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INTRODUCTION

The upper Grande Ronde River basin extends over an area of more than 4,200 km^2 in the north central part of the Blue Mountains Province of northeastern Oregon. All of the area drained by the Grande Ronde River and its tributaries upstream from the confluence with the Wallowa River is included within the basin (Figure 1). The Grande Ronde River and its major tributary stream, Catherine Creek, begin in the south, flowing from glaciated uplands through forested canyon lands into the nearly flat, fault-bounded plain that is the Grande Ronde Valley. After meandering northward through the Grande Ronde Valley, the combined streams flow north into the deeply eroded canyon lands of the lower Grande Ronde River. Elevations range from 8679 ft (2060 m) at Granite Peak, in the Wallowa Mountains, to 2312 ft (705 m) at the confluence of the Grande Ronde and Wallowa rivers. The Grande Ronde Valley is a nearly flat, alluvial plain that is fringed by gently sloping alluvial fans, forming a fertile basin about 570 km^2 in size that is bordered on the east and west by abrupt, fault-bounded escarpments. Of the over 24,000 people that live in the basin, more than half of them live within the city of La Grande. Principal industries are agriculture, light manufacturing, and lumbering. Small grains, grass seed, mint, potatoes, fruit, dairy products, and livestock are the main agricultural commodities produced in the valley.

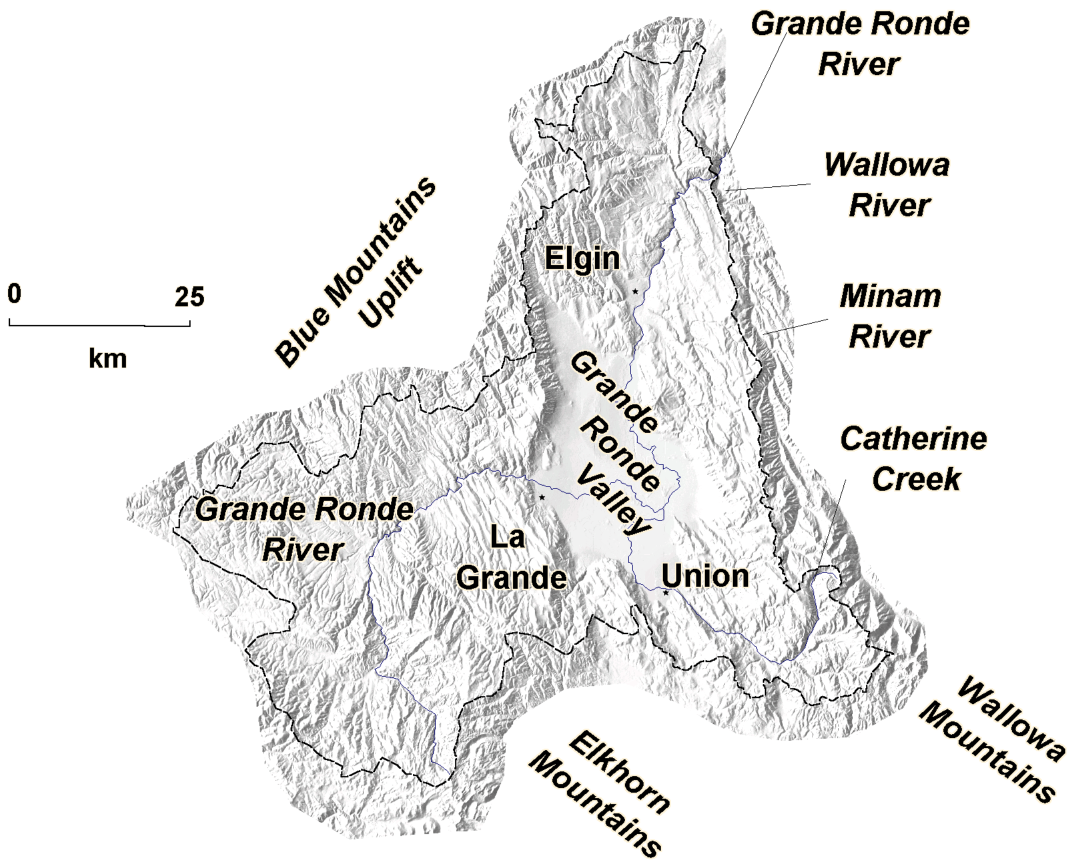

Figure 1 Shaded relief map of the upper Grande Ronde River basin showing major physiographic and cultural features. Black line marks the boundary of the upper Grande Ronde River basin hydrologic unit (HUC). Course of the Grande Ronde River and its major tributary, Catherine Creek, shown in blue.

The headwaters to the basin are heavily forested lands administered by the U.S. Forest Service, making up parts of the Umatilla and Wallowa Whitman National forests. Part of the headwaters is under the jurisdiction of the Confederated Tribes of the Umatilla, who maintain treaty rights over much of the area. Privately held lands include large timber and grazing lands owned by the Boise Corporation and various cattle ranchers. The southern headwaters to the basin lie in two glaciated mountainous regions, the Wallowa Mountains in the east, and the Elkhorn Mountains in the south. Both mountainous regions are cored by pre-Miocene basement rocks and are structural highlands, in part fault-bounded, where early to middle Miocene, tholeiitic flood basalts (Imnaha and Grande Ronde Basalt) both onlap and offlap an eroded surface of older basement rocks (Figure 2). Basement rocks include exotic Paleozoic and Mesozoic oceanic and island arc fragments, Late Jurassic and Cretaceous intrusions, Paleocene and Eocene continental sedimentary rocks, and Late Oligocene - Early Miocene bi-modal volcanic rocks. The Wallowa and Elkhorn mountains are separated by northwest-trending, lower elevation, fault-bounded ridges and valleys where lava flows of the middle Miocene to Pliocene calc-alkaline Powder River Volcanic Field are exposed.

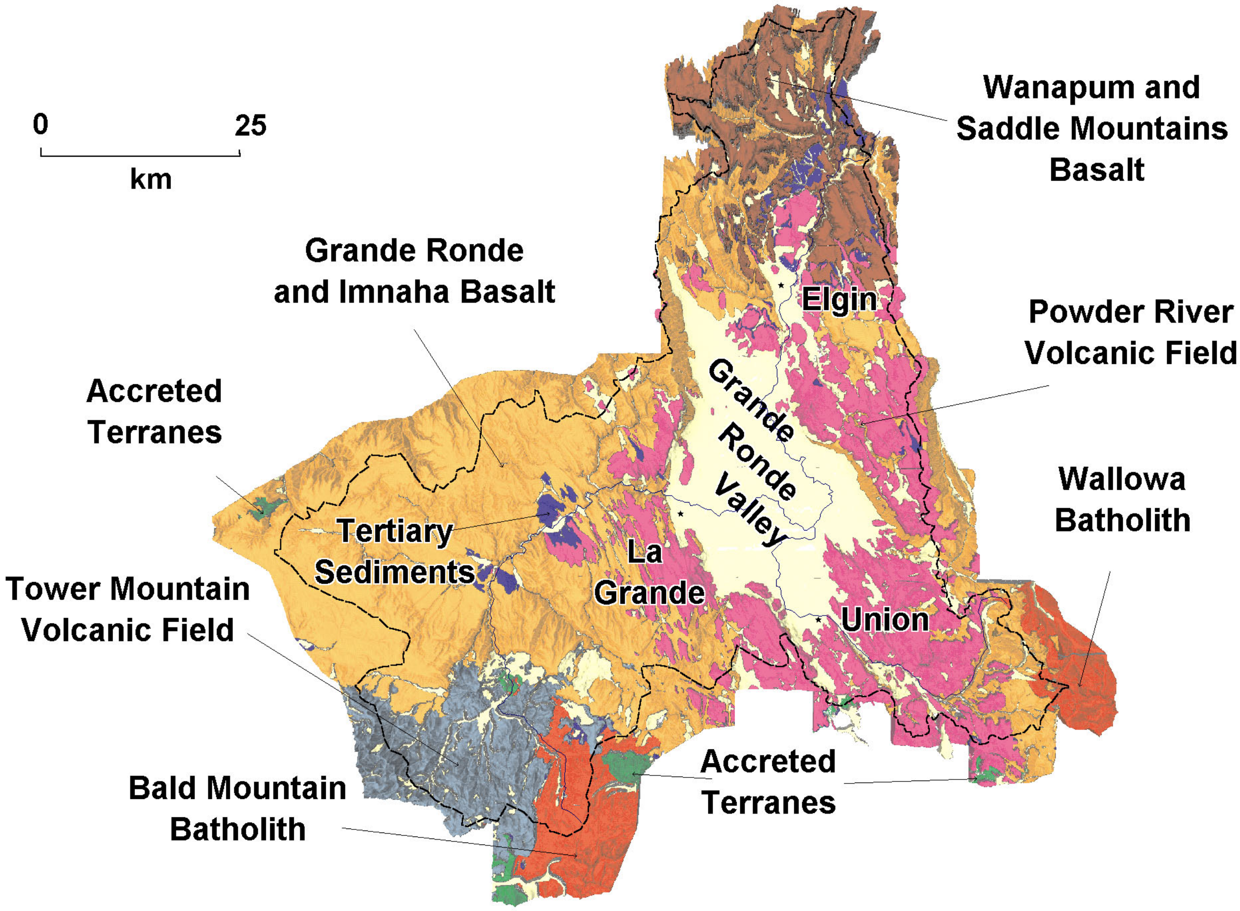

Figure 2 Shaded relief map showing the major lithologic features in the upper Grande Ronde basin. Pre-Tertiary accreted terranes shown in green; Juro-Cretaceous intrusions shown in red; Oligocene volcanics shown in gray; Grande Ronde and Imnaha Basalt shown in orange; Miocene sediments shown in dark blue; Powder River Volcanic Field shown as light purple; Wanapum and Saddle Mountains Basalt shown as brown; late Tertiary and Quaternary sediments shown as pale yellow.

Two fault-bounded basins form the central part of the basin; the larger Grande Ronde Valley in the south and the smaller Indian Valley to the north. The Grande Ronde Valley is bordered on both the east and west by steep, fault-bounded escarpments that expose Grande Ronde Basalt and capping Powder River Volcanic Field lavas. The valley itself is filled with as much as 600 m of late Miocene, Pliocene, and Pleistocene sediments. Major fault zones on the east and west side of the Grande Ronde Valley exhibit evidence for Quaternary movement and have cumulative vertical displacements in excess of 1000 m. The small alkaline and calc-alkaline, late Miocene to Pliocene shield volcanoes that make up the Elgin Volcanic Field separate the northern Grande Ronde Valley from Indian Valley. Indian Valley is bounded on the southwest by a faulted escarpment and is filled with as much as 100 m of sediments and terrace gravels. The Grande Ronde River flows northward out of Indian Valley into deep canyon lands where the upper flows of the Grande Ronde Basalt and overlying, younger Wanapum Basalt and Saddle Mountain Basalt flows of the Columbia River Basalt Group and interbedded sediments are exposed along the canyon walls.

Methodology and Previous Work

The geologic map of upper Grande Ronde River basin is compiled from maps of the La Grande 30° x 60° quadrangle (Ferns and others, 2001), the Grande Ronde Valley (Ferns and Madin, 1999; Ferns and others, 2002a, b; McConnell and others, 2003), and unpublished mapping by Ferns in the northeast, McConnell in the southeast, and Kevin Pogue and Bob Carson in the southwest. The compilation is a National Cooperative Geologic Mapping Program project that was partially funded by the U.S. Geological Survey under assistance award #02HQAG2037. All of the geologic data were collected using standard U.S. Geological Survey 1:24,000 scale topographic maps, and air photos. Field data were converted into digital format with the MapInfo Professional software by heads up digitizing using georeferenced U.S. Geological Survey digital raster images (DRG's) as 1:24,000 scale base maps. Geologic interpretations were aided by GIS analyses based in part on georeferenced orthophotoquads and shaded relief images derived from the U.S. Geological Survey 30 m DEM (Digital Elevation Model) grids and, for the western part of the basin, a Side-Looking Airborne Radar image (EROS, 1990).. Subsurface geological interpretations were guided by water well logs (Figure 3) obtained through the Oregon Department of Water Resources online GRID system and well cuttings provided by local water well drillers. Mapping was supplemented with XRF geochemical and Ar^{40}/Ar^{39} radiometric age determinations of surface samples and water well cuttings.

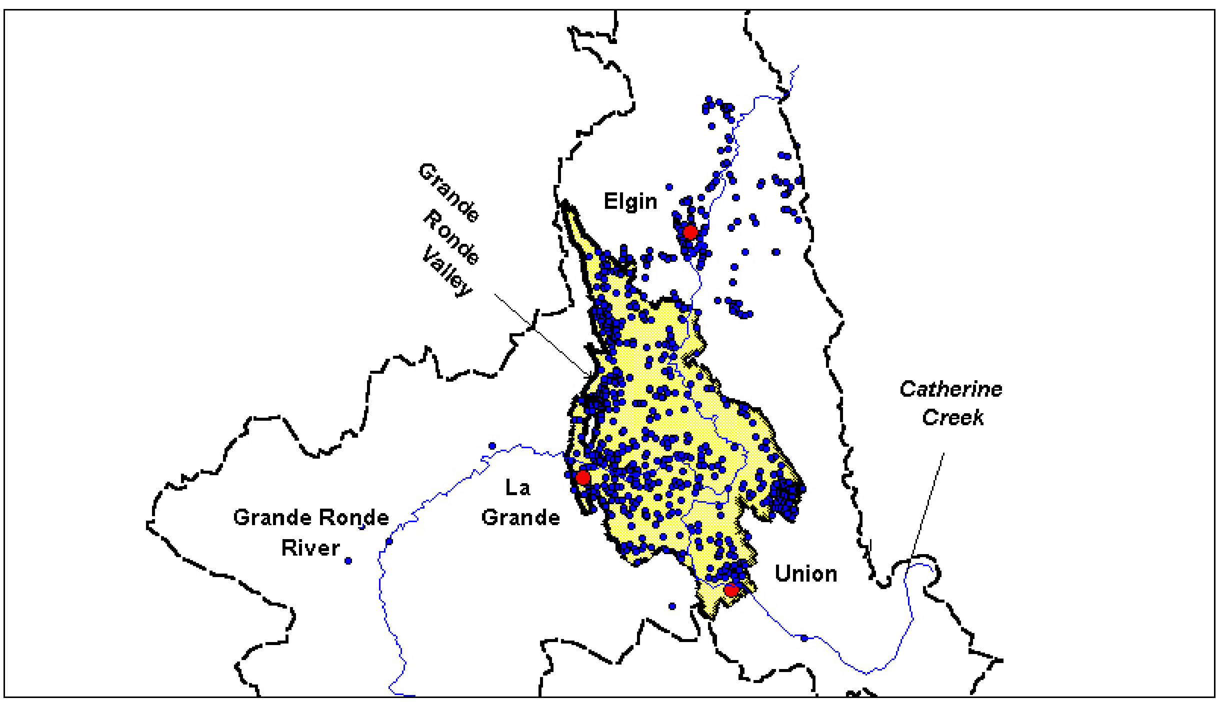

Figure 3: Location of water wells that provided logs used in this study. Most of the wells are located in the Grande Ronde Valley proper, shown in yellow. All locations are approximate. Well logs are available through the Oregon Department of Water Resources.

Geologic units displayed on the 1:125,000 scale geologic map plot that are part of this report include, for reasons of scale, composite units that combine several different units that could be displayed at the 1:24,000 scale. The geology database from which the 1:125,000 scale map was derived contains all of the original data that was collected at 1:24,000 scale resolution. Differences in resolution are shown in Figure 4.

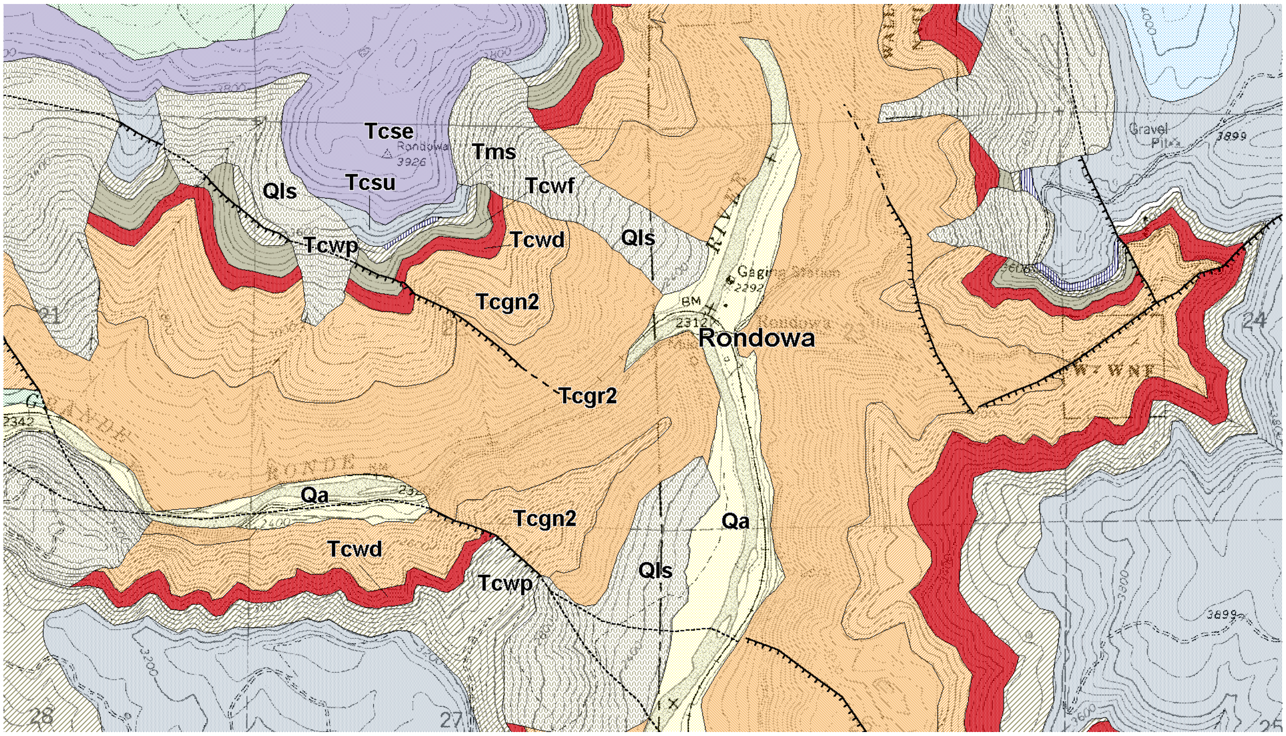

Figure 4 Geologic map of confluence of the Grande Ronde and Wallowa rivers, showing the geology at the 1:24,000 scale and plotted using Unit_24k attributes. Here the Grande Ronde Basalt is broken up into two units (Tcgn2 and Tcgr2) using magnetic polarity measurements. The Wanapum Basalt is broken up into three units (Tcwd – Dodge member; Tcwf – Frenchman Springs member; Tcwp – Powatka member). The Saddle Mountains Basalt is broken up into two units (Tcsu – Umatilla member and Tcse, Eden member). Each member is assigned a unique identifier in the geologic map data base.

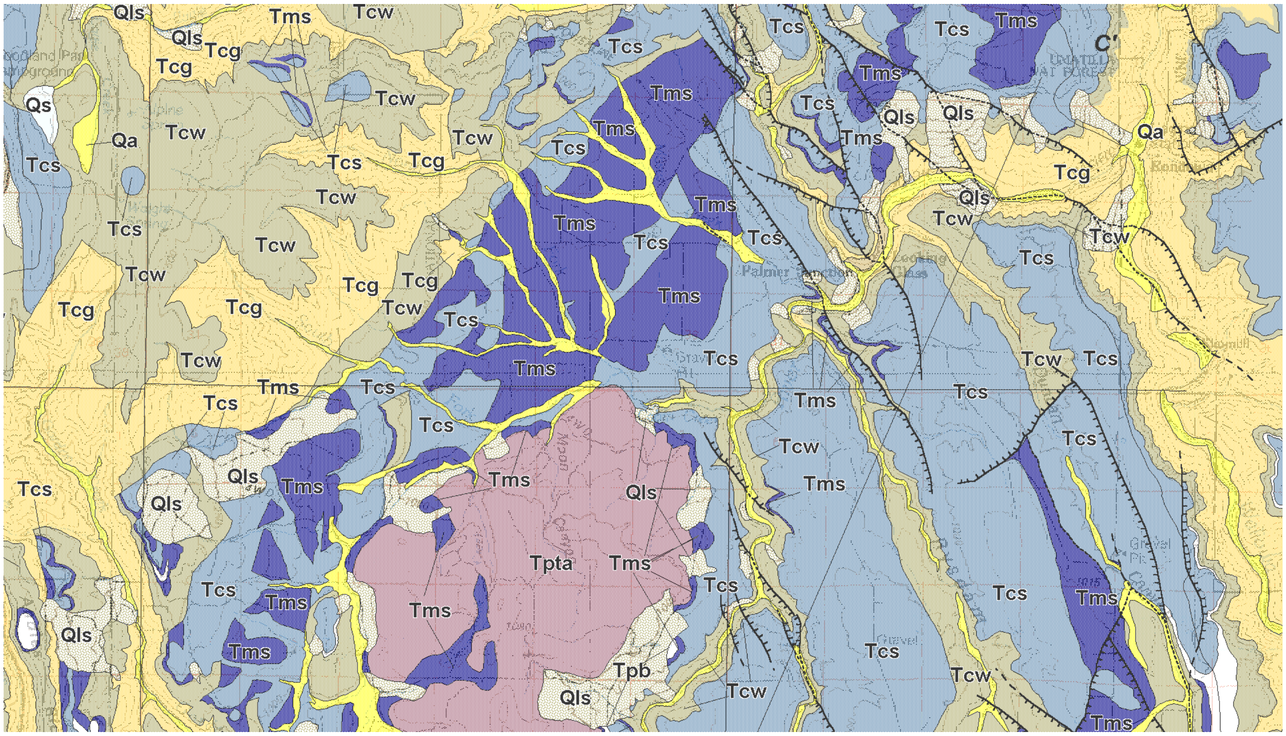

Figure 5 Geologic map of the same area showing the geology at the 1:100,000 scale and using the Unit_100k attributes. Tms includes sediments interbedded with Tcs flows.

Attributed geochemical, geochronological, structural, mineral resource, and water well lithology databases that contain point and line data are included with the map. All data sets contain geologic unit fields and location data that allow them to be plotted as separate overlays or incorporated into more detailed thematic maps. Geochemical data (Figure 5) are from Bailey (1990), Wright and others (1979; 1980; 1982), Kuehn (1995), Shubat (1979), Ferns and McConnell (2003), Beeson (unpublished data) and Reidel (unpublished data).

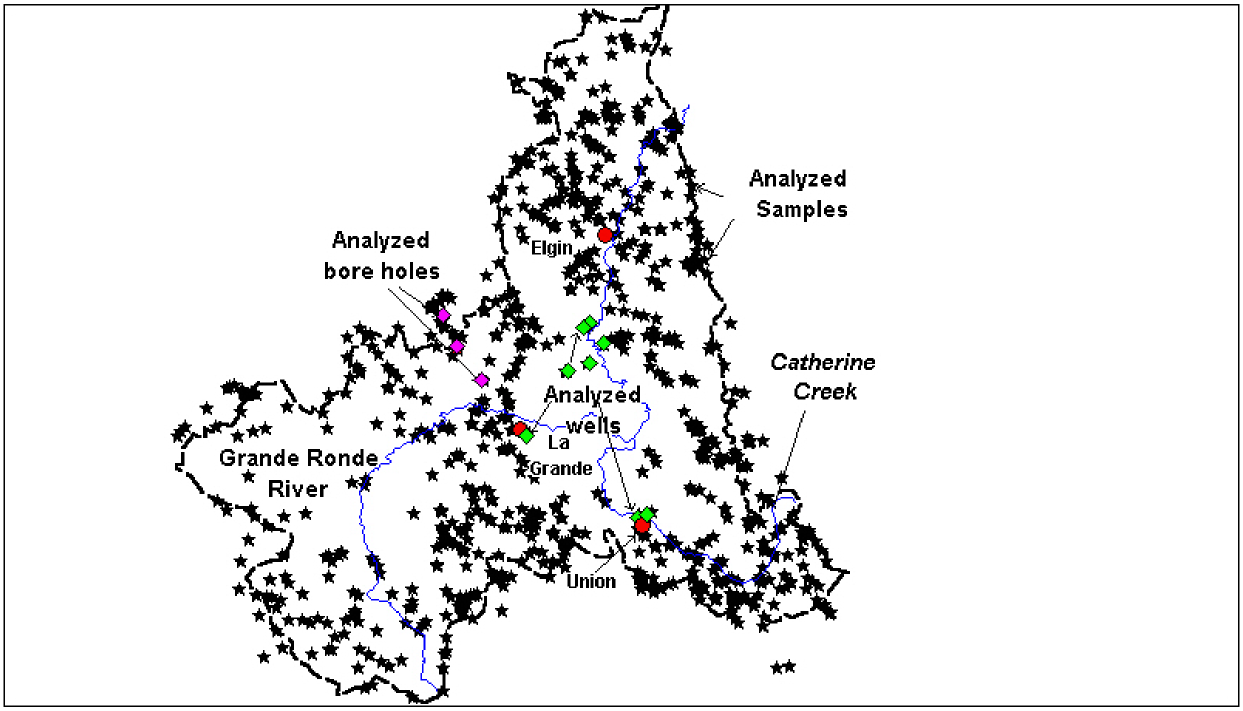

Figure 6: Whole rock xrf sample locations. Outcrop samples shown as stars. Well cuttings from deep water wells shown as green diamonds. Cuttings from deep bore holes shown as purple diamonds.

Geothermal and mineral resource databases are modified extracts from statewide databases released by the Oregon Department of Geology and Mineral Industries (Gray, 1993; Black, 1994). Descriptive names for rock units are based in part on British Geological Survey classification schemes (Gillespie and Styles, 1999; Robertson, 1999; and Hallsworth and O'B Knox, 1999). Rock names for volcanic rocks are based on geochemical data and were derived by plotting the data on the total alkali silica (TAS) diagram (after Le Bas and others, 1986). The chemical analyses were recalculated to a 100 per cent total without volatiles and with all iron calculated as Fe^{++}.

The first regional scale geologic maps of the Upper Grande Ronde River basin include a water resource investigation map by Hampton and Brown (1964) and 1:250,000-scale reconnaissance geologic maps of the Pendleton and Grangeville quadrangles (Walker, 1973; 1979). The western part of the basin is included on the La Grande 1:100,000 quadrangle (Ferns and others, 2001). Detailed studies in the basin include an engineering geology report for the La Grande area (Schlicker and Deacon, 1971); a tectonic study of the Grande Ronde Valley (Barrash and others, 1980); both of which contain 1:24,000 scale maps for the city of La Grande; and a basin analyses of the southern Grande Ronde Valley (Ferns and others, 2002a). More recent 1:24,000 scale geologic quadrangle maps include the Limber Jim Creek (Ferns and Taubeneck, 1994); Tucker Flat (Madin, 1998), Fly Valley (Ferns, 1999), Summerville (Ferns and Madin, 1999); Imbler (Ferns and others, 2002b) and Mt Fanny – Little Catherine Creek (McConnell and others, 2003).

EXPLANATION OF MAP UNITS

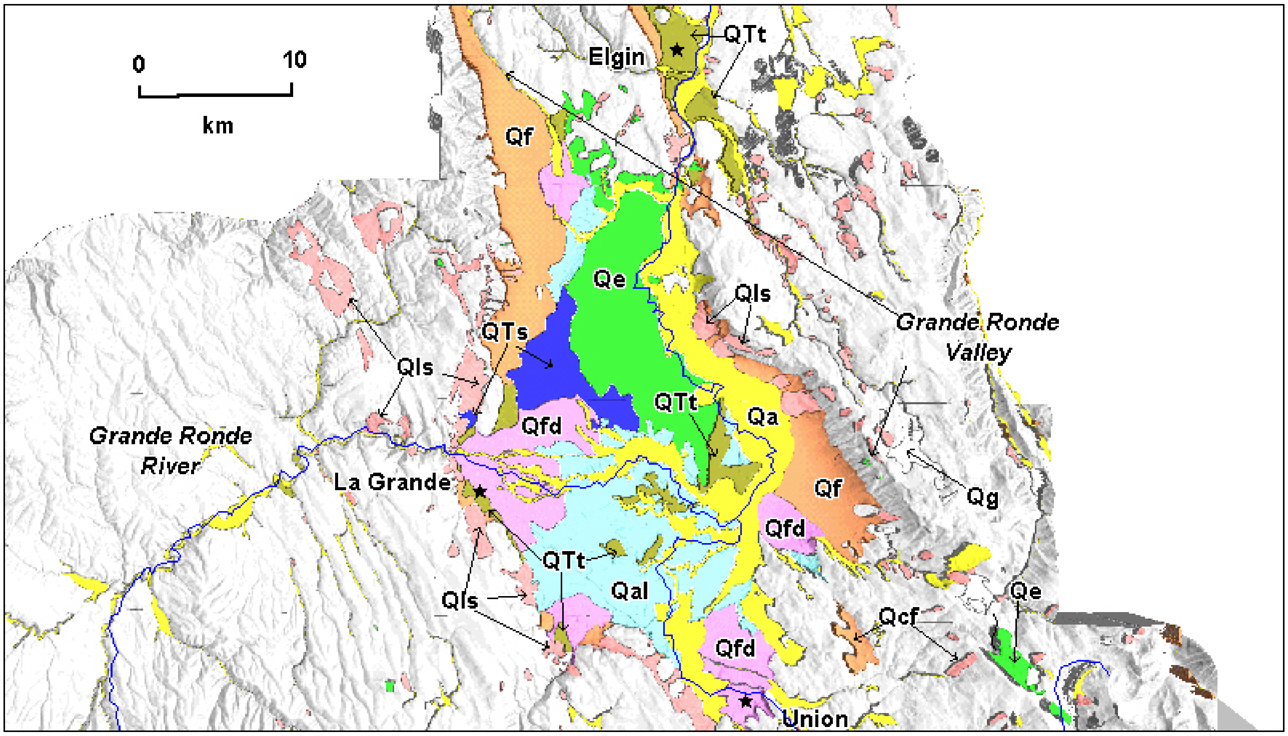

Figure 7 Shaded relief map showing Quaternary and late Tertiary sedimentary units located in and around the margins of the Grande Ronde Valley. Individual units (Qa, Qfd, etc) are described below.

SURFICIAL AND LATE CENZOIC VALLEY-FILL UNITS

Surficial and late Cenozoic sedimentary units are found throughout the basin. Largest accumulations are in and along the margins of the Grande Ronde and Indian Valleys. Important surficial units in the Grande Ronde Valley (which covers more than 570 km^2 of the map area) include alluvial plain, fluviatile fan-delta, and eolian deposits and fringing landslides, debris flows, and alluvial fans (Figure 6). Map units include:

Qa Alluvium (Holocene and upper Pleistocene) Gravel, sand, and silt deposited in active stream channels and on flood plains. Mainly gravel and channel sand deposits but includes overbank sand, silt, and clay deposits on low terraces along the Grande Ronde River. Locally includes alluvial fan deposits too small to map separately at the mouths of small tributary streams. Also locally includes overbank deposits of waterlain ash as much as 3 m thick. Also includes channel sand, silt, and clay deposits in abandoned distributary channels and sloughs on the Grande Ronde River fan. Holocene and late Pleistocene ages based on presence of ca 6,700 yr BP Mazama and ca 10,700 yr BP Glacier Peak ashes (Cochran, 1988). Local stratigraphy is complex, Cochran (1988) has documented 5 alluvial aggradation-stable surface-erosion cycles in Ladd Canyon over the last 11,000 years.

Qe Ash, sand, and loess (Holocene and upper Pleistocene) Mainly wind-deposited sand and loess. Includes local accumulations of white, air-fall ash. In the Grande Ronde Valley, wind-blown sand has accumulated to thicknesses of 15 m along the Sand Ridge; an undulating and vegetated surface of north-trending longitudinal dunes. As much as 5 m of light brown, wind-blown silt locally mantles land surfaces north of the Sand Ridge. The alluvial plain south of Sand Ridge is interpreted as the deflation basin from which the sand and loess was derived. 0.5- to 1-m-thick accumulations of white air fall ash occurs as erosional remnants along stream channels, in landslide sag ponds, and timbered uplands. In most upland areas, the ash is intermixed with loess and forms a light brown soil. Unit includes Mazama and possibly older ash fall deposits. The Mazama ash is Holocene, while the sand and loess deposits are mostly late Pleistocene.

Qal Lacustrine and alluvial plain deposits (Holocene? and upper Pleistocene) Mainly silt, clay, and diatomite deposited in the alluvial plain of the Grande Ronde Valley. Includes minor lenses of pebbly, coarse- to medium grained sand and organic and diatomite-rich clays. Locally marked by thick black loamy soil (Hot Lake and Conley soils of Dyykesterhuis and High, 1985). Indicative of marsh, low-energy fluvial, and shallow lake conditions at time of deposition. Includes marsh deposits at Ladd Marsh. Grades vertically into underlying unit QTs. Unit is no more than 10 m thick at Ladd Marsh.

Qfd Fluviatile fan delta deposits (Holocene and upper Pleistocene) Subarial delta plain deposits. Mainly stratified gravel, sand, and silt deposited where the Grande Ronde River and its major tributaries enter the Grande Ronde Valley. Locally overlain by overbank silt and fine sand deposits. Unit interfingers with unit Qal. in the lower part of the Ladd Creek fan. Below the surface of the Grande Ronde Valley, the unit grades vertically and laterally into underlying unit QTs. Grades down slope into the valley from coarse gravel with clay to medium and fine grained gravel and sand. The unit may be as much as 150 m thick at La Grande, based on 33,000 yr BP radiocarbon date from a log at 146 m depth (Van Tassel, 1993).

Qf Alluvial fan deposits (Holocene and Pleistocene). Mainly unconsolidated, poorly-sorted deposits of coarse boulder gravel, gravel, and sand deposited along mountain range fronts fringing the Grande Ronde Valley. Deposits grade down slope from coarse, clay-rich boulder gravels to fine- to medium-grained gravel, sand, and silt. At La Grande, includes very coarse block breccias with andesite blocks as much as 1 m in diameter that were deposited by rock falls and small debris avalanches. Upper slopes include unstable colluvial wedges of intermixed soil and rock that mantle fault contacts. Coalescing fans form extensive bajada surfaces extending along the both the east and west margins to the Grande Ronde Valley. Includes both active and inactive alluvial fans. The northern end of the bajada surface on the west side of the valley has been deeply incised by modern active stream channels. Locally in fault contact with bedrock units.

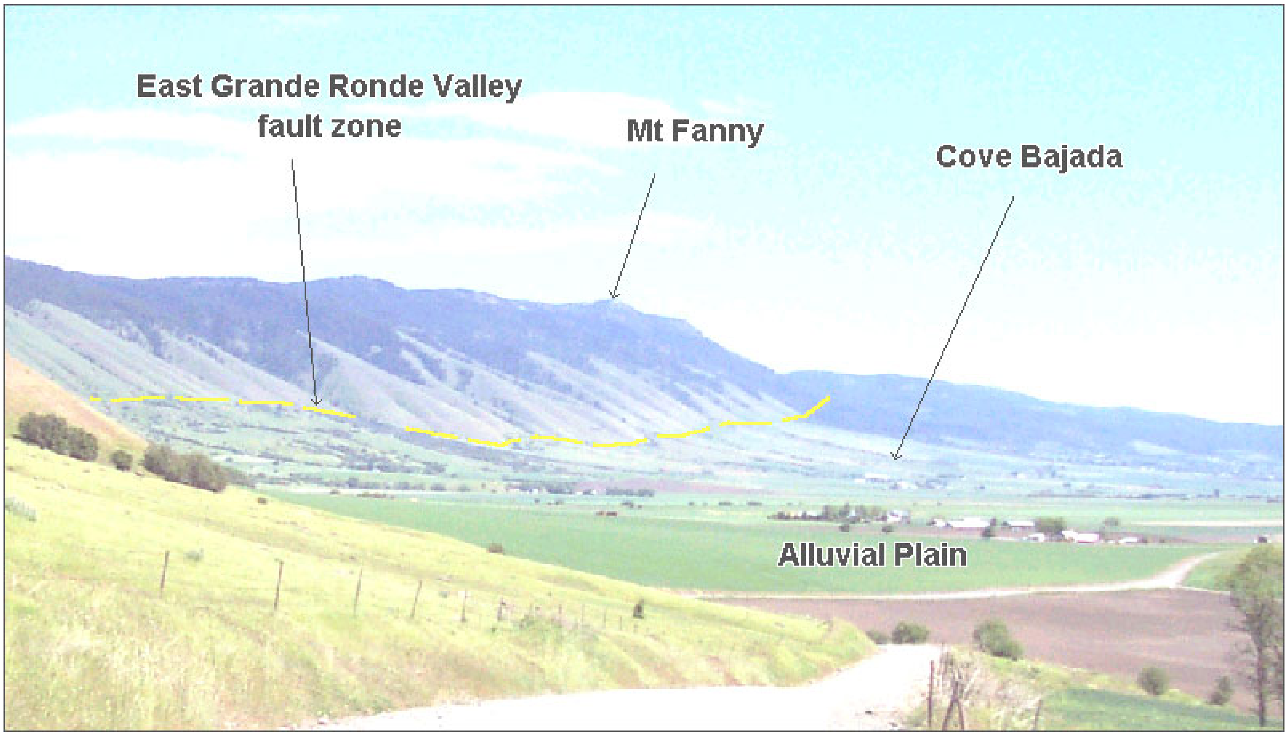

Figure 8 Photograph of the east side of the Grande Ronde Valley, showing the Cove bajada and Eastern Grande Ronde Valley fault zone (yellow dashed line). Looking southeast from near Grays Corner.

Qcf Colluvium and scree, and talus deposits (Holocene and upper Pleistocene) Includes boulder-to gravel-sized masses of angular rock debris with little or no soil at the base of steep cliff faces (talus) and hill slope deposits of poorly sorted soil and rock (colluvium). Scree deposits includes boulder- to gravel-sized masses of angular rock debris that are found some distance down slope from the cliffs. Each deposit is usually monolithologic, and is derived from cliff forming Powder River Volcanic Field units. Unit is only mapped where thick enough to mantle the underlying bedrock or where the deposit has developed into a recognizable landform. Individual deposits may vary from meters to tens of meters in thickness. Formed by mechanical failure due to gravity and periglacial (frost heaving and solifluction) processes. May grade down slope into alluvial fan deposits and laterally into colluvial landslide and debris flow deposits.

Qls Landslide deposits (Holocene and Pleistocene) Unconsolidated, chaotically mixed masses of rock and soil. Landforms typified by sloping hummocky surfaces marked by closed depressions, springs and wet seeps, scarps, and cracks and crevices. Active or recently active landslides marked by tilted trees and bent tree trunks. Often traceable upslope to headwall scarps or slip surfaces. Unit includes rock fall, mudflow and debris flow deposits. Bedrock landslide in the map area typically form where coherent lava flows are in contact with tuffaceous sediments. Includes extremely large composite landslides along the Grande Ronde River that are as large as 7 km^2 in size. The composite slides commonly consist of individual slides of different ages that form coalescing masses. Includes shallow-rooted landslides of colluvium, rapidly-emplaced debris flow deposits; and more deeply rooted bedrock slides. Debris flow deposits typically form lobate masses on alluvial fans down slope of the range front that are disconnected from the landslide scarp or failure zone. Debris flow deposits along the margins of the Grande Ronde Valley apparently formed during catastrophic collapse of high standing dacite cliffs at Mt Emily and Mt Harris. Older slides are commonly mantled by loess and Mazama ash. Open ground fissures and marginal levees mark younger, active slides, such as those at the north end of Indian Valley, north of Elgin.

Qg Glacial deposits (upper and middle Pleistocene) Unconsolidated, poorly stratified deposits of glacial till, coarse gravel, fine silt, sand, and loess, derived largely from granitic rocks of the Bald Mountain and Wallowa batholiths. Glacial till -exposed mainly in lateral moraines along the upper reaches of the Grande Ronde River, and Catherine Creek- typically consists of granitic boulders and blocks as much as 150 cm in diameter. Till on the upper reaches of Mill Creek and Indian Creek is made up of large andesitic boulders and blocks. Unit includes well preserved lateral and recessional moraines of the Late Pleistocene (10,000 - 30,000 yr BP.) Pinedale glaciation and poorly preserved lateral moraines of the middle Pleistocene (150,000 - 200,000 yr BP.) Bull Lake glaciation (Crandall, 1967; Richmond, 1986; Bilderback, 1999; Geraghty, 1999). Younger Pinedale till forms sharp, topographically distinct glacial features marked by solid granitic boulders. Older Bull Lake till on the Grande Ronde River forms less distinct glacial features marked by grussy soils formed from disintegrating heavily weathered granitic clasts.

QTt Terrace deposits (Pleistocene and Pliocene?) Mainly unconsolidated to poorly consolidated deposits of gravel, pebbly coarse sand and medium- to fine-grained sand. In the Sheep Creek area on the headwaters of the Grande Ronde River, includes coarse gravel terraces preserved at two levels. Upper terrace stands 60 m above the modern streambed. Along the west side of the Grande Ronde Valley, unit includes remnants of a fringing, east-sloping terrace that stands 20 - 30 m above the modern valley floor. Also includes sinuous, 5 –12 m high ridges of fine-grained gravel and sand in the central part of the Grande Ronde Valley (Ferns and others, 2002a,b). Also includes a 50+ m thick section of medium to coarse, volcanic-clast gravels in Indian Valley near Elgin. Possible Pliocene age for the older terraces in part based on inference that the Indian Valley gravels underlie the 2 Ma Jones Butte (Walker, 1979; Bunker and others, 1982). Pleistocene age based in part on a radiocarbon age of 15,280 $\pm$ 180 yr BP from a mammoth tooth recovered atop the terrace gravels at the Eastern Oregon University campus (Ferns and others, 2001).

QTs Fluviatile and lacustrine deposits (Pleistocene, Pliocene, and upper Miocene) Poorly consolidated and poorly exposed deposits of clay, silt, sand, and gravel. Unit includes all sediments situated between the top of the Powder River Volcanic Field and the base of late Pleistocene and Holocene geomorphic landforms. Unit is more than 560 m thick in the Grande Ronde Valley and includes alluvial plain, fan-delta, stream-channel, and alluvial fan deposits. In the Grande Ronde Valley, unit consists mainly of alluvial plain deposits of sandy silt and clay with thin interbeds of sand and fine-grained gravel. Also includes black organic-rich clay, pale red paleosol, white diatomite, and white air-fall tuff. Stream channel deposits include poorly sorted, upward-coarsening fluviatile gravels exposed near the divide between Catherine Creek and Beagle Creek. Based on water well driller's logs, unit in the Grande Ronde Valley coarsens upwards from alluvial plain clays and silts to stream channel and fan delta gravels and laterally to clay-rich alluvial fan gravels along the valley's margins. Base of the unit in the northern Grande Ronde Valley is marked by peaty clay and fine sand indicative of marsh and bog environments (Van Tassel and others, 2001). Lower late Miocene age based on a 7.5 $\pm$ 0.11 Ma isochron age from glass shards in a water lain ash that were recovered from a depth of 472 m below land surface (Ferns and others, 2001). Van Tassell and others (2001) report a $^{40}Ar/^{39}Ar$ age of 3.1 $\pm$ 0.3 Ma from glass shards in a water lain ash recovered from a depth of 110 m below land surface.

CENOZOIC VOLCANIC AND SEDIMENTARY UNITS

Three topographically distinct Cenozoic volcanic suites, the Powder River Volcanic Field, the Columbia River Basalt, and the Tower Mountain Caldera, provide the framework to the upper Grande Ronde River basin. The Powder River Volcanic Field, centered on the Grande Ronde Valley, is middle Miocene to Pliocene in age and is made up of calc alkaline and alkaline lavas erupted from small shield and stratovolcanoes. The Columbia River Basalt, underlying most of the middle and northern parts of the basin, is a regionally extensive series of mainly middle Miocene tholeiitic flood lavas that extend across northern Oregon and southern Washington from the Snake River to the Pacific coastline. The Tower Mountain Caldera is a large, late Oligocene rhyolite eruptive center that forms the part of the highlands along the southwestern margin of the basin (Ferns, 2002).

Powder River Volcanic Field (Pliocene to middle Miocene) Lava flows from several small, middle Miocene to Pliocene shield and strato-volcanoes make up the Powder River Volcanic Field (Hooper and Swanson, 1990; Ferns and others, 2001, 2002a). Powder River Volcanic Field flows are exposed along the margins of the Grande Ronde Valley over an area of about 825 km^2 , reaching combined thicknesses of as much as 400 m. Water well logs indicate that most, if not all of the floor of the Grande Ronde Valley is underlain by a similar thickness of superimposed lava flows. The base to the field is marked by a series of olivine basalt lava flows (Tpb) which, in places, reach as much as 100 m in thickness. The olivine basalt flows are locally and intermittently underlain by tuffaceous fluviatile sediments that contain interbedded silicic tuff breccia and obsidian clast gravels. The olivine basalt flows are overlain by a complexly interfingering series of dacite (Tpd), andesite, basaltic andesite (Tpa), and basanite (Tpbo) lava flows. The andesites and dacites are for the most part fine-grained, aphyric lavas that apparently emanate from local eruptive centers marked by thick accumulations. Although several small basaltic andesite cinder cones (Tpv) crop out along the southern margin of the Grande Ronde Valley, the thickened masses of andesite and dacite lavas that presumably mark eruptive centers to the east are notably lacking andesitic and dacitic pyroclastic deposits. Mt Harris, the most notable of the east margin vents, is marked by a central dacite spire. Individual dacite flows can be fairly extensive, covering areas as large as 50 km^2 to depths of as much as 130 m. Most of Tpd and Tpa lavas display calc-alkaline affinities. Younger intracanyon flows of much more mafic olivine-rich lavas (Tpbo) lap around the dacite highs in the Indian Creek region, east of the Grande Ronde Valley. The Tpbo flows are basanites and trachybasalts that may locally interfinger with dacite and andesite flows. The northern part of the Powder River Volcanic Field is defined by a number of small domes and shield volcanoes, herein referred to as the Elgin Volcanic Complex. Most of the Elgin volcanoes are small, covering less than 5 km^2 in area and with many consisting of only of a single lava flow of trachyandesite (Tpta) or basaltic trachyandesite (Tptb). The more mafic lavas contain abundant black amphibole crystals. Similar small basaltic trachyandesite and trachyandesite volcanoes that are exposed west of the Grande Ronde Valley in the Sugarloaf Mountain region are of late Miocene age (Kienle and others, 1979; Ferns and others, 2001). Pliocene volcanism is represented by two very small, aphyric andesites - Jones Butte, and Tamarack Mountain- that, although separated by the Grande Ronde Valley, have remarkably similar chemical compositions.

Tpay Andesite and dacite (Pliocene) Fine-grained gray and red high silica andesite and dacite lavas. Includes a pale red to pinkish gray, vesicular hornblende dacite at Jones Butte and a gray trachytic andesite at Tamarack Mountain. The Jones Butte dacite forms a rounded hill that rises 120 m from the surface of Indian Valley (Figure 8). The Tamarack Mountain andesite is a 100 m thick intracanyon flow that forms a low-relief table top. The top of Jones Butte has been intensely altered by vapor phase mineralization. In thin section, the dacite contains blocky feldspar and heavily oxide-rimmed hornblende crystals set in a matrix of heavily altered glass. Hornblende phenocrysts are almost totally replaced by opaque iron oxide minerals. The Tamarack Mountain andesite is a platy flow that, in thin section, displays a trachytic texture with orthopyroxene and plagioclase phenocrysts set in a groundmass of plagioclase crystals and brown, interstitial glass. The two lavas are markedly high in alumina and display somewhat similar chemistries, with 61 – 63 wt % SiO_2; 18.8 – 18.9 wt % Al_2O_3; and 0.9 – 1.3 wt % K_2O. Pliocene age based on an Ar^{40}/Ar^{39} determination of 3.18 $\pm$ 0.15 Ma for the andesite of Tamarack Mountain (Ferns and others, 2001) and on a K/Ar radiometric age determination of 2.0 $\pm$ 0.8 Ma (Bunker and others, 1982).

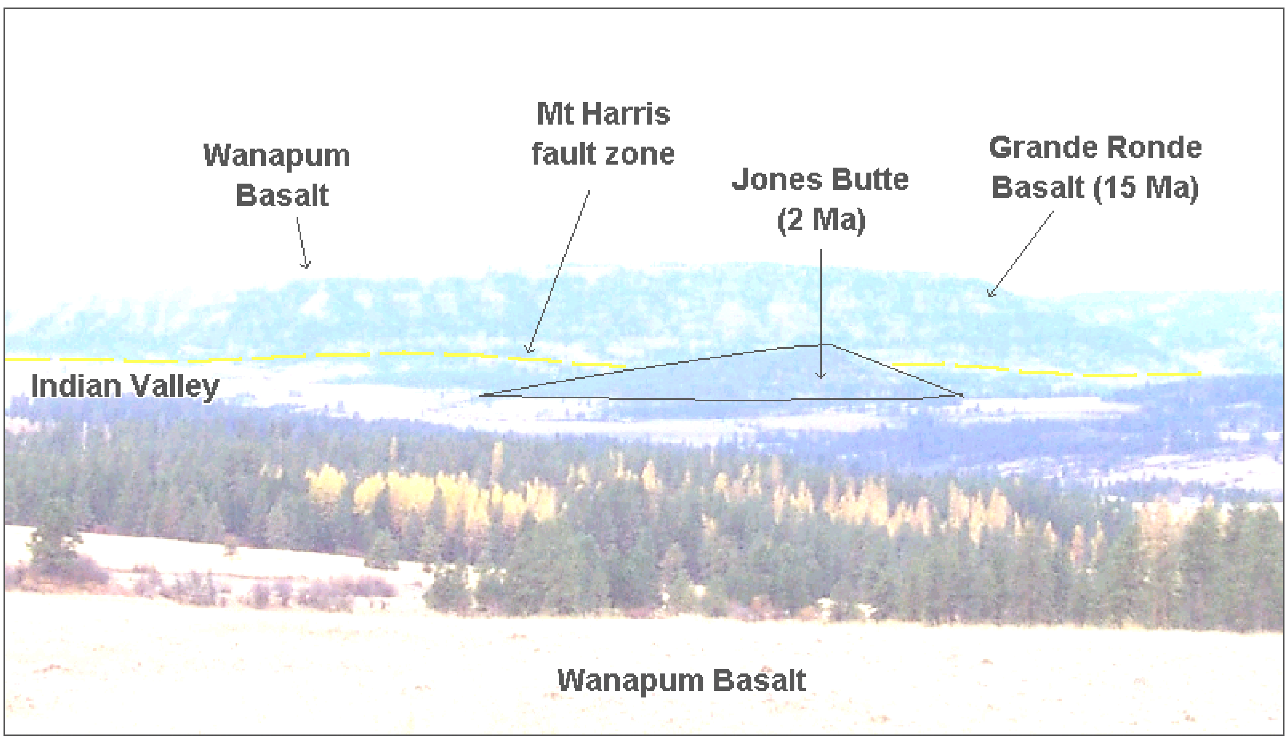

Figure 9 Photograph of the late Pliocene volcano at Jones Butte in Indian Valley. Looking west from Cricket Flat. The Mt Harris fault zone separates Indian Valley from an uplifted block of older Grande Ronde and Wanapum Basalt flows

Tpta Trachyandesite and andesite (upper Miocene) Light bluish-gray to gray, aphyric to phyric trachy andesite and andesite flows that form small, broad buttes extend from Green Mountain, west of Mt Emily, through Elgin and east to Stubblefield Mountain. Unit consists of small (< 1 km^2) lava flows and small shield volcanoes. Lavas are typically fine grained, flow foliated, and have small, irregularly shaped vesicles. Some, such as Stubblefield Mountain, have hornblende phenocrysts. Fine-grained pilotaxitic textures are common in thin section. Typically display a mat of aligned, needle shaped plagioclase crystals that wrap around rotated and partially resorbed orthopyroxene, clinopyroxene, or olivine microphenocrysts. Includes andesites and trachyandesites with 57.31 – 62 wt % SiO2; 17.19 – 18.67 wt % Al2O3, and 5.64 – 7.08 wt % Na2O + K2O. Late Miocene age is based on stratigraphic position and a $^{39}Ar/^{40}Ar$ isochron age of 5.7 $\pm$ 0.9 Ma for the Rock Wall flow north of Elgin.

Tptb Basaltic trachyandesite (upper Miocene) Light bluish-gray to gray, fine-grained basaltic trachyandesite flows that form small, broad buttes extending from Sugarloaf Mountain, west of Mt Emily, to Indian Creek, southeast of Elgin. Unit consists of small (< 1 km^2) lava flows and small shield volcanoes. Lavas are typically fine grained, flow foliated, are markedly porphyritic with black amphibole phenocrysts, and often have small, irregularly shaped vesicles. In thin section, the relict amphibole phenocrysts are usually replaced by opaque iron oxides. The oxide masses are sometimes rimmed or cored by small clinopyroxene crystals. Individual flows are commonly trachytic, with green clinopyroxene and, more rarely, plagioclase phenocrysts as much as 3 mm in length. Basaltic trachyandesites with compositions ranging from 51.05 – 54.55 wt % SiO2; 15.55 – 17.49 wt % Al2O3; and 6.24 – 6.96 wt % Na2O + K2O. Late Miocene age based on stratigraphic position and K/Ar dates of 6.54 +/- 0.14 ma; 7.26 +/- 0.11 ma; and 7.32 +/- 0.15 Ma (Kienle and others, 1979) for the small shield volcanos near Sugarloaf Mountain.

Tpbo Basanite and trachybasalt (upper or middle Miocene) Dark bluish gray to black, glassy, olivine-phyric lava flows. Weathered surfaces typically bluish gray or red in color. Individual flows are as much as 80 m thick and weather to form blocky, talus strewn slopes. Fresh, jet black surfaces are marked by abundant clear yellow olivine phenocrysts as much as 2 mm in diameter. Includes at least three different flows, including basanite flows at Horseshoe Basin on the east side of the Grande Ronde Valley and at Glass Hill on the southwest side of the valley. Unit also includes a trachybasalt flow exposed at Phys Point, between Cove and Union. The basanite flows are phonolitic, ringing like a bell when struck by a hammer. Typically tough, breaking with difficulty to form conchoidal fractures. In thin section, the basanite typically contains as much as 10 percent euhedral olivine crystals and 7 % iron/titanium oxides. The olivine phenocrysts are as much as 2 mm in diameter and are set in a microcrystalline groundmass of intersertal to intergranular plagioclase, FeTi oxides, clinopyroxene, alkali feldspar, and biotite. Distinguished chemically by low silica (41.61 – 48.45 wt % SiO2) and high titanium (2.49 – 3.49 wt % TiO2 and total alkalis (5.57 – 6.26 wt % K2O + Na2O). Middle Miocene age based on plateau $^{40}Ar/^{39}Ar$ age of 10.85 $\pm$ 0.18 Ma for the Horseshoe Basin flow and a plateau $^{40}Ar/^{39}Ar$ age of 11.6 $\pm$ 0.4 Ma for a vent-related flow near South Baldy (McConnell and others, 2003). Stratigraphic position is not always clear; the Horseshoe Basin flow is in part an intracanyon flow that filled in an older paleotopographic surface and in places clearly overlies Tpd dacite flows and in other places appear topographically below Tpd dacite flows. The trachybasalt flow at Phys Point is exposed in one outcrop along a fault scarp where it appears to be overlain by dacite flows of unit Tpd and in another outcrop where it appears to overlie the same dacite flow. Includes the basanite of Horseshoe Basin (McConnell and others, in press), the “Bell Tone” basanite of Ferns and others (2002b), and the black olivine basalt of Barrash and others (1980).

Figure 10 Photograph of the basanite of Horseshoe Basin, looking southeast from near the headwaters of Clarkes Creek. Dark gray blocky talus is characteristic of this unit.

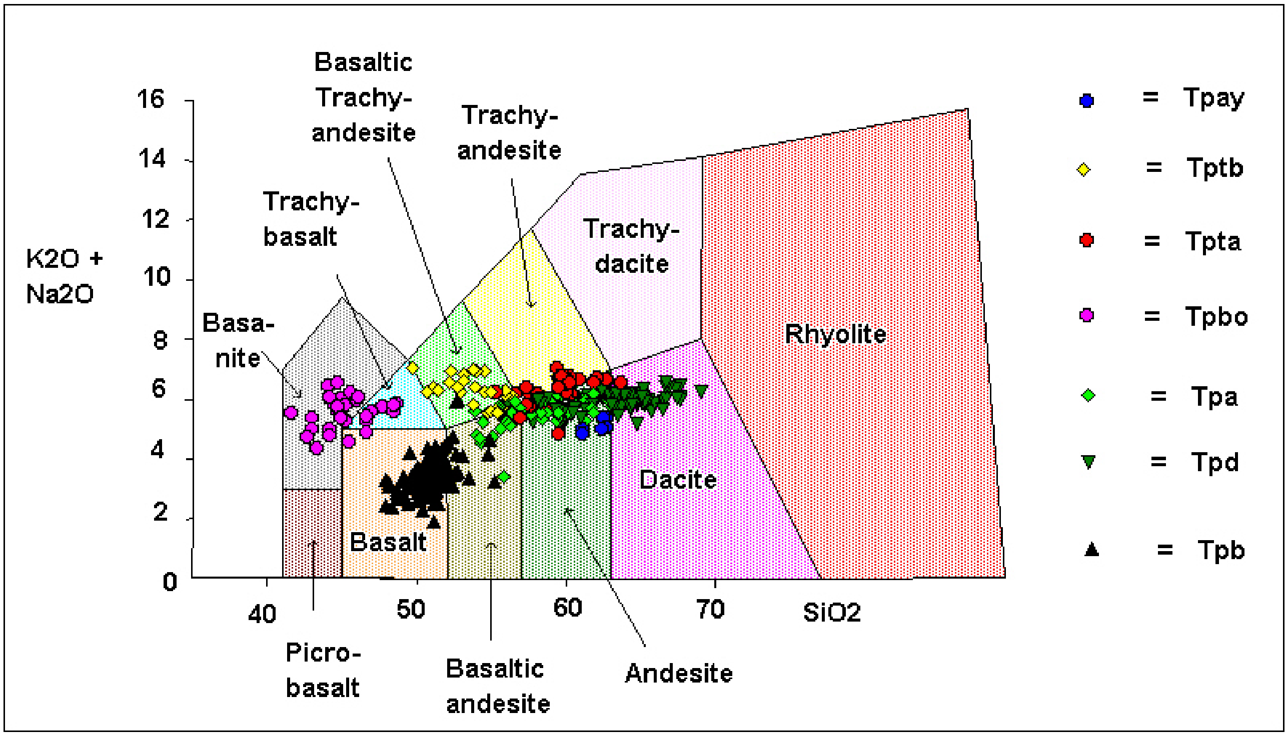

Figure 11 TAS diagram for Powder River Volcanic Field lavas. Youngest flows (Tpay) at Jones Butte and Tamarack Mountain are high silica andesites. Note that the phyric flows from the small volcanos in the north end of the field (Tptb and Tpta) are richer in K_2O and Na_2O than the large, aphyric flows in the south (Tpa and Tpd).

Tpv Basaltic andesite and andesite cinder and scoria (upper or middle Miocene) Poorly to moderately well-bedded vent deposits of brick-red to reddish-gray scoria, lapilli, and volcanic bombs. Lithic clasts average 1-10 cm across but include angular clasts and spindle bombs as much as 80 cm in length. Unit includes three partially eroded cinder cones near Ramo Flat , southeast of Union, which are aligned parallel to a northwest-trending fault system. The north cinder cone is over 70 m high and is cut by a massive, 10-m-high, highly resistant plagioclase-phyric basaltic andesite dike on its northwest flank. Southern flanks of the cones are mantled by thin basaltic andesite flows.

Tpa Andesite and basaltic andesite (middle Miocene) Mainly dark grayish-black to black, vesicular, glassy lava flows. Includes platy-jointed, gray, aphyric lavas and light to medium-gray holocrystalline lavas erupted from different volcanos at different times. Unit includes a flow-on-flow sequence 180 m thick of red-weathering flows that forms the base to the Mt Harris volcano. Includes andesite flows at the base of Gasset Bluff south of Mt Harris (McConnell and others, 2003). Also includes a multiple flow-on-flow sequence southwest of La Grande and flows associated with the Ramo Flat cinder cones. In thin section, characterized by 2 – 5 mm, blocky plagioclase phenocrysts set in either a hyalophitic or pilotaxitic groundmass. Some Mt Harris flows contain orthopyroxene microphenocrysts while Ramo Flat flows contain olivine and orthopyroxene microphenocrysts. Lavas are mostly andesites, compositions range from basaltic andesite to dacite; with 53.

88 – 63.00 wt % SiO2; 16.43 – 18.02 wt % Al2O3; and 5.44 – 6.04 wt % K2O + Na2O. Flows at Mt Harris overlie platform-forming dacite flows and are in turn intruded by a 11.86 $\pm$ 0.12 Ma dacite flow. Andesite flows near the base of Gasset Bluff yielded a (McConnell and others, 2003). Radiogenic argon measurements of a Ramo Flat flow produced a maximum $^{40}Ar/^{39}Ar$ age of 12.0 $\pm$ 0.17 Ma Ma for a sample that did not yield either a plateau $^{40}Ar/^{39}Ar$ or isochron age. Bailey (1990) reports total fusion $^{40}Ar/^{39}Ar$ age of 13.0 +/- 0.1 Ma for an andesite flow at Sawtooth Crater; located southeast of the Upper Grande Ronde River basin. Unit includes the glassy basalt unit of Barrash and others (1980), the andesite unit of Bailey (1990), the basaltic andesite of Ramo Flat and the andesite and basaltic andesite units of Ferns and others (2001, 2002a).

Tpd Dacite (middle Miocene) Light bluish-gray to light pinkish gray, aphyric dacite lava flows and domes. Outcrops are typically marked by steeply dipping, narrowly spaced, subhorizontal to subvertical partings and readily weather to form small angular chips. Unit includes early platform lava flows that are as much as 130 m thick and extend over areas as large as 90 km^2. Also includes domes and plugs that form the cores to individual volcanoes such as Mt Harris. Interiors to thick flows, such as those exposed at Mt Emily and Point Prominence, are commonly marked by 1+ m thick columnar joints. Coarse, matrix-supported, vitrophyre-block breccias are locally exposed at the base of the Mt Emily flow, which in places is marked by a vesicular flow top. In hand sample the flows are steel blue-gray and generally aphyric with platy millimeter to centimeter scale partings. The partings commonly display a pink coloration indicative of vapor phase crystallization of feldspar and hornblende microcrysts. In thin section, the flows typically contain disseminated microphenocrysts of Fe-Ti oxide and/or clinopyroxene set in a very fine grained pilotaxitic groundmass of plagioclase, clinopyroxene, orthopyroxene, and Fe-Ti oxide crystals. On the east and south sides of the Grande Ronde Valley, the unit is made up of more than 1 flow and thickens to more than 250 m. Near Mill Creek, a thin, black, vesicular, glassy aphyric dacite flow crops out between two thick dacite flows. Near Ladd Canyon, the unit contains at least two separate flows that are locally separated by a thin (0.5 m) lithic sandstone (Barrash and others, 1980). Flows are mostly dacites, with 61.70 – 68.96 wt % SiO2; 16.18 – 17.45 wt % Al2O3; and 5.27 – 6.48 wt % Na2O + K2O. Middle Miocene age based on $^{40}Ar/^{39}Ar$ age plateau age of 11.9 $\pm$ 0.12 Ma for the summit of Mt Harris; a $^{40}Ar/^{39}Ar$ plateau age of 11.8 $\pm$ 0.18 Ma for the flow at the top of Mt Fanny; (McConnell and others, 2003), a $^{40}Ar/^{39}Ar$ plateau age of 12.10 $\pm$ 0.10 Ma for a at Dunns Bluff; $^{40}Ar/^{39}Ar$ plateau age of 12.02 $\pm$ 0.2 Ma for a black, glassy aphyric dacite flow near Medical Springs; and a $^{40}Ar/^{39}Ar$ plateau age of 13.38 +/- 0.24 Ma for the Mt Emily flow (Ferns and Madin, 1999). Other than Mt Harris, source vents have not been positively identified. In areas not broken up by younger faults, low relief topographic highs mark thickened accumulations of lavas flows, which may mark eruptive sites.

Figure 12 Dacite exposures in Little Valley, showing the typical folded appearance in the upper, platy part of the flow as contrasted to the more massive, blocky weathering interior of the flow. Such flows can be as much as 100 m thick.

Tpb Basalt of Little Catherine Creek (middle Miocene) Flow-on-flow sequence of vesicular holocrystalline olivine basalt flows herein named the basalt of Little Catherine Creek. Generally gray or light gray in color and weathering to compact rounded boulders in a granular soil. Often characterized by a diktytaxitic texture where olivine phenocrysts as much as 3 mm in diameter are set in an open-textured groundmass of coarse feldspar laths. Also includes porphyritic holocrystalline flows with olivine phenocrysts set in subophitic to intersertal groundmasses of feldspar, clinopyroxene, FeTi oxides, and olivine. Individual basalt flows are typically 5 to 10 m thick and, based on well cuttings, are separated from one another by fine grained sediment and soil. Individual flows can be as much as 70 m or as little as 1 m thick. The 1 m thick flow on Indian Creek is pillowed and rests on a yellow hydroclastic breccia. Unit thickness ranges from 5 m in the west, where a single flow is exposed near Starkey, to more than 150 m (based on drill cuttings) in the Grande Ronde Valley at La Grande. Unit consists of multiple flows with different geochemical characteristics. Bailey (1990) notes 3 geochemical variants; including A) high alumina olivine tholeiite; B) low titanium and phosphorous olivine tholeiite, and C) high titanium and phosphorous olivine tholeiite. Based on analyzed water well cuttings, flows at the top of the unit contain more phosphorous and titanium than do flows at the base of the unit. Locally separated from underlying Grande Ronde Basalt by a thin layer of tuffaceous sediments, ash-flow tuff, or cobble gravels. Where overlain by units Tpd or Tpa, the unit has tendency to form large landslides. Lowermost flows have reversely polarized thermal remnant magnetism while uppermost flows are of normal polarity. Unit's middle Miocene age based on whole rock $^{40}Ar/^{39}Ar$ ages of 13.3 +/- 0.8; 13.7 +/- 0.1 and 14.4

+/- 0.2 Ma determinations on flows to the southeast (Bailey, 1990). Includes the diktytaxitic basalt unit of Barrash and others (1980), the basalt of Cricket Flat (Hooper and Swanson, 1990) the Levi flow of Shubat (1979), and the basalt of Red Ridge (Madin, 1999). North of Elgin, Tpb olivine basalt flows overlie and underlie the Umatilla member of the Saddle Mountains Basalt.

Figure 13 Tpb olivine basalt flow exposure along the road near Starkey. Here the lava flow overlies coarse fluvial gravels. Blocky columnar jointing is common in the thicker flows.

Tpi Basalt, andesite, dacite, and basanite intrusions (middle Miocene) Dikes and sills; including gray, hackly jointed, hornblende phyric basaltic trachyandesite and dacite; bluish black, olivine phyric basanite, aphyric dacite, and olivine basalt. Includes a 30 m thick trachy basaltic andesite sill exposed below the summit of Mt Emily on the west side of the Grande Ronde Valley. Also includes a 30 m thick dacite sill and a 400 m long dike exposed north of Cove on the east side of the Grande Ronde Valley at Warm Creek Canyon and a columnar jointed dacite dike at Mill Creek. In thin section, the Mt Emily sill contains small clinopyroxene crystals and as much as 2 percent euhedral hornblende crystals up to 5 mm in length set in a trachytic groundmass of feldspar and granular clinopyroxene crystals. Unit includes nearly all of the lava types in the Powder River Volcanic Field.

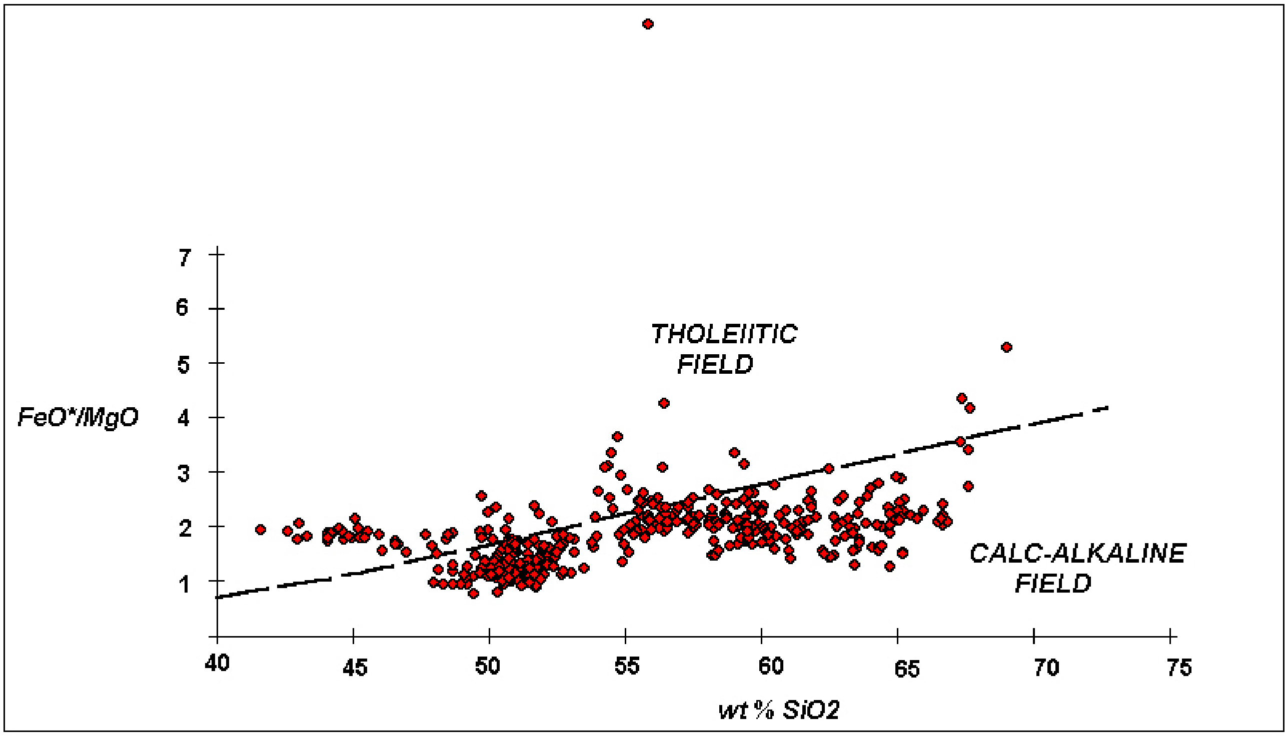

Figure 14 FeO*/MgO vs SiO2 plot of Powder River Volcanic Field lavas; showing their overall calc-alkaline trend. Although the low silica flows plot in the tholeiitic field, overall trend is strongly calc-alkaline. Strong iron enrichment in uppermost flow of the 98 Bingaman well may be due to post emplacement alteration.

Tms Sedimentary rocks (early Pliocene ? to middle Miocene) Weakly indurated, tuffaceous and arkosic gravel, sand, and silt. The map unit includes sedimentary rocks deposited between eruptions of the last Wanapum Basalt flow of the Columbia River Basalt Group and the last Powder River Volcanic Field flow. Generally separated into members on basis of stratigraphic position (Stoffel, 1984) and geographic distribution (Ferns and others, 2001; Walker, 1990), assuming that the modern basins in which the thickest part of the sediments are now found were middle Miocene depocenters. Two members (sediments of La Grande (Ferns and others, 2001) and the Squaw Creek interbed (Ross, 1978), overlie the Grande Ronde Basalt and Wanapum Basalt respectively. More localized members occur as interbeds within both the Saddle Mountain Basalt and Powder River Volcanic Field. Unit readily forms landslides where it is capped by younger lava flows. Usually exposed only in recent road cuts. Also preserved in small, disconnected basins where mantled by coarse terrace and alluvial fan gravels. Includes the sedimentary rocks of Starkey and La Grande (Ferns and others, 2001), the sediments of Camp Creek (McConnell and others, 2003), the Menatchee Creek interbed (Stoffel, 1984), and Grouse Creek, and Squaw Creek interbeds Ross (1978). The lowermost Squaw Creek and La Grande members are laterally extensive and are marked by rhyolitic, lithic ash-flow tuff, mud flow breccias, and air-fall tuff. The La Grande member crops out beneath an olivine basalt flow at the base of the Powder River Volcanic Field and includes tuffaceous siltstone, mudstone, fine-grained tuffaceous and arkosic sandstone, diatomite, and rhyolitic lithic tuff. Rhyolitic lithic tuff is also exposed beneath basal Powder River Volcanic Field olivine basalt flows west of Elgin and on Cricket Flat, east of Elgin (Carson, 2001). The Cricket Flat exposures also contain broken quartzite cobble gravels; presumably derived the older Tertiary gravels exposed at Jim White Ridge, in the headwaters of the Minam River. Tuffaceous siltstone and diatomite are also exposed beneath the basal Powder River Volcanic Field olivine basalt flows located in the extreme southern part of the basin. Where exposed between the top of the Wanapum Basalt and base of the Saddle Mountains Basalt at Lookingglass Creek, the Squaw Creek member forms a 30 m thick sequence of fine-grained, tuffaceous sandstone, diatomite, and vitric air-fall tuff. Tuffaceous sandstone and obsidian clast gravel are also exposed beneath the base of the Saddle Mountains Basalt near Tollgate to the west. A 1 – 5 m thick rhyolite lithic ashflow tuff crops out above Grande Ronde Basalt flows at the base of the Starkey member near Spring Creek (Ferns and others, 2001). The olivine basalt flow that marks the base of the Powder River Volcanic Field is locally exposed near the base of the 100 m thick Starkey member, a sequence of interbedded, weakly-indurated, coarse tuffaceous sandstone, siltstone, and pre-Tertiary-clast, gold-bearing, pebble conglomerate. The Starkey member gravels contain well rounded quartzite cobbles presumably derived from the older Tertiary gravels at Camp Carson. Based on water well logs, the upper part of the unit more than 150 m thick north of Elgin, where it is consists largely of tuffaceous and arkosic, fine-grained sandstone and siltstone. The Menatchee Creek and Grouse Creek interbeds in the northern exposures of the unit are marked by 1 – 4 m thick lignite coal beds (Stoffel, 1984). Unit also includes unnamed, poorly exposed cobble gravels interbeds within the Powder River Volcanic Field. Middle Miocene to Pliocene age based on stratigraphic position. Lower Squaw Creek and La Grande members are middle Miocene, based on stratigraphic position beneath the basalt of Umatilla (13.64 $\pm$ 0.17 Ma) and above the ferroandesite of Fiddlers Hell (15.54 $\pm$ 0.1 Ma) respectively. Upper part of the unit at Elgin is overlain by the 5.7 $\pm$ 0.9 Ma trachyandesite flow at the Rock Wall and the 2 Ma andesite at Jones Butte. Northern part of the unit is considered by Stoffel (1984) to be correlative with the Ellensburg Formation of Smith (1901). Southern part of the unit extends southwestward into the lower Powder River Valley where it thickens to 150 m in thickness (Walker, 1990).

Figure 15 Photograph of the Squaw Creek interbed near Lookingglass Creek. Here the interbed includes waterlain ash, fine-grained tuffaceous sandstone, and diatomite. Note large blocks of overlying Saddle Mountains Basalt in the landslide debris to right.

Columbia River Basalt Group Much of the upper Grande Ronde River basin is underlain by middle Miocene tholeiitic flood lavas of the Columbia River Basalt Group (CRBG). Tolan and others (1989) estimate that more than 175,000 km^3 of Columbia River Basalt flood lavas underlie the Pacific Northwest (Tolan and others, 1989). Individual Columbia River Basalt Group units were mapped on the basis of stratigraphic position, geochemistry, thermal remanent magnetic polarity, and petrography following the work of Swanson and others (1981); Reidel and others (1989) and Ferns and others (2001). Columbia River Basalt Group formations exposed in the map area include the Saddle Mountains Basalt, the Wanapum Basalt, the Grande Ronde Basalt, and the Imnaha Basalt. North of Elgin, the Umatilla flow, the oldest member of the Saddle Mountains Basalt, interfingers with the basalt of Little Catherine Creek, the oldest member of the Powder River Volcanic Field

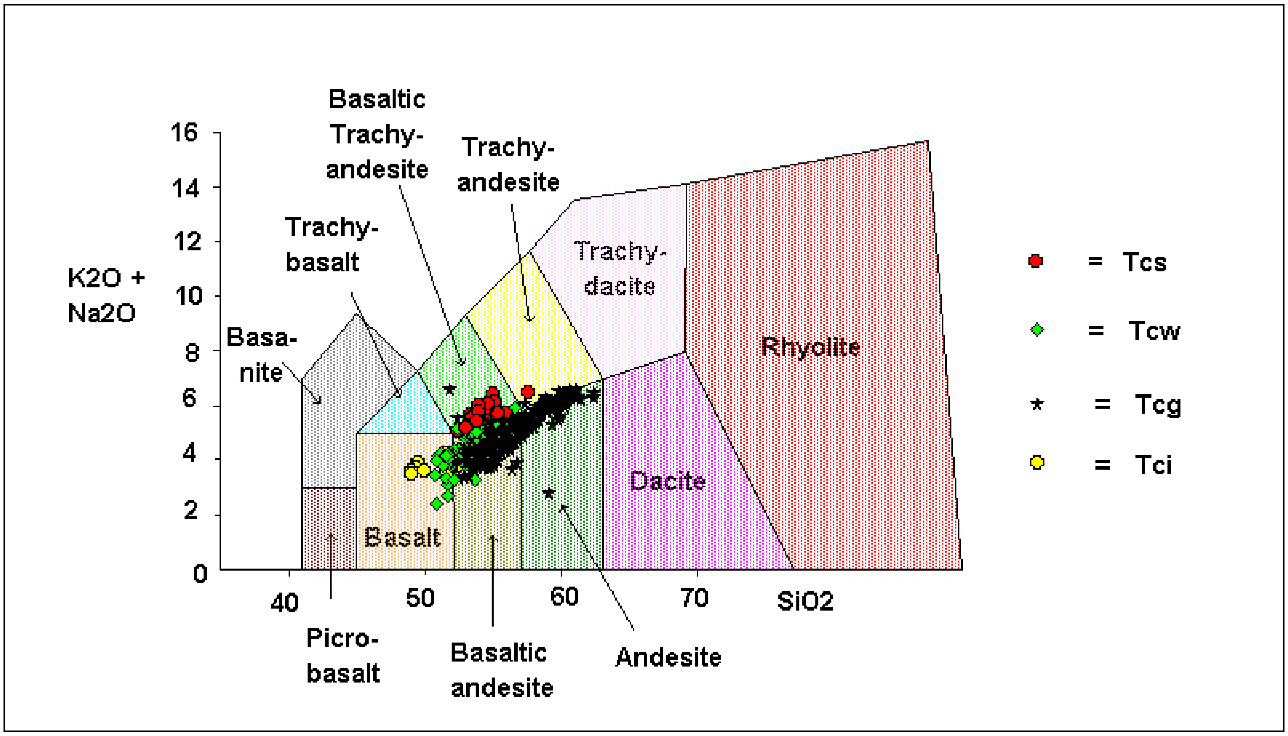

Figure 16 TAS Diagram for the Columbia River Basalt Group. Note that the Imnaha and Wanapum Basalt are basalts while the Grande Ronde Basalt is mostly basaltic andesite and andesite according to the TAS classification scheme while the Saddle Mountains Basalt is mostly basaltic trachyandesite. Fields are from Le Bas and others (1991).

Tcs Saddle Mountains Basalt (upper and middle Miocene) Bluish gray to dark bluish black and black, aphyric and plagioclase phyric, iron-rich basaltic trachyandesite and trachyandesite. Unit includes two separate flows, the basalt of Eden, and the basalt of Umatilla. Each flow varies markedly in thickness; with the Umatilla flow locally being as much as 60 m thick. Both flows often weather to large blocks and readily form talus slopes and landslides. The basalt of Eden is a porphyritic holocrystalline flow marked by conspicuous feldspar phenocrysts as much as 0.5 cm in length and clear green olivine phenocrysts as much as 0.2 cm in diameter. The basalt of Umatilla is a gray to blue-black, fine to medium grained holocrystalline flow that typically weathers to pale yellow brown and pale orange brown. Goethite-filled vesicles are often found at the base of the Umatilla flow. Each flow is underlain by tuffaceous and arkosic sediments and readily forms landslides. The basalt of Eden is an iron-rich basaltic trachyandesite marked by high potassium (> 2 wt % K2O), phosphorous (> 1.4 wt % P2O5) and barium (>1,800 ppm Ba). The basalt of Umatilla ranges from in composition from an iron-rich trachyandesite to an iron-rich basaltic trachyandesite marked by high potassium (>2.5 wt % K2O) phosphorous (> 1 wt % P2O5) and exceptionally high barium (>3,000 ppm Ba). Both flows display normal remanent magnetic polarity. Middle Miocene age based on stratigraphic position and $^{36}Ar/^{40}Ar$ – $^{39}Ar/^{40}$ Ar isochron age of 13.64 $\pm$ 0.17 ma for the basalt of Umatilla. A $^{39}Ar/^{40}$ Ar plateau age could not be determined due to excess radiogenic argon in the dated Umatilla sample.

Tcw Wanapum Basalt (middle Miocene) Light bluish gray, grayish brown, and dark bluish gray, iron-rich, basalt and basaltic andesite lava flows. Includes four petrographically and chemically distinctive units. From top to bottom, unit includes the basalt of Powatka, the Frenchman Springs member, the basalt of Lookingglass, and the basalt of Dodge. Unit is as much as 130 m thick. The basalt of Powatka is a light bluish gray, platy, medium- to fine-grained aphyric basaltic andesite that is commonly deeply weathered and seldom forms good outcrops. The basalt of Powatka thins to less than 5 m in thickness to the west. The underlying Frenchman Springs member consists of thin, grayish black, fine to medium-grained aphyric basalt flows that are marked by orangish-red or red weathering rinds. The Frenchman Springs member thickens to the west. The basalt of Lookingglass is a black, fine-grained aphyric basaltic andesite that seldom forms good outcrops. The basalt of Dodge consists of grayish brown, medium- to coarse-grained olivine basalt flows; one of which contains distinctive plagioclase phenocrysts as large as 3 cm in length. Dodge flows are commonly deeply weathered, forming grussy outcrops marked by spheroidal weathering core stones. In covered areas, the basalt of Dodge is often marked by springs and wet seeps. Both the Dodge and Lookingglass members thin to the west. Individual Wanapum Basalt flows are chemically distinctive. The basalt of Powatka is an iron-rich basaltic andesite with notably high phosphorous ($\geq$ 1.2 wt % P_2O_5). Frenchman Springs are marked by high titanium ($\geq$ 3.00 wt % TiO_2). The basalt of Lookingglass is an iron-rich basaltic andesite marked by moderate phosphorous (~ 0.8 wt % P_2O_5). The basalt of Dodge is a basalt marked by low titanium ($\leq$ 1.5 wt % TiO_2) and potassium ($\leq$ 0.5 wt % K_2O). Based on geographic distribution, the Lookingglass and Powatka flows erupted from buried vents within the quadrangle. The Frenchman Springs eruptive center is probably marked by the Frenchman Springs dike complex mapped by Kuehn (1995) in the headwaters of the Walla Walla River. The feeder dike for the Dodge flow is located to northeast of Rondowa (Hooper and Swanson , 1990). All members display normal remanent magnetic polarity. The Frenchman Springs member is generally considered to be about 15.3 Ma (Tolan and others, 1989).

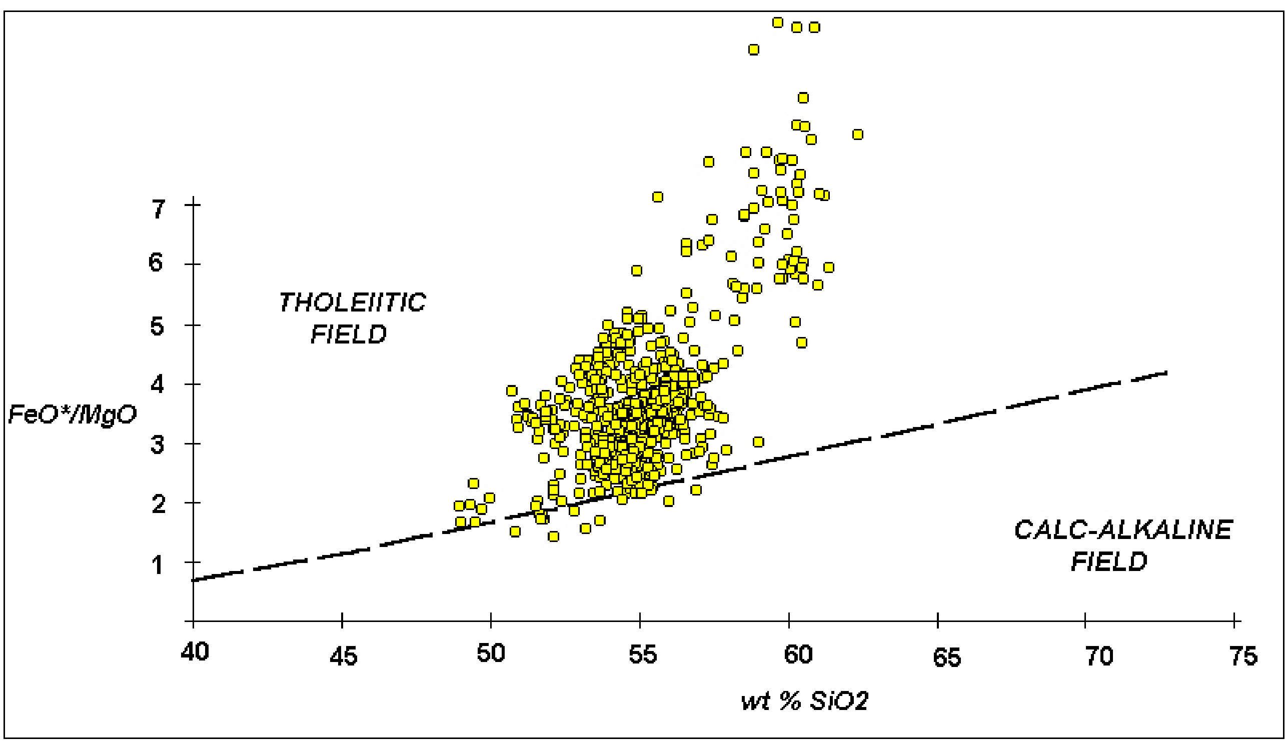

Figure 17 FeO*/MgO vs SiO2 diagram showing the strong iron enrichment trend that defines the tholeiitic nature of the Columbia River Basalt Group. Tholeiitic and Calc-alkaline fields are from Myashiro (1974).

Tcg Grande Ronde Basalt (middle and lower Miocene)- Flow-on-flow sequence of bluish-black aphyric to sparsely plagioclase phyric iron-rich basaltic andesite and andesite lava flows. Includes both holocrystalline and glassy lavas that weather to form steep slopes. Individual flows generally weather to orange-brown, angular blocks. Commonly platy or hackly jointed; thicker flows are sometimes columnar jointed. Differential weathering often results in distinctive bench topography, where the more easily erodable intraflow breccias are marked by bands of trees and the more resistant flow interiors form grass covered benches and continuous cliffs. Includes four magnetostratigraphic units that elsewhere have been mapped as separate members (Swanson and others, 1979; Ferns and others, 2001). Unit is made up of chemically distinctive flow packages that mark either recurring eruptions of a single magma type or successive lobes of a single, long lasting eruption. Distinctive flow packages are not distributed uniformly over the map area. Top of the unit in the subsurface of the Grande Ronde Valley is marked by a series of thin (< 15 m thick), chemically distinctive, sparsely plagioclase-phyric, glassy iron-rich andesite flows (ferroandesite of Fiddlers Hell, Ferns and others, 2001) that are among the most evolved lavas in the Grande Ronde Basalt. Fiddlers Hell flows are marked by relatively high silica (≥ 56 wt % SiO_2), potassium (≥ 2 wt % K_2O) and phosphorus ($\geq$ 0.6 wt % P_2O_5), and low magnesium (≤ 3 wt % MgO). The Fiddlers Hell thins to the north and west. Top of the Grande Ronde Basalt northwest of Elgin is marked by a series of thin (<15 m thick), medium-grained, holocrystalline, iron-rich basaltic andesite flows of the Sentinel Bluffs chemical type (Reidel and others, 1989). Sentinel Bluff flows are among the most primitive lavas in the Grande Ronde Basalt and are marked by relatively low potassium (≤ 1.5 wt % K_2O), phosphorus (≤ 0.3 wt % P_2O_5), titanium (≤ 1.9 wt % TiO_2) and high magnesium (≥ 4.5 wt % MgO). The Sentinel Bluff thickens westward across the northern part of the basin, forming a package of flows as much as 150 m thick. Compositions of other flow packages generally fall somewhere between these two chemical types. Unit apparently thickens to the northwest; showing an overall pattern of northward offlapping of successively younger flows (Hooper and Swanson, 1990). Base of the unit in the southwest part of the basin is locally marked by sparsely olivine phyric holocrystalline flows of the Buckhorn Springs chemical type of Reidel and others (1989) (Ferns and others, 2001). Unit disconformably overlies a deeply eroded surface of older units, with flows of both the oldest (Buckhorn Springs type) and youngest (Fiddlers Hell type) locally filling channels in eroded pre-Tertiary units. A 15.54 ± 0.01 $^{40}Ar/^{39}Ar$ age determination (Madin, 1999) for the ferroandesite of Fiddlers Hell places a middle Miocene limit on the youngest Grande Ronde Basalt flows. The entire Grande Ronde Basalt section is generally considered to have erupted between 15.0 and 16.1 Ma (Hooper and others, 2002).

Figure 18 Canyon of Lookingglass Creek, showing the typical topography and outcrop pattern formed by stacked Grande Ronde Basalt flows. Interiors of flows commonly form benches while tree bands, which here define horizontal strips, often mark intraflow zones.

Tcgv Vent and hydrovolcanic deposits (middle Miocene)— Scoria, welded spatter, and cinder deposits. Includes northwest elongated vent complexes as much as 70 meters high that are capped by banded red and black glassy, welded spatter. Welded spatter typically a dense black glass that breaks to a hackly fracture. Unit also includes 200 – 400 m diameter cylindrical masses of massive, matrix supported diatreme breccias (Taubeneck, 1980). The Indian Rock breccia is a massively bedded, matrix-supported breccia containing vesicular clasts as large as 30 cm in length. Matrix is comprised of comingled altered gray glass, volcanic rock fragments, and rare plagioclase phenocrysts Unit also includes bedded brown, yellowish-brown, or orangish brown basaltic scoria and cinder deposits at that are clast-supported breccias with dark gray to black, finely vesiculated lapilli as much as 3 cm in diameter set in a orange matrix of orange palagonite glass. Analyses of glass and scoria indicate that these are Grande Ronde vent complexes. Analyses of glassy scoria are iron-rich basaltic andesite or andesite (~ 56 wt % SiO_2) marked by relatively high titanium ($\geq$ 2.4 wt % TiO_2) and phosphorus ($\geq$ 0.4 wt % P_2O_5). The scoria and welded spatter mounds overlie flows displaying normal remanent magnetic polarity. Stratigraphic position suggests that the spatter mounds may be a vent complex related to the Winter Water flows of Reidel and others (1989, 1996). Individual lapilli are fine-grained and sparsely plagioclase-phyric.

Figure 19 Indian Rock vent complex. Indian Rock is a cylindrical mass some 400 m in diameter of massive, matrix supported breccias. Indian Rock has been described as a diatreme (Taubeneck , 1980) and may be a hydrovolcanic complex that formed beneath a now eroded palagonitic vent.

Tcbi Columbia River Basalt dikes (middle and lower Miocene) Bluish black to black dikes. Generally blocky weathering and hackly jointed. Includes both Grande Ronde and Imnaha Basalt dikes on the headwaters of Catherine Creek and Grande Ronde Basalt dikes on the upper Grande Ronde River. Also includes a dike at the summit of Tower Mountain that may be a feeder for Picture Gorge Basalt flows exposed to the west of the basin. Individual dikes often form positive relief, vertically standing outcrops marked by horizontal columnar joints.

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Tci Imnaha Basalt (lower Miocene) Flow-on-flow sequence of black to brownish black and gray, medium- to coarse grained, plagioclase and olivine phyric, iron-rich, basalt and basaltic andesite flows. Unit readily weathers to form bare gravelly slopes marked by discontinuous cliffs. Vesicular flow tops commonly marked by zeolite amygdules. Typically holocrystalline with plagioclase phenocrysts as large as 3 cm in length. Locally includes diktytaxitic and aphyric flows. Outcrops are often deeply weathered, with spheroidal core stones. Typically iron-rich basalts and basaltic andesites with nominally low potassium ($\leq$ 1.2 wt % K_2O). In comparison to overlying Grande Ronde Basalt flows, marked by generally low silica (49 – 54 wt % SiO_2) and high magnesium (4.45 – 6.75 wt % MgO). Disconformably overlies a deeply eroded surface of pre-Tertiary units. Unit includes both normally and reversely polarized flows (Shubat, 1979 and McConnell and others, 2002). Hooper and others (2002) consider the Imnaha Basalt to have erupted at about 16.1 Ma.

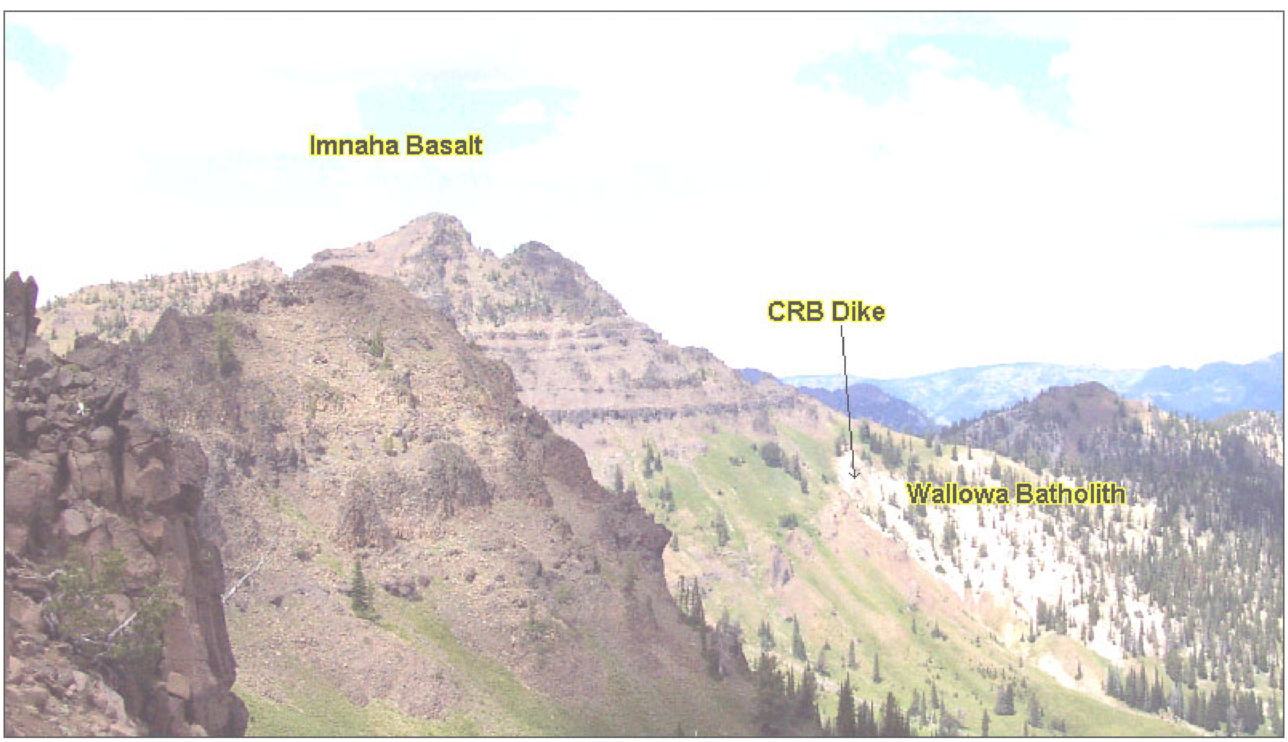

Figure 20 High Hat, looking from the south on the divide between Catherine Creek and the headwaters of the Little Minam River. Here Imnaha Basalt flows, marked by the horizontal bands fill a paleocanyon cut into the deeply weathered Wallowa Batholith. Columbia River Basalt feeder dikes form vertical, dark outcrops.

Tower Mountain caldera (lower Miocene and Oligocene) – Volcanic rocks exposed near the headwaters of the Grande Ronde River are part of the large Tower Mountain caldera, which formed in the late Oligocene (Ferns and others, 2001; Ferns, 2002c). Although considered by Robinson and others (1990) to be coeval with the eastern facies of the John Day Formation, the Tower Mountain caldera is the northernmost of a string of large rhyolite eruptive centers that formed in eastern Oregon during the late Oligocene and early Miocene (Ferns, 2002c). Fringed by dacite, andesite, and basalt flows and dacitic and rhyolitic breccias and ash-flow tuffs, the resurgent core to the 14 km wide caldera is a highlands made up of lithic ash-flow tuff and subvolcanic rhyolite and dacite intrusions. An arcuate belt of rhyolite domes and flows defines the caldera margin (ferns and others, 2001). The caldera margin is marked by prominent gravity and aeromagnetic anomalies (Ferns, 2003c). Mapped lithologic units include:

Tta Andesite and dacite flows (lower Miocene)--Sparsely plagioclase-phyric andesite and dacite flows. Includes the dacite of Johnson Rock, andesite of Chicken Hill, and rhyodacite of Sheep Creek of Ferns and others (2001). The unit is made up of gray, flow-foliated, platy and massive, aphyric and porphyritic lavas. The Johnson Rock flow has a micaceous luster due to partially resorbed biotite phenocrysts. The Chicken Hill and Sheep Creek flows are each porphyritic with plagioclase, hypersthene, and augite phenocrysts. Flows are irregular in shape, reaching thicknesses of more than 140 m. Unconformably overlies volcaniclastic breccias, ash-flow tuff and porphyritic lava flows. Early Miocene age is based on 22.4 $\pm$ 0.16 Ma whole rock $^{40}Ar/^{39}Ar$ radiometric determination for the Johnson Rock flow (Ferns, 1999; Ferns and others, 2001).

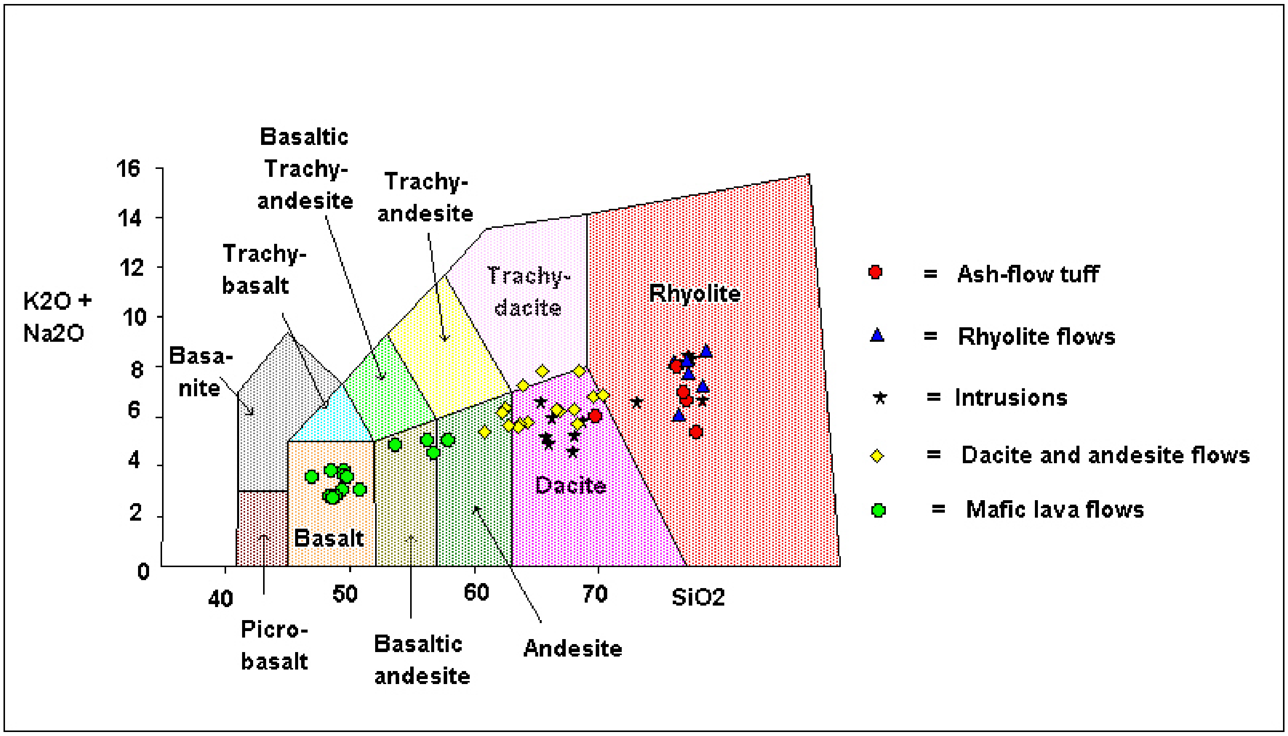

Figure 21 TAS diagram for lavas, tuffs, and intrusions associated with the Tower Mountain caldera.

Ttr **Rhyolite (upper Oligocene)--**White to yellowish-gray, flow-banded, platy porphyritic and aphyric rhyolite domes and flows. Unit includes an arcuate flow-dome ring complex that was emplaced along the southern margin of the Tower Mountain caldera. Steeply dipping matrix-supported and clast-supported tuffaceous, rhyolite-clast breccias and complexly folded flow-banded rhyolite lava mark individual dome margins. Dome margins are locally marked by steeply dipping perlitic zones as much as 50 m wide that contain lenses of massive pale reddish-brown and light-green lithophysal rhyolite. Dome interiors are marked by platy white rhyolite. In hand sample, the porphyritic varieties commonly show a mottled texture due to presence of 2 to 5 percent feldspar phenocrysts. These are commonly spherulitic and feldspar phyric with 3 mm plagioclase and potassium feldspar phenocrysts set in a groundmass of quartz, potassium feldspar, and plagioclase. Aphyric rhyolites commonly contain partially zeolitized spherulites set in a groundmass of quartz, potassium feldspar and plagioclase. Although the contact between the rhyolite domes and the caldera-fill, lithic ash-flow tuff (unit Ttt) is steep and generally poorly exposed; the rhyolites appear to have been emplaced following the ash-flow eruption. Rhyolite flows overrun non-welded ash-flow and air-fall tuff at the top of unit Ttvs. Unit also includes porphyritic dome complexes on Fly Creek and the Grande Ronde River (Ferns and others, 2001) which intrude dacite lava flows north and east of the caldera margin. The dome complex on the Grande Ronde River is coarsely porphyritic, containing about 10 percent plagioclase and quartz phenocrysts as large as 5 mm in diameter. Interpreted as a shallow intrusion into Ttvs lahars; Based on an upper contact zone of intensely bleached, brecciated rhyolite, this dome was interpreted by Ferns and others (2001) as being a shallow intrusion into the lahars of unit Ttvs. All of the domes are high silica rhyolites, with 75 – 78 wt percent SiO_2.

Upper Oligocene age is based on K/Ar age determination of 28.10 ± 1.5 Ma on anorthoclase from a porphyritic rhyolite (Fiebelkorn and others, 1982; Ferns and others, 2001).

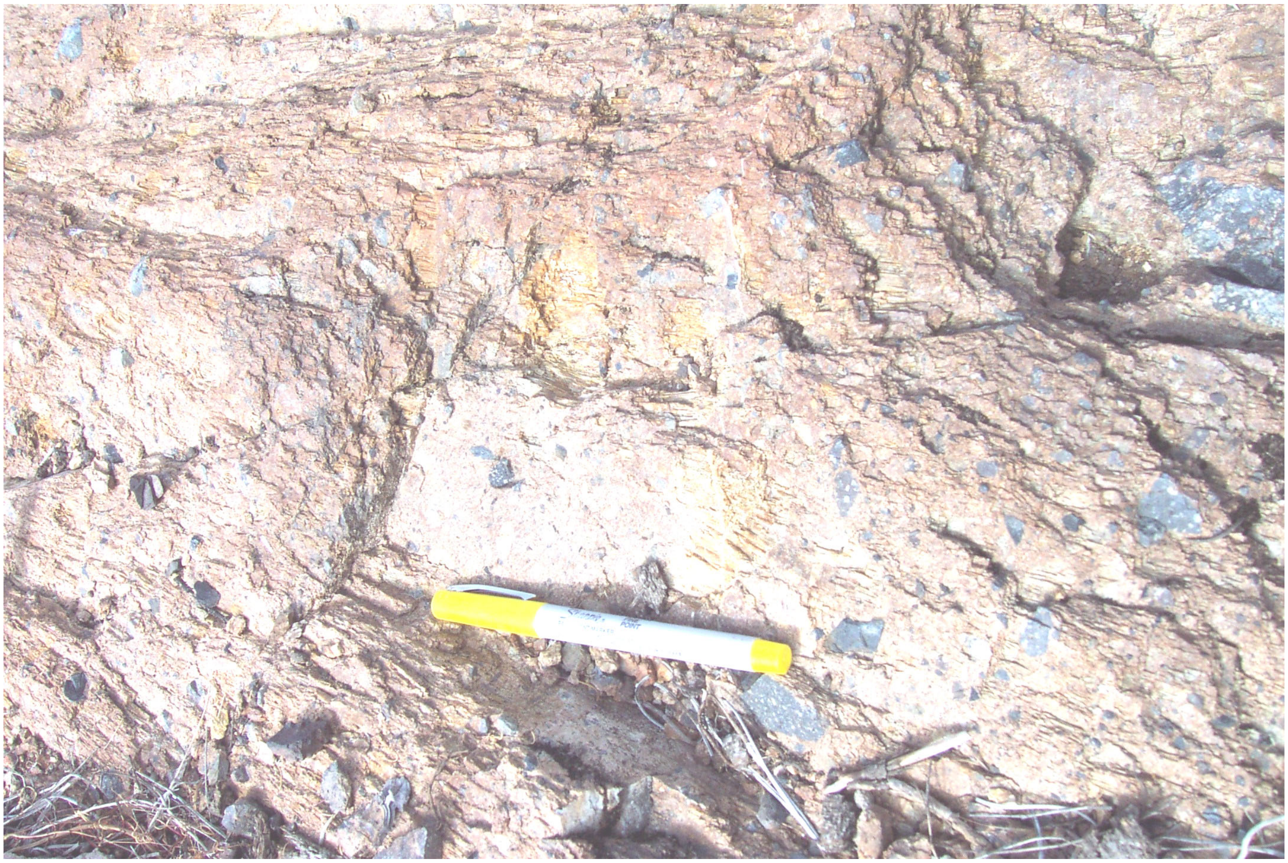

Figure 22 Photograph of lithic tuff (Ttt) within the Tower Mountain caldera. Here the intracaldera tuff is densely welded and marked by flattened fiamme and aphyric rhyolite clasts. Dark gray, angular lithic clasts are porphyritic dacite.

Ttt Welded ash-flow tuff (upper Oligocene)—Unit includes high silica rhyolite and dacitic ash-flow tuffs. Most of the unit is a light-gray, gray, white, and pale yellow, crystal lithic ash-flow tuff deposited in the core of the Tower Mountain caldera. The caldera-fill tuff contains as much as 5 per cent phenocrysts of plagioclase, and quartz with minor amounts of potassium feldspar and altered biotite. Contains as much as 15 percent lithic clasts, including coarsely porphyritic dacite clasts and flattened pumice clasts as much as 15 cm in length. Commonly intensely altered, with groundmass recrystallized to a felted mat of fine-grained quartz and potassium feldspar. Unit is over 100 m thick in the central part of the map area and is considered to be a caldera fill sequence of ash-flow and air-fall tuff. Based on whole rock analyses, the caldera-fill ash-flow is a high silica rhyolite with 77 percent SiO_2, 14.8 percent Al_2O_3 and 3.6 – 4.7 percent K_2O. Unit also includes a thin crystal-rich, dacitic ash-flow tuff that locally crops out at the base of the overlying andesite (Tta) and dacite (Ttd) flows. The dacitic tuff is about 25 m thick with an upper welded zone marked by light-gray tuff with subhorizontal flattened fiamme. Lower zone is poorly exposed and consists of devitrified white to pale orange tuff. Welded zone is devitrified with 2 - 5 percent plagioclase phenocrysts less than 2 mm in diameter and highly altered, skeletal green hornblende phenocrysts rimmed with opaque oxide minerals. Based on whole rock analyses, the dacite tuff contains 69.71 wt percent SiO_2, 16.06 wt percent Al_2O_3, and 1.85 wt percent K_2O (Table 1, Ferns, 1998). Although mapped only east of Sheep Creek, welded tuff float occurs below unit Tta on the headwaters of Chicken Creek.

Ttd Porphyritic lavas of Chicken Creek (upper Oligocene) Massive gray, purplish-gray, and bluish-gray, porphyritic andesite and dacite lava flows. Conspicuously porphyritic, with as much as 15 percent phenocrysts and xenoliths as large as 5 cm in diameter. Individual flows commonly grade upward from a coarsely plagioclase-phyric basal vitrophyre into massive, platy-jointed stony lava. Flow tops and margins are marked by coarse, clast-supported breccias. At least three separate flows are exposed, each containing phenocrysts up to 7 mm in length set in a variably altered, glassy groundmass. Phenocryst assemblages include plagioclase, hypersthene, and augite; plagioclase, olive green hornblende, and hypersthene; and plagioclase, quartz, hypersthene, and augite. Individual flows typically contain numerous (as much as 2 percent) holocrystalline xenoliths made up of hypersthene, augite, and plagioclase. Includes flow-banded dacite lava flows with about 5 percent plagioclase phenocrysts as large as 2 mm in diameter and underlying, 1 - 2 m thick tuffaceous conglomerates and lithic breccias. Compositions range from high-silica andesite to dacite (63 - 68 wt percent SiO_2) (Ferns, 1998; Ferns and Taubeneck, 1994). Unit is more than 300 m thick and locally interfingers with underlying pyroclastic deposits of unit Ttvs. Oligocene age based on K – Ar date of 28.8 Ma (Fiebelkorn and others, 1983) on a porphyritic hornblende-phyric andesite on Sheep Creek.

Ttba Basalt, basaltic andesite, and andesite (upper Oligocene) Platy, grayish-red to grayish-black, sparsely phyric basalt, basaltic andesite, and andesite flows that locally fill channels within unit Ttvs. Includes hyalopilitic to pilotaxitic olivine-plagioclase-phyric flows with granular clinopyroxene microphenocrysts. Also includes plagioclase-augite phyric andesite and orange weathering, bluish-black olivine basalts that contain ophitic clinopyroxene. Compositions range from basalt with about 49 wt percent SiO_2 to andesite with 56 wt percent SiO_2. (Ferns and Taubeneck, 1994).

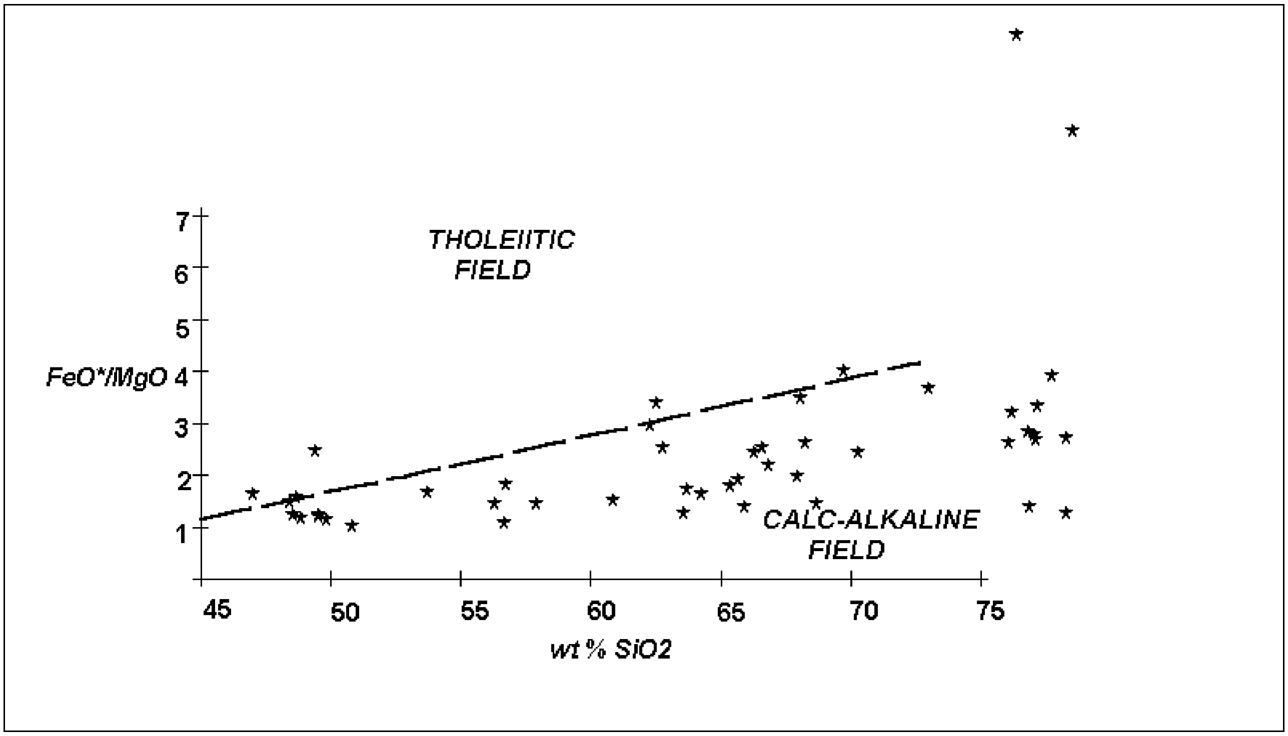

Figure 23 FeO*/MgO diagram for lavas related to the Tower Mountain caldera, showing calc-alkaline affinities. Note that the extreme iron enrichment shown by some of the rhyolites reflects the nearly total depletion of magnesium in these lavas. Some of the Tower Mountain rhyolites show extreme iron enrichment and plot out of the field of view. This extreme iron enrichment is due to the near total depletion of magnesium in these high silica rocks.

Ttvs Volcaniclastic deposits of Limber Jim Creek (upper Oligocene)-- Mainly debris flow deposits locally interbedded with and underlying porphyritic dacite and andesite flows of unit Ttd. Unit consists of coarse, matrix- and clast-supported, tuffaceous breccia largely composed of angular to subrounded clasts of porphyritic andesite and dacite. Unit includes a gray or light gray, hackly jointed, crystal-lithic, hornblende-bearing tuffaceous breccia with porphyry clasts as large as 5cm in diameter. Consists mainly of poorly sorted, massive-bedded breccia exposed adjacent to massive exposures of Ttd lavas. Includes primary debris-flow deposits associated with Ttd lava flows. Locally includes medium grained, tuffaceous conglomerates made up of rounded dacite, andesite, and rhyolite clasts. Along the southern flank of the Tower Mountain caldera, unit grades from matrix supported rhyolite-clast breccias to matrix and clast-supported dacite-porphyry clast breccias. Locally contains large casts of . Unit thickens to the east, where over 225 m of interbedded breccias and tuffaceous conglomerates are exposed along Limber Jim Creek (Ferns and Taubeneck, 1994). Easternmost exposures on Beaver Creek consist mainly of massive tuffaceous siltstone. Age of unit is based on stratigraphic association with unit Ttd.

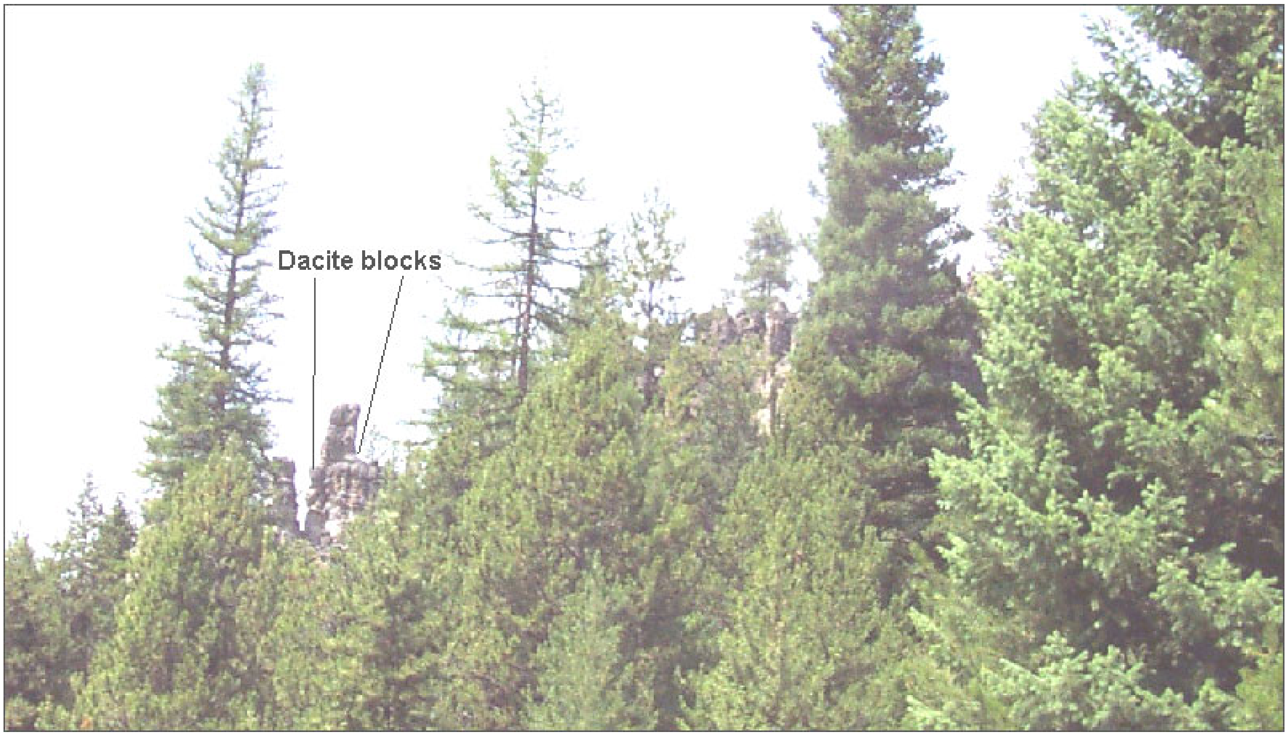

Figure 24 The volcaniclastic deposits of Limber Jim Creek often form cliffs and spires. Dacite capstones protect some spires, readily forming a hoodoo topography that is usually masked by dense forest cover. These exposures crop out along the upper Grande Ronde River.

Ttb Basalt and basaltic andesite (Oligocene) Mainly fine-grained equigranular, brownish-gray to brownish-black vesicular olivine basalt flows. Unit includes widely separated flows locally exposed at the base of unit Ttvs that are chemically and petrographically distinct. Flow compositions range from potassium- and titanium-rich alkali olivine basalt flows (47.37 wt percent SiO_2; 15.44 wt percent Al_2O_3, 4.6 wt percent TiO_2; 1.59 wt percent K_2O) to low potassium olivine basalt flows (48.38 wt percent SiO_2; 15.21 wt percent Al_2O_3, 1.30 wt percent TiO_2, 0.33 wt percent K_2O) (Ferns and Taubeneck, 1994). Individual flows are generally hyalophitic with subophitic clinopyroxene. Commonly altered or deeply weathered, with thick spheroidal weathering rinds and zeolite- and/or calcite-filled vesicles. Overlain by unit Ttvs and underlain by various pre-Tertiary units. Oligocene age based on $^{40}Ar/^{39}Ar$ radiometric age of 29.80 $\pm$ 0.39 Ma for a flow in the Anthony Butte quadrangle (Ferns and others, 2001; Madin and Taubeneck, in press).

Tertiary Subvolcanic Intrusions

Ttbi **Mafic intrusions (upper Oligocene)**--Basalt and basaltic andesite dikes and sills. Mainly black to grayish-black, aphyric to glomeroporphyritic dikes. Includes a 100-m-wide, east-west trending dike near the headwaters of Sheep Creek.

Ttri **Rhyolite intrusions (lower Miocene - upper Oligocene)**-- Mainly aphyric to plagioclase-phyric rhyolite dikes and small intrusions that are locally columnar jointed. The dikes are white to light gray on fresh surfaces and weather to shades of light purple. Often finely laminated with as much as 5 percent plagioclase phenocrysts. Rare mafic phenocrysts altered to fine-grained mass of chlorite and biotite. Groundmass may be altered to fine-grained mat of quartz, biotite, and potassium feldspar. Unit includes high silica rhyolite stocks with 77 percent SiO_2. Rhyolite intrusions include small, irregularly shaped stocks intrusive into the caldera fill sequence (Ttt) and a small, west-northwest trending swarm of rhyolite dikes that cut across the caldera margin. Within the caldera, the rhyolite intrusions are usually intensely silicified and cut by cryptocrystalline quartz seams less than 1 mm thick. Age based on intrusive relationships within the caldera.

Ttdi **Dacite and andesite intrusions (upper Oligocene)--** Mainly dikes and small plugs of hornblende-phyric dacite intrusive into caldera fill tuffs of unit Ttt. Unit also includes a number of aphyric to slightly plagioclase-phyric, bluish-gray silicic andesite and dacite intrusions exposed east of the caldera. Irregularly shaped, platy-jointed, subvolcanic intrusions exposed on Little Fly Creek contain less than 1 percent plagioclase and hypersthene phenocrysts 1-2 mm in length. The porphyritic intrusions commonly contain as much as 15 percent phenocrysts as much as 6 mm across. Phenocrysts include plagioclase, quartz, and potassium feldspar. Unit also includes unaltered dikes and small plugs of hornblende-phyric rhyodacite that form massive to columnar-jointed, gray to light-bluish-gray outcrops. Also includes a small, unaltered hornblende phyric rhyodacite plug exposed east of the caldera margin (Ferns, 1998). Most of the intrusions are dacites with between 65 and 69 wt percent SiO_2. Many of the dikes within the caldera are hydrothermally altered; alteration assemblages range from chlorite + carbonate to potassium feldspar + biotite. Thin argillic alteration zones and pyritic seams occur along small faults and joints in the large Chicken Creek intrusion.

Teg **Conglomerate, sandstone, and siltstone (lower Oligocene? to Paleocene?)** Compositionally heterogeneous unit that includes conglomerate, siltstone, and sandstone. Poorly exposed and only moderately lithified. Best exposures are in the old hydraulic placer mine workings, where a basal, gold-bearing, boulder conglomerate fills channels cut into underlying pre-Tertiary units. The basal conglomerate, locally referred to as the Carson Wash (after Lindgren, 1901) is marked by light orange-weathering metamorphic quartzite clasts as large as 60 cm in diameter. The quartz and feldspar-rich sand matrix to the conglomerate contains pink translucent garnet and placer gold. Where exposed at the old Camp Carson placer mine, the basal conglomerate is 2 - 6 m thick and is overlain by at least 8 m of tuffaceous sandstone, finely-laminated dark organic-rich silt- and mudstone and 12 m of matrix-supported, tuffaceous chert-clast conglomerate. An upper conglomerate contains clasts 1 - 10 cm across of bluish-black chert and argillite and deeply weathered white tuff and rhyolite. Lava flow and tuffaceous units of the Tower Mountain Volcanic Field unconformably overlie the unit. Through much of the map area, poorly exposed and mapped on the basis of quartzite boulders or black chert pebbles. Locally includes tuffaceous sedimentary rocks that are most likely distal facies of units in the overlying Tower Mountain Volcanic Field. Probable Eocene/Paleocene age is based on interpretation that the unit is a high-energy river channel deposit associated with the deltaic sandstones of the Herren Formation that are exposed to the west (Ferns and others, 2001).

MESOZOIC INTRUSIVE ROCKS

Two large Mesozoic intrusions (Bald Mountain Batholith and Wallowa Batholith) are exposed in the headwaters of the upper Grande Ronde River basin. Both batholiths are made up of smaller individual intrusions that are chemically and petrographically distinct. The composite Bald Mountain Batholith (Lindgren, 1901; Taubeneck, 1957, 1995) forms the core to the Elkhorn Mountains, at the headwaters of the Grande Ronde River. The Wallowa Batholith (Taubeneck, 1964a,b, 1967) forms the core to the Wallowa Mountains and the headwaters area to Catherine Creek.

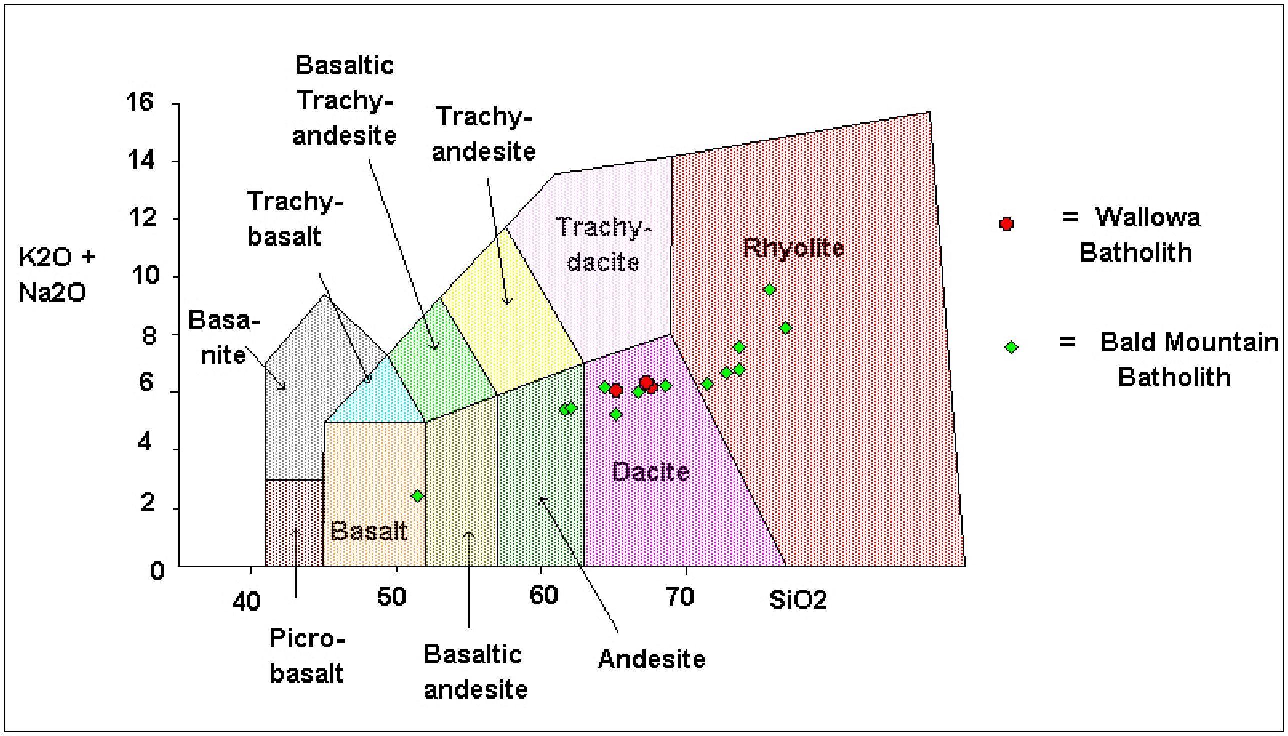

Figure 25 Although the TAS diagram is generally not applicable for naming coarse grained intrusive rocks; the diagram is useful for showing evolutionary trends. Intrusives associated with the Bald Mountain Batholith show a wider range of values in the upper Grande Ronde River basin than do those associated with the Wallowa Batholith.

Wallowa Batholith (lower Cretaceous) Composite intrusion that contains 4 separate compositionally zoned plutons, each ranging in composition from tonalite to granodiorite. Unit includes the westernmost exposures of the tonalitic Wallowa Batholith a small satellite intrusion exposed along Catherine Creek.

Kwt (lower Cretaceous) Tonalite and granodiorite of the Wallowa Batholith Gray, to light gray, medium-grained granodiorite and tonalite, best exposed in the ridges bordering the head of Catherine Creek. According to Taubeneck (1995), the main exposure belt at the head of Catherine Creek is made up of two discrete compositionally zoned plutons (Units 2 and 3; Taubeneck, 1987) that range in composition from tonalite to granodiorite. Tonalite phase is typically fine to medium grained and composed largely of quartz, plagioclase, and hornblende. Interstial biotite and potassium feldspar is common. The deeply-weathered tonalite exposed in road cuts and mine workings at the confluence of the South and North forks of Catherine Creek, intrudes calcareous sediments and appears identical to the main intrusive mass exposed in the Wallowas. Limited geochemical analyses are typical of calc-alkaline tonalities, with 67.27 – 67.6 wt % SiO_2; 15.80 – 16.09 wt % Al_2O_3; 2.58 – 2.75 wt % K_2O and 3.61 – 3.63 wt % Na_2O. Main tonalite phase of the Wallowa Batholith is generally considered to be early Cretaceous in age; Walker, 1988 reported U-Pb (zircon) ages of ~ 137 Ma for the oldest pluton in the Wallowa Batholith.

Kwi Trondjhemite of Catherine Creek (lower Cretaceous or upper Jurassic) Gray, fine- to medium-grained trondjhemite and diorite exposed in a road cut downstream of the Catherine Creek State Park (Ferns and others, 2002a). The intrusion is poorly exposed and, where forming outcrops, largely altered, with mafic minerals replaced by chlorite. Pegmatites with pink potassium feldspar and quartz are found as float. Based on mineralogy and geochemistry, considered to be a trondjhemite, having 65.13 wt % SiO_2; 17.02 wt % Al_2O_3; 1.70 wt % K_2O and 4.39 wt % Na_2O. Age is unknown. Trondjhemite composition may indicate the Catherine Creek intrusion may be younger than main Wallowa Batholith. Johnson (1995) and Johnson and others (1995) indicate that undeformed trondjhemite intrusions in the Blue Mountains are generally younger than the more common tonalite and granodiorite intrusions. Older trondjhemites are generally deformed and metamorphosed. It is unclear whether the extensive alteration present in the Catherine Creek intrusion is due to age or hydrothermal alteration.

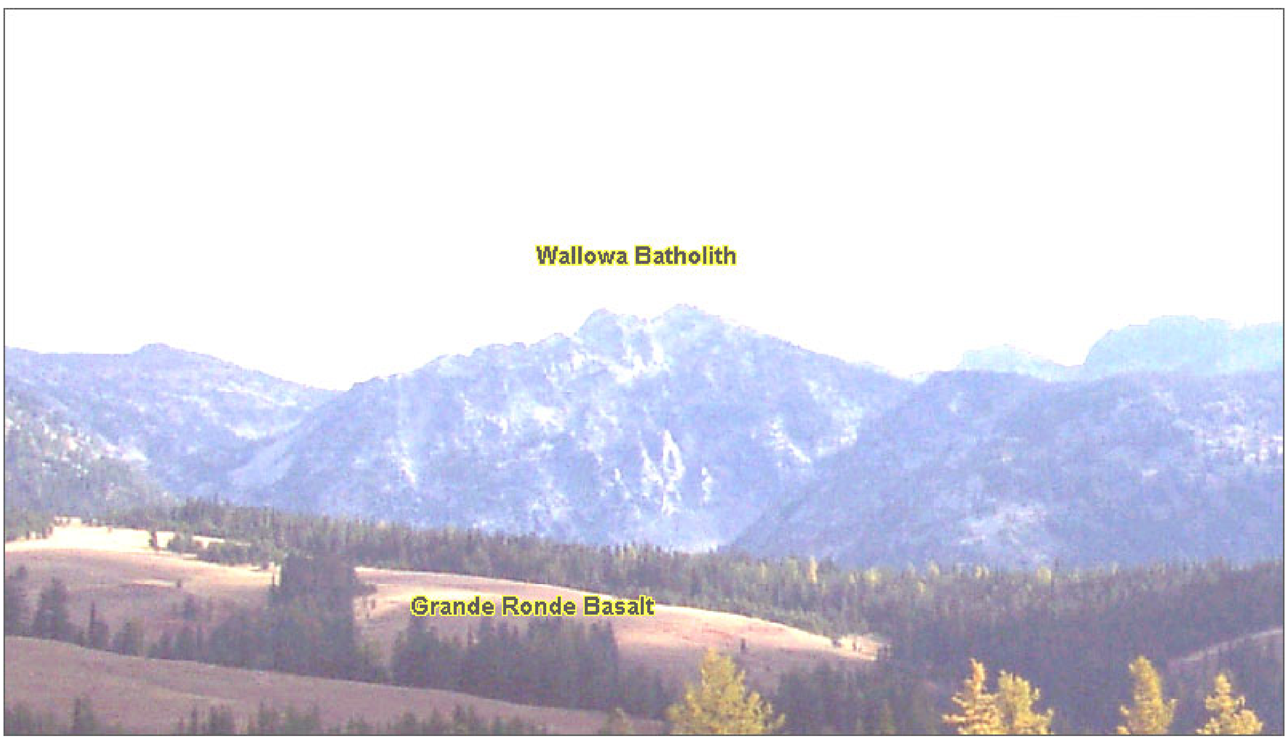

Figure 26 Looking east into the Wallowa Batholith near the headwaters to Catherine Creek, showing the contrast in topography and vegetation between the rugged, glaciated core of the batholith and the grass covered benches in the fore ground that are formed by Grande Ronde Basalt.

Bald Mountain Batholith (lower Cretaceous and upper Jurassic) Composite intrusion whose main phase, the Elkhorn pluton (Taubeneck, 1995) ranges in composition from tonalite to granodiorite. Includes smaller intrusive masses of gabbro, diorite, quartz diorite, granite, and lamprophyre that are mapped separately on the basis of composition. Also includes highly metamorphosed inclusions of older country rock that are entrained along intraplutonic contacts. For detailed descriptions of individual intrusives, and inclusions, see Taubeneck, (1995).

KJbt Granodiorite and Tonalite (lower Cretaceous and upper Jurassic) White to light-gray, medium- to coarse-grained, hypidiomorphic-textured biotite-hornblende tonalite and -granodiorite. Includes the Elkhorn pluton, the largest intrusion in the Bald Mountain Batholith, as well as several small satellite intrusions, including the granodiorite of the Indianna Mine Road; the granodiorite of Beaver Meadow, and the tonalite of North Fork. Commonly forms rounded, hummocky outcrops that are mantled by grussy soil. Best natural exposures occur in the glaciated uplands. The Elkhorn pluton is a single intrusion that constitutes about 93 percent of the Bald Mountain Batholith (Taubeneck, 1995). The Elkhorn pluton is typically a medium-grained, pale-gray granodiorite with biotite and euhedral hornblende. The granodiorite of the Indiana Mine Road is a deeply weathered, light gray to white, medium-grained granodiorite that contains small, scattered biotite flakes that define a distinct foliation (Taubeneck, 1995). The granodiorite of Beaver Meadow is a medium grained, light gray granodiorite characterized by scattered megacrysts of potassium feldspar as much as 2.5 cm across (Taubeneck, 1995). The tonalite of North Fork is a light gray, medium-grained mass that intrudes amphibolite and metasediments just north of the North Fork of Anthony Creek. Unit also includes several small, poorly exposed granodiorite and tonalite intrusions in the Guard Station inlier. The Guard Station inlier intrusions are noteworthy as they include pinkish-white to light-gray biotite granodiorites that contain both biotite and muscovite (Taubeneck, 1995; Ferns and Taubeneck, 1994). Upper Jurassic and Lower Cretaceous age based on limited radiometric age determinations. Walker (1989) most recently reported a U/Pb zircon age of ~143 Ma for an early gabbronorite phase of the Bald Mountain Batholith that is exposed on the headwaters to the North Fork of the John Day River. Arrnstrong and others (recalculated by Fiebelkorn and others) reported K/Ar ages for biotite and hornblende ranging between 134 $\pm$ 4 and 159 $\pm$ 5. Armstrong and others also reported a whole rock Rb-Sr isochron date of 147 $\pm$ 17 Ma for the Bald Mountain Batholith.

KJbg Granite (lower Cretaceous?) Includes all small granite stocks intrusive into and peripheral to the Bald Mountain Batholith. Granite intrusions include the granite of Clear Creek (Ferns and Taubeneck, 1994; Taubeneck, 1995), the granite of Anthony Butte, the leucogranite of Dutch Creek (Taubeneck, 1995; Madin, 1998), the leucogranite of Trail Creek (Taubeneck, 1995), and the granite of Isham Spring (Taubeneck, 1995; Madin and Taubeneck, unpublished mapping, Anthony Butte 7.5" quadrangle). The unit also includes several small, poorly exposed granites situated west and north of the main mass of the Bald Mountain Batholith. Granites and granodiorites are generally white to shades of yellow-white in color and are recognized by their pink to white potassium feldspar crystals. The Clear Creek and Anthony Butte granites intrude the main stage tonalite phase of the Elkhorn pluton. The granite of Clear Creek is a white to pale-pinkish white granite that crops out at the confluence of Clear Creek and the Grande Ronde River. The Clear Creek intrusion contains several small muscovite-bioitite-orthoclase pegmatite and aplite dikes. The granite of Anthony Butte is a white to light gray, medium-grained, porphyritic granite that commonly weathers to a yellow-white and orange gruss. The Anthony Butte intrusion contains potassium feldspar megacrysts as much as 3.5 cm long. The leucogranite of Dutch Creek is a deeply-weathered, light grayish white granite comprised of quartz, plagioclase, orthoclase, and less than 2 modal percent biotite. The granite of Isham Spring is a medium, light-gray granite marked by small, scattered biotite flakes that define a distinct foliation (Taubeneck, 1995). The granite of Isham Springs intrudes schistose metasedimentary rocks of unit TRPe.

Figure 27 Photograph of the Anthony Butte granite. Large crystals are potassium feldspar megacrysts. Groundmass is made up of quartz, plagioclase, biotite, and potassium feldspar. Potassium feldspar crystals are found only in the more silicic phases of the Bald Mountain Batholith.

KJbi Mafic and Intermediate Intrusions (lower Cretaceous or upper Jurassic) Dark gray, gray, and greenish-black intermediate and mafic intrusions associated with the Bald Mountain Batholith. Most of the unit consists of quartz diorites; including the quartz diorite of Wolf Creek, the Boundary quartz diorite unit, a small unnamed intrusion in the Guard Station inlier, and several large inclusions enclosed by the granite of Anthony Butte (Taubeneck, 1995). Unit also includes a small lamprophyre stock that is exposed along the Rainbow Mine Road; a small quartz gabbro intrusion exposed in the Guard Station inlier. The quartz diorites are generally gray to grayish white in color and contain both hornblende and biotite crystals. The lamprophyre is a conspicuously coarse grained rock that contains 2-3 cm equant, poikilophitic hornblende crystals with intergrown green clinopyroxene, orthopyroxene, and olivine crystals. . The quartz diorite of Wolf Creek is gray, medium-grained quartz diorite that is made up of aligned tabular, deformed plagioclase crystals set in an interstitial groundmass of quartz and potassium feldspar. The Boundary quartz diorite unit is gray, medium grained quartz diorite characterized by a greenish-gray gruss. The quartz gabbro is a gray, medium grained rock made up of hornblende, augite, plagioclase, and strained quartz crystals. On basis of contact relationships, the lamprophyre is considered to be a late mafic intrusion into the Elkhorn pluton while the quartz diorites and quartz gabbro appear to be precursors to the pluton. The quartz diorites clearly predate the latest granitic intrusions, as the Wolf Creek intrusion, which encloses large quartz diorite inclusions, is cut by the granite of Anthony Butte and the boundary intrusion is cut by the leucogranite of Dutch Creek (Taubeneck, 1995).

KJm Metamorphosed Inclusions (lower Cretaceous or upper Jurassic) Unit consists of masses of pyroxene and hornblende-bearing country rock that are entrained along intra-plutonic contacts within the Bald Mountain Batholith. Unit includes thermally metamorphosed ultramafic, metavolcanic, and metasedimentary rocks that are presumed to have been originally part of the Baker Terrane. Typically gneissic in texture with well defined compositional banding.

MESOZOIC AND PALEOZOIC UNITS

Variably metamorphosed Mesozoic and Paleozoic igneous and sedimentary rocks protrude through younger volcanic cover in several, widely separated areas in the headwaters to the upper Grande Ronde River basin. Based on lithology and complex internal stratigraphy, units are included as parts of the Baker and Wallowa terranes (Silberling and others, 1984; Vallier, 1995; Ave Lallemant, 1995). Mapped units by area include:

Wallowa Terrane

Fine grained calcareous sediments, epiclastic silt- and sandstone, tuff, lava flows, and subvolcanic intrusions exposed in the Catherine Creek drainage are part of the Wallowa terrane, a late Paleozoic and early Mesozoic island arc complex that is best exposed in the Wallowa Mountains and Hells Canyon areas. Wallowa terrane units exposed in the upper Grande Ronde River basin include:

TRws Undifferentiated volcaniclastic and clastic sedimentary rocks (Triassic?) Mainly bluish-gray to light gray argillite and siltstone. Unit is heterogeneous and also includes bluish black calcareous argillite, feldspar-bearing tuffaceous argillite, volcaniclastic sandstone, limestone, and volcaniclastic breccia. Seldom forms outcrops, readily weathering to rounded slopes mantled by angular rock fragments. Commonly thinly bedded (1 – 50 cm) and marked by fracture cleavage. Based on lithology and apparent stratigraphic position, considered to be correlative with the Lower Sedimentary Series of Smith and Allen (1941). Triassic age based on fossil localities in similar appearing strata exposed near Medical Springs (Koch and Bostwick, 1962).

TRPwc Clover Creek Greenstone (Triassic or Permian) Mainly dark-green to dark bluish-gray, metamorphosed volcanic, subvolcanic intrusive, and volcaniclastic rocks that weather to shades of dark brown. Unit is heterogeneous and contains many varieties of metamorphosed volcanic rocks; including quartz keratophyre, quartz keratophyre tuff, spilite, diabase, and meta-andesite. Very poorly exposed, weathering to form rounded hills. Where exposed along roads to the south, typically sheared and chloritized. Equivalent to the Clover Creek Greenstone of Gilluly (1937), which contains both Permian and upper Triassic strata.

Baker Terrane

The Baker terrane is largely made up of broken formation and mélange. Exposures along the upper Grande Ronde River include internally disrupted, fine-grained siliceous deep water sediments of the Elkhorn Ridge Argillite and large, stratally-disrupted slabs of metamorphosed island arc volcanic rocks. Mapped units include:

TRPbe Elkhorn Ridge Argillite (Triassic, Permian, Pennsylvanian and Devonian?) Mainly dark bluish-black to black siliceous argillite and chert. Unit is heterogeneous and includes carbonaceous argillite, feldspar-bearing tuffaceous argillite, and ribbon chert. Generally forms massive outcrops marked by steeply dipping layers. Stratified layers are typically fault- or cataclasite-bounded slabs of steeply-dipping, isoclinally folded chert and argillite. Isoclinal fold noses are commonly sheared. Readily forms jagged outcrops. Typically marked by shallow soils containing abundant angular chips of chert and argillite. Many exposures in the map area show effects of thermal metamorphism due to nearby Mesozoic intrusions. Contact aureoles along the Bald Mountain Batholith are marked by recrystallization of chert to coarser-grained banded quartzities containing biotite and garnet. Hornblende hornfels (hornblende + plagioclase + quartz $\pm$ diopside) and pyroxene hornfels (orthopyroxene + diopside + hornblende + plagioclase +quartz $\pm$ biotite) assemblages occur along contacts between argillite and intrusive rocks (Taubeneck, 1995; Evans, 1989). Godwin (1999) reports biotite + andalusite + cordierite and biotite + andalusite + garnet in the contact aureole of the Bald Mountain Batholith south of the map area. Regional metamorphic grade for the Elkhorn Ridge Argillite is lower greenschist facies; diagnostic mineral assemblages include biotite + chlorite + white mica and white mica + chlorite + quartz (Ferns and Brooks, 1995; Kays and others, 1987). Chemical analyses for regionally metamorphosed chert collected south of the Bald Mountain Batholith show 78.30 - 94.72 wt percent SiO_2; 0.12 - 0.47 wt percent Al_2O_3; and 0.44 - 1.79 wt percent K_2O (Ken Johnson, written communication, 1998). Unit is structurally disrupted, generally dipping steeply to the south. Permian and Triassic age range based on invertebrate fossils from limestone pods and ribbon chert. Pennsylvanian (Coward, 1983; Ferns and others, 1987: Blome and others, 1986), and (questionably) Devonian fossils have also been reported (Morris and Wardlaw, 1986; Evans, 1989; 1995) from Elkhorn Ridge Argillite exposures to the south.

Figure 28 Exposure of Elkhorn Ridge Argillite on the Grande Ronde River. Thin to massively bedded cherty argillite that has been sheared and folded along bedding planes. Most of the Elkhorn Ridge Argillite is marked by steep dips. This exposure is cut by several aplite dikes.

TRPba **Amphibolite and metamorphosed intrusive rocks (Triassic and Permian)** Dark green, green, and yellowish white to light green, fine, medium- and coarse-grained amphibolite and metamorphosed intrusive rock. Composite unit that includes the TRPa and TRPi units at the 1:24k scale. Heterogeneous unit made up of complexly intermixed intrusive, volcanic, and volcaniclastic sedimentary rocks that have been deformed and metamorphosed. Typical outcrops are massive and blocky. Unit is usually only moderately exposed, tending to weather to shallow subcrops marked by 4 cm subangular blocks. Often cut by closely-spaced, randomly oriented, anastomosing microbreccia zones as much as 5 cm thick. Relict intrusive textures are generally hypidiomorphic-granular (Evans, 1989). Displays a fairly large range in composition; ranging from gabbro to trondjhemite. Typical quartz diorites contain hornblende, plagioclase, and quartz crystals. Diorites are typified by ophitic green hornblende and andesine plagioclase; while trondhjemites are composed largely of oligoclase plagioclase and quartz. Feldspar and hornblende crystals typically partially recrystallized. exposed along intrusive margins that have been largely recrystallized to foliated amphibolite. Gneissic layering is defined in intensely metamorphosed metagabbro by light colored, plagioclase-rich layers and dark-colored hornblende and diopside-rich layers (Taubeneck, 1995). Generally recrystallized to hornblende hornfels (hornblende + plagioclase $\pm$ diopside $\pm$ garnet along the margins of the Bald Mountain Batholith (Taubeneck, 1995). Intermediate composition rocks are low potassium trondhjemites; with 58.32 wt percent SiO_2; 15.05 wt percent Al_2O_3; and 0.14 wt percent K_2O. Late Permian - Triassic age based on 243 Ma Pb-U zircon date from similar rocks along the North Fork of the John Day River (Brooks and others, 1982; Ferns and Brooks, 1995). Includes both the TRPi and TRPa units of Ferns and others (2001).

STRUCTURE

The upper Grande Ronde River basin is part of the Blue Mountains physiographic province. This is an uplifted, mountainous region with several large, crudely north oriented fault-bounded valleys and depressions. Since the basin is largely buried by middle Miocene and younger volcanic rocks, the folds and faults that shape the modern topography are relatively young, having developed over the last 15 million years. Historically, the major younger faults have been viewed as having formed in conjunction with regional movement along the enigmatic Olympic Wallowa Lineament (OWL), a topographic lineament that extends from the Olympic Mountains of northwest Washington through northeast Oregon (Hooper and Conrey, 1989; Mann and Meyer, 1993). The Olympic Wallowa Lineament was originally defined by Raisz (1945) to include the Wallowa Fault on the northeast side of the Wallowa Mountains, and was believed to extend across the northern end of the upper Grande Ronde River basin. Absence of suitably oriented topographic features in the north end of the upper Grande Ronde River basin led Mann (1989) to suggest that the faults that form the OWL are deflected south to form the north and east margins of the Grande Ronde Valley, eventually linking through a zone of normal and right oblique faults to the western Snake River plain in Idaho.

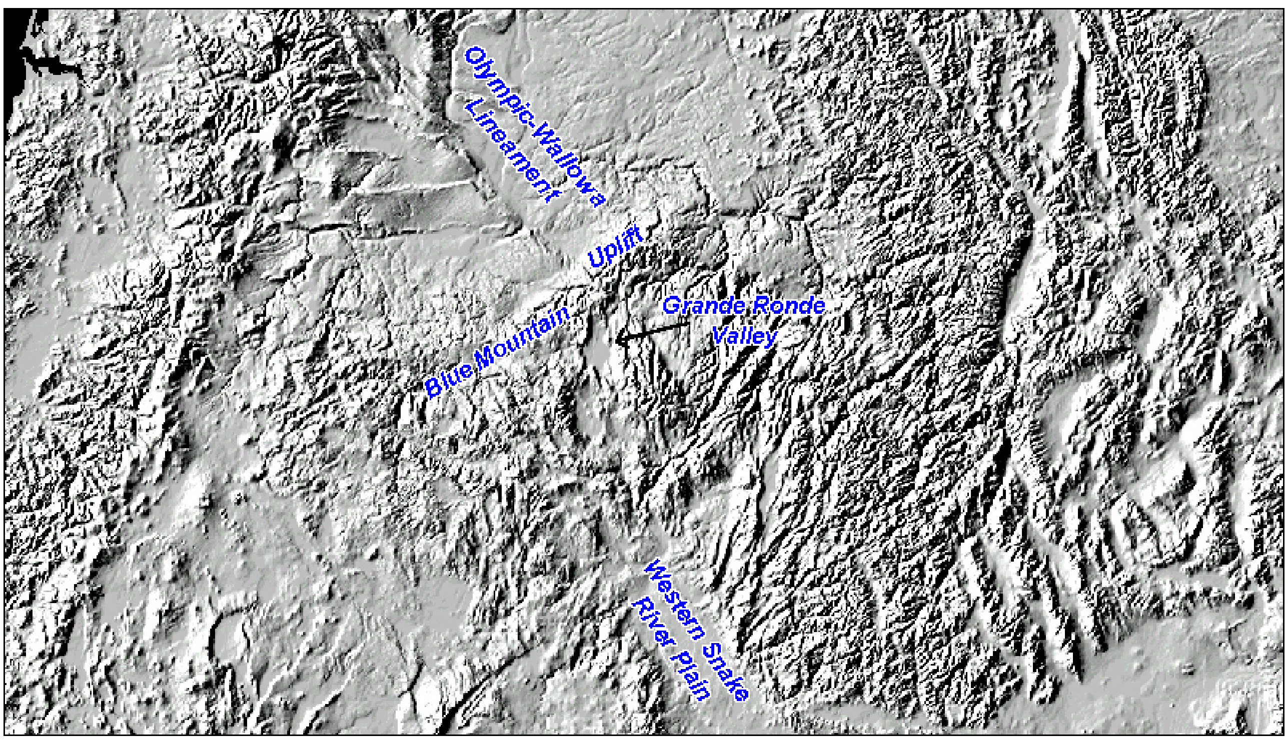

Figure 29 Shaded relief map of northeast Oregon, southeast Washington, and western Idaho; showing how the Grande Ronde Valley lies between the Olympic-Wallowa lineament and the western Snake River plain.

The structural framework to the upper Grande Ronde River basin is complex but can be divided into five sections: 1) the Grande Ronde Valley; 2) the western uplands, encompassing the Grande Ronde River and tributary streams entering upstream of the Grande Ronde Valley; 3) the southern uplands, which includes most of the tributary streams that join the Grande Ronde River in the Grande Ronde Valley; 4) the eastern block, which encompasses Indian Valley, the Grande Ronde River downstream of the Grande Ronde Valley, and tributary streams joining the Grande Ronde River from the east; and 5) the northern block; which includes the tributary streams that enter Indian Valley from the west.

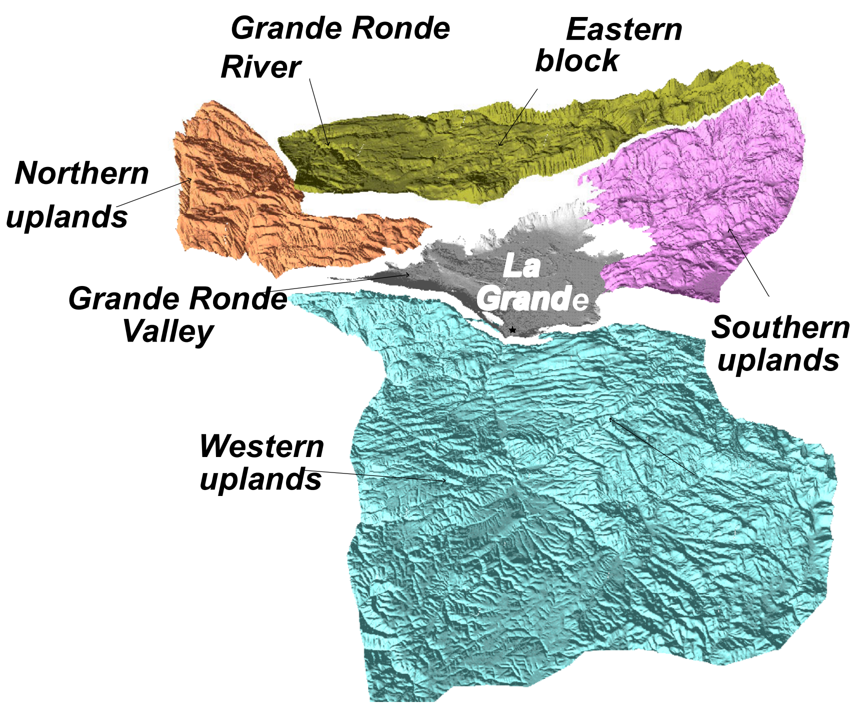

Figure 30 Exploded shaded relief map of the upper Grande Ronde River basin showing the Grande Ronde Valley, the tilted eastern block, and the northern, western, and southern uplands.

Grande Ronde Valley

The modern Grande Ronde Valley lies in a 50 km long, fault-bounded depression that is as much as 20 km wide. The valley is bounded on both the east and west sides by major fault zones and has been described as a pull-apart basin (Gehrels, 1981; White, 1980. The basin floor, as defined by the top of the Powder River Volcanic Field, is a faulted and tilted surface that plunges to depths of more than 600 m below the valley floor. Water well and geophysical data -including regional gravity and magnetic profiles (AMAX EXPLORATION, INC., 1975; Ferns and others, 2002a) and a seismic refraction line across the south end of the valley (Ferns and others, 2002a) indicate that the basal sedimentary section dips to the west (Liberty and Barrash, 1998). The west and east sides of the valley are bounded by major through-going fault zones that form prominent bounding escarpments that abruptly separate the valley fill sequence from the volcanic basement. The southern margin of the valley is defined by an irregularly-shaped, north-sloping uplands that dives beneath the valley fill sequence. The valley's northern margin is defined by an irregularly-shaped, south-sloping uplands that also dives beneath the valley fill.

The west margin to the Grande Ronde Valley is marked by an abrupt escarpment that rises as much as 770 m above the valley. The West Grande Ronde Valley fault zone separates Grande Ronde Basalt flows exposed in the steep sloping escarpment from the more gently sloping bajada surface. The West Grande Ronde Valley fault zone is a 40 km long and 3 km wide band of mainly down-to-the-east, subparallel normal faults that separate the valley floor from the western uplands. Within the West Grande Ronde Valley fault zone, individual north- and northwest-trending faults with vertical offsets as much as 700 m can be traced for as far as 10 km. Total cumulative vertical displacement along the West Grande Ronde Valley fault zone is in excess of 1,100 m. Ferns and others (2002a) report that the West Grande Ronde Valley fault zone is marked by a strong aeromagnetic gradient. Subtle topographic features -including linear range fronts, low linear escarpments on alluvial fans and terraces, faceted spurs, and "Z"-shaped topographic inflections along bedrock-alluvial fan contacts (Simpson and others, 1993; Personius, 1998; Ferns and Madin, 1999), indicate that surface ruptures along the West Grande Ronde Valley fault zone are Late Quaternary and possibly Holocene in age. An exposed fault plane on one of the faults in the zone dips 70^{o} to the southeast. The northern part of the West Grande Ronde Valley fault zone continues out of the Grande Ronde Valley to the northwest and crosses the crest of the Blue Mountain uplift, where it looses topographic expression in the deeply eroded upper Umatilla River basin. The southern part of the West Grande Ronde Valley fault zone is made up by subparallel fault strands that separate rotated blocks of volcanic rocks that dip into the valley. One fault segment -the Taylor Creek fault of Gehrels (1981)- crosses into the valley floor south of La Grande beneath Ladd Marsh, trending toward Hot Lake.

The south margin to the Grande Ronde Valley is marked by a relatively topographically subdued, faulted uplands that slopes downward to the northwest. Individual fault blocks are generally tilted to the west and bounded by down-to-the-east faults. The most pronounced escarpment along the south margin is marked by the Hot Lake fault (Gehrels, 1981), which swings to the west at Hot Lake, and projects into the Grande Ronde Valley on trend with the West Grande Ronde Valley fault zone. A seismic profile across the valley east of the Hot Lake fault (Ferns and others; 2002a) indicates that the basin floor north of Union forms a westward tilted surface that drops to more than 300 m below the valley floor. Total displacement along the Hot Lake and companion faults is in excess of 1,000 m. Many of the northwest-trending ridges in the uplands to the south are bounded by smaller faults that continue into the Grande Ronde Valley. Northeast of Union, a sinuous, 1 – 3 m high scarp of possible Holocene age extends into the valley for 1 km along the projected northern extension of the Little Creek Fault (White, 1981; Gehrels, 1981). Ferns and others (2002a) indicate that the base of the valley fill sediments is vertically offset about 25 m along the Little Creek fault. Seismic profiles and water well data (Ferns and others, 2002a) along the south margin show the volcanic basement underlying the Grande Ronde Valley is here broken up into a series of west-dipping blocks.

The east margin to the Grande Ronde Valley is marked by an abrupt escarpment that rises to as much as 760 m above the valley floor. The East Grande Ronde Valley fault zone abruptly separates Grande Ronde Basalt flows exposed in the steep sloping escarpment from the more gently sloping bajada. The East Grande Ronde Valley fault zone consists of several large displacement, long strike length en echelon faults that can be traced for as much as 20 km and is considered by some to be part of the Olympic Wallowa Lineament (Mann, 1989). The East Grande Ronde

Valley fault zone is about 1 km in width and is offset on the south by the east-west trending Mill Creek fault (White, 1981). The Cove segment of the East Grande Ronde Valley fault zone consists of a single fault that extends for nearly 20 km along the faceted spurs that mark the prominent eastern escarpment of the Grande Ronde Valley (Simpson and others, 1993; Personius, 1998; McConnell and others, in prep.). Ferns and others (2002b) show a strong aeromagnetic gradient coincident with the trace of the East Grande Ronde Valley fault zone. At least 1,200 m of cumulative down-to-the-west vertical displacement is indicated across the East Grande Ronde Valley fault zone (Ferns and others, 2002a). The surface of the upthrown block on the east side of the East Grande Ronde Valley fault zone dips to the north-northwest, forming a topographic ramp sloping beneath the Mt Harris volcano. At Mt Harris, the intersecting Cove and Mt Harris segments intersect beneath a large landslide complex at Grays Corner (Simpson and others, 1993; Personius, 1998). Although the landslides at Grays Corner cover a faulted surface and are marked by linear ridges and closed depressions, inset fans do not appear to be offset by faulting (Personius, 1998; Ferns and others, 2002b). North of Mt Harris, the valley margin is marked by a closely spaced series of short-strike-length faults that are considered by Simpson and others (1993) to be segments to the larger East Grande Ronde Valley fault zone. Apparent lateral displacement of volcanic units along the base of Mt Harris may indicate as much as 300 m of right lateral displacement and 450 m of vertical displacement along the south margin of the Mt Harris fault zone (Ferns and others, 2002b).

The north margin to the Grande Ronde Valley is marked by a southeast dipping homocline (White, 1981) that is bounded on the west by the northwest-trending, down-to-the-west Dry Creek fault. The homocline is cut by small displacement, northwest- and northeast-trending faults that do not appear to continue into the valley. The Dry Creek continues north and eventually intersects the down-to-the-east West Grande Ronde Valley fault zone. The Dry Creek fault may extend eastward beneath the valley and link up with the East Grande Ronde Valley fault zone, forming part of the Olympic Wallowa Lineament.

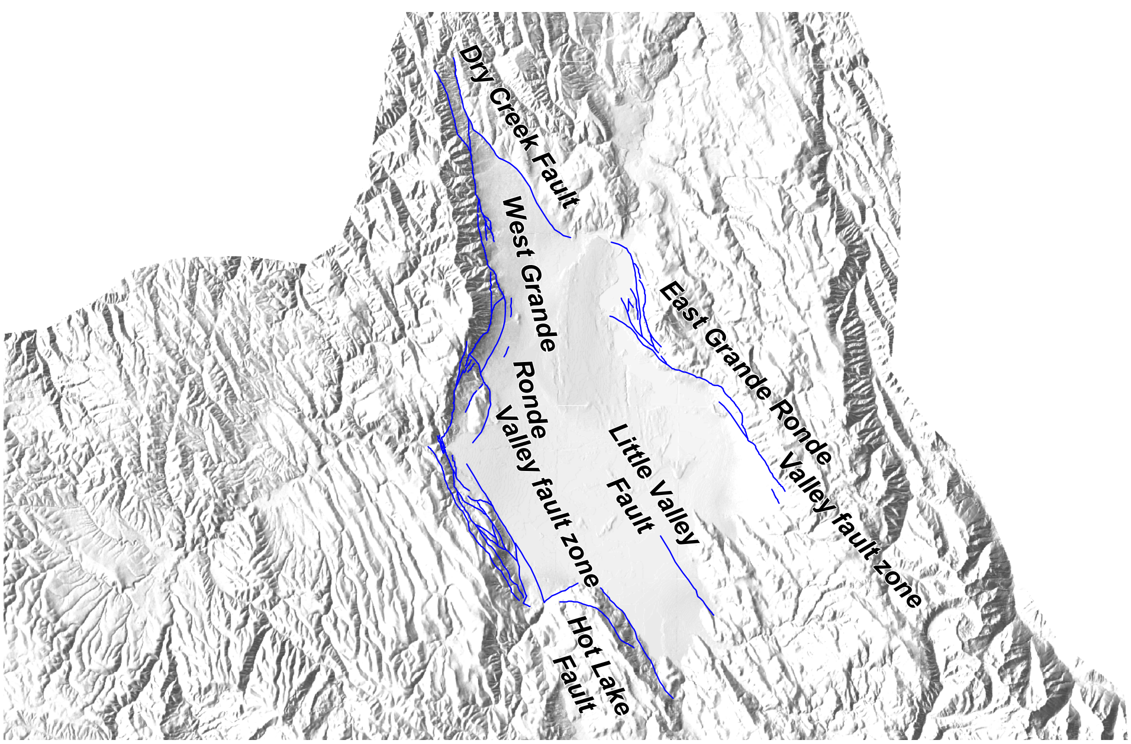

Figure 31 Shaded relief map of the Grande Ronde Valley showing (in blue) the major fault zones and faults that define the valley's margins. Many of these faults are show evidence for late Quaternary movement. The Little Valley Fault and several segments of the West Grande Ronde Valley and East Grande Ronde Valley fault zones show evidence of probably Holocene movement.

Western Uplands

All of the area drained by the Grande Ronde River upstream of the Grande Ronde Valley is herein referred to as the western uplands to the upper Grande Ronde River basin. Major structural features in the western uplands include 1) northeast trending folds and faults of the Blue Mountains uplift and 2) cross-cutting northwest-trending fault zones that break the core of the uplift into a series of shallow basins that are separated by faulted ridges.

Northeast-Trending Folds

The Blue Mountains uplift is a broad anticlinorium that forms an extensive uplands. Anticlinal crests are marked by flat-lying lava flows that appear in the upper part of the Grande Ronde Basalt (N2 and Fiddler's Hell members of Ferns and others, 2001). These Grande Ronde Basalt flows unconformably overlie an irregular surface of pre Miocene strata that, in places, is exposed at the surface along the uplift. In other places, these same flows overlie as much as 500 m of older Grande Ronde Basalt flows. The crest of the anticlinorium forms a broad arc that curves to the northwest and, over much of its length, forms a gently rolling surface marked by broad open folds. Trends to fold axes range from N85^{o}W to N50^{o}E. The crest of the anticlinorium generally separates the upper Grande Ronde River basin from the Umatilla River basin to the northwest. The upper Grande Ronde River flows eastward along the southeast flank of the anticlinorium, through the axial trough of the Grande Ronde syncline (Hampton and Brown, 1964; Walker, 1973); a feature that is best described as a bowl-like, concave surface with several monoclonal to synclinal flexures (Barrash and others, 1980). At Tower Mountain, to the southwest of the Grande Ronde syncline, northward tilting, upper Grande Ronde Basalt flows lap onto the deeply dissected highlands formed by the Tower Mountain caldera. Further east, tilted lower Grande Ronde Basalt flows fill canyons cut into the deeply eroded pre-Tertiary highlands and off lap to the north.

Northwest-Trending Fault Zones

Northwest trending fault zones cut across the Blue Mountains uplift; forming strong topographic lineaments. The lineaments are characterized by short strike-length faults that bound shallow, northwest trending structural depressions that are partially filled by middle and late Miocene sediments. In places, the Grande Ronde River and major tributary streams, such as Fly Creek, Beaver Creek, and Meadow Creek, flow parallel to the fault zones. Dominant sense of vertical displacement changes along the length of each fault zone, shifting along strike from predominantly down-to-the-southwest to predominantly down-to-the-northeast and then back to down-to-the southwest displacements. Shifts in sense of displacements occur where the fault zones are disrupted by crosscutting, north-northeast trending high-angle normal and reverse faults.

The Fly Valley fault zone (Ferns, 1998, Ferns and others, 2001) is a series of short strike-length faults that can be traced for 60 km, forming a N65^{o}W trending zone about 7 km wide. Individual fault strands can be traced for as much as 8 km with as much as 130 m of vertical offset. Sense and magnitude of vertical displacement varies along the zone. Sense of displacement shifts from down-to-the-southwest north of Ukiah to down-to-the-northeast at Lehman

Springs, then back to down-to-the-southwest at Fly Valley. Locally, stream gradients change markedly across the Fly Valley fault zone (Ferns and Taubeneck, 1994). More than 400 m of cumulative vertical displacement is apparent where the Fly Valley fault zone forms the course of the Grande Ronde River.

The Shaw Mountain fault zone consists of a series of northwest-trending, generally down-to-the-southwest fault strands. Madin (1998) reports at least 365 m of cumulative vertical displacement along the east end of the zone. The zone can be traced westward from Shaw Mountain to Beaver Ridge, where it is broken up by a series of short strike length, N0^{o} to 15^{o}E normal and high angle reverse faults. Sense of displacement along fault strands then shifts to down-to-the northwest then back to down-to-the-southeast faults where the zone forms the northern margin of the Starkey basin. Measured dips on fault planes range from 85^{o} to 90^{o}.

The Spring Creek basin is bounded by two fault zones (Ferns and others, 2001). The N35^{o}W striking Coleman Ridge fault zone forms the western margin of the Spring Creek basin. Individual fault segments, including the Spring Creek and Coleman Ridge faults (Kienle and others, 1979) may be as long as 7 km with as much as 150 m of down-to-the-northeast vertical displacement. The Coleman Ridge fault zone does not cross the crest of the Blue Mountain uplift but instead merges with a set of down-to-the west, N5^{o}E trending faults. The south end of the Coleman Ridge fault zone merges the north side of the Shaw Creek fault zone.

The eastern margin of the Spring Creek basin is bounded by the N35^{o}W trending Hilgard fault zone, a series of fairly long (5 - 15 km) faults. The zone includes the Hilgard and Peach Canyon faults of Kienle and others (1979) and the Rock Creek East, Rock Creek West, and Little Coyote Canyon faults of Barrash and others (1980). General sense of displacement varies along the Hilgard fault zone, shifting from down-to-the-northeast on the southern end of the zone to down-to-the-southwest to the north across the axis Grande Ronde syncline and then back to down-to-the-northeast further near the crest of the Blue Mountain uplift. Vertical displacements along individual faults are typically less than 100 m. Some of the shorter splaying segments show evidence of strike-slip displacement (Kienle and others, 1979). Longer faults such as the Peach Canyon fault show changes in sense of relative movement, shifting form down-to-the-northeast north of the Grande Ronde synclinal axis to down-to-the-southwest south of the axis (Barrash and others, 1980). Apparent right lateral offset is suggested where faults cut the Powder River Volcanics olivine basalt flow that caps Glass Hill. The south end of the Hilgard fault zone also merge with the north side of the Shaw Creek fault zone.

The Drumhill Ridge fault zone, which includes the Drumhill Ridge, Perry, and Wilbur Mountain faults of Kienle and others (1979) consists of a series of normal faults with small displacements that trend N35^{o}W. Vertical displacement along individual faults is no more than 100m and commonly less than 30 m. Paralleling down-to-the-southwest and down-to-the northeast faults along the north end of the fault zone form a narrow horst that runs between the Green Mountain vent and the Spring Mountain and Sugarloaf Mountain vents. Dominant sense of vertical displacement shifts from down-to-the-southwest where the zone cuts east of Mt Emily, to down-to-the-northwest, where the zone merges with West Grande Ronde fault zone. As much as 1 km of dextral displacement may be evident by possible right lateral offset of a Powder River Volcanics dacite flow east of Mahogany Mountain. Gehrels (1981) cites shallow plunging striations and mullion on nearly vertical fault planes as evidence for right lateral movement along these faults.

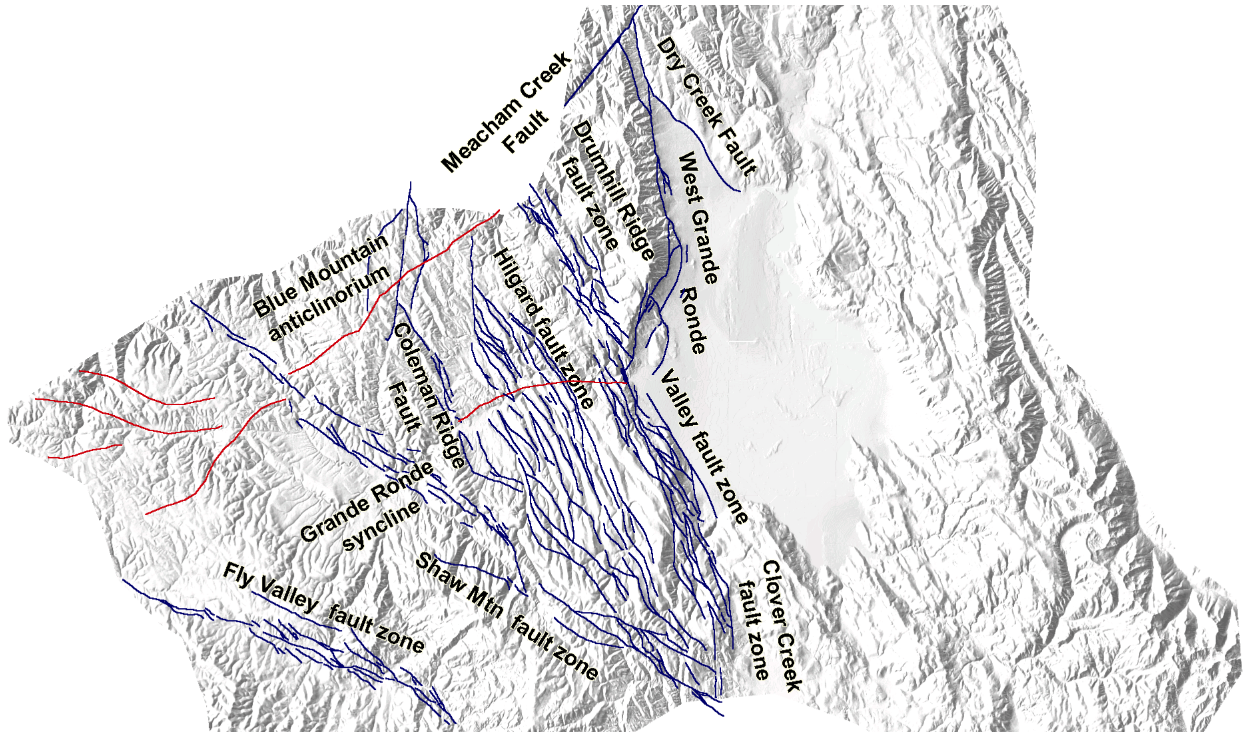

Figure 32 Shaded relief map of part of the upper Grande Ronde River basin showing the major structural features on the western uplands. Faults shown as blue lines, folds shown as red lines. A great number of small displacement faults cut across the western uplands are not shown on this diagram.

Southern Uplands

The southern uplands includes the entire Catherine Creek basin south of the Grande Ronde Valley and is bordered the west by Ladd Creek and on the east by Mill Creek. Here a northward tilted ramp of Powder River Volcanic Field lavas is broken up by northwest-trending faults. Discontinuous fault zones continuing south from the West and East Grande RondeValley fault zones separate the southern uplands from the higher standing Elkhorn Mountains to the west and the Wallowa Mountains to the east. The topography is dominated by a series of northwest-trending ridges that slope northward to plunge into the Grande Ronde Valley. Although most of the topography is fault controlled, some constructional volcanic features are preserved locally.

Bounding Fault Zones

The Clover Creek fault zone consists of a series of N0^{o}W to N20^{o}W trending faults that continue south from the West Grande Ronde Valley Fault Zone to a series of north-trending faults on the northwest of the Baker valley. Vertical displacement along individual faults may exceed 100 m, with the predominant sense of displacement being down to the east. Cumulative down to the east vertical displacement along the Clover Creek fault zone is more than 300 m. Gehrels (1981) reports predominantly vertical dips on slickensides along the Clover Creek fault zone.

The South Baldy fault zone links the East Grande Ronde Valley fault zone with the Wallowa Fault to the south east. The South Baldy fault zone consists of a series of N25^{o}W to N45^{o}W trending faults whose cumulative sense of vertical displacement is down to the southwest. The South Baldy fault zone includes several small grabens, such as the Moss Springs graben (McConnell and others, 2003). Cumulative southwest vertical displacement appears to be about 300 m, with individual faults having vertical displacements of more than 100 m. Although primary sense of displacement is vertical, offset of stream drainages and contacts suggest some right lateral component of movement (McConnell and others, 2003). The South Baldy fault zone is considered to be part of transfer zone that links the Olympic Wallowa Lineament to the Eagle Fault.

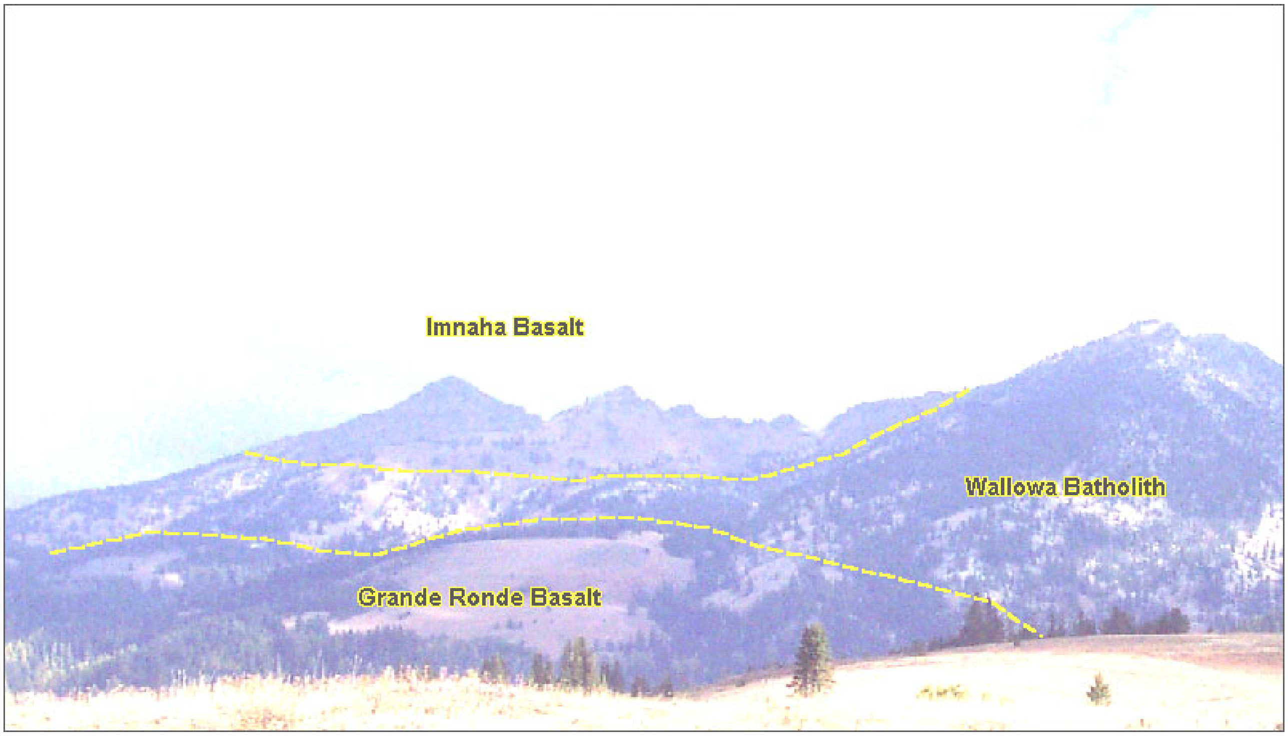

Figure 33 A large fault, shown here as a dashed yellow line, separates Grande Ronde Basalt on the left from the Wallowa Batholith on the right near Sand Pass. The fault is part of the South Baldy fault zone. that defines the boundary between the southern uplands and the eastern margin. The upper dashed yellow line marks a paleochannel in the Wallowa Batholith that was filled by flows of Imnaha Basalt. Cumulative down to the southwest displacement along the fault here is in excess of 300 m.

Northwest-trending faults, fault zones, and cinder cones

Faults; fault zones, and cinder cones are aligned along a common N40^{o}W to N50^{o}W trend in the southern uplands. Major fault zones are herein named the Pyles Canyon and Little Creek fault zones. Northwest-trending faults near the head of Pyles Canyon can be traced north to where they merge with Hot Lake and other faults of Gehrels (1981). At the northern end of the Pyles Canyon fault zone, near Hot Lake, the Pyles Canyon fault zone is separated from the Clover Creek fault zone by several east-west trending low angle faults (Gehrels, 1981) that tilt the lava flows to the north. Further south, along the east face of Craig Mountain, a structurally disrupted zone (jumbled block unit of Barrash and others, 1980) of massive landslides and steeply-tilted, fault-bounded blocks of broken rock separate the Hot Lake Fault and Craig Mountain faults. The Pyles Canyon fault zone is truncated on the south by a north east trending fault zone.

Four basaltic andesite and trachybasalt vents are aligned along a northwest axis east of the Pyles Canyon fault zone. The northern three vents are deeply eroded basaltic andesite cinder and scoria cones that are exposed near the top of the Powder River Volcanic Field. The southern vent is the source for a small trachybasalt flow that is also exposed near the top of the Powder River Volcanic Field.

The Catherine Creek fault is marked by the high escarpment south of the lower part of Catherine Creek. The northwest-trending fault can be traced south into a large landslide, where it is broken up by several west- northwest-trending faults. The fault crosses an area where there is rapid lateral thinning and thickening of volcanic units due to considerable paleotopography. Welded spatter and scoria mounds exposed along both sides of the fault mark the location of Grande Ronde Basalt and Powder River basalt and basaltic andesite vents. Although the total amount of displacement is uncertain, the Catherine Creek fault exhibits as much as 210 m of down to the east offset.

Late Pleistocene and possibly Holocene movement is indicated the Little Creek fault, which forms a 1 to 3 m high, east facing scarp in fan gravels. The Little Creek fault can be traced into the southern uplands, where it splays into two segments (White, 1981). Predominant sense of displacement is down-to-the-east. The southern splay may continue south and link up with the Catherine Creek fault (White, 1981).

The Phys Point, Mill Creek, High Valley, and Little Catherine Creek faults are part of a northwest-trending fault zone herein referred to as the Little Catherine Creek fault zone. The Little Catherine Creek fault zone extends from the Grande Ronde Valley to where Catherine Creek makes a 90^{o} turn; from southwest to northwest. Sense of displacement along the north end of the zone is predominantly down-to-the-east. Dominant sense of displacement shifts to down-to-the-west further south along the High Valley and Little Catherine Creek faults. Dextral shifts in crossing stream channels at or near some of the faults in the Little Catherine Creek fault zone may indicate some right lateral displacement. Andesite scoria and agglutinate exposed in the escarpment along the Phys Point fault may mark another small Powder River vent.

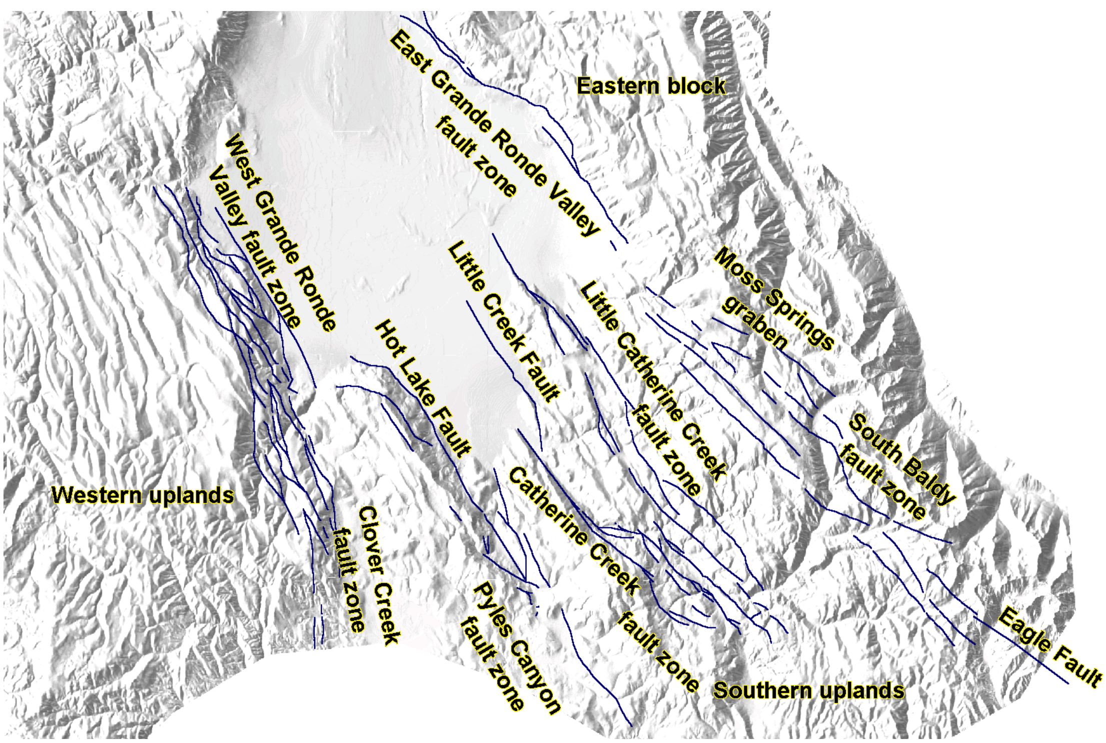

Figure 34 Shaded relief map of a part of the upper Grande Ronde River basin showing the major structural features in the southern uplands. Faults shown as blue lines. The Clover Creek fault zone and the South Baldy fault zones are the major bounding structures to the southern uplands.

Eastern block

The eastern block includes Indian Valley and all of the Upper Grande Ronde River basin that is drained by streams that join the Grande Ronde from the east downstream of the Grande Ronde Valley. The eastern block is bordered on the west by the South Baldy, East Grande Ronde Valley, and Mt Harris fault zones and on the northwest by the Big Hole and Lookingglass fault zones. The eastern block is a northwest sloping plateau, the higher parts of which are referred to as the Mt Fanny plateau (McConnell and others, 2002, 2003). Major streams originating on the Mt Fanny plateau include Indian Creek and Clarks Creek. The lower, northern part of the eastern block is cut by the Grande Ronde River and includes some streams entering in from the west.

Most of the eastern block is relatively undeformed, marked by a northwest tilt of 1^o – 4^o that culminates in a broad, northeast-oriented syncline north of Elgin. Many of the topographic highs on the eastern block are small volcanoes. Some ridges are erosional remnants of intracanyon lava flows. Fault escarpments are relatively rare; most of the recognizable faults are minor faults that display northwest or northeast orientations. Fault displacements are typically less than 50 m. The margins to the eastern block that lie north of the Grande Ronde Valley are defined by the Mt Harris, Big Hole, and Lookingglass fault zones. Significant structures include northeast-trending folds and faults; north- northwest- trending fault zones, and northwest-trending faults.

Northeast-trending folds and faults

Northeast-trending structures include an asymmetric syncline at the north end of the eastern block and the Big Hole fault zone. The synclinal trough is occupied by a late Miocene or Pliocene andesite flow. The east limb of the syncline dips shallowly to the northwest, while the west limb dips steeply to the east and is broken by numerous fault The largest northeast-trending faults lie along the Big Hole fault zone, which is marked by a series of down-to-the-east N50^{o}E to N60^{o}E trending faults that have a maximum cumulative vertical displacement of 240 m. Amount of offset decreases to the northeast, where the zone terminates against the north to northwest trending faults of the Lookingglass fault zone. Northeast-trending faults also occur east of Mt Harris, where they truncate against the East Grande Ronde Valley fault zone.

North- and northwest-trending fault zones

The south end of the Mt Harris fault zone consists of closely spaced, N0^{o}W to N15^{o}W, short-strike-length faults that merge with the main East Grande Ronde at Mt Harris. These faults form a scissors zone along which the dominant down-to-the-west sense of displacement in Grande Ronde Valley changes to a dominant down-to-the-east sense of motion to the north. The Mt Harris fault zone swings to the northwest at Elgin and continues northward for about 8 km, where it is disrupted by the northeast trending Big Hole fault zone. Approximately 270 m of cumulative, down-to-the-east vertical displacement is indicated at Elgin. At Elgin, fault planes dip between 60^o and 65^o to the east.

The Lookingglass fault zone is marked by a series of short strike-length, vertical faults with N35 ^{o}W to N55^{o}W trends. Lookingglass Creek makes a sharp right hand bend where the Lookingglass fault zone truncates the Big Hole fault zone in an area marked by poor exposures, and landslides. Fault displacements along individual faults are typically on the order of a few meters. Slickenside striations are subhorizontal. Cumulative west-side-down displacement along the Lookingglass fault zone is about 200 m.

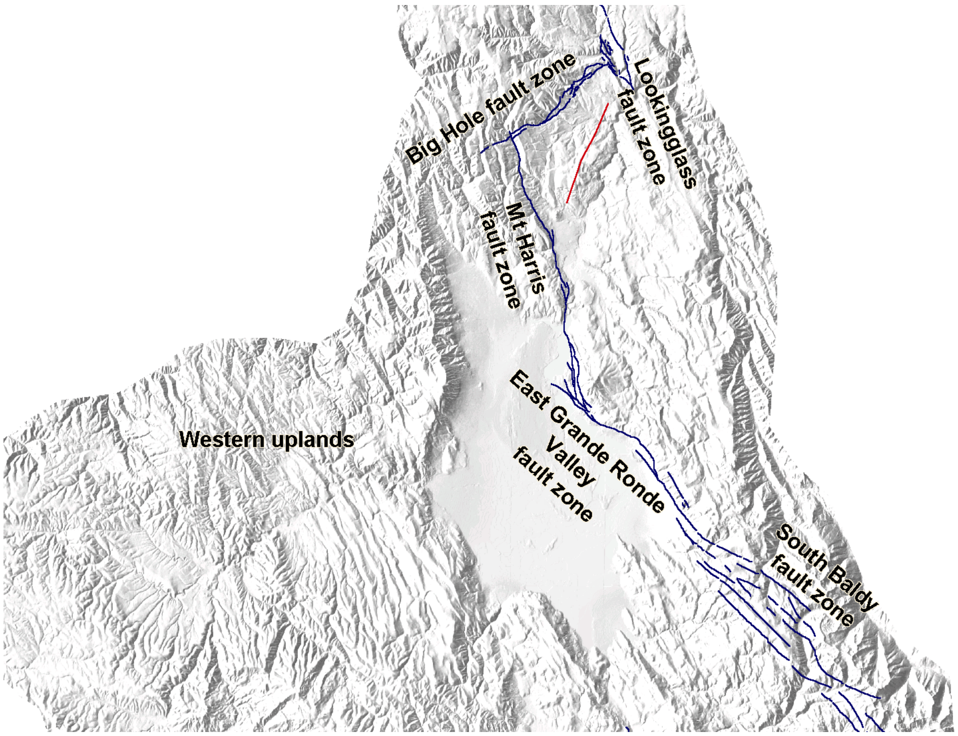

Figure 35 Shaded relief map of a portion of the upper Grande Ronde River basin showing major structural in and along the eastern block. Note the northward tilt to the eastern block. Faults shown as blue lines. Syncline east of Big Hole fault zone shown as red line. In contrast to the western block, the eastern block is a stable platform cut by relatively few faults.

Northern Uplands

All of the Blue Mountains uplift east of the Grande Ronde Valley is referred to herein as the northern uplands to the upper Grande Ronde River basin. The northern uplands extends east along the crest of the Blue Mountains from the head of Dry Creek to the head of Jarbidge Creek. Phillips Creek and Lookingglass Creek are the major streams that head in the northern uplands. The northern uplands form southward tilted ramp that is broken by northwest-, north-, and northeast-trending faults. Major structural features include northeast-trending folds and faults; north- northwest-trending faults; and west- northwest-trending fault zones.

Northeast trending folds and faults

The northern and western uplands are similar and may more properly be considered to be a single province. Both are defined by the Blue Mountains anticlinorium, a rolling highlands marked by broad, gentle folds. The crests of the N45^{o}E – N60^{o}E trending anticlines are defined by flat-lying Saddle Mountain Basalt and Wanapum Basalt flows and intervening sedimentary units. The younger strata conformably overlie a surface of older Grande Ronde Basalt flows.

The northern uplands are cut by N0^{o}E to N40^{o}E trending faults. The westernmost of these, the Meacham Creek fault (Kienle and others, 1979) trends N30^{o}E and truncates the West Grande Ronde Valley fault zone. The next major northeast-trending fault to the southeast, the N20^{o}E trending Pedro Ridge fault, truncates the Big Hole fault zone. Sense of displacement along the Pedro Ridge fault is down-to-the-east. The Balloon Tree fault zone also trends N20^{o}E and extends north from the Big Hole fault zone; cutting the nose of one of the anticlines. N40^{o}E trending faults form a small graben along the crest of Blue Mountain uplift further north at Jubilee Lake. Sense of displacement along the Jubilee Lake fault is down-to-the-west, toward the anticlinal axis. The upthrown block is tilted to the southeast. Still further east, the Little Lookingglass Creek and Brock Meadows faults trend N0°E to N15°E and cross out of the upper Grande Ronde River basin. Although both faults can be traced for considerable distance along strike, cumulative vertical offset is small and sense of displacement is down-to-the-east. The southern ends of the Brock Meadows and Little Lookingglass Creek faults are truncated by the northwest-trending Lookingglass fault zone.

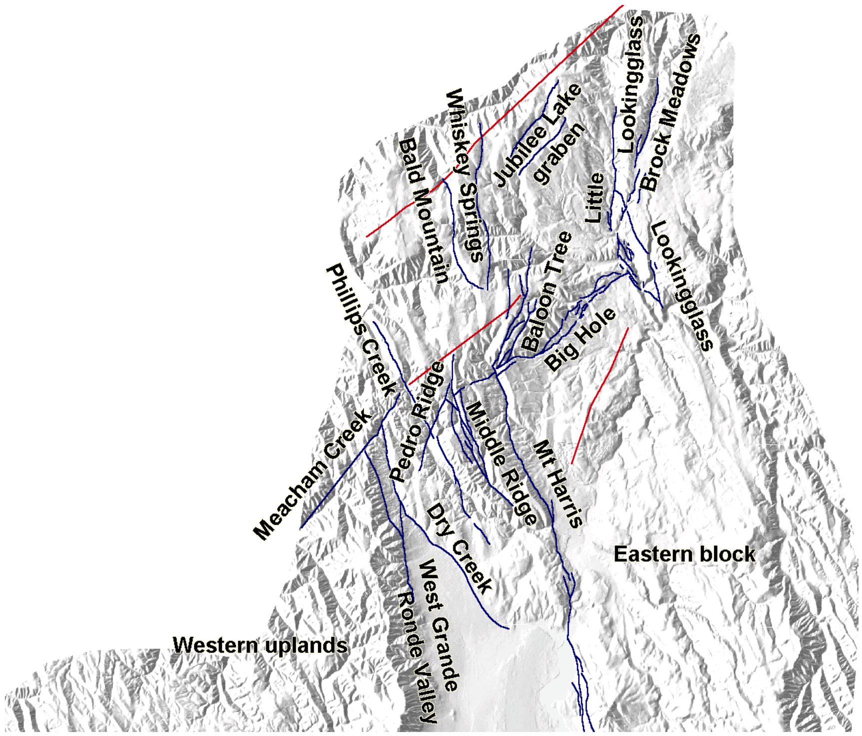

Figure 36 Shaded relief map of the northern part of the upper Grande Ronde river basin, showing the major structural features in the northern uplands. Faults shown as blue lines, folds shown as red lines.

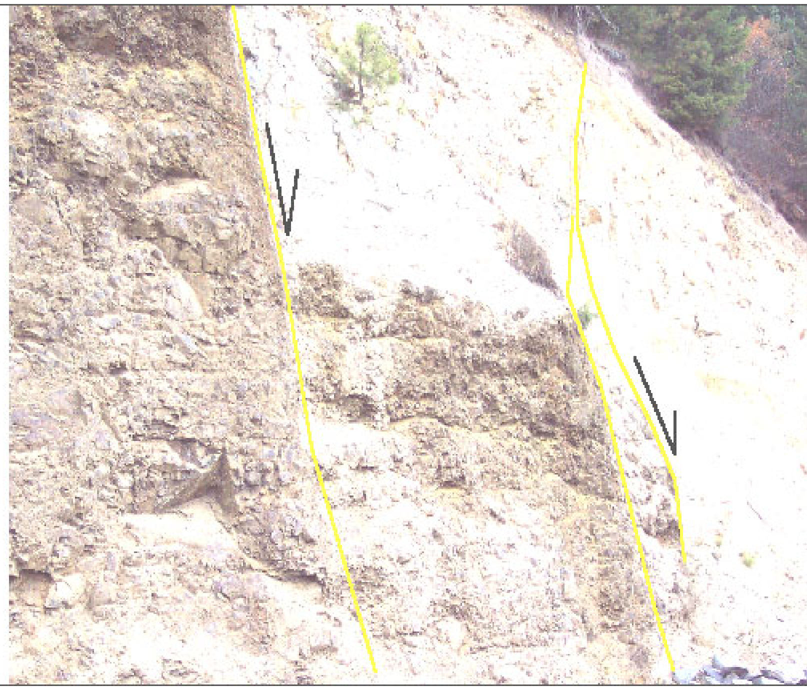

Figure 37 Photograph of fault zone exposed in a road cut near Lookingglass Creek. Here Tms sediments overlie the Powatka member of the Wanapum Basalt. Sense of displacement is down to the northeast. This is one of the faults that in the Lookingglass Creek fault zone, many of which display subhorizontal slickensides. Outcrops such as this are quickly mantled by bank debris and small landslides.

Northwest trending faults

Northwest trending faults cross the anticlinal crest of the Blue Mountains on the west side of the northern uplift. The N25^{o}W Phillips Creek fault truncates the northeast-trending Meacham Creek fault and crosses into the Umatilla River drainage. The Phillips Creek fault dips 85^{o}W with more than 100 m of down-to-the-west displacement The Middle Ridge fault zone consists of a number of N15^{o}W to N25^{o}W trending, down-to-the east faults. which truncate against the south end of the Big Hole fault zone. The intersection of the Middle Ridge and Big Hole fault zones is a complex corner that forms a broken transition zone between the eastern block and the northern uplands. A similar complex corner occurs at the intersection of the northern end of the Big Hole fault zone and the Lookingglass Creek fault zone. Here the west end of the Lookingglass Creek fault zone is deflected northward and truncates the southern ends of the Little Lookingglass Creek and Brock Meadows faults.

Large faults within the northern block include several paralleling faults that form horsts and grabens. One horst is formed where the Bald Mountain and Whiskey Springs faults cross Lookingglass Creek. The Bald Mountain fault is N0^{o}W to N10^{o}W trending structure that has about 185 m of down-to-the-west offset. The Whiskey Springs fault has a N10^{o}W trend and about 125 m of down-to-the-east offset. Both faults cross the Blue Mountain uplift.

GEOLOGIC HISTORY

Rocks exposed in the upper Grande Ronde River basin record a complex and tectonically active geologic story that began some 250 million years ago and continues to the present day. Although the basin's early pre-Tertiary and early Tertiary history is only partly known because of the limited exposures of rocks older than 15 million years, seven important regional events are recognized (Ferns and others, 2001). These are: 1) Deep ocean subduction and island arc volcanism in an exotic environment during the Permian and Triassic. 2) Deformation, plutonism, and metamorphism related to the tectonic "docking" of the resulting "exotic" terranes onto the North American continent during the Late Jurassic and Early Cretaceous. 3) Uplift and extensive erosion during the Late Cretaceous and Early Tertiary following docking. 4) Explosive bi-modal continental volcanism in the Oligocene. 5) Extensive tholeiitic flood basalt vulcanism in the middle Miocene, possibly related initiation of the Yellowstone plume. 6) Subsequent rift-related calc-alkaline volcanism, and 7) Regional uplift and warping along the Blue Mountain anticlinorium accompanied by formation of structural basins.

Fragments of the Baker and Wallowa terranes, two of the five pre-Tertiary exotic terranes recognized by Silberling and others (1984) in northeast Oregon, are exposed in the upper Grande Ronde River basin . As all of the exotic terranes have undergone significant post-accretion rotation (Wilson and Cox, 1980; Hillhouse and others, 1982), the relative position of the terranes are generally described in what is now assumed to be their pre-rotation positions. The Baker terrane is divided into two subterranes: the northern Bourne subterrane, an accretionary complex dominated by deepwater chert and siliceous argillite, and the southern Greenhorn subterrane, a forearc complex dominated by serpentinite-matrix melange (Ferns and Brooks, 1995). The Bourne subterrane is made up mostly by the Elkhorn Ridge Argillite (Gilully, 1937), a severely deformed and stratally disrupted sequence of late Paleozoic and early Mesozoic deepwater ocean floor chert and fine-grained siliceous argillite. The Elkhorn Ridge Argillite is considered to be the accretionary prism part of a Permian and Triassic fore-arc terrane/subduction complex (Dickenson, 1979; Ave' Lallemant, 1995; Ferns and Brooks, 1995). Deformation in the accretionary prism is generally considered to have resulted from eastward subduction of oceanic and island arc crust beneath a west-facing Huntington/Olds Ferry volcanic arc, which, following post-accretion rotation, is now exposed to the southeast of the upper Grande Ronde River basin (Dickenson, 1979; Ave' Lallemant, 1995; Ferns and Brooks, 1995).

The Wallowa terrane is a volcanic arc complex that, in the upper Grande Ronde River basin, is made up of two units: 1) the volcanic-dominated Clover Creek Greenstone (Gilully, 1937) on the south and 2) a volcanic and calcareous sedimentary unit considered to be equivalent to the Lower Sedimentary Series of Smith and Allen (1941) on the north. Although the Lower Sedimentary Series generally unconformably overlies the Clover Creek Greenstone; the two units are in fault contact along a significant northwest-trending fault near Medical Springs. Although not exposed in the upper Grande Ronde Basin, rocks of the Mountain Home metamorphic complex probably underlie the Grande Ronde Basalt at no great depth in the western part of the basin. The Mountain Home metamorphic complex and some of the tectonically dismembered fragments of island arc volcanic and plutonic rocks intermixed with the Elkhorn Ridge Argillite in the southern part of the La Grande 30' x 60' quadrangle may be detached fragments from the Wallowa terrane (Ferns and Brooks, 1995). Assuming significant post accretion rotation (Wilson and Cox, 1980; Hillhouse and others, 1982), the Wallowa arc would have originally been located to the west of the Baker Terrane (Brooks and others, 1978, Brooks, 1979, Dickenson, 1979, Ave' Lallemant, 1995). Tectonic dismemberment along the Baker-Wallowa terrane boundary culminated during the late Jurassic as the Wallowa and Olds Ferry terranes collided. The collision resulted in east-directed folding and thrusting along north-south axes (Ave' Lallemant, 1995); tectonic mixing of deep water ocean floor and island arc volcanic, plutonic, and shallow water sedimentary rocks along the terrane boundary (Ferns and Brooks, 1995); closely followed by province wide plutonism and, at Mountain Home, regional, amphibolite-facies grade metamorphism (Ferns and others, 2001).

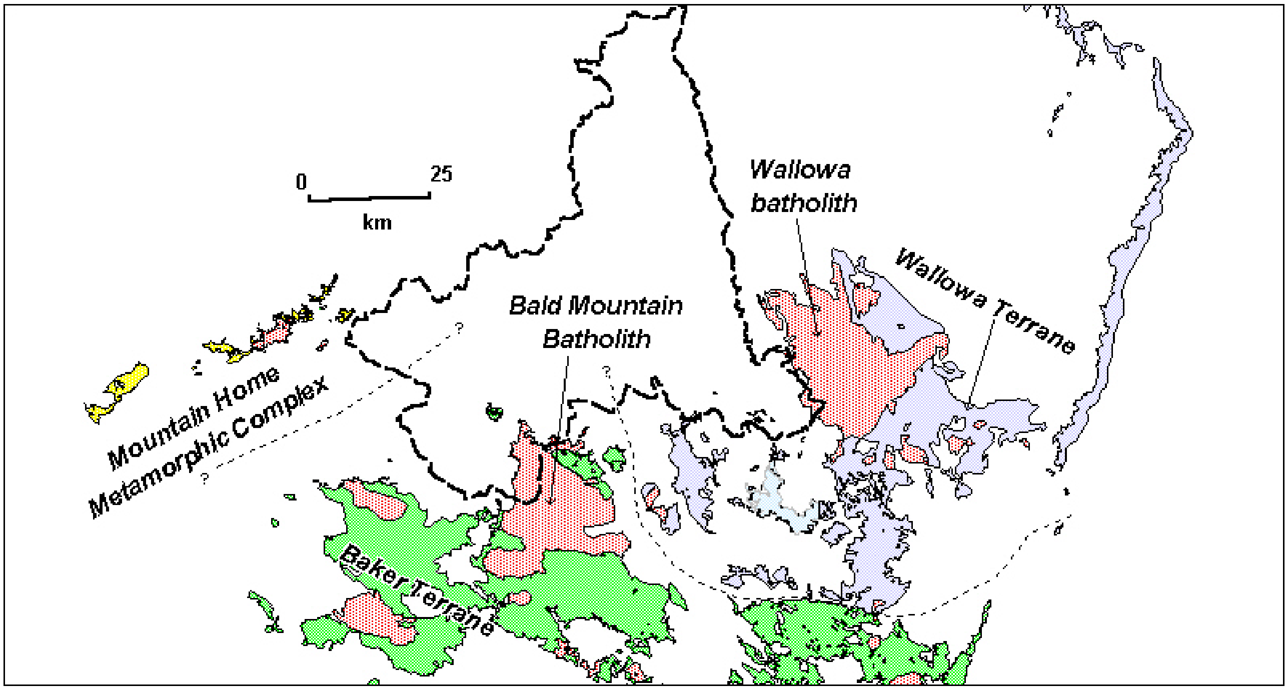

Figure 38 Sketch map showing geographic distribution of the accreted terranes and the Bald Mountain and Wallowa batholiths. Juro-Cretaceous intrusive rocks shown in red, Wallowa Terrane in blue, Baker Terrane in Green, and Mountain Home Metamorphic Complex in yellow. Note that the projected trace of the boundary between the Baker and Wallowa terranes projects northward beneath Grande Ronde Valley.

Two large intrusive complexes, the Bald Mountain and Wallowa batholiths, were emplaced along/across major stuctural discontinuities in the Baker and Wallowa terranes in the Late Jurassic and/or Early Cretaceous. At Mountain Home, sillimanite gneisses, migmatites, and garnet-tourmaline pegmatities were produced when the Carney Butte stock was emplaced (Ferns and others, 2001). Metamorphic mineral assemblages suggest emplacement at pressures somewhat greater than 3.5 kb. The largest and most complex pluton, the Bald Mountain Batholith was emplaced along the boundary between the Baker and Wallowa terranes while the Wallowa Batholith was intruded into the Wallowa terrane. Sphalerite geobarometry (Reinthal, 1986) and contact metamorphic mineral assemblage of andalusite + biotite + garnet (Godwin, 1999) indicate that the Bald Mountain batholith was the shallowest of the intrusive complexes, having been emplaced at 1 - 2 kb pressure. Although absolute emplacement ages for the Bald Mountain and Wallowa batholiths are poorly constrained, intraplutonic contact relationships indicate that for each, the most mafic phases (gabbronorite through diorite) were the emplaced first; followed by larger tonalite intrusions. Emplacement of small, more evolved granodiorite and granite magmas generally marked cessation of intrusive activity. The Bald Mountain Batholith displays a general evolution from diorite through tonalite and granodiorite. The Wallowa Batholith shows an evolution from gabbro to tonalite and granodiorite. Small satellite intrusions, such as the one on

Catherine Creek are more alumina rich trondjhemites. Work by Johnson and others (1995) indicate that in northeast Oregon; Mesozoic magmatism can be divided into two episodes; a Late Jurassic - Early Cretaceous tonalite-dominated event and a later Cretaceous trondhjemite dominated episode.

The upper Grande Ronde River basin underwent significant uplift through the middle and late Cretaceous as the Mesozoic intrusions were unroofed. Between 5 and 15 km of overlying rocks was stripped by erosion from above the plutonic complexes, the eroded material was redeposited as sediment in middle and late Cretaceous marine basins near Mitchell in central Oregon (Wilkenson and Oles, 1968). Fossilferous beach sands place the edge of the marine basin a short distance northeast of John Day in the late Cretaceous (Cenomonian-Turonian) (Brooks and others, 1984). During the Paleocene and Eocene, river systems draining the continental interior deposited the Herren Formation -a thick sequence of deltaic sandstone- just west of the basin (Fisk, 1986). Detrital muscovite in the Herren Formation was likely derived from an Idaho Batholith source (Heller and others, 1985). Further east, quartzite-boulder-filled channels cut into the Bald Mountain and Wallowa batholiths are all that remain of a westward-flowing river system (Cisneros, 1999) that once fed the deltaic sequence. The old channels, which locally contain placer gold, are marked by hydraulic placer pits such as those at Camp Carson and on Jim White Ridge (Figure 42). Percussion-marked quartzite boulders as much as 0.60 m in diameter most likely came from the Proterozoic or lower Paleozoic quartzites of central Idaho (Trafton, 1999),

Tertiary continental volcanism began in northeast Oregon during the Eocene with eruption of the calc-alkaline Clarno Formation. Basalt, basaltic andesite, andesite, dacite, and rhyodacite flows and associated small subvolcanic intrusions were emplaced south of the map area between 33.6 and 40 Ma (Ferns and others, 1982; Brooks and others, 1982; 1984; Lilligren, 1992). Mid-Tertiary bi-modal volcanism in the upper Grande Ronde River basin began with small eruptions of tholeiitic and alkalic basalts at about 29.8 Ma. Eruptions from the central vent area at Tower Mountain began at about 28.8 Ma, when large eruptions of dacite and rhyolite magmas generated lahars, and lava flows that buried old river channels on the flanks of the granitic and metamorphic highlands of the Elkhorn Mountains. Later explosive eruptions produced a 100+ m thick welded ash-flow tuff that flowed southwestward from Tower Mountain. Collapse along arcuate ring fractures produced a subsiding, lithic-tuff filled cauldron nearly 15 km in diameter. At about 28 Ma, a series of rhyolite domes extruded along the arcuate ring fractures. Caldera-fill tuffs were later intruded by porphyritic and aphyric dacite and rhyolite masses, forming a resurgent caldera core complex that today is marked by a pronounced gravity low. Volcanism ceased at Tower Mountain at about 22 ma with eruption of dacite and andesite lavas east of the caldera margin.

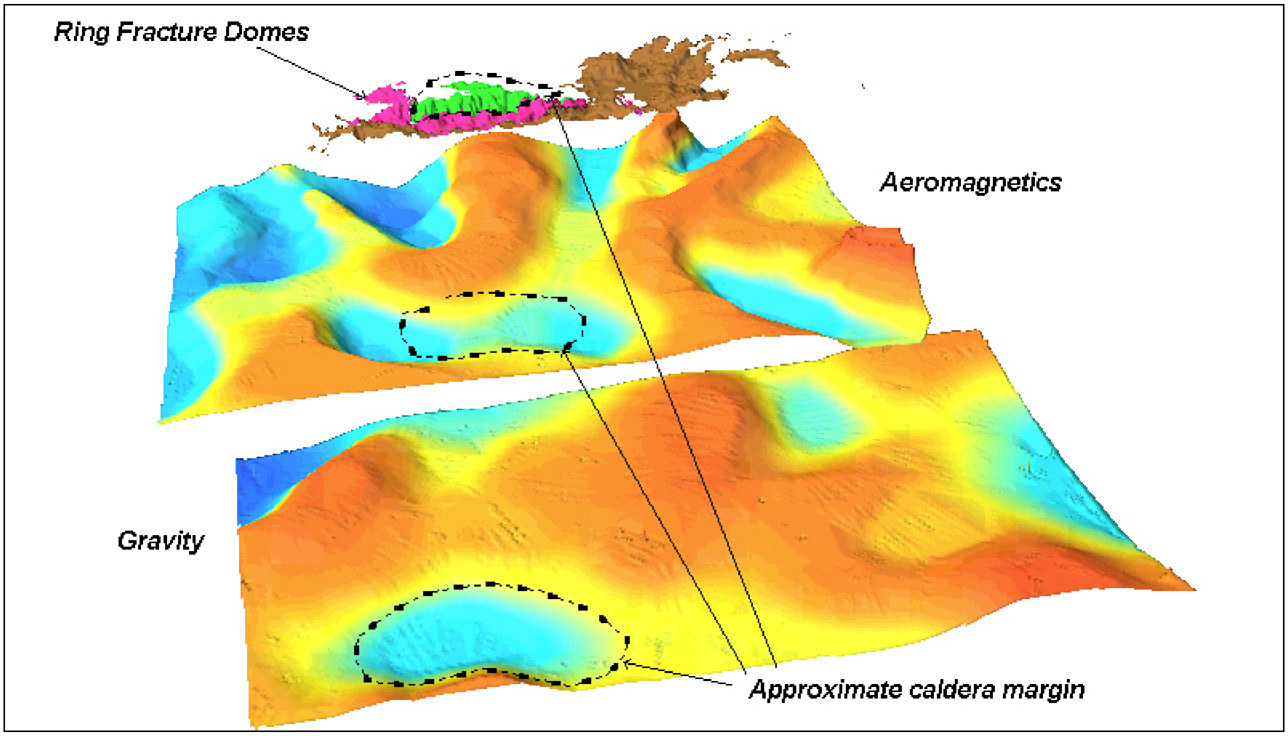

Figure 39 Shaded relief map showing the location of the Tower Mountain caldera in relationship to regional gravity and aeromagnetic anomalies. Caldera fill tuff is shown in green, ring fracture domes in purple and bordering tuffs, breccias, and lava flows in brown. The caldera is situated above distinct gravity and magnetic lows that are shown in blue.

The northern flank of the Tower Mountain caldera was buried by Columbia River Basalt flows. These middle Miocene tholeiitic flood basalts are exposed over an area of more than 1,500 km^2 in the basin, reaching thicknesses as great as 700 m. Flood basalt magmatism began about 17 Ma with eruption of basal units of the Imnaha Basalt. Early Imnaha Basalt flows erupted from vents along the eastern edge of the basin and flowed northwest onto a highly irregular surface of deeply eroded pre-Tertiary rocks. Although several early Grande Ronde Basalt flows apparently erupted from a small, north-trending dike swarm exposed along the west margin of the Bald Mountain Batholith, most of the Grande Ronde flows in the basin apparently erupted from vents located near the east margin of the Grande Ronde Valley. In the southeast quadrant of the map area, the last Grande Ronde flows formed an onlap sequence across an actively tilting surface of older Grande Ronde flows and underlying basement rocks. At least some of the tilting was accompanied by vertical movement along the Shaw Mountain fault zone (Madin, 1998).

Grande Ronde volcanism culminated at about 15.5 Ma with eruption of the highly evolved, low MgO ferroandesites of Fiddler's Hell (Ferns and others, 2001) from vents along the southeast margin of the modern Grande Ronde Valley. Diatremes, spatter mounds, and northeast-trending dikes exposed high in the Grande Ronde section at Indian Rock and at Cricket Flat north of the Grande Ronde Valley mark the location of other low MgO Grande Ronde vents. High MgO flows of the Sentinel Bluffs member (Reidel and others, 1995) that flowed eastward across the northern end of the upper Grande Ronde River basin may be the last of the Grande Ronde Basalt flows to erupt Although individual Grande Ronde Basalt flows usually rest directly atop one another, the last Fiddlers Hell and Sentinel Bluff eruptions show evidence for interaction with water. Fiddler's Hell flows locally invade diatomaceous sediments near Wolf Creek Reservoir (Madin, 1998) and Ladd Canyon along the east edge of the La Grande 30' x 60' quadrangle (Ferns and others, 2001). Palagonite breccias also occur at the top of the Grande Ronde Basalt near Cricket Flat. Local interactions between flows and water are considered as evidence for the beginning development of structural basins atop the Grande Ronde Basalt surface.

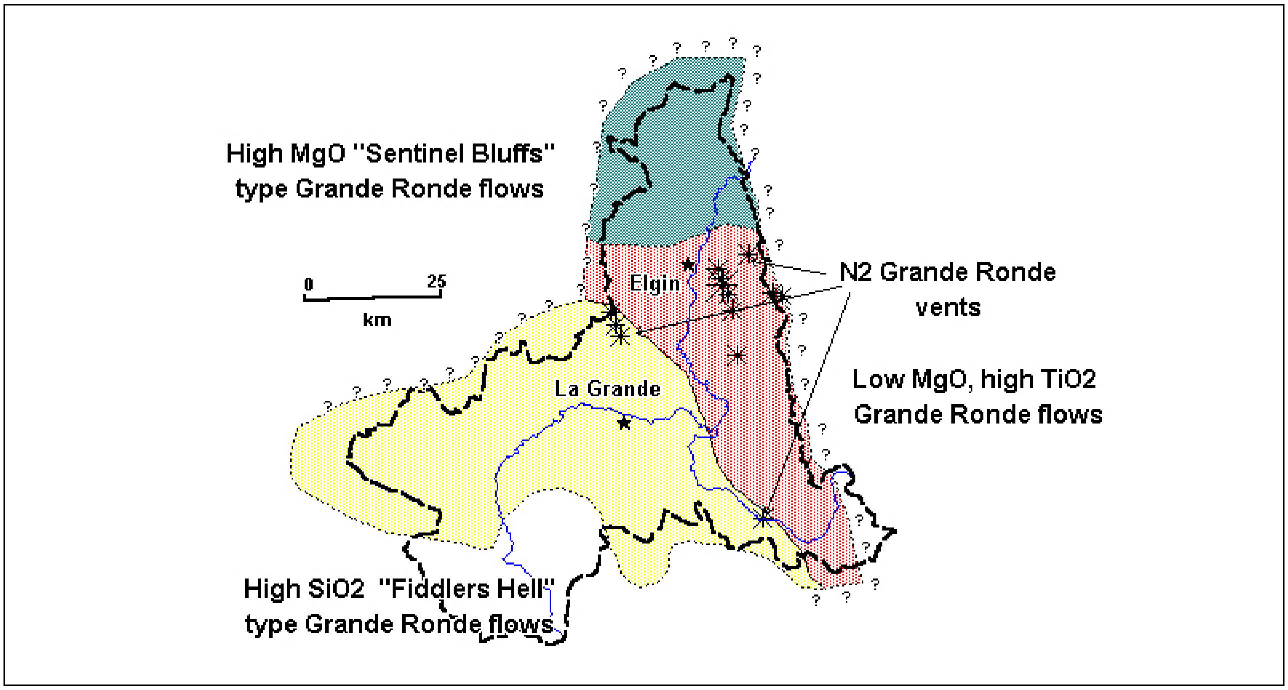

Figure 40 Diagram showing distribution of late Grande Ronde Basalt flows and vents. The Fiddlers Hell flow erupted from vents along the present-day eastern margin to the Grande Ronde Valley and flowed westward. Other low MgO, high TiO2 flows subsequently erupted from vents in the northern part of the basin, where they were buried by still younger high MgO “Sentinel Bluffs” flows, which flowed across the northern end of the basin. Location of the Sentinel Bluffs vents is presently unknown.

Palagonitc flows at the top of the Grande Ronde Basalt are commonly marked by a red, saprolitic soil zone that separates the top of the Grande Ronde Basalt from the basal flows of the Wanapum Basalt. Many Wanapum Basalt flows in the upper Grande Ronde River basin are also deeply weathered and show evidence of interaction with water. Wanapum Basalt volcanism began with eruption of coarsely crystalline, high MgO, low TiO2 olivine basalt flows of the Dodge member from a dike swarm to the east (Hooper and Swanson, 1990). The Lookingglass flow, a fine-grained lava that is chemically and petrographically similar to the more evolved low MgO flows exposed at the top of the Grande Ronde Basalt to the south, erupted from a buried source in the northern part of the basin. The Lookingglass eruption was followed by arrival of a single Frenchman Springs flow. The Powatka flow, a more evolved low MgO lava that is also very similar to more evolved low MgO Grande Ronde Basalt flows, then erupted from a now buried source near Cricket Flat. In the northern part of the basin, the upper Grande Ronde Basalt flows and Wanapum Basalt flows display similarities. High MgO flows, including the Sentinel Bluff member of the Grande Ronde Basalt and the Dodge and Frenchman Springs members of the Wanapum Basalt, erupt from sources outside of the upper Grande Ronde Basin and flow westward across the northern part of the basin. More evolved low MgO flows, including the Fiddlers Hell member of the Grande Ronde Basalt and the Lookingglass and Powatka members of the Wanapum

Basalt, erupt from a line of vents located along the eastern margin of the basin. The short hiatus that separates Grande Ronde volcanism (which ended at approximately 15.5 Ma) from the eruption of the first of the Wanapum Basalt flows at 15.3 Ma is marked by saprolitic soils and water-affected basalt. Present-day configuration of the Wanapum flows (Swanson and others, 1981) indicate that the Wanapum lavas flowed across the present day Blue Mountains axis without impediment; showing that that the Blue Mountains uplift postdates Wanapum volcanism. Westward thickening of the Frenchman Springs member to the west can be attributed to paleogeography. The cluster of Frenchman Springs dikes in the northern Umatilla and southern Walla Walla river drainages suggests that the Frenchman Springs volcano was situated to the west of the upper Grande Ronde River basin.

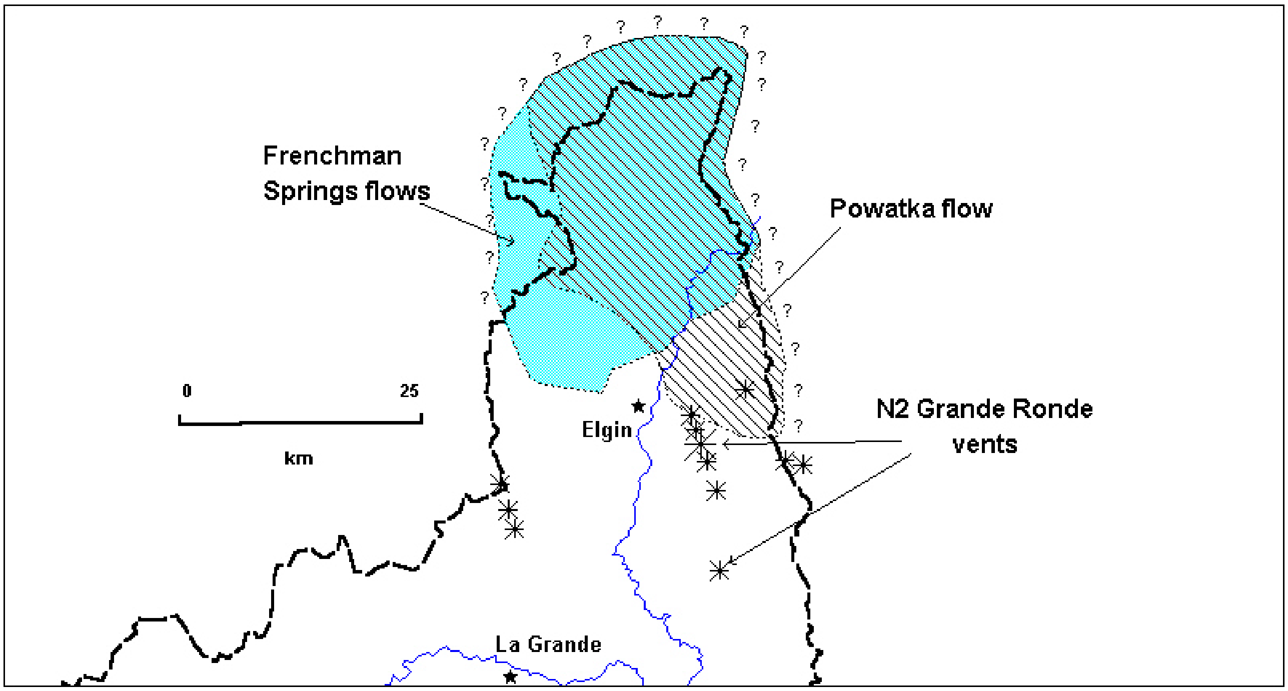

Figure 41 Diagram showing extent of late Wanapum Basalt flows. Areal extent of the Powatka flow indicates that it probably erupted from a now buried series of vents northeast of Elgin. The Frenchman Springs flows thicken to the west, toward a dike complex exposed on the South Fork of the Walla Wall River. The Frenchman Springs flows exposed in the quadrangle may have flowed eastward from a Frenchman Springs eruptive complex located in that area.

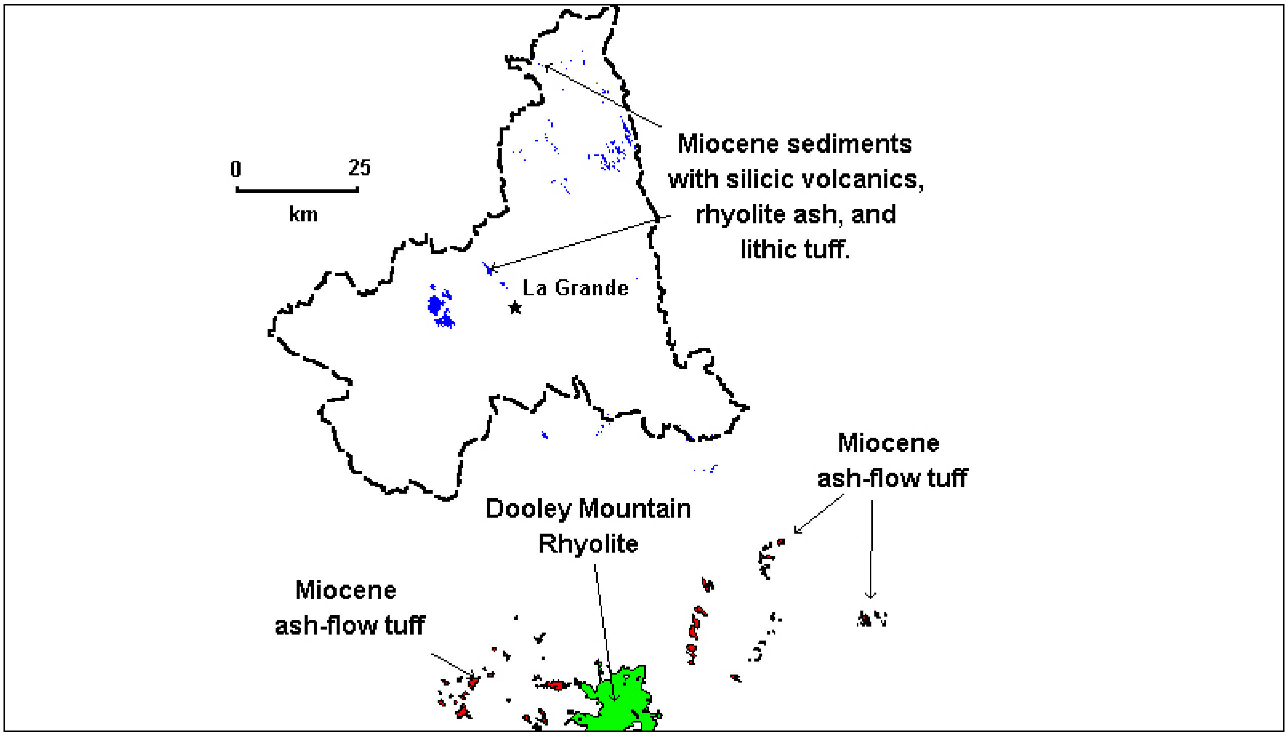

Figure 42 Diagram showing, in blue, the distribution of middle Miocene sediments (Tms) that contain rhyolitic tuff and ash. Closest middle Miocene rhyolite eruptive center is located at Dooley Mountain, shown in green, located over 50 km south of the basin. Ash-flow tuff exposures are shown in red.

Fluviatile sands and gravels, and thin discontinuous lenses of rhyolitic lithic ash-flow tuff were subsequently deposited in shallow basins extending from the southern part of the upper Grande Ronde River basin north into the Umatilla Basin. The sediments were preserved in: 1) structural basins developed atop the Grande Ronde and 2) areas where they were protected by younger overlying volcanic rocks. Isolated, widely separated remnants of presumably once extensive flows of olivine basalt and ash-flow tuff are preserved between Starkey and La Grande. Although the source for the ash-flow tuff has not been identified, the thickest ash-flow exposures so far identified crop out to the southeast of the basin, along the northwest margin of the Baker valley (Madin, 1998). A regionally extensive ash-flow (informally referred to as the tuff of Pleasant Valley) is exposed over a large area south and east of the Baker valley may correlate with the La Grande exposures. Source of the tuff of Pleasant Valley is generally considered to be the large rhyolite complex at Dooley Mountain that lies south of the Baker Valley (Evans, 1992). Limited radiometric dates indicate the tuff erupted at about 14.7 - 14.8 Ma (Bailey, 1990; Fiebelkorn and other, 1983). Northward transport directions are also indicated by lithologic makeup of interbedded gravels near Starkey, La Grande, and Elgin. (unit Tms). The gravels contain quartzite, blue chert, rhyolite, dacite, and granitic and metamorphic clasts, micaceous sands, and, locally, small amounts of placer gold. The Tower Mountain caldera is the most likely source for the rhyolite and dacite clasts. Nearby exposures of Elkhorn Ridge Argillite and Carson Wash gravels are likely southern sources for the blue chert and quartzite clasts.

The middle Miocene ash-flow and sedimentary rocks were quickly buried by the first eruptions of the Powder River Volcanic Field. Diktytaxitic olivine basalt flows began erupting at about 14.5 Ma (Bailey, 1990), filling local channels and spreading laterally over much of the eastern part of the basin. Deep water wells in the Grande Ronde valley indicate that successive olivine basalt eruptions filled a north- northwest-trending ancestral Grande Ronde Valley with as much as 150 m of olivine basalt. On the west margin of the valley, the olivine basalt flows extend laterally over an area of some 580 km^2, thinning to the west, where they are interbedded with middle Miocene gravel in the Starkey units.

In the northern part of the basin, presumably the same middle Miocene sediments were buried by the first Saddle Mountains Basalt flow, the Umatilla member, which erupted from a source east of the basin (Hooper and Swanson, 1990) at about 13.5 Ma. Continued sedimentation in the northern part of the basin resulted in formation of extensive coal swamps; perhaps in response to initial blockage of a west flowing ancestral Grande Ronde-Salmon River drainage system by the Umatilla flow (Hooper and Swanson, 1987, 1990; Swanson and Wright, 1983). The next youngest Saddle Mountains Basalt flow, the Eden flow, which erupted from source located near the confluence of the Wallowa and Grande Ronde Rivers and flowed northeastward, into the Lewiston area (Hooper and Swanson, 1990).

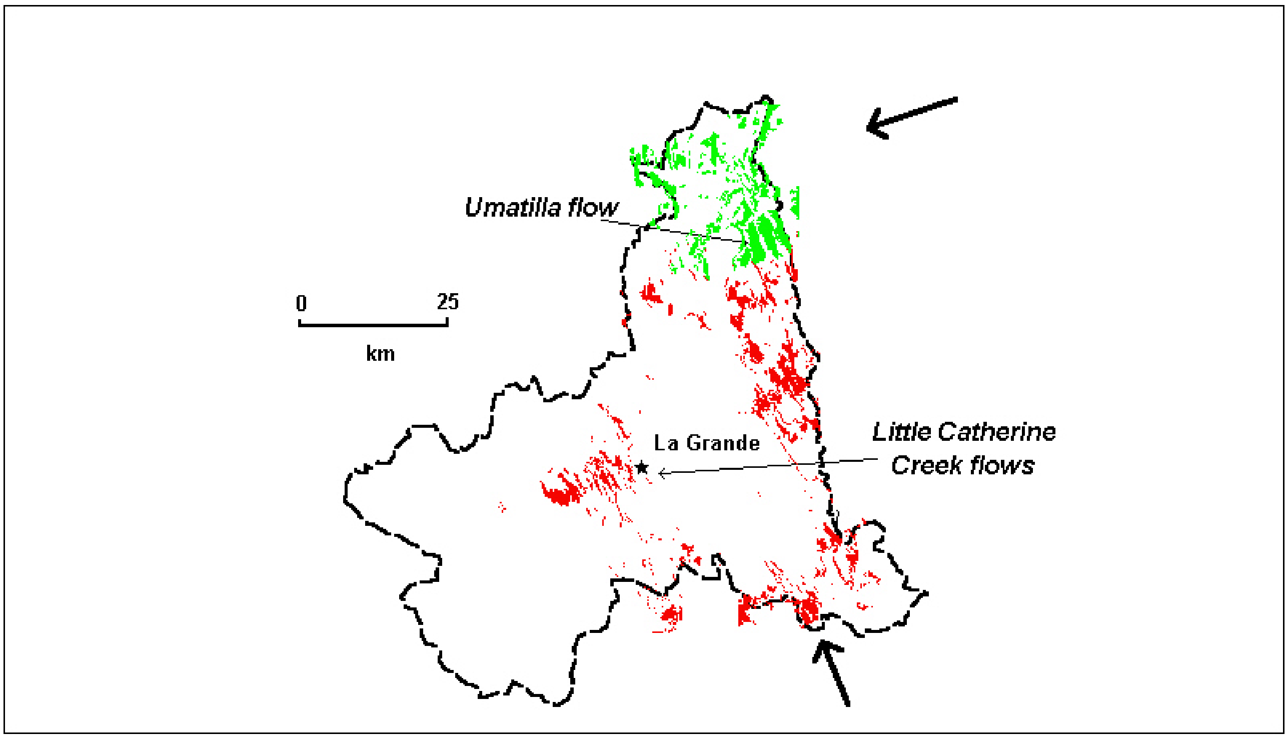

Figure 43 Diagram showing regional distribution of Saddle Mountain Basalt, shown in green, and early Powder River Volcanic Field olivine basalt, shown in red. Vents from both units were presumably located outside of the basin. Arrows show presumed flow directions.

Dacite volcanism in the Powder River Volcanic Field began at about 13.4 Ma, with the eruption of Mt Emily dacite flow on the west side of the Grande Ronde Valley. Continued calc-alkaline volcanism continued through 12 Ma, with formation of a moderate sized stratovolcano at Mt Harris; eruption of large dacite and andesite flows at the top of Mt Fanny; and formation of the small basaltic andesite cinder cones at Ramo Flat. The N35^{o}W trend of the Ramo Flat vents suggests that the fault zones within and marginal to Grande Ronde valley may have became active during initial stages of Powder River volcanism (Ferns and others, 2001). Later alkalic eruptions between 10.5 and 12 Ma produced small basanite and alkali olivine basalt flows that filled northwest-trending channels.

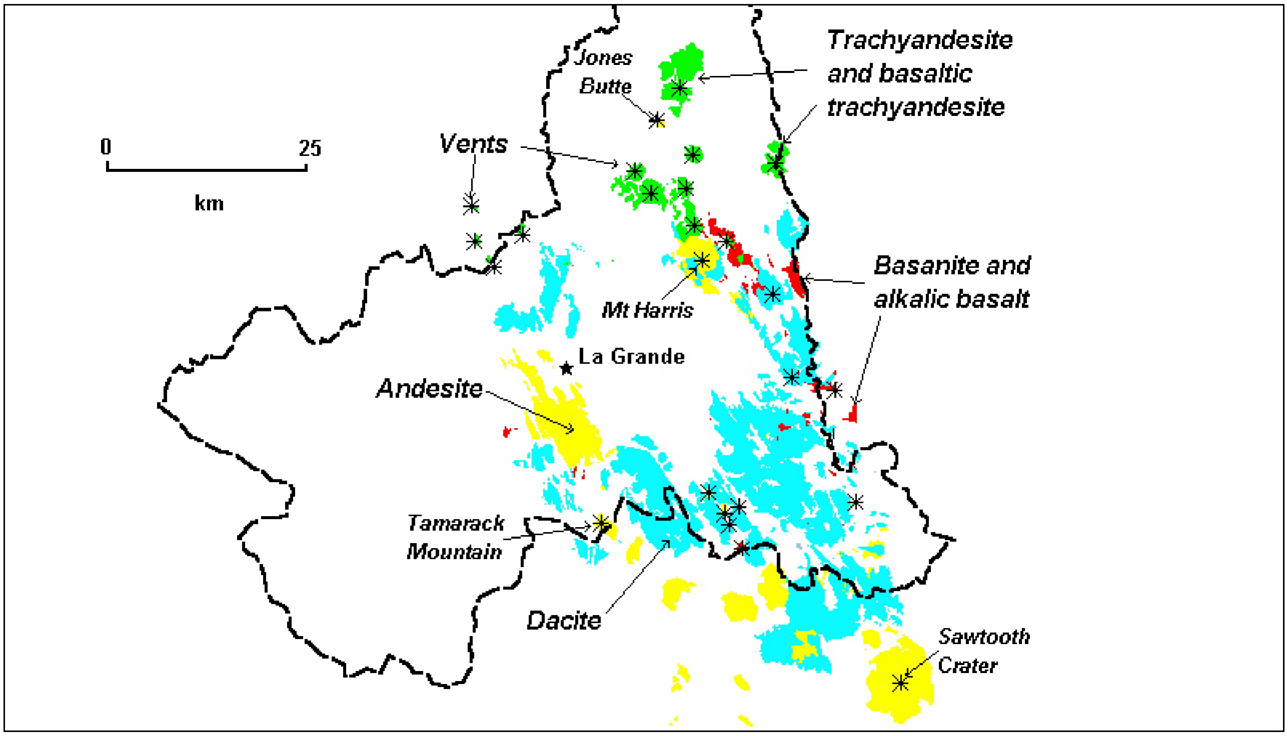

Figure 44 Diagram showing regional distribution of younger Powder River Volcanic Field units. Dacite flows are shown in blue, andesite flows in yellow, basanite and alkali basalt flows in red, trachy basalt, trachy basaltic andesite, and trachyandesite in green. Vents at Tamarack Mountain and Jones Butte are late Pliocene in age, all others are late Miocene or early Pliocene in age.

Between 10 and 7 Ma, the modern upper Grande Ronde River basin began to take form as the Blue Mountain anticlinorium began uplifting to form a topographic barrier to the westward movement of lava flows and sediments (Hooper and Swanson, 1990). By 8 Ma, the Grande Ronde Valley was subsiding to form a major, fault-bounded catch basin for air fall tuffs and fine-grained silts. Post-Grande Ronde Basalt sediments were preserved in basins developed along the Shaw Mountain fault zone. At about 7 Ma, small trachybasalt, trachy basaltic andesite, and trachyandesite flows erupted onto the faulted Grande Ronde Basalt highlands west of Mt Emily (Kienle and others, 1979) and at Elgin. Eruptions in both areas formed a cluster of small -typically < 1 km^2, compositionally distinct shield volcanoes that formed along northwest-trending fault zones. Major uplift and deformation waned by the middle Pliocene at about 3.2 Ma when a small high silica andesite of Tamarack Mountain erupted along the south end of the Hilgard fault zone. The Tamarack Mountain flow unconformably overrode an older faulted and tilted surface of Grande Ronde and Glass Hill lavas. A young (~2 Ma) high silica andesite also erupted at Jones Butte (Fiebelkorn and others, 1983), flowing out on to older terrace gravels (Walker, 1979).

Pliocene and post-Pliocene subsidence along the eastern edge of the map area resulting in the formation of the Grande Ronde Valley. Although the Grande Ronde Valley is described as a pull-apart basin that formed in response to regional strike-slip movement along the Olympic Wallowa Lineament (OWL) (Hooper and Conrey, 1989; Mann and Meyer, 1993); the overlapping sequence of Columbia River Basalt and Powder River Volcanic Field vents along the East Grande Ronde Valley fault zone suggests a more complicated tectonic history involving volcanic induced uplift, extension and subsidence. The Grande Ronde Valley's west and east margins are marked by active normal faults whose north and south margins are marked by inward-dipping blocks that project under valley-fill sediments. Valley subsidence was accompanied by uplift and deep dissection of the batholith-cored Elkhorn and Wallowa Mountains, with eroded material from these highlands being deposited in the both valleys. Multiple terrace and alluvial fan levels and erosional bedrock highs in the north end of the Grande Ronde Valley formed as the basin floor tilted southward, deepening toward more active faults along the south and west valley margins.

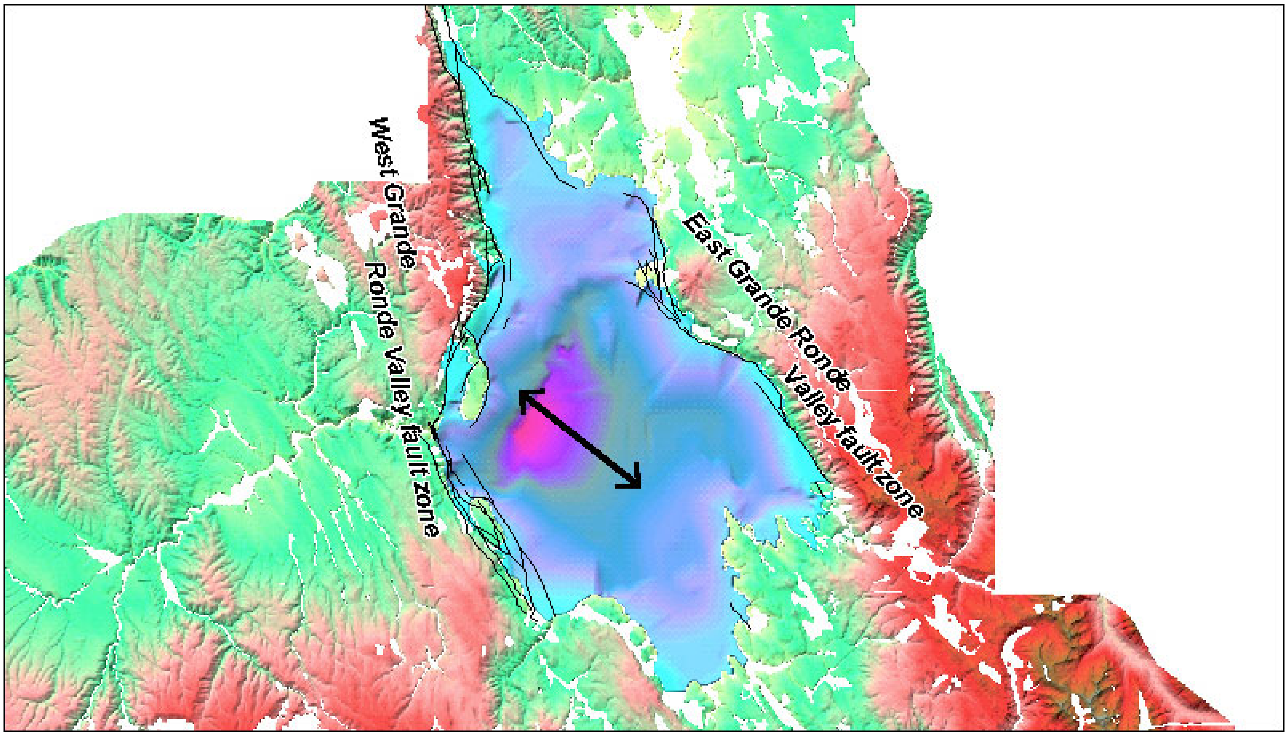

Figure 45 False color shaded relief model of the top of the volcanic section as projected beneath the Grande Ronde Valley. Deepest part of the valley shows as vivid purple. Arrows show presumed sense of extension. Model is based on a limited number of well logs, seismic lines, and geologic cross sections.

The Grande Ronde valley floor was also tilted toward the west as the valley the gradually deepened. The top of the Miocene Glass Hill section eventually subsided to a depth of more 650 m in the central part of the valley. As the valley floor dropped, a thick section of interbedded silt and fine sand gradually accumulated in the central part of the valley. In the southern part of the valley, the valley floor and overlying sediments tilted westward as the valley continued subsiding along the West Grande Ronde Valley fault zone. Coarse sand and gravel accumulated along the front of the West Grande Ronde fault zone as a delta plain formed where the Grande Ronde River entered the valley.

In the middle and late Pleistocene, alpine glaciers formed in the Elkhorn Mountains, feeding valley glaciers that extended down the Grande Ronde River to an elevation of about 1500 m. The valley glacier on the Grande Ronde River reached it's maximum extent during the Bull Lake (150,000 - 200,000 yr BP) glaciation, with little ice reaching the Grande Ronde River during the younger Pinedale (10,000 - 30,000 yr BP.) glaciation (Geraghty, 1999). More extensive glaciers developed in the Wallowa Mountains, where at least three stages of Pleistocene glaciation are recorded (Crandell, 1967; Bentley, 1974; Richmond and Fullerton, 1986). Bentley (1974) notes that all three branches of Catherine Creek contained glaciers with the North Fork of Catherine Creek glacier extending down to an elevation of 1460 m. Bentley (1974) suggested that Mt. Fanny was the site of an isolated body of ice of approximately 21 km^2 in size that was isolated and upwind from the massive accumulations of ice in the higher elevation Wallowa Mountains further east. McConnell and others (2003) report that ice may have covered the Mt. Fanny plateau over an area of as much as 50 km^2 during the glacial maximum. Ice accumulation on the Mt. Fanny plateau apparently built up without tremendous flowage. A series of alpine glacial valleys and nivation hollows developed along the edges of the plateau, feeding a few glaciers that flowed far enough to reach the deeper valley glaciers. One valley glacier flowed down Indian Creek to the north. McConnell and others report cirques at elevations as low as 1780 m elevation near Moss Springs, lower than Bentley's (1974) suggested cutoff elevation of 1900 m. Lower elevation glaciation at Moss Springs apparently resulted from the unusually high levels of snowfall that accumulate on the Mt Fanny plateau (McConnell and others, 2003). Today the average yearly Moss Springs snow pack is equivalent to those of elevations of 2100 m in the Elkhorn Mountains to the south (Bentley, 1974).

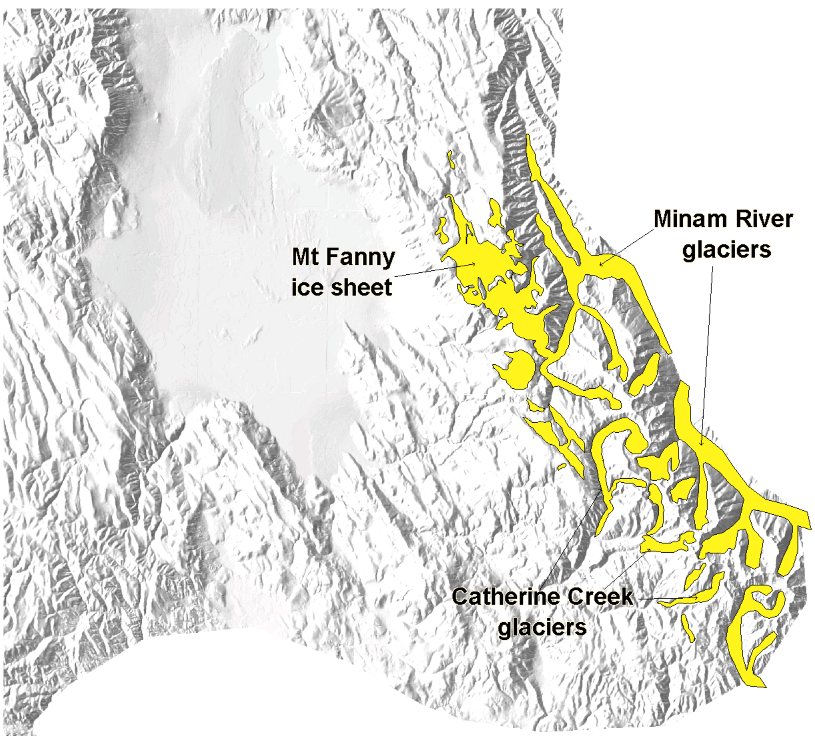

Figure 46 Shaded relief map of the upper Grande Ronde River basin showing, in yellow, extent of glaciers and ice sheets on the eastern block. The Mt Fanny ice sheet fed small glaciers on Indian Creek and the Minam River.

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Throughout the Quaternary, the fan deltas at La Grande and Union expanded and contracted as sedimentation rates fluctuated during glacial advances and retreats (Van Tassell, 1997). Continued subsidence along the West Grande Ronde Valley fault zone acted to form an ever-deepening alluvial gravel trap at La Grande. Airfall tuff from Cascade volcanic eruptions and loess from outburst glacial flood deposits near Pendleton was blown into the basin. Ephemeral lakes and marshes developed in the central part of the valley, perhaps in response to periodic blockage of the outlet of the Grande Ronde River by debris avalanches off of the side of Mt Harris.

GEOLOGIC RESOURCES

Aggregate and industrial minerals

Locally-used aggregate in the form of crushed rock and gravel has been the major mineral resource mined in the upper Grande Ronde River basin. Aphanitic flows of Grande Ronde Basalt units are the main sources for the road metal used on the extensive network of US Forest Service and private industry access and haul roads. Platy, flow banded rhyolite, dacite, and andesite have also been used as road metal sources. Sand and gravel resources suitable for aggregate are more restricted; occurring mainly as fluvial fan and terrace surfaces in the Grande Ronde valley. Coarser gravel lenses in the middle Miocene sedimentary units at Ukiah, Starkey, and Spring Creek are locally used for aggregate.

Clay used for firing brick has been mined from clay beds where the Grande Ronde River enters the Grande Ronde Valley. Clay was originally mined from lacustrine clays deposited when the Grande Ronde Valley was partially filled by a shallow lake (Wagner, 1947). Clay deposits at La Grande were largely mined out between 1900 and 1966 for feed stock at the La Grande Brick yard.

Other industrial mineral resources in the basin include perlite and rhyolite facing stone in the ring fracture domes flanking the Tower Mountain caldera. Some flow banded rhyolite is white to pale yellow in color and has been used as facing stone on buildings in La Grande. Palagonitic breccia from hydrovolcanic deposits in the upper part of the Grande Ronde Basalt have been used in buildings at Elgin. Red and pink andesite from the Jones Butte vent has also been used in buildings at Elgin.

Massive dacite from the Powder River Volcanic Field is locally used as rip rap for stream bank stabilization. Some of the Powder River Volcanic Field dacites have zones where regular vapor phase partings, when weathered, yield an attractive pink and brown flagstone. Some of the platy dacites are especially attractive due to large black, pyrolusite dendrites.

Some of the intrusions in the Bald Mountain batholith may hold some promise for decorative building stone. Equigranular white granodiorite exposed in the glaciated core of the Bald Mountain batholith near Anthony Lakes; the pinkish-orange weathering, potassium feldspar megacryst-bearing granite of Anthony Buttes exposed along USFS Road 43; and the hornblende-olivine phyric lamprophyre mass exposed on USFS Road 5125 (Ferns and Taubeneck, 1994) are particularly attractive.

Semi-precious gemstones

Semi-precious gemstones, in the form of opal, chalcedony, and quartz locally occur in the rhyolite domes marginal to the Tower Mountain caldera. Lithophysae cavities up to 3 cm across with terminated quartz crystals are found in silicified rhyolite domes exposed west of Sheep Creek (Ferns, 1999). Small (2 cm) thundereggs partially filled with bands of brown jasper, blue chalcedony, and crystalline quartz have been found in silicified banded rhyolite (Ferns and others, 2001).

Metallic mineral resources

Only a small part of the upper Grande Ronde River basin shows evidence indicative of potential precious metal mineralization. Potential gold resources in the quadrangle occur in three distinct geologic settings. These are, in order of importance: 1) Placer deposits in modern or ancient stream channels; 2) Pre-Tertiary-aged hydrothermal alteration zones within and marginal to the Bald Mountain and Wallowa batholiths; and 3) Tertiary-aged hydrothermal alteration zones found mostly within and marginal to the Tower Mountain caldera. Other than a very few areas of weak clay and opaline quartz alteration along fault zones, the large (>1,500 km^2) expanse of middle Miocene and younger volcanic rocks bear no evidence of hydrothermal alteration.

Placer Deposits

Based on historical records, less than 50,000 ounces of gold was probably produced by placer mines in the basin (Ferns and others, 2001). The large hydraulic placer mines at Camp Carson are the only workings of significant size. The workings exploited Tertiary gravel channels along the contact between the Bald Mountain batholith and the base of unit Teg. No reliable production records are available; the Camp Carson mine is alleged to have produced $500,000 in gold during the peak operating years of 1892-1893 (Ferns and Taubeneck, 1994). Based on size of the hydraulic pits, more than 2.5 million yds^3 of Teg sediments were worked at Camp Carson. Based on available records, grade of material mined was apparently low, averaging about no more than 0.01 oz/yd^3. Significantly smaller hydraulic pits worked channels in the upper blue chert gravel part of unit Teg. Dilution due to influx of clay-rich volcanic debris likely lowered the overall grade of the upper gravel. In the 1940's, a small dragline dredge operated along the modern stream channel along Tanner Gulch and the Grande Ronde River for a distance of about 3.2 km. downstream of the Camp Carson mine. Similar gold-bearing Tertiary gravels overlie granite bedrock at Wolf Creek, at Frenchman Diggings, and along Jim White Ridge. A small amount of placer gold was apparently recovered from arkosic gravels in the middle Miocene sedimentary units. Ferns and others report (2001) report old, gold-bearing placer workings on lower Beaver Creek, Sand Creek, and Five Points Creek.

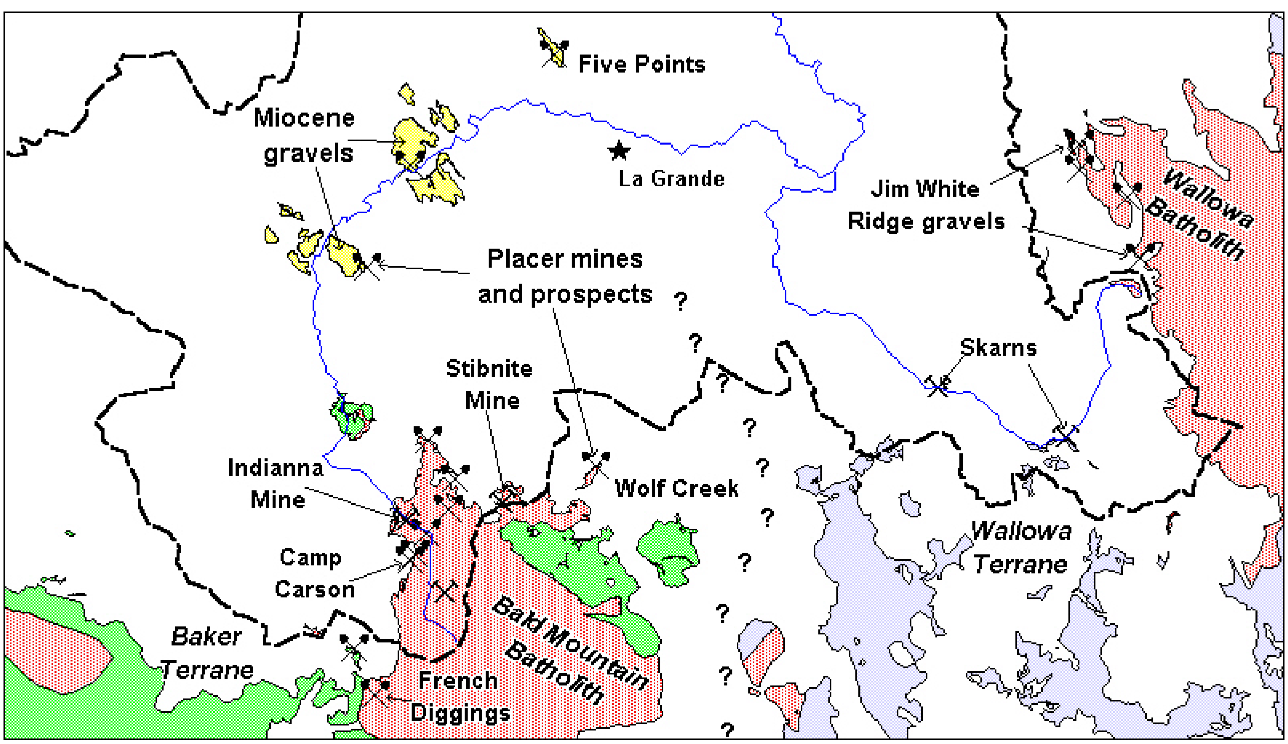

Figure 47 Diagram showing distribution of gold placers and lode prospects associated with the Wallowa and Bald Mountain batholiths in the upper Grande Ronde river basin. Several small skarns are located along Catherine Creek. Diagram shows only the lode prospects and mines located within the basin. Numerous mines and prospects south of the basin are not shown.

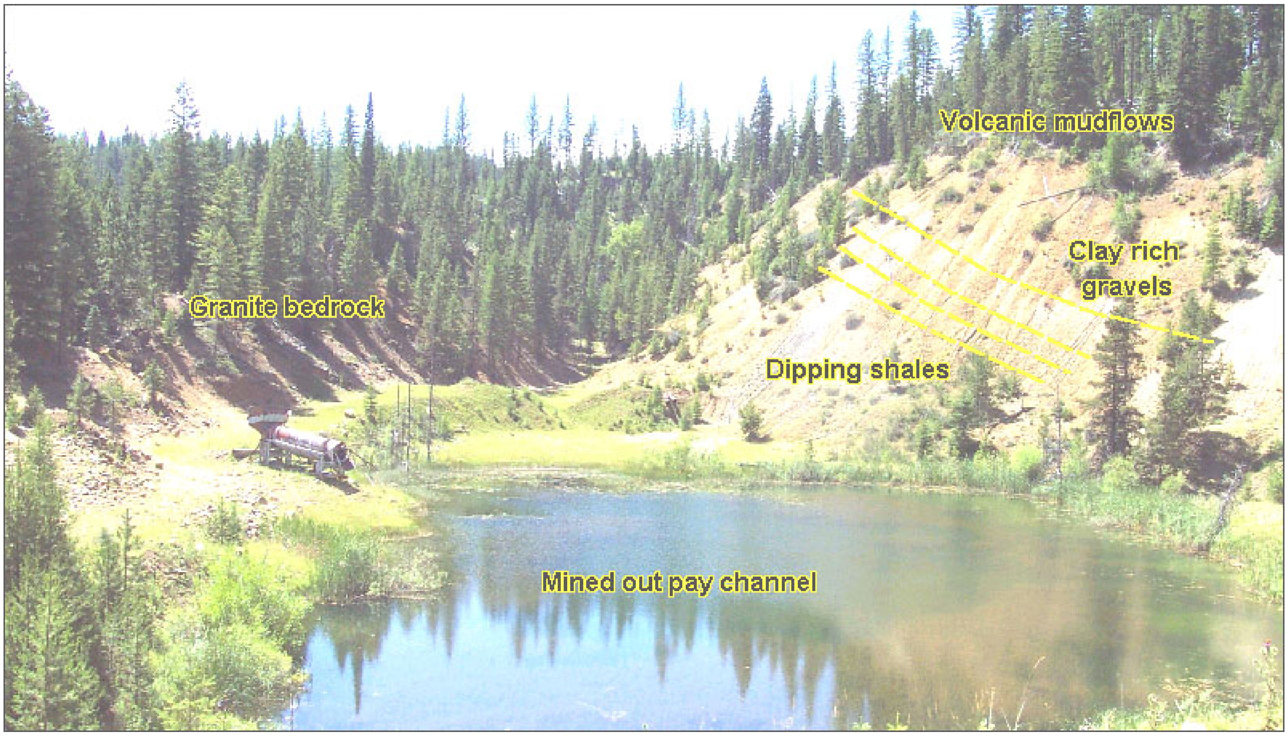

Figure 48 The largest gold mine in the basin was the Camp Carson Mine, shown here. This placer pit was part of a large hydraulic mine. The small pond shown here was originally drained by a tunnel through the granite bedrock. Based on available records from the 1890's, the pay streak was confined to coarse quartzite boulder channel gravel. The barren carbonaceous shales and clay-rich gravels that overlie the channel had to be removed before the gold bearing material could be reached. The trommel to the left of the pond is a relict of an iil-fated attempt to mine some of the clay rich material in the 1980's.

Pre-Tertiary mineralization associated with the Bald Mountain Batholith

A very small amount of silver, gold, and antimony have been produced from lode mines in and adjacent to the Bald Mountain Batholith (Figure 16). Ferns and Taubeneck (1994) report that small, discontinuous lenses of silver-bearing galena and sphalerite were mined from altered Elkhorn Pluton tonalite near the contact with the granite of Clear Creek. Here discontinuous quartz stringers with streaks and kidneys of massive galena and sphalerite occur in altered tonalite. According to Wagner (1945), lead-silver sulfide lenses at the Indianna Mine were found in a vein with a strike of N 25^{o} E and a dip of 45^{o} SE. Total production from the Indianna and adjacent mines was likely small; historic records are limited to a 1944 smelter shipment of 28 tons that assayed 0.15 oz/ton gold, 35.2 oz/ton silver, 2.4 % lead, and 1.5 % zinc (Wagner, 1945).

Three carloads of antimony ore were reportedly shipped from the Stibnite Mine during World War I (Richards, 1942; Wagner and Ramp, 1969). Here small bunches of stibnite occur in a 0.3 - 1' thick quartz vein. The vein strikes about N 45^o E and dips 80^o NE in a host of disintegrating Elkhorn Pluton granodiorite.

Pre-Tertiary mineralization associated with the Wallowa Batholith

A couple of small prospects explore skarns where the Wallowa Batholith and satellite intrusions cut calcareous sediments of the Lower Sedimentary Series. Small, discontinuous iron-stained lenses of garnet, epidote, calcite, and fine-grained quartz occur in limestone and calcareous argillite at the confluence of the South and North forks of Catherine creek and along Catherine Creek downstream of the Catherine Creek State Park. There is no history of production at either location. Traces of gold and silver are reported from similar skarns elsewhere in the Wallowa Mountains (Weis and others, 1976).

Tertiary mineralization associated with the Tower Mountain caldera

Ferns and others (2001) report several mineralized zones in the Tower Mountain caldera. Most intense areas of alteration occur in late stage rhyolite domes on the east flank of the caldera. The quartz-phyric rhyolite that crops out between Fly Creek and the Grande Ronde River appears the most intensely altered (Ferns and others, 2001). Massive opalite and chalcedonic quartz lenses are exposed in rhyolite vitrophyre along the contact between a porphyritic rhyolite and porphyritic dacite flows near Chicken Creek (Ferns and others, 2001). Mineralization within the caldera is associated with small silicic dikes and stocks (Ferns and others, 2001).

Energy resources

Geothermal

The Grande Ronde Valley and western uplands are areas in the upper Grande Ronde River basin with potential low temperature geothermal resources. The Lehman Hot Springs resort, the Cove swimming pool and the RV resort near Hot Lakes are the only places is the only places in the basin where low temperature geothermal waters are currently exploited.

The warmest surface waters in the basin are found near Hot Lake, where a large spring of 85^{o}C water flows at 170 gpm (Hampton and Brown, 1964). Other springs, including the Duck Pound and Union Junction springs, ranging in temperatures from 20^{o}C to 35^{o}C, are located further south along the foot of the Hot Lake fault (Barrash and others, 1980; Baxter and others, 1978). The Hot Lake spring is located near the where the N35^{o}W trending Hot Lake fault makes a sharp left hand bend to the west. The warm springs at Cove yields 226 gpm at 29^{o}C water (Hampton and Brown, 1964). Two deep water wells in the central part of the Grande Ronde Valley tap significant artesian flows of low temperature geothermal waters at depth. The well at Alicel (Oregon Water Resources Department # UNIO-50687) intercepted an artesian flow of 43^o C water in Grande Ronde Basalt flows at approximately 840 m depth. The Greg Bingaman well (Oregon Water Resources Department # UNIO-50684) first encountered an artesian flow of 32^o C water in Powder River Volcanics at a depth of approximately 640 m. This well penetrated about 580 m of sediment before entering Powder River Volcanics. Significant artesian flow of warmer water (approximately 42^o C) was encountered after penetrating into the underlying Grande Ronde Basalt at a depth of about 830 m. Nearly all of the deeper artesian wells in the Grande Ronde valley produce from low temperature geothermal aquifers (20^o to 30^o C)

(Brown and others, 1980; Baxter and others, 1978). Well cuttings from the producing zones in the deeper warm wells in the north end of the valley invariably show evidence of weak hydrothermal alteration. Vesicles and fractures are lined with alteration minerals such as pyrite, opaline and chalcedonic quartz, zeolite, and unidentified, light blue white to blue green clay minerals.

Several warm springs are located along the Fly Valley and Shaw Mountain fault zones on the western uplands. Lehman Hot Springs issues from Grande Ronde Basalt flows along the projected intersection of the Fly Valley fault zone and the buried margin of the Tower Mountain caldera. Controlling structures at Lehman appear to be a set of N 15^{o} to 20^{o} W trending faults that splay off of the larger N 65^{o} W trending Fly Valley fault zone. Surface temperature at Lehman is 61^{o} C. Several lower temperature (25^{o} to 31^{o} C) springs issue from NW trending faults south of the Shaw Mountain fault zone. These springs, which include the Starkey warm spring, Hunters warm spring, and the Meadow Creek warm spring, are less likely to be underlain at shallow depths by pre-Miocene rock. The Starkey warm spring issues from a hydrothermally-altered fault zone in Grande Ronde Basalt that contains thin chalcedonic quartz seams.

Water resources

A full discussion of the geologic controls on surface and groundwater movement is beyond the scope of this report. General geologic investigations do not collect sufficient water data to allow for a detailed discussion of the processes that influence surface and groundwater interaction. Stream flow measurements, using both long term gauging stations and short term seepage runs; water well measurements, including pump tests and monitoring wells; and water use analyses are needed before the water use capacity in the upper Grande Ronde River basin can be determined.

Movement and interactions between surface and subsurface waters in the upper Grande Ronde River basin appears to be influenced mainly by stratigraphy and only secondarily by structure. The older basement units, including the pre-Tertiary units and the older Tertiary volcanic rocks, are relatively impermeable and form poor aquifers. Much of the precipitation that falls on the older basement units is released into streams that tend to flow year long. Wells drilled into these units can be expected to yield little if any water. Water bearing zones can be expected only where permeability has been increased by fracturing.

Wells drilled into Columbia River Basalt Group lavas may yield large amounts of water. The Wanapum and Grande Ronde Basalt units are a stacked series of lava flows. Individual lava flows are separated by rubbly interflow zones that are generally porous and may be permeable enough to transmit significant quantities of water both laterally and vertically. Central parts to individual flows are often dense enough to form barriers to vertical flow between the interflow zones and may act as confining layers. Although individual flows may be traced for many miles; both the permeable interflow zones and impermeable central zones tend be discontinuous. Interflow breccias do not necessarily indicate successive eruptions. Some interflow breccias may result from the overtopping of an early flow lobe by a later flow lobe from the same eruption. Hampton and Brown (1964) note that, because of these discontinuities, nearby wells drilled to the same depth may obtain water from different intraflow zones and have different static water levels and different hydraulic characteristics. In the eastern block and upland areas marginal to the Grande Ronde Valley, the level of the regional water table is profoundly influenced by the depth of the canyons cut by the Grande Ronde and tributary streams. In some areas, where the deep canyons lie above the regional water table, water within intraflow zones escapes from the stream and recharges the regional groundwater system. In other areas, where the canyons cut below the regional water table, water entering from the interflow zones as springs will increase the stream's base flow. Loosing and gaining reaches are best be determined by seepage runs.

The Wanapum Basalt and low MgO flows at the top of the Grande Ronde Basalt appear to be less permeable than the bulk of the Grande Ronde Basalt. Deep wells drilled in the Grande Ronde Valley generally penetrate several hundred feet of Grande Ronde Basalt before reaches interflow zones permeable enough to generate sufficient artesian flow for commercial irrigation uses. North of the Grande Ronde Valley, Wanapum Basalt flows appear to be more densely forested than the underlying Grande Ronde Basalt flows. The base of the Dodge flow is commonly heavily vegetated and marked by springs. Flows at the top of the Grande Ronde Basalt on the western block also appear more heavily vegetated. Perched aquifers occur in several places on the eastern block where near-vent, palagonitic breccias form barriers to groundwater flow. Similar near-vent palagonite breccias, intraflow palagonitic breccias, and water-affected basalt palagonitic alteration zones may act to retard vertical ground water movement within the Wanapum and upper Grande Ronde Basalt flows.

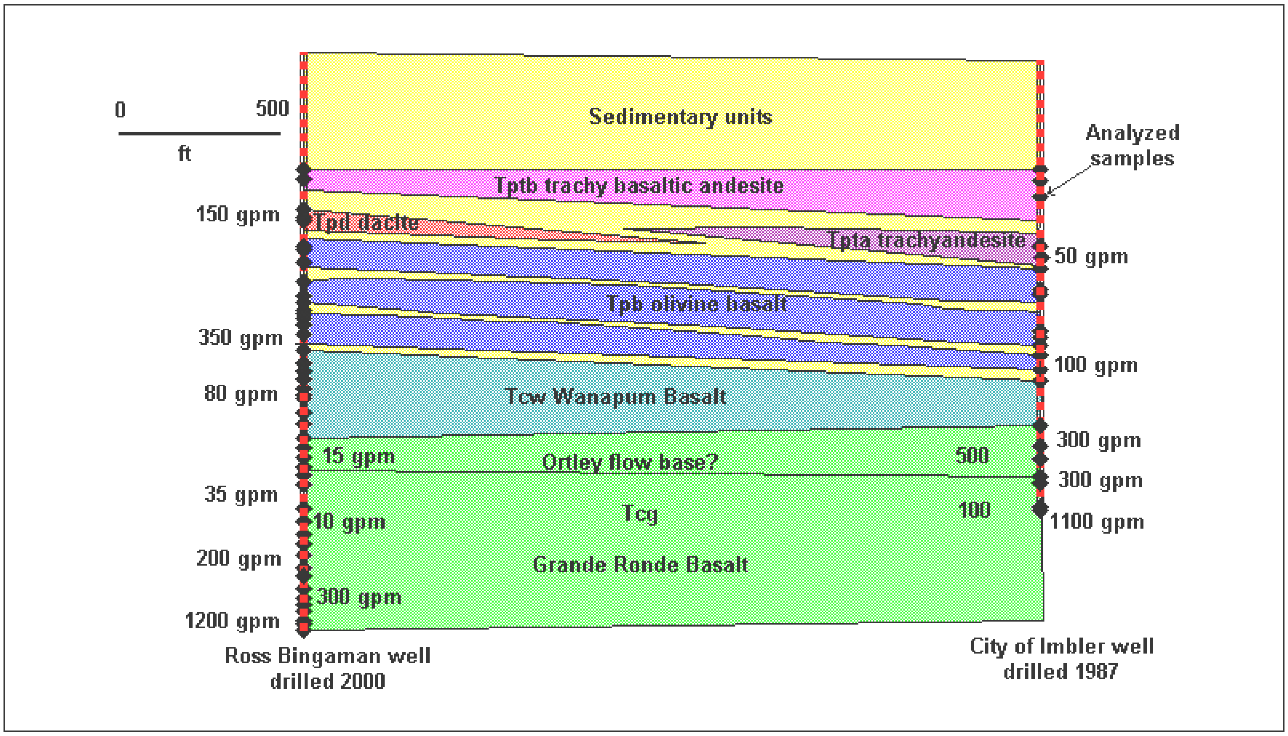

Figure 49 Stratigraphic diagram based on well logs and analyzed well cuttings from two deep wells drilled in the northern end of the Grande Ronde Valley near Imbler. Zones where significant amounts of artesian water were encountered, based on drillers' logs, are marked by xxx gpm. Both wells reportedly yield in excess of 2,000 gpm. Stratigraphic correlations is based on analyzed samples, locations of which are shown as black diamonds. The base of a somewhat chemically distinctive flow, the Ortley, is shown near the top of the Grande Ronde Basalt. Tptb, Tpta, Tpd, and Tpb flows are readily distinguishable from one another and the Wanapum and Grande Ronde Basalt. Flows in the Wanapum and Grande Ronde Basalt are much less readily distinguishable.

Miocene sediments at the top of the Wanapum Basalt and Grande Ronde Basalt locally form perched aquifers atop clay rich zones. Sandy horizons are marked by springs and yield water for hand dug wells near Elgin. In steeper regions, the same perched aquifers tend to readily form landslides.

Physical properties of the Powder River Volcanic Field lavas vary greatly. The laterally extensive dacite and andesite flows (Tpd) have properties similar to the basement rocks. Based on deep wells in the Grande Ronde Valley, individual dacite and andesite flows are as much as 130 m thick. Intervening interflow breccias are generally thin and discontinuous, glassy breccias that readily alter to clay minerals. The thicker flows make very poor aquifers. Much of the precipitation that falls on the thicker flows is retained in colluvium, soil, and disconnected bedrock fractures and is released into streams that tend to flow year long. The underlying olivine basalt flows may have permeable interflow zones similar to those in the Grande Ronde Basalt and, when overlying clay-rich sediments, form perched aquifers and spring lines. The clay-rich sediments tend to inhibit vertical movement of groundwater between interflow zones. Based on well cuttings and driller's logs, individual olivine basalt flows are often bounded by thin, clayey sedimentary horizons and generally do not yield significant quantities of groundwater.

In places, such as the north end of the Grande Ronde Valley, basaltic andesite and andesite flows in upper part of the Powder River Volcanic Field form flow-on-flow sequences physically similar to the Grande Ronde Basalt flow-on-flow sequences. Laterally discontinuous interflow breccias between thin and discontinuous dense flow centers may yield appreciable amounts of groundwater. Storage capacity for the stacked flow sequences is small, as they do not extend over more than areas more than several km^2.

The distribution of alluvial plain, fan-delta, stream-channel, and alluvial fan deposits in the Grande Ronde varies both laterally and vertically. Based on water well logs, the distal edges of the fan deltas at La Grande and Union are the best sedimentary aquifers in the Grande Ronde Valley. The most productive wells in the fan delta aquifer (including the La Grande municipal wells) are located where lenses of coarse, well-sorted gravel overlap to form a thick, continuous sequence of permeable strata. Ferns and others (2002a) indicate that the surface of the fan delta expands laterally at shallow depths and then contracts at greater depths. Although the alluvial plain deposits are generally fine-grained and relatively impermeable, well-sorted channel sand and fine-gravel lenses along the central axis of the valley (Ferns and others, 2002a) form shallow aquifers of limited capacity.

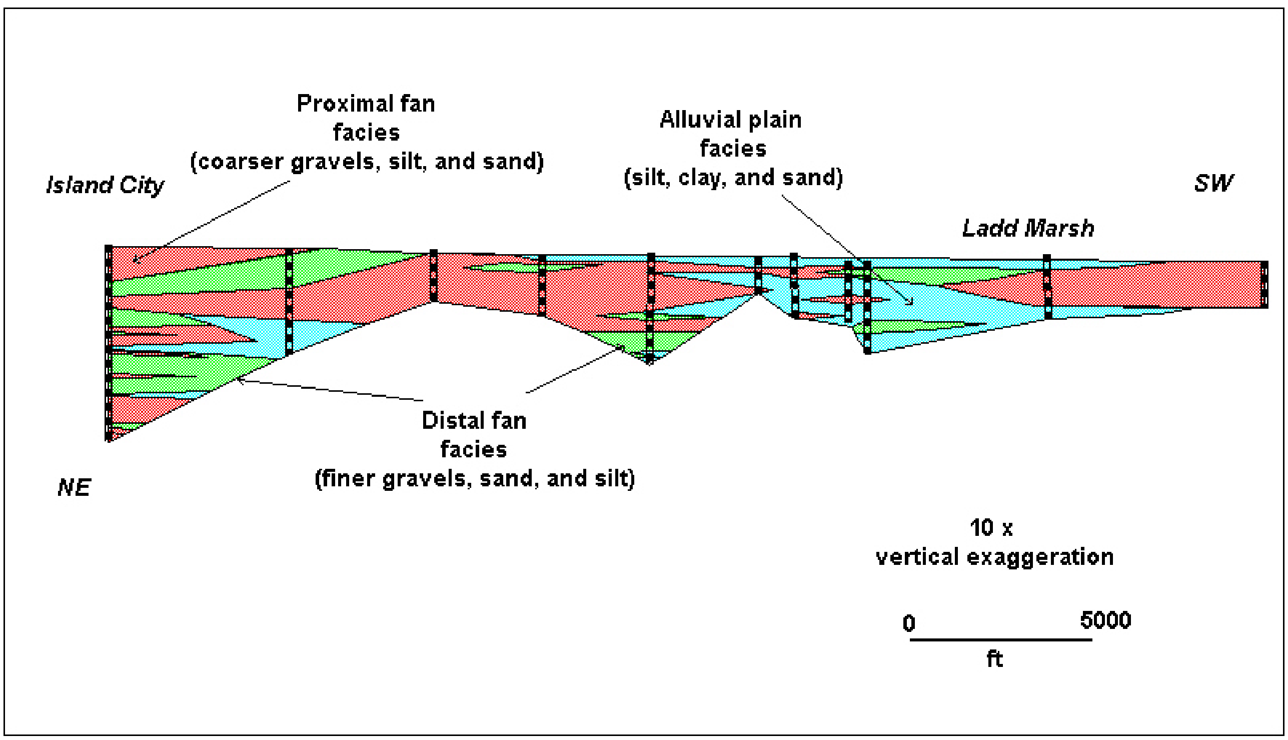

Figure 50 Diagram illustrating subsurface variability between water wells drilled into QTal sediments in the Grande Ronde Valley. Facies interpretations are based on driller's logs, which vary greatly in descriptive nomenclature and completeness.

GEOLOGIC HAZARDS

Geologic hazards are most evident along the active margins of the Grande Ronde Valley . Close proximity of active or potentially active faults, high valley margins, and the unstable contact between Grande Ronde Basalt and overlying Powder River Volcanics make the margins of the Grande Ronde valley structurally unstable. Where the unstable contact is exposed on the escarpments above the valley at Mt Emily and Gasset Bluff, debris flows and rock falls have cascaded down the face of the escarpment, flowing out onto the valley in rapidly-moving debris avalanches. Landslides and nonpoint source trace metals are the major geologic hazards for the rest of the upper Grande Ronde River basin

Seismic Hazards

The West Grande Ronde Valley fault zone, the East Grande Ronde Valley fault zone, and the Little Creek fault can all be considered as being potentially active. All three display Quaternary offset. Individual faults along the West Grande Ronde Valley fault zone can be traced for as much as 10 km along strike. Subtle topographic features – including linear range fronts, low linear escarpments on alluvial fans and terraces, faceted spurs, and "Z"-shaped benches marking faulted bedrock-alluvial fan contacts (Simpson and others, 1993; Personius, 1998; Ferns and Madin, 1999), indicate that surface ruptures along the West Grande Ronde Valley fault zone are Late Quaternary and very likely Holocene in age. The East Grande Ronde Valley fault zone can be traced for about 20 km. For most of that distance it consists of a single, 15 km long fault line. Personius (1998) identified fault scarps below Gasset Bluff that indicate latest Pleistocene offset along the East Grande Ronde Valley fault zone.

The Little Valley fault can be traced for about 1.5 km out into the Grande Ronde Valley, where it forms a subdued scarp 1 – 3 m high. The fault can be traced across the southern uplands for about another 3 km before it merges with the Catherine Creek fault. Latest movement along the Little Valley fault is generally considered to have been late Pleistocene (White, 1981).

Hazard studies indicate that the West Grande Ronde Valley fault zone is capable of generating a maximum credible earthquake of magnitude 7 (Simpson and others, 1993). Geomatrix Consultants (1995) defined the 1,000 year probabilistic peak acceleration for the La Grande area as 0.07, based on slip rates of 0.03 – 0.05 mm/year. Madin and Mabey (1996) consider the 1,000 year probabilistic peak acceleration as 0.16. Ferns and others (2001) note that, since slip rate calculations were based on earlier studies (Simpson and others, 1993) that did not recognize the western Mt Emily fault, the 1,000 year probabilistic peak acceleration for the La Grande area may be greater than 0.07.

Landslides

Down slope movement of rock and soil present major geologic hazards to populated areas. Although deposits formed by down slope movement are generically identified as "landslides", there are three general types of "landslides" in the upper Grande Ronde River basin that need to be evaluated separately. General types include rock fall- and landslide-generated debris- and mudflows; complex landslides involving slow-moving, unstable masses of rock and colluvium; and colluvium derived landslides and slumps. Differentiation is based on the speed and manner in which the rock and soil moves and are defined by geologic setting and triggering mechanisms.

Debris flow avalanches and debris flows

Generated-generated debris flow avalanches pose a significant geologic hazard in the Grande Ronde Valley. Such avalanches may cascade down the east flank of Mt Emily or the west flank of Gasset Bluff at any moment. Remnants of old debris-flow avalanches and rockfalls form boulder fields that extend out into the valley for as much as 2 km. Boulder fields are made up of 2-3 m diameter dacite blocks that came from steep-faced cliffs cropping out high above. The high standing dacite cliffs periodically collapse, sending large blocks of dacite cascading down the mountain to the valley floor, some 800 m below. Triggering mechanisms for these types of debris avalanches are apparently varied; heavy rainfall, earthquakes, and simple freeze-thaw cycles could all trigger cliff collapse. Debris flow hazard is most extreme where high Tpd cliffs crop out precipitously above the valley floor. Old landslide and terrace surfaces from Owsley Canyon, located 5 km north of La Grande, south to the Grande Ronde River are mantled by large dacite boulders from past debris flows. The shear and partially undercut dacite cliff at Halfway Spring is a likely future source for a debris flow avalanche. Benches floored by Grande Ronde Basalt, such as the one south of Mt Harris, form local catch basins that may act to diminish future collapse-generated debris flows before they reach the valley floor.

Landslide-generated debris and mudflows also pose a significant geologic hazard in the Grande Ronde Valley. Several lobate masses extend from the valley floor upslope to slide headwalls on the west side of the valley north of La Grande. It is not known whether these landslide masses initially failed as large, relatively-slow moving landslides, such as the Hole-In-The-Wall slide, located 90 km southeast of La Grande, (Jacobson and others, 1985) or as catastrophic mudflows (Schlicker and Deacon, 1971). One of the larger lobate masses covers about 3.7 km^2 and extends northward from an andesite highwall down slope into the City of La Grande. Other potentially hazardous landslide complexes are located on Owsley Canyon and on the Grande Ronde River about 6 km upstream of La Grande. Slack water deposits upstream of this slide indicate that this landslide may have temporarily dammed the Grande Ronde River.

Collapse of landslide dams can result in debris and mudflows during flood events. Madin (1998) notes that many slides in narrow, steep-walled canyons appear to have blocked streams in the past. Along the Grande Ronde River, areas that may be at risk of landslide damming include a point at about 4 km south of Elgin; Andy's Rapids, about 6 km north of Elgin; and at a point near Perry, about 5 km upstream of La Grande. Major tributary streams at risk of landslide damming include Beaver Creek, at a point about 24 km southwest of La Grande and downstream of the La Grande Reservoir; Catherine Creek, in the area of the Catherine Creek State Park, and along Lookingglass Creek, near the confluence of the Little Lookingglass Creek. Storm-generated debris and mudflows may also flow onto alluvial fan surfaces during flashfloods. Channels at the mouths of both Mill Creek and Deal Creek are cut into Holocene mudflow deposits (Personius, 1998) on the west side of the City of La Grande. Both channels contain remnants of younger mudflows.

Composite landslides

Composite landslides are those in which different parts of the complex may be active at different times. They are typically large and may involve coherent blocks of bedrock as large as 0.5 km^2 in size. In the upper Grande Ronde River basin, the composite landslides typically form where incompetent tuffaceous Tertiary sediments underlie competent lava flows. Very large landslide complexes are located in the headwaters of the Grande Ronde River and Catherine Creek, where tuffaceous Tertiary volcanic units rest on pre-Tertiary basement rocks. They are also located Individual composite landslides, such as those on Beaver Creek, can be quite large, covering as much as 16 km^2. The larger landslide complexes on the upper Grande Ronde River generally have two or more zones of weakness; a basal zone where tuffaceous, poorly consolidated tuffs overlie pre-Tertiary units and an upper zone where Columbia River Basalt or more coherent Oligocene units overlie tuffaceous sediments. Small portions of the slide complexes are periodically and perhaps continuously reactivated. It is presently unclear as to when or even whether any of the larger slide complexes have experienced large-scale catastrophic failures in the past. Relative proportion of Mazama ash on landslide surfaces may provide a key for determining which slides are most active. As an example, reworked debris from large slides along Fly Creek are overlain by undeformed Mazama ash terraces; indicating relative stability in this area. Mazama ash along the Grande Ronde River immediately to the east is either absent or churned up with other landslide debris; indicating that the slides here are comparatively more active.

Composite landslides in the northern part of the upper Grande Ronde River basin typically form where thick Saddle Mountain Basalt or Powder River Volcanic Field lavas are underlain by tuffaceous sediments. Spectacular slides occur at The Rock Wall, where blocks as much as 0.5 km long are calving off of a 30 m headwall scarp. The toe of one of the Rock Wall slides extends 1.5 km down slope to the Grande Ronde River, where is being eroded to form Andy's Rapids. The headwall is marked by sag ponds and open linear crevices. Similar sackung features at the base of the headwall to the large slide that crosses Highway 82 south of Elgin.

Large composite landslides also occur along the west and east margins of the Grande Ronde Valley. Some of the west margin slides, including the "jumbled block" unit of Barrash and others (1980), encompass areas of large, nearly coherent masses of internally disrupted and broken lava flows that tilt inward toward the valley.

Colluvial landslides

Many of the landslides in the immediate vicinity of La Grande are slow moving, unstable wedges of soil and rock that mantle bedrock - alluvium fan fault contacts along the West La Grande fault zone. Schlicker and Deacon (1971) note that structures constructed on these unstable surfaces are susceptible to damage from continued down slope movement. Unstable colluvial wedges are also found along faulted contacts between alluvial fan gravels and bedrock units.

Geochemical Hazards

Mineralized areas with elevated levels of elements such as lead, arsenic, and mercury may need evaluation for possible impacts on downstream water quality. Assessment and mitigation strategies need to determine whether water quality problems can be attributed to point sources such as specific mine workings or whether they result from nonpoint sources of naturally weathering outcrops of mineralized rock. Ore samples from Bald Mountain batholith lead-silver veins show elevated levels of lead, zinc, and mercury (Ferns and Taubeneck, 1994). Small mine workings (dumps, tunnels, and shafts) on the lead silver veins may be potential point sources. Mineralized zones associated with the Tower Mountain caldera are also possible nonpoint sources for mercury and arsenic.

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