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CASCADES:

A SUMMARY OF THE GEOLOGY AND GEOTHERMAL POTENTIAL WITH COMPILED BIBLIOGRAPHY

by

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OREGON CASCADES

Introduction

The Cascades in Oregon are structurally divided into the Western Cascade Range which consists of mid-Tertiary basaltic to intermediate composition volcanic rocks which have been uplifted and deeply dissected, and the High Cascades, characterized by Pliocene to Recent volcanic activity, to the east. The rocks of the Western Cascades group extend east under the younger High Cascades. To the east of the narrow, north-trending, High Cascades Provinces, the basalt of the Columbia River group form most of Washington (Fig. 1) and to the south the Basin and Range Province extends into eastern Oregon.

A brief summary of events in the Central Cascades and their relation with the Basin and Range is well stated by Priest and Vogt (1983):

> "Eruption of voluminous silicic tuffs and lesser volumes of iron-rich basaltic to silica lavas between about 40 and 18 m.y. B.P. and eruption of intermediate calc-alkaline lavas and subordinate tuffs between about 18 to 9 m.y. B.P. formed most of the volcanic pile in the central Western Cascade Range. The axis of volcanism had shifted to the vicinity of the High Cascade province by about 9 m.y. B.P., when eruption of more mafic, alkaline, and iron-rich lavas began. Slight local folding in the north-central Western Cascade Range also ended by about this time. Widespread north-south- to north-northwest-trending normal faulting accompanied uplift of the Western Cascade block relative to the High Cascade province between about 5 and 4 m.y. B.P. Voluminous basaltic lavas formed a broad platform in the High Cascades in the early Pliocene, and a north-south-trending chain of composite volcanoes developed along the High Cascade axis in the Quaternary as volcanism became slightly more silicic. The youngest composite cones are chiefly andesitic in composition, with local dacitic to rhyodacitic eruptions, although basaltic eruptions have continued to occur on the surrounding platform into the Holocene.
>
> Compositional and textural similarity of some of the 9- to 0-m.y. B.P. basalts in the Basin and Range and the Cascades and the contemporaneity of changes in volcano-tectonic events in the Basin and Range and the Cascades suggest that the geologic histories of the two areas are closely related. A major change in the plate-tectonic regime about 10 to 8 m.y. B.P. may have affected both areas, resulting in increased extensional tectonic influence in the central Cascades. An additional change in the interaction of lithospheric plates at the end of the Miocene is probably

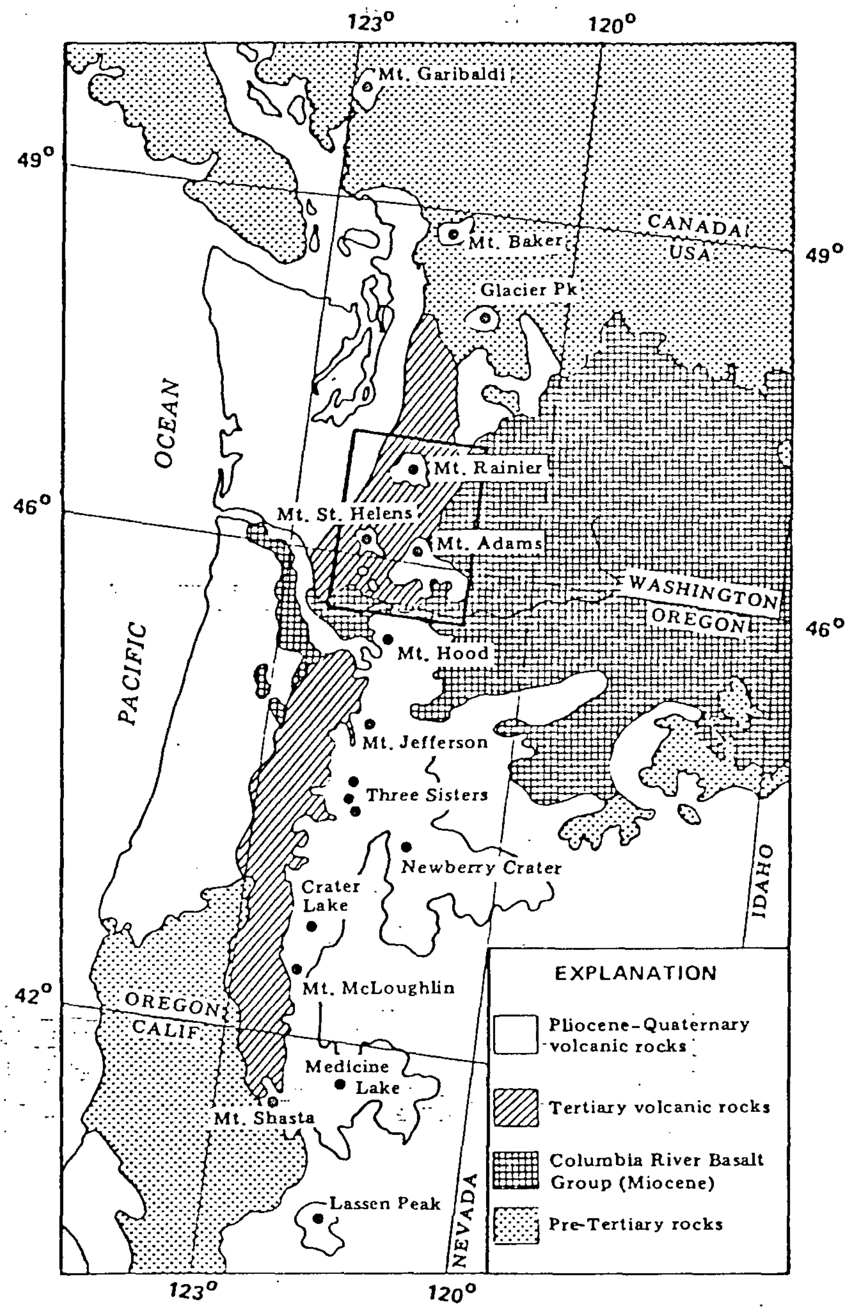


Figure 1. — Index map showing location of the Southern Cascade Mountains study area and major geologic elements of the Cascade Mountain Range (after McBirney, 1968). Dots indicate location of Quaternary Cascade stratovolcanoes.

necessary to account for the pronounced uplift and north-south faulting which occurred 5 to 4 m.y. B.P. in the Cascades. The central Oregon High Cascade Range is viewed as a subduction-related volcanic arc which has been strongly affected by Basin-and-Range-type extension".

GEOLOGY

Stratigraphy

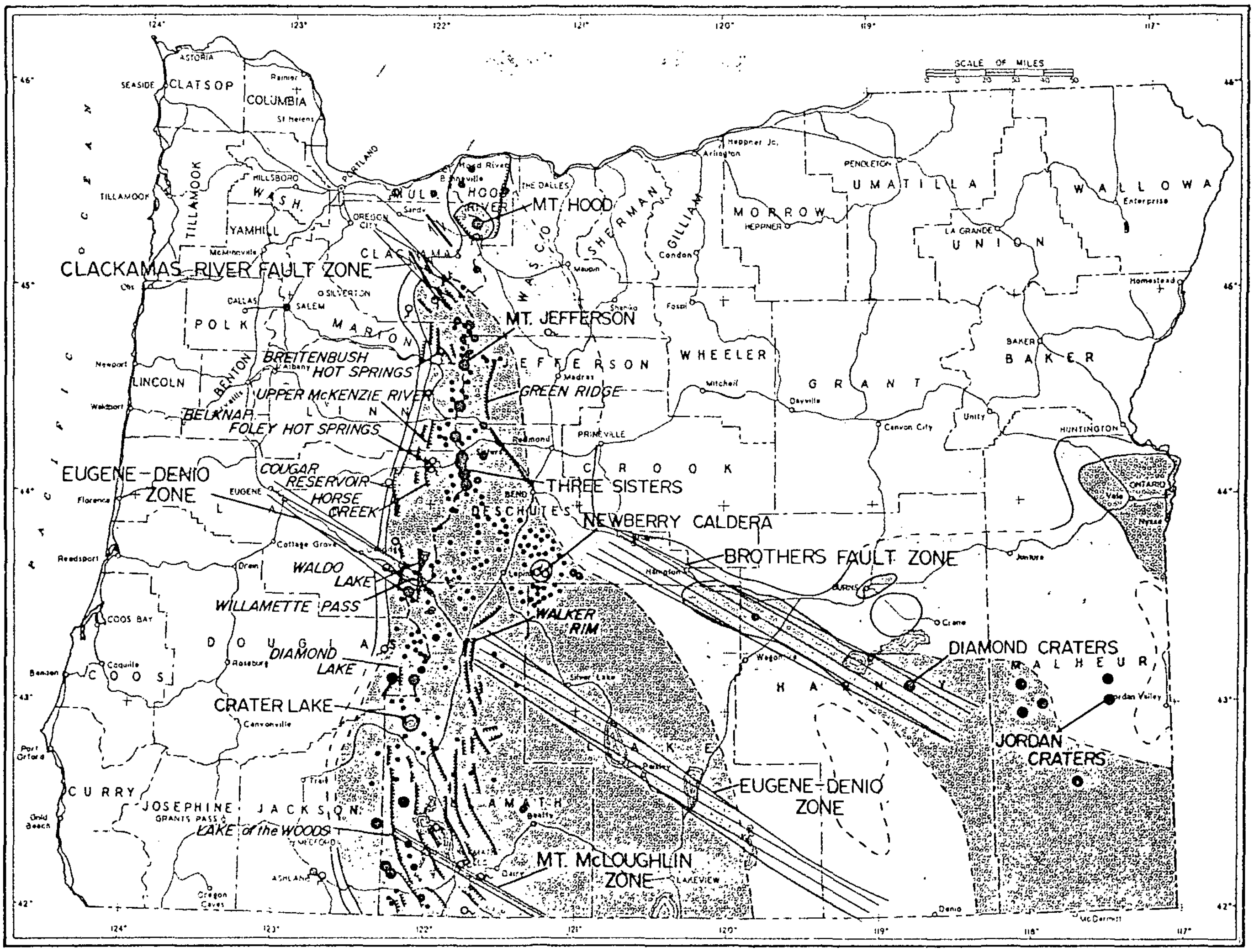
During Oligocene and Miocene time the Western Cascades were the site of subduction related arc-volcanism (Priest and Vogt, 1983). These rocks are mostly basaltic andesite to dacite pyroclastics forming numerous ash flow tuffs and the full range of eruptive products (Peterson and Youngquist, 1975). The base of the formation is not exposted, but Peterson and Youngquist (1975) estimate a thickness of 20,000 to 30,000 feet. All of the Western Cascades volcanic rocks are somewhat altered and have low permeability due to alteration of their vitric, fragmental nature (Priest and Vogt, 1983).

About 9 m.y. B.P. the volcanic activity shifted to the High Cascades and changed to more mafic basalt and basaltic andesite lava flows forming shield volcanoes. These dominantly basaltic rocks of the early High Cascade episode (9 to 4 m.y. B.P.) are thickest in the central Oregon Cascades and may be absent to the north and south in Washington and California (Fig. 1). Basalts of this episode that spread west are now exposed capping ridges in the Western Cascades. During the Pliocene basaltic lavas and rhyolite domes and ash-flows were emplaced from the Western Cascades to the Idaho border (McBirney and White, 1982).

The start of the late High Cascade episode is set at 4 m.y. by Priest and Vogt (1983). By 4 m.y. ago the Western Cascades had been uplifted relative to the High Cascades province casting a rain shadow on eastern Oregon. Late Cascade basalt flows follow present drainages into the Western Cascades. During Pleistocene time the proportion of basaltic andesite and less abundant andesite, dacite and rhyodacite increased and composite cones formed. Although impressive, the stratovolcanoes are a minor part of the volcanism in the central area where basaltic lavas beneath and between the cones account for 85% of the total Quaternary volcanic rocks (McBirney and White, 1982).

Structure

This section will begin with a brief review of the tectonic history of western Oregon, then summarize the structural setting. The Coast Range consists of a seamount province, subaerial basalts over submarine basalts forming a 15 to 20 km thick oceanic crust accreted to the continent in early Eocene (Magill and Cox, 1980). The Coast Range rotated 46° clockwise during the collision (Magill and Cox, 1980) and moved 350 km north relative to the magnetic pole prior to or during accretion (Beck, 1984). Part of a paleo-subduction zone (Roseburg Fm) is exposed at the south end of the Coast Range (Magill and Cox, 1980). Later, post 25 m.y. B.P., the Western Cascades and the Coast Range were rotated 25 to 30% clockwise about a pivot point just north of Mt. Hood (Magill and Cox, 1980). This rotation was due to Basin and Range extension. About 9 m.y. B.P. volcanic activity narrowed or shifted east and changed from andesitic to basaltic (beginning of High Cascades episode). At 4 to 5 m.y. B.P. the Western Cascades were uplifted relative to the High Cascades across N-S and NNW faults (Priest and Vogt, 1983). After 4 m.y. the High Cascades graben formed and in the last 700,000 years the composite cones formed (Fig. 2). The graben appears to be deeper, 1000 to 3000 feet, in the central area where Quaternary volcanic rocks are most abundant. Blakely and others (1985) interpreted regional magnetic and gravity data to suggest the volcanoes from Crater Lake south are located on the margins of large subsidence structures. Priest and Vogt (1983) state that most movement on N-S faults occurred in late Miocene to early Pliocene. Therefore, subsidence along the faults precedes major eruption episodes. This suggests that graben formation is not the result of crustal loading or magmatic withdrawal, but



EXPLANATION

= Heat flow over 100 mW/m²

= Heat flow between 100 mW/m² and 80 mW/m²

= Major northwest-trending lineaments; names are from Lawrence (1976); Clackamas River fault zone is from Anderson (1978) and Beeson and others (in preparation)

= Mapped normal faults, hachured on the downthrown side. Only faults in or closely adjacent to areas of high heat flow in the Cascades are shown; areas west of the high-heat-flow zone tend to have fewer well-defined fault scarps, partly because less mapping has been done in those areas and possibly also because the faulting is older

= Lateral fault showing relative displacement

= Quaternary volcanic centers. Size of dot is crudely related to the size of the volcanic center relative to other centers. Many more centers exist than are shown, particularly in the High Cascades, but scale does not allow more detail

= Calderas (diameter = actual diameter)

= Thermal springs in and adjacent to the Cascades

Heat flow isotherm, dashed where inferred

Figure 2. Map showing some major faults, lineaments, hot springs, and Quaternary volcanic centers relative to zones of anomalously high heat flow in the Cascade Range and adjacent areas of Oregon. Geologic data are from Wells and Peck (1961), Hales (1975), Peterson and others (1976), Walker (1977), Barnes (1978), Beeson and Moran (1979), Brown and others (1980a), Hammond and others (1980), Avramenko (1981), Flaherty (1981), Priest and others (1982a), Smith and others (1982), Woller and Black (Chapter 6), and Beeson and others (in preparation). Heat-flow data are from Blackwell and others (1978) and Black and others (Chapter 7). (From Priest and Vogt, 1983)

Priest and Vogt (1983) draw the opposite conclusion. Where detailed mapping has been done, graben bounding faults are overlapped by the Quaternary lava flows (Priest and Vogt, 1983; Fig. 3).

The Western Cascade Province seems to be a relatively stable block with NW and NE trending structures (Venkatakrishnan and others, 1980; Kienle and others, 1981). East of the High Cascades the Basin and Range and other provinces have more N-S faulting. In southern Oregon, a strong NW trending fault set (Mt. McLoughlin zone) in the Klamath Lakes area (Fig. 2), curves to N-S at Upper Klamath Lake, extends to north of Crater Lake then turns to a NE trend where they cross the Eugene-Denio zone (Kienle and others, 1981). Structural trends within the High Cascades are more irregular with NW, NE and NS linears (Venkatakrishnan and others, 1980; Kienle and others, 1981). Structurally the High Cascades appear to be a transition zone between the Western Cascades and the Basin and Range. The eastern High Cascades overlaps onto the Basin and Range structures (Kienle and others, 1981).

Several NW trending lineaments or zones which extend into the High Cascades have been proposed (Fig. 2). These are thought to be controlled by right lateral faults. However, where detailed mapping has been done in the High Cascades along these zones, such as Waldo Lake and Lookout Point (Eugene-Denio zone), or Breitenbush quad and Devil's Creek (Brothers Fault Zone) no evidence of structures associated with these megatrends were found (Priest and Vogt, 1983). The Brothers fault zone is discussed in more detail by Walker and Nolf (1981).

The composition and distribution of High Cascade rock chemistry suggest subduction is occurring (Priest and Vogt, 1983), however McBirney and White (1982) point out that there is no trench or Benioff zone. Blackwell and others (1982) explain the lack of earthquakes along a Benioff zone by the close proximity of the ridge and thick sediment cover so that the subducted plate is relatively warm and deforms aseismically.

THERMAL ACTIVITY

Heat Flow

Average heat flow in the High Cascades is 104 ± 9 mW/m^2 and the gradient is 66° ± 7°C/km (Priest and Vogt, 1983). In the Willamette Valley and Western Cascades heat flow is 43 mW/m^2 and the gradient 30°C/km. The transition between the low heat flow to the west and the High Cascade anomaly is very abrupt (Fig. 2), less than 10 km and trends NNE (DOGAMI, 1984; Blackwell and others, 1982). The high heat flow extends east of the Cascades, SE onto the Basin and Range (Blackwell and others, 1982). The major change in heat flow occurs 20-30 km west of the axis of the High Cascades (Blackwell and others, 1982) or 10 km west of the province boundary (Priest and Vogt, 1983). The heat flow boundary corresponds to a steep gravity gradient and both can be explained by a hot, low-density region about 60 km wide and 7-10 km below the surface (Blackwell and others, 1982). The heat flow pattern is described as subduction-zone type by Blackwell and others (1982).

Hot Springs

Western Cascades thermal springs occur within the narrow band between the west edge of the high heat flow and the High Cascades structural province boundary (Priest and Vogt, 1983). Abundant thermal springs associated with NW trending faults are present east of the Cascades in the Klamath Lakes area (Olene Gap Hot Springs on Fig. 4) (Kienle and others, 1981). Hot springs in the Western Cascades (Fig. 4), from north to south are Austin Hot Springs (86°C, geothermometry-181°C), Breitenbush, Hot Springs (92°C, geothermometry-185°C), Bigelow Hot Springs (61°C), Belknap Hot Springs (86.7°C, est. 148°C), and Foley Hot Springs (80.6°C) (Priest and Vogt, 1983). Chemical analysis for most of these springs are listed in Table 1. Three thermal springs are

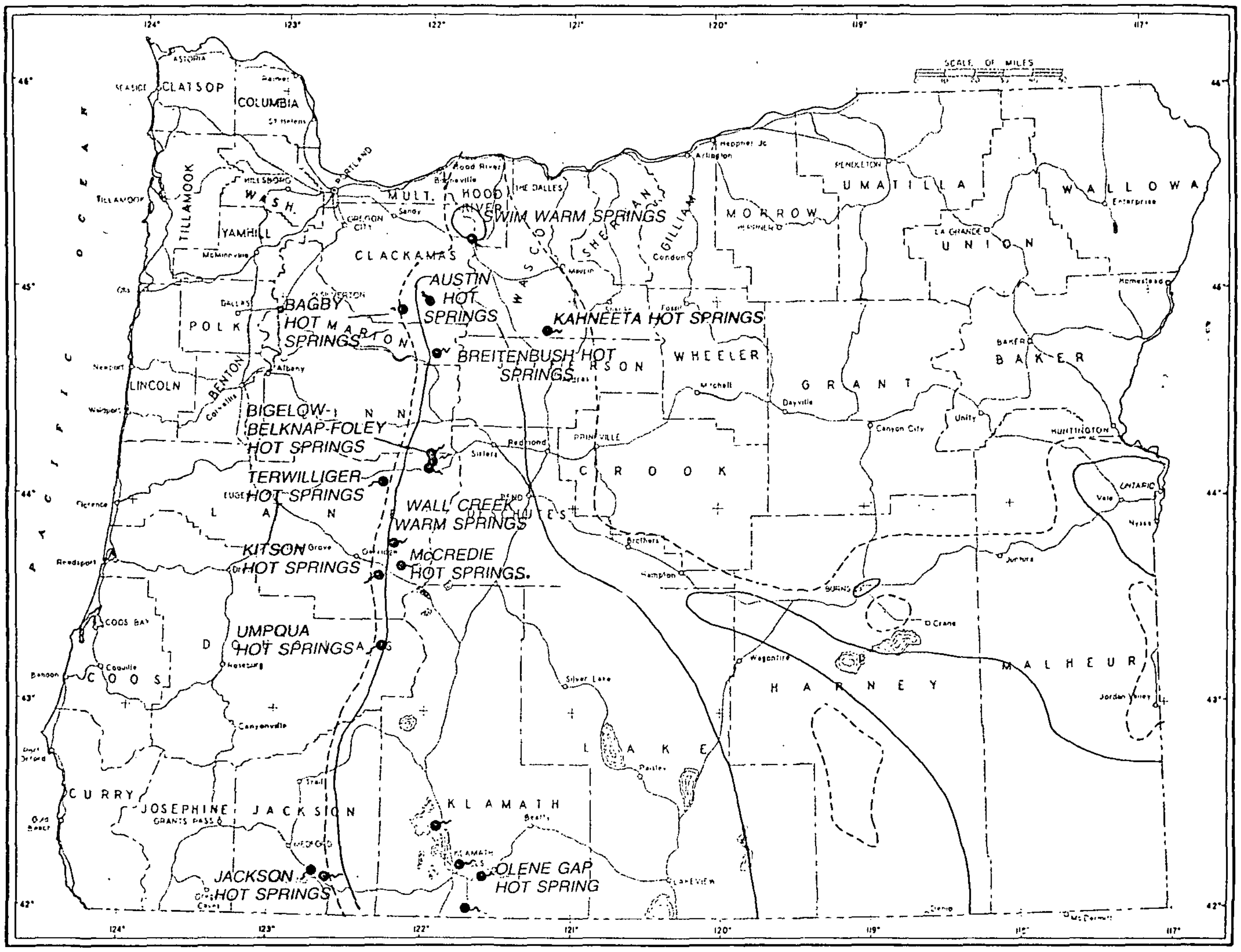


Figure 4. Thermal springs in and adjacent to the Oregon Cascade Range. Solid lines are the 100-mW/m² heat-flow contour; dashed lines are the 80-mW/m² contour of Blackwell and others (1978) and Black and others (this volume).
(From Priest and Vogt, 1983.)

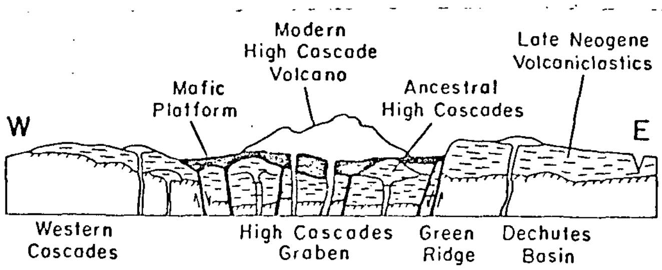


FIG. 3. Diagrammatic cross-section of central Oregon Cascade Range (modified from Taylor, 1981).

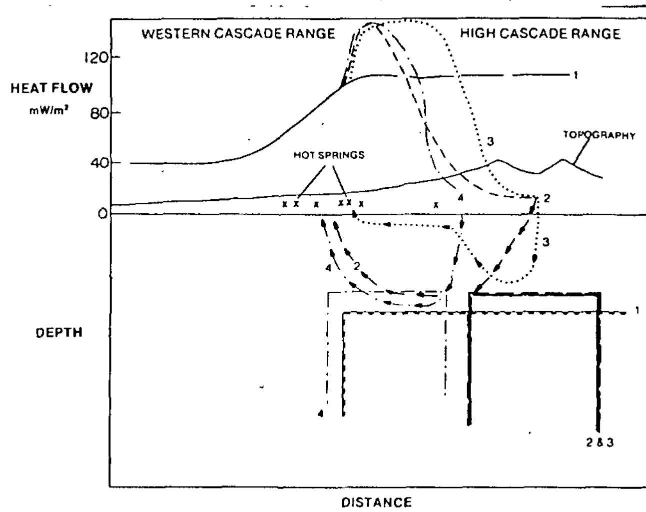


Figure 5. Several models of the relationship of hot springs to the heat-flow transition observed at the Western Cascade Range-High Cascade Range boundary. Four curves are shown, with three different variations in fluid circulation. In curve 1, the observed conductive anomaly (see Figure 7.3) is shown. In the other three models, the hot-spring anomalies are interpreted in terms of various controls on water circulation (see text) (from Blackwell and others, 1982).

Table 1. Chemistry of Thermal Springs in the Oregon Cascades.

Spring	pH	T°C	B	Na	Mg	SiO_2	S	Cl	K	Ca	Fe	F	Li	HCO_3	SO_4	Alkalinity $CaCO_3$
Mount Hood[1] (swim warm)		Analyses in mg/l														
Pool MH-6*	7.5	26	3.0	120	40	80	63	140	9.2	60	47	-		-	-	
Pipeline MH-4	7.5	22	2.0	92	34	75	54	110	7.5	50	70	-		-	-	
Screen MH-5	7.5	25	1.0	95	36	75	62	120	8	55	27	-		-	-	
Screen	7.3	25	0.4	114	44	71	-	139	10	57	<.05	0.23	0.12	191	193	157
Pipeline	7.3	20	0.28	79	29	55.4	-	103	6	42	0.05	0.15	0.08	141	149	116
Old Maid Flats Well MH-40	10	11	7	132	<1	31	25	123	<0.2	11	<10	-				
Breitenbush KGRA[2]		Analyses in ppm														
Spring		98		65.1	1.51	175			15.5	103			1.78			
Well (1980)		97.8		600	<0.5	116			27	81			1.5			Hardness
Terwilliger H. Spr.[3]		Analyses in mg/l														$CaCO_3$
Upper Spring	8.2	42	6.2	320	0.2	4.7		693	6.8	196	0.1	0.87	0.64	-	185	484
Lower Spring	8.4	38	6.4	335	0.2	46		769	7.3	210	0.1	0.86	0.7	-	192	557
Belknap Spring[3]																
Main	7.6	89	7.6	525	0.3	79.9		1195	16.8	208	0.1	1.11	1.04	17	105	541
East	7.5	66	7.1	490	0.4	70.6		1036	15.2	198	0.1	0.98	0.95	19	85	544
Foley Spring[3]	8.0	80.6	10	475	0.8	60		1304	11	494	tr	0.81	0.96	-	550	1284
Bigelow Spring[3]	7.8	61	6.5	540	1	69		1148	17	188	0.1	1.4	1.1	-	102	459
Willamette Pass Area[4]		Analyses in mg/l														
McCredie Spring	7.3	73	18	1000	0.9	79		2200	22	460	.02	2.7	1.4	-	240	-
Wall Creek Spring	7.2	41	6.6	315	1.0	63		602	11	130	.05	4.1	0.57		108	
Kitson Spring	7.4	44.4	25	1450	5.7	47		3420	28	726	.01	2.8	1.8	27	197	1900
Salt Spring	7.4	18	10.5	1250	51	29		2800	46	490	21.7	3.7	0.93		82.9	1433

*See Wollenberg and others (1979) for location of samples

[1] Wollenberg and others, 1979
[2] Priest and Vogt, 1983.
[3] Brown and others, 1980a.
[4] Brown and others, 1980b.

reported for the High Cascades; Summit Lake Warm Springs (see Mt. Hood discussion), warm spring at the bottom of Crater Lake, and a warm spring 2 km north of Devils Lake, Three Sisters area (Priest and Vogt, 1983).

Blackwell and others (1982) have presented models to explain the relationship of hot springs to heat flow and fluid circulation paths (Fig. 5). In all of these models the recharge area and heat source is to the east of the hot springs in the High Cascades.

Comprehensive but untabulated thermal spring data is available in the Geotherm computer printout. Mariner and others (1980) present tabulated chemical and isotopic data for water from thermal springs in Oregon. A copy of this open file report is in the Cascades' file.

Chemical analysis for thermal waters from the Mount Hood area are presented by Wollenberg and others (1979) and a partial list of their data appears in Table 1. Brown and others (1980a,b) give chemical analysis for several of the Western Cascade hot springs (Table 1). Chemical analysis of ground and surface waters in the Newberry Volcano area are listed by Sammel and Craig (1983). This data is presented in the section on Newberry Caldera in this report.

CRATER LAKE

The geology and eruptive history for Crater Lake are taken totally from Bacon (1983) and the interested reader is referred to this publication for detailed discussions of petrology and eruptive history.

Exposures in the caldera walls indicate andesitic cone formation started 400,000 yr. B.P. Subsequently, andesite to dacite lava flows and pyroclastics were erupted from several vents in the central part of the volcano. Through the same period basaltic to mafic andesitic vents were active on the flanks. From about 50,000 yr. to 7,000 yr. B.P. the general pattern of mafic eruptions occurring around a central area of silicic andesite to dacite volcanism continued. By 7015 ± 45 yr. B.P. the central magma chamber had begun to leak rhyodacite magma. The climatic eruption began 6845 yr. B.P. with eruption of large volumes of pyroclastics, including the Mazama ash. All the events of the climatic eruption are explained in detail by Bacon (1983). A total of 51-59 km^3 of magma with a compositional zonation was ejected.

The post-caldera volcanism has been restricted to within the caldera. This post 6845 ± 50 yr. activity has consisted of a rhyodacite dome on the lake bottom, and andesitic cinder cones, Merriam Cone (underwater) and Wizard Island.

Bacon (1983) does not discuss structure in any detail. He does suggest that the deformation near the caldera was dominated by the volcano or magma chamber induced stress field. The volcano produced a radial fracture system.

Heat Flow

An extensive water temperature survey has been conducted in Crater Lake by Williams and von Herzen (1983). They found two large thermal anomalies in the deep lake waters produced by thermal springs. Average conductive heat flow at the lake bottom is 3.3 ± 2.9 HFU, but convective heat flow is estimated to be 16 to 33 HFU (Williams and von Herzen, 1983). Based on their study they estimate the thermal reservoir to be 1.5-2 km wide and thick, the top of which is located 1-2 km below the lake bottom, and has a temperature of 100°-200°C.

MOUNT HOOD

Mount Hood is the northernmost Pleistocene composite volcano in the Oregon High Cascades. Fumaroles near the Summit, Swim Hot Springs on the southern flank and historic eruptions make Mt. Hood a prime target for geothermal exploration. Exploration of the volcano has been a cooperative effort of the Oregon Department of Geology and Mineral Industries, DOE, Northwest Natural Gas Co. and the U.S.G.S. (Priest and Vogt, 1982).

Geothermal

Mt. Hood is centered on a heat flow high of 130 to 150 mW/m^2 measured at 5 to 8 km from the strato-volcano's apex, and 80 mW/m^2 at 12 km distance as compared to the Western Cascades heat flow of 45 mW/m^2 (Steele and others, 1982). Bowen (1981) reports a gradient of 150°C/km on the upper flanks of Mt. Hood. Data from 25 wells, including three deep holes, have provided considerable data on Mt. Hood and the vicinity. Two deep holes at the west foot of the mountain, OMF-1 to 1,200 m (3936') and OMF-7A to 1837 m (6025') (Fig. 6) found generally low permeability and only moderate temperatures (Priest and Vogt, 1982). At T.D. OMF-7A was 119°C with a gradient of 63°C/km. Water geothermometry of well fluids did not indicate temperatures above that measured (Wollenberg and others, 1979). Below about 610 m of andesite to dacite volcanoclastics (Fig. 6) the holes penetrated Columbia River basalt flows to a depth of 1219 m (2000' below sea level). Tertiary epiclastics and greenstones of the Western Cascades sequence underlie the Columbia River basalts (Priest and Vogt, 1982). These deep clastic rocks are metamorphosed to laumontite-grade and self-sealed.

Vertical permeability is restricted at depth (below 600' to 2000') by alteration of intermediate pyroclastic rocks. Good lateral permeability is

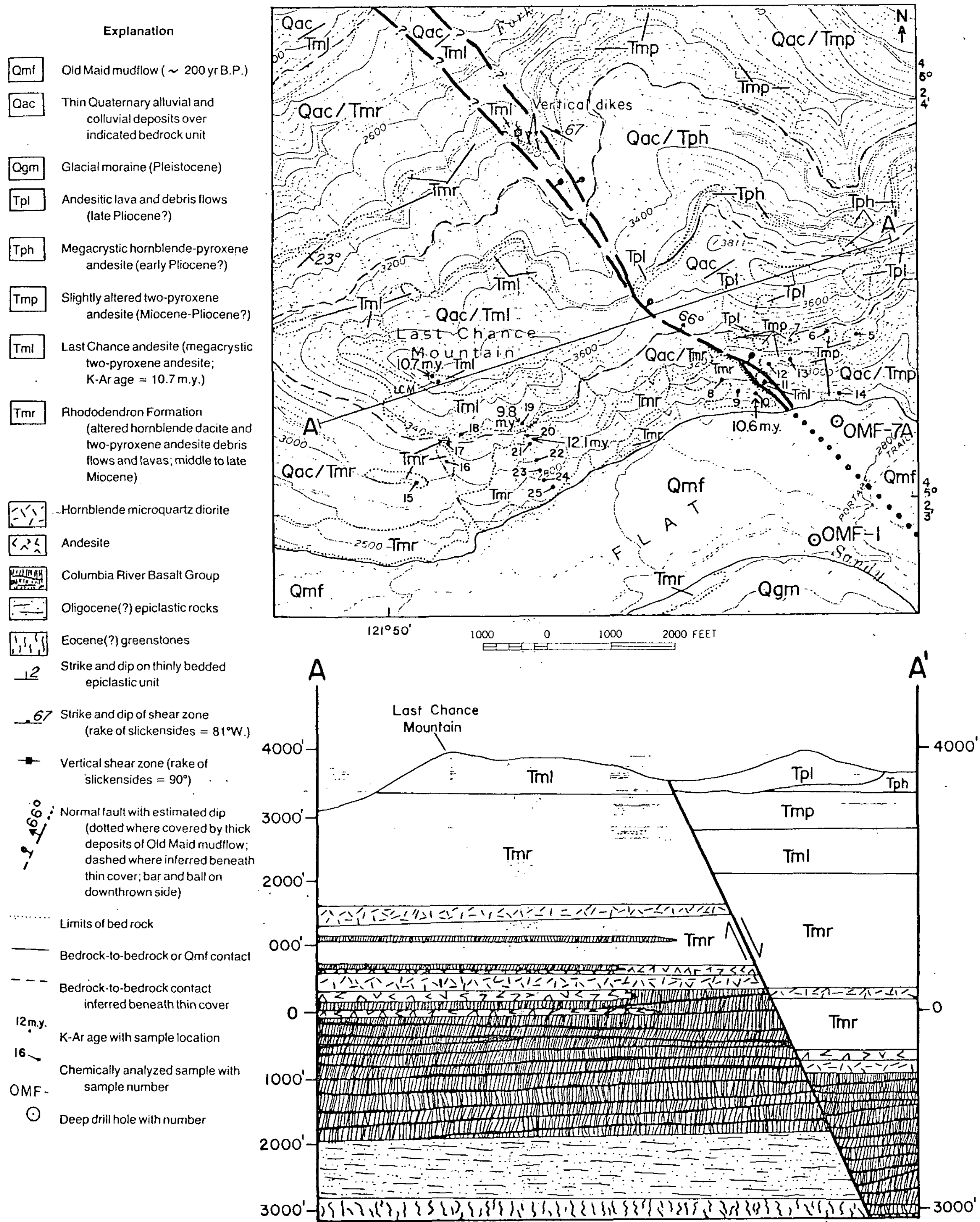


Figure 6. *Outcrop map and cross section of the Last Chance Mountain-Old Maid Flat area.*

(From Priest and Vogt, 1982)

present in some strata with deeper aquifers underpressured. The Columbia River basalt flows are considered to have the better aquifer potential for pre-Pleistocene bedded rocks, but are isolated by impermeable andesite to dacite units above and below.

At Timberline Lodge on the south slope of Mt. Hood, the third deep hole was drilled to 1220 m (4002'). The maximum temperature in the hole is 80°C and the gradient 88°C/km (Priest and Vogt, 1983). Geothermometry of Swim Warm Springs near this hole suggested a subsurface temperature of 100-125°C and possibly 150° to 200°C (Wollenberg and others, 1979). Mixing model estimates by Bowen (1981) indicate 190°-240° thermal component.

Steele and others (1982), based on heat flow, concluded that no large shallow magma chamber (4-6 km diameter) is present under Mt. Hood but a small neck like magma conduit is probable. Geochemical considerations (White, 1980) also suggest that any large magma chamber is at considerable depth.

Although exploration results to date are not encouraging, it should be noted that most of the thermal gradient holes, particularly the deep holes, are on the west and south sides of the volcano. The central and east to north sides, where more favorable aquifer rock are present at greater depth, have not been tested. It is not surprising that hot springs are absent when deep aquifers are underpressured, vertical permeability is limited and a thick, near surface cold water aquifer is present.

Geologic History

The Tertiary geologic history and general setting of Mt. Hood area is similar to that of the central Cascade province as discussed above with two significant differences. The Miocene Columbia River Basalts are present in a significant thickness and the early High Cascades basalts (9 m.y., late Miocene to Pliocene) are less abundant than in the central Cascades (Priest and Vogt, 1982;1983).

The history of the Mt. Hood strato-volcano began about 700,000 years ago with calc-alkaline basaltic andesite to hornblende dacite magmatism (Priest and Vogt, 1982), which is more silicic than the typical High Cascades activity (Priest and Vogt, 1983). Priest and Vogt (1982) divide Mt. Hood's formation into 6 major episodes (based on a present-looking back bias), see also Crandell (1980).

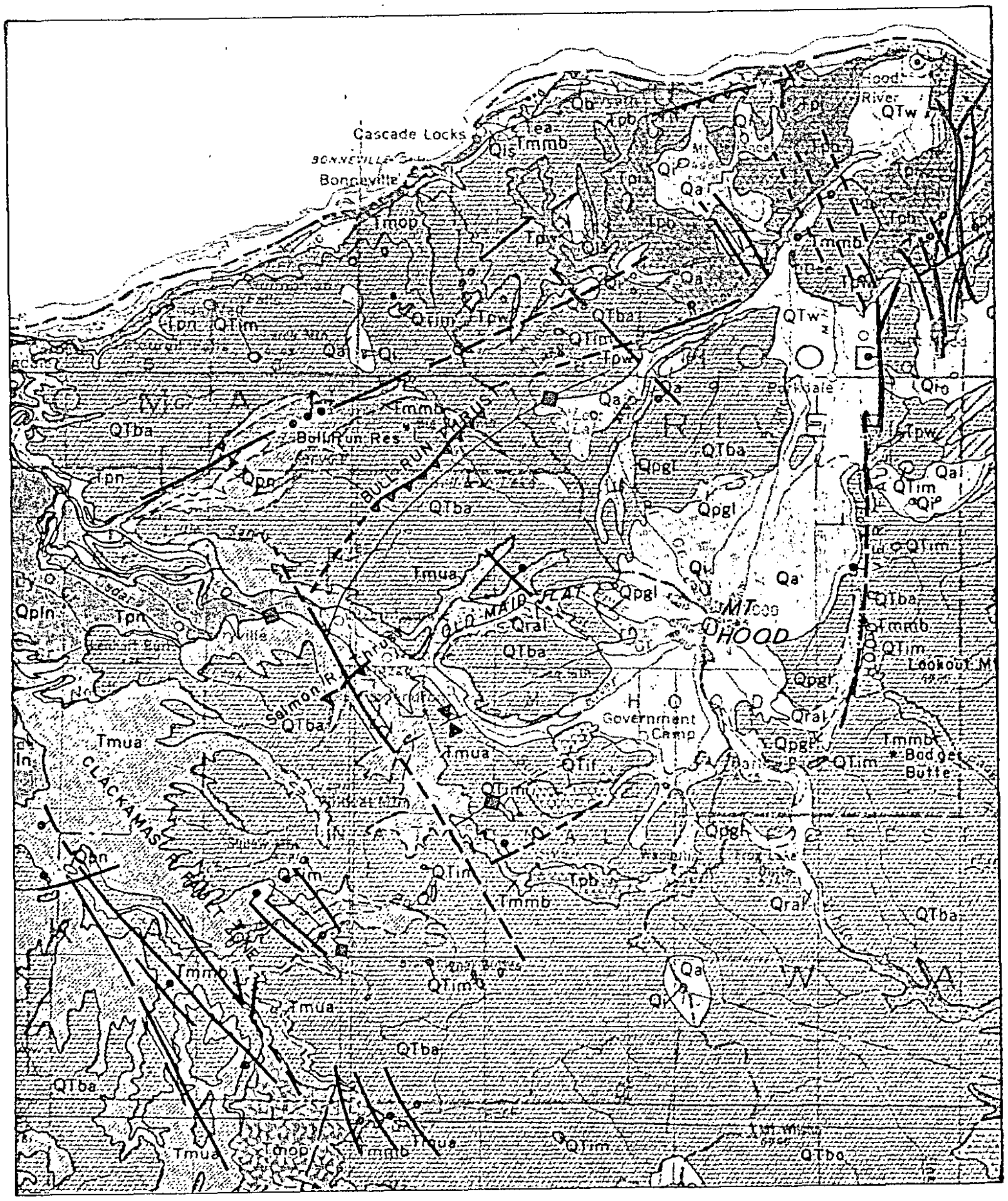
1. Main Stage, 700,000-29,000 yr. B.P., 90% of cone formed by lava flows and pyroclastics of basaltic andesite, pyroxene andesite and hornblende dacite.
2. Pollalie eruptive, 15,000 to 12,000 yr. B.P., hot pyroclastic debris flows and lithic ash from a hypersthene dacite plug dome.
3. Temberline eruptive, 1,800-1,500 yr. B.P., hot debris flows, lithic ash and mudflows from formation of a hornblende-hypersthene dacite plug dome near Crater Rock.
4. Old Maid eruptive, 250 to 175 yr. B.P., mudflow from hypersthene-hornblende dacite plug dome.
5. Crater Rock dome, about 200 yr. B.P., hypersthene-hornblende andesite, 62.6% SiO_2, 20 fumaroles present (should be part of #4 episode).
6. Historic eruptions, 1850 and 1865, hypersthene-hornblende dacite pumice, 63.5% SiO_2.

Structure

The general regional structural setting of the Oregon Cascades has been discussed above and the Mt. Hood area is covered in more detail by Priest and

Vogt (1982). In the Western Cascade strata some northeast trending compressive folds and faults are present (Fig. 7) and formed during the Miocene (Priest and Vogt, 1982). Northwest striking dextral faults formed about the same time but continued to be active after folding ceased (Fig. 7).

A major graben structure present under Mt. Hood is bounded on the east by the N-S Hood River fault (Fig. 7). The structural boundary on the west is more diffuse with some faults striking N45°W (Priest and Vogt, 1982; Fig. 6). Total subsidence within the graben is not well defined but offset on the N45°W fault in Old Maid Falt is thought to be 400 m (1300'). Gravity data suggest high porosity in the rocks filling the graben. High Cascade rocks extend to 3 km depth in the western margin of the province (Priest and Vogt, 1983). East west extension was occurring as early as 8 m.y. B.P. based on N-S to N20°W dikes but the graben and Hood River fault are thought to be younger than 3 m.y. and east-west extension is continuing (Priest and Vogt, 1982). Although not well constrained by data, it appears that at Mt. Hood, as in the Central High Cascades, graben subsidence preceded strato-volcano formation. Therefore crustal loading and magma withdrawal of late High Cascades volcanism (Pleistocene-Holocene) were not significant factors in graben formation.



Scale 1:500,000

Explanation

Qral	Recent alluvium and landslide deposits
Qpgl	Glacial deposits
Qpln	River terrace deposits
Qa	Pleistocene andesite to dacite
Qb	Pleistocene basalt
Qi	Pleistocene mafic intrusive rocks
QTba	Pliocene-Pleistocene basalt, andesite, and pyroclastic rocks
QTw	Pliocene-Pleistocene volcaniclastic deposits
QTim	Pliocene-Pleistocene mafic intrusive rocks
Tpb	Pliocene basalt
Tpi	Pliocene mafic intrusive rocks
Tpw	Dalles Formation (Miocene-Pliocene)
QTif	Upper Miocene hornblende diorite intrusives
Tmua	Upper Miocene Rhododendron Formation
Tmmb	Middle Miocene Columbia River Basalt Group
Tmop	Eagle Creek Formation (Oligocene)
	Anticline (dotted where covered)
	Syncline (dotted where covered)
	Normal fault—bar and ball on downdropped side (dotted where covered)
	Wrench fault—arrows indicate relative motion (dotted where covered)
	Thrust fault—teeth indicate upper plate (dotted where covered)

Figure 7. Generalized geologic map of the Mount Hood area. Geology taken from Wells and Peck (1961); additional structures taken from Anderson (1980), Hammond and others (1980), Beeson and others (this volume), and Beeson and others (in preparation). Geologic symbols are modified from Wells and Peck (1961), but descriptions listed here are specific to local geology. (From Priest and Vogt, 1982)

NEWBERRY CALDERA

Geology

The Newberry Volcano is located east of the main trend of the High Cascades where the NE trending Walker Rim normal faulting zone curves to NW as the Tumalo fault zone (Fig. 8). The Brothers fault zone, thought by some investigators to be involved, trends NW, 20 miles NE of the caldera (Priest and others, 1983). The regional tectonic setting of the southern Cascades has been interpreted by Blakely and others (1985). The shield building activity started about 700,000 yr. B.P. with eruptions of basalt and basaltic andesite lava flows forming most of the 900 m thick flanks (Priest and othes, 1983; Walker and Nolf, 1981). Andesite and rhyolite also formed domes and flows. Eruptions of mixed lavas and the bimodal nature of magmatism indicates continued heat input and a significant magma system supplying the volcano.

Caldera-forming eruptions started about 510,000 yr. B.P., but the most recent collapse is only several 10,000s yrs. B.P. (Priest and others, 1983). The caldera has subsided about 900 m based on the U.S.G.S. Newberry 2 hole, and the caldera pyroclastic fill is 500 m thick. The Mazama ash (Crater Lake origin), dated at 6,845 yr., blankets the area and provides a convenient marker. Rhyolite rocks 6,700 yr. to 1,350 yr. B.P. are dominant in the east 2/3 of the caldera and on the SE flank (Fig. 9). The most recent eruption emplaced the aphyric Big Obsidian flow (Fig. 10) from the southern rink fracture 1,350 yr. B.P. (Priest and others, 1983). Ciancanelli (1983a) has made a compilation of the geology, geophysics, geochemistry and thermal gradient data.

Hydrology

The regional water table is 680 m below the caldera floor and flows to

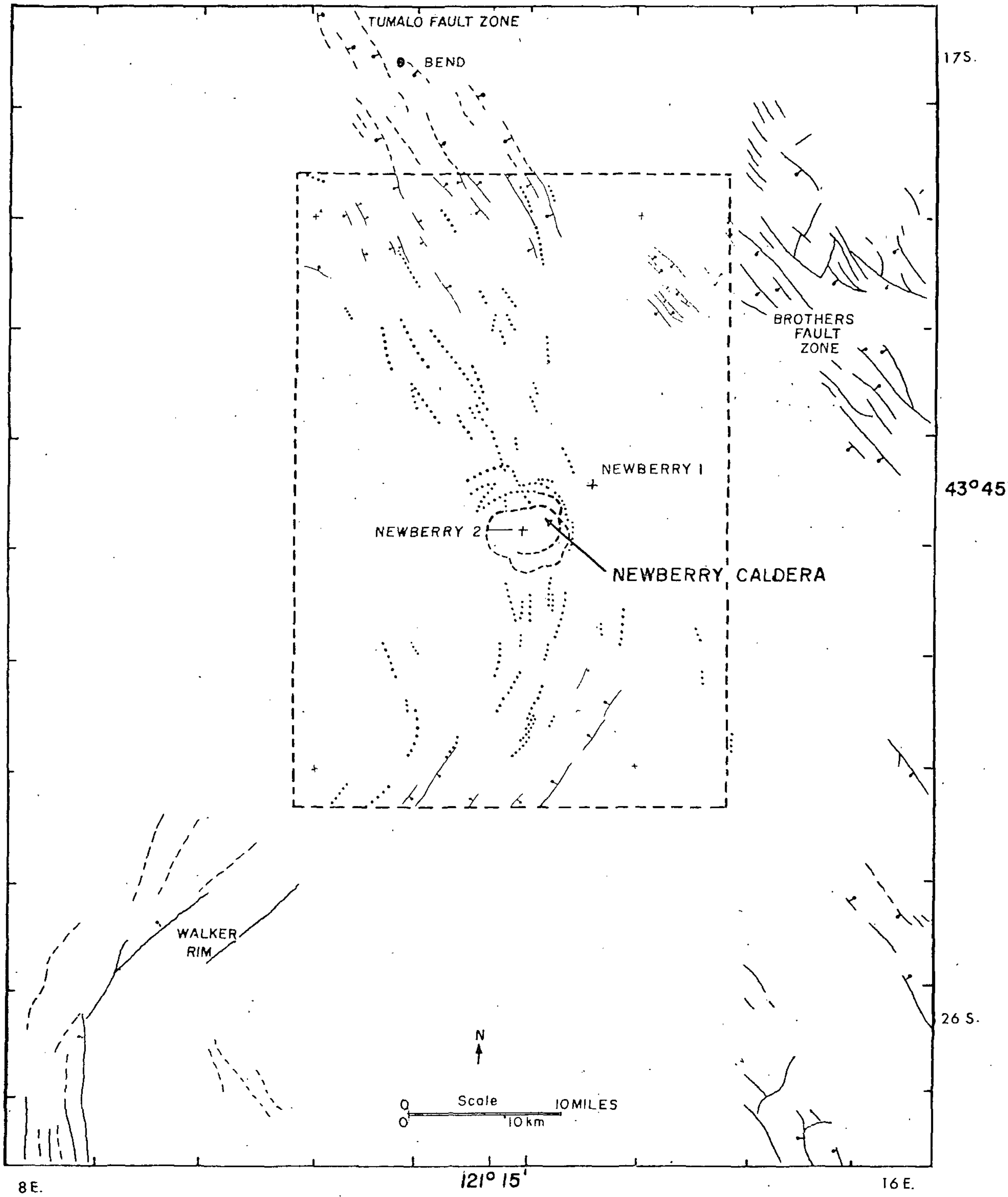
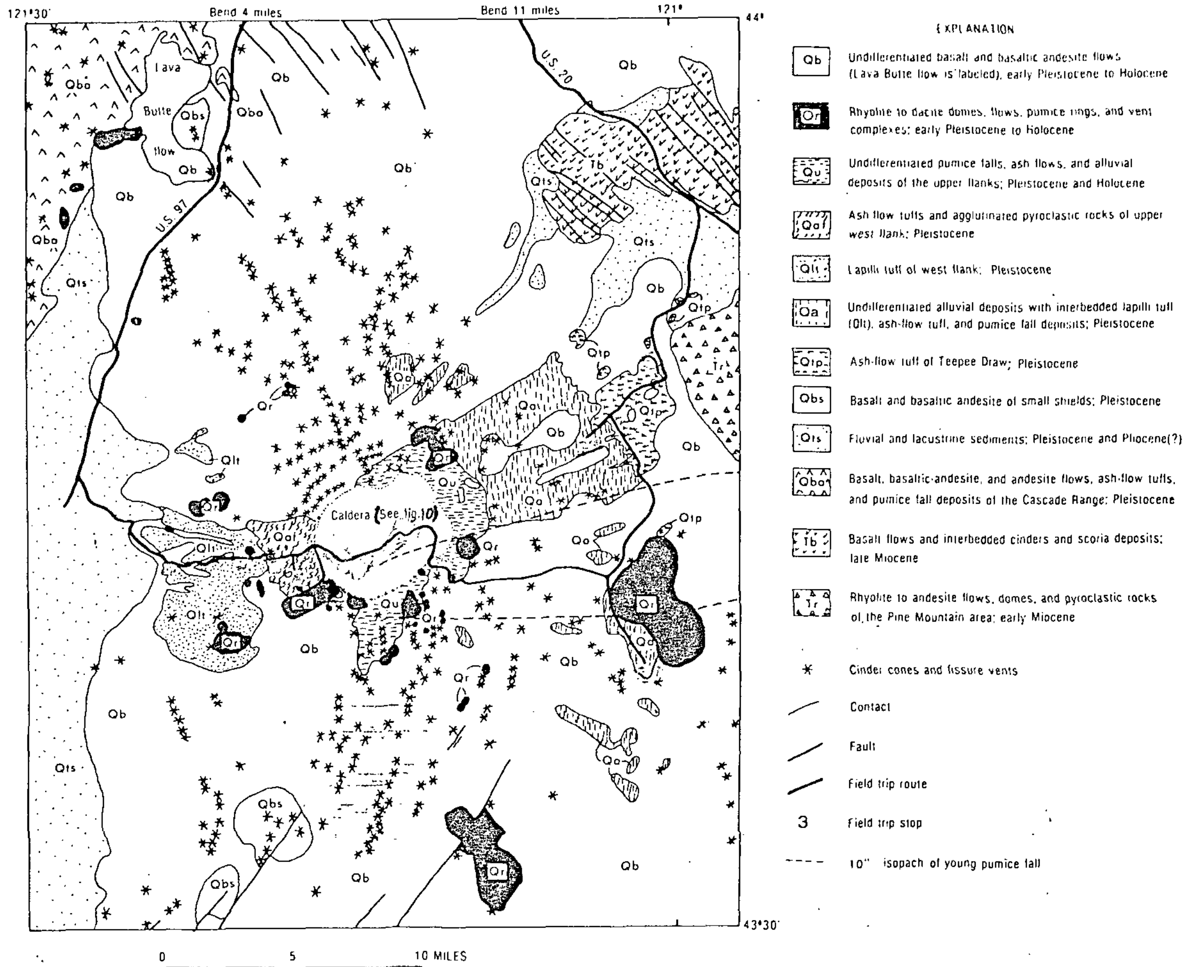


Figure 8. Faults and volcanic vent alignments. Crosses are USGS drill holes Newberry 1 and Newberry 2. Dashed rectangle outlines the geologic map of MacLeod and others (1982). Other data are from Wells and Peck (1961), Walker (1977), and Peterson and others (1976). Thin solid lines = faults; dotted lines = fissures and associated volcanic vent alignments.

(Figure from Priest et al., 1983)



(From Macleod and others, 1981)

Figure 9. Geologic sketch map of Newberry Volcano. Geology of the caldera is shown in figure 10.

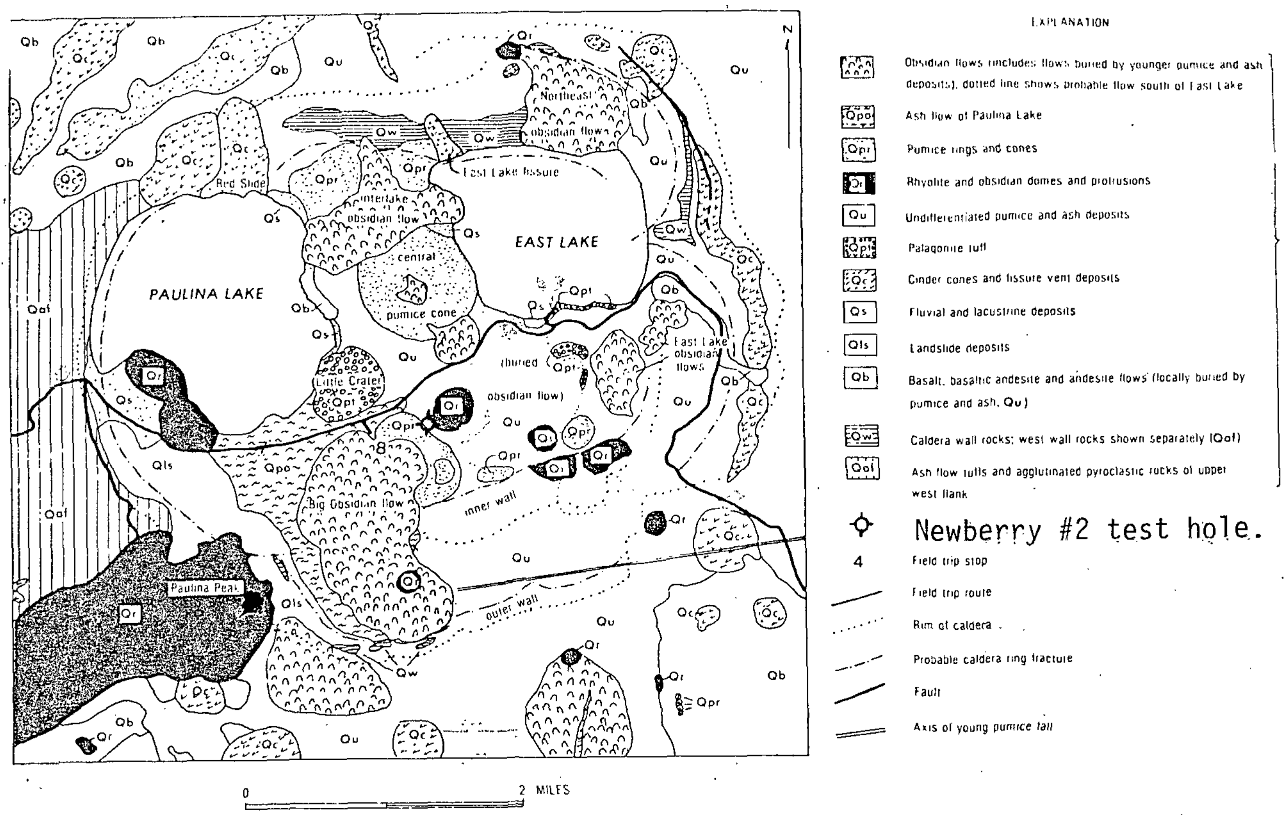


Figure 10. Geologic sketch map of Newberry caldera.

(From Macleod and others, 1981)

the NNE. The flanks of the volcano generally have good permeability, but within the caldera vertical permeability is near zero and lateral permeability is very limited to favorable horizons. Hence, Paulina and East Lakes are part of a perched water table. The hydrology of the Newberry Caldera is discussed in detail by Sammel and Craig (1983). They have analyzed well water in the Newberry Volcano area and the data are presented in Table 2. The permeability of the pre-caldera formations are unknown.

Geothermal

Two hot springs occur at the edge of the lakes and a fumarole is present in the caldera. Since the regional water table is 680 m down, the hot springs are drowned fumaroles and their chemistry is of questionable value. Warm groundwater zones are present to the NE and NNE of Newberry Volcano, the direction of groundwater flow (Priest and others, 1983). Mercury anomalies parallel the ring fracture, occur along a NE trend SE of the caldera rim, and on the east flank.

Two thermal gradient holes have been drilled on the volcano by U.S.G.S. (Sammel, 1981). The first hole, on the NE flank was shallow and did not yield any significant information. Newberry 2, drilled to a depth of 932 m, next to the northeast end of the recent obsidian flow (Fig. 10), in the center of the caldera, had a T.D. temperature of 265°C (Sammel, 1981). The mean gradient is 285°C/km, and the bottom hole gradient (800-930 m) is 505°C/km. The temperature profile was irregular above the water table, 680 m down. Permeability is very low in the hole. Union and Oxy geothermal have drilled deep holes in the area but no data is available on these holes. Sandia also drilled a hole in the Newberry area but a publication on this hole was not found.

Table 2. Chemical Analyses of Ground and Surface Water from Newberry Volcano Area.
(From Sammel and Craig, 1983)

Concentrations in milligrams per liter unless otherwise indicated.
(µg/L = micrograms per liter; µmho/cm = micromhos per centimeter)

Owner/ Name	Temp. (°C)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	SiO_2	As (µg/L)	B (µg/L)	Fe (µg/L)	Li (µg/L)	Mn (µg/L)	Dissolved Solids[1]	Specific Cond. (µmho/cm)	pH	Date Sampled
Paulina Lake Resort	5	35	24	28	6.1	315	5.0	2.8	0.3	29	1	460	120	13	11	286	400	6.95	10/07/81
	6.7	39	35	38	7.7	398	1.9	2.7	.4	33	2	700	180	--	1500	356	565	6.9	10/27/84
Paulina Lake Resort	4	44	39	44	6.4	450	6.0	3.1	.5	36	24	780	6700	88	2300	410	600	7.15	10/07/81
Paulina Guard Station (USFS	6	3.3	2.6	6.5	1.8	27	5.0	.2	.7	46	3	20	23	17	<1	79	65	6.65	09/06/81
Mike Mathews (summer home)	8	18	41	41	5.0	376	2	2.6	--	.90	--	--	--	--	--	--	700[5]	6.97	06/30/82
Jack Hogg (summer home)	--	30	65	68	7.4	585	5.0	5.2	.8	110	39	1500	<10	120	2	581	900	6.15	09/06/81
Little Crater Picnic Area	16	42	44	64	8.3	535	5.0	4.6	.7	90	32	1600	180	100	30	532	710	6.80	10/07/81
Little Crater Camp Site 27	6	28	17	25	2.6	215	5.0	1.7	.3	46	16	570	43	29	10	232	360	7.10	10/07/81
Little Crater Camp Site 49	33	59	57	97	12	690	5.0	6.8	.5	156	<1	1800	360	140	270	733	900	6.21	09/06/81
	35.5	54	48	83	10	679	<1	5.1	.6	161	--	2500	4000	120	250	702	900	6.46	08/--/75
	36	56	51	96	12	691	2.5	4.5	.5	140	2	1000	5000	--	350	709	880	6.3	10/17/74
East Lake Campground well	6	33	15	26	6.0	200	43	2.8	.2	40	1	210	19	9	3	265	390	6.80	09/06/81
Cinder Hill Campground well	5	7.1	1.9	11	1.3	56	5.0	2.5	.4	30	5	10	27	8	5	87	110	6.70	09/06/81

Table 2 (Continued).

Owner/ Name	Temp. (°C)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	SiO_2	As	B	Fe (µg/L)	Li	Mn	Dissolved Solids[1]	Specific Cond. (µmho/cm)	pH	Date Sampled
Cinder Hill Camp Site 34	4	14	7.2	6.3	3.5	88	5.0	<.1	.1	34	<1	10	120	<4	57	113	140	7.20	10/06/81
Paulina Hot Springs	--	56	60	140	17	856	<1	6.0	.6	205	--	870	--	220	--	907	--	6.82	07/00/77
	50	51	43	120	16	699	4.0	4.7	.5	190	16	840	90	--	1700	776	960	6.9	10/26/74
	52	50	42	110	13	689	2	5.0	--	184	--	--	--	--	--	--	--	7.26	06/30/84
Lost Lake gas vent	5	13	8.2	7.9	1.1	0	200	1.1	0.0	31	1	180	15000	--	450	--	400	3.4	10/27/74
East Lake Hot Springs	49	70	34	53	--	547	28	.7	.2	199	--	1100	660	40	900	658	767	6.42	08/00/75
	55	77	39	59	9.7	581	20	1.3	.1	120	1	260	500	--	1400	614	840	6.7	10/26/74
	57	73	33	56	9.7	413	120	1.3	--	197	--	--	--	--	--	--	--	6.10	06/30/82
Paulina Lake[2]	--	26	39	47	5.2	352	3.8	2.8	.6	.46	--	--	--	--	--	366	566	8.8	09/10/60
	6	28	38	47	5.0	402	4	2.4	--	--	--	--	--	--	--	--	--	8.38	06/30/82
East Lake[2]	--	27	13	27	4.5	120	64	.3	.2	10	--	640	20	--	--	206	334	7.8	00/00/73
		26	10	23	3.7	125	59	.2	.1	13						197	323	8.1	09/11/60
	10	25	11	24	3.7	123	64	<1	--	8.8	--	--	--	--	--	--	--	8.07	06/30/82

[1] Estimated by summation of HCO_3 x 0.4917 and other ions listed (Hem, 1970).

[2] Sample (6/30/82) obtained at a depth of 45 feet near the center of the lake.

Geophysics

Gravity data suggest a ring intrusion within the ring fracture. Although gravity and aeromagnetic data are not conclusive, they have been interpreted to indicate a magma or still hot (+ 580°C) pluton 2 to 6 km deep (to the top of pluton) and 10 to 18 km in diameter under the volcano (Priest and others, 1983). Blackwell and Steele (1983) have modeled the convective geothermal system based on heat flow and magma chamber size. Their models indicate that the high temperature (+200°C) system would have an approximate lateral extend equal to the extent of the magma chamber with some plumming out of the system producing an overturn in temperatures above the edges of the magma chamber. They conclude that the high temperature system would extend beyond the caldera if a shallow ($\leq$ 3 km deep) magma chamber is present.

CALIFORNIA CASCADES

Medicine Lake Volcano

"Medicine Lake volcano is a Quaternary bimodal shield volcano of the Cascade Range in California. The volcano possesses a shallow silicic magma chamber which during the last 1,300 years has erupted voluminous rhyolitic lavas over a broad area. Intense faulting on the volcano has produced numerous open fissures during the last several thousand years. The extensive fault network provides an excellent fracture reservoir potential. Geologic and geochemical studies have defined areas of intense faulting with associated volcanism and anomalous mercury concentrations which suggest the presence of high subsurface temperatures" (Ciancanelli, 1983b).

The Glass Mountain KGRA is located on the upper part of the Medicine Lake volcano.

Andesite lavas are the dominant rocks of this volcanic complex which has formed in the last million years. Bimodal silicic and basaltic activity has occurred, however, throughout the volcanic activity (Ciancanelli, 1983b). An andesite ash-flow tuff is thought to have formed during initial caldera collapse but this event does not seem to be well constained by age dates. The oldest platy andesite (Ciancanelli, 1983b) are 0.21 ± 0.05 m.y. so caldera formation must be that young or younger.

The youngest rhyolite and dacite eruptions formed glass flows, domes and pumice fall deposits dated by carbon-14 to be between 130 and 1,360 yr B.P. (Ciancanelli, 1983b). During this time basalt vents have been restricted to outside of the caldera (Ciancanelli, 1983b), under which a silicic magma chamber is believed to be located at a depth of 4 km (Finn and Williams, 1982). Plinian type eruptions and the nature of the magma system is discussed by Heiken (1978) and rhyolite flow morphology is discussed by Fink (1981). Mechanism of magma mixing is discussed by Eichelberger (1981).

The volcano's shield and the caldera are cut by many recent faults, most of which trend north to northwest (Ciancanelli, 1983b). The caldera rim is not defined by mapped faults, although arcurate alignment of vents appears to indicate its presence.

Mercury anomalies are present across the caldera and along the Vulcan Lineament which trends northeast across the northwest edge of the caldera (Ciancanelli, 1983b). A fumarole called The Hot Spot (in the caldera?) has a mercury anomaly associated with it. A few areas of "surficial" hydrothermal alteration are reported but locations are not specified.

Heat flow and thermal gradient data in northern California is given by Mase and others (1982). Their conclusion seems to be that heat flow in the California Cascades cannot be measured due to convective transfer, but they think it is about 100 mWm^{-2}.

Mount Shasta

Mount Shasta in northern California consists of overlapping pyroxene-andesite composite cones built during the past 500,000 yrs (Miller, 1980). After construction of each andesitic cone, eruption of dacitic domes and pyroclastic flows occurred. The Shastina and Shasta cones forming the two peaks of Mount Shasta are dacite domes extruded during the Holocene, Shastina is carbon-14 dated at about 9500 yrs b.p. (Miller, 1980). Block and ash flows were produced from these domes and from Black Butte (Fig. 11) on the southwest flank. Black Butte consists of several dacite domes formed shortly after

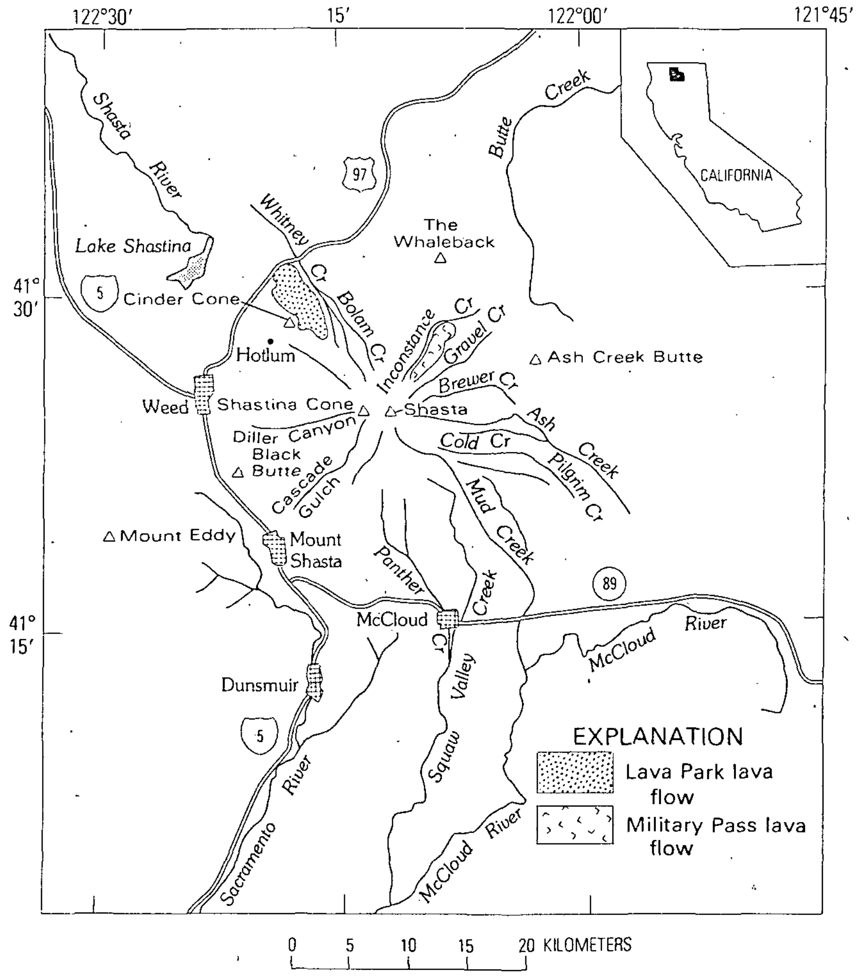


FIGURE 11 Index map showing Mount Shasta and vicinity.
(From Miller, 1980)

Shastina (Miller, 1980). The most recent activity was two possible "normal explosions" in 1855 (MacDonald, 1972).

A magnetic survey indicates a north-trending structural zone through the summit of Mount Shasta which controls some vents. Also the area beneath the main summit has a smaller field intensity than would be expected for uniform magnetization of the mountain (Blakely and Christiansen, 1978). No other detailed structural data was obtained. Blakely and others (1985) present a regional structural interpretation of magnetic and gravity data which suggest that the southern Cascade volcanoes are located on the margin of large subsidence structures.

Mount Shasta is highly permeable near the surface, so few springs are present and a high influx of meteoric water occurs. Active sulfurous fumaroles occur in two small areas, with a small acid hot spring at one, near the summit of Mount Shasta (Christiansen and Tuchek, 1984). Small areas of old intense alteration are present near the center of older vents.

Heat flow and thermal gradient hole data for northern California has been compiled by Mase and others (1982). Actual measured heat flow in this part of the Cascades is very low to negative. Mase and others (1982) conclude that convective heat transfer dominates and suggest a heat flow of about 100 mWm^{-2}. This report appears to be a typical example of the practical value of heat flow studies.

Lassen Peak

Geology

Lassen Peak in northern California is at the southern end of the Cascade range. The regional basement rocks are not well exposed but are thought to be

Mesozoic granite and metamorphic rocks overlain by thin Cretaceous sedimentary rocks (Muffler and others, 1982). These Mesozoic rocks are overlain by Pliocene andesitic debris flows with minor lava flows and ash-flow tuffs 3.5 to 2.0 m.y. old. Late Pliocene to Holocene volcanic rocks were extruded mostly from three volcanic centers (Fig. 12). Dittmar vent, 1.2 to 2.5 m.y, 9 miles southeast of Lassen Peak; Maidu vent, 1.0 to 1.8 m.y., 12 miles south-southwest of Lassen Peak; and Lassen Peak-Brokeoff vents, 0.6 m.y. to present (Muffler and others, 1982). Each volcanic center progressed through andesitic ash and lava flows to siliceous andesite, then dacite to rhyolite domes. Lassen Peak dacite and rhyodacite domes were emplaced starting 250,000 yrs ago, the Lassen Peak dacite dome formed about 11,000 yrs ago and the rhyodacite pyroclastics flows of Chaos Crags on the north slope formed soon after (Crandell, 1972; Crandell and others, 1974). Historic eruptions have occurred at Cinder Cone to the northeast (Fig. 12) in 1851 and at Lassen Peak summit in 1915-1917 (Muffler and Denton, 1984). Basaltic shield volcanoes have formed to the north and east.

Geothermal System

At Bumpass Hell, on the south side of Lassen Peak (Fig. 12) abundant superheated fumaroles up to 159°C, mudpots and acid-sulfate hot springs are active (Muffler and others, 1982). The rocks are intensively altered to opal, kaolinite and alunite. Fumaroles, mudpots and alteration also occur at the Devil's Kitchen to the southeast, Little Hot Springs Valley just to the west of Bumpass Hell, Sulphur Works (Fig. 12), Boiling Springs Lake and Terminal Geyser (Muffler and others, 1982). The single large vapor-dominated reservoir is 500 to 600 m thick and overlies a Na-Cl hot water system with upflow under Bumpass Hell. The hot water system discharges at Morgan and Growler Hot Springs along Mill Creek (Fig. 12), 4 miles south of Bumpass Hell (Muffler and

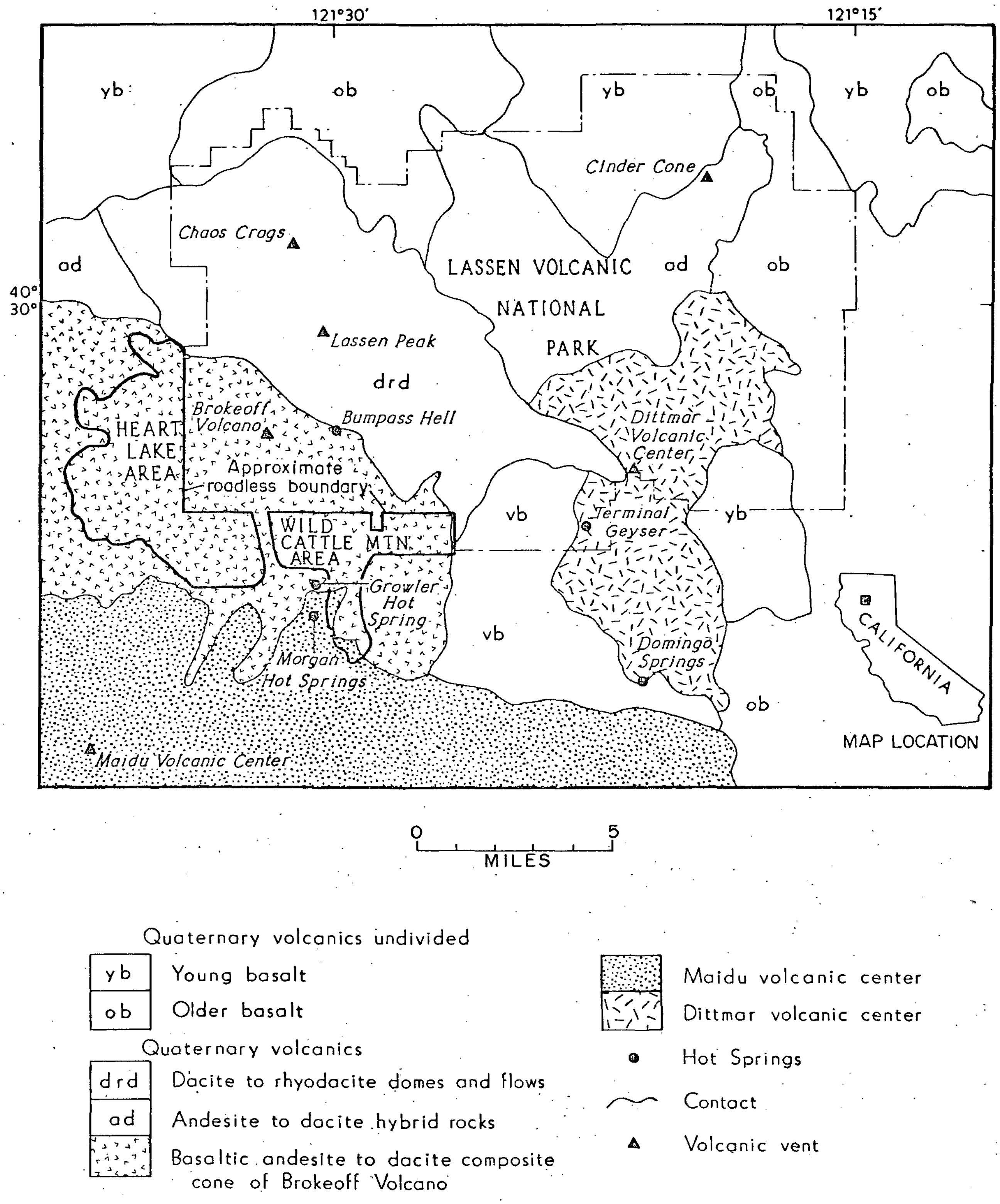


Figure 12. Geologic sketch map of Lassen Peak (from Muffler and Denton, 1984).

Denton, 1984).

Geothermometers indicate a hot water reservoir temperature of 220-240°C, and isotopes studies suggest the system is recharged by meteoric water falling on the Lassen Peak volcanic dome field (Muffler and others, 1982; Truesdell and others, 1983). Distribution of reactive gases (CO_2, H_2S, H_2, N_2, CH_4) suggest lateral flow of fluid away from an upflow center near Bumpass Hell and gas geothermometer indicates a temperature of 244°C or more (Truesdell and others, 1983). Isotope studies have found that carbon-13 contents of CO_2 and sulfur-34 contents of H_2S vary with distance from the center of the system (Janik and others, 1983).

The center of the geothermal system under Bumpass Hell is about 2 miles inside Lassen Volcanic National Park and Growler Hot Springs is about 2 miles south of the park boundary (Fig. 12). Most of the area between Growler Hot Springs and the park boundary is covered by Wild Cattle Mountain Roadless Area (Muffler and Denton, 1984).

A thermal gradient hole was drilled to a depth of 1222 m at Terminal Geyser (not a true geyser but a fumarole) inside the southeast corner of Lassen Volcanic Park in 1978. A maximum temperature of 176°C was measured between 603 and 640 m, below which the temperature decreased to 124°C at T.D. (Beall, 1981). The thermal water produced from the well had a pH range from 8.1 to 8.6 and Na 1300 mg/l, K 180 mg/l, Cl 2200 mg/l for major chemical constituents (Muffler and others, 1982; Beall, 1981). Inconclusive results from a heat flow study of the California Cascades is reported by Mase and others (1982).

WASHINGTON CASCADES

Thermal Springs and Thermal Gradients in Washington

Korosec and others (1983) have tabulated the chemistry, predicted reservoir temperature and location of about 47 thermal and mineral springs and wells in Washington. Brief descriptions of 9 springs are also included. Representative chemical analyses of springs in Washington are listed in Tables 3 and 4 and their locations are listed in Table 5. For the original data sets the reader is referred to Korosec and others (1983), a copy of which is in the files. Mariner and others (1982) have also sampled and analyzed thermal springs in the Washington Cascades. More comprehensive spring chemistry data is listed in the Geotherm file printout. A trilinear plot of spring chemistry is presented as Figure 13. The measured temperature of the hotter springs are 40° to 50°C with one spring at 65°C. Predicted reservoir temperatures are variable but generally between 100° and 200°C.

The Washington geothermal evaluation team drilled 11 thermal gradient holes, 101 to 198 m deep during 1981. About half the holes were sited to test regional gradient and were cold with low gradients, 16°-51°C/km. High gradients were 66° to 93°C/km except for a hole near the Columbia River which had a 368°C/km gradient for 80-113 m deep (Korosec and others, 1983). Locations and heat flow data are also listed by Korosec and others (1983).

Southern Washington Cascades, Quaternary Volcanism

The White Pass area, southeast of Mount Rainier National park, marks the northern limmit of the South Cascades Volcanic Province (Clayton, 1983), which continues south into Oregon and California. North of the White Pass area (latitude 47°N) isolated but large stratovolcanoes (Rainier, Glacier Peak, Mount Baker) site on mostly Pre-Tertiary foliated rocks.

Table 3. Chemical Analyses for Thermal and Mineral Spring and Well Waters in Washington.
(From Korosec and others, 1983)

Spring	umhos/cm Cond	pH	T°(C)	Cl	SO_4	P	Alk B	Total	SiO_2	ppm Na	K	Ca	Mg	Li	F	Br	Fe
Ahtanum Soda	1,100	5.6	12.6	5.6	7	0	650	650	107	83	10.6	73	60	LD	0.2	0.2	47
Block House Well	710	6.4	12.4	4.7	3	0	360	360	100	45	6.0	40	52	0.1	0.6	0.15	4
Bumping Ri. Spr.	2,750	6.0	9.7	210	10	0	1570	1570	104	290	5.0	386	63	0.6	1.0	2.5	16
Bonneville H.S.	790	9.9	36.3	187	72	-	-	-	50	134	1.0	30	LD	LD	0.6	2.2	LD
Bonneville Hole	2,800	11.6	27.7	238	92	257	8	265	26	162	2.6	197	LD	LD	0.4	3.2	LD
Flaming Geysers Spr.	180	8.5	10.1	3.1	LD	0	93	93	35	16	1.4	18	11	LD	0.1	0.07	LD
Flaming Geyser Well	29,000	7.0	12.1	5460	LD	0	1850	1850	12	4150	34	34	27	0.5	2.4	44	LD
Goldmeyer H.S.	600	8.8	47.5	140	46	-	-	-	61	122	3.0	6.2	LD	0.2	0.8	1.8	LD
Government M. Spr.	3,900	6.0	6.7	640	120	0	1000	1000	68	420	9.0	268	91	0.9	0.05	7.0	15
Klickitat M. Spr.	1,500	6.2	26.2	4.6	9	0	860	860	150	68	10.4	118	115	0.1	0.4	0.11	13
Little Soda Spr.	4,000	6.0	7.7	48	57	0	1350	1350	47	310	3.5	218	200	LD	0.06	6.0	1.6
Miocene Petroleum Well	555	9.3	31.7	88	2	19	101	120	120	123	17.5	2.8	LD	LD	21	0.11	LD
Rock Cr. H.S.	400	9.7	33.5	85	40	4	31	35	41	80	0.1	11.5	LD	LD	0.7	1.2	LD
Scenic H.S.	220	9.6	47	24	14	-	-	-	48	50	0.4	2.2	LD	LD	0.9	0.57	LD
Scenic H.S.	180	9.3	39.2	18	14	9	43	52	41	40	0.5	2.3	LD	LD	0.7	0.29	LD
St. Martins H.S.	2,200	8.5	50.0	680	16	0	22	22	51	325	5.2	68	0.4	0.4	0.6	7.3	LD
Shipherds H.S.	220	8.5	40.8	38	12	13	30	43	47	43	LD	4.2	0.1	LD	0.4	0.6	LD
Detection Limit				1	2	1	1	1	1	1	0.1	0.02	0.1	0.1	0.02	0.05	0.5

*Table explanation on following page.

Table 3 Explanation

The table of chemical analyses, includes conductivity (Cond), pH, temperature (Temp), chloride (Cl), sulfate (SO_4), alkalinity (Alk), silica (SiO_2), sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), lithium (Li), fluoride (F), bromide (Br), and iron (Fe). All analyses were conducted in the Division of Geology and Earth Resources' geochemistry laboratory.

(1) - Temperature is °C.

(2) - Conductivity is measured in umhos/cm.

(3) - All other analyses are listed as parts per million (ppm), approximately equivalent to milligrams per liter (mg/l).

(4) - "LD" means less than detection limit. The detection limits for the various chemical species are listed in the last row of the table.

(5) - Dashes indicate that analyses were not performed.

(6) - For alkalinity, the Phenolphthalein (P), Brom Cresol Green-Methyl Red (B), and total alkalinity (T) are listed separately and are represented as mg/l $CaCO_3$.

(7) - Baker and Kennedy Hot Springs samples were collected in 1978. The results are included here because this is the first analyses of these waters by the Division.

See Table 5 for locations of springs.

Table 4. Thermal and Mineral Spring Chemistry for Washington, 1978-1980, Analyses from Division of Geology and Earth Resources Laboratory (From Korosec and others, 1983). See Table 5 for locations of springs.

I.D.	T	Cond	pH	Cl	SO_4	SiO_2	Na	K	Ca	Mg	Li	Br	I
Bonneville Hot Spr.	36.2	805	8.2	196	8	50	160	1	31	0.5	1.0	1.2	0.01
	29.2	790	-	-	78	50	146		28	0.5	-	-	-
Goose Egg Soda Spr.	9.5	2700	6.0	192	4	100	269	10	171	92	0.06	2.4	0.04
Lester Hot Spr.	48.4	520	-	215	30	67	104	3	7	LD	0.35	-	-
Longmine M. Spr.	22.0	5400	6.0	876	40	112	508	43	460	150	1.9	5.3	0.05
	13.3	600	5.2	63	5	31	50	4	43	15.3	0.1	0.4	LD
	25.1	6550	6.2	1204	-	141	645	51	582	-	2.4	6.2	0.04
	11.2	1920	5.8	112	-	82	72	10	210	42	0.3	0.7	LD
Medicine Cr. M. Spr.	8.7	300	7.4	-	-	37	70	-	3	0.3	0.3	-	-
Newskah M. Spr.	17.5	380	-	-	-	51	76	-	4	0.6	LD	-	-
Ohanapecosh H. Spr.	39.5	4400	-	1010	175	106	895	47	68	5.1	2.81	-	-
	45.0	4500	-	1000	-	107	889	47	65	4.9	2.83	-	-
	43.6	-	-	987	-	108	825	44	64	4.9	2.82	-	-
Orr Cr. Warm Spr.	21.7	175	-	28	LD	29	29	9	3	LD	LD	-	-
St. Martins H. Spr.	32	2350	-	756	-	57	360	6	73	0.5	0.3	4.5	0.02
Sol Duc H. Spr.	34	355	9.2	20	-	64	81	1	3	LD	0.1	0.2	0.01
	50	342	9.2	18	-	65	75	1	1	LD	0.1	0.2	0.01
Studebaker M. Spr.	5.3	110	-	-	-	47	17	-	8	2.8	-	-	-
	8.1	120	-	-	-	28	9	-	5	2.4	-	-	-
Summit Creed Soda Spr.	11.6	8500	-	1620	2	104	1684	73	240	100	5.52	-	-
	9.7	2000	-	253	1	30	235	12	14	13	0.80	-	-
Corbett Station W. Spr.	18.3	-	-	88	5	56	88	9	9	0.9	0.03	0.5	LD
YMCA Warm Well	22.2	-	-	87	-	66	101	9	6	0.3	LD	0.6	LD

Table 4 (Continued)

I.D.	T	Cond	pH	Cl	HCO_3	CO_3	SO_4	SiO_2	Na	K	Ca	Mg	Li	F	B
Baker H. Spr.	42	820	7.93	109	157	0	95	125	179	11.8	5.8	0.2	0.4	3.0	3.1
		780	7.96	99	124	0	90	90	154	10.5	5.9	0.3	0.3	3.0	2.7
Kennedy H. Spr.		3200	8.17	626	1143	0	2	180	741	132	187	62	4.8	1.0	9.7
Longmire M. Spr.	13	600	6.89	69	247	0	5	-	47	15.5	58	18	0.1	3.0	0.2
Olympic H. Spr.		320	8.95	10	85	19	37	80	60	-	1.2	0.01	0.03	1.0	0.8
		-	-	10	-	-	-	-	62	2.4	1.0	0.01	0.03	-	0.8
Sol Duc H. Spr.		380	7.93	20	137	3	34	80	75	2.2	1.3	0.01	0.1	1.0	1.3
		360	8.43	18	129	-	35	-	74	2.6	1.1	0.01	0.1	1.0	1.3
Sulphur H. Spr.		480	7.62	54	102	0	60	100	102	2.8	1.6	0.01	0.1	3.0	0.6
Suiattle R. M. Seep		2350	6.93	709	63	0	30	23	292	79	222	3.2	1.2	1.0	3.0

Table 4 (continued). USGS Analyses of Washington Thermal and Mineral Springs.
Part I. Analyses from Robert Mariner, U.S. Geological Survey, for samples collected from 1977 to 1980 (From Korosec and others, 1983).

Spring Name	T	pH	Cl	Alk	SO_2	SiO_2	Na	K	Ca	Mg	Li	F	B	Fe
Kennedy	35	6.27	625	1660	2	175	670	72	190	48	3.5	1.2	7.5	3.0
Garland	29	6.46	3600	2600	160	105	2500	200	390	87	9.4	1.6	64	5.4
Ohanapecosh	48	6.8	880	1060	170	100	920	52	60	4.9	2.9	5.2	12	0.04
Longmire	19	6.35	810	2700	41	125	580	46	540	170	2.2	0.4	3.7	11
Bumping R.	5	6.22	190	1910	1	95	290	5.2	380	52	0.40	1.2	2.2	15
Goose Egg	10	6.25	150	1530	2	92	260	9.2	170	100	0.04	0.15	0.16	18
Summit Cr.	11	6.24	1450	1610	LD	100	1750	85	240	93	5.8	0.24	50	-
Klickitat	22	5.89	4.2	1070	2	140	64	10	120	100	-	0.34	LD	-
Green R.	10	6.58	1250	2715	2	94	1350	79	220	93	-	0.45	28	-
Pigeon	8	8.34	22000	18	280	9.2	6100	-	7100	5.5	-	-	3.0	-
Gov. Bubbling Mike	15	6.41	820	1610	170	75	585	14	360	100	1.0	.16	21	0.06
Gov. Iron Mike Well	18	6.01	570	1250	120	65	420	9.1	260	80	.76	.12	15	13
Green River BN	-	6.47	1250	1585	1	96	1320	90	286	24	3.3	.42	25	.25

Table 5 - Basic Data for Thermal and Mineral Springs of Washington State
(from Korosec and others, 1983)

COUNTY	SPRING NAME	Location T.	Location R.	Sec.	Temperature(1) °C	Estimated(2) Flow l/min	Conductivity umhos/cm
Chelan							
	Medicine Spring	26N	18E	13D	C		
	Little Wenatchee Soda Spring	27N	15E	10B	7°		
	Little Wenatchee Ford Soda Spring	28N	13E	14	9°		
Clallam							
	Olympic Hot Springs	29N	8W	28B	40°- 48°	500	320
	Sol Duc Hot Springs	29N	9W	32	23°- 50°	560	350
	Piedmont Sulfur Spring	30N	9W	11	C		
Cowlitz							
	Pigeon Springs	7N	1E	36BA	8°		
	Green River Soda Springs	10N	4E	2A	13°- 25°		
Grays Harbor							
	Newskah Mineral Springs	16N	9W	9	16°- 19°	400	400
King							
	Lester Hot Springs	20N	10E	21	40° - 49°	200	520
	Diamond Mineral Spring	21N	6E	21C	11°		

COUNTY	SPRING NAME	Location T.	Location R.	Sec.	Temperature(1) °C	Estimated(2) Flow l/min	Conductivity umhos/cm
King (cont.)							
	Flaming Geyser Springs	21N	6E	27DD	12°	10	22,000
	Goldmeyer Hot Springs	23N	11E	14B	46° - 53°	500	630
	Ravenna Park Sulfur Spring	25N	4E	9	C		
	Skykomish Soda Springs	26N	11E	27B	C		
	Money Creek Soda Springs	26N	11E	30D	C		
	Scenic Hot Springs	26N	13E	28D	23° - 50°	110	200
Kitsap							
	Bremerton Sulphur Spring	24N	1E	3AD	C		
Kittitas							
	Medicine Creek Mineral Spring	21N	17E	22CD	9°	6	300
Klickitat							
	Klickitat Mineral Springs	4N	13E	23, 24	18° - 32°		1,500
	Blockhouse Mineral Springs	4N	15E	9C	12° - 16°	0 - 40	700
	Klickitat Soda Springs	5N	13E	25AD	15° - 17°		
	Fish Hatch Warm Spring	6N	13E	4AD	24°	15	1,660

COUNTY	SPRING NAME	Location T.	Location R.	Sec.	Temperature(1) °C	Estimated(2) Flow l/min	Conductivity umhos/cm
Lewis							
	Vance Mineral Spring	12N	7E	22CB	C		
	Alpha Mineral Spring	13N	2E	5	C		
	Packwood Hot Spring	13N	9E	32	38°		
	Packwood Mineral Well(Spring)	13N	10E	6B	C	0	
	Ohanapecosh Hot Springs	14N	10E	4B	50°	110	4,650
	Summit Creek Soda Springs	14N	11E	18CA	12°	100	8,500
Okanogan							
	Poison Lake	39N	27E	5D	40° - 50° (?)		
	Hot Lake	40N	27E	18A	40° - 50° (?)		
Pierce							
	St. Andrews Soda Spring	15N	7E	1	C		
	Longmire Mineral Springs	15N	8E	29D	12° - 25°	250	6,500
	Mt. Rainier Fumaroles	16N	8E	23	52° - 72°		
Skamania							
	Bonneville Hot Springs	2N	7E	16C	28° - 36°	80	800
	Rock Creek Hot Springs	3N	7E	27AB	34°	20	400

COUNTY	SPRING NAME	Location T.	R.	Sec.	Temperature(1) °C	Estimated(2) Flow l/min	Conductivity umhos/cm
Skamania (cont.)							
	St. Martin Hot Springs	3N	8E	21DD	48° - 53°	65	2,200
	Shipherds Hot Springs	3N	8E	21DB	30° - 45°	100	220
	Collins Hot Springs	3N	9E	31C	40° - 50° (?)		
	Little Soda Spring	4N	7E	5D	8°	100	4,000
	Government Mineral Springs	5N	7E	31	5° - 18°	200	3,900
	Mt. St. Helens Fumaroles	8N	5E	4	88° - 800°		
	Orr Creek Warm Springs	10N	10E	19A	19° - 22°	100	180
Snohomish							
	Garland Mineral Springs s	28N	11E	25B	24° - 29°	100	
	Kennedy Hot Springs	30N	12E	1A	38°	60	3,400
	Gamma Hot Springs	31N	13E	24D	65°	15	2,800
	Suiattle River Mineral Seep	31N	15E	18A	10°	8	2,350
	Sulphur Creek Hot Springs	32N	13E	19A	37°	10	500
Walla Walla							
	Warm Springs Canyon Warm Spring	6N	32E	2D	22°		

COUNTY	SPRING NAME	Location T.	Location R.	Sec.	Temperature(1) °C	Estimated(2) Flow l/min	Conductivity umhos/cm
Whatcom							
	Dorr Fumarole Field	38N	8E	17BB	90°		
	Sherman Crater Fumaroles	38N	8E	19AC	90° - 130°		
	Baker Hot Springs	38N	9E	20C	40° - 44°		820
Yakima							
	Mt. Adams Fumaroles	8N	10E	1	+ 50°		
	Soda Spring Creek Soda Spring	9N	12E	35AB	C		
	Castile Soda Springs	9N	13E	18CD	12°		1,800
	McCormick Meadow Soda Springs	11N	12E	24CA	10°	8	1,500
	Klickitat Meadow Soda Springs	11N	13E	4DB	14°	25	440
	Simcoe Soda Springs	11N	15E	9C	+ 20°		
	Ahtanum Soda Springs	12N	15E	8	10° - 14°	500	1,100
	Goose Egg Soda Spring	14N	14E	33C	10°	80	2,700
	Indian Mineral Springs	15N	12E	10AA	C		
	Little Rattlesnake Soda Springs	15N	14E	34	C		
	Bumping River Soda Springs	17N	13E	34BB	10°	8	2,750

(1) The letter designation "C" indicates that the temperature of the spring is cold (less than 18° C), but an exact temperature is not known or has not been reported. When temperature ranges are reported, they may indicate that seasonal variations have been observed, that different spring orifices within the same system produce that range of temperature, or both.

(2) The flows reported are rough estimates and represent the total flow from all springs within the system.

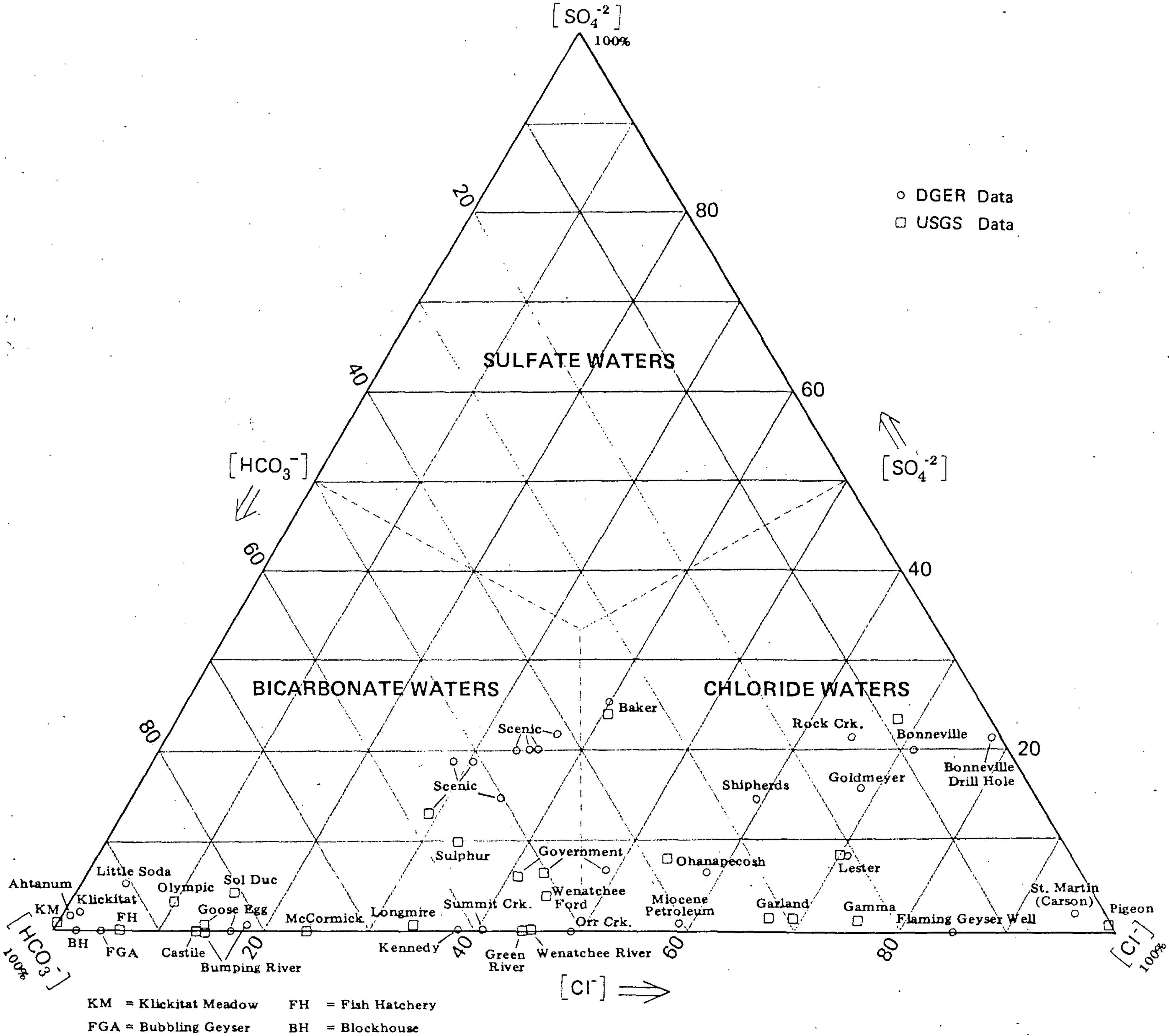


Figure 13 - Trilinear plot of percentage of reacting anions for thermal and mineral springs and wells of Washington. (from Korosec and others, 1983).

In the White Pass area southeast of Mt. Rainier, Pliocene-Pleistocene volcanism began 3 to 4 m.y. ago with brief but voluminous vitric rhyolitic ash-flows and dacite porphyry flows (Clayton, 1983). Silicic volcanism ended about 3 m.y. ago and was directly followed by basalts building shield volcanoes and andesitic strato-volcanoes. Granodiorite intrusions were emplaced 1.1 m.y. ago (Clayton, 1983). Andesite lava flow eruptions have continued in the White Pass area until about 20,000 yrs ago, with no eruptions since the Fraser glaciation. Exceptions to the recent mafic volcanism are the Spiral Butte dacite dome and lava flow, 64-66% SiO_2, and the Clear Lake dacite, 59-62% SiO_2 (Clayton, 1983). Clayton (1983) groups Spiral Butte with 0.79 m.y. old hornblende andesites, describing Spiral Butte as "one of the youngest" and Late Pleistocene in age. The Clear Lake dacite is described as having a lower SiO_2 content than the andesites? For the White Pass area Clayton (1983) gives a long list of references.

South of White Pass and Mount Rainier, basalts and basaltic andesites, younger than 700,000 years, form several north-south volcanic zones spread from Mount St. Helens to Mount Adams and extend to the Columbia River (Korosec and others, 1983). Rocks more silicic than 48 to 56% SiO_2 are restricted to the major stratovolcanoes in this area. The recent volcanism appears to occur over a much broader zone east to west than in Oregon, and a well-defined graben structure is not present in Washington.

Mount Baker

Mount Baker is the northern-most Quaternary stratovolcano in Washington (Fig. 14). Mount Baker's activity extends from 400,000 years ago to minor activity in the 19th Century (Hyde and Crandell, 1978). Post-glacial deposits include tephra, lava flows and pyroclastic-flow deposits. A fumarole field is active within the Sherman crater on the upper part of the cone south of the summit. The Dorr Fumarole Field is a small area of thermal activity on the north flank of Mt. Baker. The thermal reservoir associated with this activity has been studied by Frank and Friedman (1975), and Hyde and Crandell (1978).

Baker Hot Springs (45°C) is located 11 km east of the peak and water chemistry suggests a reservoir temperature of 150° to 170°C (Korosec et al., 1983). Other hot springs are reported in the area (locations not reported), including submerged thermal springs in the Swift Creek drainage and along the North Fork Nooksack River north of the volcano.

A geothermal exploration program started in 1981 was conducted in the Mount Baker area for Seattle City Light (Korosec et al., 1983). This effort included resistivity and soil mercury. The data are proprietary, but it is expected to be released "in the near future".

Glacier Peak

Glacier Peak is a dacitic to andesitic stratovolcano in the northern Cascades of Washington (Fig. 14). The volcano sets on a crystalline core complex of pre-Tertiary gneiss, schist and foliated intrusives (Church and Strotelmeyer, 1984; Church and others, 1984; Fig. 14). Several mining districts with proven reserves of low grade (~ 0.34% Cu) Cu, Mo, Ag and Au porphyry deposits are present in the area. Breccia pipes and vein deposits with higher grade but lower tonnage reserves are also present (Church and others, 1984).

Glacier Peak is a Pleistocene to Holocene volcano with post-Pleistocene eruptions consisting of domes producing pyroclastic flows and lahar deposits (Beget, 1983). Known eruptions over the last 5,000 years have occurred about

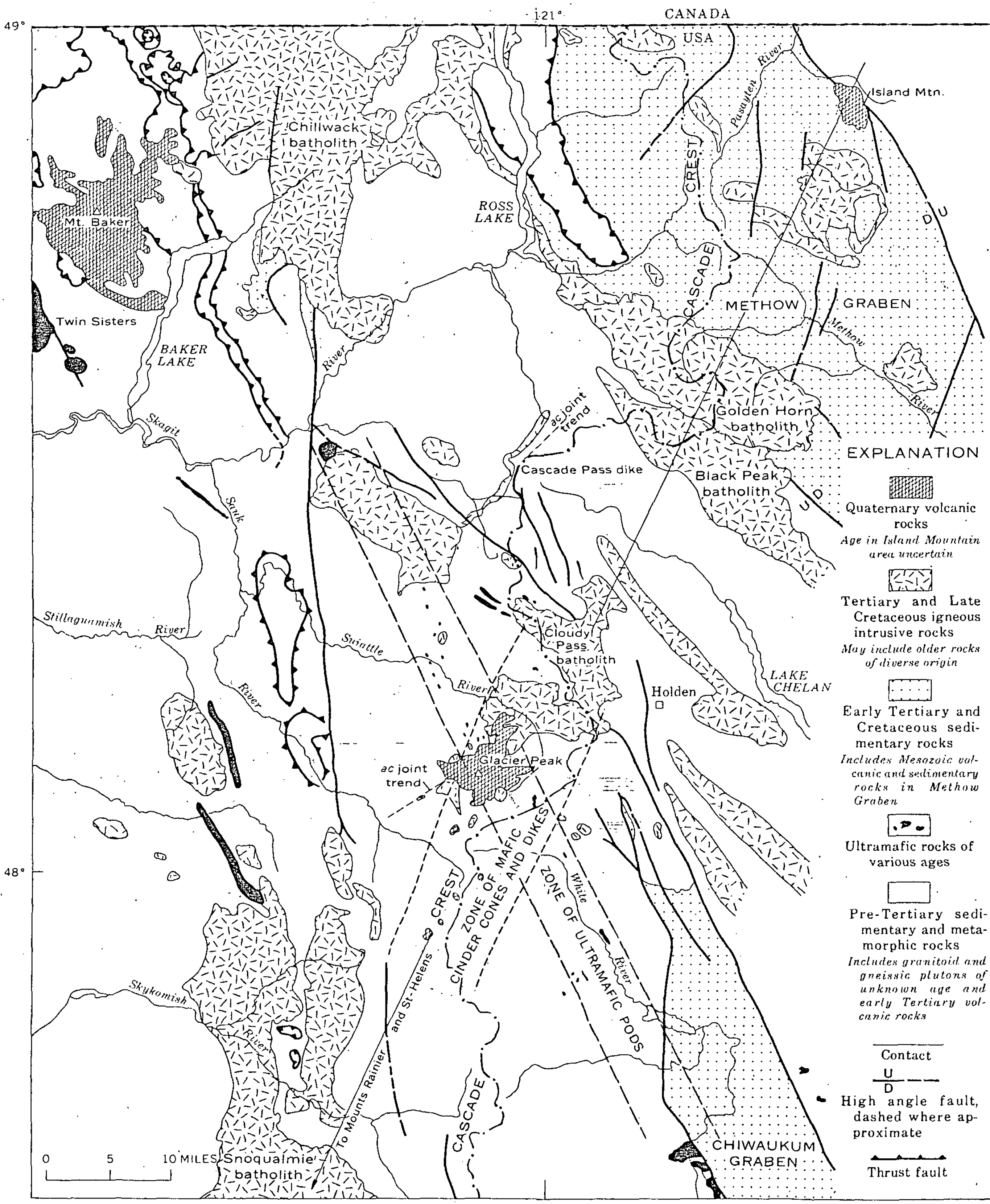


Figure 14. Regional geologic setting of Mt. Baker and Glacier Peak, northern Washington (From Tabor and Crowder, 1969).

every 900 to 1,100 years. The last major pyroclastic flow and lahar, possibly from dome formation, occurred 1,000 yrs. B.P., and tephra producing eruptions took place until 200-300 yrs. B.P. (Beget, 1983).

The prime area of geothermal potential is the volcano itself which is tied up in the Glacier Peak Wilderness Area. Therefore no geothermal exploration has been conducted in the area. Two hot springs and one mineralized seep are present around the volcano's flanks. Chemistry of Kennedy Hot Springs (38°C), located 5 km west of Glacier Peak, indicates a reservoir temperature of 170°-200°C (Korosec et al., 1983). Geothermometry of the sodium chloride waters from Gamma Hot Springs (65°C), 5 km northeast of the peak, indicate an equilibration temperature of 200°-215°C. Cold seeps 11 km northeast of the peak are also sodium chloride in nature and yield a reservoir temperature of 170°-225°C (Korosec et al., 1983). Sulphur Creek Hot Springs (37°C), 17 km north of the peak is not related to the Glacier Peak system and represents only moderate temperature water from deep circulation.

Mount Rainier

There is evidence of a thermal system within the upper cone and Longmire Hot Spring (28°C) and Ohanapecosh Hot Spring (50°C), south and southeast of the cone, have chemistry suggesting a system at 150° to 175°C (Korosec et al., 1983). All of this is within the national park, however Ohanapecosh Hot Springs is near the southeast corner of the park.

Mount Adams

The central part of Mount Adams is closed to development by wilderness and roadless areas (Hildreth and Miller, 1984). Very little exploration has therefore occurred in the area. The only reported thermal manifestation in the region is Orr Creek warm springs (20°C), for which chemistry suggests a reservoir temperature of over 200°C for the Na-K-Ca (Mg.-corr.) geothermometer, but only 47° to 78°C with chalcedony and quartz (Korosec and others, 1983). The U.S.G.S. feels the volcano has no geothermal potential because of "no indication of a shallow magma..." (Hildreth and Miller, 1984). This could be said of many geothermal systems.

CANADIAN CASCADES

Meager Creek

Geology

The Meager Creek geothermal prospect in British Columbia is associated with a Pliocene to Recent volcanic complex (Fairbank and others, 1981). Rock types are andesite, dacite and rhyodacite lava flows, breccia and tuff forming a stratovolcano. The last eruption was 2550 yr. B.P.

The volcanic rock rests on the Mesozoic Coast Range Plutonic Complex (Read, 1979) and the geothermal system occurs in faults and dikes in these rocks. The Mesozoic rocks in the Meager Creek area (south reservoir) consist of gneiss intruded by foliated quartz diorite. The gneiss is quartz rich and medium grained. Quartz monzonite and metamorphic rocks are present in the north reservoir, 12 km north of Meager Creek (Reader and Fairbank, 1983), and possible monzonite was penetrated below 2800 m in Meager Creek hole MCG-1. Silicic felsite, dacite and a few possible diabase dikes have intruded the crystalline rocks.

Thermal fluid flow is thought to be controlled by the Meager fault zone with an east-west strike and north 45° dip (Reader and Fairbank, 1983) and by the dikes (Moore and others, 1983). Faults are also mapped trending northwest to northeast (Moore and others, 1983). Thermal alteration by the current system has produced silica, calcite, dolomite, gypsum, barite, kaolinite and other clays in a crude zoning (Fairbanks and others, 1981). Both siliceous and carbonate sinters are associated with hot springs.

Thermal Gradients and Heat Flow

Twenty-five shallow diamond drill holes and three deep holes have been drilled in the Meager Creek area. Maximum bottom hole temperature is 202°C at a depth of 367 m in the southern or Meager Creek reservoir. Detail on subsurface lithology and alteration is given by Moore and others (1985). Thermal gradients vary greatly but are generally higher in the southern reservoir with values as high as 330°C/km (Fairbank and others, 1981) and 1230°C/km (Reader and Fairbank, 1983). In the northern reservoir gradients are more uniform, with 85°C/km typical.

Heat flow in the Meager Creek area has a background range of 120-185 mW/m^2 compared to a regional heat flow of 80 mW/m^2 for the Garibaldi Volcanic Belt (Reader and Fairbank, 1983). Heat flows values up to 2530 mW/m^2 are measured above convective flow areas. In the north reservoir heat flows range from 176-322 mW/m^2.

Hot spring geochemistry indicates 59° to 166°C reservoir for the silica geothermometer and 96° to 250°C with Na-K-Ca (Fairbank and others, 1981). The chlorine spring waters contain 200 to 2,000 ppm TDS and drill hole samples are 6000 to 10,400 ppm TDS with 28 ppm boron. The limiting factor for development of Meager Creek has been failure to obtain significant production volume.

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SILICIC VOLCANIC ROCKS - CASCADES

Rhyolitic to dacitic rock reported in the following areas.

Area	References	Remarks
Oregon:		
Crater Lake	Bacon, 1983	Cites several other studies
Mt. Jefferson	Sutton, 1974	
Devils Cr.	White, 1981a Priest & Vogt, 1983 Rollins, 1976	5.75 m.y. BP, p. 30
Devils Lake	Priest & Vogt, 1983	
Mt. Hood	White, 1980b Wise, 1969 Crandall, 1980	200 yr. BP pyroclastics
Newberry Caldera	Priest and others, 1983	
South Sister	Priest and Vogt, 1983	
Yamsay Mtn.	Hering, 1981	bimodal

Washington:

White Pass Area	Clayton, 1983, p. 232	Late Pleistocene (0.79 m.y.), 64-66% SiO_2 Spiral Butte dacite dome and flow
Clear Fork Dacite	Clayton, 1983, p. 234 Ellingson, 1972	59-62% SiO_2
Simcoe Mountains	Korosec and others, 1983, p. 286	Dacite domes & rhyolite flows on basaltic shield-Pleistocene

California:

Burney Mountain	Muffler and Campbell, 1984	Dacite, 0.24 m.y.
Lassen Peak	Muffler and others, 1982 Crandell and others, 1974	Dacite to rhyolite domes Hornblende dacite pyroclastics, Chaos Crags
Medicine Lake Volcano	Ciancanelli, 1983	Rhyolite and dacite

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