | 816             | 105                    | 25        | 0           | Tms, 0-454, Tba?, 454-816   | 121.789471     | 42.258926      |
| 53      | 11657    | 246             | 37                     | 100       | 62          | Qs, 0-20, Tba, 20-169, Tm, 169-234, Tba, 234-246  | 121.811313     | 42.26055       |
| 54      | 11658    | 210             | 143                    | 45        | 56          | Tm + Tg, 0-35, Tm, 35-58, Tba?, 58-68, Tm, 68-85, Tba, 85-210   | 121.803902     | 42.269521      |
| 55      | 11659    | 280             | 97                     | 150       | 64          | Tm, 0-1, Tba, 1-20, Tm, 20-37, Tba, 37-84, Tm, 84-236, Tba, 236-241, Tm, 241-249, Tba, 249-265, Tm, 265-267, Tba, 267-280   | 121.809032     | 42.263357      |
| 56      | 11669    | 170             | 28                     | 15        | 0           | Qac, 0-16, Tm, 16-56, Tba, 56-170   | 121.808739     | 42.269531      |
| 57      | 11671    | 267             | 7                      | 40        | 60          | Mf?, 0-20, Tm, 20-55, Ts, 55-58, Tm, 58-92, Tms, 92-100, Tm, 100-161, Tms, 161-165, Tm, 165-258, Tms, 258-267   | 121.812456     | 42.254871      |
| 58      | 11672    | 349             | 8                      | 20        | 60          | Mf?, 0-15, Tm?, 15-112, Ts, 112-115, Tm, 115-160, Tms, 160-180, Tm, 180-275, Ts, 275-276, Tm, 276-336, Ts + Tg, 336-349   | 121.813831     | 42.251237      |

Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)   | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|---|----------------|----------------|
| 59      | 11674    | 1021            | 9                      | 1700      | 62          | Qs, 0-5, Tm, 5-9, Ts, 9-15, Tm, 15-223, Tba, 223-365, Ts, 365-376, Tm, 376-565, Tba, 565-785, Tm, 785-962, Tba, 962-1021  | 121.804715     | 42.250126      |
| 60      | 11676    | 120             | 27                     | 20        | 0           | Tm, 0-95, Ts, 95-120  | 121.808583     | 42.245209      |
| 61      | 11679    | 188             | 132                    | 2         | 81          | Mf, 0-3, Tm, 3-66; Tms?, 66-188   | 121.750206     | 42.233203      |
| 62      | 11821    | 530             | 462                    | 90        | 0           | Ts, 0-6, Tm, 6-411, Tba, 411-530  | 121.790343     | 42.24426       |
| 63      | 11824    | 929             | 299                    | 30        | 170         | Qac, 0-12, Tm, 12-260, Tba?, 260-312, Tm?, 312-409, Tg?, 409-511, Ts?, 511-549, Tg?, 549-639, Tm?, 639-654, Tg?, 654-663, Ts?, 663-692, Tba?, 692-818, Tg?, 818-929 | 121.778026     | 42.243383      |
| 64      | 11825    | 1205            | 449                    | 500       | 92          | Tba, 0-43, Tg, 56-58, Tm, 58-68, Tba, 68-1205   | 121.779343     | 42.257143      |
| 65      | 11826    | 1288            | 333                    | 105       | 182         | Tms, 0-135, Tba?, 135-191, Tm?, 191-197, Tba?, 197-208, Tm?, 208-238, Tba?, 238-1288  | 121.781216     | 42.253812      |
| 66      | 11828    | 1224            | 315                    | 330       | 87          | Tms, 0-50, Tba?, 50-86, Tms?, 86-157, Tba?, 157-163, Tms?, 163-240, Tba?, 240-1224  | 121.780594     | 42.25572       |
| 67      | 11829    | 1805            | 359                    | 250       | 146         | Tms, 0-278, Tba, 278-305, Tms?, 305-315, Tba?, 315-380, Tms?, 380-472, Tba?, 472-1805   | 121.781716     | 42.252374      |
| 68      | 11829    | 1805            | 146                    | 181       | 0           | Tm, 0-278, Tba, 278-1805  | 121.784548     | 42.244146      |
| 69      | 11830    | 1716            | 358                    | 470       | 194         | Tms, 0-106, Tba?, 106-1700, Ts?, 1700-1716  | 121.780171     | 42.252546      |
| 70      | 11833    | 1584            | 323                    | 400       | 196         | Tms, 0-841, Tba?, 841-1584  | 121.783155     | 42.253619      |
| 71      | 11836    | 314             | 86                     | 250       | 74          | Tms, 0-314  | 121.784762     | 42.251068      |
| 72      | 11837    | 371             | 234                    | 125       | 97          | Tms, 0-332, Tba?, 332-371   | 121.785381     | 42.251178      |
| 73      | 11844    | 500             | 34                     | 35        | 71          | Tm, 0-226, Ts?, 226-500   | 121.759533     | 42.248352      |
| 74      | 11848    | 0               | 0                      | 0         | 0           | QTfs (gravel facies), 0-58, QTfs (mudstone +sand), 58-96  | 121.740124     | 42.251533      |
| 75      | 11855    | 696             | 385                    | 60        | 79          | QTfs, 0-130, Tms, 130-394, Ts?, 394-393, Tm?, 398-583, Tba? or Thb?, 583-696  | 121.74021      | 42.247865      |
| 76      | 11863    | 374             | 196                    | 30        | 91          | Tm, 0-108, Tba? or Thb?, 108-374  | 121.754992     | 42.236851      |
| 77      | 11868    | 243             | 149                    | 0         | 196         | Qc, 0-5; Tba, 5-8, Tms, 8-145, Tba, 145-243   | 121.774617     | 42.240295      |
| 78      | 12019    | 400             | 0                      | 50        | 0           | no record, 0-150, Tms?, 150-378, no record, 378-400   | 121.768547     | 42.228907      |
| 79      | 12021    | 300             | 0                      | 300       | 198         | Qac, 0-14, Tm, 14-40, Tg, 40-43, Tm, 43-137, Tms?, 137-245, Tba?, 245-250, Tm, 250-300  | 121.77023      | 42.228975      |
| 80      | 12042    | 250             | 15                     | 0         | 198         | Qc, 0-2; Tm, 2-34, Tba, 34-250  | 121.76729      | 42.234916      |
| 81      | 12046    | 240             | -1                     | 350       | 0           | 0-223, no data, Tba (hot aquifer), 223-228, no data, 228-240  | 121.778864     | 42.229771      |
| 82      | 12047    | 455             | 0                      | 0         | 217         | Qc, 0-10, Tba, 10-255, Tm, 255-385, Tba:385-456   | 121.772026     | 42.238505      |
| 83      | 12050    | 900             | 60                     | 0         | 0           | Tm, 0-108, Tba, 108-138, Tm, 138-226, Tba, 226-360, Tm, 360-465, Tba, 465-565, Tg?, 565-640, Tba, 640-900   | 121.765007     | 42.230245      |
| 84      | 12051    | 364             | 60                     | 280       | 0           | Tm, 0-325, Tba, 325-364   | 121.769875     | 42.22952       |
| 85      | 12062    | 193             | 85                     | 0         | 220         | Tm, 0-136, Tba, 136-193   | 121.765972     | 42.23135       |
| 86      | 12066    | 448             | 65                     | 0         | 180         | Tm, 0-92, Tba, 92-448   | 121.774612     | 42.236772      |
| 87      | 12073    | 600             | 140                    | 60        | 208         | Qc, 0-5, Tm, 5-68, Tba, 68-600  | 121.778075     | 42.237892      |
| 88      | 12076    | 840             | 8                      | 0         | 130         | Qac, 0-5, Tm, 5-77, Tba, 77-145, Tm, 145-160, Tba, 160-215, Tm, 215-314, Tba, 314-336, Tm, 336-384, Tba, 384-429, Tm, 429-814, Tba, 814-840                         | 121.779965     | 42.229261      |



Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)   | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|---|----------------|----------------|
| 89      | 12082    | 170             | 0                      | 0         | 208         | Qc, 0-9, Tm, 9-117, Tba, 117-170  | 121.777125     | 42.239757      |
| 90      | 12084    | 272             | 0                      | 0         | 0           | Mf + Qac + Tm, 0-30, Tba, 30-80, Tm, 80-215, Tba, 215-272   | 121.778604     | 42.233156      |
| 91      | 12085    | 625             | 80                     | 0         | 0           | Qc boulders, 0-20, Tm?, 20-170, Tba, 170-625  | 121.789478     | 42.240159      |
| 92      | 12086    | 330             | 0                      | 0         | 202         | no data, 0-242, Tba, 242-330  | 121.779229     | 42.234341      |
| 93      | 12098    | 187             | 160                    | 75        | 0           | Qal boulders, 0-15, Tba, 15-40, Tm, 40-170, Tba, 170-187  | 121.793623     | 42.223308      |
| 94      | 12101    | 263             | 0                      | 65        | 72          | Qs, 0-4, Tm, 4-79, Tba, 79-263  | 121.782099     | 42.223523      |
| 95      | 12102    | 627             | -1                     | 4200      | 70          | Qal, 0-56, Tba, 56-278, Tm?, 278-417, Tba, 417-452, Tm, 452-520, Tba, 520-553, Tm, 553-556, Tba, 556-627  | 121.791353     | 42.221589      |
| 96      | 12111    | 35              | 4                      | 10        | 58          | Qal, 0-14, Tm, 14-26, Ts, 26-35   | 121.79116      | 42.219214      |
| 97      | 12115    | 125             | 5                      | 210       | 71          | Qal boulders, 0-10, Tba, 28-125   | 121.792221     | 42.222337      |
| 98      | 12116    | 155             | 16                     | 15        | 64          | Qs, 0-3, Tm, 3-40, Tba, 40-155  | 121.784727     | 42.22353       |
| 99      | 12117    | 500             | 156                    | 30        | 68          | Tba, 0-500  | 121.789476     | 42.221954      |
| 100     | 12118    | 1069            | 8                      | 275       | 74          | Tm, 0-310, Tba, 310-425, Tm, 425-551, Tba?, 551-692, Tm, 692-874, Tba?, 874-914, Tm, 914-941, Tba?, 941-949, Tm, 949-1053, Tba?, 1053-1069  | 121.778293     | 42.21773       |
| 101     | 12121    | 435             | 0                      | 4600      | 68          | Qal boulders, 0-100, Tba, 100-227, Tm, 227-331, Tba, 331-435  | 121.791949     | 42.222114      |
| 102     | 12129    | 406             | 25                     | 0         | 230         | Tm, 0-269, Tba? or Thb?, 269-406.5  | 121.760131     | 42.225703      |
| 103     | 12131    | 679             | 0                      | 50        | 176         | Qs, 0-5, Tm, 5-15, Tba? or Thb?, 12-20, Tms, 20-70, Tba? or Thb?, 70-85   | 121.764977     | 42.223939      |
| 104     | 12137    | 710             | 35                     | 50        | 200         | Qac, 0-5, Tm, 5-174, Tba, 174-180, Tm?, 180-302, Tba, 302-307, Tm, 307-312, Tba, 312-314, Tm, 314-337, Tba?, 337-340, Tm, 340-412, Tba, 412-511, Tm, 511-554, Tba, 554-555, Tm, 555-640, Tba, 640-643, Tm, 643-661, Tba, 661-663, Tm, 663-672, Tba, 672-675       | 121.768783     | 42.228094      |
| 105     | 12138    | 367             | 30                     | 80        | 200         | Tm, 0-140, Tms, 140-155, Tm, 155-246, Tba? or Thb?, 246-275, Tm?, 275-305, Tba? or Thb?, 305-318, Tm?, 318-331, Tba? or Thb?, 331-349, Tm, 349-367  | 121.762256     | 42.226379      |
| 106     | 12141    | 545             | 8                      | 10        | 0           | no record, 0-480, Tba? or Thb?, 480-545   | 121.768077     | 42.226621      |
| 107     | 12143    | 800             | 0                      | 250       | 192         | Tm, 0-142, Ts, 142-147, Tm, 147-437, Tg, 437-438, Tm?, 438-458, Tba, 458-505, Tm, 505-545, Tba, 545-553, Tm, 553-654, Tba, 654-668, Tg, 668-670, Tm, 670-684, Tba? or Thb?, 684-699, Tm, 699-712, Tba? or Thb?, 712-800, D/T, 425/140, 500/154, 550/165, 575/155, | 121.766391     | 42.224387      |
| 108     | 12147    | 545             | 40                     | 10        | 152         | Tm?, 0-425, Tba? or Thb?, 425-545   | 121.757547     | 42.223092      |
| 109     | 12149    | 1220            | 7                      | 75        | 130         | Tm, 0-858, Tba? or Thb?, 858-874, Tm, 874-909, Tba? or Thb?, 909-935, Tm, 935-961, Tba? or Thb?, 961-1035, Tm, 1035-1051, Tba? or Thb?, 1051-1128, Tm, 1128-1169, Tba?, 1169-1173, Tm, 1173-1187, Tms, 1187-1220  | 121.754859     | 42.225788      |
| 110     | 12155    | 1400            | 8                      | 175       | 127         | Qs, 0-4, Tms, 4-1173, Tba? or Thb?, 1173-1400   | 121.757525     | 42.214638      |
| 111     | 12162    | 1401            | 366                    | 760       | 151         | Tm, 0-850, Tba? or Thb?, 850-1401   | 121.747765     | 42.223427      |

Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)  | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|--|----------------|----------------|
| 112     | 12164    | 1529            | 42                     | 430       | 160         | Tm, 0-1254, Tba? Thb? Ts?, 1254-1303, Tba? or Thb?, 1303-1409, Tm, 1408-1421, Tba? or Thb?, 1421-1439, Tm, 1439-1479, Tba? or Thb?, 1479-1490, Tm, 1490-1494, Tba?-1494-1529           | 121.739292     | 42.217966      |
| 113     | 12167    | 530             | 135                    | 750       | 0           | QTfs, 0-28, Tms, 28-530  | 121.723098     | 42.215882      |
| 114     | 12182    | 970             | 0                      | 225       | 75          | Qc, 0-8, Ts, 8-150, Tba, 150-246, Tm, 246-276, Tba?, 276-389, Tm, 389-627, Tba, 627-710, Tm, 710-813, Tba, 813-970   | 121.705265     | 42.217032      |
| 115     | 12183    | 1100            | 354                    | 100       | 80          | Qc, 0-23, Ts (weathered), 23-100, Ts (hard), 100-108, Tba, 108-168, Ts?, 168-204, Tba, 204-244, Tm?, 244-740, Tms?, 740-905, Tba?, 905-945, Tm, 935-980, Tba, 980-1040, Tba, 1070-1100 | 121.705253     | 42.216785      |
| 116     | 12185    | 580             | 150                    | 225       | 58          | Qac, 0-21, QTfs, 21-81, Tba?, 81-85, Ts?, 85-145, Tba?, 145-151, Ts?, 151-220, Tm, 220-330, Tg, 330-331, Tms, 331-388, Tba? or Thb?, 388-406, Tm, 406-503, Tg, 503-506, Tms, 503-580   | 121.710252     | 42.217563      |
| 117     | 12487    | 1000            | 230                    | 710       | 69          | QTfs, 0-28, Tm, 28-76, Ts, 76-92, Tm, 92-230, Tg, 239-276, Ts, 276-390, Tm, 390-980, Tba? or Thb?, 980-1000  | 121.705145     | 42.207744      |
| 118     | 12495    | 1562            | 0                      | 450       | 0           | QTfs, 0-20, Ts?, 20-145, Tm, 145-200, Tg +Tm?, 200-305, Tba? or Thb?, 305-310, Tm, 310-500, Ts, 500-520, Tm, 520-1190, Tba? or Thb?, 1190-1562   | 121.707689     | 42.20987       |
| 119     | 12518    | 300             | 10                     | 5         | 56          | Qac, 0-4, Tms, 6-300   | 121.738175     | 42.200511      |
| 120     | 12520    | 1520            | -1                     | 320       | 114         | Qs, 0-8, Tms, 8-1040, Tba? or Thb?, 1040-1158, Tm, 1158-1520   | 121.759237     | 42.208775      |
| 121     | 12537    | 438             | 113                    | 350       | 72          | Tbv, 0-85, Tba, 85-126, Tms, 126-171, Ts?, 171-407, Tba?, 407-438  | 121.807965     | 42.191755      |
| 122     | 12548    | 131             | 100                    | 18        | 0           | Tms, 0-101, Tba, 101-131   | 121.803969     | 42.193043      |
| 123     | 12563    | 265             | 84                     | 663       | 75          | Ta?, 0-16, Ts, 16-68, Tba, 68-113, Ts?, 113-124, Tba, 124-265  | 121.793044     | 42.190282      |
| 124     | 12578    | 200             | 5                      | 15        | 56          | Qs, 0-1.3, Tm, 1.3-200   | 121.749741     | 42.195103      |
| 125     | 12579    | 667             | 5                      | 10        | 66          | Qs, 0-2, Tm, 2-380, Tms, 380-390, Tm, 390-667  | 121.749709     | 42.199223      |
| 126     | 12580    | 1210            | 16                     | 450       | 136         | Mf, 0-6, Tm, 6-780, Tg?, 780-782, Tm, 782-1098, Tba? or Thb?, 1098-1210  | 121.732954     | 42.197921      |
| 127     | 12588    | 110             | 25                     | 35        | 52          | QTfs?, 0-13, Tms, 13-110   | 121.702823     | 42.187748      |
| 128     | 12595    | 138             | 5                      | 20        | 53          | QTfs?, 0-3, Tms, 3-31, Tm, 31-125, Tms, 125-138  | 121.699363     | 42.191324      |
| 129     | 12601    | 95              | 13                     | 8         | 50          | Qs, 0-3, Tm, 3-95  | 121.708136     | 42.176465      |
| 130     | 12602    | 260             | 18                     | 0         | 0           | QTfs, 0-14, Ts, 14-20, Tm, 20-32, Ts, 32-40, Tm, 40-43, Ts, 43-65, Tg?, 65-87, Ts, 87-188, Tms, 188-205, Tg?, 205-210, Ts?, 210-252, Tm?, 252-260                                      | 121.699028     | 42.183757      |
| 131     | 12605    | 817             | 0                      | 100       | 0           | Tm, 0-75, Tba?, 75-817   | 121.818504     | 42.174128      |
| 132     | 12607    | 434             | 4                      | 9         | 60          | Qs, 0-4, Tms, 4-423  | 121.700974     | 42.171094      |
| 133     | 12609    | 155             | 42                     | 60        | 82          | Qs, 0-4, Tm, 4-9, Tba, 9-155   | 121.725588     | 42.175549      |
| 134     | 12616    | 122             | 4                      | 3         | 0           | Qs, 0-4, Tm, 4-122   | 121.725102     | 42.182053      |
| 135     | 12617    | 150             | 24                     | 8         | 58          | Tm, 0-150  | 121.73001      | 42.182161      |
| 136     | 12618    | 300             | 5                      | 10        | 54          | Qs, 0-3, Tm, 3-300   | 121.734781     | 42.182002      |

Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)  | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|--|----------------|----------------|
| 137     | 12619    | 640             | 0                      | 50        | 0           | Qs, 0-4, Tm, 4-640   | 121.723608     | 42.178491      |
| 138     | 12620    | 78              | 11                     | 30        | 72          | Tms, 3-31, Tba, 31-78  | 121.734921     | 42.174964      |
| 139     | 12622    | 215             | 5                      | 8         | 0           | Qs, 0-4, Tm, 4-215   | 121.72048      | 42.171258      |
| 140     | 12632    | 435             | 4                      | 75        | 70          | Qs, 0-15, Tm, 15-435   | 121.764523     | 42.178542      |
| 141     | 12633    | 200             | 10                     | 8         | 58          | No record, 0-23, Tm, 23-200  | 121.771704     | 42.180395      |
| 142     | 12635    | 40              | 8                      | 50        | 60          | Qs, 0-7, Tm, 7-40  | 121.774065     | 42.182258      |
| 143     | 12636    | 615             | 8                      | 0         | 0           | Qs, 0-6, Tm, 6-611, Tba, 611-615   | 121.77421      | 42.178639      |
| 144     | 12639    | 80              | 20                     | 20        | 58          | Qs, 0-16, Tm, 16-80  | 121.786973     | 42.176796      |
| 145     | 12640    | 190             | 18                     | 40        | 86          | Qs, 0-14, Tm, 14-196   | 121.794067     | 42.171506      |
| 146     | 12642    | 332             | 15                     | 5         | 0           | no record  | 121.794003     | 42.17492       |
| 147     | 12645    | 125             | 43                     | 40        | 0           | Tm, 0-58, Tba, 58-125  | 121.799007     | 42.181881      |
| 148     | 12653    | 545             | 94                     | 1225      | 0           | Tms, 0-65, Tba, 65-524   | 121.813673     | 42.174881      |
| 149     | 12657    | 92              | 13                     | 10        | 61          | Qs, 0-6, Tms, 6-92   | 121.789063     | 42.156453      |
| 150     | 12661    | 335             | 17                     | 60        | 66          | Qs, 0-12, Tm, 12-335   | 121.779552     | 42.156507      |
| 151     | 12667    | 105             | 4                      | 15        | 67          | Qs, 0-15, Tms, 15-105  | 121.769343     | 42.1822        |
| 152     | 12668    | 146             | 39                     | 20        | 49          | Qs, 0-1, Tm, 1-131, Ts, 131-139, Tm, 139-146   | 121.784358     | 42.156558      |
| 153     | 12670    | 329             | 12                     | 20        | 0           | QTfs, 0-3, Tm, 3-329   | 121.774739     | 42.156767      |
| 154     | 12678    | 200             | 7                      | 20        | 60          | No record, 0-55, Tm, 55-200  | 121.767321     | 42.162053      |
| 155     | 12683    | 300             | 12                     | 10        | 0           | Tm, 0-300  | 121.774344     | 42.167453      |
| 156     | 12690    | 554             | 16                     | 40        | 0           | Qs, 0-4, Tm, 4-520, Tba?, 520-554  | 121.774601     | 42.16392       |
| 157     | 12705    | 1388            | 6                      | 0         | 85          | Qs, 0-3, Tms, 3-1368; Tba, 1368-1388   | 121.732614     | 42.165782      |
| 158     | 12710    | 500             | 9                      | 3         | 54          | Qs, 0-10, Tm, 10-500   | 121.725624     | 42.156621      |
| 159     | 12719    | 425             | 10                     | 5         | 60          | Qs, 0-3, Tm, 3-425   | 121.712923     | 42.168474      |
| 160     | 12724    | 45              | 4                      | 50        | 53          | Qs, 0-3, Ts+Tg, 3-12, Tm, 12-17, Ts, 17-18, Tm, 18-35, Ts+Tg, 35-45                                | 121.70122      | 42.149038      |
| 161     | 12727    | 102             | 15                     | 30        | 53          | Qs, 0-1, Tm, 1-8, Tms, 8-15, Tm, 15-19, Ts, 19-74, Tm, 74-81, Ts, 81-95, Tg?, 95-101, Tms, 101-102 | 121.698829     | 42.142252      |
| 162     | 12730    | 52              | 6                      | 25        | 58          | Qs, 0-2, Tms, 2-52   | 121.710867     | 42.152568      |
| 163     | 12737    | 135             | 18                     | 1         | 0           | Ts, 2-6, Tm, 6-21, Tg, 21-22, Tm, 22-135   | 121.708362     | 42.147253      |
| 164     | 12739    | 127             | 10                     | 30        | 56          | Qs, 0-10, Tm, 10-120, Ts, 120-127  | 121.752277     | 42.151082      |
| 165     | 12747    | 500             | 133                    | 295       | 86          | Tm, 0-52, Tba, 52-500  | 121.767294     | 42.147279      |
| 166     | 12748    | 298             | 165                    | 0         | 216         | Ts, 108-161, Tba, 161-298  | 121.768584     | 42.233235      |
| 167     | 12757    | 62              | 6                      | 10        | 0           | Ts, 3-17, Tm, 17-45, Ts?Tba?, 45-62  | 121.708153     | 42.161951      |
| 168     | 12758    | 65              | 4                      | 15        | 0           | Qs, 0-3, Ts, 3-15, Tm, 15-41, Ts, 41-61, Tm, 61-65   | 121.786627     | 42.147174      |
| 169     | 12759    | 173             | 60                     | 35        | 58          | Qs, 0-2, Tm, 2-24, Ts, 24-40, Tm, 40-50, Ts, 60-79, Tm, 79-160, Ts, 160-173                        | 121.784502     | 42.149017      |
| 170     | 12768    | 340             | 25                     | 90        | 62          | Qal, 0-6, Tm, 6-340  | 121.808534     | 42.149043      |
| 171     | 12772    | 375             | 3                      | 25        | 0           | Tm, 0-355, Tba, 355-365, Tm, 365-375   | 121.813808     | 42.141924      |
| 172     | 12773    | 80              | 32                     | 25        | 55          | Tm, 0-34, Tba, 34-80   | 121.813917     | 42.127331      |
| 173     | 12781    | 80              | 20                     | 15        | 56          | Qs, 0-4, Tm, 4-73, Tms, 73-80  | 121.808821     | 42.130832      |
| 174     | 12784    | 177             | 12                     | 20        | 0           | Qs, 0-10, Tm, 10-162, Tba, 162-177   | 121.813423     | 42.130943      |



Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)  | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|--|----------------|----------------|
| 175     | 12785    | 93              | 1                      | 20        | 55          | Qs, 0-2, Tg, 2-6, Ts, 6-16, Tms, 16-93   | 121.794316     | 42.127426      |
| 176     | 12793    | 110             | 5                      | 20        | 58          | Tms, 0-110   | 121.774747     | 42.134684      |
| 177     | 12795    | 61              | 15                     | 35        | 62          | QTfs?, 0-3, Tm, 3-50, Tba, 50-61   | 121.745255     | 42.130944      |
| 178     | 12805    | 105             | 18                     | 40        | 0           | Qs, 0-4, Tms, 4-105  | 121.755244     | 42.127631      |
| 179     | 12813    | 500             | 135                    | 240       | 88          | Tm, 0-52, Tba, 52-500  | 121.754896     | 42.134781      |
| 180     | 12816    | 161             | 7                      | 20        | 54          | Qs, 0-13, Tm, 13-60, Ts (loose), 60-161  | 121.730673     | 42.131246      |
| 181     | 12817    | 57              | 4                      | 30        | 0           | Qs, 0-3, Ts, 3-10, Tm, 10-16, Tms, 10-38, Ts + Tg, 38-52, Tm, 52-57  | 121.728192     | 42.132965      |
| 182     | 12821    | 1050            | 29                     | 85        | 98          | Qs, 0-2.6, Ts (hardened), 2.6-7, Tm, 7-86, Tms, 86-305, Ts (loose, fine), 305-380, Tm (hardened), 380-1015, Tba, 1015-127, Tm, 1027-1035, Ts+Tg, 1035-1050 | 121.750233     | 42.127499      |
| 183     | 12825    | 49              | 6                      | 15        | 0           | Qs, 0-2, Tm, 2-49  | 121.715556     | 42.127349      |
| 184     | 12827    | 64              | 6                      | 30        | 54          | Qs, 0-5, Ts (loose), 5-30, Tm, 30-40, Ts (loose), 40-64  | 121.703606     | 42.129122      |
| 185     | 12843    | 227             | 56                     | 60        | 74          | Tms, 0-202; Tba, 202-227   | 121.678386     | 42.199786      |
| 186     | 12856    | 460             | 230                    | 350       | 72          | QTfs, 0-36, Tba, 36-42, Tm, 42-58, Tba, 58-61, Tm, 61-90, Tba, 90-93, Tm, 93-138, Ts, 138-156, Tm, 156-341, Tba, 341-349, Tm, 349-369, Tba, 369-460        | 121.698015     | 42.206521      |
| 187     | 12860    | 333             | 150                    | 0         | 63          | no data  | 121.691262     | 42.201538      |
| 188     | 12861    | 312             | 55                     | 20        | 0           | QTfs, 0-14, Tm, 14-275, Tba, 275-312   | 121.693479     | 42.187821      |
| 189     | 12864    | 338             | 20                     | 10        | 69          | Qac, 0-3, Tms, 3-338   | 121.686149     | 42.189503      |
| 190     | 12872    | 123             | 20                     | 18        | 55          | QTfs, 0-48, Tms, 48-123  | 121.688526     | 42.191326      |
| 191     | 12879    | 287             | 30                     | 20        | 64          | QTfs, 0-14, Tm, 14-185, Ts, 185-186, Tm, 186-244, Ts (hard), 244-276, Tba, 276-287   | 121.691039     | 42.185997      |
| 192     | 12886    | 720             | 87                     | 42        | 82          | QTfs, 0-15, Tms, 15-692, Tba, 692-720  | 121.67072      | 42.19912       |
| 193     | 12892    | 1080            | 62                     | 75        | 86          | no data, 0-590, Tm, 590-1036, Ts, 1036-1038, Tm, 1038-1046, Tba, 1046-1080   | 121.664356     | 42.188706      |
| 194     | 12893    | 285             | 40                     | 75        | 0           | no data  | 121.661021     | 42.190162      |
| 195     | 12944    | 406             | 43                     | 420       | 72          | Qc, 0-3, QTfs, 3-38, Tm, 38-353, Tms, 353-378, Tba, 378-406  | 121.679633     | 42.199057      |
| 196     | 12944    | 406             | 43                     | 420       | 72          | Qc, 0-3, QTfs, 3-38, Tm, 38-353, Tms, 353-378, Tba, 378-406  | 121.676342     | 42.196697      |
| 197     | 12997    | 503             | 115                    | 35        | 56          | QTfs, 0-7, Tm, 7-480, Tms, 480-503   | 121.649757     | 42.191219      |
| 198     | 12998    | 1090            | 91                     | 75        | 69          | QTfs, 0-6, Tm, 6-299, Tms, 299-307, Tm, 307-847, Ts, 857-860, Tm, 860-931, Tms, 931-938, Tm, 938-1050, Ts? Tba?, 1050-1090                                 | 121.656914     | 42.185859      |
| 199     | 13033    | 978             | 128                    | 14        | 54          | QTfs?, 0-39, Tm, 39-875, Tms, 875-978  | 121.653484     | 42.19588       |
| 200     | 13035    | 237             | 150                    | 40        | 57          | QTfs?, 0-36, Tm?, 36-105, Tms?, 105-127, Tm, 127-135, Tm?, 135-144, Tm, 144-158, Tba, 158-237  | 121.644735     | 42.194745      |
| 201     | 13062    | 451             | 128                    | 16        | 56          | Qc, 0-2, Tm, 2-330, Tms, 330-416, Tba, 416-451   | 121.648069     | 42.196537      |
| 202     | 13076    | 53              | 21                     | 7         | 54          | QTfs, 0-53   | 121.644925     | 42.18751       |
| 203     | 13085    | 850             | 281                    | 30        | 69          | Qc, 0-18, Tba, 18-28m Tm, 28-34, Tba, 34-92, Ts?, 92-150, Tms?, 150-166, Tba, 166-188, Tms?, 188-198, Tba, 198-210, Tms, 210-275, Tm, 275-850              | 121.63478      | 42.185675      |
| 204     | 13122    | 200             | 6                      | 50        | 56          | Qac, 0-13, Tm, 13-18, Ts, 18-200   | 121.671647     | 42.174832      |

Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)  | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|--|----------------|----------------|
| 205     | 13129    | 198             | 7                      | 35        | 62          | Qac, 0-15, Ts?, 15-130, Tm, 130-180, Tms, 180-195, Ts, 195-198   | 121.664367     | 42.172921      |
| 206     | 13136    | 453             | 43                     | 15        | 64          | QTfs, 0-17, Tms, 17-453  | 121.68129      | 42.178379      |
| 207     | 13139    | 319             | 10                     | 4         | 54          | QTfs, 0-4, Tm, 4-35, Ts, 35-52, Tms, 52-73, Tm, 73-319   | 121.691008     | 42.17849       |
| 208     | 13143    | 142             | 38                     | 45        | 55          | Mf, 0-2, Ts, 2-142   | 121.690871     | 42.182173      |
| 209     | 13148    | 300             | 0                      | 0         | 0           | Qac, 0-4, Tms, 4-21, Tm, 21-300 (dry hole so no water data)  | 121.686192     | 42.174889      |
| 210     | 13149    | 167             | 55                     | 12        | 0           | QTfs, 0-36, Tm, 36-50, Ts, 50-120, Tm, 120-150, Ts, 150-167  | 121.681211     | 42.1822        |
| 211     | 13153    | 102             | 23                     | 300       | 0           | QTfs, 0-27, Tg, 27-79, Tg + Ts, 79-102   | 121.696754     | 42.182414      |
| 212     | 13155    | 170             | 35                     | 1000      | 56          | QTfs, 0-23, Tms, 23-92, Tg, 92-97, Ts, 97-102, Ts + Tg, 97-170   | 121.696046     | 42.183312      |
| 213     | 13161    | 71              | 3                      | 20        | 54          | Qs, 0-2, Tm, 2-7, Ts, 7-12, Tm, 12-18, Ts, 18-44, Tm, 44-60, Ts, 60-71   | 121.68393      | 42.15825       |
| 214     | 13173    | 505             | 18                     | 10        | 61          | Qs, 0-2, Tms, 2-505  | 121.69593      | 42.167444      |
| 215     | 13224    | 114             | 6                      | 20        | 54          | Qs, 0-3, Tm, 3-7, Ts, 7-45, Tm, 45-55, Ts, 55-65, Tm, 65-114   | 121.693714     | 42.158362      |
| 216     | 13225    | 175             | 35                     | 3         | 0           | Ts, 3-8, Tm, 8-175   | 121.69618      | 42.160411      |
| 217     | 13232    | 63              | 18                     | 25        | 53          | Tm, 0-11, Ts, 11-63  | 121.67717      | 42.167659      |
| 218     | 13245    | 305             | 12                     | 25        | 63          | Qs, 0-2, Tm, 2-220, Tms, 220-225, Tm, 225-290, Ts?, 290-305  | 121.64967      | 42.162066      |
| 219     | 13246    | 87              | 10                     | 40        | 52          | Qs-0-4, Tms, 4-65, Ts, 65-70, Tm, 70-78, Tg, 78-80, Tm, 80-87  | 121.656796     | 42.156593      |
| 220     | 13248    | 344             | 9                      | 188       | 66          | Qs, 0-2, Tm, 2-315, Ts?, 315-344   | 121.644808     | 42.158333      |
| 221     | 13270    | 206             | 16                     | 75        | 60          | Qs, 0-2, Tms, 2-32, Tm, 32-37, Tms, 37-90, Tm, 90-206  | 121.632213     | 42.152771      |
| 222     | 13272    | 206             | 17                     | 35        | 59          | Qs, 0-2, Tm, 2-23, Ts, 23-31, Tms, 31-39, Tm, 39-50, Tms, 50-65, Tm, 65-206  | 121.642239     | 42.149085      |
| 223     | 13283    | 350             | -1                     | 25        | 0           | Tm, 0-348, Tba, 348-350  | 121.643785     | 42.144028      |
| 224     | 13290    | 1210            | -1                     | 45        | 84          | Qac, 0-5, Tm, 5-1135, Tba, 1135-1210   | 121.665984     | 42.141032      |
| 225     | 13293    | 88              | 5                      | 20        | 52          | Qs, 0-1, Tm, 1-8, Tg, 8-12, Tms, 12-18, Tg, 18-43, Tm, 43-58, Ts, 58-62, Tm, 62, 70, Tms, 70-78, Ts, 78-88                 | 121.661665     | 42.149125      |
| 226     | 13295    | 112             | 16                     | 100       | 61          | Qs, 0-2, Tms, 2-112  | 121.695827     | 42.141979      |
| 227     | 13296    | 1506            | 2                      | 1000      | 128         | Qs, 0-4.5, Tm, 4.5-392, Ts, 392-432, Tm, 432-479, Ts, 479-491, Tm, 491-1116, Tba, 1116-1207, Tm, 1207-1220, Tba, 1220-1506 | 121.691304     | 42.151048      |
| 228     | 13298    | 845             | 31                     | 100       | 72          | Qs, 0-1, Ts, 1-9, Tm, 9-385, Ts, 385-388, Tm, 388-840, Ts, 840-845   | 121.681388     | 42.14909       |
| 229     | 13315    | 916             | 58                     | 875       | 81          | QTfs?, 0-24, Tm, 24-841, Tba, 841-916  | 121.665972     | 42.138345      |
| 230     | 13317    | 1185            | -1                     | 60        | 96          | no data, 0-720, Tm, 720-1070, Ts, 1060-1062, Tm, 1062-1090, Ts, 1090-1092, Tm?, 1092-1114, Tba, 1114-1185                  | 121.674161     | 42.140211      |
| 231     | 14060    | 540             | 81                     | 1800      | 0           | Qac, 0-2, Tba, 2-14, Tms?, 14-149, Tba, 149-286, Tm?, 286-428, Tba, 428-540  | 121.830589     | 42.206573      |
| 232     | 14086    | 242             | 44                     | 40        | 66          | Tm, 0-208, Tba, 208-242  | 121.833404     | 42.204026      |
| 233     | 14093    | 225             | 38                     | 40        | 63          | Tm, 0-155, Tba, 155-225  | 121.818839     | 42.203828      |

Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)  | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|--|----------------|----------------|
| 234     | 14103    | 150             | 43                     | 10        | 66          | Tm, 0-102, Tba, 102-150  | 121.818972     | 42.200235      |
| 235     | 14138    | 360             | 260                    | 40        | 72          | Tg, 0-10, Tba?, 10-20, Ts?, 20-46, Tba?, 46-69, Tm?, 46-127, Tms?, 127-211, Tba?, 211-360  | 121.847971     | 42.189381      |
| 236     | 14139    | 765             | 343                    | 500       | 80          | Tba, 0-765   | 121.850863     | 42.195213      |
| 237     | 14141    | 380             | 53                     | 730       | 74          | Qac, 0-5, Tba, 5-61, Tms, 61-248, Tba, 248-380   | 121.818602     | 42.198537      |
| 238     | 14148    | 145             | 23                     | 38        | 66          | Tm, 0-74, Tba, 74-145  | 121.83321      | 42.196589      |
| 239     | 14161    | 155             | 50                     | 20        | 57          | Tms, 0-155   | 121.819606     | 42.190792      |
| 240     | 14168    | 286             | 37                     | 200       | 72          | Tm, 0-23, Ts, 23-101, Tms, 101-186, Tba, 186-286   | 121.828311     | 42.192945      |
| 241     | 14182    | 133             | 16                     | 18        | 59          | Tm, 0-30, Tba, 30-76, Tms, 76-110, Tba, 110-133  | 121.832946     | 42.182049      |
| 242     | 14183    | 203             | 88                     | 30        | 70          | Qac, 0-3, Tba, 3-203   | 121.823446     | 42.178362      |
| 243     | 14184    | 366             | 2                      | 700       | 68          | Qs, 0-35, Ts, 35-95, Tm?, 95-224, Tba, 224-395   | 121.83423      | 42.172187      |
| 244     | 14186    | 165             | 48                     | 24        | 60          | Qc, 0-8, Tm, 8-135, Ts, 135-160, Tm, 160-168   | 121.816755     | 42.177762      |
| 245     | 14187    | 110             | 90                     | 100       | 0           | Qc, 0-14, Tm, 14-27, Tms, 14-52, Tbv, 52-103, Tba, 103-110   | 121.820897     | 42.180157      |
| 246     | 14188    | 817             | 28                     | 100       | 0           | Tm, 0-140, Tba, 140-817  | 121.818924     | 42.17461       |
| 247     | 14197    | 400             | 250                    | 35        | 68          | Qc, 0-5, Tm?, 5-36, Tba?, 36-400   | 121.852879     | 42.174693      |
| 248     | 14202    | 229             | 24                     | 150       | 63          | Tm, 0-143, Ts, 143-165, Tg, 165-171, Ts?, 171-212, Tm, 212-218, Ts, 218-222, Tm, 222-229   | 121.840515     | 42.171216      |
| 249     | 14211    | 135             | 52                     | 20        | 64          | Tm, 0-25, Tg, 25-45, Tm, 45-63, Tg, 63-88, Tm, 88-118, Tg, 118-125, Tba?, 125-135  | 121.844168     | 42.177313      |
| 250     | 14236    | 126             | 45                     | 19        | 0           | Ts, 0-6, Tm, 6-85, Tg, 85-105, Tm, 105-126   | 121.845343     | 42.176204      |
| 251     | 14239    | 220             | 137                    | 35        | 70          | Tm, 0-114, Tba?, 114-182   | 121.848081     | 42.171091      |
| 252     | 14241    | 175             | 146                    | 30        | 47          | Tg?Tba?, 0-111, Tm?, 111-160, Tba?, 160-195  | 121.843154     | 42.174595      |
| 253     | 14243    | 363             | 204                    | 30        | 73          | Qc, 0-34, Tba, 34-363  | 121.867557     | 42.174585      |
| 254     | 14254    | 415             | 57                     | 1000      | 68          | Qac, 0-6, Tm, 6-130, Tba, 130-415  | 121.833731     | 42.192134      |
| 255     | 14260    | 80              | 48                     | 30        | 58          | Tm, 0-10, Ts, 10-45, Tm, 45-61, Ts, 61-80  | 121.868461     | 42.158189      |
| 256     | 14264    | 177             | 120                    | 30        | 60          | Ts, 0-80, Tba, 80-177  | 121.865263     | 42.161796      |
| 257     | 14269    | 156             | 50                     | 40        | 56          | Tm, 0-74, Ts, 74-112, Tm, 112-156  | 121.857922     | 42.160019      |
| 258     | 14271    | 155             | 57                     | 30        | 54          | Tm, 0-143, Tba, 143-156  | 121.858002     | 42.163627      |
| 259     | 14275    | 170             | 38                     | 75        | 54          | Tm, 0-47, Ts, 47-56, Tm, 56-132, Ts, 132-170   | 121.85267      | 42.163521      |
| 260     | 14277    | 170             | 24                     | 82        | 57          | Qac, 0-3, Ts, 3-18, Tm, 18-60, Tba, 60-185   | 121.843121     | 42.167042      |
| 261     | 14295    | 175             | 64                     | 15        | 0           | Tms, 0-175   | 121.840539     | 42.165199      |
| 262     | 14299    | 110             | 27                     | 22        | 54          | Tm, 0-55, Tms, 55-110  | 121.847814     | 42.167026      |
| 263     | 14449    | 83              | 14                     | 15        | 53          | Tm, 0-75, Ts, 75-83  | 121.818543     | 42.130742      |
| 264     | 14451    | 155             | 28                     | 55        | 62          | Qs, 0-3, Tm, 3-133, Ts?, 133-155   | 121.823286     | 42.127201      |
| 265     | 14458    | 112             | 18                     | 20        | 53          | Qs, 0-4, Tm, 4-60, Tba, 60-62, Tms, 62-112   | 121.825581     | 42.132429      |
| 266     | 14468    | 145             | 14                     | 30        | 66          | Qs, 0-7, Tm + minor sands (soft), 7-47, Tms (hard), 47-95, Tg, 95-145  | 121.821048     | 42.128991      |
| 267     | 14478    | 140             | 12                     | 500       | 58          | Qs, 0-11, Tm, 0-144  | 121.823482     | 42.130798      |
| 268     | 14521    | 930             | 7                      | 150       | 70          | Qs, 0-4, Tm, 4-80, Ts, 80-86, Tms, 86-490, Tba, 490-510, Tm, 510-590, Tba, 590-593, Tm, 593-800, Tba, 800-815, Tm, 815-840, Tba, 840-858, Tm, 858-870, Tba, 870-879, Tm, 879-885, Tba, 885-930 | 121.801053     | 42.125824      |



Table A1. — continued

| Map No. | Well No. | Total Depth, ft | Static Water Depth, ft | Flow, gpm | Temp, deg F | Stratigraphy (depth intervals in feet following unit names)   | West Longitude | North Latitude |
|---------|----------|-----------------|------------------------|-----------|-------------|---|----------------|----------------|
| 269     | 50045    | 12              | 6                      | 5         | 0           | Mf, 0-2, Tms, 2-12  | 121.804144     | 42.25117       |
| 270     | 50152    | 1111            | 135                    | 75        | 67          | QTfs, 0-35, Tm, 35-59, Tms, 59-96, Tm, 96-587, Tms, 587-601, Tm, 601-998, Tms, 998-1111   | 121.647298     | 42.189298      |
| 271     | 50173    | 84              | 58                     | 18        | 54          | QTfs, 0-5, Ts, 5-24, Tms, 24-56, Ts, 56-84  | 121.68151      | 42.171196      |
| 272     | 50197    | 125             | 8                      | 12        | 56          | QTfs, 0-47, Tms, 47-109, Tm, 109-125  | 121.695836     | 42.178591      |
| 273     | 50222    | 391             | 98                     | 20        | 0           | Ts, 0-198, Tm, 198-318, Ts, 318-391   | 121.789207     | 42.24077       |
| 274     | 50233    | 261             | 126                    | 80        | 66          | Tm, 0-11, Tba?, 11-261  | 121.84733      | 42.175707      |
| 275     | 50266    | 306             | 6                      | 7         | 70          | Qs, 0-14, Tm, 14-306  | 121.701147     | 42.152614      |
| 276     | 50269    | 98              | 5                      | 15        | 50          | Qs, 0-2, Tms, 2-98  | 121.719693     | 42.144969      |
| 277     | 50293    | 50              | 0                      | 0         | 0           | Tba 0-50'   | 121.805116     | 42.236243      |
| 278     | 50315    | 70              | 19                     | 1000      | 0           | Qs peat, 0-10'; Qal boulders, 10-33; Tba 33-70'   | 121.804056     | 42.23896       |
| 279     | 50328    | 971             | 153                    | 330       | 60          | Qc, 0-27, Tm, 27-123, Ts, 123-128, Tm, 128-136, Ts, 136-139, Tm, 139-866, Tba, 866-971  | 121.644394     | 42.192742      |
| 280     | 50344    | 425             | 1                      | 100       | 58          | Qs, 0-5, Tm, 5-7, Ts, 7-40, Tm, 40-75, Tms, 75-395, Tm, 395-425   | 121.686302     | 42.163783      |
| 281     | 50365    | 613             | 10                     | 300       | 62          | Qs, 0-6, Ts, 6-9, Tba, 9-123, Tms, 123-261, Tba, 261-275, Tms, 261-522, Tba, 522-613  | 121.789385     | 42.189108      |
| 282     | 50379    | 338             | 49                     | 640       | 72          | Tm, 0-160, Tba, 160-338   | 121.83347      | 42.200432      |
| 283     | 50417    | 768             | 38                     | 5         | 64          | Qac, 0-5, Tba, 5-25, Tm, 25-40, Tms, 40-48, Tm, 48-117, Tms, 117-163, Tm, 163-197, Tms, 197-206, Tm, 206-230, Tms, 230-236, Tm, 236-458, Tms + Tg, 458-485, Tm, 485-768 | 121.642324     | 42.174798      |
| 284     | 50429    | 334             | 49                     | 30        | 64          | QTfs, 0-36, Tm, 36-297, Tba, 297-334  | 121.691073     | 42.193067      |
| 285     | 50447    | 875             | 200                    | 2000      | 0           | no data, 0-605, Tba? or Thb?, 605-711, Tm?, 711-875   | 121.747432     | 42.224554      |
| 286     | 50449    | 248             | 6                      | 5         | 65          | Qs, 0-5, Tms, 5-248   | 121.715291     | 42.167495      |
| 287     | 50468    | 398             | 328                    | 22        | 58          | Tcba, 0-335, Tm, 335-366, Tba?, 366-398   | 121.822767     | 42.27146       |
| 288     | 50598    | 130             | 72                     | 28        | 60          | Qac, 0-6, Tba? or Tg + Tm?, 6-11, Tms, 11-130   | 121.79904      | 42.26939       |
| 289     | 50600    | 300             | 18                     | 150       | 120         | no data; nearby well has Tba @ 595'   | 121.775217     | 42.225698      |
| 290     | 50616    | 15              | 7                      | 0         | 0           | Qs, 0-15  | 121.789547     | 42.236546      |
| 291     | 50617    | 15              | 7                      | 0         | 0           | Qs, 0-15  | 121.794374     | 42.236597      |
| 292     | 50643    | 22              | 0                      | 0         | 0           | Mf, 0-9, Qs, 9-22   | 121.804262     | 42.247537      |
| 293     | 50667    | 269             | 51                     | 15        | 62          | Tms, 0-269  | 121.823568     | 42.18937       |
| 294     | 50779    | 74              | 10                     | 10        | 54          | QTfs, 0-27, Tms, 27-62, Ts, 62-74   | 121.695787     | 42.193204      |

\*Location and data for water wells from Oregon Department of Water Resources (ODWR) database; lithologic unit assignments are based on interpretations of the ODWR data.

Map no.: Integer identification number.

Well no.: Integer identification number from Oregon Department of Water Resources, accessible on the web at [http://apps2.wrd.state.or.us/apps/gw/well\\_log/Default.aspx](http://apps2.wrd.state.or.us/apps/gw/well_log/Default.aspx).

Total depth: Total depth in feet.

Static water depth: Depth in feet to standing water in the hole; 0 value generally indicates artesian flow.

Flow: Yield of pumped well in gallons per minute

Temp, degrees F: Temperature in degrees Fahrenheit of water; 0 indicates no temperature data.

Stratigraphy: Interpreted geologic units penetrated by well with depth intervals in feet following unit name; based on descriptions by water well drillers; queried where unit assignment is highly uncertain.