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U.S. GEOLOGICAL SURVEY

Geologic map of the Tower Rock quadrangle, southern Cascade Range, Washington

by

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Open-File Report 91-314

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CONTENTS

Introduction 1
Acknowledgments 2
Rock terminology and chemical classification 2
General geology 6
Tertiary rocks 7
- Volcaniclastic rocks 7
- Lava flows 7
- Dikes and sills of pyroxene andesite and basaltic andesite 8
- Dikes and sills of hornblende andesite, dacite, diorite, and quartz diorite 9
- Ages 10

Young olivine basalt 12
- Basalt northwest of Tongue Mountain 12
- Basalt of Juniper Creek 14
- Basalt of Spring Creek (Korosec, 1987) 14

Structure 16
Description of map units 18
References cited 23
Correlation of map units 25
Explanation 26

FIGURES

1. Map showing locations of Tower Rock and other quadrangles 1
2. Map of Tower Rock quadrangle, showing geographic features mentioned in text 1
3. Total alkali-silica classification diagram for rocks in Tower Rock quadrangle 2
4. Plot of phenocryst assemblage vs. SiO_2 for rocks in Tower Rock and other mapped quadrangles 5
5. Locations of samples collected in Tower Rock quadrangle 5
6. Alkali-lime classification for Tertiary rocks in Tower Rock quadrangle 5
7. Plot of FeO*/MgO vs. SiO_2 for Tertiary and Quaternary rocks in Tower Rock quadrangle 6
8. Plot of K_2O vs. SiO_2 for rocks in Tower Rock quadrangle 6
9. Equi-area rose diagram of dikes in Tower Rock quadrangle 9
10. Plot of FeO* vs. SiO_2 for Tertiary and Quaternary rocks in Tower Rock quadrangle 10

TABLES

1. Chemical analyses of rocks from Tower Rock quadrangle 3
2. Radiometric ages from rocks in Tower Rock quadrangle 11
3. Radiometric ages from rocks near but outside Tower Rock quadrangle 11
4. Modes of young olivine basalt in Tower Rock and Greenhorn Buttes quadrangles 11

PLATES

Geologic map of Tower Rock quadrangle .... Separate sheet
Cross sections of Tower Rock quadrangle .... Separate sheet

GEOLOGIC MAP OF THE TOWER ROCK QUADRANGLE, SOUTHERN CASCADE RANGE, WASHINGTON

By Donald A. Swanson

INTRODUCTION

The Tower Rock 7.5-minute quadrangle is centered about 40 km northeast of Mount St. Helens and 30 km west of the crest of the Cascade Range in southern Washington (fig. 1). The quadrangle borders the east side of the Greenhorn Buttes quadrangle and the northeast corner of the French Butte quadrangle, both of which have recently been mapped geologically (Swanson, 1989). The Greenhorn Buttes and French Butte quadrangles in turn lie just east of the Cowlitz Falls and Spirit Lake East quadrangles, respectively (Evarts and Ashley, in press a, b). Most of the Tower Rock quadrangle is drained by the Cispus River and its major tributaries, McCoy and Yellowjacket Creeks; the northernmost part of the quadrangle straddles the divide between the Cispus and Cowlitz Rivers (fig. 2).

The quadrangle is underlain mainly by mid-Tertiary (chiefly late Oligocene and early Miocene) volcanic deposits, both lava flows and more abundant volcaniclastic rocks, that range from olivine-bearing basalt (uncommon) to rhyolite but consist dominantly of basaltic andesite, andesite, and dacite. Numerous dikes and sills, chiefly of andesite and SiO_2-poor dacite, cut the section, as do several larger intrusions of similar composition that may once have been subvolcanic magma bodies. Very low-grade (zeolite-facies) metamorphism pervades most of the Tertiary rocks and gives a greenish cast to many of the once-glassy volcaniclastic rocks. Flows and pyroclastic deposits of Pliocene(?) and Quaternary olivine basalt rest unconformably on the Tertiary rocks in a few places. Unconsolidated deposits related to at least two episodes of late Pleistocene glaciation cover parts of the area (Crandell and Miller, 1974). The quadrangle is downwind from Mount St. Helens, and tephra from eruptions of the past 50,000 yr mantles all units (Mullineaux, 1986). The tephra was not mapped owing to its ubiquitous presence.

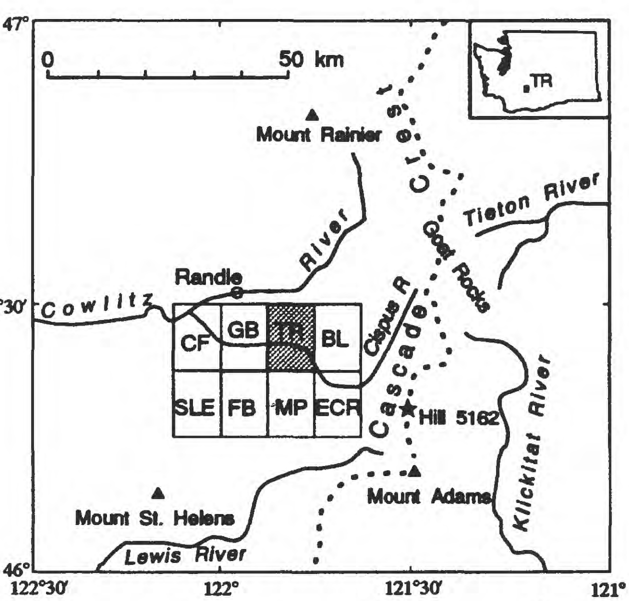

Figure 1. Map showing locations of Tower Rock quadrangle (TR, shaded) and other 7.5′ quadrangles mentioned in text. Quadrangle abbreviations are: CF, Cowlitz Falls; SLE, Spirit Lake East; GB, Greenhorn Buttes; FB, French Butte; MP, McCoy Peak; BL, Blue Lake; ECR, East Canyon Ridge.

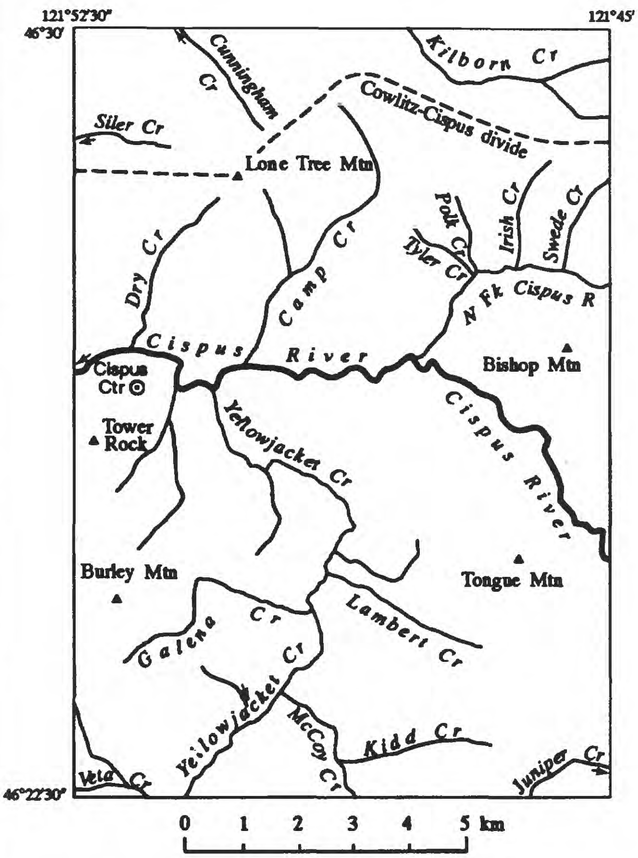

Figure 2. Map of Tower Rock quadrangle, showing major streams and high points mentioned in text.

Bedrock exposures are relatively limited in many places, owing to dense forest cover and locally thick glacial drift, but overall the number of exposures is much greater than in the quadrangles to the west, owing to a thinner mantle of tephra. Natural exposures along creeks and hillsides, combined with road cuts, permit adequate determination of most stratigraphic relations.

The rationale for this research is given in Swanson (1989). In brief, the intent is to tie the stratigraphy of the area near and northeast of Mount St. Helens (Evarts and Ashley, 1984, in press a, b; Evarts and others, 1987; Swanson, 1989) into the classic Tertiary stratigraphic section in the Mount Rainier-White Pass area as defined by Fiske and others (1963) and modified by Vance and others (1987). This work will establish an improved regional stratigraphic framework for the southern Washington Cascades and complete a geologic transect across the west side of the Cascade Range. In addition, the research will test whether a major electrical conductivity layer in the upper crust, the Southern Washington Cascades Conductor of Stanley and others (1987) has a recognizable influence on the geology of the area. The quadrangles being mapped lie well within the boundaries of the conductor.

Only small-scale (1:100,000 and smaller) reconnaissance geologic work had been done in the quadrangle before this research. Chief among the reconnaissance mapping was that by Hammond (1980), Korosec (1987; included in Walsh and others, 1987), and Smith (1990). Schuster (1973) wrote a learning guide for students on the geology near the Cispus Environmental Center.

ACKNOWLEDGMENTS

I thank Chuyler Freeman, Jack Kleinman, Rick Wessels, and Barbara White for help in the field and Jeff Marso for many discussions about the hornblende-bearing intrusive rocks. Jeff also separated the hornblende for the K-Ar work and contributed one of his samples to the cause. Barry Goldstein (University of Puget Sound) provided many stimulating ideas on the glacial history of the area, which I'm leaving for him to follow up on. Wes Hildreth and Judy Fierstein permitted use of an unpublished ^{14}C age for the basalt of Spring Creek. Mike Korosec (formerly of the Washington Department of Natural Resources, Division of Geology and Earth Resources) kindly furnished unpublished field sheets and chemical analyses from his reconnaissance work for the new geologic map of Washington. Continued discussions with Russ Evarts, Roger Ashley, and Jim Smith have taught me a lot, and Evarts was instrumental in obtaining four K-Ar ages. Joe Vance (University of Washington) donated considerable time and effort to obtain three zircon fission-track ages in and near the quadrangle.

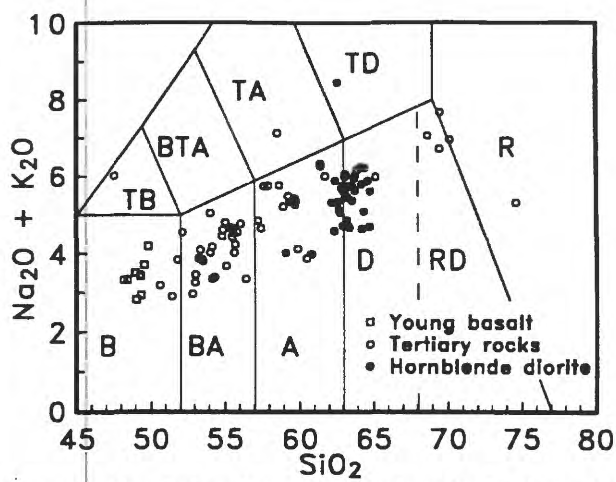

Figure 3. Chemical analyses of volcanic rocks in Tower Rock quadrangle plotted on total alkali-silica classification diagram, modified from Le Bas and others (1986) to include a field for rhyodacite. B, basalt; BA, basaltic andesite; A, andesite; D, dacite; RD, rhyodacite; R, rhyolite; TB, trachybasalt; BTA, basaltic trachyandesite; TA, trachyandesite; TD, trachydacite. Data from table 1. Samples in fields TB, TA, and TD are altered (table 1, nos. 1, 44, and 62, respectively). Hornblende diorite suite is of Tertiary age but younger than the other Tertiary rocks.

Russ Evarts and Dave Sherrod reviewed and greatly improved the map and text.

ROCK TERMINOLOGY AND CHEMICAL CLASSIFICATION

I classified chemically analyzed samples according to recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks (Le Bas and others, 1986), which I slightly modified to include a field for rhyodacite (fig. 3). For the total alkali contents found, the analyzed rocks can be 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 the following rather consistent phenocryst assemblages (fig. 4), with minerals given in approximate order of decreasing abundance: *basalt*, ol ± cpx ± pl ± rare hyp; *basaltic andesite*, pl ± cpx ± hyp ± ol; *andesite*, pl ± cpx ± hyp ± rare ol ± hb; *dacite*, assemblage similar to that for andesite (except for rare quartz and no olivine), but hypersthene 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 has been found only in

Table 1. Chemical Analyses from the Tower Rock Quadrangle, Washington, 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	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	Ta[1]	MK85720	47.4	0.80	16.3	2.80	3.20	0.28	4.88	18.07	6.00	0.00	0.28				100.01	47.50	0.80	16.35	5.74	0.28	4.90	18.13	6.02	0.00	0.28	6.02	1.17	121	46.50	46	29.70
2	Qba	87-191	47.4	1.42	17.2	3.41	7.55	0.17	7.70	10.50	3.10	0.18	0.14	0.05	0.14	0.05	99.01	48.16	1.44	17.47	10.79	0.17	7.82	10.67	3.15	0.18	0.14	3.33	1.38	121	45.63	46	25.66
3	Qba	87-104	47.8	1.32	17.4	2.22	8.35	0.17	7.70	10.80	3.10	0.20	0.14	0.16	0.21	0.06	99.43	48.39	1.34	17.61	10.48	0.17	7.80	10.73	3.14	0.20	0.14	3.34	1.34	121	51.50	46	27.08
4	Qba	87-227	48.5	1.40	17.4	1.58	9.02	0.17	7.20	10.40	3.30	0.20	0.14	0.12	0.36	0.06	99.85	48.92	1.41	17.55	10.53	0.17	7.26	10.49	3.33	0.20	0.14	3.53	1.45	121	47.08	46	27.24
5	Qba	MK98431	48.7	1.47	16.4	5.38	6.16	0.18	8.41	10.23	2.70	0.12	0.17				99.92	49.01	1.48	16.52	11.06	0.18	8.46	10.29	2.71	0.12	0.17	2.84	1.31	121	45.52	46	25.47
6	QTbt	88-027	48.9	1.46	16.0	1.82	9.25	0.18	8.50	9.72	2.95	0.49	0.21	0.39	0.12	0.00	99.99	49.25	1.47	16.11	10.96	0.18	8.56	9.79	2.97	0.49	0.21	3.46	1.28	121	48.47	46	25.97
7	QTbt	88-025	48.8	1.33	16.6	6.78	4.88	0.18	7.68	9.89	2.99	0.40	0.17	0.32	0.14	0.00	100.16	49.28	1.34	16.76	11.09	0.18	7.76	9.99	3.02	0.40	0.17	3.42	1.43	121	48.08	46	25.60
8	Qba	MK98412	49.1	1.43	16.3	5.33	6.11	0.18	8.28	10.03	2.77	0.17	0.17				100.07	49.34	1.44	16.35	10.96	0.18	8.32	10.08	2.78	0.17	0.17	2.95	1.32	121	46.95	46	27.05
9	QTbt	88-026	49.4	1.62	16.0	1.71	9.08	0.17	8.33	9.57	3.05	0.66	0.28	0.35	0.09	0.02	100.33	49.55	1.62	16.05	10.65	0.17	8.36	9.60	3.06	0.66	0.28	3.72	1.27	121	48.25	46	25.60
10	Qbj	89-073	49.5	1.27	16.4	4.25	4.93	0.15	8.45	10.30	2.98	1.20	0.41	0.19	0.16	0.00	100.19	49.79	1.28	16.50	8.81	0.15	8.50	10.36	3.00	1.21	0.41	4.20	1.04	121	45.29	46	22.58
11	Tb	89-002	49.7	1.35	19.8	5.52	4.19	0.21	3.38	11.10	2.76	0.39	0.16	0.48	0.76	0.47	100.27	50.61	1.37	20.16	9.33	0.21	3.44	11.30	2.81	0.40	0.16	3.21	2.77	121	46.97	46	28.12
12	Tb	89-082	49.8	1.78	16.0	3.54	7.07	0.16	6.45	9.61	2.65	0.18	0.18	1.34	1.04	0.14	99.72	51.41	1.82	16.52	10.40	0.17	6.66	9.92	2.74	0.19	0.19	2.92	1.56	121	48.29	46	26.85
13	Tbi	87-113	48.5	1.66	16.0	7.27	4.08	0.22	4.20	8.60	2.70	0.92	0.30	1.33	3.18	0.00	98.96	51.75	1.77	17.07	11.33	0.23	4.48	9.18	2.88	0.98	0.32	3.86	2.53	121	52.11	46	24.35
14	Ta	87-110	49.4	1.68	17.1	3.98	6.23	0.19	3.40	8.62	3.40	0.92	0.24	3.86	0.63	0.03	99.68	52.13	1.77	18.05	10.35	0.20	3.59	9.10	3.59	0.97	0.25	4.56	2.88	121	50.63	46	24.62
15	Ta	MK85721	52.6	1.43	16.5	4.76	5.46	0.16	6.18	9.76	2.61	0.37	0.21				100.04	52.80	1.44	16.60	9.79	0.16	6.21	9.81	2.62	0.37	0.21	2.99	1.58	121	46.72	46	29.44
16	Ta	87-098	51.7	1.44	17.2	2.79	7.75	0.18	4.30	9.08	2.90	0.30	0.18	0.89	0.70	0.02	99.43	53.00	1.48	17.63	10.52	0.18	4.41	9.31	2.97	0.31	0.18	3.28	2.39	121	50.02	46	24.45
17	Tai	89-074	51.1	1.29	16.7	4.51	4.55	0.16	5.01	9.89	2.70	0.65	0.22	1.02	2.04	0.03	99.87	53.05	1.34	17.34	8.94	0.17	5.20	10.27	2.80	0.67	0.23	3.48	1.72	121	46.18	46	23.15
18	Ta	88-048	52.8	1.53	17.3	2.94	6.98	0.18	3.97	9.65	3.20	0.66	0.25	0.50	0.31	0.03	100.30	53.24	1.54	17.45	9.71	0.18	4.00	9.73	3.23	0.67	0.25	3.89	2.42	121	51.79	46	28.57
19	Ta	89-098	51.9	1.66	16.6	2.01	7.91	0.17	3.74	9.21	3.16	0.84	0.27	0.93	0.33	1.57	100.32	53.35	1.73	17.06	9.99	0.17	3.84	9.47	3.25	0.86	0.28	4.11	2.60	121	49.79	46	28.67
20	Ta	87-090	51.9	1.48	17.8	3.57	6.24	0.18	3.40	9.02	3.30	0.46	0.24	1.29	0.45	0.16	99.29	53.48	1.52	18.34	9.55	0.19	3.50	9.29	3.40	0.47	0.25	3.87	2.73	121	50.40	46	24.58
21	Tai	88-003	51.9	1.23	16.6	5.76	3.63	0.11	5.27	9.18	3.22	0.49	0.14	1.54	0.56	0.30	99.93	53.53	1.27	17.12	9.09	0.11	5.44	9.47	3.32	0.51	0.14	3.83	1.67	121	49.11	46	24.47
22	Ta	89-097	52.7	1.27	16.9	2.23	6.58	0.16	4.53	9.26	3.11	0.84	0.23	0.65	0.47	1.06	99.99	54.00	1.30	17.32	8.80	0.16	4.64	9.49	3.19	0.86	0.24	4.05	1.90	121	49.78	46	28.79
23	Tai	87-160	51.0	1.60	16.3	7.60	2.34	0.15	3.40	7.46	3.30	1.46	0.30	1.56	2.52	0.20	99.39	54.05	1.70	17.49	9.73	0.16	3.60	7.91	3.50	1.55	0.32	5.05	2.70	121	51.78	46	23.65
24	Ta	89-028	53.0	1.76	15.9	3.34	7.25	0.19	3.87	8.61	3.49	0.61	0.24	0.76	0.40	0.79	100.21	54.12	1.80	16.24	10.47	0.19	3.95	8.79	3.56	0.62	0.25	4.19	2.65	121	45.15	46	29.88
25	Tai	88-050	52.6	1.22	17.3	3.60	5.35	0.19	4.33	9.42	2.85	0.43	0.19	0.90	1.67	0.03	100.08	54.16	1.26	17.81	8.84	0.20	4.46	9.70	2.93	0.44	0.20	3.38	1.98	121	50.74	46	28.48
26	Ta	MK85621	54.1	1.42	16.9	4.64	5.32	0.16	4.89	9.02	2.72	0.67	0.23				100.07	54.31	1.43	16.95	9.54	0.16	4.91	9.06	2.73	0.67	0.23	3.41	1.94	121	49.80	46	28.80
27	Ta	89-084	53.4	1.86	15.4	2.68	7.94	0.19	3.53	8.04	3.70	0.65	0.29	0.59	0.40	1.24	99.91	54.82	1.91	15.81	10.63	0.20	3.62	8.25	3.80	0.67	0.30	4.47	2.93	121	48.67	46	27.16
28	Tai	89-023	53.5	1.58	16.3	5.04	4.75	0.19	3.88	8.00	3.70	0.81	0.23	0.55	1.12	0.01	99.64	54.90	1.62	16.73	9.51	0.19	3.98	8.21	3.80	0.83	0.24	4.63	2.39	121	45.95	46	26.95
29	Ta	87-046	52.6	1.54	16.1	5.14	4.37	0.15	3.50	7.74	3.40	1.20	0.32	1.03	2.13	0.09	99.31	55.05	1.61	16.85	9.42	0.16	3.66	8.10	3.56	1.26	0.33	4.81	2.57	121	51.90	46	22.80
30	Tai	89-088	52.8	0.84	15.4	3.52	4.37	0.13	6.98	8.44	2.79	0.76	0.17	2.42	0.96	0.07	99.65	55.09	0.88	16.07	7.86	0.14	7.28	8.81	2.91	0.79	0.18	3.70	1.08	121	47.64	46	23.98
31	Thac	89-017	52.6	1.82	15.2	2.15	8.07	0.21	3.05	7.46	3.84	0.61	0.30	0.82	0.52	3.45	100.08	55.32	1.91	15.99	10.50	0.22	3.21	7.85	4.04	0.64	0.32	4.68	3.27	121	48.32	46	27.87
32	Thac	89-013	54.3	1.57	17.7	3.34	5.99	0.15	2.41	8.15	3.51	0.83	0.26	0.47	1.04	0.07	99.79	55.48	1.60	18.08	9.19	0.15	2.46	8.33	3.59	0.85	0.27	4.43	3.73	121	49.33	46	27.53
33	Ta	89-019	54.6	1.76	16.1	4.71	5.57	0.18	3.34	7.58	3.79	0.80	0.37	0.32	0.79	0.02	99.93	55.53	1.79	16.37	9.98	0.18	3.40	7.71	3.85	0.81	0.38	4.67	2.94	121	50.15	46	27.73
34	Ta	88-038	54.8	1.85	15.5	6.29	5.11	0.09	3.44	7.33	3.58	0.91	0.31	0.44	0.96	0.07	100.68	55.59	1.88	15.72	10.93	0.09	3.49	7.44	3.63	0.92	0.31	4.55	3.13	121	49.05	46	29.43
35	Tai	89-016	53.6	1.74	15.5	4.39	5.23	0.18	3.34	8.57	3.38	0.52	0.31	1.25	1.63	0.11	99.75	55.65	1.81	16.09	9.33	0.19	3.47	8.90	3.51	0.54	0.32	4.05	2.75	121	49.22	46	27.08
36	Tagt	87-168	54.3	1.22	16.5	4.02	5.06	0.15	4.30	8.04	3.20	0.94	0.18	0.31	0.99	0.00	99.21	55.69	1.25	16.92	8.90	0.15	4.41	8.25	3.28	0.96	0.18	4.25	2.02	121	52.41	46	24.42
37	Tai	89-043	54.5	1.34	17.2	4.04	5.45	0.16	2.83	7.73	3.40	1.06	0.25	0.76	1.09	0.01	99.82	55.87	1.37	17.63	9.31	0.16	2.90	7.92	3.49	1.09	0.26	4.57	3.21	121	48.20	46	25.17
38	Tai	89-058	55.0	1.70	15.5	3.09	7.57	0.19	3.19	7.21	3.82	0.87	0.28	0.88	0.42	0.00	99.72	56.06	1.73	15.80	10.55	0.19	3.25	7.35	3.89	0.89	0.29	4.78	3.24	121	48.20	46	25.52
39	Ta	MK98415	56.2	1.26	17.0	4.21	4.82	0.13	4.21	8.68	2.99	0.36	0.21				100.07	56.43	1.27	17.02	8.64	0.13	4.23	8.71	3.00	0.36	0.21	3.36	2.04	121	45.35	46	27.27
40	Ta	88-002	56.2	1.76	15.6	6.30	4.14	0.17	2.77	6.80	3.93	0.85	0.26	0.37	0.86	0.00	100.01	57.26	1.79	15.89	9.99	0.17	2.82	6.93	4.00	0.87	0.26	4.87	3.54	121	50.56	46	25.39
41	Ta	89-027	55.5	1.33	17.1	4.96	3.22	0.12	2.20	7.85	3.32	1.19	0.28	1.37	1.23	0.03	99.70	57.47	1.38	17.71	7.96	0.12	2.28	8.13	3.44	1.23	0.29	4.67	3.49	121	45.10	46	29.40
42	Ta	87-225	55.6	1.56	15.6	3.66	5.33	0.17	3.20	5.86	5.00	0.54	0.26	2.23	0.43	0.10	99.54	57.67	1.62	16.18	8.94	0.18	3.32	6.08	5.19	0.56	0.27	5.75	2.69	121	45.10	46	28.24
43	Ta	89-010	56.9	1.60	16.1	3.16	5.44	0.20	3.14	6.13	4.77	0.89	0.24	0.90	0.34	0.09	99.90	57.91	1.63	16.39	8.43	0.20	3.20	6.24	4.85	0.91	0.24	5.76	2.64	121	45.29	46	28.31
44	Ta	88-052	56.0	1.12	16.6	5.20	2.21	0.11	3.19	4.71	5.35	1.47	0.26	1.53	0.95	0.10	98.78	58.52	1.17	17.35	7.20	0.11	3.33	4.92	5.59	1.54	0.27	7.13	2.16	121	47.79	46	26.94
45	Tai	89-053	57.3	1.10	16.8	4.02	3.14	0.11	3.04	6.67	4.50	1.15	0.24	1.31	0.28	0.00	99.66	58.67	1.13	17.20	6.92	0.11	3.11	6.83	4.61	1.18	0.25	5.78	2.22	121	49.07	46	24.29
46	Ta	87-103	56.9	1.36	15.8	2.25	6.66	0.18	2.20	6.02	4.10	0.94	0.38	1.44	0.59	0.17	98.99	58.92	1.41	16.36	8.99	0.19	2.28	6.23	4.25	0.97	0.39	5.22	3.94	121	50.36	46	26.68
47	Thd	89-091	55.9	0.89	17.6	2.71	3.23	0.10	3.07	7.32	3.64	0.18	0.21	2.32	2.27	0.02	99.46	59.10	0.94	18.61	5.99	0.11	3.25	7.74	3.85	0.19	0.22	4.04	1.85	121	46.36	46	24.79
48	Ta	89-096	58.1	1.53	15.6	2.24	6.24	0.17	2.45	6.22	4.41	0.98	0.30	1.10	0.40	0.01	99.75	59.28	1.56	15.92	8.42	0.17	2.50	6.35	4.50	1.00	0.31	5.50	3.37	121	51.02	46	28.44
49	Thai	89-065	57.6	0.88	16.8	3.77	2.28	0.09	3.89	6.59	4.16	1.03	0.29	1.19	0.36	0.41	99.34	59.38	0.91	17.32	5.85	0.09	4.01	6.79	4.29	1.06	0.30	5.35	1.46	121	47.13	46	22.66
50	Ta	88-049	59.2	1.58	15.4	3.36	5.98	0.20	2.26	5.80	4.25	1.13	0.32	0.21	0.59	0.04	100.32	59.71	1.59	15.53	9.08	0.20	2.28	5.85	4.29	1.14	0.32	5.43	3.98	121	50.98	46	28.10
51	Ta	87-215	58.2	1.50	15.7	1.63	6.81	0.17	2.20	5.98	4.20	0.94	0.28	1.28	0.20	0.00	99.09	59.72	1.54	16.11	8.50	0.17	2.26	6.14	4.31	0.96	0.29	5.27	3.76	121	51.31	46	28.31
52	Ta	87-111	57.7	1.34	15.4	3.96	5.04	0.17	2.20	5.42	3.70	1.48	0.54	1.31	0.64	0.00	98.90	59.76	1.39	15.95	8.91	0.18	2.28	5.61	3.83	1.53	0.56	5.36	3.91	121	50.75	46	24.30
53	Tai?	88-030	56.6	1.11	16.2	3.48	3.09	0.14	2.05	8.03	2.97	0.95	0.25	1.28	0.90	3.09	100.14	59.88	1.17	17.14	6.58	0.15	2.17	8.50	3.14	1.01	0.26	4.15	3.04	121	47.89	46	27.19
54	Ta	MK8578	60.3	1.24	16.7	4.04	4.62	0.14	2.26	6.70	2.79	1.09	0.20				100.08	60.49	1.24	16.74	8.29	0.14	2.27	6.73	2.80	1.09	0.20	3.89	3.65	121	51.62	46	28.55
55	Thd[2]	89-035	56.3	0.83	16.9	2.98	2.43	0.09	2.54	6.90	3.47	0.23	0.21	3.64	2.72	0.02	99.26	60.81	0.90	18.25	5.52	0.10	2.74	7.45	3.75	0.25	0.23	4.00	2.01	121	46.00	46	25.01
56	Ta	87-045	59.4	1.34	15.3	4.12	3.88	0.16	2.00	4.44	4.60	1.52	0.36	0.58	1.16	0.00	98.86	61.42	1.39	15.82	7.85	0.17	2.07	4.59	4.76	1.57	0.37	6.33	3.79	121	52.22	46	23.02
57	Tai	89-057	58.7	0.82	16.0	3.01	2.22	0.09	2.75	5.91	3.82	2.16	0.36	1.67	0.31	1.64	99.46	61.44	0.86	16.75	5.16	0.09	2.88	6.19	4.00	2.26	0.38	6.26	1.79	121	48.53	46	22.55
58	Ta	MK8581	61.5	1.11	16.6	3.50	4.01	0.13	3.06	3.78	4.28	1.71	0.28				99.96	61.75	1.11	16.67	7.19	0.13	3.07	3.79	4.30	1.72	0.28	6.01	2.34	121	45.68	46	25.83
59	Thdb	87-044	59.7	0.80	16.9	4.35	1.25	0.09	2.60	5.40	3.80	1.32	0.20	0.98	1.77	0.00	99.16	62.20	0.83	17.61	5.38	0.09	2.71	5.63	3.96	1.38	0.21	5.33	1.99	121	51.79	46	24.43
60	Thd	89-103	58.5	0.70	16.5	2.05	2.88	0.10	2.41	6.35	3.10	1.21	0.20	2.34	0.64	3.12	100.10	62.37	0.75	17.59	5.04	0.11	2.57	6.77	3.31	1.29	0.21	4.60	1.96	121	47.99	46	22.83
61	Thd	85-071	60.1	0.76	17.0	2.65	2.46	0.08	2.49	5.13	4.60	1.07	0.18	2.84	0.36	0.00	99.72	62.44	0.79	17.66	5.04	0.08	2.59	5.33	4.78	1.11	0.19	5.89	1.95	121	49.97	46	22.70
62	Thd	87-180	60.4	0.78	16.8	2.67	2.82	0.09	2.40	2.44	6.30	1.86	0.20	0.98	0.69	0.18	98.61	62.60	0.81	17.41	5.41	0.09	2.49	2.53	6.53	1.93	0.21	8.46	2.17	121	46.64	46	26.24
63	Thdt	89-041	60.8	0.69	16.4	3.09	1.99	0.07	3.15	5.82	4.07	1.18	0.18	0.64	1.42	0.01	99.46	62.63	0.71	16.89	4.91	0.07	3.24	5.99	4.14	1.22	0.19	5.36	1.51	121	46.17	46	24.76
64	Thd	89-054	60.9	0.77	16.6	2.93	2.36	0.08	2.62	6.13	3.99	1.01	0.19	1.45	0.51	0.00	99.44	62.66	0.79	17.08	5.04	0.08	2.70	6.31	4.11	1.04	0.20	5.14	1.87	121	48.99	46	23.90
65	Thd	89-068	59.9	0.79	16.8	3.44	1.50	0.08	1.83	6.43	3.68	1.16	0.22	1.54	0.75	1.25	99.37	62.73	0.83	17.59	4.81	0.08	1.92	6.73	3.85	1.21	0.23	5.07	2.51	121	47.00	46	23.51
66	Tdi	87-222	60.3	0.76	16.2	3.65	2.09	0.11	2.50	5.02	3.90	1.56	0.20	1.18	0.62	1.11	99.20	62.86	0.79	16.89	5.60	0.11	2.61	5.23	4.07	1.63	0.21	5.69	2.15	121	48.42	46	27.81
67	Thdt	89-109	61.3	0.70	16.6	2.51	2.39	0.08	2.75	5.46	4.14	1.47	0.21	1.03	0.99	0.02	99.63	62.96	0.72	17.05	4.78	0.08	2.82	5.61	4.25	1.51	0.22	5.76	1.69	121	46.36	46	25.48
68	Thd	89-086	60.3	0.79	16.9	2.51	2.82	0.09	2.47	5.38	3.79	0.73	0.21	2.59	0.61	0.06	99.27	62.97	0.83	17.65	5.32	0.09	2.58	5.62	3.96	0.76	0.22	4.72	2.06	121	47.82	46	23.55

Table 1. Chemical Analyses from the Tower Rock Quadrangle, Washington, arranged in order of increasing SiO_2 (cont.)

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	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
69	Tvd	89-081	60.3	0.84	15.4	1.95	4.87	0.13	1.65	5.20	4.09	1.29	0.20	2.45	0.93	0.24	99.54	62.99	0.88	16.09	6.92	0.14	1.72	5.43	4.27	1.35	0.21	5.62	4.02	121	49.10	46	26.80
70	Tdi	88-044	61.3	1.02	15.4	2.25	4.88	0.15	1.69	4.56	4.34	1.48	0.33	1.61	0.75	0.45	100.21	63.08	1.05	15.85	7.11	0.15	1.74	4.69	4.47	1.52	0.34	5.99	4.09	121	51.59	46	28.96
71	Tvd	87-178	60.6	0.86	15.7	1.64	5.09	0.13	1.50	5.10	3.90	1.48	0.20	2.46	0.77	0.00	99.43	63.10	0.90	16.35	6.84	0.14	1.56	5.31	4.06	1.54	0.21	5.60	4.38	121	49.43	46	26.57
72	Tvd	88-029	60.4	0.83	15.5	4.05	3.45	0.16	0.92	4.74	4.23	1.56	0.28	0.43	0.44	3.10	100.07	63.12	0.87	16.20	7.40	0.17	0.96	4.95	4.42	1.63	0.29	6.05	7.69	121	48.44	46	27.37
73	Thdo	89-047	60.9	0.74	16.6	2.98	2.04	0.08	2.43	5.51	4.00	1.26	0.20	1.07	1.25	0.22	99.28	63.15	0.77	17.21	4.90	0.08	2.52	5.71	4.15	1.31	0.21	5.45	1.94	121	51.60	46	25.70
74	Thd	89-063	60.7	0.74	17.2	2.82	2.09	0.08	1.93	5.82	4.37	0.29	0.23	2.29	0.52	0.41	99.49	63.24	0.77	17.92	4.82	0.08	2.01	6.06	4.55	0.30	0.24	4.85	2.40	121	46.38	46	23.30
75	Thdt	89-090	61.4	0.65	16.4	2.92	1.98	0.08	2.87	5.29	4.20	1.37	0.19	0.77	1.45	0.00	99.57	63.26	0.67	16.90	4.75	0.08	2.96	5.45	4.33	1.41	0.20	5.74	1.61	121	48.09	46	24.45
76	Thdo	89-059	61.2	0.74	16.6	3.61	1.47	0.08	2.43	5.48	4.05	1.23	0.19	0.84	1.50	0.02	99.44	63.28	0.77	17.16	4.88	0.08	2.51	5.67	4.19	1.27	0.20	5.46	1.94	121	51.36	46	25.81
77	Thd	89-104	60.7	0.65	17.2	2.23	2.37	0.06	2.28	5.86	4.06	0.42	0.16	2.84	0.66	0.02	99.51	63.38	0.68	17.96	4.57	0.06	2.38	6.12	4.24	0.44	0.17	4.68	1.92	121	45.90	46	23.03
78	Thdt	89-038	61.7	0.70	16.4	2.92	1.88	0.07	2.54	5.36	4.17	1.43	0.20	1.31	0.74	0.01	99.43	63.56	0.72	16.89	4.64	0.07	2.62	5.52	4.30	1.47	0.21	5.77	1.77	121	46.48	46	25.70
79	Thdo	89-048	61.1	0.74	16.5	3.87	1.18	0.08	2.33	5.36	3.87	1.30	0.19	1.30	1.66	0.01	99.49	63.56	0.77	17.16	4.85	0.08	2.42	5.58	4.03	1.35	0.20	5.38	2.00	121	52.12	46	23.97
80	Thdo	89-049	61.4	0.74	16.3	3.24	1.86	0.09	2.36	5.53	3.97	1.23	0.20	0.77	1.64	0.06	99.39	63.58	0.77	16.87	4.94	0.09	2.44	5.72	4.11	1.27	0.21	5.38	2.02	121	52.07	46	26.02
81	Thdt	89-040	62.2	0.69	16.6	2.89	1.87	0.07	2.55	5.03	4.33	1.48	0.19	1.18	0.56	0.07	99.71	63.72	0.71	17.01	4.58	0.07	2.61	5.15	4.44	1.52	0.19	5.95	1.75	121	45.94	46	24.60
82	Thdt	89-037	62.3	0.63	16.5	2.50	2.14	0.08	2.65	5.48	4.16	1.35	0.19	0.62	1.04	0.02	99.66	63.75	0.64	16.88	4.49	0.08	2.71	5.61	4.26	1.38	0.19	5.64	1.66	121	46.01	46	25.14
83	Thd	88-012	61.4	0.72	16.5	2.63	2.26	0.08	2.24	4.72	4.35	1.45	0.18	2.19	0.23	0.46	99.41	63.78	0.75	17.14	4.81	0.08	2.33	4.90	4.52	1.51	0.19	6.02	2.07	121	50.55	46	22.85
84	Twd	88-028	62.9	1.04	14.8	2.70	5.05	0.16	1.32	4.30	4.34	1.74	0.36	0.51	0.48	0.35	100.05	63.91	1.06	15.04	7.58	0.16	1.34	4.37	4.41	1.77	0.37	6.18	5.65	121	49.02	46	26.83
99	Tvd[3]	MK85628	63.9	0.88	15.8	3.55	4.07	0.14	1.69	5.27	2.92	1.55					100.15	64.07	0.88	15.84	7.28	0.14	1.69	5.28	2.93	1.69	0.19	4.62	4.30	121	49.43	46	26.57
85	Tdi	87-210	60.3	0.96	15.0	6.31	1.32	0.11	0.55	3.84	4.40	1.46	0.36	0.24	3.16	0.00	98.01	64.16	1.02	15.96	7.45	0.12	0.59	4.09	4.68	1.55	0.38	6.24	12.63	121	51.38	46	28.84
86	Thd	89-087	62.2	0.65	16.6	2.37	2.41	0.08	2.23	4.72	4.38	1.24	0.21	1.75	0.47	0.29	99.60	64.22	0.67	17.14	4.69	0.08	2.30	4.87	4.52	1.28	0.22	5.80	2.04	121	47.63	46	23.85
87	Thd	87-201	60.0	0.58	15.8	2.84	1.66	0.08	2.10	6.06	3.09	1.34	0.22	4.41	0.77	0.07	98.95	64.25	0.62	16.92	4.51	0.09	2.25	6.49	3.21	1.43	0.34	4.65	2.00	121	49.61	46	23.86
88	Thd	87-200	61.8	0.68	16.1	3.28	1.85	0.09	2.50	4.96	4.30	0.60	0.20	1.82	0.41	0.28	98.87	64.35	0.71	16.76	5.00	0.09	2.60	5.16	4.48	0.62	0.21	5.10	1.92	121	49.30	46	24.25
89	Thd	89-110	62.5	0.67	16.3	2.91	2.05	0.09	2.15	4.42	4.20	1.85	0.19	1.43	0.56	0.00	99.32	64.41	0.69	16.80	4.81	0.09	2.22	4.55	4.33	1.91	0.20	6.23	2.17	121	45.49	46	25.09
90	Thd	89-061	62.5	0.64	16.4	2.26	2.30	0.07	2.23	4.64	4.41	1.29	0.19	1.48	0.42	0.77	99.60	64.63	0.66	16.96	4.48	0.07	2.31	4.80	4.56	1.33	0.20	5.89	1.94	121	46.26	46	22.88
91	Thd	89-080	62.3	0.64	16.4	2.28	2.26	0.08	1.99	5.72	3.91	0.61	0.18	1.43	0.38	1.43	99.49	64.76	0.67	17.08	4.49	0.08	2.07	5.96	4.07	0.64	0.19	4.71	2.17	121	48.90	46	22.89
92	Thd	85-034	63.0	0.63	16.9	2.27	2.12	0.05	1.79	5.02	4.17	1.30	0.18	1.70	0.23	0.20	99.56	64.81	0.65	17.39	4.28	0.05	1.84	5.16	4.29	1.34	0.19	5.63	2.33	121	48.21	46	22.83
93	Tai	88-046	62.6	0.82	14.7	5.55	1.60	0.10	1.07	4.12	4.03	1.72	0.28	0.91	2.06	0.23	99.79	65.18	0.85	15.31	6.87	0.10	1.11	4.29	4.20	1.79	0.29	5.99	6.16	121	51.78	46	28.15
100	Thd[3]	MK98430	65.0	0.73	16.9	2.47	2.82	0.08	1.94	4.97	3.85	1.05					100.02	65.15	0.73	16.97	5.05	0.08	1.94	4.98	3.86	1.05	0.18	4.91	2.60	121	47.49	46	28.33
94	Tri	89-005	64.7	0.40	14.1	1.04	3.68	0.09	0.59	2.91	4.12	2.54	0.14	0.55	0.29	4.25	99.40	68.68	0.42	14.97	4.90	0.10	0.63	3.09	4.37	2.70	0.15	7.07	7.82	121	46.56	46	27.77
95	Trc	89-022	67.2	0.47	14.4	1.53	3.10	0.13	0.43	2.07	5.31	2.12	0.12	0.30	0.30	2.32	99.80	69.47	0.49	14.89	4.63	0.13	0.44	2.14	5.49	2.19	0.12	7.68	10.41	121	49.71	46	28.33
96	Trc	89-020	66.6	0.61	13.8	1.62	3.24	0.12	0.80	2.63	4.68	1.77	0.15	0.37	0.35	2.74	99.48	69.48	0.64	14.40	4.90	0.13	0.83	2.74	4.88	1.85	0.16	6.73	5.87	121	49.55	46	28.04
97	Trc	87-219	67.4	0.44	15.8	1.02	2.11	0.07	0.10	2.42	4.30	2.40	0.12	0.72	0.34	1.85	99.09	70.15	0.46	16.45	3.15	0.07	0.10	2.52	4.48	2.50	0.12	6.97	31.50	121	48.07	46	28.50
98	Trc	88-053	71.2	0.39	14.7	3.82	0.13	0.05	0.18	0.16	2.90	2.17	0.09	2.80	0.50	0.12	99.21	74.63	0.41	15.41	3.74	0.05	0.19	0.17	3.04	2.27	0.09	5.31	19.82	121	47.93	46	29.35

X-ray fluorescence analyses, except those prefixed by MK, done in U.S. Geological Survey laboratories in Menlo Park, Calif., (analyst Marsha Dyslin) and Denver, Colo., (analysts J.E. Taggart, A.J. Bartel, and D.F. Siems)

FeO and carbon dioxide analyses done in U.S. Geological Survey laboratories in Menlo Park (analysts S.F. Bader, J. Consul, L. Espos, and K. Lewis) and Denver (analyst E. Brandt)

Water analyses done in U.S. Geological Survey laboratory in Menlo Park (analysts S.F. Bader, J. Consul, L. Espos, and K. Lewis)

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

[1]Analysis for sample MK85720 almost certainly reflects presence of secondary calcite (note high CaO; no carbon dioxide reported) and was probably andesitic before alteration

[2]Sample 89-035 (map no. 55) is a dike of unit Thd that is too small to show on map; it intrudes margin of unit Thdt and probably is related to that unit

[3]Analyses 99 and 100 not plotted on any figure in text

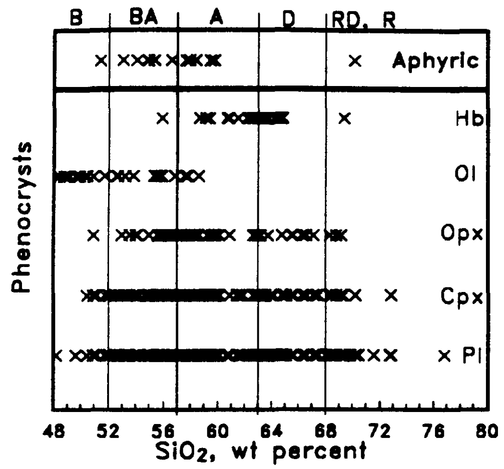

Figure 4. Plot of phenocryst assemblage vs. SiO_2 for 192 porphyritic and 13 nonporphyritic Tertiary rocks, chiefly in Tower Rock, French Butte, and Greenhorn Buttes quadrangles but including a few from the McCoy Peak quadrangle. X, phenocryst observed in thin section; Hb, hornblende; Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Pl, plagioclase. Rock types along top edge from figure 3.

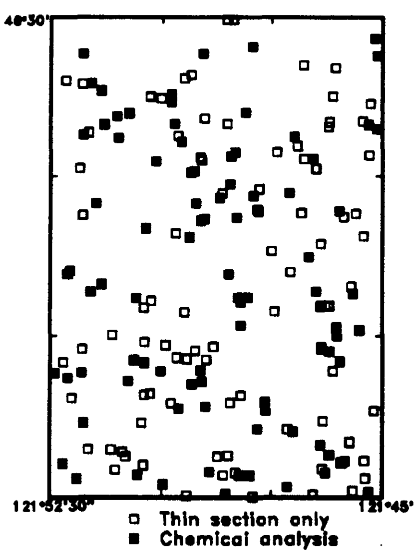

Figure 5. Map showing distribution of 184 sample localities in Tower Rock quadrangle, including eight localities for samples collected by M. A. Korosec and listed in table 1.

intrusive rocks, with one or two exceptions in which it occurs in lava flows.

Samples for which thin sections but no chemical analyses were available could therefore be classified on the basis of their phenocryst assemblage and groundmass texture. In all, 184 samples from the Tower Rock quadrangle were sectioned (fig. 5); of these, 90 were chemically analyzed (table 1). In addition, table 1 includes 10 chemical analyses previously published by Korosec (1987).

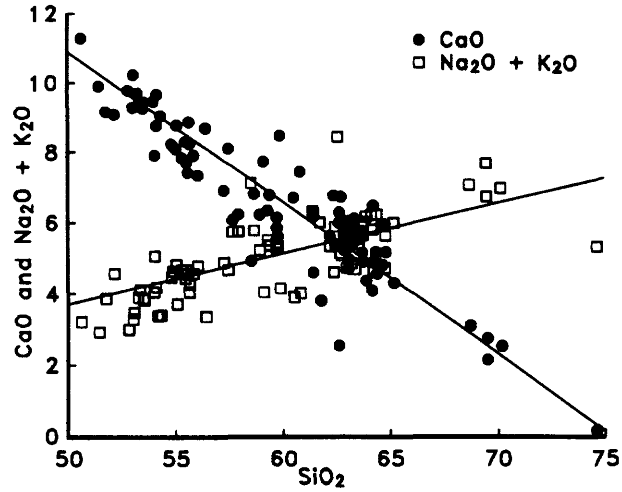

Figure 6. Plot of CaO and ($Na_2O + K_2O$) vs. SiO_2 for Tertiary volcanic rocks in Tower Rock quadrangle. Best-fit linear regressions cross at SiO_2 = 62.5 percent and indicate calcic suite in terminology of Peacock (1931).

The Tertiary suite is calcic (Peacock, 1931), with an alkali-lime index of about 62.5 (fig. 6), equal to that for Tertiary rocks in the French Butte and Greenhorn Buttes quadrangles (Swanson, 1989). Most analyses of the Tertiary rocks fall in the tholeiitic field on a plot of FeO*/MgO vs. SiO_2 (fig. 7), according to the classification of Miyashiro (1974), as do the analyses of the young olivine basalt. The suite of Tertiary hornblende-bearing intrusive rocks is decidedly calcalkaline on this plot. On an AFM diagram (not shown), the hornblende-bearing intrusive rocks are also calcalkaline (Irvine and Baragar, 1971), but the rest of the Tertiary rocks are evenly divided between the tholeiitic and calcalkaline magma series.

A diagram of K_2O vs. SiO_2 shows that most of the rocks with SiO_2 between 52 and 63 percent are medium-K mafic and silicic andesite according to Gill (1981; basaltic andesite and andesite, respectively, in IUGS terminology); the rest are low-K types (fig. 8). This plot also illustrates the substantial range of K_2O in the young basalt; discussion in a later section shows that this range correlates with different stratigraphic units.

At SiO_2 = 57.5 percent (a value used by Gill [1981] to compare andesitic arcs throughout the world), the Tertiary rocks have an average K_2O content ($K_{57.5}$) of 0.96 percent and an average FeO*/MgO ratio (FeO*/$Mg_{57.5}$) of 2.6, as determined by linear regression of the data in figures 8 and 7, respectively. These values, similar to those obtained for rocks in the French Butte and Greenhorn Buttes quadrangles (Swanson, 1989), are within the range given by Gill (1981, table 7.1 and appendix) for volcanic arcs, but the

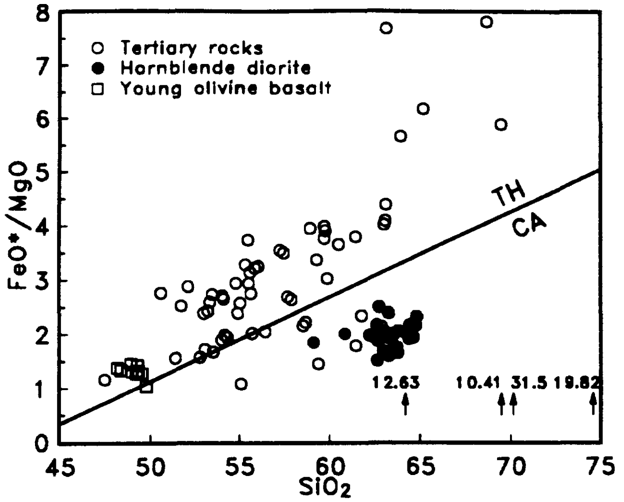

Figure 7. Plot of FeO*/MgO vs. SiO_2 for Tertiary and Quaternary volcanic rocks in Tower Rock quadrangle. Subdivision between tholeiitic (TH) and calcalkaline (CA) suites after Miyashiro (1974). Note distinction between hornblende diorite and most other Tertiary rocks. Young olivine basalt is dominantly tholeiitic, in contrast to young basaltic andesite in neighboring French Butte and Greenhorn Buttes quadrangles (Swanson, 1989). Arrows indicate values of FeO*/MgO too high to show on plot (three samples from unit Trc and one sample from unit Tdi.

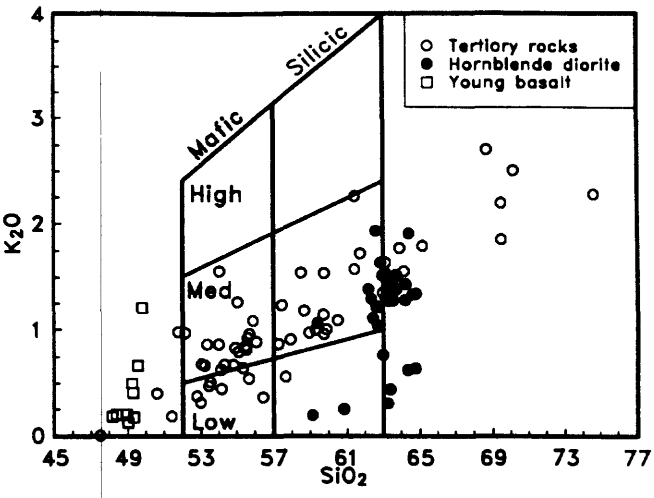

Figure 8. Plot of K_2O vs. SiO_2 for volcanic rocks in Tower Rock quadrangle. Fields modified from Gill (1981), so that mafic andesite (basaltic andesite in IUGS terminology used in this paper) extends down to 52 percent.

$K_{57.5}$ value is comparatively low and the $FeO^*/Mg_{57.5}$ value rather high. The $K_{57.5}$ value may be low owing to loss of K_2O during hydration and leaching of several samples (for example, see table 1, map nos. 47, 55, 74, 77, and others, which have very low K_2O contents and high total water contents, especially H_2O^+).

According to Gill (1981, p. 208), $FeO^*/Mg_{57.5}$ ratios greater than 2.5 "occur only at volcanic fronts, if at all, in volcanic arcs." The $FeO^*/Mg_{57.5}$ ratio of 2.6 for the rocks in the Tower Rock quadrangle is inconsistent with Gill's statement, for the volcanic front was probably located far west of the quadrangle during the Oligocene and early Miocene (Evarts and others, 1987; Walsh and others, 1987). Moreover, such a ratio is most characteristic of an arc whose front rests on crust less than 25 km thick (Gill, 1981, p. 208–216), a thickness only about 60 percent that of the present crust beneath the entire width of the modern arc (Mooney and Weaver, 1989, fig. 10). Either the chemical data are poor discriminants of crustal thickness, the crust has thickened substantially since the early Miocene, or other unrecognized factors complicate Gill's interpretations.

GENERAL GEOLOGY

The rocks in the quadrangle are mostly late Oligocene and early Miocene basaltic andesite and andesite lava flows and andesitic and dacitic volcaniclastic deposits. Less abundant rock types include flows of basalt and flows and volcaniclastic rocks of dacite and rhyodacite. Flows of andesite and basaltic andesite dominate the section in the northwest and northeast parts of the quadrangle, where an extensive unit of rhyodacite also occurs. Andesite and basaltic andesite dikes are common in this area, many of which form a swarm trending west-northwest. South of the Cispus and North Fork Cispus Rivers, volcaniclastic rocks make up most of the layered part of the section, but they are extensively intruded by sills and dikes of hornblende andesite, dacite, and quartz-bearing diorite whose age is approximately 12 Ma (middle Miocene).

The Tertiary section dips rather uniformly west-southwestward, toward the trough of the Pole Patch syncline 2–4 km west of the quadrangle. The dips are generally 25°–35° but reach as high as 70° on Bishop Mountain and along faults north of there. The folding probably was complete before the hornblende-bearing sills and related dikes formed about 12 Ma. High-angle faults of north-northwest strike and uncertain sense of displacement cut the steeply dipping rocks on and north of Bishop Mountain.

Tephra and several thin flows of high-K olivine basalt were erupted, probably during the late Pleistocene, from a vent in the extreme southeast part of the quadrangle. Two other map units of young olivine basalt, a low-K flow of late Pleistocene age and at least two reversely magnetized flows older than about 0.73 Ma, entered the quadrangle from vents farther east. Late Pleistocene glacial deposits, the Hayden Creek and Evans Creek Drifts, cover bedrock in many places, especially north of the Cispus River, and an extensive outwash deposit of Evans Creek age forms the floor of the Cispus River valley.

TERTIARY ROCKS

Volcaniclastic rocks—Volcaniclastic rocks are abundant in the quadrangle, especially south of the Cispus and North Fork Cispus Rivers. They are generally moderately to well bedded and sorted and for the most part were probably deposited in aprons away from centers of active volcanism. The local presence of ash-flow tuff, air-fall tuff, and debris-flow deposits containing prismatically jointed, "hot" blocks indicates that volcanoes were erupting in nearby areas, however. Deposits best attributed directly to contemporaneous volcanism probably occur more commonly in the younger half of the section (that is, in the western half of the quadrangle) than in the older half, such as on Bishop Mountain and in the Kidd Creek basin, where fluvial sandstone is more prominent. This statement is very general, however, and interbedding of all rock types typifies the entire stratigraphic section, including that exposed on Bishop Mountain and in the Kidd Creek basin, where lapilli tuff is common. In fact, depositional environments doubtless changed frequently and varied laterally over short distances in the dynamic system characteristic of aprons surrounding active volcanoes.

The volcaniclastic rocks in the quadrangle are in general better sorted than those in the Greenhorn Buttes quadrangle and include fewer ash-flow tuffs than occur farther west. Viewed very broadly, then, the section of volcaniclastic rocks across the two quadrangles shows an overall trend of increasing abundance of freshly erupted debris upsection and(or) westward, from the Bishop Mountain area to the trough of the Pole Patch syncline.

An unusual deposit at least 75 m thick crops out on the west side of the summit of Lone Tree Mountain. Here a crudely bedded diamictite containing clasts of andesite tens of centimeters to several meters in diameter caps a section of interbedded similar (but thinner) diamictites and lava flows. Similar deposits (undivided on the map from associated lava flows owing to complexity) also occur on the northern flank of Lone Tree Mountain. Taken together, these deposits probably formed near an andesitic vent, an interpretation also suggested by the prevalence of andesite flows and dikes in this part of the quadrangle. In fact, the geologic map of the Lone Tree Mountain area does not come close to portraying adequately the complexity in this area. Cuts along the road on the northeast flank of Lone Tree Mountain expose lava flows, intrusive bodies, and volcaniclastic rocks in a bewildering assemblage lumped into unit Ta for simplicity.

The only quartz-phyric volcaniclastic rock found in the quadrangle occurs at an elevation of 777 m (2,550 ft) in a creek bed between Veta and Galena Creeks, just downstream from the small fault dipping 60° northeast shown on the geologic map. This bed is 50–60 cm thick, white, and interbedded with pumice- and lithic-lapilli tuff of obvious pyroclastic origin. The bed contains abundant sand-sized grains of unstrained quartz, strained alkali feldspar, and small flakes of brown biotite in a matrix consisting of devitrified pumice lapilli and glass shards. The origin of this deposit is problematic. I think it most likely to be a vitric-crystal tuff, with the strained alkali feldspar coming from crystalline inclusions in the erupting magma. Another possibility is a mixture of air-fall ash and subarkosic detritus eroded from an unknown source, such as the Mesozoic Rimrock Lake inlier (Miller, 1989) east of the Cascade crest, the crystalline terrane in northern Washington, or Eocene sandstone that crops out along Chambers Creek just west of the Goat Rocks (Winters, 1984) or along Summit Creek north of the Goat Rocks (Clayton, 1983; Vance and others, 1987).

Lava flows—Andesite and basaltic andesite lava flows occur throughout the section but are common only north of the Cispus River. South of the Cispus River, one narrow belt of flows interbedded with volcaniclastic rocks crops out along the east side of Tongue Mountain, and several individual flows occur higher in section west of Yellowjacket Creek. The ridge just east of Cispus Environmental Center is composed mostly of andesite but is capped by a distinctive vitrophyric dacite flow (unit Tvd) that extends north of the river and helps to place the lava flows on both sides of the river in proper stratigraphic context. Most of the flows south of the Cispus River apparently advanced some distance from their vents, none of which is exposed in the area. Some of them could have been erupted from vents north of the river, where lava flows make up most of the section.

North of the Cispus River, the Lone Tree Mountain area is the most likely source for the thick accumulation of lava flows and associated rubble that forms the western part of the ridge separating the Cispus and Cowlitz Rivers. Numerous dikes occur in this area, at least some of which might be related to the flows. Attitudes of flows and coarse volcaniclastic deposits in the Lone Tree Mountain and upper Siler Creek area diverge from the consistent north-northwest strike characteristic of most of the quadrangle, probably because of high initial dips associated with the volcanic center. No clear sign of a volcanic edifice remains, however, and most likely only the basal, perhaps shieldlike, part of the former center is preserved.

A small remnant of a cone that erupted cinder and hydromagmatic debris (unit Tpt), now palagonitized, is exposed in road cuts and, most notably, a cliffy area east of lower Camp Creek. Bedding in the exposed parts of the cone strikes east-northeast, nearly at right angles to the regional strike, and dips moderately southward. Removing the effects of later regional tilting changes the observed attitudes only slightly, so that they apparently record part of the southern flank of a cone of unknown dimension. The palagonitic tephra (unit Tpt) and the overlying basaltic andesite of Camp Creek (unit Tbac) are cut by a basaltic andesite dike that strikes northward, an unusual direction for the area that perhaps reflects a radial stress system within the cone.

A somewhat older cinder deposit is exposed on the hill slope due north of the mouth of the North Fork Cispus River (unit Tav). The deposit is poorly exposed and cannot be traced far.

A thick section of andesite and basaltic andesite lava flows is exposed in the northeast corner of the quadrangle. Most likely its source is farther east or northeast. These flows dip relatively gently southwestward, and for a long time I believed that they rested unconformably on more steeply dipping older rocks. However, I later found steeply dipping flows along Swede and Irish Creeks that seem to correlate with the gently dipping flows. I presently interpret all of these flows to be conformable with the overall section and attribute the shallow dips to either a monoclinal flexure (as shown on the geologic map and in cross section B-B′) or to a shallowing or even reversing of original eastward primary dips.

Olivine basalt (unit Tb), the most mafic rock in the Tertiary section, crops out between Polk and Tyler Creeks and along a down-dip projection in the Cispus River valley (unit Tb; table 1, nos. 11 and 12, respectively). At least two flows form the unit. The basalt is coarse, almost diabasic, along Polk and Tyler Creeks and only slightly finer grained farther southwest. It is tholeiitic on the basis of a plot of FeO*/MgO vs. SiO_2 (Miyashiro, 1974).

A notable accumulation of rhyodacite flows, the rhyodacite of Camp Creek (unit Trc), covers a broad area east of Lone Tree Mountain and west of Irish Creek. The rhyodacite is poorly exposed along the broad crest of the ridge, where it is mantled by the Hayden Creek Drift, but exposures of the rhyodacite north and south of the crest suggest that it underlies the crest as well. The rhyodacite is interbedded with the thick pile of andesite on Lone Tree Mountain (part of unit Ta) and apparently overlies the andesite cropping out in the northeast corner of the quadrangle. Lack of bedding within the rhyodacite precludes determining its attitude, and flow layering, though common, is commonly swirled and hence unreliable for measuring attitudes. The unit appears to be conformable with other units in section, although its outcrop relations are irregular and largely unpredictable except along its northern and southwestern borders. Most likely the rhyodacite formed a domal mass or a thick flow (or flows) that controlled the distribution of younger units.

The rhyodacite of Camp Creek (unit Trc) and the vitrophyric dacite (unit Tvd) are probably about the same age, because both units underlie the basaltic andesite of Camp Creek (unit Tbac; table 1, analyses 31 and 32). Taken together, the two silicic units apparently record the most voluminous episode of silicic volcanism within the quadrangle. Thin flows of older dacite (unit Td) occur randomly throughout the section.

Dikes and sills of pyroxene andesite and basaltic andesite—Dikes of pyroxene andesite and basaltic andesite (unit Tai) are common in the quadrangle north of the Cispus River in the upper Kilborn Creek, Lone Tree Mountain, and upper Irish Creek areas. The dikes chemically and petrographically resemble the lava flows they cut, but no example of a dike merging with a flow was found.

Most of the dikes strike west-northwest (fig. 9). The mean strike is 274° for the 61 pyroxene andesite and basaltic andesite dikes measured, virtually identical to the mean strike of 280° for 60 similar dikes in the French Butte and Greenhorn Buttes quadrangles and to that of 277° for more than 300 pyroxene andesite and basaltic andesite dikes in the McCoy Peak quadrangle (Swanson, 1989, 1990, and unpub. data). This direction is so consistent that it suggests control by a regional stress system. Only locally do pyroxene andesite and basaltic andesite dikes diverge significantly from this strike, probably in response to local stress fields associated with volcanic edifices and their subvolcanic intrusive complexes.

No definitive age relation could be established between the west-northwest dikes and those of other orientations in the Tower Rock quadrangle, but in the McCoy Peak quadrangle the west-northwest dikes are consistently younger than the other pyroxene andesite and basaltic andesite dikes at each dike intersection seen.

Most of the dikes dip steeply, although those few dikes that strike at low angles to the regional north-northwest structural trend commonly dip less than 70° east and apparently record tectonic tilting of once nearly vertical bodies (see western part of cross section B-B′).

Several sills of pyroxene andesite and basaltic andesite (unit Tai) are interleaved with volcaniclastic rocks south of the Cispus River. The most prominent is a body more than 100 m thick exposed in the high northeast-facing cliff overlooking the large landslide along Lambert Creek. This basaltic andesite (table 1, nos. 17 and 30) is locally almost

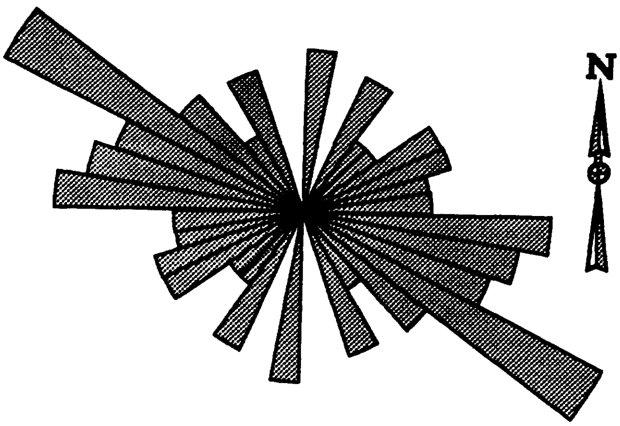

Figure 9. Equi-area rose diagram of 61 dikes of andesite and basaltic andesite in Tower Rock quadrangle, in 10° intervals. Mean azimuth, 274°; standard deviation, 43°.

gabbroic in texture but overall has a finer grain size. Chilled margins define the top and bottom of the sill, whose coarse columnar joints are at right angles to stratification in the 30°-dipping host rock. Other broadly sill-like but somewhat discordant and strongly platy intrusions of basaltic andesite (table 1, no. 28) and andesite (table 1, no. 53) occur on the west side of Bishop Mountain and just northwest of the mouth of North Fork Cispus River, respectively. A body mapped as a sill just east and northeast of the right-angle bend in Yellowjacket Creek could be a lava flow, for its upper contact was not observed; however, its coarse grain size and thickness seem more consistent with a sill. A composite basalt and basaltic andesite sill-like body (unit Tbi), consisting of at least two intrusions of different composition (table 1, nos. 13 and 23), occurs south of Burley Mountain; its northern end is cut off by the hornblende diorite of Burley Mountain.

Dikes and sills of hornblende andesite, dacite, diorite, and quartz diorite—Dikes of hornblende-phyric silicic andesite and mafic dacite are confined to the area south of the Cispus and North Fork Cispus Rivers. Most occur south of Lambert Creek, but similar dikes have been found as far north as Bishop Mountain and as far west as the area between Galena and Veta Creeks. The dikes define a fanning array focused at a point along McCoy Creek about 2 km south of the quadrangle, which is the locus of a large radial dike swarm (Swanson, 1990). The hornblende-phyric dikes are subvertical—even those that cross the strike of bedding at low angles, such as the dike between Veta and Galena Creeks and those at the west end of the Lambert Creek cluster. This relation implies that the dikes are younger than the age of tilting, and indeed the neat radial pattern defined by dikes throughout the entire swarm is thrown into disarray if "corrected" for regional tilt on the assumption that the dikes predate deformation.

Most of the dikes contain some fresh hornblende, and those farthest from the focus of the swarm are least altered and contain more fresh hornblende than do the dikes nearer the focus (for example, the dike between Galena and Veta Creeks is fresher than those on the ridge south of Lambert Creek). This difference might reflect the degree of hydrothermal alteration associated with the subvolcanic center with which the radial dikes are associated. The host rock shows a similar range in degree of hydrothermal alteration.

Prominent sills of hornblende-phyric diorite, quartz diorite, and fine-grained varieties of these two rock types characterize the southern half of the Tower Rock quadrangle. Many of the highest points south of the Cispus River—Burley Mountain, Tongue Mountain, and Tower Rock—are made of this material. Sills also form high cliffs overlooking the right-angle bend of Yellowjacket Creek and along the canyons of McCoy and Yellowjacket Creeks. The sills range from a few tens of centimeters to as much as 500 m thick. The thickest parts of some sills occur at their northern terminations, such as Tower Rock (more than 330 m), Burley Mountain (more than 220 m), the body at the right-angle bend of Yellowjacket Creek (more than 300 m), and Tongue Mountain (more than 500 m). Generally the tops of the sills are nearly planar and follow bedding in the host rock. However, the sills steeply cross cut their host rock in places where they thicken markedly, as along the southern end of Tongue Mountain (the site of sample 81 in table 1), where a nearly vertical contact separates the diorite from the enclosing andesite. The western margin of Tongue Mountain also exhibits a nearly vertical contact, near the site of sample 47 (cross section A-A'). At another location, the thick intrusion on the inside of the right-angle bend of Yellowjacket Creek domed the host rocks upward, as shown by north-northeast dips adjacent to the northern margin of the body (cross section A-A'). These thick intrusions might once have been vertical feeders for eruptions and so might better be termed small stocks or even plugs, but their geometric relations with the sills—sharing the same base and merging into the sills without recognizable contacts—suggest a common origin from a sheet-like sill that blossomed upward into a crosscutting body.

Upper and lower contacts of the sills with the host rock are commonly exposed. The sill rock typically exhibits a fine-grained chill zone and is coarsely columnar jointed. The thicker sills commonly have a "tiered" appearance defined by differences in jointing habit and possibly grain size; such features suggest a composite origin from multiple injections of magma. The host rock, invariably consisting of fine- to medium-grained volcaniclastic rocks except where the thickest bodies intrude upward and cut across andesite flows, is little metamorphosed even adjacent to the contact, although commonly it is veined with zeolites and calcite. Contact metamorphism, as manifested by noticeable hardening, is strongest below the thickest bodies and along their steep terminations, such as along the clearly exposed base and sides of the Tongue Mountain body on both sides of Tongue Mountain itself. The host rocks surrounding the thin sills are not visibly metamorphosed.

The thinner sills resemble the hornblende-phyric dikes texturally and mineralogically as well as chemically (table 1, numerous analyses of unit Thd), and both are distinct from virtually all of the other analyzed rocks in the quadrangle (fig. 10). The thicker crosscutting bodies, however, are more strongly altered than are the thinner sills and dikes and commonly contain abundant chlorite, clay minerals, and locally calcite and zeolites. Thin sections of the altered rocks generally reveal small relics or

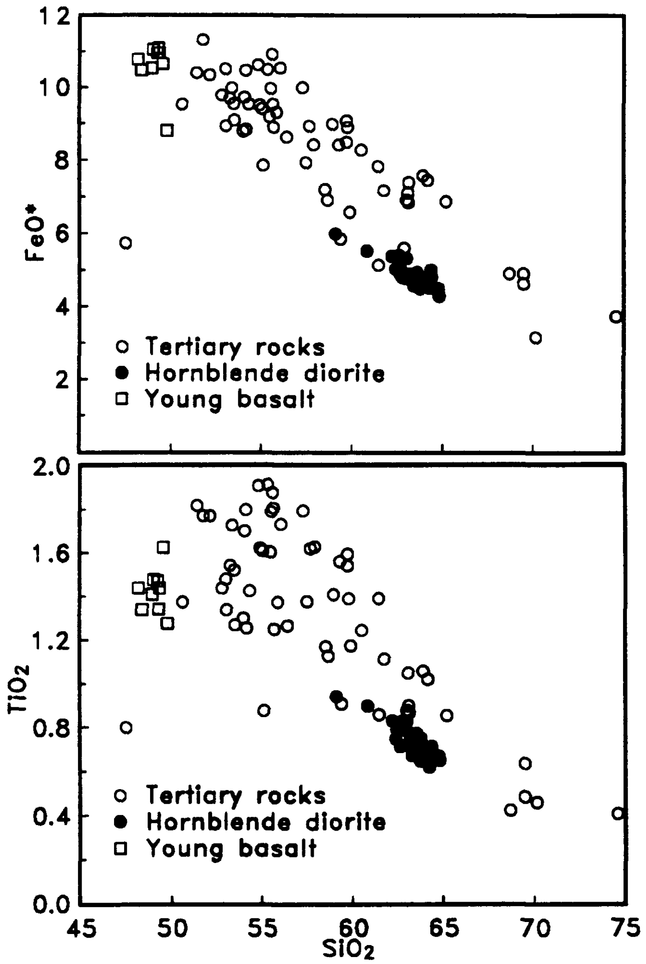

Figure 10. Plot of FeO* and TiO_2 vs. SiO_2 for rocks in Tower Rock quadrangle. Note that hornblende diorite and related rocks are distinct from most other rocks in quadrangle.

pseudomorphs of hornblende as well as nearly ubiquitous glomerophyric clots of plagioclase similar to those in the thinner dikes and sills. Chemically, the thicker bodies are indistinguishable from the thinner sills and dikes, all of which collectively define a compositional range (the "Kidd Creek suite" of Swanson, 1989) that is distinct from that of the other extrusive and intrusive rocks in the quadrangle.

Dikes cut sills but not vice versa. Only a few crosscutting dikes have been found in the entire radial swarm; the only one in the Tower Rock quadrangle is the dike between Veta and Galena Creeks, and that relation is only inferred from exposures of the dike well above and below the sill. Generally, a dike in contact with a sill appears to blend into the sill, with no obvious crosscutting relation except near the margin of the sill. Such blending can be seen at the site of sample 47 on the west flank of Tongue Mountain and inferred, in poor exposures, at the site of sample 68 between Lambert and Kidd Creeks. I interpret these relations to suggest that the sills and dikes are broadly contemporaneous, but that certain dikes, at least locally, are slightly younger than certain sills.

The relation between the dikes and sills is the subject of ongoing research. My present interpretation is that both are products of the same episode of magmatism. This episode apparently took place after regional folding, because the dikes are vertical where they cut tilted rocks and because their radial pattern is well preserved. Both are probably related to the development of a large subvolcanic complex centered in the northern part of the McCoy Creek quadrangle. The complex is defined by the focus of the radial dike swarm and the presence of a quartz diorite stock, the quartz diorite of McCoy Creek (Simon, 1972; Link, 1985). No eruptive products are known from this center; indeed hornblende-bearing rocks are extremely rare in the Tertiary section except for those in the sills and dikes. Whether both the sills and dikes were injected laterally away from this complex, or whether the complex (and perhaps the thicker bodies described above) sprouted from the sills (with the dikes injected radially from the complex), is unresolved.

Ages—Several radiometric ages exist for Tertiary rocks within or adjacent to the quadrangle. Phillips and others (1986) report a K-Ar age of 22.1 ± 1.3 Ma (whole-rock) for an andesite flow (sample 54, table 1) collected from the west shoulder of Lone Tree Mountain (table 2, map no. 3A). They also give a K-Ar age of 30.1 ± 2.2 Ma (whole-rock) for a basaltic andesite flow (sample 39, table 1) on the north flank of Bishop Mountain (table 2, map no. 4A). (Note that the location given in their paper for the Bishop Mountain sample is incorrect; it should be lat 46°27.27′ N.,

Table 2. Radiometric ages from the Tower Rock quadrangle

Map No.[1]	Sample No.	Reference	Unit	Method[2]	^{40}Ar, %[3]	Age, Ma
1A (62)	87-180	This paper[4]	Thd	K-Ar (HB)	4.0	20.3 ± 2.0
2A (92)	85-34	do.[4]	do.	do.	4.8	24.8 ± 2.2
Do.	do.	do.[5]	do.	FT (Zircon)	—	10.4 ± 1.0
3A (54)	MK8578	Phillips and others (1986)	Ta	K-Ar (WR)	54.8	22.1 ± 1.3
4A (39)	MK98415	do.	Ta	do.	13.7	30.1 ± 2.2

[1]Map number, with number of corresponding chemical analysis in parentheses (table 1)
[2]K-Ar, potassium-argon; FT, fission track; HB, hornblende; WR, whole rock
[3]Percent radiogenic argon relative to total argon
[4]Hornblende K-Ar determinations by Robert J. Miller, U.S. Geological Survey, Menlo Park
[5]Zircon FT determination by Joseph A. Vance, University of Washington, Seattle

long 121°45.35′ W., as determined from an unpublished field map by M. A. Korosec, who collected the sample and shows its location on the field map. The location of the sample as shown on Korosec's open-file map and table [1987, table 1, sample 27] is correct, although the location for the corresponding chemical analysis [Korosec, 1987, table 2] is wrong and should be SW¼NE¼ sec. 12, not SW¼NW¼ sec. 12.) Hammond (1980) reported two K-Ar ages of 18.4 ± 0.3 Ma and 18.9 ± 0.3 Ma (plagioclase) from the same ash-flow tuff near the trough of the Pole Patch syncline, 2.5 km west of the Tower Rock quadrangle (Swanson, 1989; table 3). The four ages from Phillips and others and from Hammond are broadly consistent with the stratigraphy and structure of the area, which show that the Tertiary section becomes younger toward the west within the Tower Rock quadrangle.

These ages allow a crude calculation of the rate of accumulation of the volcanic deposits. From cross section A-A′ and the geologic map of the Greenhorn Buttes quadrangle (Swanson, 1989), a stratigraphic thickness of roughly 5 km can be calculated between the stratigraphic level of the dated sample on Bishop Mountain and the trough of the Pole Patch syncline. This section accumulated at an average rate of about 435 m per million years (range of 352 m/m.y. to 575 m/m.y.), given the roughly 11.5-m.y. interval and error limits suggested by the K-Ar ages. Prior to 22 Ma, the accumulation rate averaged about 380 m/m.y. (3 km of section in 8 m.y.; range of 260 m/m.y. to 665 m/m.y.); after 22 Ma, the rate averaged about 570 m/m.y. (2 km of section in 3.5 m.y.; range of 380 m/m.y. to 1,250 m/m.y.). These rates are somewhat greater than those of 237 m/m.y. to 360 m/m.y. calculated by Smith (1989, p. 15-16) for four areas in the southern Washington area. I know neither why these differences should exist nor whether they are real or the product of analytical errors and thickness estimates. In any case the differences are relatively minor and provide a reasonable range of values for the accumulation rates. In other words, the average rate is several hundred meters per million years, not several tens or several thousands.

Table 3. Radiometric ages near but outside the Tower Rock quadrangle

Quadrangle	Sample No.	Reference	Unit	Method[1]	^{40}Ar, %[2]	Age, Ma
Greenhorn Buttes[3]	PEH-77-1	Hammond (1980)	Ttv	K-Ar (PL)	?	18.4 ± 0.3
Do.	do.	do.	do.	do.	?	18.9 ± 0.3
McCoy Peak[4]	85-51	This paper[6]	Thd	K-Ar (HB)	7.4	15.4 ± 1.3
Do.	do.	do.[7]	do.	FT (zircon)	—	13.4 ± 1.3
East Canyon Ridge[5]	JM87-22	do.[6]	do.	K-Ar (HB)	6.2	15.0 ± 1.3
Do.	do.	do.[7]	do.	FT (zircon)	—	11.4 ± 1.1

[1]K-Ar, potassium-argon; FT, fission track; HB, hornblende; PL, plagioclase; WR, whole rock
[2]Percent radiogenic argon
[3]Lat 46°22.68′ N., long 121°54.50′ W.
[4]Lat 46°17.94′ N., long 121°50.20′ W.
[5]Lat 46°21.03′ N., long 121°37.96′ W.
[6]Hornblende K-Ar determinations by Robert J. Miller, U.S. Geological Survey, Menlo Park
[7]Zircon FT determinations by Joseph A. Vance, University of Washington, Seattle

Four K-Ar ages on hornblende separates, and three zircon fission-track (FT) ages, have been obtained for the hornblende-bearing diorite sills, with inconsistent results (table 2, map nos. 1A and 2A; table 3). Two of the dated samples, equivalent to samples 62 and 92 in table 1, come from within the Tower Rock quadrangle. The four K-Ar hornblende ages range from 15 to 25 Ma, and the spread within the quadrangle is from 20.3 ± 2.0 (sample 62) to 24.8 ± 2.2 Ma (sample 92). I believe that these dates are unreliable owing to the small fraction of radiogenic Ar in the hornblende and(or) the presence of excess Ar (E. H. McKee, oral commun., 1991). The hornblende with the highest ratio of radiogenic to atmospheric Ar yields younger ages of about 15 Ma (compare the two samples in table 3 with the two in table 2) and comes from sills otherwise identical to those in the Tower Rock quadrangle.

The zircon FT ages were obtained from three of the four samples dated by K-Ar; sample 92 is the only one in the Tower Rock quadrangle. The FT ages agree much more closely with one another than do the corresponding K-Ar ages, and all are younger, averaging about 12 Ma. I favor the FT ages over the K-Ar ages for two reasons. One reason is their better internal consistency. The second reason relies on my interpretations that the dikes and sills are comagmatic and that the dikes are younger than the regional west-southwest tilting, as shown by their radial pattern and their vertical attitudes in tilted rocks. If these interpretations hold, the K-Ar ages of the sills would, if taken at face value, indicate erroneously that regional west-southwest tilting had occurred before 20-25 Ma, whereas rocks in the Greenhorn Buttes quadrangle as young as 18.5 Ma have demonstrably been tilted together with the rest of the section (Hammond, 1980; Swanson, 1989).

If the zircon FT ages are approximately correct, then the dikes and sills are about the same age as part of the Ellensburg Formation on the western Columbia Plateau, much of which contains hornblende-dacite pumice and heavy mineral suites rich in volcanic hornblende (Smith and others, 1989). Clayton (1983) determined a zircon FT age of 11.5 ± 0.4 Ma for a hornblende quartz diorite intrusion 9.5 km west-northwest of White Pass (just north of Goat Rocks in figure 1). Thus a body of evidence is growing that hornblende diorite and quartz diorite magma was intruded about 12 Ma over a wide area in the southern Washington Cascades, and that some of this magma erupted to form hornblende-bearing dacite. In fact, even younger intrusions of hornblende diorite and dacite near and north of White Pass (Smith and others, 1988; Clayton, 1983) suggest that such magmatism characterized the late middle and late Miocene in parts of the southern Washington Cascades.

YOUNG OLIVINE BASALT

Three map units of olivine basalt unconformably overlie the Tertiary section. The youngest (unit Qbs) is late Pleistocene on the basis of a radiocarbon age. The next youngest (unit Qbj) is almost certainly of Pleistocene age on the basis of geomorphic relations and freshness. The oldest unit (unit QTbt) is of early Pleistocene or possibly Pliocene age, on the basis of reversed magnetic polarity combined with geomorphic relations, freshness, and relation to the regional stratigraphy.

Basalt northwest of Tongue Mountain—The oldest of these units, the basalt northwest of Tongue Mountain, consists of at least two and possibly three or more chemically distinct flows of olivine basalt with reversed magnetic polarity and hence an age greater than about 0.73 Ma. The flows were not individually mapped, because they themselves consist of numerous flow units that cannot be grouped in the field into distinct flows without the aid of chemical analyses. The flows now form a ridge-capping unit that reflects an inversion of topography. At least two flows occur in a paleovalley trending northeast and eroded into tilted Tertiary rocks; good oblique exposures of the east side of the paleovalley can be seen in the cliff forming the landslide headwall on the north side of the largest outcrop of basalt. The basalt southeast of this cliff apparently underlies a flat, drift-covered plateau extending nearly to Tongue Mountain. Maximum relief on the basalt in this area is at least 105 m, from 850 m (2,800 ft) at an exposure of the basalt on the plateau to 745 m (2,450 ft) at the northwest end of the plateau.

The two recognizable flows in the paleovalley are chemically dissimilar; the older flow (table 1, no. 9) is richer in K_2O and especially P_2O_5 than the younger flow. Both flows have diktytaxitic to intersertal textures and are sparsely porphyritic with phenocrysts of olivine, but the older flow has distinctly less olivine (table 4, nos. 7, 9). The contact between the two flows shows no evidence of a significant time break and in fact looks no different than the contacts between discontinuous flow units; only the chemical analyses distinguish the flows.

A knob about 700 m northwest of the northwest end of the plateau is underlain by olivine basalt that has reversed magnetic polarity and petrographically resembles the flows of the plateau. The elevation of this basalt is similar to that of the plateau. Modally the basalt in the knob most closely resembles the older of the two flows in the paleovalley, although it is decidedly more crystalline than either of those flows and has a subophitic to intergranular texture (table 4, no. 6). Chemically this basalt also most closely resembles the older flow, although its content of K_2O and

P_2O_5 is intermediate relative to those of the two sequential flows and may indicate a separate flow.

The source of the magnetically reversed flows is unknown. No vent in the Tower Rock quadrangle was identified. Most likely the flows were erupted from farther up the Cispus or North Fork Cispus Rivers and moved downstream to the present exposure. If so, erosion has removed all remnants of the flows in those drainages, at least within the Tower Rock quadrangle. The base of the unit is about 335 m above the modern Cispus River and would, if erupted farther upstream, attest to at least that much downcutting since the flows were emplaced. Reconnaissance up both rivers has not yet discovered potential vents or correlative flow remnants. A less likely source of the flows is somewhere within the large areas now covered by landslide debris north and south of the divide between the Cispus River and Yellowjacket Creek.

The location and orientation of the paleovalley suggest that it represents the course of ancestral Yellowjacket Creek. Perhaps the flows are preserved here because they backfilled the ancestral Yellowjacket drainage a short distance upstream from its confluence with the ancestral Cispus. The right-angle bend in modern Yellowjacket Creek could result from this blockage, which diverted the creek to a westerly course, around the northern margin of a large hornblende diorite intrusion.

Maximum rates of incision can be estimated for the Cispus River and Yellowjacket Creek since the basalt flows were erupted. If the basalt is 0.73 Ma, its youngest possible age, the calculated maximum rate of downcutting for the Cispus River (about 335 m from the base of the basalt to present river level) would be 46 cm/1,000 yr and for Yellowjacket Creek (about 320 m from the base of the basalt) would be 44 cm/1,000 yr. These rates are similar because the Cispus River forms local base level for Yellowjacket Creek.

As pointed out by Sherrod (1986), the thickness of the basalt fill must be included in the incision calculation if the downcutting stream were flowing on the surface of the fill rather than along its margin. This situation is impossible to judge for the ancestral Cispus River, but if the river had to erode through the basalt, the total depth of incision would have been 335 m plus the thickness of the flows, unknown along the Cispus but about 130 m where currently exposed. The total amount of incision by the Cispus River calculated using these assumptions is then about 465 m, yielding a maximum rate of 64 cm/1,000 yr. Presumably Yellowjacket Creek did not have to erode through the complete flow sequence, for it apparently found a lower route to the southwest along which to flow to the Cispus; otherwise it would have simply entrenched itself in the basalt. Consequently the maximum rate of incision by Yellowjacket Creek is probably more than 44 cm/1,000 yr but less than 64 cm/1,000 yr.

These maximum incision rates, whether flow thickness is taken into account or not, are 1.5–4 times higher than the actual rates calculated by Sherrod (1986) for the central Oregon Cascades. Perhaps this difference is a crude measure of how much older than 0.73 Ma the basalt northwest of Tongue Mountain actually is. If so, then the age of the basalt is about 1–3 Ma. This is speculation added on uncertainty but probably provides a better estimate of age than can be determined in any other way short of obtaining a radiometric age.

Table 4. Modes of young olivine basalt in the Tower Rock and Greenhorn Buttes quadrangles

	Tower Rock quadrangle										Greenhorn Buttes quadrangle		
Unit													
Map No.	3	2	4	7	9	6	10	NA	NA	NA	NA	NA	NA
Sample No.	87-104	87-191	87-227	88-025	88-026	88-027	89-073	90-21A	90-21B	90-21D	90-1	90-1	90-125C
No. points	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Phenocrysts													
Olivine	2.3	3.9	2.0	5.6	2.4	2.5	3.3	1.7	1.9	1.2	1.6	0.1	2.0
Groundmass													
Olivine	16.4	12.3	10.4	9.8	9.5	9.1	6.8	14.8	11.5	14.7	18.7	15.6	16.8
Plag	47.9	42.3	57.9	28.0	18.6	28.9	26.6	44.3	42.5	48.7	40.9	38.8	42.0
Cpx	20.8	14.4	19.9	9.9	8.8	20.8	23.3	18.2	25.6	22.0	18.5	20.1	20.7
Opaque	4.5	4.2	3.4	2.2	2.4	7.2	4.2	3.1	3.9	2.8	3.1	3.2	2.6
Glass	8.1	22.9	6.4	44.5	58.3	31.5	35.8	17.9	14.6	10.6	17.2	22.2	15.9
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total Ol	18.7	16.2	12.4	15.4	11.9	11.6	10.1	16.5	13.4	15.9	20.3	15.7	18.8

[1]Gravel of unit Qbs in outwash of unit Qeo

[2]Clasts possibly of unit Qbs in till(?) of unit Qet(?)

Basalt of Juniper Creek—Olivine basalt was erupted explosively from a vent just south of Juniper Creek in the extreme southeast corner of the quadrangle. The high point on the cone at the vent is in a small saddle at about 1,070 m (3,520 ft) elevation, the site of sample 10 (table 1). The cone extends into the adjacent three quadrangles and is best exposed just inside the McCoy Peak and East Canyon Ridge quadrangles. The cone consists of well bedded, commonly well-sorted, cinder and black sideromelane sand, all of which is altered to some degree to palagonite. Surge beds, low-angle cross bedding, and shallow channels are common, and ballistic fragments of Tertiary rocks are strewn through the deposit. In one notable exposure just inside the McCoy Peak quadrangle at about 975 m (3,250 ft) elevation, 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 several tens of meters in diameter. The evidence clearly shows that the cone was constructed largely by phreatomagmatic explosions. An extensive remnant of the cone in the East Canyon Ridge quadrangle, separated from the remnant in the Tower Rock quadrangle by a narrow canyon, contains proportionally more cinder and apparently records drier, less steam-rich explosions that alternated with the wetter, phreatomagmatic explosions.

The base of the cone is at an elevation of about 935 m on the Tower Rock-McCoy Peak quadrangle boundary southeast of the top of the cone, but the contact drops rapidly northeastward into the Blue Lake quadrangle, more or less paralleling the current slope (and paleoslope) of the ridge. In other words, much of the cone mantles a 50 percent slope from its summit northeastward for about 700 m to an elevation of about 700 m (2,300 ft) in the Blue Lake quadrangle. A similar situation holds for the remnant of the cone in the McCoy Peak and adjacent East Canyon Ridge and Blue Lake quadrangles.

Lava flows were erupted from the cone, although in much less abundance than ejecta. The summit of the cone appears to be a flow remnant, possibly a small solidified lava pond; this is the site of sample 10 (table 1). Other thicker flows crop out in the Blue Lake quadrangle. The flows seem to have been produced throughout the eruptive history of the cone. The flow on top of the cone is clearly one of the last products of the eruption, whereas a 50 m thick, columnar flow occurs between 770 m (2,520 ft) and 720 m (2,370 ft) at the base of the cone in the Blue Lake quadrangle 700 m due east of the crest of the cone.

The thick basal flow is quite columnar, with narrow, 10-15-cm-diameter columns oriented subhorizontally as if the flow cooled against a northwest-trending vertical surface, parallel to and about 180 m (600 ft) above the present Cispus River in the Blue Lake quadrangle. It is possible that the subhorizontal columns record cooling against something related to the presence of the river, such as a lava dam created as the flow entered the Cispus River, or perhaps the margin of an ice sheet occupying the floor of the valley during Hayden Creek time. No remnant of the flow has been recognized along the Cispus River downstream from the site of this columnar flow. Little is known about the age of the unit, except that it is probably younger than 0.73 Ma on the basis of its normal magnetic polarity and overall youthful appearance. It probably was erupted into a glacially sculpted valley, but whether it predates or postdates the Hayden Creek Drift awaits examination of its surface in the adjacent quadrangles, where remnants of the drift probably occur.

One sample from the lava flow atop the cone, and several samples in adjacent quadrangles, were collected. The sample from the Tower Rock quadrangle (table 1, no. 10) has substantially higher K_2O (about 1.2 percent), P_2O_5 (about 0.4 percent), and FeO* (about 8.8 percent) than does typical olivine basalt in the Cascades. It is highly oxidized (high-temperature oxidation, not weathering, probably owing to its presence above the vent of the cone) and has no normative nepheline, but less oxidized samples from the Blue Lake and East Canyon Ridge quadrangles carry 2-3 percent *ne*. The sample is similar to several other highly potassic samples (my unpub. data) that characterize a cluster of Pleistocene olivine-basalt vents in a southwest-trending zone extending from the volcano that dams Blue Lake (Korosec, 1987; Walsh and others, 1987) through the Juniper Creek and Spud Hill (East Canyon Ridge quadrangle) areas into the McCoy Peak quadrangle. Olivine basalt of similar composition occurs in the Simcoe Mountains east of the Cascades in southern Washington (Leeman and others, 1990) but is older (Pliocene) than the basalt of Juniper Creek. Furthermore, the Simcoe rocks were probably erupted above a deeper Benioff zone and hence are more likely to be potassic.

Basalt of Spring Creek (Korosec, 1987)—This low-K olivine basalt occurs as remnants of an intracanyon flow or flows that issued from a low cone (hill 5162; fig. 1) at the north base of Mount Adams (Hammond, 1980; W. E. Hildreth, written commun., 1987) and flowed westward into the Cispus River valley and eastward into the Klickitat River valley. The unit is equivalent to the "basalt of Hill 5162" of Hammond (1980) and is named for a creek just west of that hill. A ^{14}C age (USGS 2714) of 21,550 ± 460 radiocarbon years was obtained by Wes Hildreth and Judy Fierstein (oral commun., 1991) from organic-rich soil at the base of the basalt of Spring Creek in the Cispus River valley upstream from the Tower Rock quadrangle.

In the Tower Rock quadrangle, the basalt of Spring Creek apparently consists of one flow, locally composed of several flow units. The basalt occurs in three areas: along Road 23 south of Bishop Mountain (about 45 m thick), overlooking the confluence of the Cispus and North Fork Cispus Rivers (maximum thickness of about 30 m), and along a low bench near the mouth of Dry Creek northwest of Cispus Center (no thicker than 25 m). The Dry Creek locality is the westernmost known outcrop of the unit, about 36 km by river from the vent. The flow closely followed the course of the modern Cispus River, which clearly had been established at the time the flow was erupted.

In the Tower Rock quadrangle, the base of the flow is generally shrouded by talus or, as at the Dry Creek locality, covered by outwash gravel (unit Qeo), but it can be seen at an elevation of about 470 m (1,550 ft) in road cuts along Road 23 south of Bishop Mountain and at about 510 m (1,680 ft) along the base of the cliff overlooking the North Fork Cispus River just downstream from the mouth of Irish Creek. At both localities, the lower several meters of the flow contain pillow breccia and hyaloclastic debris that rests on well-sorted pebble to boulder river gravel and sand tens of centimeters to more than 4 m thick overlying Tertiary rocks. The gravel at both localities is barren of olivine basalt, whereas clasts of the basalt of Spring Creek are abundant in gravel that is younger than that unit. Apparently older olivine basalt units, such as the basalt of Juniper Creek and several other units to the east, did not occur extensively enough along the ancestral Cispus River to contribute much material to the river gravel.

The basalt of Spring Creek is sparsely olivine phyric and has distinctive mauve clinopyroxene in the groundmass. Its chemical composition and mode distinguish the unit from other olivine basalt in all of the quadrangles shown in figure 1. It is characterized by a very low K_2O content, about 0.2 wt percent or less (table 1, nos. 2-5, 8), and a high content of olivine, 19-12 vol percent (table 4, nos. 2-4, and several other chemically and modally analyzed samples from outside the quadrangle). The basalt northwest of Tongue Mountain (unit QTbt) also has abundant olivine (table 4) but is much glassier than the basalt of Spring Creek and lacks mauve clinopyroxene. Leeman and others (1990, their table 2, samples DS80A and DS15A-80) published chemical analyses of low-K_2O olivine basalt from Berry Mountain in the Indian Heaven volcanic field that resemble those of the basalt of Spring Creek.

The high olivine content and presence of mauve clinopyroxene in the basalt of Spring Creek enable clasts in gravel and drift within the quadrangle to be identified without resorting to chemical analysis. For example, three cobbles from outwash of Evans Creek Drift at the abandoned bridge across the Cispus River 1 km northwest of Cispus Center yield modes indistinguishable from those of the basalt of Spring Creek (table 4) and hence show that the basalt is older than the Evans Creek Drift.

Three stones in the upper 1–2 m of drift at a quarry in the Greenhorn Buttes quadrangle (site of samples 96 and 114 and K-Ar sample 4A in Swanson [1989]) also are modally equivalent to the basalt of Spring Creek (table 4). These drift stones are especially interesting, because they occur at an elevation of about 915 m (3,000 ft), presumably too low for Evans Creek Drift, and yet have barely perceptible weathering rinds suggestive of Evans Creek age. Either the drift is indeed of Evans Creek age, or the basalt was derived from some flow older than Hayden Creek age that closely resembles the basalt of Spring Creek and is unknown in the quadrangles within which I have worked.

Korosec (1987, his table 2, sample MK8575) assigned a chemically analyzed sample of low-K_2O basalt to the basalt of Spring Creek, although its location in the Greenhorn Buttes quadrangle just downstream from the Dry Creek locality does not coincide with any known outcrops of the unit. This sample, collected from an angular block not demonstrably in place (M. A. Korosec, oral commun., 1991 and unpublished field map), is most likely from a clast in a deposit of Evans Creek Drift.

The depth of incision by the Cispus River from the top of the basalt flow to the present channel level is remarkably similar at the three outcrop localities in the Tower Rock quadrangle. Along Road 23, the incision depth is 70 m (top of flow, 515 m; channel, 445 m). At the cliff just downstream from the mouth of Irish Creek, the depth is also 70 m (top of flow, 540 m; channel, 470 m). At Dry Creek, the incision depth is 75 m (top of flow, 445 m; channel, 370 m). The top rather than the base of the flow is taken as the datum for these calculations, because the flow may have covered the entire width of the valley, as suggested from exposures in the Blue Lake and East Canyon Ridge quadrangles, where it occurs on both sides of the valley (Hammond, 1980; Walsh and others, 1987). If none of the flow had to be eroded away, incision depths from the flow base to present channel level are 25 m along Road 23 and 40 m near Irish Creek; the base of the flow near Dry Creek is not exposed.

An average rate of downcutting by the Cispus River of 3.25 m/1000 yr can be calculated, using the unpublished ^{14}C age of 21,550 radiocarbon years (Wes Hildreth and Judy Fierstein, oral commun., 1991) for soil at the base of the basalt of Spring Creek. This rate is extremely high but can be substantially lower only if my assumption is wrong that the river eroded through the entire thickness of the flow. Even if the Cispus River was able to avoid the flow completely by eroding *around* rather than *through* it, the calculated incision rates (from flow base to river channel) are still very high, between 1.2 and 1.9 m/1,000 yr.

The most likely means of such rapid downcutting is the increased discharge of the Cispus River during Evans Creek time. Probably meltwater torrents from Evans Creek glaciers were able to slice through the basalt and its substrate far faster than during interglacial periods. Such torrents, laden with suspended and bed-load sediment, hence must have been far more erosive than are the smaller, "cleaner" modern rivers in the Cascades. The basalt of Spring Creek may have been rather quickly incised owing to the presence of a dam of weakly resistant pillows and hyaloclastite. In addition, Howard and others (1982) pointed out that the short-term incision rate along a river dammed by a basalt flow can be very rapid owing to the increased gradient of the river at the front of the flow. The rate drops off as soon as erosion through the flow is complete. Hence the actual rate of downcutting through the basalt of Spring Creek could have been substantially greater than the average rate calculated above.

The basalt of Spring Creek apparently was erupted just before, or at the very start of, the deposition of outwash of Evans Creek Drift in the quadrangle. The deposit of sand and gravel below the flow is thin to absent and may well record normal fluvial deposition, whereas younger outwash gravel deposits are thick and form several terrace levels, the highest of which is significantly lower than the top of the flow. The 21,550-yr age of the basalt of Spring Creek therefore provides one of the better available constraints on the timing of the onset of Evans Creek glaciation.

STRUCTURE

The west-southwest-dipping Tertiary section of the Tower Rock quadrangle is on the east limb of a major syncline in the southern Washington Cascades, the Pole Patch syncline. The Pole Patch and its possibly *en echelon* segment, the Elk Creek syncline (Swanson, 1989), dominate the structure of the French Butte, Greenhorn Buttes, and Tower Rock quadrangles. The section exposed in the east limb of the Pole Patch syncline is at least 5 km thick between Bishop Mountain and the trough of the syncline; the east limb extends an unknown distance beyond Bishop Mountain.

The strikes are remarkably consistent (fig. 11), and dips are generally 25°–35°. Attitudes that deviate from this pattern probably result from both deposition on the slopes of local volcanic edifices and post-depositional deformation related to faulting and to emplacement of sills. The mean strike of 346° is similar to that of 357° for 183 measurements in the Greenhorn Buttes and French Butte quadrangles (Swanson, 1989). The data from the three quadrangles illustrate the notable uniformity of the trend of the Pole Patch syncline and indicate that the syncline has a low plunge, if any.

Most or all of the folding took place before intrusion of the suite of hornblende-bearing sills and dikes. Evidence for this interpretation is given in the section describing those intrusions.

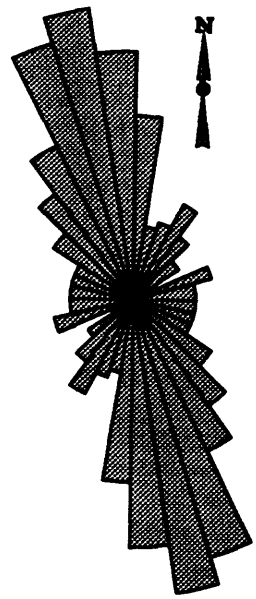

Figure 11. Equi-area rose diagram of 225 measured strikes of bedding and lava flows in Tower Rock quadrangle, in 10° intervals. Mean azimuth, 346°; standard deviation, 31°.

In the Tower Rock quadrangle, the east limb of the syncline is cut in several places by faults, generally of uncertain sense and unknown (but probably small) magnitude of offset. The faults are defined by shear zones, accompanied along Irish Creek by unusually steep dips in the Tertiary rocks. Most of the faults were drawn on the map by connecting outcrops exposing sheared rocks. Such outcrops are generally aligned along north-northwest trends, as are the shear planes within these outcrops. None of the faults or shear zones is exposed for more than a few meters along strike. Locally, veins of quartz, calcite, or zeolite occur within the fault and shear zones.

Few direct measurements of offsets could be made owing to uncertainties of various kinds. One of the most obvious displacements, about 0.6 m in a down-to-the-south sense, is shown by the lower of the two faults near the Lewis-Skamania County line between Galena and Veta Creeks.

The north-northwest-striking fault just east of McCoy Creek is exposed in two places near the Lewis-Skamania

County line. North-northwest-striking fault planes that dip 60° west cut hornblende diorite in an abandoned quarry just north of the line; slickensides and small steps on the planes indicate an oblique normal-left-slip displacement. Logging-road cuts just south of the county line expose sheared hornblende diorite, veined with calcite and zeolite(?), in contact with volcaniclastic rocks. The fault abruptly terminates a hornblende diorite sill along Kidd Creek. No estimate of the amount of displacement can be made.

Several fault strands weave together to form a north-northwest-striking fault zone in the northeastern part of the quadrangle that broadly corresponds to the Pin Creek fault of Hammond (1980), a normal, west-side-down structure. Right-lateral, northwest-striking shear planes in the rhyodacite of Camp Creek are exposed in a roadcut along the westernmost strand 600 m west of Tyler Creek. Most of the faults dip steeply, but a small fault just downstream from the mouth of Tyler Creek dips only about 20° east-northeast.

Several small, northeast-striking faults and shear zones occur within the Pin Creek fault zone along lower Polk and Irish Creeks. The two zones crossing lower Polk Creek both have polished surfaces and slickensides that plunge down the dip of the surfaces.

The west-side-down displacement portrayed on cross section B-B′ is problematic and based mainly on Hammond's (1980) interpretation in the Pin Creek area itself, far south of the quadrangle. However, the monoclinal axis mapped just northeast of the Pin Creek fault zone may be related to the faulting. If so, the fault zone would clearly have a dip-slip component as proposed by Hammond and would be more than just a right-lateral strike-slip zone, small examples of which are rather common in the southern Washington Cascades (Swanson, 1989). Lacking clearer evidence, however, it is hard to know how significant the Pin Creek fault zone might be.

The age of the youngest faulting and shearing is likewise uncertain. The highest shear zone near the Lewis-Skamania County line between Galena and Veta Creeks cuts the hornblende dacite dike there and hence is younger than about 12 Ma, though the dike is offset less than its country rock. It is uncertain if this shear zone is representative of others in the quadrangle. Many joints in some of the hornblende-bearing sills, for example several of those exposed in roadcuts along the west side of Yellowjacket Creek, show evidence of small offsets but no coherent pattern of displacement. No unit of Quaternary age was observed to be offset by faulting.

The course of the Cispus River upstream from the mouth of the North Fork Cispus follows the trace of the westernmost strand of the Pin Creek fault zone and may be controlled by it. Upstream from the mouth of the North Fork, the river flows generally north-northwestward for 14 km; downstream from the North Fork, the river flows generally westward for 16 km. Hence the left bend in the river where it leaves the Pin Creek fault zone is a significant feature that seems best explained by fault control.

Even the westerly course of the Cispus River downstream from the North Fork may be controlled by faulting or shearing, although the magnitude of offset cannot be great. A narrow, steeply dipping shear zone exposed in a roadcut 1.5 km east-northeast of Cispus Center has horizontal slickensides and stepped surfaces indicating a right-lateral sense of movement. The shear zone projects along the Cispus River valley both upstream and downstream from the roadcut. However, the distinctive vitrophyric dacite flow (unit Tvd) occurs on both sides of the river in positions consistent within errors with its attitude. This relation indicates that the amount of lateral displacement along the shear zone is probably 200–300 m (as portrayed on the geologic map) or less. The amount of vertical displacement, if any, is unknown but also cannot be great.

The contrast is striking between the stratigraphic sections north and south of the Cispus River west of the confluence of the North Fork Cispus River. Lava flows dominate the section north of the river, volcaniclastic rocks dominate south of the river, and hornblende-bearing sills occur only south of the river. These contrasts might suggest that a significant fault separates the two areas, but the continuity of the vitrophyric dacite across the river, and its small (if any) offset on the shear zone, argue convincingly against the presence of a significant fault along the river. Instead, the contrast is probably a rapid facies change that reflects the presence of a volcano at Lone Tree Mountain, which erupted numerous lava flows, a few of which occur south of the river. Possibly the sills failed to penetrate farther north because of the lateral discontinuity between the well bedded volcaniclastic rocks south of the Lone Tree center and the mound of relatively poorly layered, probably mechanically stronger lava flows that piled up around the center. Perhaps the abrupt thickening of the ends of some of the hornblende-phyric sills was a response to the lack of lateral stratigraphic continuity; upon encountering a "barrier" of lava flows to the north, the magma required less energy to intrude upward than laterally into the flows. Finally, the northernmost sills are 10 km from their parent(?) subvolcanic complex in the McCoy Peak quadrangle and may simply have reached as far from the complex as they could, given the existing magmatic driving pressure. Whatever the explanation of the contrasting sections on either side of the Cispus, a stratigraphic rather than a fault explanation is demanded by the evidence.

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. Narrow deposits of alluvium along Cispus River mostly included with outwash deposits of Evans Creek Drift (Qeo). Mostly Holocene and late Pleistocene. Locally includes colluvium and drift

Qc **Colluvium (Holocene and Pleistocene)**—Unsorted, unconsolidated deposits of slope wash and local open-work talus, mostly on lower slopes of Cispus River valley. Mostly Holocene and late Pleistocene

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 over clay-rich volcaniclastic rocks. Much of unit in large area just north of Lambert Creek appears degraded and may be late Pleistocene. Queried where possibly confused with colluvium or glacial outwash above unit Qbs south of Bishop Mountain

Evans Creek Drift (Pleistocene)—Till, moraine, and outwash deposits. Unweathered; most clasts in B soil horizon lack significant weathering rinds. Age is late Pleistocene, approximately 17–25 ka (Barnosky, 1984; Crandell, 1987). In quadrangle, less than 21,550 ± 460 radiocarbon years (unpublished ^{14}C date from Wes Hildreth and Judy Fierstein for soil at the base of the basalt of Spring Creek; see text). Divided into:

Qet **Till deposits**—Diamictons on floors of two small cirques on north flank of Lone Tree Mountain. Floors of these cirques are at elevations of only about 1,070–1,220 m (3,500–4,000 ft), scores of meters lower than floors of most other cirques of Evans Creek age at this longitude (W. E. Scott, oral commun., 1989). Contains locally derived clasts. Locally includes postglacial alluvium and colluvium. Queried where possibly confused with landslide deposits, as along upper Kilborn Creek

Qem **Moraine deposits**—Lithologically resembles till but forms morphologically distinct low ridges along margins of till deposits in the two cirques on north flank of Lone Tree Mountain

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, presumably reflecting episodic glacier retreat. Highest terrace level is about 30 m above channel floor. Deposited by meltwater streams draining glaciers in headwaters of Cispus River and, west of Dry Creek, partly from meltwater streams that carried outwash southward and southeastward from margin of Cowlitz River glacier (Swanson, 1989). Cispus River mostly entrenched into these deposits. Includes modern alluvium along channel of Cispus River

Hayden Creek Drift (Pleistocene)—Till and morainal 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). Mostly deposited by Cispus and(or) Cowlitz River glaciers. 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. Divided into:

Qhd **Till deposits**—Diamictons at elevations from 425 m (1,400 ft) along side of Cispus River valley to 1,310 m (4,300 ft) on Lone Tree Mountain. Locally includes modern colluvium. Queried where possibly confused with other surficial deposits, especially colluvium and landslide deposits. Mapped only where thick and obscuring bedrock

Qem **Moraine(?) deposits**—Diamicton underlying low, linear, west-trending ridges and valleys a few meters high northwest of Tongue Mountain. Appears to grade laterally into till. Could be of Evans Creek age

BASALT FLOWS

Qbs **Basalt of Spring Creek of Korosec (1987) (Pleistocene)**—Nonporphyritic to sparsely olivine-phyric, diktytaxitic olivine basalt along right bank (looking downstream) of Cispus River valley. Equivalent to the "basalt of Hill 5162" of Hammond (1980). Forms prominent benches above outwash of Evans Creek Drift (unit Qeo) at mouth of North Fork Cispus River and near east edge of quadrangle. Low, inconspicuous bench near mouth of Dry Creek is westernmost known outcrop of unit. One flow consisting locally of several flow units. Probably erupted from vent at knob 5162 in Glaciate Butte quadrangle north of Mount Adams (fig. 1; Hammond, 1980; W. E. Hildreth, written, commun., 1987). Characterized by low K_2O content (0.12–0.20 percent; table 1), deep mauve clinopyroxene, and distinctive mode (table 4). Occurs in valley probably carved largely by glacier of Hayden Creek age. Rests on charred, organic-rich soil with age of 21,550 ± 460 radiocarbon years (Wes Hildreth and Judy Fierstein, oral commun., 1991). Gravel derived from unit occurs in outwash deposits of Evans Creek Drift. Normal magnetic polarity

Qbj **Basalt of Juniper Creek (Pleistocene)**—Nonporphyritic to sparsely olivine-phyric, diktytaxitic olivine basalt forming tuff cone and associated thin flows in southeastern corner of quadrangle. Characterized by high K_2O content (1.2 percent; table 1), rare red-brown biotite in groundmass, and distinctive mode (table 4). Age not known but probably late or middle Pleistocene. Degree of dissection suggests it is older than basalt of Spring Creek and Evans Creek Drift. Possibly erupted during Hayden Creek time (see text). Normal magnetic polarity

QTbt **Basalt northwest of Tongue Mountain (Pleistocene or Pliocene)**—Nonporphyritic to sparsely olivine-phyric, diktytaxitic olivine basalt filling paleovalley and forming flat plateau 2 km northwest of Tongue Mountain. Correlative flow remnant caps knob 1.5 km farther northwest. Unit includes at least two flows, each consisting of several flow units. Chemical composition has moderate K_2O and is not distinctive (table 1), but reversed magnetic polarity and relatively high content of glass (table 4) sets unit apart from other olivine basalt in quadrangle. Overlain by Hayden Creek Drift. Age unknown but at least as old as about 0.73 Ma, age of Brunhes-Matuyama polarity chron boundary

INTRUSIVE ROCKS

Thd **Hornblende diorite and related rocks (Miocene)**—Hornblende-clinopyroxene-plagioclase-phyric diorite, quartz diorite, dacite, and andesite forming sills and dikes south of Cispus and North Fork Cispus Rivers. Unit extends into the French Butte (Swanson, 1989), McCoy Peak, East Canyon Ridge, and Blue Lake quadrangles and forms extensive suite (termed "Kidd Creek type" by Swanson, 1989) of co-magmatic intrusive rocks. Grain size largely dependent on nature of body: andesite and dacite (rarely glassy) in dikes, thin sills, and chilled margins of larger bodies, and microdiorite and quartz microdiorite to diorite and quartz diorite in most sills. 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 occurs in some samples. Inclusions of variously textured diorite, and clots of hornblende and plagioclase, fairly common. Chemically the unit forms a distinct grouping of mafic dacite and silicic andesite, with characteristically low TiO_2, FeO^*, and MnO (table 1). In general much fresher than host rock, although large pluglike bodies (such as Tower Rock, Tongue Mountain, and Burley Mountain) contain abundant deuteric(?) clay and other secondary minerals, and only pseudomorphs of hornblende and generally clinopyroxene remain. Age not well known but probably about 12 Ma on basis of three zircon fission-track ages from intrusive suite, one sample of which is from within quadrangle (tables 3 and 4; J. A. Vance, written commun., 1990). Subdivided locally to delineate major pluglike, coarsest, and most altered, bodies:

Thdo **Hornblende diorite and quartz diorite of Tower Rock**

Thdt **Hornblende diorite and quartz diorite of Tongue Mountain**

Thdb **Hornblende diorite of Burley Mountain**

Also includes:

Thai **Hornblende andesite sill of Kidd Creek basin**—Hornblende-plagioclase-phyric, fine-grained, pilotaxitic to cryptocrystalline andesite sill. Contains needle-shaped hornblende phenocrysts. Inclusions of hornblende diorite and clots of hornblende and plagioclase abundant. Chemical analysis (table 1, no. 49) indicates that unit belongs to comagmatic suite of other hornblende-phyric intrusions in quadrangle (units Thd, Thdo, Thdt, and Thdb). However, texturally distinct from these other units

Tai **Andesite and basaltic andesite intrusions (Miocene and Oligocene)**—Dikes and small, less common, subequant hypabyssal intrusions of aphyric and one- or two-pyroxene-plagioclase-phyric andesite and basaltic andesite. Includes a few dikes of mafic dacite (table 1, no. 93) that resemble andesite in the field and thin section. Fine-grained and texturally resembles lava flows (unit Ta). Dikes characterized by horizontal columnar jointing, quenched margins, steep contacts with host rocks, and widths of 1–5 m. Broadly sill-like but locally discordant bodies on west flank of Bishop Mountain and just west of mouth of North Fork Cispus River are rather platy. Slightly discordant sill south of Lambert Creek is columnar and locally coarse enough to be termed diorite or gabbro. Both dikes and sill-like bodies are locally vesicular. Most dikes occur on Lone Tree Mountain and define east-southeast-trending swarm. Dikes of similar orientation occur along Irish and Kilborn Creeks. This orientation is similar to that of most dikes mapped in southern half of French Butte (Swanson, 1989) and McCoy Peak (D. A. Swanson, unpub. data; Swanson, 1990) quadrangles. Length of single dikes shown schematically; most dikes crop out for only a few meters or tens of meters along strike. Sill south of Lambert Creek is cut by several hornblende microdiorite dikes (unit Thd), the only place in quadrangle that unit is in contact with hornblende-bearing bodies (units Thd, Thdo, Thdt, and Thdb). In McCoy Peak quadrangle, however, intersections of dikes of unit with hornblende-bearing intrusions are common, and at every intersection the hornblende-bearing unit is younger. Probably in part feeders for flows of unit Ta, but many dikes could be younger by an unknown amount than any flows in quadrangle. Queried where possibly confused with lava flow

Tbi **Basalt to basaltic andesite sill south of Burley Mountain (Miocene)**—Sill of relatively coarse-grained basalt and basaltic andesite or microdiorite. Cut off by hornblende diorite of Burley Mountain. Samples near Burley Mountain contain scattered phenocrysts of clinopyroxene and plagioclase; those near south end of sill are aphyric. Columnar and platy. Contains abundant clay minerals. Chemical compositions of two samples (table 1, nos. 13 and 23) are so different that body is either a composite sill or two or more sills

Tdi **Silicic andesite and mafic dacite intrusions (Miocene)**—Dike and irregular intrusion along Siler Creek (table 1, no. 70), small body poorly exposed in road cut between Camp and Polk Creeks (table 1, no. 66), and dike(?) on south flank of Bishop Mountain. Light gray, weathering to pink or rose. Vitrophyric to very fine-grained; small phenocrysts of plagioclase and clinopyroxene. Glassy groundmass altered to clay, zeolite and carbonate

LAVA FLOWS AND VOLCANICLASTIC ROCKS

Ttv **Volcaniclastic rocks, undivided (Miocene and Oligocene)**—Lithic- and lesser pumice-lapilli tuff, fine-grained tuff, and bedded conglomerate, sandstone, siltstone, and lithic diamictite containing volcanic-derived clasts. Typically green but locally buff, white, or mauve. Different rock types interbedded at all scales, and attempts to map them separately proved unworkable. In general, however, lapilli tuff and tuff are most abundant in central and western parts of quadrangle (in the middle and upper part of the stratigraphic section) and epiclastic rocks are most abundant in the eastern part of the quadrangle (lower part of section). Well-bedded, mostly epiclastic rocks are especially abundant on Bishop Mountain and in Kidd Creek basin.

Pumice-lapilli tuff, common farther west in the Greenhorn Buttes and French Butte quadrangles (Swanson, 1989), is much less abundant in the Tower Rock quadrangle. It is probably of ash-flow origin. Welding is uncommon. Thickness ranges from several meters to more than 10 m. Typically plagioclase-phyric, with minor clinopyroxene; no quartz or hornblende. Lithic clasts, generally andesite or dacite, sparse to abundant.

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 entirely of volcanic derivation, chiefly basaltic andesite and andesite but including dacite. Wood, chiefly stems and twigs, plentiful locally. Detritus probably derived by reworking of freshly erupted debris or by erosion of slightly older volcanic rocks and deposited in fluvial environment.

Clasts in lithic diamictite range in size from sand to boulders. Wide range in degree of rounding, with 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. Wood abundant in some beds. Commonly interbedded with fluvial sandstone. Probably mostly of debris-flow origin. Coarse, poorly sorted, crudely bedded debris just west of summit of Lone Tree Mountain may in part be near-vent explosion breccia

Ta **Andesite and basaltic andesite lava flows, undivided (Miocene and Oligocene)**—Highly phyric (>20 percent) to slightly phyric (<5 percent), darkly hued, fine-to medium-grained flows and associated basal and flow-top breccia of andesite and basaltic andesite not assigned to other units. Flows typically 5–20 m thick, commonly platy and(or) columnar, with vesicular or amygdaloidal zones in many places. Phenocrysts dominantly plagioclase, with lesser clinopyroxene and hypersthene; most common phenocryst assemblage (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), and very rare phenocrysts of hornblende. Groundmass texture chiefly fine-grained intersertal or intergranular, with flow-aligned microlites common; very fine-grained pilotaxitic texture common in more silicic rocks. Fresh glass uncommon; glass generally altered to clay minerals. Compositions range from mafic basaltic andesite to silicic andesite (table 1). 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 unit. Interbedded extensively with volcaniclastic rocks (unit Ttv) and includes some volcaniclastic beds too thin to map separately. Flows most common north of Cispus River; possible eruptive center near Lone Tree Mountain suggested by thickness of andesite section and presence of explosion(?) breccia near summit of mountain (mapped with unit Ttv)

Tagc **Basaltic andesite of Greenhorn Creek (Miocene)**—Highly plagioclase-phyric lava flows in southwestern part of quadrangle. Plagioclase phenocrysts abundant and generally several millimeters long (10–30 percent of rock). Phenocrysts of clinopyroxene and hypersthene much less abundant and smaller than those of plagioclase. Typically fine- to medium-grained, intergranular to intersertal groundmass. Mapped only adjacent to Greenhorn Buttes quadrangle, within which unit is areally prominent (Swanson, 1989). Near or at top of Tertiary stratigraphic section in Tower Rock quadrangle

Tbac **Basaltic andesite of Camp Creek (Oligocene)**—Thin flow or flows of plagioclase-clinopyroxene-phyric basaltic andesite (table 1, no. 32). Directly overlies palagonitic tephra of unit Tpt with no evidence of intervening soil. This association, and unusual southeast dip of both units Tbac and Tpt, suggest eroded vent complex, possibly resting unconformably on underlying rocks. Includes poorly exposed aphyric andesite directly overlying rhyodacite of Camp Creek 1 km north of main outcrop area (table 1, no. 31).

Tpt **Palagonitic tephra (Oligocene)**—Poorly sorted, well bedded, palagonitized lithic and pumiceous andesitic or basaltic andesitic tephra underlying basaltic andesite of Camp Creek. At least 30 m thick. Beds are several centimeters to 2 m thick. Delicately laminated in several places. Small shallow channels but no obvious low-angle stratification typical of surge deposits. Lithic clasts mostly angular and nonvesicular; many elongate clasts lie in plane of bedding. Pumice lapilli dominate several beds a few centimeters thick. Possibly proximal facies of hydromagmatic eruption, with basaltic andesite of Camp Creek extruded following explosive stage of activity

Tvd **Vitrophyric dacite (Oligocene)**—At least one flow of vitrophyric dacite underlying palagonitic tephra and basaltic andesite of Camp Creek. Characterized by narrow glassy columns resembling entablature of some basalt flows. Contains small phenocrysts and microphenocrysts of plagioclase, clinopyroxene, and hypersthene. Occurs on both sides of Cispus River just east of Cispus Center. Three chemical analyses (table 1, nos. 69, 71, and 72) are nearly identical, and two others (table 1, nos. 84 and 99) resemble one another but are more silicic than the other three. Analyses suggest either two flows or one flow of inhomogeneous composition

Trc **Rhyodacite of Camp Creek (Oligocene)**—Nonporphyritic to sparsely and finely plagioclase-phyric rhyodacite and rhyolite (table 1, nos. 95–98) underlying broad, relatively flat headwaters of Camp Creek and southwest side of Kilborn Creek valley. Pastel colors typical. Flow-layering and rubble common. Groundmass texture cryptocrystalline to devitrified; snowflake devitrification texture common. Contacts mostly obscured by colluvium or drift and highly interpretative. Overall outcrop pattern is complex, perhaps indicative of several episodes of eruption or of complex morphologic forms created during one eruption. Used extensively for road aggregate in Lone Tree Mountain area

Tb **Basalt (Oligocene)**—Nonporphyritic to plagioclase- and olivine-phyric flows of olivine basalt between Polk and Tyler Creeks and along a down-dip projection from this area along the Cispus River. Intergranular to intersertal groundmass. Olivine pseudomorphed by clay minerals but clearly recognizable by its crystal form. Most mafic Tertiary unit in Tower Rock quadrangle (table 1, nos. 11 and 12)

Tav **Andesite vent deposits (Oligocene)**—Small area of oxidized, amygdaloidal, locally agglutinated andesitic cinder just west of mouth of North Fork Cispus River. Interpreted as vent area for units Ttv or Ta

Td **Dacite and rhyodacite flows and domes, undivided (Oligocene)**—Light-colored, fine-grained, sparsely plagioclase-phyric flows and(or) domes not assigned to other units. Commonly flow-layered. The one chemical analysis for unit indicates rhyodacite composition (table 1, no. 94). Occurs at several stratigraphic levels in northeast quarter of quadrangle

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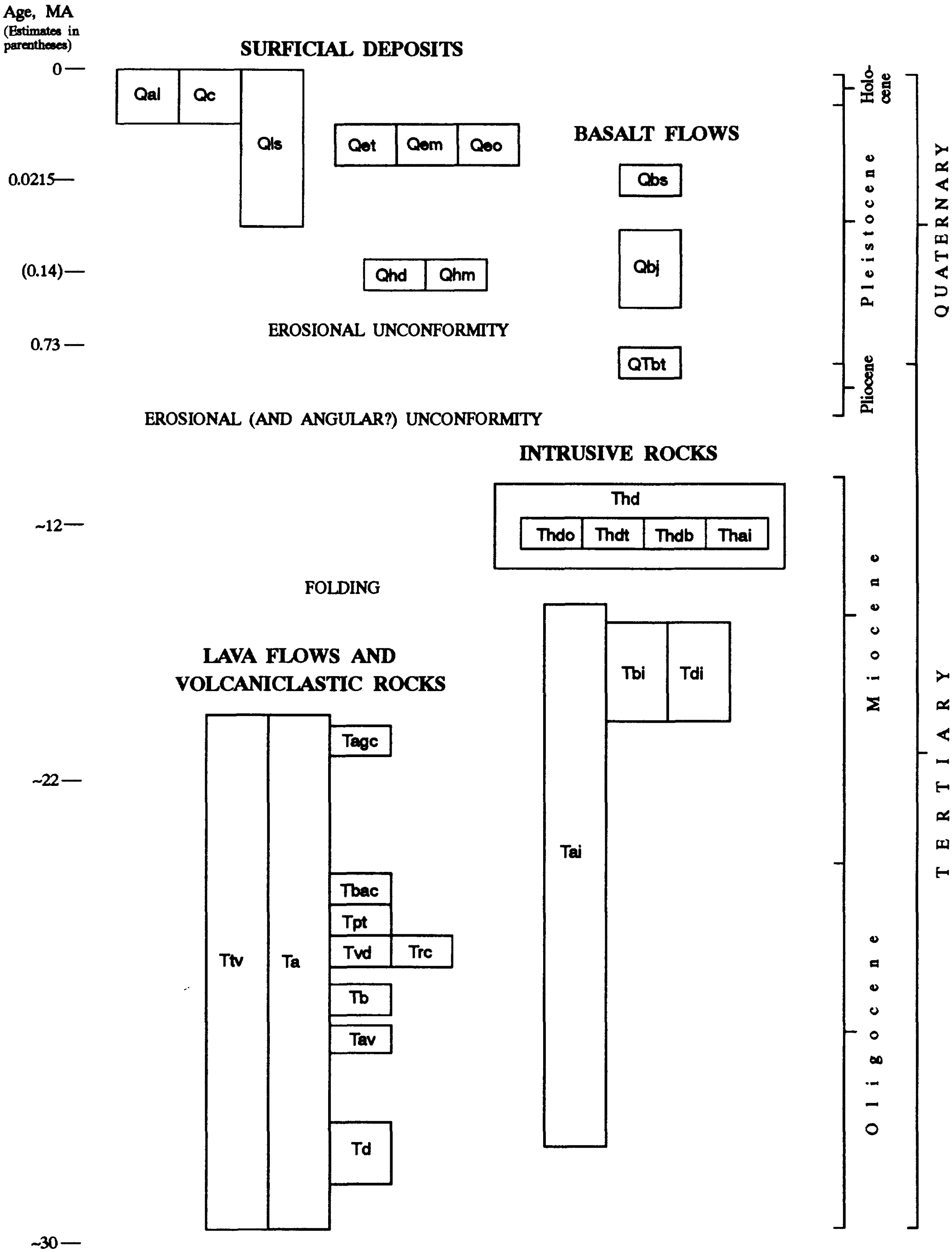
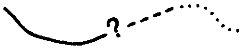
CORRELATION OF MAP UNITS

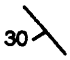


EXPLANATION



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

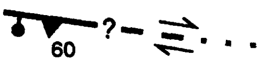
Strike and dip of bedding and flow contacts



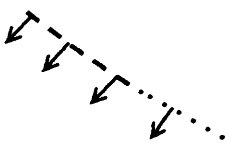
Inclined

Vertical

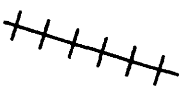
Strike and dip of planar jointing in hornblende diorite



Fault or shear zone, with dip of slip plane if known, dashed where approximately located, dotted where concealed; arrows denote relative sense of lateral movement, queried where uncertain; bar and ball on downthrown side where known



Monoclinal axis, dip steepening in direction of arrows, dotted where concealed



Dike

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

Basalt

Basaltic andesite

Andesite

Dacite

Rhyodacite and rhyolite

Site of radiometrically dated sample, with map number. Number refers to table 2