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Geologic map of the Blue Lake quadrangle, southern Cascade Range, Washington

by

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CONTENTS

FIGURES

TABLE

PLATES

GEOLOGIC MAP OF THE BLUE LAKE QUADRANGLE, SOUTHERN CASCADE RANGE, WASHINGTON

by Donald A. Swanson

INTRODUCTION

The Blue Lake 7.5–minute quadrangle is centered about 45 km northeast of Mount St. Helens, 50 km south of Mount Rainier, and 15–23 km west of the crest of the Cascade Range in southern Washington (fig. 1). It is the most recent in a series of adjoining quadrangles that I have studied geologically. Geologic maps and accompanying text have been open-filed for the French Butte, Greenhorn Buttes, Tower Rock, and McCoy Peak quadrangles (Swanson, 1989, 1991, 1992) and finished but not yet compiled for the East Canyon Ridge quadrangle (D.A. Swanson, unpublished mapping, 1992). I plan to map the Hamilton Buttes quadrangle in summer 1993. In addition, Richard B. Moore is starting to map the adjoining quadrangles north of the Cowlitz River shown in figure 1.

The geologic research in these quadrangles forms part of a project, which began small but over the years has become a major effort, to understand the development of the Cascade arc in southern Washington from its inception in the late Eocene or early Oligocene. A major goal has been to tie the Tertiary stratigraphy of the area near and west of Mount St. Helens (Evarts and Ashley, 1984, 1990a, 1990b, 1991, 1992, in press a–d; Evarts and others, 1987; Swanson, 1989, 1991, 1992) into the now classic stratigraphic section in the Mount Rainier-White Pass area defined by Fiske and others (1963; see also Waters, 1961) and modified by Vance and others (1987). This work is establishing an improved regional geologic framework for the southern Washington Cascades and defining a geologic research corridor across the west side of the Cascade Range (Swanson and Evarts, 1992), from the lower Tertiary marine rocks of the Puget Lowland to the Late Jurassic–Early Cretaceous Rimrock Lake inlier (Miller, 1989) along and just east of the crest in the White Pass-upper Tieton River area (fig. 1). The ongoing study will provide necessary support for a major geophysical corridor linking coastal Washington with the Columbia Plateau, now planned for fiscal years 1995 and 1996 (C.S. Weaver, personal commun., 1993). Detailed field work is testing whether a pronounced electrical conductivity layer in the middle crust, the *southern Washington Cascades conductor* (SWCC) of Stanley and others (1987, 1992), has a recognizable influence on the geology of the area. All quadrangles being mapped lie within and astride the margin of the SWCC.

The Blue Lake quadrangle drains principally into the North Fork of the Cispus River and its main stem, the Cispus itself (fig. 2); the North Fork empties into the Cispus just west of the quadrangle. Streams in the northern quarter of the quadrangle (mainly Kilborn, Smith, and Deception Creeks) flow northward into the Cowlitz River. Roads follow all major drainages and climb some slopes. Most of the high country (Bishop Ridge, Blue Lake Ridge, and ridge crests north of the North Fork) lacks roads but is rather open and readily accessible by trail and cross-country traverses.

Oligocene volcaniclastic and volcanic rocks, mainly of basaltic andesite and andesite composition (table 1), underlie most of the quadrangle. The volcaniclastic rocks east of Timonium Creek intertongue with fluvial arkose 3.5 km east of the quadrangle (Winters, 1984) and form the local base of the Cascade arc. Many Tertiary intrusions, mostly sills, cut the layered rocks. Comparatively small eruptions of olivine basalt took place in the Pleistocene in the southwest part of the quadrangle.

Glacial drift covers large areas, but generally bedrock crops out along creeks, steep slopes, and ridges. Mapping of the bedrock involved traverses along most drainages, large and small; such work finds many exposures, even in densely forested terrain. The quadrangle is so far from Mount St. Helens that the Holocene tephra is typically less than a few centimeters thick and only rarely obscures small outcrops of bedrock.

Only small-scale (1:100,000 and smaller) reconnaissance geologic mapping had been done in the Blue Lake quadrangle before this research, principally by Hammond (1980), Korosec (1987), and J.G. Smith (unpublished map of the Yakima 2–degree sheet). One larger scale map accompanied Stine's (1987) detailed sedimentologic study of the volcaniclastic rocks east of Timonium Creek.

ACKNOWLEDGMENTS

I thank Barbara White (my wife) for logistic help on several long traverses. Rick Wooten (U.S. Forest Service) guided me in late September 1987 to Blue Lake volcano, which he and his colleagues had discovered in the early 1980s while preparing a regional geologic map of part of the National Forest. Cindy Stine gave me a copy of her thesis and provided locations for her chemically analyzed samples, and she and Paul

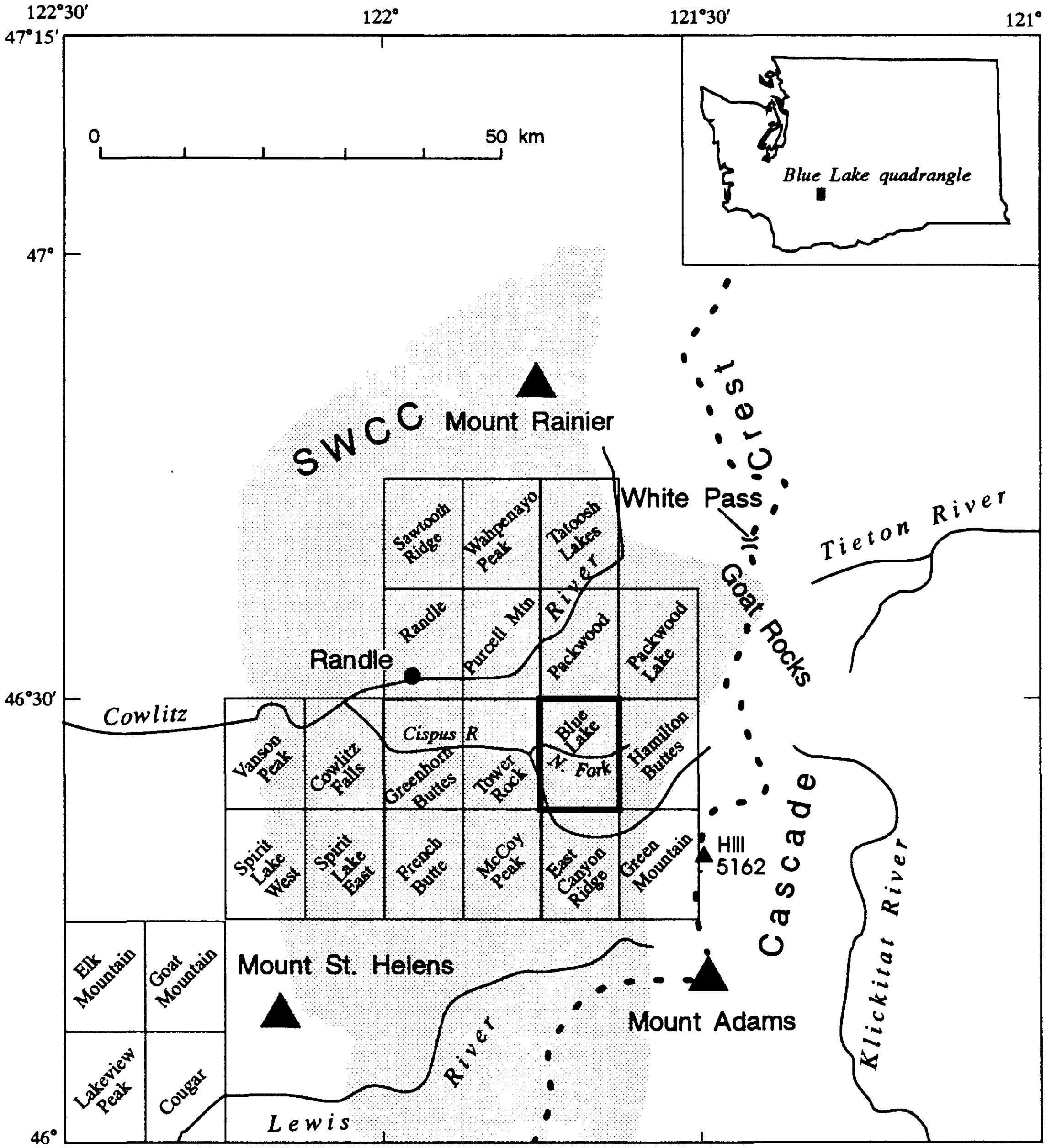

Figure 1. Index map showing location of Blue Lake quadrangle relative to the three Holocene and late Pleistocene composite volcanoes in southern Washington, crest of Cascade Range, Pleistocene-Pliocene volcano at Goat Rocks, Southern Washington Cascades Conductor (SWCC; see text), and other 7–1/2′ quadrangles in which geologic mapping has been completed recently or is planned for the near future. Mapping west of longitude 122° by Russ Evarts and Roger Ashley; mapping east of 122° and south of Cowlitz River by me; mapping planned north of Cowlitz River by R.B. Moore.

Hammond introduced me to the volcaniclastic rocks east of Timonium Creek on a delightful autumn day in 1985. Russ Evarts made valuable comments during a field trip in 1992. Mike Korosec kindly provided field maps and chemical analyses that he used in preparing his regional 1:100,000 map (Korosec, 1987). Rick Conrey arranged for several chemical analyses, and Willie Scott commented on several glacial problems in the Cispus drainage. Three programs within the U.S. Geological Survey have supported my research—National

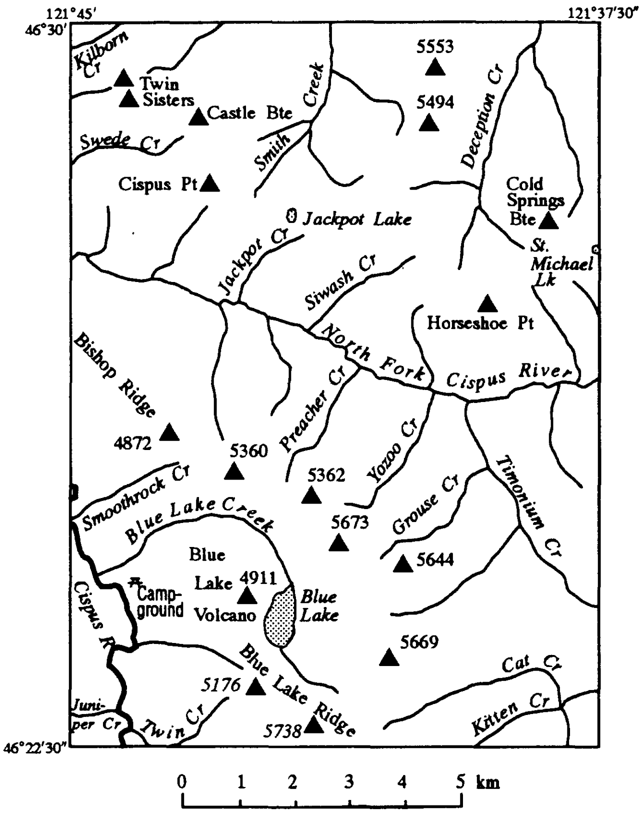

Figure 2. Map of Blue Lake quadrangle showing locations of geographic features mentioned in text.

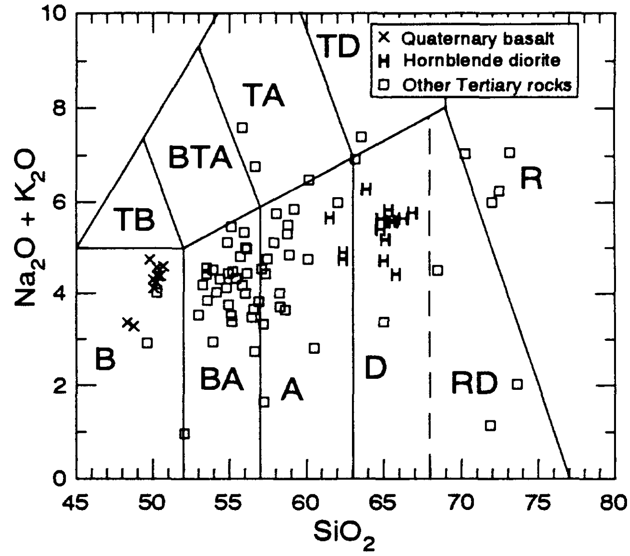

Figure 3. Total alkali-silica classification diagram for chemical analyses from the Blue Lake quadrangle, modified from Le Bas and others (1986) to include field for rhyodacite. B, basalt; BA, basaltic andesite; A, andesite; D, dacite; RD, rhyodacite; R, rhyolite; TB, trachybasalt; BTA, basaltic trachyandesite; TA, trachyandesite; TD, trachydacite. Data from table 1. Extreme values of alkalies represent altered rocks either enriched or depleted in Na_2O. Hornblende diorite includes all samples in intrusive suite of Kidd Creek.

Cooperative Geologic Mapping (the principal sponsor), National Earthquake Hazards Reduction, and most recently Deep Crustal Studies. Dick Moore and Willie Scott reviewed and improved the map and text.

ROCK TERMINOLOGY AND CHEMICAL CLASSIFICATION

I followed the classification scheme used in my previous open-file reports—the IUGS system (Le Bas and others, 1986) modified to include a field for rhyodacite (fig. 3). For the total alkali contents found, the analyzed rocks are grouped under six names: *basalt* (<52 per cent SiO_2), *basaltic andesite* (52–57 per cent SiO_2), *andesite* (57–63 per cent SiO_2), *dacite* (63–68 per cent SiO_2), *rhyodacite* (generally between 68 and about 72 percent SiO_2; fig. 3), and *rhyolite* (generally greater than about 72 percent SiO_2; fig. 3). These samples have rather consistent phenocryst assemblages (fig. 4) (minerals listed in most common order of decreasing abundance): *basalt*, ol ± pl ± cpx ± rare opx; *basaltic andesite*, pl ± cpx ± opx ± ol; *andesite*, pl ± cpx ± opx ± rare ol ± hb; *dacite*, assemblage similar to that for andesite (except for rare quartz and no olivine), but orthopyroxene is less common, and the groundmass commonly displays snowflake texture owing to high-temperature devitrification; *rhyodacite* and *rhyolite*, generally almost aphyric with pl>cpx and no quartz. Hornblende occurs only in the intrusive suite of Kidd Creek, the composition of which is silicic andesite and dacite (Marso and Swanson, 1992), although the sample with the highest SiO_2 content (Swanson, 1989, table 1, map no. 61) has a trace-element pattern unlike other samples of the Kidd Creek suite (J.N. Marso, written commun., 1989). Samples plotting in the trachyandesite and trachydacite fields of figure 3 are probably enriched in alkalies through alteration and are called andesite and dacite in the text.

From figure 4, samples with thin sections but no chemical analyses can be classified by their phenocryst assemblages and groundmass textures. In all, 96 samples from the Blue Lake quadrangle were sectioned (fig. 5); of these, 60 samples were chemically analyzed (table 1). In addition, table 1 includes eight chemical analyses previously published by Korosec (1987) and 12 analyses

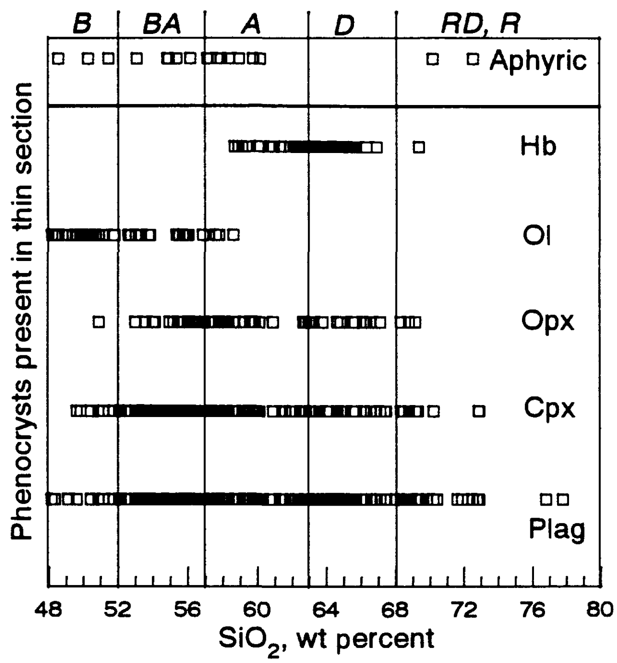

Figure. 4. Plot of phenocryst assemblage vs. SiO_2 for 314 porphyritic and 18 non-porphyritic Tertiary rocks, chiefly in the five mapped quadrangles but including several in the East Canyon Ridge quadrangle and a few in other quadrangles. □, phenocryst observed in thin section; Hb, hornblende; Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Plag, plagioclase. Rock types along top edge from figure 3. Corrected from less complete version in Swanson (1992).

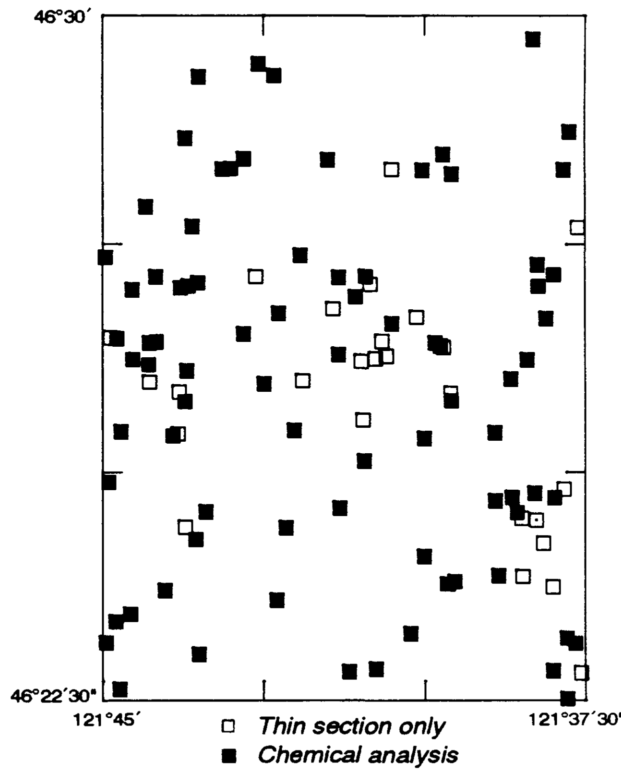

Figure 5. Map showing distribution of 96 sample localities in Blue Lake quadrangle, including localities for samples collected by Korosec (1987) and Stine (1987) and listed in table 1.

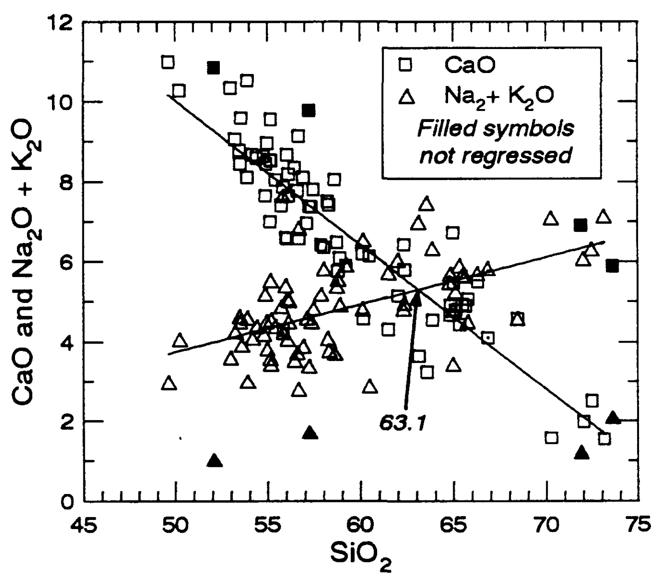

Figure 6. Plots of CaO and (Na_2O + K_2O) vs. SiO_2 for all analyzed Tertiary rocks in Blue Lake quadrangle. Linear regressions of both plots cross at SiO_2 content of 63.1, indicating slightly calcic suite in terminology of Peacock (1931).

in Stine (1987). These additional analyses, as well as the six indicated analyses in table 1, were done in the XRF laboratory of the Geology Department at Washington State University.

The Tertiary suite is calcic (Peacock, 1931). Its alkali-lime index is about 63 (fig. 6), slightly higher than that of 62.3–62.6 in the previously mapped quadrangles (Swanson, 1989, 1991, 1992); I place no significance on this observation.

Most of the analyzed Tertiary rocks, except those of the hornblende-bearing intrusive suite of Kidd Creek (H in figure 7), are tholeiitic on a plot of FeO*/MgO vs. SiO_2, according to the classification of Miyashiro (1974). This pattern resembles that in the adjacent quadrangles. The two analyses of the basalt of Spring Creek (a low-K basalt; table 1, nos. 1 and 2) are tholeiitic, whereas all eight analyses of the relatively high-K basalt of Juniper Creek and Blue Lake Creek are marginally calc-alkaline.

Most of the analyses are subalkaline on a plot of total alkalis vs. SiO_2 (fig. 8; Macdonald and Katsura, 1964; Irvine and Baragar, 1971). The basalt of Juniper Creek and of Blue Lake Creek are slightly alkalic in the usage of Macdonald and Katsura (1964).

A plot of K_2O vs. SiO_2 (fig. 9) shows that most samples with SiO_2 between 52 and 63 percent are medium-K

Table 1. Chemical analyses from the Blue Lake Quadrangle, arranged in order of increasing SiO_2

Map No.	Map Unit	Field No.	Original Analysis SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+	H_2O^-	CO_2	Total
1	Qbs[1]	91-083															
2	Qbs	89-111	48.7	1.29	17.2	3.49	6.94	0.18	7.73	11.30	3.02	0.25	0.16	0.12	0.17	0.03	100.58
3	Tg	91-004	47.4	0.87	20.0	2.46	6.64	0.16	4.87	10.50	2.43	0.36	0.11	1.23	0.62	0.00	97.65
4	Qbbl[1]	87-188															
5	Qbj[1]	91-059															
6	Qbj	91-091	49.7	1.26	16.6	2.39	6.44	0.15	8.39	10.10	2.91	1.17	0.41	0.37	0.21	0.00	100.10
7	Qbbl	91-093	49.8	1.30	16.3	2.55	6.36	0.16	8.85	9.50	2.95	1.26	0.41	0.11	0.14	0.00	99.69
8	Tg	91-069	48.2	0.96	18.5	2.86	7.15	0.18	4.57	9.86	3.40	0.45	0.11	3.06	0.55	0.00	99.85
9	Qbbl[1]	87-190															
10	Qbbl[2]	87-189	49.6	1.32	16.2	4.32	4.68	0.15	8.40	9.70	3.10	1.22	0.38	0.11	0.14	0.01	99.33
10	Qbbl[1]	87-189															
11	Qbbl[1]	91-065															
12	Tg	MK98420	50.8	1.00	20.5	4.39	5.03	0.16	4.45	10.58	0.54	0.41	0.15				97.97
13	Ta	91-051	52.3	1.25	17.3	3.56	5.72	0.17	4.86	10.20	2.94	0.55	0.18	0.43	0.31	0.00	99.77
14	Ta	89-067	52.0	1.78	15.9	4.46	6.34	0.21	4.23	8.84	3.46	0.63	0.24	1.01	0.59	0.01	99.70
15	Taiw	91-019	51.5	1.44	19.5	2.70	5.66	0.14	2.51	8.46	3.71	0.68	0.24	2.14	0.68	0.00	99.36
16	Ta	91-045	51.7	1.63	16.4	4.06	6.34	0.18	3.99	8.16	3.45	0.83	0.25	2.03	0.79	0.00	99.81
17	Taiw	91-014	51.8	1.37	19.7	3.33	4.60	0.13	2.82	9.27	3.16	0.56	0.22	1.05	1.68	0.00	99.69
18	Taiw	91-002	52.8	1.24	17.0	3.00	5.88	0.15	4.77	10.30	2.64	0.24	0.20	1.21	0.52	0.00	99.95
19	Ta	MK98411	53.7	1.28	16.8	4.61	5.28	0.16	5.46	8.08	3.50	1.01	0.18				100.05
20	Tai	91-064	52.7	1.68	16.0	5.14	5.90	0.20	3.55	8.43	3.27	0.65	0.24	1.02	0.93	0.00	99.71
21	Taiw	91-018	52.8	1.59	18.9	5.92	3.09	0.14	2.40	8.33	3.50	0.69	0.27	1.90	0.49	0.04	100.06
22	Tai	91-073	53.7	1.68	16.0	3.26	6.70	0.16	4.09	8.46	3.33	0.72	0.23	0.74	0.66	0.26	99.99
23	Tai	91-046	52.8	1.43	17.5	3.39	5.84	0.16	2.86	7.35	3.94	0.99	0.29	2.55	0.67	0.00	99.77
24	Taim	85-083	53.1	1.23	16.4	3.68	5.11	0.14	4.69	8.16	3.30	0.99	0.23	2.11	0.56	0.10	99.80
25	Taim	91-055	53.5	1.35	16.4	3.98	5.08	0.15	4.63	8.72	3.29	0.37	0.23	0.90	1.54	0.00	100.14
26	Tdi	91-031	53.2	1.29	15.9	3.73	5.63	0.17	5.09	8.24	2.99	0.41	0.19	2.20	1.25	0.00	100.29
27	Ta	91-052	53.7	1.80	15.7	4.98	5.60	0.17	3.50	6.82	4.78	0.54	0.26	1.40	0.49	0.00	99.74
28	Ta	91-013	53.5	1.26	17.1	3.40	5.09	0.16	4.03	9.26	2.99	0.29	0.22	1.70	0.79	0.00	99.79
29	Ta	91-054	54.0	1.32	17.7	4.13	4.22	0.16	3.64	8.34	3.69	0.70	0.33	0.67	1.06	0.00	99.96
30	Tdi	91-070	54.1	1.22	16.5	2.24	5.94	0.14	5.39	7.85	3.52	0.70	0.20	1.34	0.80	0.12	100.06
31	Tai	91-037	54.7	1.56	16.2	4.36	5.80	0.18	3.46	7.27	3.84	0.88	0.32	0.93	0.40	0.00	99.90
32	Tai	91-043	53.6	1.40	18.0	3.33	5.46	0.15	2.77	4.13	5.46	1.82	0.21	2.43	0.79	0.00	99.55
33	Ta	91-038	54.5	1.82	16.7	3.81	6.20	0.18	2.70	7.68	3.33	0.75	0.30	1.11	0.70	0.00	99.78
34	Tai	91-080	53.6	1.54	16.9	4.09	4.68	0.15	3.49	6.32	4.15	0.96	0.29	2.22	0.80	0.18	99.37
35	Ta	91-008	54.1	1.80	15.2	5.21	5.66	0.18	3.39	6.34	3.79	1.04	0.31	1.89	0.47	0.25	99.63
36	Ta	91-021	54.8	1.16	16.9	2.66	5.85	0.16	3.87	8.47	2.90	1.01	0.22	4.23	0.69	0.20	103.12
37	Ta	91-053	54.9	1.35	16.5	4.87	4.41	0.14	3.57	8.01	3.60	0.74	0.19	0.80	0.74	0.00	99.82
38	Ta	91-050	55.0	1.37	15.9	4.40	5.04	0.15	3.90	7.49	3.80	1.07	0.27	0.92	0.36	0.00	99.67
39	Ta	MK10844	56.2	1.44	16.4	4.42	5.07	0.16	4.17	8.31	3.16	0.30	0.31				99.97
40	Ta	MK98422	56.4	1.22	16.9	4.24	4.86	0.14	4.65	7.74	2.99	0.66	0.22				100.05
41	Ta	WW-8	56.1	1.32	17.0	9.38		0.15	4.09	9.04	2.27	0.44	0.19				99.88
42	Ta	91-088	55.1	1.01	19.8	3.23	2.58	0.14	2.44	6.39	5.65	0.93	0.24	1.21	0.97	0.00	99.69
43	Ta	NR-11	56.3	1.54	17.0	9.71		0.14	3.21	8.02	2.79	0.99	0.22				99.86
44	Ta	91-048	55.8	1.73	15.1	4.02	6.64	0.19	3.14	6.79	3.66	0.77	0.25	1.03	0.70	0.00	99.82
45	Ta	CS-11	56.6	1.29	16.6	9.72		0.14	4.73	7.30	2.37	0.92	0.21				99.89
46	Ta[3]	91-062	47.3	1.22	14.4	0.48	6.70	0.15	2.52	8.07	0.62	0.75	0.45	4.13	0.97	12.50	100.26
47	Ta	91-085	55.8	1.61	15.8	3.48	5.96	0.15	3.00	7.17	3.34	0.97	0.33	1.03	0.62	0.13	99.39
48	Ta	91-086	55.5	0.96	17.6	3.82	3.32	0.12	3.22	7.54	3.25	1.35	0.27	1.73	0.65	0.00	99.33
49	Ta	91-087	56.3	1.68	15.6	4.43	5.55	0.19	2.46	6.24	4.25	0.73	0.27	0.79	0.88	0.22	99.59
50	Tais	89-029	56.0	1.56	15.9	3.41	4.93	0.18	2.90	6.13	4.78	0.77	0.25	1.92	0.68	0.04	99.45
51	Ta	TC-4	57.6	1.57	15.8	10.33		0.16	2.77	7.41	2.86	1.11	0.26				99.86
52	Qls(Ta)[5]	MK98416	58.1	1.32	17.6	4.20	4.81	0.14	2.55	7.39	3.10	0.60	0.24				100.02
53	Ta	MK98410	58.4	1.23	16.0	3.97	4.55	0.15	3.81	8.02	2.74	0.89	0.22				99.98
54	Ta	91-074	57.4	1.45	16.3	3.76	4.92	0.15	2.24	6.33	3.95	1.24	0.33	1.25	0.36	0.00	99.68
55	Tais	89-031	56.7	1.64	15.9	4.18	4.11	0.19	2.99	5.55	4.42	0.88	0.26	1.98	0.76	0.07	99.63
56	Tai	91-044	54.9	0.99	14.0	8.68	3.35	0.27	1.22	5.66	3.57	0.95	0.45	1.68	4.38	0.00	100.10
57	Tai	85-085	57.3	1.22	16.1	2.39	5.54	0.13	2.63	5.69	4.06	1.59	0.30	1.39	0.34	0.11	98.79
58	Ta	91-071	55.9	0.95	17.0	1.52	4.30	0.10	2.94	5.75	3.59	0.83	0.25	5.49	0.93	0.23	99.78

Map No.	Map Unit	Field No.	Recalculated H_2O- and CO_2-free to 100 percent, with iron as FeO SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Na_2O+ K_2O	FeO*/ MgO	Longitude Deg	Longitude Min	Latitude Deg	Latitude Min
1	Qbs[1]	91-083	48.34	1.44	17.16	10.98	0.18	7.75	10.32	3.17	0.19	0.13	3.36	1.42	121	43.93	46	24.56
2	Qbs	89-111	48.74	1.29	17.22	10.09	0.18	7.74	11.31	3.02	0.25	0.16	3.27	1.30	121	44.50	46	22.82
3	Tg	91-004	49.61	0.91	20.93	9.27	0.17	5.10	10.99	2.54	0.38	0.12	2.92	1.82	121	42.00	46	26.63
4	Qbbl[1]	87-188	49.78	1.39	15.74	8.66	0.15	9.61	9.48	3.30	1.45	0.45	4.75	0.90	121	43.60	46	24.69
5	Qbj[1]	91-059	50.01	1.25	16.31	8.77	0.15	8.83	10.01	3.13	1.18	0.36	4.31	0.99	121	44.71	46	22.52
6	Qbj	91-091	50.06	1.27	16.72	8.65	0.15	8.45	10.17	2.93	1.18	0.41	4.11	1.02	121	44.72	46	23.18
7	Qbbl	91-093	50.21	1.31	16.43	8.73	0.16	8.92	9.58	2.97	1.27	0.41	4.24	0.98	121	43.65	46	23.87
8	Tg	91-069	50.23	1.00	19.28	10.13	0.19	4.76	10.28	3.54	0.47	0.11	4.01	2.13	121	38.47	46	23.70
9	Qbbl[1]	87-190	50.24	1.30	16.37	8.53	0.15	8.74	9.73	3.29	1.27	0.38	4.56	0.98	121	42.97	46	23.80
10	Qbbl[2]	87-189	50.28	1.34	16.42	8.69	0.15	8.52	9.83	3.14	1.24	0.39	4.38	1.02	121	42.49	46	24.08
10	Qbbl[1]	87-189	50.47	1.28	16.53	8.08	0.15	8.87	9.84	3.13	1.26	0.40	4.39	0.91	121	42.49	46	24.08
11	Qbbl[1]	91-065	50.69	1.31	16.31	8.43	0.15	8.86	9.57	3.35	1.25	0.38	4.60	0.95	121	42.87	46	23.78
12	Tg	MK98420	52.09	1.03	20.98	9.21	0.16	4.56	10.85	0.55	0.42	0.15	0.97	2.02	121	40.24	46	26.74
13	Ta	91-051	53.00	1.27	17.53	9.04	0.17	4.93	10.34	2.98	0.56	0.18	3.54	1.84	121	39.00	46	29.34
14	Ta	89-067	53.25	1.82	16.28	10.60	0.22	4.33	9.05	3.54	0.65	0.25	4.19	2.45	121	44.85	46	23.12
15	Taiw	91-019	53.50	1.50	20.26	8.40	0.15	2.61	8.79	3.85	0.71	0.25	4.56	3.22	121	40.58	46	27.38
16	Ta	91-045	53.53	1.69	16.98	10.35	0.19	4.13	8.45	3.57	0.86	0.26	4.43	2.50	121	41.01	46	28.43
17	Taiw	91-014	53.61	1.42	20.39	7.86	0.13	2.92	9.59	3.27	0.58	0.23	3.85	2.69	121	41.60	46	27.15
18	Taiw	91-002	53.92	1.27	17.36	8.76	0.15	4.87	10.52	2.70	0.25	0.20	2.94	1.80	121	41.44	46	26.92
19	Ta	MK98411	53.92	1.29	16.86	9.47	0.16	5.48	8.11	3.51	1.01	0.18	4.53	1.73	121	40.00	46	25.98
20	Tai	91-064	54.19	1.73	16.45	10.82	0.21	3.65	8.67	3.36	0.67	0.25	4.03	2.97	121	42.29	46	23.23
21	Taiw	91-018	54.41	1.64	19.48	8.67	0.14	2.47	8.58	3.61	0.71	0.28	4.32	3.51	121	41.18	46	27.13
22	Tai	91-073	54.79	1.71	16.33	9.83	0.16	4.17	8.63	3.40	0.73	0.23	4.13	2.36	121	37.78	46	25.44
23	Tai	91-046	54.88	1.49	18.19	9.24	0.17	2.97	7.64	4.10	1.03	0.30	5.12	3.11	121	38.90	46	27.70
24	Taim	85-083	54.93	1.27	16.97	8.71	0.14	4.85	8.44	3.41	1.02	0.24	4.44	1.80	121	37.96	46	27.00
25	Taim	91-055	54.98	1.39	16.85	8.90	0.15	4.76	8.96	3.38	0.38	0.24	3.76	1.87	121	37.54	46	27.36
26	Tdi	91-031	55.15	1.34	16.48	9.32	0.18	5.28	8.54	3.10	0.43	0.20	3.52	1.77	121	38.33	46	27.14
27	Ta	91-052	55.16	1.85	16.13	10.36	0.17	3.60	7.01	4.91	0.55	0.27	5.46	2.88	121	38.72	46	27.02
28	Ta	91-013	55.18	1.30	17.64	8.41	0.17	4.16	9.55	3.08	0.30	0.23	3.38	2.02	121	38.82	46	26.12
29	Ta	91-054	55.21	1.35	18.10	8.11	0.16	3.72	8.53	3.77	0.72	0.34	4.49	2.18	121	38.99	46	27.08
30	Tdi	91-070	55.44	1.25	16.91	8.15	0.14	5.52	8.05	3.61	0.72	0.20	4.32	1.48	121	37.93	46	23.44
31	Tai	91-037	55.74	1.59	16.51	9.91	0.18	3.53	7.41	3.91	0.90	0.33	4.81	2.81	121	41.19	46	24.61
32	Tai	91-043	55.84	1.46	18.75	8.81	0.16	2.89	4.30	5.69	1.90	0.22	7.58	3.05	121	39.93	46	29.48
33	Ta	91-038	55.85	1.86	17.11	9.87	0.18	2.77	7.87	3.41	0.77	0.31	4.18	3.57	121	42.50	46	25.37
34	Tai	91-080	55.97	1.61	17.65	8.73	0.16	3.64	6.60	4.33	1.00	0.30	5.34	2.40	121	41.75	46	22.84
35	Ta	91-008	56.06	1.87	15.75	10.72	0.19	3.51	6.57	3.93	1.08	0.32	5.01	3.05	121	42.75	46	26.38
36	Ta	91-021	56.07	1.19	17.29	8.44	0.16	3.96	8.67	2.97	1.03	0.23	4.00	2.13	121	38.23	46	26.42
37	Ta	91-053	56.14	1.38	16.87	8.99	0.14	3.65	8.19	3.68	0.76	0.19	4.44	2.46	121	38.84	46	27.04
38	Ta	91-050	56.15	1.40	16.23	9.19	0.15	3.98	7.65	3.88	1.09	0.28	4.97	2.31	121	39.70	46	28.44
39	Ta	MK10844	56.47	1.45	16.51	9.09	0.16	4.19	8.35	3.17	0.30	0.31	3.48	2.17	121	42.47	46	28.32
40	Ta	MK98422	56.61	1.22	16.99	8.71	0.14	4.67	7.77	3.00	0.66	0.22	3.66	1.87	121	44.39	46	26.68
41	Ta	WW-8	56.65	1.33	17.13	8.53	0.15	4.13	9.14	2.29	0.44	0.19	2.74	2.06	121	38.21	46	26.19
42	Ta	91-088	56.69	1.04	20.37	5.65	0.14	2.51	6.57	5.81	0.96	0.25	6.77	2.25	121	42.79	46	28.50
43	Ta	NR-11	56.92	1.56	17.14	8.84	0.14	3.25	8.11	2.82	1.00	0.22	3.82	2.72	121	37.72	46	26.47
44	Ta	91-048	57.12	1.77	15.46	10.50	0.19	3.21	6.95	3.75	0.79	0.26	4.53	3.27	121	39.37	46	28.33
45	Ta	CS-11	57.24	1.30	16.77	8.84	0.14	4.78	7.38	2.40	0.93	0.21	3.33	1.85	121	38.79	46	25.78
46	Ta[3]	91-062	57.26	1.48	17.43	8.63	0.18	3.05	9.77	0.75	0.91	0.54	1.66	2.83	121	44.20	46	24.77
47	Ta	91-085	57.37	1.66	16.24	9.35	0.15	3.08	7.37	3.43	1.00	0.34	4.43	3.03	121	43.59	46	25.43
48	Ta	91-086	57.47	0.99	18.23	7.00	0.12	3.33	7.81	3.37	1.40	0.28	4.76	2.10	121	44.19	46	29.74
49	Ta	91-087	57.89	1.73	16.04	9.81	0.20	2.53	6.42	4.37	0.75	0.28	5.12	3.88	121	42.92	46	28.28
50	Tais	89-029	58.05	1.62	16.48	8.29	0.19	3.01	6.35	4.95	0.80	0.26	5.75	2.76	121	44.76	46	28.74
51	Ta	TC-4	58.25	1.59	16.01	9.41	0.16	2.80	7.50	2.89	1.12	0.26	4.02	3.36	121	38.95	46	24.26
52	Qls(Ta)[5]	MK98416	58.33	1.33	17.64	8.62	0.14	2.56	7.42	3.11	0.60	0.24	3.71	3.37	121	44.52	46	27.17
53	Ta	MK98410	58.64	1.24	16.07	8.16	0.15	3.83	8.05	2.75	0.89	0.22	3.65	2.13	121	38.60	46	25.40
54	Ta	91-074	58.75	1.48	16.68	8.50	0.15	2.29	6.48	4.04	1.27	0.34	5.31	3.71	121	39.11	46	24.57
55	Tais	89-031	58.82	1.70	16.49	8.17	0.20	3.10	5.76	4.58	0.91	0.27	5.50	2.63	121	44.67	46	28.32
56	Tai	91-044	58.92	1.06	15.03	11.98	0.29	1.31	6.07	3.83	1.02	0.48	4.85	9.15	121	40.17	46	29.35
57	Tai	85-085	59.25	1.26	16.65	7.95	0.13	2.72	5.88	4.20	1.64	0.31	5.84	2.92	121	38.79	46	28.67
58	Ta	91-071	60.12	1.02	18.28	6.10	0.11	3.16	6.18	3.86	0.89	0.27	4.75	1.93	121	37.55	46	23.12

Table 1. Chemical analyses from the Blue Lake Quadrangle, arranged in order of increasing SiO_2 (cont.)

Original Analysis

Map No.	Map Unit	Field No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+	H_2O^-	CO_2	Total
59	Ta	91-049	58.4	1.46	16.2	4.59	3.45	0.19	2.22	4.43	4.96	1.33	0.30	1.65	0.42	0.00	99.60
60	Ta	WW-7	59.8	1.29	15.7	10.49		0.12	3.38	6.06	2.55	0.24	0.22				99.88
61	Thdy	91-035	57.4	0.78	15.2	2.98	2.09	0.09	5.43	4.03	4.08	1.20	0.32	2.77	2.02	1.48	99.87
62	Ta	91-072	60.5	1.20	14.9	2.86	4.96	0.18	2.08	5.01	4.39	1.44	0.30	1.26	0.43	0.18	99.69
63	Thd	91-063	58.8	0.84	16.3	2.35	2.94	0.10	2.46	6.06	3.26	1.22	0.21	2.18	0.66	2.32	99.70
64	Thd	91-009	60.4	0.72	17.6	5.49		0.09	2.50	5.60	3.78	0.96	0.22	1.83	0.51	0.23	99.93
65	Ta	91-039	61.5	1.20	15.1	3.65	3.81	0.16	1.60	3.55	5.67	1.07	0.45	1.23	0.60	0.00	99.59
66	Ta	91-030	61.9	1.37	14.0	3.95	4.08	0.15	1.56	3.16	4.85	2.36	0.39	1.32	0.38	0.00	99.47
67	Thd	91-028	61.5	0.63	16.4	3.28	1.51	0.08	2.63	4.37	4.53	1.50	0.17	1.96	1.12	0.36	100.04
68	Thdr	89-032	62.8	0.74	16.2	2.18	2.62	0.07	2.56	4.53	4.21	1.03	0.20	1.99	0.54	0.00	99.67
69	Thdp	91-040	63.1	0.60	16.2	2.71	1.78	0.05	2.27	4.73	4.34	1.11	0.18	1.48	0.93	0.00	99.48
70	Ttv?	NR-5A	64.5	1.20	14.7	7.11		0.12	2.04	6.68	3.10	0.26	0.19				99.90
71	Thd?	91-041	61.3	0.60	16.5	1.87	2.51	0.09	1.82	5.15	3.84	0.62	0.18	2.38	0.94	2.14	99.94
72	Qls(Thd)[5]	MK98417	65.0	0.77	16.4	2.51	2.88	0.09	2.30	4.78	3.66	1.51	0.17				100.07
73	Thdy	91-005	63.6	0.61	16.6	2.47	2.10	0.09	1.90	4.84	4.24	1.16	0.19	1.44	0.52	0.00	96.76
74	Thdy	91-036	63.5	0.64	16.5	2.86	1.78	0.10	1.97	4.30	4.26	1.40	0.18	1.43	0.56	0.78	100.26
75	Thd	91-068	62.9	0.62	16.1	2.06	2.37	0.08	1.87	4.73	3.88	1.49	0.17	1.40	0.45	1.86	99.98
76	Thdy	91-033	64.3	0.58	16.4	2.70	1.64	0.06	2.13	4.79	4.20	1.25	0.17	1.07	0.80	0.00	100.09
77	Thd	MK98432	65.6	0.70	16.9	2.41	2.77	0.08	1.84	5.05	3.42	1.00	0.17				99.97
78	Thd	91-081	63.0	0.58	15.6	2.16	1.92	0.08	1.15	5.23	4.00	1.36	0.17	1.43	0.79	2.09	99.56
79	Thd	91-082	64.7	0.55	16.1	1.84	2.22	0.06	1.76	3.97	4.43	1.15	0.16	1.68	0.64	0.06	99.32
80	Ttv[4]	HBL3	68.2	1.21	14.2	5.27		0.14	1.49	4.56	3.76	0.74	0.61				100.13
80	Ttv[4]	HBL1	69.7	0.71	14.3	5.41		0.13	0.76	1.56	4.19	2.79	0.17				99.75
80	Ttv[4]	HB22A	71.1	0.43	14.5	4.32		0.09	0.86	6.83	0.61	0.53	0.01				99.30
80	Ttv[4]	HBL2	72.3	0.71	13.9	5.41		0.08	0.39	1.98	5.48	0.54	0.15				100.86
80	Ttv[4]	HBL4	72.2	0.77	14.1	3.14		0.06	0.76	2.49	3.31	2.91	0.19				99.87
80	Ttv[4]	HBL5	72.7	0.61	13.3	4.32		0.04	0.14	1.53	4.00	3.03	0.14				99.81
81	Ttv	91-047	64.9	0.30	12.8	1.19	1.65	0.06	0.35	5.19	1.11	0.68	0.06	7.94	3.56	0.38	100.17

Recalculated H_2O- and CO_2-free to 100 percent, with iron as FeO

Map No.	Map Unit	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Na_2O+ K_2O	FeO*/ MgO	Longitude Deg	Longitude Min	Latitude Deg	Latitude Min
59	Ta	60.16	1.50	16.69	7.81	0.20	2.29	4.56	5.11	1.37	0.31	6.48	3.41	121	39.50	46	28.34
60	Ta	60.50	1.31	15.93	9.55	0.12	3.42	6.13	2.58	0.24	0.22	2.82	2.79	121	37.97	46	26.24
61	Thdy	61.52	0.84	16.29	5.11	0.10	5.82	4.32	4.37	1.29	0.34	5.66	0.88	121	42.92	46	25.79
62	Ta	62.03	1.23	15.28	7.72	0.18	2.13	5.14	4.50	1.48	0.31	5.98	3.62	121	37.70	46	23.36
63	Thd	62.35	0.89	17.28	5.36	0.11	2.61	6.43	3.46	1.29	0.22	4.75	2.05	121	43.86	46	24.72
64	Thd	62.39	0.74	18.18	5.10	0.09	2.58	5.78	3.90	0.99	0.23	4.90	1.98	121	42.67	46	26.42
65	Ta	63.14	1.23	15.50	7.28	0.16	1.64	3.64	5.82	1.10	0.46	6.92	4.43	121	43.84	46	26.03
66	Ta	63.57	1.41	14.38	7.84	0.15	1.60	3.25	4.98	2.42	0.40	7.40	4.89	121	39.70	46	26.52
67	Thd	63.88	0.65	17.04	4.63	0.08	2.73	4.54	4.71	1.56	0.18	6.26	1.70	121	44.26	46	27.27
68	Thdr	64.79	0.76	16.71	4.73	0.07	2.64	4.67	4.34	1.06	0.21	5.41	1.79	121	44.10	46	26.24
69	Thdp	64.84	0.62	16.74	4.36	0.05	2.35	4.89	4.48	1.15	0.19	5.63	1.86	121	40.35	46	24.39
70	Ttv?	64.99	1.21	14.86	6.45	0.12	2.06	6.73	3.13	0.26	0.19	3.39	3.14	121	38.34	46	26.44
71	Thd?	65.01	0.64	17.50	4.45	0.10	1.93	5.46	4.07	0.66	0.19	4.73	2.30	121	39.00	46	23.00
72	Qls(Thd)[5]	65.12	0.77	16.43	5.15	0.09	2.30	4.79	3.67	1.51	0.17	5.18	2.23	121	44.27	46	27.04
73	Thdy	65.20	0.63	17.02	4.43	0.09	1.95	4.96	4.35	1.19	0.19	5.54	2.28	121	41.17	46	26.29
74	Thdy	65.33	0.66	16.97	4.48	0.10	2.03	4.42	4.38	1.44	0.19	5.82	2.21	121	41.57	46	25.12
75	Thd	65.48	0.65	16.76	4.40	0.08	1.95	4.92	4.04	1.55	0.18	5.59	2.26	121	40.21	46	23.60
76	Thdy	65.65	0.59	16.74	4.16	0.06	2.17	4.89	4.29	1.28	0.17	5.56	1.91	121	40.49	46	25.46
77	Thd	65.78	0.70	16.98	4.95	0.08	1.84	5.06	3.43	1.00	0.17	4.43	2.68	121	44.52	46	24.72
78	Thd	66.29	0.61	16.42	4.07	0.08	1.21	5.50	4.21	1.43	0.18	5.64	3.36	121	41.34	46	22.81
79	Thd	66.87	0.57	16.64	4.01	0.06	1.82	4.10	4.58	1.19	0.17	5.77	2.20	121	37.76	46	22.62
80	Ttv[4]	68.46	1.21	14.22	4.76	0.14	1.50	4.58	3.77	0.74	0.61	4.52	3.18	121	37.58	46	24.89
80	Ttv[4]	70.28	0.72	14.42	4.91	0.13	0.77	1.57	4.22	2.81	0.17	7.04	6.41	121	37.58	46	24.89
80	Ttv[4]	71.90	0.43	14.70	3.93	0.09	0.87	6.91	0.62	0.54	0.01	1.15	4.52	121	37.58	46	24.89
80	Ttv[4]	72.02	0.71	13.83	4.85	0.08	0.39	1.97	5.46	0.54	0.15	6.00	12.48	121	37.58	46	24.89
80	Ttv[4]	72.47	0.77	14.15	2.84	0.06	0.76	2.50	3.32	2.92	0.19	6.25	3.72	121	37.58	46	24.89
80	Ttv[4]	73.13	0.61	13.40	3.91	0.04	0.14	1.54	4.03	3.05	0.14	7.07	27.77	121	37.58	46	24.89
81	Ttv	73.61	0.34	14.52	3.09	0.07	0.40	5.89	1.26	0.77	0.07	2.03	7.77	121	38.17	46	27.92

X-ray fluorescence analyses, except those otherwise indicated, done in U.S. Geological Survey laboratory in Denver, Colo. (lab chief, D.F. Siems)

FeO, CO_2, and water done in U.S. Geological Survey laboratory in Menlo Park, Calif. (analysts, N.H. Elsheimer and S.F. Bader)

Analyses for field numbers prefixed by MK given in Korosec (1987) and done at Washington State University using XRF techniques; sample locations transferred from Korosec's field map may be slightly in error

Analyses for field numbers prefixed by WW, NR, CS, TC, or HB given in Stine (1987) and done at Washington State University using XRF techniques; sample locations transferred from Stine's map, augmented by written communication from Stine in 1991 for samples prefixed by HB

[1]Analyses done at Washington State University by R.M. Conrey and Diane Johnson using XRF techniques

[2]Analysis done in U.S. Geological Survey laboratory in Menlo Park, Calif. (XRF analyst, M. Dyslin; FeO, CO_2, and water analyst, J. Consul)

[3]Highly altered sample; thin-section and field appearance most closely resembles that of dacite or rhyolite

[4]Lithic clast in volcanic diamictite (Stine, 1987)

[5]Sample is from landslide block derived from unit in parentheses

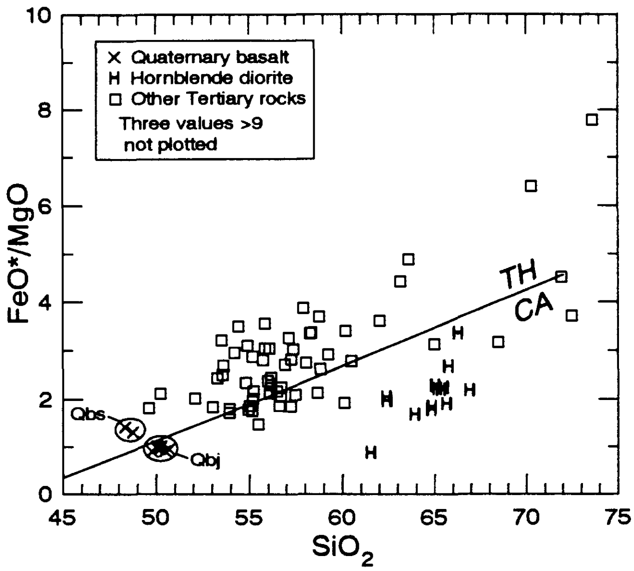

Figure 7. Plot of FeO*/MgO vs. SiO_2 for chemically analyzed rocks from Blue Lake quadrangle. Subdivision into tholeiitic (TH) and calc-alkaline (CA) suites after Miyashiro (1974). Most Tertiary rocks are tholeiitic, but the hornblende diorite in the intrusive suite of Kidd Creek is clearly calc-alkaline. Young basalt lies close to the boundary between the two suites; the basalt of Juniper Creek (Qbj) is slightly calc-alkaline, and the basalt of Spring Creek (Qbs) is tholeiitic (it has both higher FeO* and lower MgO than the Juniper Creek analyses [table 1]). Three altered samples (table 1, no. 56 and two numbered 80) not plotted.

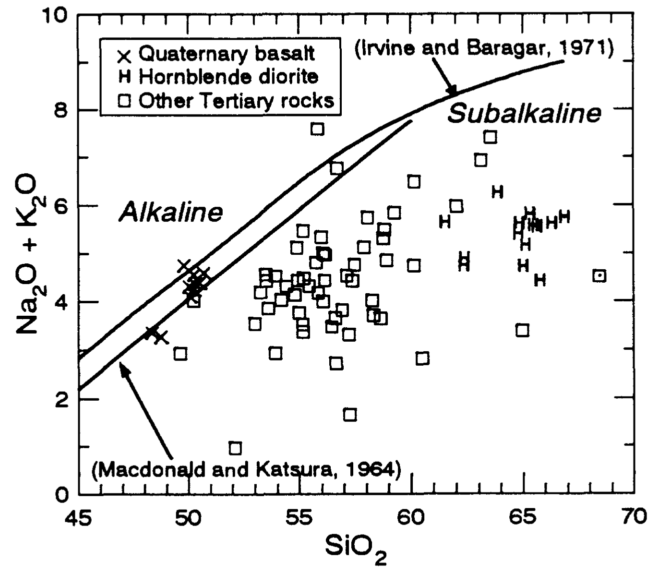

Figure 8. Plot of (Na_2O + K_2O) vs. SiO_2 for rocks in the Blue Lake quadrangle. Boundary shown between subalkaline and alkaline suites after Macdonald and Katsura (1964) and Irvine and Baragar (1971). The basalt of Juniper Creek is marginally alkaline. Tertiary sample in alkaline field (table 1, no. 11) probably enriched in Na_2O during alteration.

mafic and silicic andesite according to Gill (1981; basaltic andesite and andesite, respectively, in the IUGS terminology used here). Nearly all the rest are low-K types. This diagram nicely distinguishes the basalt of Spring Creek (unit Qbs) from the basalt of Juniper Creek and Blue Lake Creek (units Qbj and Qbbl, respectively).

GEOLOGIC OVERVIEW OF QUADRANGLE

Bedded volcaniclastic rocks underlie most of the quadrangle. They range from siltstone to diamictite and are most typically volcanic sandstone and fine-grained conglomerate. The rocks are generally well bedded and display lensing, channeling, and other features indicative of a fluvial environment (Stine, 1987). Lithic-lapilli tuff, pumiceous tuff, and tuff are most common high in the section.

Andesite and basaltic andesite flows, ranging from nonporphyritic to highly plagioclase-phyric, occur throughout the section. Dacite or more silicic flows are uncommon, though clasts in some volcanic diamictites are rhyodacite and rhyolite (table 1, no. 80).

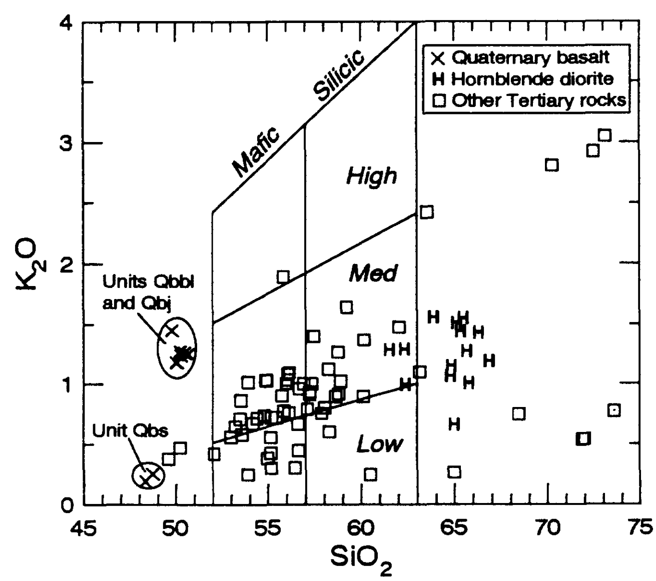

Figure 9. Plot of K_2O vs. SiO_2 for rocks from the Blue Lake quadrangle. Fields modified from Gill (1981), so that mafic andesite (basaltic andesite in IUGS terminology used in this paper) extends down to 52 percent. Values of K_2O greater than 1.9 percent probably reflect relative addition of K_2O during alteration. The Quaternary basalt of Juniper Creek (Qbj) is distinctly different than the Quaternary low-K basalt of Spring Creek (Qbs).

Volcaniclastic rocks dominate the Blue Lake quadrangle to a greater extent than the other mapped quadrangles to the west, which include rocks that are mostly younger than those in the Blue Lake. A measure of this dominance is seen in the number of rock samples collected from the quadrangle (96), which is considerably smaller than those collected from the previously mapped quadrangles (379 samples from the French Butte and Greenhorn Buttes quadrangles, 184 samples from the Tower Rock quadrangle, and 232 samples from the McCoy Peak quadrangle). The reduced number at least in part reflects the dominance of volcaniclastic rocks in the quadrangle; I collect most samples to characterize lava flows and fine-grained intrusive bodies, which are far less common in the Blue Lake quadrangle than in the other mapped quadrangles.

Hammond (1980), Korosec (1987), and Stine (1987) assigned many of the bedded volcaniclastic rocks to the Ohanapecosh Formation, the oldest and thickest of the units that Fiske and others (1963) defined. I believe that correlation is reasonable but am deferring such an assignment until future mapping ties directly into the type section along the White Pass highway.

Irregular but locally sill-like intrusions of andesite, basaltic andesite, and coarser equivalents occur throughout the quadrangle but concentrate north of the North Fork Cispus River. Thin dikes of andesite and basaltic andesite are likewise most common there, where several concentrations (near Castle Butte, on the ridge between Smith and Deception Creeks, and in the Cold Springs Butte-Deception Creek area) suggest proximity to local centers now eroded away (sheet 1; fig. 10).

All layered rocks, and probably the intrusions as well (see below), are folded by the northwest-trending Bishop Ridge anticline and its apparent northwest extension, a west-facing monocline. The anticline is asymmetric, for dips on the northeast limb are markedly shallower than those on the southwest limb (sheet 2, sections C–A′ and D–D′). The anticline is paired with the Pole Patch syncline, the trough of which is 12–13 km farther west in the Greenhorn Buttes quadrangle (fig. 10; Swanson, 1989). Such broad folds typify the southern Washington Cascades.

Sills and associated crosscutting bodies of hornblende diorite, quartz diorite, and dacite intrude the layered section south of the North Fork Cispus River. On chemical and petrographic grounds, these rocks form part of the intrusive suite of Kidd Creek (Marso and Swanson, 1992), which zircon fission-track ages suggest is about 12 Ma (Swanson, 1992).

Quaternary basaltic volcanism in the southwest part of the quadrangle built Blue Lake volcano and probably at least two tephra and hyaloclastic cones near Juniper Creek; all of these vents were partly subglacial. A late Pleistocene flow, the basalt of Spring Creek (Korosec, 1987) follows the Cispus River but was erupted far east of the quadrangle, along the Cascade crest at the north base of Mount Adams (Hammond, 1980; Hildreth and Fierstein, in press).

TERTIARY ROCKS OLDER THAN INTRUSIVE SUITE OF KIDD CREEK

Volcaniclastic rocks—The oldest rocks in the quadrangle are volcanic conglomerate, sandstone, siltstone, and lithic diamictite (map unit Ttv). These rock types are also the most common throughout the section. They consist entirely of clasts either eroded from slightly older Cascade volcanic rocks, reworked from deposits of contemporary eruptions, or produced directly by an eruption (pumice, for example). Clasts range in grain size from silt to gravel but are predominantly coarse sand. Wide ranges in degree of sorting and rounding characterize the deposits; in many places, well-sorted volcanic sandstone is interbedded with poorly sorted rocks including even diamictite with a matrix-supported framework. Beds range in thickness from less than 1 cm to more than 50 cm, averaging a few centimeters. Channels and lensoid beds are especially common, and cross bedding is locally apparent. Woody material, generally poorly preserved, occurs in many beds and along bedding planes. These deposits are best exposed on the slope east of Timonium Creek and in road cuts on the north side of the North Fork Cispus River near the east edge of the quadrangle and in the adjoining Hamilton Buttes quadrangle.

Lithic-lapilli tuff and pumice-lapilli tuff commonly intertongue with other volcaniclastic deposits and dominate the younger part of the section. Many of these rocks were probably emplaced as pyroclastic flows, although some could be debris flows. Welding, if present, clearly identifies the deposit as a pyroclastic flow. However, welding is uncommon, and so assigning an origin to many individual deposits is ambiguous. I have described similar deposits at length in previous open-file reports (Swanson, 1989, 1991, 1992). Owing to good exposure, two beds of possibly welded lithic-lapilli tuff, each several meters thick, can be traced for some distance along the west side of Deception Creek valley; they are not recognizable where exposure worsened. These diamictites are indicated by form lines on the geologic map. Another welded tuff crops out in several small creek beds flanking Jackpot Creek.

Diamictite below Castle Butte—This striking volcaniclastic deposit (unit Tdcb on the geologic map), is very coarse, containing angular clasts several meters in diameter floating in a poorly sorted, finer-grained

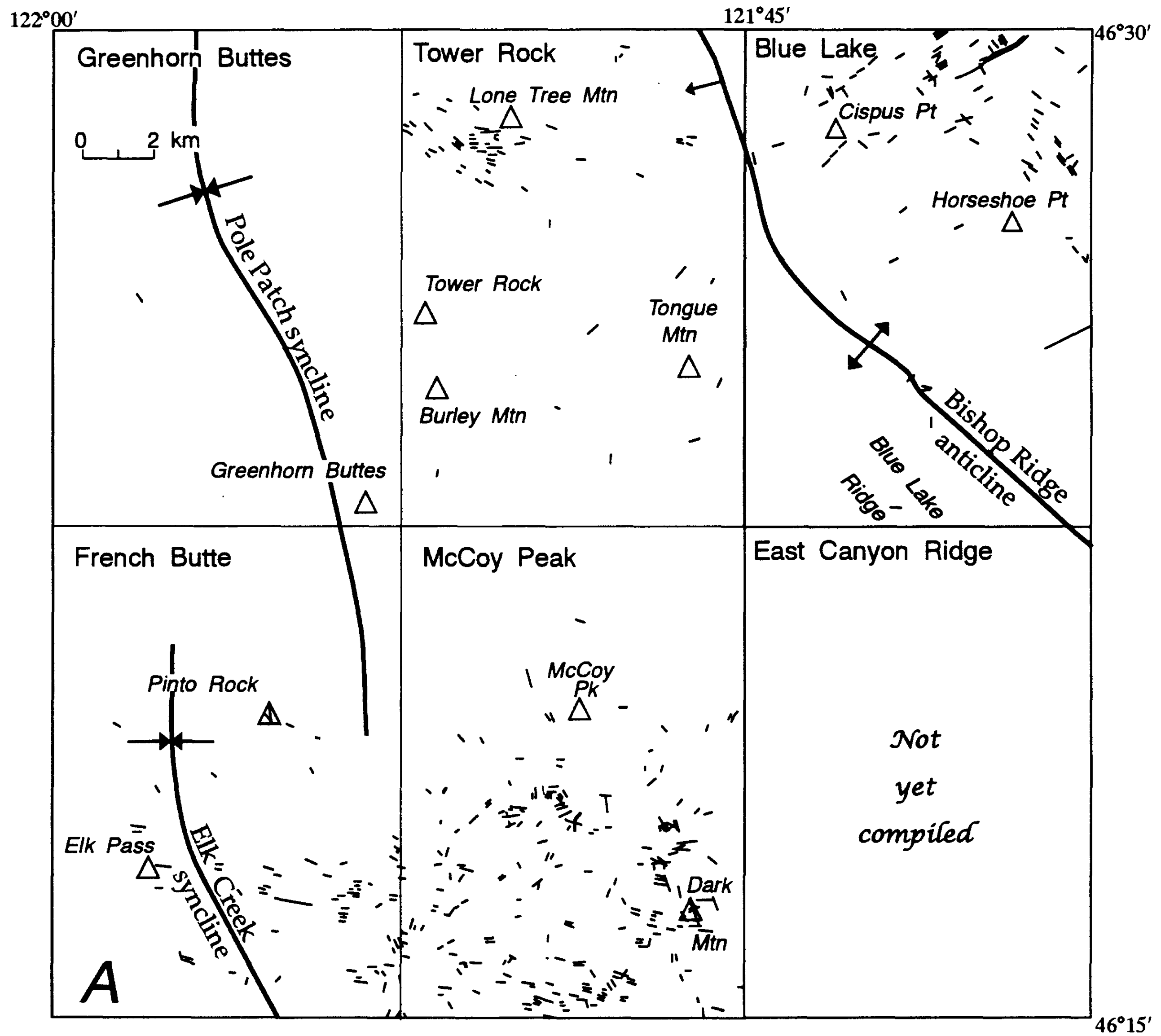

Figure 10. Generalized distribution of about 560 dikes of pyroxene andesite and basaltic andesite in quadrangles mapped to date. Only those dikes are shown for which strike could be measured. Larger intrusions, even those consisting of multiple dikelike intrusions, are not plotted. Note dike-poor area in middle of mapped area. Axial traces of major folds also shown.

matrix. The unit is more than 120 m thick in many places, but thins westward and as a result is no longer recognizable as a mappable unit in the adjoining Tower Rock quadrangle. The diamictite may be more than 200 m thick along the inaccessible east-facing cliff 1 km north-northeast of the northern peak at Twin Sisters. At least locally the base of the diamictite appears gradational with the underlying basaltic andesite flow; a good place to see this relation is at the top of the high cliff at 1,490 m (4,900 ft) elevation on the east side of Kilborn Creek basin (sample site of analysis no. 48 in table 1). However, the diamictite contains a varied assemblage of volcanic rocks (mostly andesite and basaltic andesite with various amounts of phenocrysts) and so is not entirely derived from the underlying flow. The unit was probably hot when emplaced, because a carbonized tree limb occurs in the diamictite at 1,565 m (5,140 ft) elevation 700 m west-southwest of Cispus Point.

This diamictite probably formed from a debris avalanche or very thick debris flow from some unknown but nearby volcano. I recognized no evidence of a hummocky surface on the deposit, but erosion could have removed the hummocks (if ever present) before deposition of the younger rocks. Indeed, the elevation of the western part of the diamictite is very irregular and might reflect substantial erosion, irregular topography covered and (or) created by the diamictite, or my mistake in trying to map the unit in an area of unfavorable exposure.

The diamictite below Castle Butte is interlayered with lava flows and intruded by several dikes. These relations suggest relative proximity to a vent area. It is, therefore, not surprising that such a thick diamictite occurs here but not lower in the section, where andesite flows are less common and potential source volcanoes were probably more distant. In the mapped quadrangles farther west, several thick diamictites occur in areas probably near coeval volcanoes. By all measures, however, none is as striking as the diamictite below Castle Butte.

Depositional environment—The physical nature of the thinly bedded volcaniclastic rocks throughout much of the quadrangle (lensoid bedding, obvious channels, cross bedding) indicates that most were deposited by streams bounded at times by broad flood plains and local shallow lakes. Interbedded diamictite and lapilli tuff share this depositional environment and represent catastrophic punctuations to the otherwise fluvial environment. Most of the volcaniclastic rocks probably record erosion of slightly older volcanic rocks and in that sense are epiclastic. Many other deposits, such as the lithic- and pumice-lapilli tuffs, are most likely pyroclastic flows resulting from eruptions of nearby volcanoes. The diamictites probably formed from debris flows and could have had either syn-eruption or posteruption origins; they surely imply close and steep highlands.

Stine (1987), after detailed sedimentologic analysis, reached similar conclusions and assigned the deposits east of Timonium Creek and in the adjacent part of the Hamilton Buttes quadrangle to an "alluvial apron setting." Winters (1984) made a similar interpretation after detailed sedimentologic study of arkose interbedded with volcaniclastic rocks slightly lower in the section along the North Fork Cispus River 3.5 km (and farther) east of the quadrangle. From paleocurrent indicators, both Winters (1984) and Stine (1987) concluded that rivers flowed westward into the area from a crystalline highland (thought to be northern Washington) and later became choked with andesitic detritus eroded and erupted from a chain of volcanoes in the growing Cascades. As Stine (1987, p. 2) wrote, "The influx of these volcanic sediments gradually overwhelmed drainages previously dominated by arkosic sediments from the east." Winters (1984) found arkose interbedded with volcaniclastic rocks throughout the lower 650 m of the volcaniclastic section in the headwaters of the North Fork Cispus River—a reflection of how long it took for the drainages carrying arkosic detritus to be completely overwhelmed by the volcanic detritus.

The section dominated by water-deposited but subaerial volcaniclastic rocks is thick in the Blue Lake quadrangle. More than 670 m of clastic rocks are exposed nearly continuously along creeks draining into the North Fork from Horseshoe Point. A similar thickness crops out along Jackpot Creek. Bare slopes east of the headwaters of Timonium Creek reveal a section about 550 m thick of magnificently exposed bedded volcanic sandstone and associated clastic rocks. The volcaniclastic section is less well exposed on the steep southwest limb of the Bishop Ridge anticline, and so its thickness is difficult to estimate.

Most of the bedding has attitudes consistent with the local structure; the two exceptions north and south of Cold Springs Butte are described in the section, *Description of map units*. This observation implies that the beds were coplanar and subhorizontal when deposited and do not reflect the presence of steep overlapping volcanic edifices. I believe the "alluvial apron" setting that Stine (1987) envisioned is entirely reasonable and that it developed in the intermediate to distal fluvial facies surrounding active volcanoes (Smedes and Prostka, 1972; Vessell and Davies, 1981; Smith, 1987), as in parts of Central America today (Kuenzi and others, 1979). Such an environment could incorporate detritus from several adjacent volcanoes and thus represent a mixture of source material. Indeed, a mixture is suggested by the prevalence of andesite and basaltic andesite compositions in the lava flows interbedded with the volcaniclastic section and the occurrence of far more silicic compositions as clasts in at least some volcanic diamictites (Stine, 1987, p. 36–38; table 1, no. 80).

But what kind of setting could allow deposition and preservation of such a thick section of dominantly fluvial deposits? Two possibilities come to mind. The first, aggradation as a giant alluvial fan or basin fill, seems denied by the occurrence of arkose so high in the section just east of the quadrangle; why could through-going rivers depositing arkosic detritus be so much higher than they were before volcanic sedimentation began? The second possibility seems more reasonable: deposition in a subsiding basin at a rate approximately equal to that of subsidence. Such a setting would allow rivers to flow westward into and across the basin without significantly changing grade or without requiring changes in base level or uplift of the source. Winters (1984, fig. 41) implies a similar setting in his paleogeographic reconstruction, in which a west-flowing river system is flanked to the north and south by active volcanoes, although he made no explicit mention of coeval subsidence and deposition.

A subsiding basin is consistent with other elements of the regional stratigraphy. The Tertiary section in the quadrangles that I have mapped is roughly 5 km thick

(Swanson, 1991; see later section on *Structure*) and, extended down to the base of the volcanic pile, probably totals more than 7 km (Swanson and Evarts, 1992). Clearly such a section could not have been produced by aggradation without concomitant subsidence to preserve it. Moreover, the Ohanapecosh Formation just southeast of Mount Rainier is about 3 km thick (Fiske, 1963; Fiske and others, 1963; fig. 1) and consists mostly of well-bedded volcaniclastic rocks. Fiske (1963) interpreted many of the beds to be subaqueous pyroclastic flows deposited and probably erupted under water, as in a large lake. The subaqueous depositional setting has been challenged (Vance and others, 1987), but the great thickness of the formation argues for coeval subsidence and deposition regardless of whether the deposits are subaqueous or subaerial.

Hence the stratigraphic evidence is beginning to show that at least the early development of the Cascade arc in southern Washington involved subsidence (along the axis of the arc?) as well as volcanism. The cause of such subsidence is not clear; isostasy and tectonics both may be important. Subsidence probably did not last into the late Miocene and perhaps ended much sooner; flows of the Yakima Basalt Subgroup are strongly uplifted (in an "absolute" sense) along the east flank of the Cascades (Swanson and others, 1989, p. 29), and offlap relations suggest that the uplift began sometime between 17 and 12 Ma.

Lava flows—Lava flows (map unit Ta) are prominent but less numerous and voluminous in the Blue Lake quadrangle than in quadrangles farther west (Swanson, 1989, 1991, 1992). Rarely does one flow rest directly on another without intervening volcaniclastic rocks. One thick pile of andesite and basaltic andesite flows (table 1, nos. 33, 35, 46, 47, and possibly 40 and 65) straddles Bishop Ridge, cropping out extensively along Smoothrock Creek, Blue Lake Creek, and in places on the northeast flank of the ridge. This pile, more than 300 m thick in the headwaters of Smoothrock Creek, presumably records a shield or at least the proximal facies of a volcano. Supporting this interpretation is oxidized cinder (L L L pattern on sheet 1) well exposed in road cuts just north of the crest of Bishop Ridge, as well as that in a small exposure surrounded by drift 1.5 km due west of the mouth of Jackpot Creek.

Andesite flows in the Blue Lake-upper Cat Creek area lie along strike with the thick pile on Bishop Ridge and are likely correlative. More speculatively, flows in the upper Timonium Creek-Grouse Creek area (table 1, nos. 51 and 54) are approximately along strike with the pile and could be distal equivalents. Even the lava flows north of the North Fork Cispus River west of Jackpot Creek and east of Siwash Creek could conceivably be correlative to the upper part of the Bishop Ridge pile, though there is no compelling reason to force such a correlation.

Elsewhere, lava flows are most prominent on Horseshoe Point, along the west side of upper Deception Creek, and in the Cispus Point-Castle Butte-Twin Sisters-Kilborn Creek area. These flows are several hundred meters higher in the section than the Bishop Ridge flows and almost certainly had separate sources. The lava flows along upper Kilborn Creek are part of a larger field that extends well into adjacent parts of the Tower Rock (Swanson, 1991), Purcell Mountain, and Packwood quadrangles.

The andesite unit 1.3 km east of Jackpot Lake consists of two flows, a nearly nonporphyritic flow (not analyzed) overlain by a moderately plagioclase-phyric basaltic andesite flow (table 1, no. 16). This doublet can be mapped all along the north-trending series of cliffs above Smith Creek valley. The flows apparently interdigitate with volcaniclastic rocks in the steep area overlooking the North Fork Cispus valley, however, and in the Deception Creek drainage the unit consists of a complex alternation of lava flows and various volcaniclastic rocks. The map relations in this area are very crude; details are missing owing to the complexity of the relations and poor exposures. The stratigraphically highest package of flows along Deception Creek forms a broad outcrop belt that extends down dip and eventually disappears beneath the drift filling the valley. At least two flows occur in this belt (table 1, nos. 13 and 38). Many hand samples observed in this belt are rather coarse grained, and it is possible that a sill forms part of the belt, especially in its widest part.

Intrusive andesite and basaltic andesite—The three largest intrusive bodies, the andesite intrusions of Swede Creek (map unit Tais), Siwash Creek (Taiw), and south of St. Michael Lake (Taim), crop out just north of the North Fork Cispus River. The Swede Creek body potentially is the youngest, because it cuts rocks that are about 30 Ma (the K–Ar age of an andesite on Bishop Mountain at the northwest end of Bishop Ridge just inside the Tower Rock quadrangle [Swanson, 1991; Phillips and others, 1986]), younger than those hosting the other two large intrusions. The andesite intrusion of Swede Creek is sill-like in places and cross cutting in other places. Before the cross-cutting relations were found, I thought the intrusion was one or more andesite flows and portrayed it as such on the map of the Tower Rock quadrangle. However, cross-cutting relations are evident in Swede Creek basin and along the side of the North Fork Cispus valley. The intrusion is fine to medium grained and sparsely plagioclase phyric to nonporphyritic; the coarsest part of the intrusion is exposed in a road cut at the site of analysis 50 (table 1). A small amount of quartz in the groundmass distinguishes the intrusion from andesite flows of similar grain size. Chemically the intrusion is mafic andesite (table 1, nos. 50 and 55; Swanson, 1991, table 1, nos. 42 and 43), significantly more silicic than the other two large intrusive bodies.

The basaltic andesite intrusion of Siwash Creek is well displayed along the creek itself but poorly exposed away from the gorge. Its margins on the geologic map are only approximations, and the sill-like appendages near the North Fork Cispus could be hornfelsed lava flows instead. The rock is medium grained, even microdioritic in places (especially at the northeast end of the body), and generally contains scattered small plagioclase and clinopyroxene phenocrysts. Chemically the intrusion is basaltic andesite (table 1, nos. 15, 17, 18, 21) with relatively high Al_2O_3 (>19.5 percent); analysis 18 is not as rich in Al_2O_3 and might come from an andesite flow cut by the intrusion. Gabbro that crops out opposite the mouth of Siwash Creek also is quite aluminous and conceivably could be part of the intrusion or at least genetically related to it.

The basaltic andesite intrusion south of St. Michael Lake is well exposed in road cuts at the site of analysis 24. The body forms sparsely vegetated craggy slopes and cliffs above the road. A nearly vertical contact with the host rock is nicely shown in the road cut, and another steep contact is clear along the northern margin. An unusual northwest dip of 14° in the host rock near the site of analysis 25 might reflect deformation related to emplacement of the intrusion; quaquaversal attitudes just northwest of there are apparently related to a small cone, although they could possibly record doming above a hidden intrusion. The rock is highly jointed, fine to medium grained, and generally has a finely seriate texture. Both chemical analyses are basaltic andesite (table 1, nos. 24 and 25). The intrusion apparently cross cuts a sill-like body of diorite, but the contact is not exposed and the chemical resemblance of the two bodies (compare analyses 24, 25, and 26 of table 1) suggests that the diorite might be an offshoot of the larger intrusion.

Other unnamed andesite intrusions (map unit Tai) also occur in the quadrangle. A complex fine-grained body that I interpret as an intrusion underlies rugged terrain on Blue Lake Ridge just west of Blue Lake. The basaltic andesite (table 1, no. 20) is basically concordant and could be a lava flow. However, its thickness (more than 180 m in places) and throughgoing finely columnar to vertically platy jointing habit are best interpreted as characteristics of a sill. The bottom of the sill is exposed along the north base of the cliff facing Blue Lake volcano. This area is now quite unstable, and I believe it is the likely source of the young debris avalanche that entered and dammed the Cispus River (see discussion below).

Two small andesitic intrusions crop out along the ridge crest east of Blue Lake. The northern is a sparsely to moderately plagioclase-phyric basaltic andesite (table 1, no. 31). I saw no intrusive contacts, though the body has blocky jointing such as that characterizing many of the intrusions in the mapped quadrangles; however, it could also be a dome or flow remnant. The southern body (not analyzed) is fine to medium grained and moderately but finely plagioclase phyric; its columnar jointing and outcrop pattern suggest a broadly sill-like intrusion. The southern body is cut along an exposed contact by the hornblende diorite of Point 5644.

Dikes (map unit Tai)—Two long dike-like bodies in the quadrangle trend east-northeast. Whether the parallel trend of these two bodies is more than happenstance is debatable. One of the intrusions, almost completely exposed on the ridge east of Timonium Creek, is a medium-grained basaltic andesite (table 1, no. 22) that forms a dike more than 10 m wide dipping about 75° south. This dike probably was intruded before the host rock was folded, because rotation of the bedding to horizontal results in the dike becoming nearly vertical.

The other east-northeast trending intrusion is high on the ridge west of Deception Creek near the north edge of the quadrangle. This body, an andesite with exceptionally high FeO* and MnO (table 1, no. 56; fig. 11), is well exposed where it crosses the ridge crest at the site of the analyzed sample. The body is fine grained, very sparsely plagioclase phyric, and a dirty brown color possibly reflecting hydrothermal alteration. Several similar exposures suggest that the intrusion is a wide multiple dike, and somewhat confusing exposures along trend suggest that the dike bifurcates toward the northeast. A relatively coarse-grained north-northwest-trending dike cuts the larger body just southwest of the bifurcation. Another subparallel multiple intrusion, whose limits along strike are poorly known, crops out a few hundred meters west of the main body.

More than 90 narrow andesitic dikes, generally recording only one recognizable pulse of injection, occur in the quadrangle, mostly in the northern part (fig. 10). The dikes define two equally strong trends with moderate scatter (fig. 12*B*). One trend is northeast to east-northeast (mode of 60–75°), parallel to the two larger dike-like intrusions. Narrow dikes with this strike occur in the Cispus Point-Castle Butte area, on the ridge separating Smith and Deception Creeks, on and northeast of Cold Springs Butte, 1.5 km west of Horseshoe Point, 500 m southwest of the mouth of Siwash Creek, and 1 km northeast of the north end of Blue Lake. The other favored trend is northwest (mode of 315–330°) and is

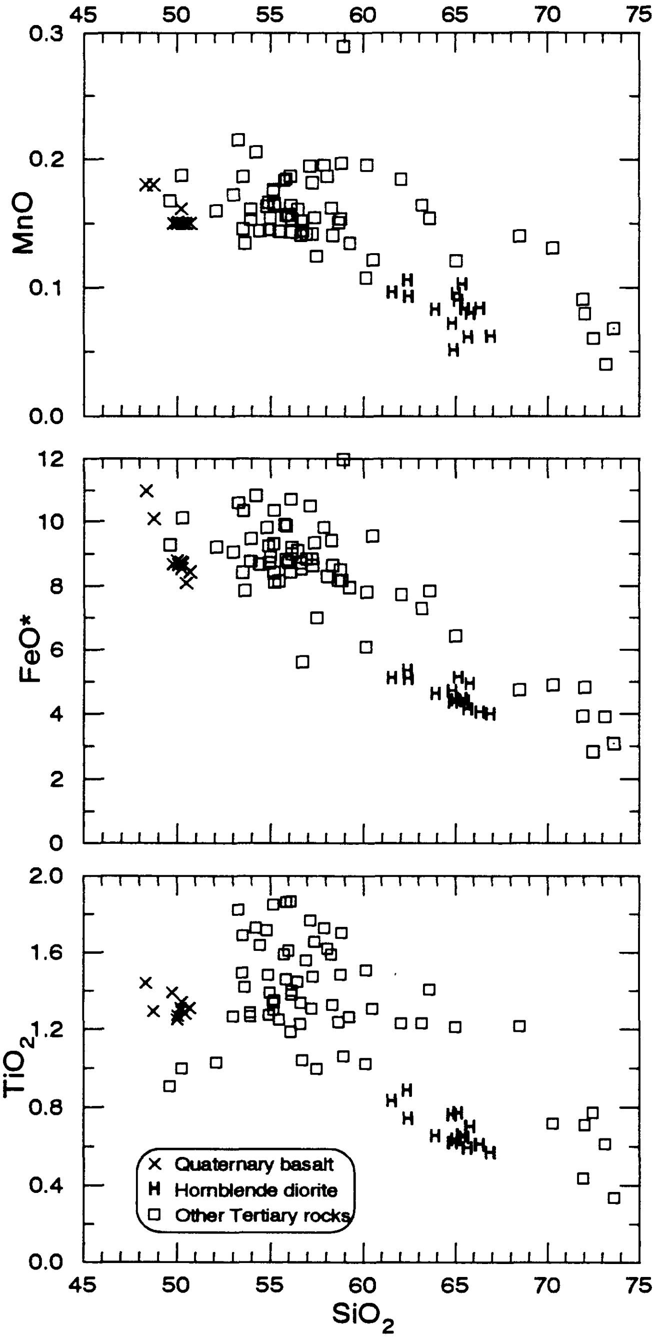

Figure 11. Plots of TiO_2, FeO*, and MnO vs. SiO_2 for all analyzed rocks in Blue Lake quadrangle. Note that the hornblende diorite and related rocks of Kidd Creek intrusive suite are chemically distinct from other rocks in quadrangle.

represented by dikes on Castle Butte, the ridge between Smith and Deception Creeks, the valley of Deception Creek, on Cold Springs Butte, and a few hundred meters south of the basaltic andesite intrusion south of St. Michael Lake.

The wide distribution of dikes of each trend suggests that both are important, but whether each might reflect the radial stress field around an intrusive center or some

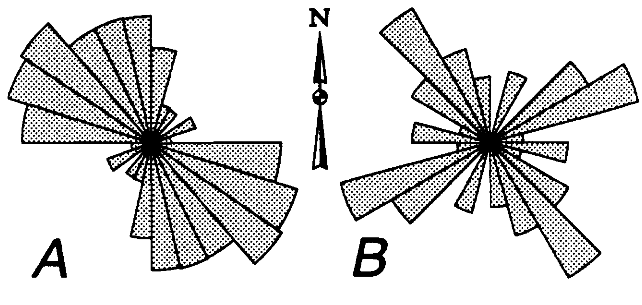

Figure 12. Equiarea rose diagrams in 15° increments of strikes of volcaniclastic rocks and pyroxene andesite dikes in Blue Lake quadrangle. *A*, 277 strikes of bedding (mean direction, 303.7°; s.d., 34.6°); *B*, 81 pyroxene andesite dikes showing two trends, one with mode in 60–75° interval, the other with mode in 315–330° interval.

regional trend will not be clear until more mapping is completed in the Packwood and Packwood Lake quadrangles. Nor are the age relations clear. I found only one exposed intersection of dikes with these two trends (at 1,130 m [3,700 ft] elevation 500 m east of Smith Creek and 1.3 km south of the north edge of the quadrangle); there the northeast-trending dike is the younger of the two.

Most of the northwest-striking dikes dip less than 75° south. Rotation of these to the vertical generally rotates the bedding in the country rock to approximate horizontal. Thus I find it probable that the pyroxene andesite dikes predate folding, a conclusion also reached in the other mapped quadrangles. The northeast-striking dikes are generally steeper, as would be expected because they trend roughly perpendicular to the strike of the host.

The distribution, though not orientation, of dikes in the quadrangle resembles that in the Tower Rock quadrangle (fig. 10). Dikes in both are clustered in the north and are comparatively uncommon in the southern two-thirds of each quadrangle as well as in the northern parts of the French Butte and McCoy Peak quadrangles (fig. 10). The Greenhorn Buttes quadrangle has only one recognized dike, and uncompiled mapping in the East Canyon Ridge quadrangle shows a pattern similar to that in the McCoy Peak. Thus the mapping defines an east-west-trending zone 12–15 km wide and more than 30 km long in which dikes are relatively scarce. In general andesite flows are relatively uncommon in this zone as well, though that pattern is less obvious than that for the dikes. Concentrations of andesite flows and dikes go hand in hand in the other quadrangles, but not in the Blue Lake quadrangle, even where the dikes are most common. Perhaps the dikes in the Blue Lake quadrangle are related to one or more younger volcanic centers, most evidence for which has been eroded away, whereas the dikes in the other quadrangles may be roughly coeval with the andesite flows they cut.

A regional swarm of dikes striking 260–300° is prominent in the southern part of the French Butte and McCoy Peak quadrangles, and a similar though much smaller swarm occurs near Lone Tree Mountain in the Tower Rock quadrangle (fig. 10; Swanson, 1990, 1992). Only a few dikes in the Blue Lake quadrangle have such a trend, and so apparently the Lone Tree Mountain swarm dies out eastward near 121°45′.

INTRUSIVE SUITE OF KIDD CREEK

Hornblende-bearing intrusive rocks (map unit Thd and its subdivisions) are common in the quadrangle, underlying much of the divide between the Cispus and North Fork Cispus and cropping out widely in the area south of the North Fork. The rocks belong to the *intrusive suite of Kidd Creek*, a name given by Marso and Swanson (1992) for a regionally extensive suite of diorite, quartz diorite, and finer-grained equivalents that intrudes all other Tertiary rocks in the mapped quadrangles. I described the suite in the McCoy Peak quadrangle in some detail (Swanson, 1992), because there it forms a large subvolcanic complex with an associated radial dike swarm (fig. 13). In addition the suite has been recognized in the French Butte, Tower Rock, East Canyon Ridge, Green Mountain, and the Hamilton Buttes quadrangles. In reconnaissance I have found chemically and petrographically similar quartz-bearing hornblende diorite along Cortright Creek about 9 km northwest of White Pass (fig. 1), where it is known as the "Jug Lake pluton" (Clayton, 1983, p. 36; Ellingson, 1959, 1972).

Chemically the suite is dacite and silicic andesite, with characteristically low contents of TiO_2, FeO*, and MnO (table 1; fig. 11) compared to other rocks in the quadrangle at similar SiO_2 content. The suite is somewhat more silicic in the Blue Lake quadrangle than in the McCoy Peak and Tower Rock quadrangles, averaging 64.8 percent SiO_2 (n = 15, maximum = 67.3, minimum = 61.5, standard deviation = 1.6) rather than 63.4 percent SiO_2 (n = 76, max = 66.3, min = 58.9, s.d. = 1.5).

The suite in the Blue Lake quadrangle forms sills, locally cross cutting, and one northeast-trending dike (1.5 km west of Preacher Creek). The sills crop out at a (probably) lower stratigraphic level than that of the three largest pyroxene andesite intrusions north of the North Fork, although the sills are probably younger than the andesite. Three of the sills are both extensive and thick, and—as in the Tower Rock quadrangle—I have named them realizing that they are probably interconnected at depth or even along strike.

The hornblende diorite of Bishop Ridge (table 1, no. 68) intrudes andesite flows and follows roughly the contact of flows with volcaniclastic rocks just southwest of the ridge crest. A mafic dacite flow (table 1, no. 65) caps the ridge and forms the roof of the intrusion; the dacite is locally sheared (most easily seen along the trail on the southwest side of the ridge), possibly owing to forceful intrusion by the hornblende diorite. The maximum exposed thickness of this broadly sill-like body is about 120 m or a little less. The intrusion may dip southwestward along and south of Smoothrock Creek and is possibly faulted (sheet 1); both of these map portrayals are questionable, because exposure on this dip slope is poor.

The hornblende diorite of Yozoo Creek is the most extensive sill in the quadrangle. It forms the dip slope between Preacher and Yozoo Creeks and extends halfway between Yozoo and Grouse Creeks. It may send sill-like fingers into the bedded rocks west of Preacher Creek, as I have mapped it, although chemical analyses of these fingers are more mafic than the main body of the intrusion (table 1, nos. 61 and 64 *vs.* nos. 73, 74, and 76). The sill does not crop out on the southwest flank of the Bishop Ridge anticline, probably because the slope of the ridge there is greater than the dip of the sill. Alternatively, the sill could intrude to a higher stratigraphic level along the crest of the anticline. The maximum thickness of the sill is more than 200 m, as estimated along the southeast side of Yozoo Creek basin.

The hornblende diorite of Point 5644 is the smallest of the three named intrusions but makes the most spectacular outcrop, a jagged cliff more than 240 m high forming part of the cirque in the headwaters of Grouse Creek. From the road crossing of Grouse Creek the cliff looks like a miniature Matterhorn, but in reality the pinnacle is readily climbed from the south. This body could well be an offshoot of the Yozoo Creek intrusion, but I have named it separately in part to honor its inspiring outcrop. Steeply plunging columnar joints characterize the northwestern margin of the body in the crestal area of the Bishop Ridge anticline.

Thin sills of hornblende diorite and quartz diorite, and fine-grained equivalents of both, are scattered throughout the rest of the quadrangle south of the North Fork Cispus River. Most of the sills are obviously intrusive, but the hornblende diorite that forms a prominent bluff on the ridge just north of the big bend in Cat Creek has no cap, and its base is shrouded in talus. On lithologic similarity I correlate the hornblende diorite with the intrusive suite of Kidd Creek and interpret it as a sill. However, Stine (1987, p. 2) preferred to interpret the body as a valley-filling lava flow of "Miocene–Pliocene age" (and misidentified the hornblende as pyroxene). Without knowing the regional relations, her

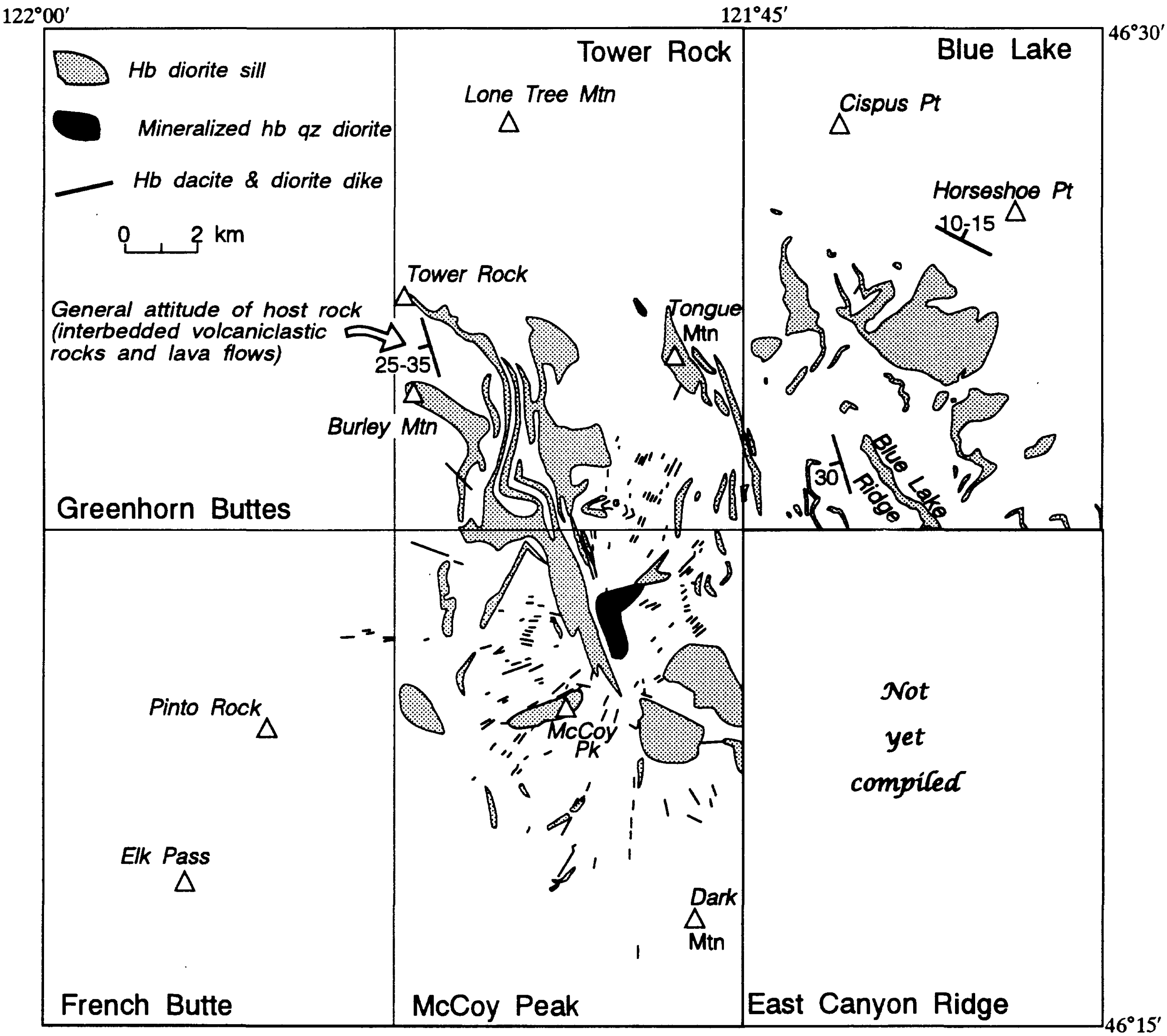

Figure 13. Generalized map showing distribution of intrusive suite of Kidd Creek in the five quadrangles indicated. Dikes radiate from site of mineralized McCoy Creek intrusion, but only one dike occurs in Blue Lake quadrangle. Around the McCoy Creek area, dikes occur preferentially in southwest and northeast quadrants, and sills in northwest and southeast quadrants. In the Blue Lake quadrangle, however, sills are common northeast of the subvolcanic center and most likely record one or more separate foci of intrusion. General attitude of host rocks shown in three locations.

interpretation as a thick, coarse-grained, holocrystalline lava flow could be reasonable.

In the other mapped quadrangles most hornblende-bearing dikes are subvertical even where they strike subparallel to the steeply dipping host rock. This evidence suggests that the intrusive suite is younger than the folding (Swanson, 1992). Only one hornblende-bearing dike was found in the Blue Lake quadrangle (3.5 km north-northwest of Blue Lake); it is vertical but strikes normal to the host rock. Thus I can only infer from the relations in other quadrangles that the suite in the Blue Lake quadrangle is also younger than the folding. The few available zircon fission-track ages (Swanson, 1992) suggest an age of about 12 Ma for the Kidd Creek intrusive suite and therefore a minimum age for the folding.

The intrusive suite in the Blue Lake quadrangle may reflect a different center than that in the quadrangles farther west, where all of the suite can readily be interpreted as part of a single subvolcanic center near Camp Creek (Swanson, 1992), defined by the focus of a radial dike swarm and a mineralized hornblende quartz diorite sill or small pluton (fig. 13). The sills in the Blue Lake quadrangle are large and occur 10–15 km northeast (across strike) of the focus of the radial dike swarm, and on stratigraphic grounds they intrude older strata. Conceivably magma could have injected along bedding planes below the level of exposure in the McCoy Peak quadrangle, followed these horizons up dip, and appeared as the sills in the Blue Lake quadrangle. However, this scenario seems more complex than one that allows magma to rise to the current level of exposure from some deeper source unconnected to the center in the McCoy Peak quadrangle. The more silicic nature (on average) of the hornblende diorite in the Blue Lake quadrangle may support the interpretation of a separate center, although this is admittedly weak evidence.

No hornblende-bearing intrusion occurs north of the North Fork Cispus River. The same relation holds in the Tower Rock quadrangle, where no hornblende diorite occurs north of the Cispus River (Swanson, 1991). A structural explanation seems evident for the Blue Lake quadrangle. Apparently the highest stratigraphic level subject to intrusion dips under the valley, and only higher levels barren of hornblende diorite crop out north of the river. This explanation cannot account for the relation in the Tower Rock quadrangle, where the dip is not toward the Cispus, and some *ad hoc* arguments (Swanson, 1991; distal limit of intrusion, barrier by andesite pile north of the river) are still the best there.

STRUCTURE

Folds—The Bishop Ridge anticline dominates the structure of the quadrangle. The crestline of the anticline closely follows the top of Bishop Ridge for about 5 km in the south-central part of the quadrangle. The axial part of the structure is rather sharp and may have localized the later intrusion of hornblende diorite magma. The anticline is less pronounced in the southeast part of the quadrangle and may die out farther southeast. The anticline apparently transforms into a monocline where it crosses the North Fork Cispus River, although exposures are poor in this area, especially those showing attitudes. The monocline continues across the northeast corner of the Tower Rock quadrangle, where it apparently bounds the parallel Pin Creek fault zone (Swanson, 1991).

Strikes average about 304° (fig. 12A), with a broad mode in the range 285–315° and considerable scatter. The average strike is rotated 35–40° counterclockwise from that in the Tower Rock and McCoy Peak quadrangles (Swanson, 1991, 1992), and about 55° counterclockwise from that in the French Butte and Greenhorn Buttes quadrangles. This pattern is consistent with the different axial trends of the two folds in these quadrangles, the north-northwest-trending Pole Patch syncline in the French Butte and Greenhorn Buttes quadrangles and the northwest- to west-northwest-trending Bishop Ridge anticline (fig. 10).

The minimum structural relief on the Bishop Ridge anticline in the quadrangle is nearly 1 km, if the hornblende diorite of Yozoo Creek is stratabound—a reasonable first approximation. That relief is calculated from the highest elevation of the sill along the crestline of the anticline (about 1,645 m [5,400 ft]) and the elevation of the North Fork Cispus down dip from there (about 670 m [2,200 ft]). Certainly the maximum structural relief is far greater than this figure.

The Bishop Ridge anticline is paired with the north-northwest-trending Pole Patch syncline (and its *en echelon* segment, the Elk Creek syncline), the trough of which is 12–13 km farther west, in the Greenhorn Buttes quadrangle (fig. 10; Swanson, 1989). Between the two structures, the average dip is 25–30°. Thus the amount of section exposed is 5.25–6.25 km. Of that, sills account for perhaps 0.7 km, so that the true stratigraphic section is about 5 ± 0.5 km thick. I used these figures and existing K–Ar ages (Hammond, 1980; Phillips and others, 1986) to calculate an average depositional rate of about 435 m per million years for the rocks in this section (Swanson, 1991).

A minor northwest-trending anticline crosses Castle Butte but extends no farther south than Cispus Point and probably no farther north than the basin north of Castle Butte. No syncline is paired with the Castle Butte anticline; instead the shallow west dips continue to the monoclinal warp along the extension of the Bishop Ridge anticline. Dips defining this Castle Rock structure are shallow and could be caused by a subtle volcanic edifice rather than by deformation. A north-south elongate constructional edifice, much larger and more evident than the Castle Butte feature, extends north from Pinto Rock in the French Butte quadrangle (Swanson, 1989) and could be analogous (though much younger).

Faults and shear zones—Only two possible faults were found in the quadrangle that might be part of the northwest-trending Pin Creek fault zone. One, halfway up the southwest flank of Bishop Ridge, may offset hornblende diorite sill(s); I found no direct evidence of this fault and infer its presence only from the outcrop pattern. The other is simply a small shear zone in an andesite flow(?) in a road cut just north of the mouth of

Blue Lake Creek; two shear planes in the zone strike 310°, dip 70–75° south, and contain slickensides plunging 60–75° southeastward. Whether the flow is faulted against volcaniclastic rocks, as portrayed on the geologic map, is not clear. Two minor(?) shear zones, with no demonstrable offset, also occur within the Pin Creek zone near the edge of the quadrangle just north of the North Fork Cispus.

Another northwest-trending fault on the west side of Cispus Point juxtaposes platy andesite and bedded volcanic sandstone and lithic-lapilli tuff. This fault, obvious in outcrop, has a vertical displacement of at least 10 m, probably northeast side down. Calcite veinlets occur adjacent to the fault, as they do in most other fault and shear zones in the mapped quadrangles.

Two other northwest-trending shear zones crop out in a small creek 1 km northeast of the mouth of Preacher Creek; no sense of displacement is evident.

Several northeast- and east-northeast-trending faults and shears occur in the northern half of the area. Four have evidence of left-lateral movement, as determined from the presence of subhorizontal slickensides on appropriately stepped polished surfaces: *a*) in the andesite intrusion of Swede Creek, *b*) in volcaniclastic rocks just east of Smith Creek, *c*) in an andesite flow in a quarry just east of the mouth of Timonium Creek, and *d*) in andesite about 1 km northeast of the previous site. Other shears of similar trend but lacking evidence for sense of motion are in *a*) volcaniclastic rocks along the north edge of the quadrangle 1.2 km west of Smith Creek (this fault juxtaposes andesite and lithic-lapilli tuff in a road cut just north of the quadrangle), *b*) volcanic sandstone 300 m south of the north edge of the quadrangle on the ridge between Smith and Deception Creeks (vertical slickensides), and *c*) andesite along the northwest margin of the hornblende diorite of Bishop Ridge.

The two general sets of faults and shears correspond with the two directions of dikes. This correspondence implies no genetic tie, although it is a reasonable interpretation. Northeast-trending left-lateral structures occur in the other mapped quadrangles and apparently form a conjugate set with northwest-trending right-lateral shears, not found in the Blue Lake quadrangle but present farther west (Swanson, 1989, 1991).

QUATERNARY OLIVINE BASALT

Basalt of two and possibly three different ages occurs in the southwest corner of the quadrangle. Two of the units, the basalt of Blue Lake Creek and the basalt of Juniper Creek, erupted in or immediately adjacent to the quadrangle, but the distinctly younger basalt of Spring Creek is an intravalley flow that followed the Cispus River for many kilometers from its vent along the crest of the Cascades.

Blue Lake volcano—In the middle or late Pleistocene an eruption of moderately high-K_2O olivine basalt built a small volcano, Blue Lake volcano, astride the northwest extension of Blue Lake Ridge. The volcano is 2.2 by 2.5 km wide at its base, covers about 3.6 km^2, and has a maximum relief of 780 m from its summit near the site of analysis number 10 to its base east of Blue Lake Creek campground. Lava flows and tephra from the volcano dammed ancestral Blue Lake Creek and created the popular motorcyclists' mecca, Blue Lake. Surprisingly, the edifice was not recognized as a young volcano until the early 1980s, when Forest Service geologists led by Rick Wooten spotted the breached summit crater on air photos.

The volcano is built of three distinct units (map unit Qbbl): a basal quenched and hyaloclastic pedestal, a thin section of "normal-appearing" lava flows, and a tephra (mainly cinder) cone. Taken together, these units constitute an excellent example of a volcano that formed beneath a glacier, eventually breached the surface of the glacier, and then erupted subaerially.

The lowest unit consists entirely of highly quenched, in places mostly glassy, dense basalt in the form of one (or possibly more) flows and hyaloclastic debris. A single cooling unit of hackly basalt at least 100 m thick (probably more than 120 m) forms rugged cliffs along Blue Lake Creek (table 1, no. 4). The flow is fine-grained and has a glass-rich groundmass resembling that of entablatures in water-quenched basalt elsewhere (Saemundsson, 1970; Long and Wood, 1986; DeGraff and others, 1989). A similar glassy flow, divided by narrow subhorizontal columnar joints, forms a 60-m cliff on the south side of the volcano; its base is shrouded in talus and landslide debris so that its total thickness cannot be estimated.

Hyaloclastic debris predominates along the low western flank of the volcano between the cliffs of the quenched flow(s). This debris is poorly exposed naturally, because it slumps and crumbles readily and is densely overgrown, but cuts along a new logging road show a complex assemblage of broken pillow breccia, quenched blocks of basalt with palagonitized rims, irregular masses meters across with entablature-type jointing (table 1, no. 7) that locally grade into finer-grained hyaloclastic debris, and partly palagonitized black sideromelane sand. In places the cuts show open-work angular gravel of similar material. Crude bedding locally suggests dips roughly parallel to the modern ground surface.

Two rubbly and locally platy a'a flows, each about

5–8 m thick, form a south-facing cliff on the south side of the volcano. This cliff gives way toward the west into the 60–m cliff formed by the glassy flow. I believe that the two a'a flows overlie the thick glassy flow, but the contact is not exposed. The a'a probably does not merge westward into the thick flow, because no evidence of rubble was identified in the thick flow, and a'a does not—and probably can not—change into more fluid lava downslope (Peterson and Tilling, 1980). The a'a flows are strongly oxidized in places, and olivine phenocrysts have rims of iddingsite. The lower flow (table 1, no. 11) overlies oxidized cinder at least 1 m thick; talus obscures the base of the cinder. The upper flow (table 1, no. 9) rests directly on the lower and underlies a fragmental deposit consisting of two end members: *a*) bedded palagonitic sideromelane sand, and *b*) a mostly younger diamicton containing mostly angular and subangular blocks of the basalt but some rounded to subangular striated stones of Tertiary rocks. In places the diamicton has a palagonitic matrix, and striated stones are scattered throughout the bedded sideromelane sand, which itself consists of abundant vesicular and scoriaceous bits of glassy olivine basalt as well as dense sideromelane.

One or more a'a flows with local surface relief of 2–3 m form the flat northern part of Blue Lake volcano, south of the bend in Blue Lake Creek. Here disrupted and tilted blocks of bedded cinder and spatter several meters across rest on top of the a'a and may have been rafted there as the flow(s) moved away from the vent, carrying some of the cone with it; exactly this process has been observed frequently at Kilauea. Nearby, cuts along a new logging road crossing the shallow west-trending valley eroded into the volcano show oxidized basaltic cinder and pumiceous lapilli, mostly oxidized and containing scattered stream-worn pebbles of Tertiary rocks probably erupted as accidental blocks with the juvenile tephra. In places this tephra overlies yellow palagonitized sideromelane sand.

A marked break in slope coincides with the change from the thick glassy basalt and associated hyaloclastic debris upward into the oxidized a'a flows and oxidized cinder. On the western flank of the volcano, the slope steepens rather abruptly below about 1,040 m (3,400 ft), the approximate elevation of the contact between the two different units. This change is delimited by the dot-dash pattern on the geologic map and portrayed on cross section C–A′ (sheet 2).

The third unit in Blue Lake volcano—a tephra cone composed of commonly oxidized basaltic cinder, spatter, and pumice—overlies and apparently intertongues with the a'a flows. Locally interbedded in the oxidized tephra is fine-grained palagonitic sandy tephra. Deposits of the cone crop out poorly, but slopes west of Blue Lake and in the summit region just east of the site of analysis 10 clearly show the tephra *in situ*, dipping parallel to the modern ground surface. At the summit of the volcano, a crater open to the west and obvious on the topographic map is surrounded by a locally agglutinated tephra rim. The shape of the crater is consistent with the prevailing wind direction toward the east. Analysis 10 is from a thin, probably rootless flow in the crater wall.

The foregoing description indicates that Blue Lake volcano is a subglacial volcano that eventually grew above the top of the glacier to form a subaerial cap. The lower, thick glassy unit was formed beneath and against ice and meltwater created by the eruption. Open-work angular gravel was likely deposited by transitory subglacial streams that formed and died as a consequence of the eruption. The top of the glassy unit represents the elevation of the surface of the glacier, and subsequent eruption built subaerial a'a flows surmounted by a tephra (dominantly cinder) cone. Hydromagmatic explosions immediately preceded and followed eruption of the a'a flows and continued intermittently during construction of the tephra cone. The volcano grew across ancestral Blue Lake Creek upstream from the ice margin, damming the creek draining the northeast side of Blue Lake Ridge and creating Blue Lake.

Which glacier and what age?—The top of the glacier at the time of eruption was about 1040 m above sea level, and the glacier was about 550 m thick. The glacier could have thickened slightly (to an elevation of about 1100 m) after the volcano was built, if the diamicton above the a'a flows is a till. However, I prefer the interpretation that the diamicton is an eruption product, either an explosion breccia or a debris flow carrying older till stones ejected during hydroexplosions as well as the dominant olivine basalt itself. In any case the glacier could not have thickened to an elevation of more than about 1100 m, because of the lack of till on the cone above that elevation. Moreover, the upper part of the tephra cone has not been glaciated, because its crater is preserved.

The Cispus valley glacier may have been in retreat at the time of the eruption. Till presumably related to the glacier mantles the lower part of the ridge of Tertiary rocks surrounded and mostly buried by the volcano. This till, well exposed in a new road cut at an elevation of 1100 m, consists wholly of Tertiary stones, even though it is completely surrounded by oxidized subaerial olivine basalt and tephra. At one time the top of the glacier was at or above this elevation, whereas it was at least 60 m lower (and likely much more) when the volcano began to grow.

The Blue Lake area itself was apparently free of ice during the eruption, even though it is considerably higher (lake level is about 1237 m) than the top of the

Cispus valley glacier. The U-shaped cross section of the valley southeast of Blue Lake indicates a period of glaciation some time before the eruption. However, ice was apparently absent from the Blue Lake area during the eruption, because no evidence of ice-lava interaction is evident—no glassy lava flow occurs north of Blue Lake, and little water-quenched debris occurs on the slope west of the lake—and the volcano grew partly within, and in essence blocks, the U-shaped valley. Hence the picture emerges of an eruption into a receding Cispus valley glacier and after ice had left at least the north end of the U-shaped valley in the Blue Lake area.

No thick deposit of tephra overlies the ridge of Tertiary rocks on the northwest flank of the volcano. The proximity of this ridge to the vent area seems to demand that tephra fell here, and tephra crops out beyond the northwest end of the ridge, along the new road crossing the shallow west-trending valley described several paragraphs earlier. Possibly the tephra has been eroded from the ridge, or possibly it is absent because it fell on a cover of snow or ice.

What is the age of the Cispus valley glacier in which Blue Lake volcano formed? I believe it must be of Hayden Creek vintage. It cannot be as young as Evans Creek Drift, because the basalt of Spring Creek—probably younger than most or all of the Evans Creek Drift—clearly occupies a valley eroded deeply into Blue Lake volcano. Along the Cispus, the basalt of Spring Creek is covered by glacial outwash rather than till (Hammond, 1980; Korosec, 1987; Hildreth and Fierstein, in press; my unpublished observations in the East Canyon Ridge quadrangle). This relation shows that the Spring Creek was erupted before or during the earliest part of Evans Creek time, and hence that the valley containing the basalt is also older than Evans Creek. Two radiometric ages on organic material in unconsolidated alluvium or colluvium just under the Spring Creek do not constrain the minimum age of the basalt but are most likely about the same age as the basalt; the younger of the two ages corresponds to early Evans Creek time, and the older clearly predates Evans Creek time (see section of the basalt of Spring Creek). Moreover, the lack of till stratigraphically above the Spring Creek shows that the Evans Creek glacier did not extend far enough downstream to reach the Blue Lake quadrangle. In fact, Hammond (1980) mapped a terminal moraine of Evans Creek age in the Cispus Valley about 16 km upriver from the Blue Lake quadrangle.

Blue Lake volcano could conceivably have formed under a glacier older than Hayden Creek; this issue cannot be convincingly resolved on stratigraphic grounds. However, the good preservation of the volcano argues that it has not been strongly glaciated, so probably it did not form during an earlier glaciation because it then would have been susceptible to erosion by the Hayden Creek valley glacier.

Barry Goldstein (University of Puget Sound) has estimated, from cross-valley profiles both upstream and downstream from Blue Lake volcano, that the elevation of the subglacial-subaerial transition in the volcano is consistent with the elevation of the change in valley morphology from glacially sculpted (U-shaped) below to nonglaciated above (oral commun., 1991). Hence the volcano was probably erupted into the glacier responsible for most of the erosion of the valley. That glacier generally has been assumed to be of Hayden Creek age, although an older glacier could conceivably have been responsible for much of the erosion.

The basalt of Blue Lake volcano is relatively rich in K_2O (table 1, nos. 4, 7, 9–11), and so should be amenable to isotopic dating despite its obvious youth. I have submitted samples to two different laboratories for dating, but the results are not yet available. If successful, the dating will provide the first isotopic age for Hayden Creek time, most likely about 140 ka (Colman and Pierce, 1981) but considered as young as 60 ka by Crandell and Miller (1974) and Crandell (1987) and as old as 300 ka by Dethier (1988).

Subglacial meltwater deposits derived from Blue Lake volcano—Angular open-work basaltic gravel crops out in two areas just west of Blue Lake volcano (unit Qgbl on geologic map). It is best exposed in a gravel pit (shown on the quadrangle map) just north of Blue Lake Creek. Here the deposit, 10 m or more thick, consists of bedded, subangular to subrounded, coarse gravel (cobbles and boulders common) derived mostly from the olivine basalt of Blue Lake volcano. All the basaltic clasts are quenched, and many resemble the sharp, fist-sized joint blocks typical of hackly entablatures and pillow interiors; no broken pillows are evident, however. A few subrounded clasts of Tertiary rocks, some greater than 50 cm in diameter, are sprinkled through the deposit. Sand beds separate some of the gravel layers. Bedding dips about 5° west (downslope) and is commonly discontinuous and lensoid. Similar gravel crops out in several places along Blue Lake Creek, mainly downstream from the gravel pit.

Angular gravel and sand mostly derived from Blue Lake volcano are exposed at 705 m (2,310 ft) elevation in a cut on a logging road 400 m northeast of the gravel pit. Clasts of Tertiary rocks, generally subrounded, are much less abundant than at the gravel pit. Much of the gravel has an open-work texture. Bedding is discontinuous, lensoid, and dips gently westward. The deposit is at least 3 m thick, with base unexposed. This deposit is 300–400 m from the deep gorge of Blue Lake Creek; the gorge separates the deposit from Blue Lake volcano, source of most of the clasts.

Both deposits are unlike those currently forming along Blue Lake Creek. The older gravel consists dominantly of angular clasts of basalt and has the appearance of rapid, very high-energy deposition. The modern gravel consists of a more even mixture of Tertiary rocks and olivine basalt, many of the clasts—even of basalt—are subrounded, and the resulting deposit resembles that of a typical mountain stream.

The older gravel was probably deposited by subglacial meltwater streams, or as the creek was cutting its gorge through and below Blue Lake volcano soon after the glacier had retreated, or both. I favor an origin that includes at least some subglacial deposition, because it is unlikely that Blue Lake Creek ever flowed far enough north of its present position in post-glacial time to deposit the gravel now exposed at 705 m (2,310 ft). More likely, a subglacial meltwater stream crossed the present coarse of Blue Lake Creek before the gorge had formed. Meltwater streams produced by heating during the eruption may even have deposited much or all of the gravel; in other words, the gravel may in part have formed by water-hot rock interaction and been transported by torrential subglacial streams fed by rapid melting of the ice. Such activity would seem an almost inescapable consequence of an eruption under ice, especially one large enough to have formed the >100–m–thick subglacial pedestal for Blue Lake volcano. The lack of evidence for broken pillows in the gravel is puzzling, however, and suggests that the gravel comes from breakup of the thick flow in the pedestal, not from the hyaloclastic facies that resulted from direct quenching of *melt* by water. It is easy to imagine how the margin of a quenched flow would crumble as it moved (much like the air-quenched margins of growing lava domes) and produce angular clasts for meltwater torrents to carry away.

The older gravel along lower Blue Lake Creek has a fan-like map pattern strongly suggestive of deposition from the creek itself. This part of the deposit probably records an early stage in the development of the creek, either subglacially or just after removal of the ice. Its preservation low in the valley argues against much if any subsequent glacial erosion, befitting the timing of the eruption during recession of the Hayden Creek glacier.

Basalt of Juniper Creek—This young olivine basalt (map unit Qbj) is petrographically and chemically similar to the basalt of Blue Lake Creek (compare nos. 5–6 with nos. 4, 7, and 9–11 in table 1; see also Swanson [1991, table 1, no. 10; 1992, table 1, no. 3]). It covers only a small area that includes contiguous parts of the four quadrangles that meet in the southwest corner of the Blue Lake quadrangle.

The basalt of Juniper Creek was erupted from at least one vent just inside the McCoy Peak and Tower Rock quadrangles; there could be two adjacent vents here, but incision by Juniper Creek has removed definitive evidence for two. Just inside the McCoy Peak quadrangle, bedding in the cone is locally vertical adjacent to an explosion pipe several meters in diameter that contains abundant blocks of Tertiary andesite and diorite; this is clear evidence of one vent.

A new road cut 800 m north of Juniper Creek exposes a thin deposit of bedded palagonitized tephra of Juniper Creek composition and appearance. Bedding in the tephra parallels the modern slope. The tephra is mainly dense but includes at least one bed of cinder or even pumice. Possibly a vent lies upslope from here, but I did not find it and it may have been eroded away if ever present.

The vent(s) nearest Juniper Creek erupted both tephra and one or more lava flows. The tephra is phreatomagmatic, consists mostly of partly palagonitized black cinder and sideromelane sand, and defines the flanks of a tuff cone that in most places mantles the Cispus valley slope. Surge beds, low-angle cross bedding, and shallow channels are common, and ballistic fragments of Tertiary rocks are strewn through the deposit. The preserved top of the cone is at 1,070 m (3,520 ft) elevation in the Tower Rock quadrangle, and the exposure on the rim of Juniper Creek gorge in the Blue Lake quadrangle is in the lower part of this tuff cone.

The youngest tephra was erupted without much water interaction and occurs as thin beds of fresh black cinder between 1,090 m (3,570 ft) and 945 m (3,100 ft) elevation in the McCoy Peak quadrangle. Similar loose black cinder occurs in a new road cut at a much lower elevation, 760 m (2,500 ft), in the East Canyon Ridge quadrangle.

Two or more lava flows erupted from the cone(s) and intertongue with the cinder. One flow is thin and apparently confined to a crater of the tuff cone in the Tower Rock quadrangle (Swanson, 1991). The other flow is much thicker and probably predates the thin flow, but I did not find outcrops showing its relation to the tuff cone. The thick flow moved downslope into the Blue Lake and East Canyon Ridge quadrangles, where it forms the upper part of the ridge east of the creek south of Juniper Creek and ends in steep slopes and cliffs 40–60 m high overlooking the Cispus River. In the cliffs the flow is quenched, hackly, dense, and cannot be distinguished in appearance from the thick subglacial flow on Blue Lake volcano. Along its eastern margin, such as the site of analysis no. 5 (table 1), the quenched flow features subhorizontal columns 10–25 cm in diameter that resemble those in complex entablatures. The flow underlies hyaloclastic debris from about 895 m (2,940 ft) (just inside the East Canyon Ridge quadrangle) to 825 m (2,700 ft). At its northern and eastern limit, the base of the cliff-forming flow is at an elevation of about 715 m (2,350 ft), where it is covered by talus. The basalt mantles the side of the U-shaped Cispus valley (pl. 2, C–A′) and so clearly postdates the glacial maximum.

These relations suggest that the flow(s) interacted with water to produce the hyaloclastic debris, and with either water or ice to quench the flow and cause it to develop the columnar joints. The subhorizontal columns suggest cooling against a steep surface, possibly ice. A reasonable interpretation is that the eruption took place when a remnant of the Hayden Creek glacier remained in the valley, possibly with its surface at least as high as the highest hyaloclastic debris, 895 m, but not higher than the vent for the black cinder, probably about 1090 m. These elevations bracket that of the subglacial-subaerial transition at Blue Lake volcano, but the most likely elevation is probably at the low end of this range. From these crude observations, I estimate that the eruption of the basalt of Juniper Creek took place at about the same time, or probably somewhat later, than the eruption that produced Blue Lake volcano.

The Juniper Creek and Blue Lake subglacial vent areas are not unique in the southern Washington Cascades. At least two other basaltic volcanoes formed under ice of the Hayden Creek glacial period. Lone Butte and Crazy Hills, about 50 km south of Blue Lake volcano at the northern end of the Indian Heaven basalt field, are subglacial volcanoes of Hayden Creek age (Hammond, 1987). Lone Butte breached the surface of the glacier and in that respect resembles both the Juniper Creek and Blue Lake vents. The vents of the Crazy Hills apparently did not erupt subaerially. A third subglacial vent area, Walupt Lake volcano (Hammond, 1980; Swanson and Clayton, 1983) 11 km east of the Blue Lake quadrangle, may be of Hayden Creek age although perhaps more likely was constructed during Evans Creek time.

The terms *tuya* and *moberg hills* are sometimes applied to subglacial volcanoes that breach or do not breach, respectively, the surface of a glacier; for example, Hammond (1987) called Lone Butte a tuya and Crazy Hills, moberg hills. Generally the term is used for subglacial pillow complexes, whereas much of the subglacial parts of Blue Lake volcano and the Juniper Creek vent(s) are quenched but not pillowed. Thus I do not use the more esoteric terms to describe the subglacial vents in the quadrangle. A possible explanation for the relative lack of pillows is that the eruption rate was relatively high so that the water/magma ratio was generally low at any one place. Where hyaloclastic debris and pillows (evidenced by broken pillow breccia locally at Blue Lake volcano) formed, the water/magma ratio was perhaps higher (Kokelaar, 1986).

Basalt of Spring Creek (Korosec, 1987)—This low-K (table 1, nos. 1–2), diktytaxitic, olivine-phyric basalt (map unit Qbs) occurs as remnants of an intracanyon flow or flows that issued from a low cone (hill 5162; fig. 1) on the Cascade crest north of Mount Adams (Hammond, 1980; Hildreth and Fierstein, in press) and flowed westward into the Cispus River valley and eastward into the Klickitat River valley. In the Cispus valley, the basalt occurs as far downstream as the mouth of Dry Creek, about 10 river kilometers from the Blue Lake quadrangle (Swanson, 1991), and clearly occupies a valley eroded into the basalt of Blue Lake. The unit is equivalent to the "basalt of Hill 5162" of Hammond (1980) and is named for a creek just west of that hill.

Two radiocarbon ages have been obtained from material at the base of the basalt in a prominent stream cut along the south side of Prospect Creek where it is crossed by Forest Road 2801, in the East Canyon Ridge quadrangle 2.1 km south-southeast of the site of analysis 2. These ages are quite different from one another but provide a crude limit on the maximum age of the Spring Creek. One age of 21.5 ± 0.5 ka (radiocarbon years; USGS 2714) was obtained by Hildreth and Fierstein (in press) from organic-rich soil just under the basalt. The second age of 41.1 ± 1.3 ka (radiocarbon years; USGS 3278) was determined by Debbie Trimble (written commun., 1993) on carbonized rootlets(?) that I collected 30–50 cm below the base of the flow in colluvium or alluvium overriden by the basalt. It is possible that both ages are correct, and that a soil was developed about 21,500 years ago on a surficial deposit in which plants had been rooted 41,100 years ago. However, the dated soil was probably not pretreated before dating, because of the dispersed nature of the organic material in it, and so could be contaminated with younger carbon (Willie Scott, oral commun., 1993). If so, the age of 41.1 ka (perhaps itself a minimum because it is near the limit of reliable ^{14}C dating) would be closer to the real age of the soil; I favor this interpretation. In either case, the flow is younger than the soil, but I feel that the geologic relations are best explained if the soil and basalt are approximately the same age.

Both ages are broadly consistent with stratigraphic relations along the Cispus River, where the basalt of Spring Creek is overlain by thick outwash deposits of Evans Creek age but overlies either thin soil developed on older rocks (my unpublished observations in the East Canyon Ridge quadrangle) or only gravel and sand deposits interpreted as bars along the ancestral Cispus (Swanson, 1991). This suggests that the Spring Creek was erupted before significant outwash gravel was being deposited along the Cispus. Quaternary geologists believe it most likely that Evans Creek Glaciation was near its peak about 21 ka (Willie Scott, oral commun., 1993), so that if the Spring Creek were of that age or younger it should overlie outwash gravel. Hence the Spring Creek is probably older than about 21 ka on stratigraphic grounds.

In the Blue Lake quadrangle, the basalt forms a distinct bench along the west side of the Cispus valley. The highest point on the bench (along Juniper Creek) is at about 640 m (2,100 ft) elevation, and the riser (in places a low cliff) of the bench extends down to about 565 m (1,850 ft). The base of the flow is exposed in only one place, about 500 m north of Juniper Creek, where it rests directly on volcaniclastic rocks; elsewhere it is either covered by colluvium or by river gravel. The bench is not well exposed in the dense forest, but its riser can be easily traced.

The basalt of Spring Creek underlies a small area north of the mouth of Blue Lake Creek between about 495 m and 535 m (1,620 and 1,730 ft) elevation, judging from sparse exposures and the topography. Its base is covered by colluvium and a hummocky diamicton (map unit Qlsb). The flow is quite vesicular here, and the high point is on a "pressure ridge" parallel to the valley side. The "pressure ridge" stands about 6 m above the adjacent road to the east and appears to mark the original margin of the flow, because only Tertiary rocks crop out on the east side of the road.

Petrographically and chemically similar basalt crops out along Blue Lake Creek at an elevation of 613–640 m (2,010–2,100 ft). This elevation is so high that it seems anomalous. It is a minimum of 78 m higher than the "pressure ridge" just described, yet is almost directly upslope. The flow could be an earlier intravalley flow of similar composition and appearance, or could indeed be the Spring Creek either on the uplifted side of a fault or simply part of an originally very thick valley fill.

These alternatives are hard to evaluate, but I tentatively favor a single thick flow by analogy with a similar but more completely exposed relation at Prospect Creek, 1.5 km south of the quadrangle along the west side of the Cispus valley. There the vesicular top of the flow crops out as high as 690 m (2,260 ft), and the base of the flow can be traced down slope from about 640 m (2,100 ft) to the site of the radiocarbon analyses (597 m [1,960 ft]). Below the radiocarbon site, the flow extends down to about 580 m (1,900 ft) just above the flood plain of the Cispus. The total range in elevation is thus at least 110 m and indicates that the flow(s) were quite thick at Prospect Creek. The range in elevation is still greater—about 145 m—in the Blue Lake Creek area. Whether this difference is significant is not clear, but the general point is that before erosion the basalt was thick at Prospect Creek and could also have been so at Blue Lake Creek. I am obtaining trace element data to check further whether the high and low outcrops could be one or two flows.

QUATERNARY SEDIMENTARY DEPOSITS

Glacial deposits—I found it very difficult to distinguish Evans Creek Drift (map units Qed, Qem, and Qeo) from Hayden Creek Drift (map unit Qhd) in the quadrangle. One of the problems is that the drift contains relatively few fine-grained, sparsely porphyritic mafic stones, so that weathering-rind thickness—defined by Colman and Pierce (1981) for such material—is not an easily applied criterion for helping to distinguish the two drifts. Most of the stones are of plagioclase-phyric andesitic compositions or relatively coarse-grained hornblende diorite or other intrusive rock. Another problem is that many landforms in the drift appear muted as if of Hayden Creek age, even in areas previously assigned to Evans Creek by glacial geomorphologists (Crandell and Miller, 1974). Without the previous geomorphic work, I would probably have assigned all of the glacial deposits in the quadrangle to the Hayden Creek. Consequently I have little confidence in many of my age assignments for the drift in the quadrangle.

Talus and other colluvium mantle the surface of Grouse Creek and Yozoo Creek basins, but I suspect that Evans Creek Drift may underlie or be the parent material for the younger deposits. Each basin is a small cirque, the headwalls of which are precipitous, and locally there are closed depressions that suggest underlying drift or perhaps a small rock glacier. These deposits may have been transported by mass-wasting and steep-stream processes onto Evans Creek glaciers and little modified (suggestion of Willie Scott, written commun., 1993).

Cispus River blockage—The broad, flat-floored Cispus River valley narrows abruptly for about 1 km south of Blue Lake Creek Campground (pl. 1; fig. 14). A 75–m–high bluff projects eastward and pinches the river along the east side of the valley. The river seems to "detour" around the bluff, bending east at the south end of the bluff and westward and then northward at the north end. The bluff is made of a coarse, unconsolidated, diamicton (map unit Qlsb) that clearly records a sudden event that must have blocked the river at some time in the recent past. The basalt of Spring Creek likewise appears to have been covered by the diamicton, which therefore is

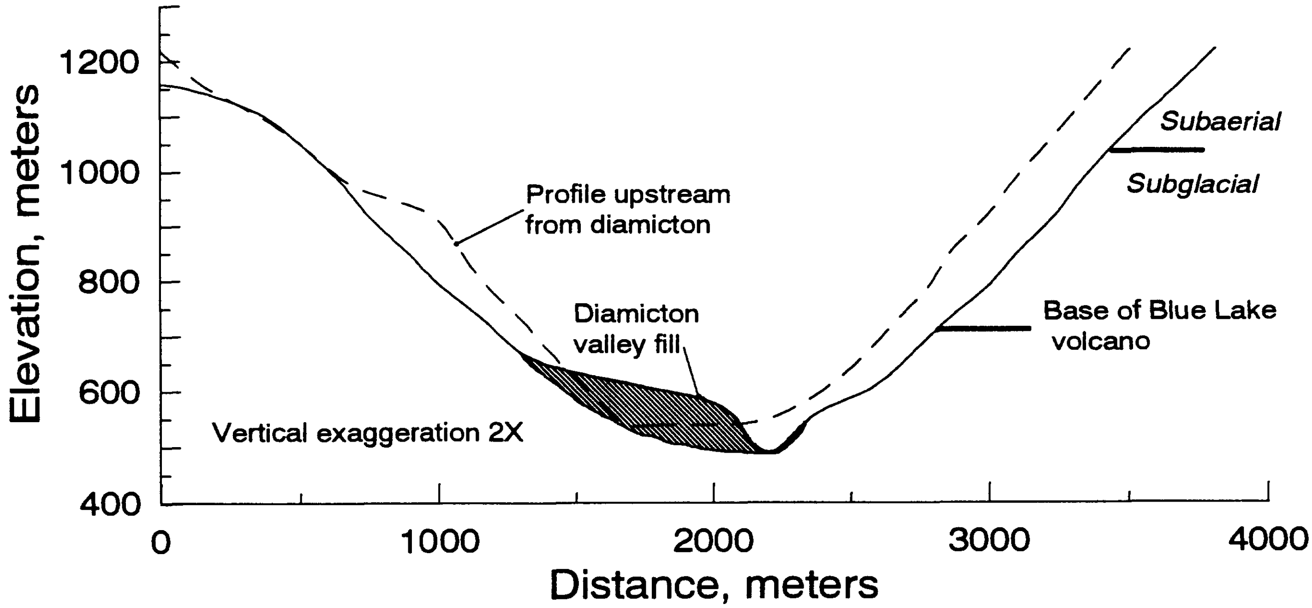

Figure 14. Profiles across Cispus River valley showing U-shape disrupted by diamicton of unit Qlsb. Dashed profile taken along Lewis County-Skamania County line. Solid profile oriented about 70° just south of highest point on diamicton. Both profiles are normal to west slope of valley. Key levels of Blue Lake volcano also indicated. Two-fold vertical exaggeration.

younger than about 21.5 ka. Probably also the outwash deposits of the Evans Creek Drift are covered, but it is difficult to prove this, for similar gravel—probably modern alluvium—follows the course of the river both upstream and downstream from the blockage.

The diamicton consists mainly of angular blocks of Tertiary rocks (andesite, lithic-lapilli tuff, and hornblende diorite) in a sand-sized matrix of similar material. Blocks are as much as 5 m across, and some lenses of highly fractured blocks of hornblende diorite—prominent because of their whitish color—reach 10 m in long dimension. Angular, typically fist-sized clasts of fine-grained, olivine-phyric basalt are locally abundant; the basalt resembles that of either Blue Lake Creek or Juniper Creek. The diamicton has no bedding or other internal breaks that would suggest several pulses of emplacement. Instead, the mass most likely moved into place as a single plug. The diamicton is best observed on the west side of the river 500–700 m due south of Blue Lake Campground. In addition, it is also well exposed on the east side of the river directly below the Blue Lake trailhead.

A tongue of the diamicton extends northward from the bluff for about 1 km along the east side of the river. Hummocks 2–5 m high dot its surface; many consist of olivine basalt but some of Tertiary rocks or mixtures of both. Such hummocks provide supporting evidence for a debris avalanche. The surface of the blockage (bluff) itself is irregular with some closed depressions but not distinctly hummocky.

The surface of the bluff slopes eastward (fig. 14), yet the west side of the valley shows no obvious scar that could mark the source for the diamicton. Where did the diamicton, which I interpret as a debris avalanche, come from?

The south wall of the unamed valley just south of Blue Lake volcano is very steep, unstable, and likely the source of the debris avalanche. All the dominant rock types in the diamicton—lithic-lapilli tuff, andesite, and hornblende diorite—crop out along the south valley wall, and piles of talus from Blue Lake volcano could readily have been picked up by the avalanche. The south side of the volcano is likewise steep, and some failure from it could have accompanied the larger avalanche. Presently the floor of the valley is underlain by loose angular rubble (boulder and cobble size) that I infer to be lag left after rain and snowmelt removed the fine matrix from the debris avalanche. The rubble is being actively and deeply incised and so apparently does not represent year-to-year alluviation.

Why does the surface of the bluff slope eastward if the source was farther east? Apparently the debris avalanche crossed the river and rode high up on west side of the Cispus valley, then slumped back and turned downstream for at least 1 km and perhaps more. A small stream draining the west side of the valley turns abruptly southward at an elevation of about 670 m (2,200 ft) before entering the Cispus at the south end of the blockage. This elevation—about 60 m (200 ft) above the general elevation of the top of the bluff—may mark the highest deposit of the debris avalanche and is a minimum for the height of runup. It is possible and even probable that the runup went much higher but left no deposit. Any small hummocks originally on the surface of the debris avalanche may have been destroyed by backflow into the valley, thereby accounting for the lack of an obvious hummocky surface on the blockage. Hummocks were then formed when the tongue of the avalanche moved northward.

The amount of time between the formation of the blockage and movement of the north-directed tongue is unknown. Perhaps it is most likely that the blockage fed the tongue as part of a continuous emplacement process, but another possibility is that the tongue developed by failure of the stationary blockage days to years later. Alternatively, the north-directed tongue may be an entirely separate debris avalanche that entered the valley from the same source after the blockage had been breached, moved downstream, and in the process forced the river farther west. I did insufficient work on these deposits to choose among these different scenarios.

Presumably the blockage dammed the river to form an ephemeral lake, but during routine field work I recognized no lacustrine deposit upstream from the blockage. More careful observation might well find pockets of such deposits. If the blockage were breached quickly, however, little if any such deposit might have formed.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Qal **Alluvium (Holocene and Pleistocene)**—Unconsolidated, moderately to well-sorted deposits of silt, sand, and gravel along major modern streams and on floors of some small cirques. Mostly Holocene and very late Pleistocene. Locally includes colluvium, fan deposits, and drift

Qc **Colluvium (Holocene and Pleistocene)**—Unsorted, unconsolidated deposits of slope wash and open-work talus, mostly along sides of major streams and below cliffs. Mostly Holocene and very late Pleistocene. Locally includes alluvium, landslide deposits, fan deposits, and drift

Qls **Landslide deposits (Holocene and Pleistocene)**—Diamictons produced by mass movement down slope. Includes both active and inactive slides. Generally results from movement of relatively dense and competent andesite and basalt lava flows or sills over clay-rich volcaniclastic rocks. Mostly Holocene and very late Pleistocene. Locally includes colluvium and drift

Qlsb **Diamicton southwest of Blue Lake Creek Campground (Holocene or Pleistocene)**—Thick, coarse-grained diamicton that partly fills Cispus River valley. Maximum thickness more than 75 m. Consists mostly of blocks of Tertiary rocks (andesite, lithic-lapilli tuff, and hornblende diorite) in finer-grained matrix. Single blocks reach 5 m in diameter, and lenses of concentrated blocks of hornblende diorite, 10 m. Locally contains scattered to abundant clasts of olivine basalt of Juniper Creek and (or) olivine basalt of Blue Lake Creek. Hummocky surface on deposit, particularly between Smoothrock Creek and Blue Lake Creek; hummocks composed mainly of blocks of olivine basalt. Probably younger than outwash deposits of Evans Creek Drift (unit Qeo). Probably Holocene but could be very late Pleistocene. Locally includes alluvium along Cispus River

Qf **Alluvial fan deposits (Holocene and Pleistocene)**—Local poorly bedded and sorted alluvial deposits at mouths of tributaries to major drainages (Deception Creek, Cispus River, and North Fork Cispus River.) Mostly Holocene and very late Pleistocene. Includes alluvium, colluvium, and possibly drift

GLACIAL DEPOSITS

Qed **Evans Creek Drift (Pleistocene)**—Till, moraine, and outwash deposits, principally in valleys of Smith and Deception Creeks. Slightly weathered to unweathered; most clasts in B soil horizon lack significant weathering rinds. However, contains some clasts with thicker weathering rinds that could be derived from local deposits of Hayden Creek Drift (unit Qhd). Some deposits assigned to Hayden Creek Drift along Timonium and Cat Creeks could belong to unit. Age is late Pleistocene, approximately 17–25 ka (Barnosky, 1984; Crandell, 1987). Queried where possibly of Hayden Creek age. Locally divided into:

Qem **Moraine deposits**—Lithologically resembles till but forms morphologically distinct low ridges along margins of till deposits along Deception Creek at north edge of quadrangle. Many stones in these deposits contain relatively thick (1–2 mm) weathering rinds and could be reworked from Hayden Creek Drift. Alternatively, the deposits should be assigned to the Hayden Creek Drift

Qeo **Outwash deposits**—Unconsolidated, bedded, moderately sorted to well-sorted boulder to pebble gravel, sand, and silt forming valley fill and terraces in Cispus River valley. Several different terrace levels recognized (most obviously in the adjacent Tower Rock quadrangle (Swanson, 1991), presumably reflecting episodic river downcutting and (or) glacier retreat. Deposited by meltwater streams draining glaciers in headwaters of Cispus River and on Mount Adams. Possibly less than 21.5 ± 0.5 ka (radiocarbon years) (^{14}C age of soil at base of basalt of Spring Creek; Hildreth and Fierstein in press), but see text for discussion. Locally includes modern alluvium and colluvium

Qhd **Hayden Creek Drift (Pleistocene)**—Principally till but may include outwash and moraine deposits. Contains numerous clasts with weathering rinds 1–2 mm thick in B soil horizon. Upper 0.5–1 m of deposit deeply weathered. These features suggest correlation with Hayden Creek Drift (Crandell and Miller, 1974; Colman and Pierce, 1981). Mapped only south of North Fork Cispus River, but some deposits mapped as Evans Creek Drift north of river might be in unit. Also, some Evans Creek Drift might be included in unit along upper Timonium and Cat Creeks. Age late Pleistocene but otherwise uncertain; estimates range from about 60 ka (Crandell and Miller, 1974; Crandell, 1987) to 300 ka (Dethier, 1988). Colman and Pierce (1981) prefer age of about 140 ka on basis of thickness of weathering rinds. Queried where possibly of Evans Creek age. Includes alluvium, colluvium, and possibly fan and landslide deposits

BASALT FLOWS AND RELATED DEPOSITS

Qbs **Basalt of Spring Creek of Korosec (1987) (Pleistocene)**—Nonporphyritic to sparsely olivine-phyric, diktytaxitic olivine basalt along Cispus River valley. Equivalent to the "basalt of Hill 5162" of Hammond (1980). Forms prominent bench—though mostly hidden by dense forest—between about 565 m and 640 m (1,850 and 2,100 ft) elevation along west side of Cispus River near Juniper Creek. Also occurs in poorly exposed area between about 495 m and 535 m (1,620 and 1,730 ft) elevation on east side of Cispus River just north of mouth of Blue Lake Creek. Characterized by low K_2O content (0.12–0.25 percent; Swanson [1991, table 1] and table 1), deep mauve clinopyroxene, and distinctive mode (Swanson, 1991, table 4). Occurs in valley probably carved largely by glacier of Hayden Creek age. Rests on charred, organic-rich soil with age of 21.5 ± 0.5 ka radiocarbon years (Hildreth and Fierstein, in press) that contains roots with age of 41.1 ± 1.3 ka radiocarbon years (USGS lab number 3278, analysis by Debbie Trimble) at road crossing of Prospect Creek 2.1 km south-southeast of Juniper Creek, along the prominent bench. Gravel derived from unit occurs in outwash deposits of Evans Creek Drift. Includes small remnant of flow tucked into gorge along Blue Lake Creek 500–600 m north-northeast of Blue Lake Creek Campground. See text for discussion of this remnant. Normal magnetic polarity

Qbj **Basalt of Juniper Creek (Pleistocene)**—Aphyric to sparsely olivine-phyric, fine-grained to glassy olivine basalt forming tuff cone and associated thin flows in extreme southwestern corner of quadrangle. Two outcrop areas extend west to one or two vents in adjacent Tower Rock and McCoy Peak quadrangles (Swanson, 1991, 1992). A third is known only from cuts along new logging road 700 m north of Juniper Creek, where deposit is chiefly palagonitized tephra. Bedding parallels topography and so uniformly dips toward Cispus valley. Characterized by high K_2O content (table 1, no. 5–6; Swanson, 1991, table 1, no. 10; Swanson, 1992, table 1, no. 3), and rare red-brown biotite in groundmass (Swanson, 1992, table 4, col. 2). Contains rare small xenoliths of strained, corroded, multigranular quartz. Flows are generally hackly jointed as in entablatures; water quenching is almost certain. Age not known but probably younger than most Hayden Creek Drift in Cispus River valley, because the flow mantles the side of a U-shaped valley eroded by a glacier in Hayden Creek time (Swanson, 1991; plate 2, cross section C–A'). Possibly erupted during waning stage of Hayden Creek time, when retreating glacier still occupied Cispus River valley (see text) and was able to quench the basalt. Degree of dissection indicates unit is older than basalt of Spring Creek. Normal magnetic polarity

Qgbl **Basaltic gravel from Blue Lake volcano (Pleistocene)**—Angular to subangular, sand- to boulder-size, poorly to moderately well sorted, open-work gravel deposit containing almost exclusively clasts derived from water-quenched basalt of Blue Lake Creek. Clasts of Tertiary rocks occur rarely, and are much better rounded and probably reworked from stones in till or carried in glacier. Deposit occurs in two areas. The largest is along lower Blue Lake Creek (elevation of 500–585 m [1,640–1,920 ft]), where the deposit is being quarried for gravel. The second outcrop area is higher (655–705 m [2,150–2,310 ft]) and just north of Blue Lake Creek (across the creek from Blue Lake volcano). Bedding in both areas dips gently west, roughly parallel to current surface slope. Possibly deposited by subglacial streams, formed by melting during eruption. See text for discussion

Qbbl **Olivine basalt of Blue Lake Creek (Pleistocene)**—Aphyric to sparsely olivine-phyric, generally fine-grained to glassy, olivine basalt forming lava flows and tephra between Blue Lake and Cispus River. Petrographically and chemically (table 1) indistinguishable from basalt of Juniper Creek, and probably part of same broad episode of basaltic volcanism. Forms a small volcano (here called Blue Lake volcano) whose lower part is subglacial and upper part is subaerial. Basalt in lower 175 m of unit above Blue Lake Creek consists of hackly jointed single(?) flow probably erupted and quenched against (under) ice. Several oxidized, finely diktytaxitic flows surmount the subglacial pedestal (contact indicated by dash-dot line on geologic map and cross section C–A′) and underlie an oxidized cinder cone (stipple); they lack evidence of quenching and probably were erupted subaerially. Edifice straddles sharp ridge underlain by Tertiary rocks (cross section C–A′). Probably formed in and above valley glacier of Hayden Creek age, but after the glacier had started to recede (see text for discussion). Normal magnetic polarity

INTRUSIVE ROCKS

Thd **Hornblende diorite and related rocks (Miocene)**—Hornblende-clinopyroxene-plagioclase-phyric diorite, quartz diorite, and fine-grained but holocrystalline variants of these rock types. Forms sills, one dike, and several small irregularly shaped masses in southern two-thirds of quadrangle, south of North Fork Cispus River. Unit extends into French Butte, Tower Rock, and McCoy Peak quadrangles (Swanson, 1989, 1991, 1992), as well as the East Canyon Ridge quadrangle (D.A. Swanson, unpublished mapping), and forms the comagmatic "intrusive suite of Kidd Creek" of Marso and Swanson (1992). Grain size largely dependent on nature of body: silicic andesite and dacite in dikes, thin sills, and chilled margins of larger bodies; and microdiorite and quartz microdiorite to diorite and quartz diorite in most sills and irregularly shaped masses. Average grain size of diorite reaches 1 mm but typically is 0.2–0.4 mm. Hornblende occurs in groundmass but chiefly as phenocrysts as long as 5 mm, with scattered megacrysts and clots to more than 1 cm in diameter. Hornblende phenocrysts form 1–5 percent of rock, clinopyroxene phenocrysts 1–3 percent, and plagioclase phenocrysts, about 5–15 (rarely 20) percent. Sparse orthopyroxene present in some samples. Quartz phenocrysts or xenocrysts, commonly partly resorbed, occur rather commonly in some bodies. Groundmass quartz present in some diorite and plentiful in quartz diorite. Inclusions of variously textured diorite, and clots of hornblende and plagioclase, fairly common. Chemically the unit is dacite and silicic andesite, with characteristically low TiO_2, FeO*, and MnO (table 1) compared to other rocks in quadrangle at similar SiO_2 content. In general much fresher than host rock, and hornblende is commonly unaltered. Large pluglike and irregular bodies are commonly more highly altered than thinner dikes and sills. Age is about 12 Ma on basis of several zircon fission-track ages outside the quadrangle (Swanson, 1991, tables 3 and 4). Three large sills are indicated separately on map but may be connected at depth:

Thdr **Hornblende diorite of Bishop Ridge**

Thdy **Hornblende diorite of Yozoo Creek**

Thdp **Hornblende diorite of Point 5644**

Tais **Andesite intrusion of Swede Creek (Miocene or Oligocene)**—Fine- to medium-grained, nonporphyritic to very sparsely plagioclase-phyric, pilotaxitic andesite and microdiorite. Plagioclase has "dirty" appearance owing to alteration. Small amount of quartz in clay-rich groundmass. Columnar joints plunging moderately to steeply southeast characterize intrusion along ridge crest south of Swede Creek. Crudely columnar normal to nearly vertical northeast margin on hillside south of Swede Creek. Mafic andesite composition (table 1, nos. 50 and 55). Incorrectly mapped as andesite lava flow(s) in adjacent Tower Rock quadrangle (Swanson, 1991); samples 42 and 43 of table 1 in Swanson (1991) are from this intrusion and chemically and petrographically resemble the samples from the Blue Lake quadrangle. The andesite intrusion of Swede Creek cuts strata roughly about 30 Ma and so can be no older than late Oligocene

Tai **Andesite and basaltic andesite intrusions (Miocene and Oligocene)**—Dikes, sills, and fewer small subequant hypabyssal intrusions of aphyric and one- or two-pyroxene-plagioclase-phyric basaltic andesite and andesite. Fine-grained and texturally resembles lava flows (unit Ta). Dikes characterized by subhorizontal columnar jointing, quenched margins, steep contacts with host rocks, and widths of 1–5 m. Dike of basaltic andesite composition (table 1, no. 22) east of Timonium Creek near east edge of quadrangle is 20–30 m wide, possibly more. Local concentrations of dikes suggest former intrusive centers near Cold Springs Butte (near east edge of quadrangle), Castle Butte (north of Cispus Point), on Bishop Ridge 1.5 km northeast of Blue Lake, and especially east of Smith Creek. No contact seen in quadrangle with unit Thd, but elsewhere unit is older than the hornblende-bearing intrusions (Swanson, 1992). Typically more highly altered than unit Thd. Probably in part feeders for flows of unit Ta, but many dikes could be younger and have fed flows now eroded away. Most dikes are roughly perpendicular to bedding and would be vertical if host rock were tilted back to horizontal. Hence the dikes are probably older than the folding, a relation found in other mapped quadrangles (Swanson, 1991, 1992)

Tg **Gabbro (Miocene and Oligocene)**—Coarse-grained, locally ophitic, dark, slightly porphyritic to seriate pyroxene gabbro. Forms two small intrusions, one a sill-like body across the North Fork Cispus River from Siwash and Jackpot Creeks, the other a small irregular body 600 m north-northwest of the big bend of Cat Creek. Interstitial quartz occurs in the sill-like body. Altered mafic mineral may be olivine. Basalt to basaltic andesite in composition, with rather high content of Al_2O_3 (table 1, nos. 3, 8, and 12; Al_2O_3 >19 percent). The body along North Fork Cispus River may be related to the basaltic andesite intrusion of Siwash Creek, for both are characterized by high contents of Al_2O_3

Taiw **Basaltic andesite intrusion of Siwash Creek (Miocene or Oligocene)**—Cross-cutting intrusive body exposed mainly along Siwash Creek. Medium-grained, in places microdioritic. Plagioclase and generally clinopyroxene-phyric. Generally holocrystalline, with intergranular groundmass, but some quenched samples have devitrified glass in groundmass. Irregular shape and in places difficult to distinguish from lava flows. Basaltic andesite in composition (table 1, nos. 15, 17, 18, 21). High content of Al_2O_3 (>19.5 percent), except for no. 18, which could be sample from host rock rather than intrusion itself

Taim **Basaltic andesite intrusion south of St. Michael Lake (Miocene or Oligocene)**—Highly jointed, fine- to medium-grained, nonporphyritic to seriate (plagioclase and clinopyroxene) intrusion cutting microdiorite of unit Tdi. Vertical contact exposed along western and northern margin of intrusion. Craggy outcrops. Basaltic andesite composition (table 1, nos. 24 and 25). Locally abundant zeolites

Tdi **Microdiorite (Miocene and Oligocene)**—Dark, medium- to fine-grained, intergranular microdiorite in two sill-like bodies, one just east of Horseshoe Point and the other, smaller body just east of the big bend in Cat Creek. Both bodies have basaltic andesite composition (table 1, nos. 26 and 30). The body near Horseshoe Point is cut by the andesite intrusion south of St. Michael Lake

LAVA FLOWS AND VOLCANICLASTIC ROCKS

Ttv **Volcaniclastic rocks (Miocene and Oligocene)**—Bedded conglomerate, sandstone, siltstone, and lithic diamictite containing volcanic-derived clasts, as well as lithic- and lesser pumice-lapilli tuff and fine-grained tuff. Typically brown to buff, with the tuffaceous rocks generally green and locally white or mauve. Different rock types are interbedded at all scales, and attempts to map them separately proved unworkable. However, well-bedded, chiefly epiclastic rocks are most common in the quadrangle and are particularly well exposed east of Timonium Creek and in road cuts along the North Fork Cispus River upstream from the mouth of Timonium Creek (Stine, 1987). Lithic-lapilli tuff and pumice-lapilli tuff are interbedded with the epiclastic rocks near Timonium Creek but are most abundant in the younger part of the section, such as along and west of Blue Lake Ridge and in the high country north of North Fork Cispus River. In Blue Lake quadrangle, Hammond (1980) and Korosec (1987) assigned most of unit to Ohanapecosh Formation, and Stine (1987) did likewise for the bedded rocks near Timonium Creek.

Bedded epiclastic rocks range in grain size from silt to gravel (dominantly sand), in sorting and rounding from poor to good, and in bed thickness from less than 1 cm to more than 50 cm (generally a few centimeters). Sedimentary structures, such as cross bedding, channels, and both normal and inverse size grading common. Clasts are entirely of volcanic derivation, chiefly basaltic andesite and andesite but including more silicic rock types. Fossil wood, chiefly stems and twigs, plentiful locally.

Clasts in lithic diamictite range in size from sand to boulders. Wide range in degree of rounding; angular boulders commonly mixed with rounded gravel and cobbles. Thickness of single beds typically several meters but ranges from 1 m to more than 15 m. Fossil wood abundant locally. Commonly interbedded with fluvial sandstone but also abundant in tuffaceous part of section. Probably mostly of debris-flow origin.

Pumice- and pumice-lithic-lapilli tuff is probably of pyroclastic-flow origin. Welding occurs but is not common. Base of one prominent welded tuff shown on the geologic map between Siwash and Jackpot Creeks. Thickness of single lapilli-tuff beds ranges from several meters to more than 10 m. Typically plagioclase-phyric, with minor clinopyroxene; no hornblende and rare quartz. Lithic clasts are sparse to abundant and generally andesite or dacite in composition. Wood, generally charred, is locally present; good example exposed in road cut just north of bridge across North Fork Cispus opposite mouth of Timonium Creek.

Unit locally includes andesite flows and sills too thin to map separately

Tdcb **Diamictite below Castle Butte (Miocene or Oligocene)**—Thick, cliff-forming andesitic diamictite underlying Cispus Point, Castle Butte, and Twin Sisters. Very coarse in most places, with angular clasts several meters in diameter common. More than 120 m thick in many places, though thinner toward west. Possibly results from debris avalanche from an erupting volcano. Could be mapped separately from rest of unit Ttv only because of exceptional exposure in cliffs. Several similar, though thinner, cliff-forming diamictites crop out east of Smith Creek, and one or more could be lateral equivalents of unit. In particular, the cliff-forming diamictite 700 m east-southeast of Jackpot Lake is a likely correlative

Ta **Andesite and basaltic andesite lava flows (Miocene and Oligocene)**—Fine- to medium-grained, highly phyric (>20 percent) to slightly phyric (<5 percent) or even aphyric, darkly hued, lava flows and associated basal and flow-top breccia of basaltic andesite, andesite, and uncommon dacite. Flows typically 5–20 m thick, commonly platy and(or) columnar, with vesicular or amygdaloidal zones in many places. Phenocrysts are dominantly plagioclase, with less abundant clinopyroxene and hypersthene; most common phenocryst assemblage (with minerals listed in decreasing order of abundance) is plagioclase-clinopyroxene, followed by plagioclase-clinopyroxene-hypersthene and plagioclase-hypersthene-clinopyroxene. Rare phenocrysts of olivine (typically altered to clay). Groundmass texture chiefly fine-grained intersertal or intergranular, with flow-aligned microlites common; very fine-grained pilotaxitic texture characterizes more silicic rocks. Fresh glass uncommon; glass generally altered to clay minerals. Compositions range from mafic basaltic andesite to mafic dacite (table 1). Dacite included in the unit resembles andesite in the field and generally in thin section and so was not mapped separately; it probably makes up less than 10 percent of the unit. In general basaltic andesite is more highly porphyritic than andesite, but exceptions are common. Andesite and basaltic andesite are interbedded and cannot be mapped separately short of analyzing each flow. Dikes and other intrusions of unit Tai probably fed some flows in this unit. Widely interbedded with volcaniclastic rocks (unit Ttv) and includes some volcaniclastic beds too thin to map separately

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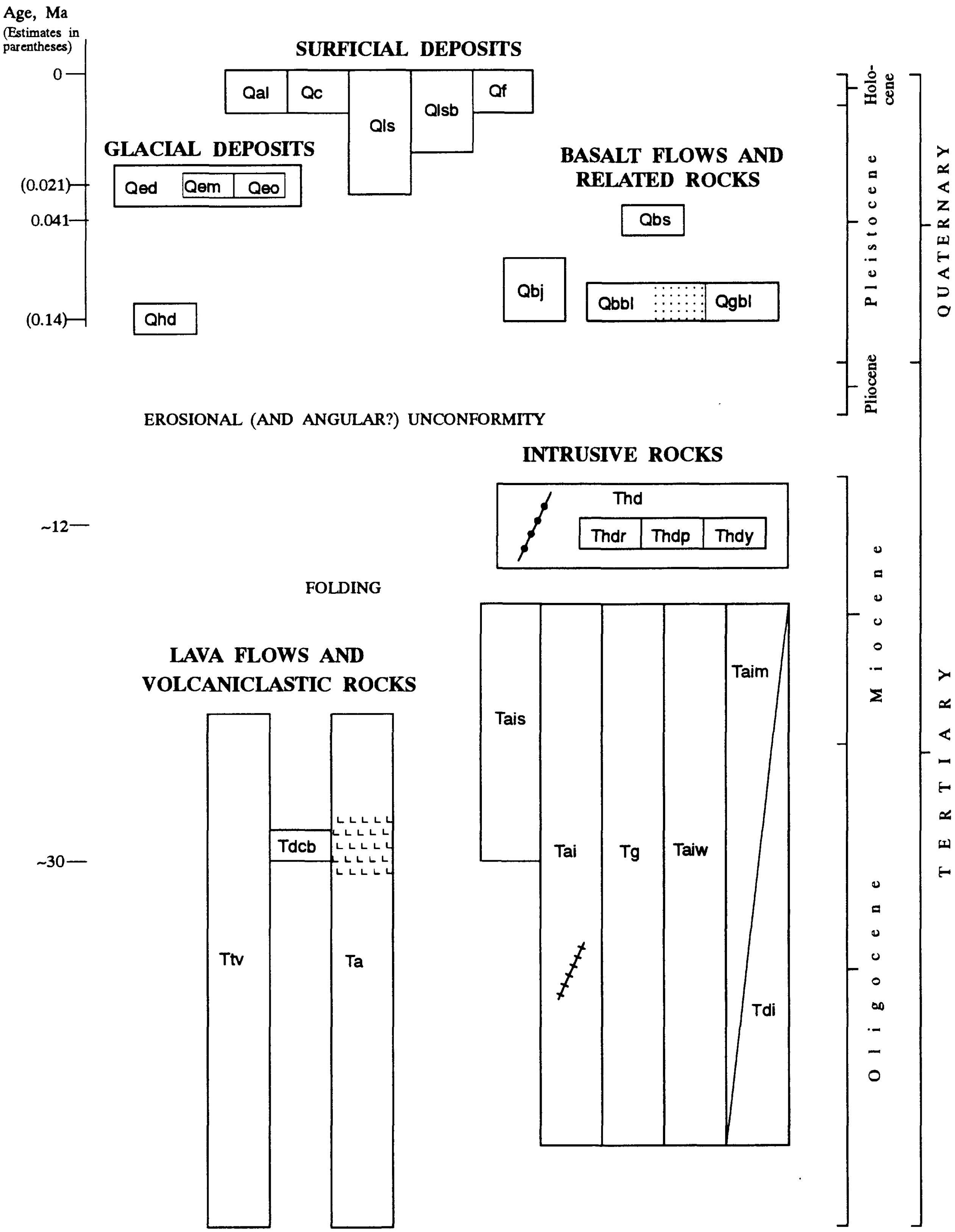
CORRELATION OF MAP UNITS



EXPLANATION OF MAP SYMBOLS

Contact, dashed where approximately located, queried where uncertain, dotted where concealed

Trace of prominent welded tuff east and west of Jackpot Creek

Trace of prominent bed of lithic-lapilli tuff west of Deception Creek

Approximate contact between subglacial and subaerial parts of Blue Lake volcano

Strike and dip of bedding and flow contacts

- Inclined
- Horizontal or dip less than 5 degrees and strike poorly defined

Attitude of prominent joint set in intrusive body

Folds, dashed where approximately located, dotted where concealed

- Trace of axis of anticline
- Trace of axis of monocline, arrow on side of greater dip

Faults, dashed where approximately located, dotted where concealed, queried where uncertain

- High-angle fault; bar and ball on downthrown side if known
- Direction and magnitude of dip of fault plane
- Fault or shear zone with apparent right-lateral sense of displacement
- Fault or shear zone with apparent left-lateral sense of displacement

Dikes, queried where location uncertain

- Hornblende diorite of unit Thd
- Dike of andesite and basaltic andesite in unit Ta

Site of chemically analyzed sample, with map number. Number refers to table 1

- Basalt
- Basaltic andesite
- Andesite
- Dacite
- Rhyodacite and rhyolite