WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
Raymond Lasmanis, State Geologist

GEOLOGIC MAP OF THE MOUNT ST. HELENS QUADRANGLE, WASHINGTON AND OREGON

Compiled by

WILLIAM M. PHILLIPS

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES

OPEN FILE REPORT 87-4

1987

(Revised Nov. 1987)

This report has not been edited or reviewed for conformity with Division of Geology and Earth Resources standards and nomenclature.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle · Commissioner of Public Lands
Art Stearns · Supervisor

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
Raymond Lasmanis, State Geologist

GEOLOGIC MAP OF THE MOUNT ST. HELENS QUADRANGLE, WASHINGTON AND OREGON

Compiled by
WILLIAM M. PHILLIPS

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES

OPEN FILE REPORT 87-4

1987

(Revised Nov. 1987)

This report has not been edited or reviewed for conformity with Division of Geology and Earth Resources standards and nomenclature.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle · Commissioner of Public Lands
Art Stearns · Supervisor

CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGIC MAP OF THE MOUNT ST. HELENS QUADRANGLE, WASHINGTON AND OREGON

Compiled by
William M. Phillips

INTRODUCTION

This map is one of a series of 1:100,000-scale geologic maps compiled by staff geologists of the Division of Geology and Earth Resources (DGER) and used as source maps for the southwest quadrant of the geologic map of Washington (Walsh and others, in press). Geologic data for the southwest quadrant were compiled on 1:100,000-sale metric topographic maps, then reduced and simplified somewhat to construct the 1:250,000-scale state map.

As the 1:100,000-scale compilations contain details of structure and stratigraphy which could not be shown at the 1:250,000 scale of the state map, they have been released as DGER open-file reports. Two exceptions are recently released maps prepared by the U.S. Geological Survey, for the Snoqualmie Pass (Frizzell and others, 1984) and Wenatchee (Tabor and others, 1982) 1:100,000-scale quadrangles. The 1:100,000-scale geologic compilation maps used in the southwestern state map quadrant are shown in Figure 1 together with bibliographic data.

The DGER 1:100,000-scale compilations differ from the state map in depicting numerous formations and informally named units as well as generic time-lithology units. On the Mount St. Helens 1:100,000-scale quadrangle, for example, the Miocene Wilkes Formation is symbolized and discussed as "Twk" or "Tertiary Wilkes Formation." On the state map, the same unit is symbolized as "Mc" or "Miocene continental sediments." Table 1 correlates the units of this report with those used on the state map.

The 1:100,000-scale compilations also depict strike and dip of bedding and/or foliation. In the text of the 1:100,000-scale maps, major element geochemical and K-Ar isotopic data are tabulated, if appropriate.

The 1:100,000-scale maps in this series that have been released to date are:

Korosec, M. A., compiler, 1987, Geologic map of the Mount Adams quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-5, 41 p., l pl., scale 1:100,000

Korosec, M. A., compiler, 1987, Geologic map of the Hood River quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-6, 42 p., 1 pl., scale 1:100,000

Logan, R. L., compiler, 1987, Geologic map of the Chehalis River and Westport quadrangles, Washington: Washington Division of Geology and Earth Resources Open File Report 87-8, 18 p., 1 pl., scale 1:100,000

Logan, R. L., compiler, 1987, Geologic map of the south half of the Shelton and the south half of the Copalis Beach quadrangles, Washington: Washington Division of Geology and Earth Resources Open File Report 87-9, 17 p., 1 pl., scale 1:100,000

Phillips, W. M., compiler, 1987, Geologic map of the Mount St. Helens quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-4, 63 p., I pl., scale 1:100,000

Phillips, W. M., compiler, 1987, Geologic map of the Vancouver quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-10, 32 p., 1 pl., scale 1:100,000

Phillips, W. M.; Walsh, T. J., compiler, 1987, Geologic map of the northwest part of the Goldendale quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-13, 9 p., 1 pl., scale 1:100,000

Schasse, H. W., compiler, 1987, Geologic map of the Centralia quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-11, 27 p., 1 pl., scale 1:100,000

Schasse, H. W., compiler, 1987, Geologic map of the Mount Rainier quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-16, 43 p., 1 pl., scale 1:100,000

Walsh, T. J., compiler, 1986, Geologic map of the west half of the Toppenish quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 86-3, 8 p., I pl., scale 1:100,000

Walsh, T. J., compiler 1986, Geologic map of the west half of the Yakima quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 86-4, 12 p., I pl., scale 1:100,000

Walsh, T. J., compiler, 1987, Geologic map of the Astoria and Ilwaco quadrangles, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-2, 30 p., 1 pl., scale 1:100,000

Walsh, T. J., compiler, 1987, Geologic map of the south half of the Tacoma quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-3, 12 p., I pl., scale 1:100,000

The geologic time scale for this map is basically that used for the "Correlation of Stratigraphic Units of North America (COSUNA)" project of the American Association of Petroleum Geologists (Salvador, 1985). Additions and modifications were made following Armentrout and others (1983), Montanari and others (1985), Prothero and Armentrout (1985), and Aquirre and Pasini (1985). These modifications entailed addition of regional floral and faunal zonations, placing the Eocene-Oligocene boundary at 35.7 m.y.B.P. and within the Refugian foraminiferal stage, and setting the Pliocene-Pleistocene boundary to 1.6 m.y.B.P.

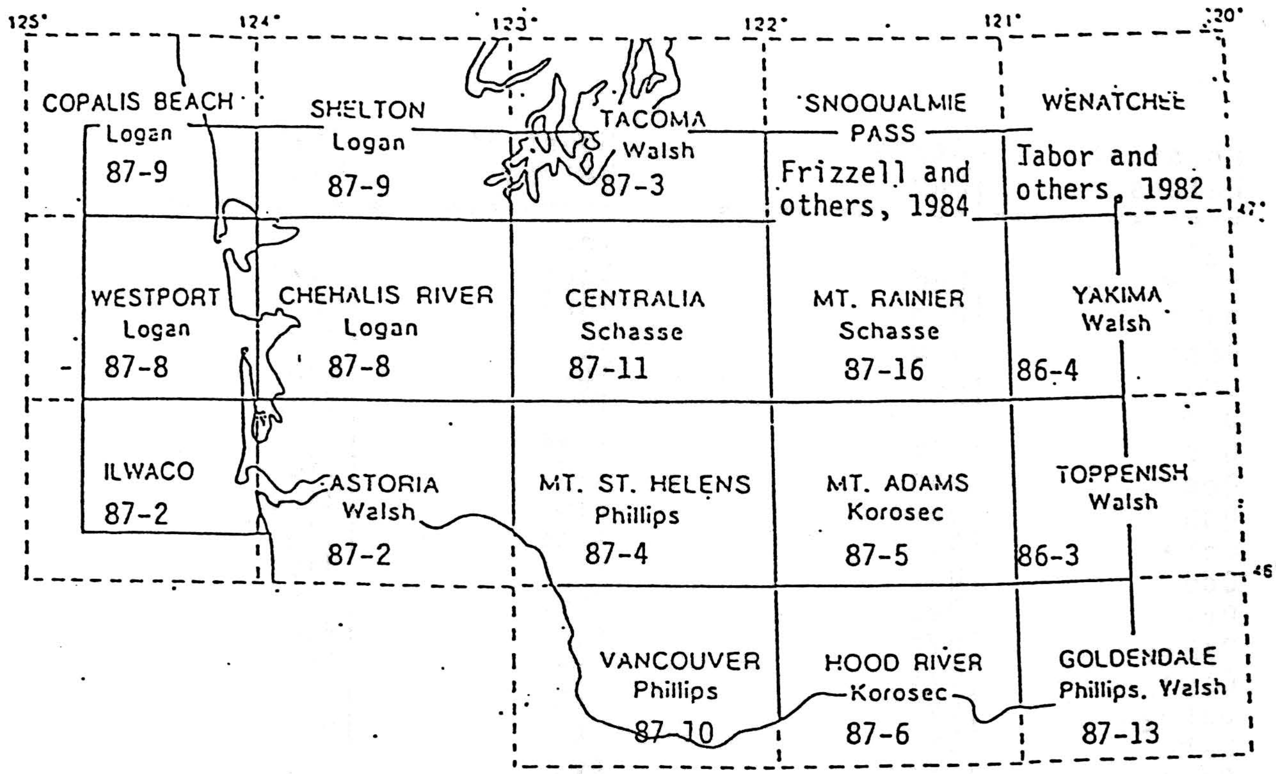


Figure 1: 1:100,000-scale geologic compilation maps used in the southwestern quadrant of the Washington State geologic map. The name of each 1:100,000 quadrangle is followed by the map compiler and an open-file report number. See pages 1-3 for a list of the complete citations for the open file reports. Complete citations for Snoqualmie Pass and Wenatchee quadrangles are provided in References Cited at the end of this report.

Table 1: Correlation of state geologic map units with map units of the Mount St. Helens quadrangle.

Mount St. Helens	State Map
Qal	Qa
Qdem	Qad
Qdet	Qad
Qdht	Qap
Qdu	Qg
Qlh	Qapo
Qls	Qls
Qoe	Qao
Qoh	Qapo
Qohe	Qapo
Qou	Qao
Qow	Qapo
Qsha$_1$	Qva
Qsha$_2$	Qva
Qshb$_2$	Qvb
Qshc	Qvc
Qshd$_1$	Qida
Qshd$_2$	Qida
Qshd$_3$	Qls
Qshd$_3$	Qida
Qshp$_3$	Qvp
Qshu$_1$	Qvc
Qshu$_1$ (part)	Qvc
Qshu$_2$ (part)	Qvl
Qshu$_3$	Qvl
Qtr	Qt
QTtd	QPc
Qvma	Qvb
Qvmm	Qvb
Qvtp	Qvb

Mount St. Helens	State Map
Tcz	En
Tgo$_1$	OEvc
Tgo$_2$	OEva
Tgr	Mvg
Tgv	Evb
Tia	Tian
Tiaa	Mia
Tidi	Tid
Tigd	Migd
Tigd	Tigd
Tipb	Mia
Tiqd	Miqd
Tiqm	Miqm
Tlc	OEm
Tsm	Mva
Tto	OEn
Tva	OEva
Tva$_1$	Ova
Tva$_2$	Ova
Tvb$_2$	Ovb
Tvb$_3$	Mvb
Tvc$_1$	Ovc
Tvc$_2$	Ovc
Tvc$_3$	Mvc
Tvd$_1$	Ovd
Tvd$_2$	Ovd
Tvd$_3$	Mvb
Tvt	Ovt
Tvt$_3$	Mvt
Twk	Mc

ACKNOWLEDGEMENTS

Field work in 1984 was assisted by Keith Kaler, Tammy Hall, and Kate Tysiak. Keith Kaler, Mike Korosec, and Matt McClincy aided with the mapping in the Elk Rock and Cougar 15-minute quadrangles in 1985. Don Hiller helped with navigation and driving in the Deer Island 7.5-minute quadrangle in 1985. Mike Korosec supplied many insights into numerous aspects of the quadrangle's geology.

Special thanks are due to Paul Hammond of Portland State University for graciously providing access to his unpublished geologic maps and field trip guides, together with many hours of helpful and stimulating discussions in both field and office. A glance at the source of data map (Fig. 2) demonstrates that Paul has mapped nearly all of the quadrangle. Without his expertise and enthusiastic assistance, this map would be far less complete.

Roger Ashley, Russ Evarts, and Jim Smith of the U.S. Geological Survey also donated generous portions of their time and data to this compilation. Especially helpful was a two-day field trip to the Spirit Lake and Mount St. Helens 15-minute quadrangles led by Russ and Roger, and discussions of K-Ar radiometric age determinations by Jim.

Early versions of this report were reviewed by Roger Ashley, Bob Deacon, Dick Dyhrman, Russ Evarts, Paul Hammond, and Jim Smith, all of whom made valuable and helpful comments.

Many other people contributed to the production of this report by sharing data and their general knowledge of the map area. They include Russ Bonker, Robert Burk, Kris McElwee, Ken Moser, Hank Schasse, Kevin Scott, Don Swanson, Tim Walsh, and Ray Wells. The friendly staff of the southwest area office of the Department of Natural Resources, especially Wimpy Clark and Dwight Carpenter, enhanced field work productivity and safety by rescuing stuck or broken-down vehicles (and geologists!), and by loaning two-way radios for use in the red zone of Mount St. Helens.

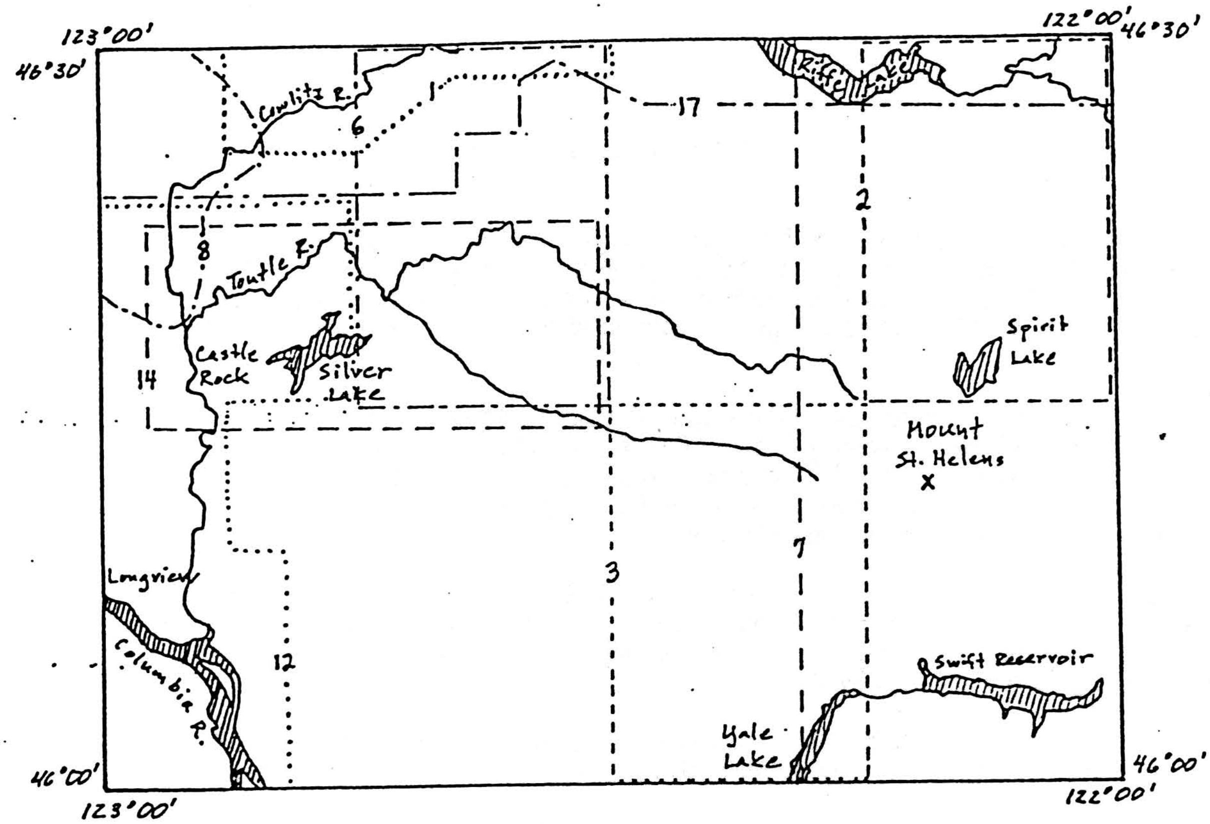
SOURCES OF GEOLOGIC MAP DATA

Principal sources of geologic map data are listed within Figure 2. Additional sources of geologic information are cited in the descriptions for each map unit. The geology shown in the Elk Rock 15-minute quadrangle is based largely upon nearly a month of field work performed by DGER staff.

GEOCHEMICAL AND K-AR DATA

Whole-rock samples of several Tertiary volcanic units were analyzed for major and minor elements in order to clarify unit correlations. These data are shown in Table 2. Trace element data for a few samples are given in Table 3. Volcanic rocks are classified geochemically in this report using the TAS diagram of Zanettin (1984).

K-Ar age determinations for five samples from the map area are provided in Table 4. Details of K-Ar sample treatment and analytical methods are given in Phillips and others (1986).



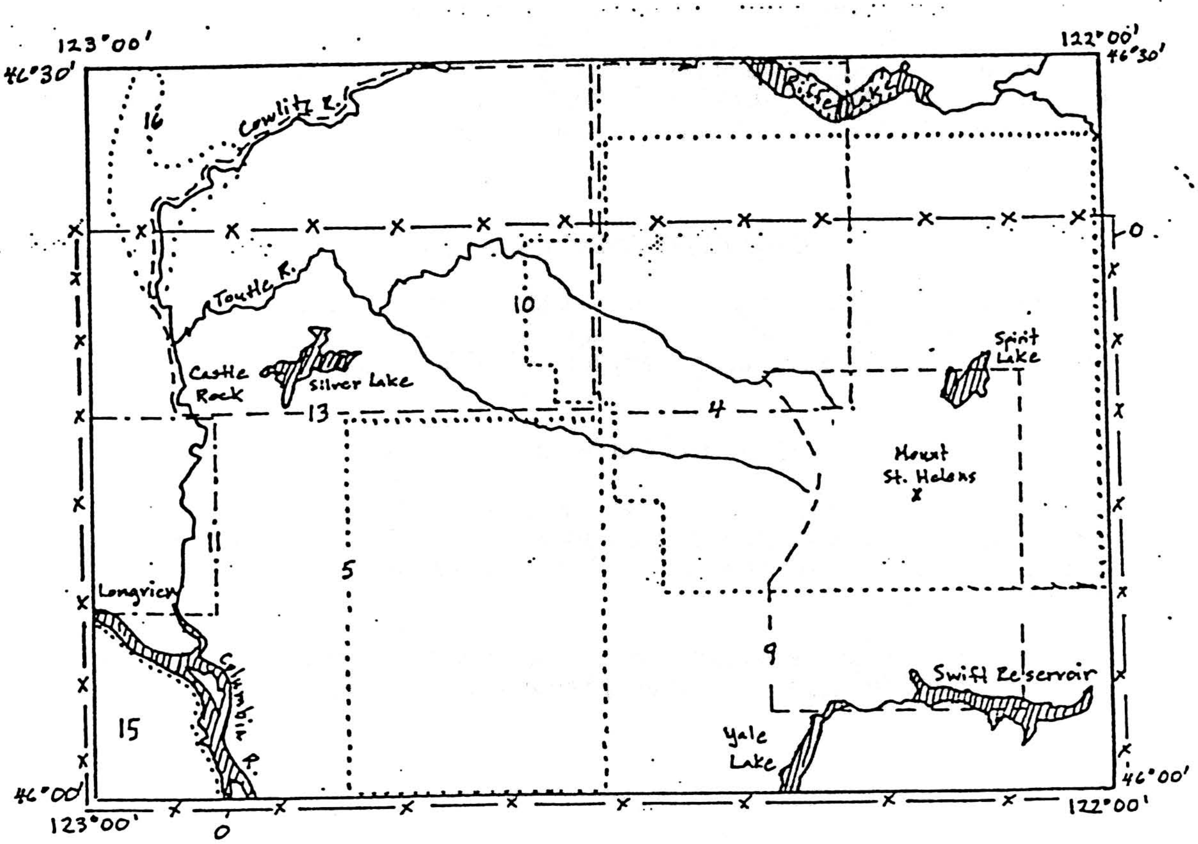


Figure 2: Source of Geologic Map Data.

Figure 2 (continued)

Source of Map Data

0. Crandell, D. R.; Mullineaux, D. R, 1978
1. Dethier, D. P.; Bethel, J. P., 1981
2. Evarts, R. C.; Ashley, R. P., 1984
3. Hammond, P. E., 1985a
4. Hammond, P. E., 1985b
5. Hammond, P. E., 1985c
6. Hammond, P. E., 1985d
7. Hammond, P. E., 1980
8. Henriksen, D. A., 1956
9. Hopson, C. A., 1980
10. Lipman, P. W.; Mullineaux, D. R., editors, 1981
11. Livingston, V. E., Jr., 1966
12. Myers, D. A., 1970
13. Roberts, A. E., 1958
14. Scott, K. M., 1986
15. Warren, W. C., and others, 1945
16. Weaver, C. E., 1937
17. Weigle, J. M.; Foxworthy, B. L., 1962

DESCRIPTION OF MAP UNITS OF THE MOUNT ST. HELENS QUADRANGLE, WASHINGTON AND OREGON

Quaternary Unconsolidated Sedimentary Deposits

Nonglacial Deposits

af

Artificial fill (Holocene)--Earthfill dam at Swift Reservoir composed of an estimated 12,115,000 m^3 of fill material (Pacific Power and Light Company, 1958).

Qal

Alluvium (upper Pleistocene (?) through Holocene)--Sand, silt, and gravel forming bars or islands within rivers and low, undissected terraces along floodplains of rivers and major creeks. Along the Columbia River, mostly sand and silt; along the Cowlitz River, dominantly sand and basaltic gravel (Livingston, 1966). Along Cedar and Salmon creeks, alluvium is composed of bars of reworked landslide debris from the Tertiary Wilkes, Toutle, or Cowlitz formations (Roberts, 1958). Gravel- and sand-sized alluvium along the Toutle River consists mostly of reworked lahar deposits from the 1980 eruptions of Mount St. Helens. Thickness of alluvial deposits highly variable but commonly ranges from about 1.5 to 15 m. Alluvial deposits are important sources of groundwater for domestic use in Cowlitz County (Myers, 1970).

Qls

Landslide deposits (Pleistocene through Holocene)--Heterogeneous mixtures of basalt and andesite blocks with weakly consolidated sand, silt and clay; typically form hummocky, poorly drained earthflows or slides into river drainages; most landslides in the map area result from the failure of incompetent sedimentary rocks (Cowlitz or Toutle formations) underlying stiff volcanic rocks (Grays River volcanics, Goble Volcanics, Grande Ronde Basalt, or unnamed Oligocene flows) (Livingston, 1966; Roberts, 1958); the bentonitic Wilkes Formation is also subject to failure on steep slopes; also includes talus cones within the crater at Mount St. Helens.

Periglacial (?) Deposits

Qtr

Terraced deposits (Pleistocene through Holocene (?))--In the Kelso and Castle Rock areas, light-colored silt containing late Pleistocene vertebrate (mammoth) fossils (Roberts, 1958; Livingston, 1966); forms dissected terrace about 12 to 24 m high; possibly correlative with Hayden Creek-age outwash deposits (unit Qoh) in the upper Cowlitz River drainage (Livingston, 1966), but more likely consists of late Pleistocene slackwater deposits from outburst floods of Glacial Lake Missoula. Although not mapped on the Mount St. Helens sheet, Waitt (1985) has described Missoula flood deposits in the Cowlitz River drainage while Roberts (1958, p. 40) noted the presence of ice-rafted granodiorite erratics near Castle Rock. Trimble (1963) discussed similar units in the adjoining Vancouver 1:100,000-scale quadrangle (Phillips, 1987).

Table 2: Whole-rock major element analyses

SAMPLE NO.	UNIT	SiO_2	AL2O5	TiO_2	FE2O3	FEO	MNO	CAO	MGO	K2O	NA2O	P2O5	QSEC	SEC	TWP	RGE
BP0604853	TGO_2	59.59	16.05	1.17	4.09	4.68	0.15	6.46	3.36	1.20	2.96	0.27	SW/4 NW/4	15	10N	02E
BP0227851	TGO_2	55.57	16.90	1.60	4.66	5.34	0.15	7.82	3.73	0.72	3.24	0.27	NE/4 SE/4	21	08N	01W
BP0402855	TGO_2	52.17	15.53	1.83	5.98	6.85	0.22	9.03	4.43	0.95	2.74	0.26	SE/4 SE/4	08	07N	01W
BP1004841	TGO_2	52.25	15.69	1.99	6.05	6.93	0.20	8.46	4.00	0.58	3.59	0.28	SE/4	36	10N	02W
BP0802841	TGO_2	54.56	17.13	1.20	4.07	4.66	0.13	9.27	5.01	0.50	3.20	0.27	CENTER	32	07N	01W
BP0711847	TGO_2	53.19	16.66	1.52	4.24	4.86	0.15	9.93	5.18	0.60	3.23	0.43	NW/4 NW/4	30	07N	01W
KK628055	TGO_2	60.42	16.34	1.08	3.45	3.95	0.14	6.67	3.40	1.26	3.05	0.25	SW/4 NW/4	4	11N	04E
BP0227853	TGO_2	55.31	17.60	1.34	4.13	4.73	0.16	8.44	4.35	0.55	3.12	0.28	CENTER	15	08N	01W
BP0710846A	TGO_2	54.78	16.09	2.18	4.57	5.23	0.18	8.21	3.86	0.70	3.70	0.48	N/2	25	11N	02W
BP0402851	TGO_2	54.64	15.90	2.08	5.44	6.23	0.18	7.55	3.37	0.76	3.51	0.33	SE/4 NW/4	18	07N	01W
BP1004842	TGO_2	59.10	16.18	1.12	3.68	4.21	0.14	6.93	3.62	1.40	3.42	0.22	SW/4 SE/4	10	10N	01W
BP0402852	TGO_2	55.84	17.59	1.50	4.19	4.80	0.16	8.31	3.44	0.74	3.15	0.28	SW/4 NE/4	18	07N	01W
BP0610851	TGO_2	51.90	17.86	1.19	4.41	5.05	0.12	10.07	6.19	0.26	2.76	0.19	SW/4 SE/3	15	07N	02W
BP1003842	TGO_2	49.75	16.48	1.49	4.99	5.72	0.21	10.45	7.66	0.40	2.60	0.25	CENTER	35	10N	01E
BP0712842	TGO_2	53.77	16.06	1.72	4.72	5.41	0.16	9.02	4.95	0.57	3.09	0.52	NW/4 SW/4	30	07N	01W
BP0815851	TGO_2	59.39	16.76	1.08	3.56	4.03	0.14	7.05	3.80	1.06	2.83	0.24	SE/4	15	08N	03E
KK628851	TGO_2	58.72	17.07	1.14	3.49	4.00	0.17	7.27	3.85	1.04	3.01	0.24	SE/4 SE/4	1	11N	03E
BP0814852	TGO_2	58.02	15.85	2.12	4.54	5.20	0.19	6.48	2.97	0.82	3.30	0.51	SW/4	15	08N	03E
BP0117855A	TGO_2	49.51	16.41	1.86	5.42	6.21	0.17	12.12	5.23	0.18	2.68	0.20	SW/4	13	09N	02W
BP0814851	TGO_2	55.74	16.44	1.57	4.50	5.16	0.15	8.41	4.06	0.50	3.16	0.31	NW/4 SW/4	16	07N	04E
BP0706845	TGO_2	57.38	17.73	1.40	2.00	5.75	0.16	7.12	3.57	1.29	3.34	0.26	NE/4	11	10N	01E
BP0117854	TGO_2	52.72	17.61	1.08	4.31	4.94	0.15	10.79	5.23	0.23	2.78	0.15	NE/4 SW/4	13	09N	02W
BP0802845	TGO_2	56.64	17.27	1.52	4.23	4.84	0.17	7.57	3.22	0.71	3.64	0.19	SW/4 SE/4	35	07N	01W
BP0404851	TGO_2	56.21	16.90	1.90	4.70	5.38	0.15	7.17	2.85	0.83	3.57	0.34	CEN. NW/4	06	07N	01W
BP0802846	TGO_2	55.88	16.93	1.67	4.64	5.31	0.16	7.46	3.11	0.86	3.70	0.29	SW/4	06	06N	01E
KKDI9	TGO_2	54.50	16.93	1.27	4.41	5.05	0.15	9.16	4.89	0.58	2.83	0.23	NE/4 SW/4	12	06N	01W
BP0404852	TGO_2	51.25	16.52	1.15	4.48	5.14	0.15	9.87	8.29	0.15	2.80	0.20	SE/4 NE/4	19	07N	01W
BP0712844A	TGO_2	52.88	18.39	0.96	4.01	4.59	0.16	10.73	4.56	0.43	3.14	0.15	E/2 SE/4	07	06N	01W
BP0706842A	TGO_2	52.68	16.65	1.69	2.00	7.37	0.17	9.36	6.90	0.39	2.52	0.28	NE/4 SE/4	13	08N	01W
KK73852	TGO_2	57.26	17.34	1.22	3.82	4.38	0.12	7.46	4.14	1.12	2.85	0.27	NE/4 NE/4	8	11N	04E
KKDI10	TGO_2	55.18	17.37	1.03	3.86	4.42	0.14	8.89	5.36	0.81	2.72	0.21	NE/4 SW/4	12	06N	01W
BP0117855C	TGO_2	53.44	17.65	1.02	3.98	4.56	0.15	11.11	5.10	0.14	2.64	0.18	SW/4	13	09N	02W
BP0712845	TGO_2	55.81	16.84	1.11	4.39	5.03	0.13	8.76	3.90	0.59	3.26	0.18	SW/4 SW/4	08	06N	01W
KK627852A	TGO_2	58.58	17.01	1.42	4.00	4.59	0.15	6.68	2.67	1.11	3.39	0.30	SE/4 SE/4	1	11N	03E
KK628851	TGO_2	60.55	16.02	1.44	3.91	4.47	0.14	5.61	3.05	1.97	2.56	0.28	NW/4 NW/4	9	11N	03E
MK8589	TGO_2	60.82	16.16	1.14	3.53	4.05	0.11	6.41	3.31	1.36	2.92	0.20	SE/4	4	09N	02E
BP0610852	TGO_2	57.22	16.34	1.31	4.05	4.64	0.15	7.82	4.11	0.77	3.17	0.40	SW/4 NE/4	26	07N	02W
BP0221851	TGR	54.62	15.58	2.12	2.00	8.46	0.25	8.43	4.61	1.16	2.48	0.29	SW/4 SW/4	06	11N	02W
BP0221852	TGR	54.01	14.96	2.03	2.00	10.05	0.21	8.23	4.77	1.12	2.32	0.30	CENTER	06	11N	02W
BP0710841	TGV	50.72	14.64	3.79	2.00	11.12	0.19	9.07	4.60	0.74	2.67	0.47	NE/4 NW/4	21	10N	02W
BP0710843	TGV	50.75	14.61	3.37	2.00	10.66	0.19	9.42	5.32	0.54	2.55	0.59	NE/4 NW/4	16	10N	02W
BP0115851	TGV	51.79	14.93	3.44	5.08	5.82	0.15	9.91	4.63	0.68	2.89	0.66	CENTER	07	10N	02W
BP1205841	TGV	50.57	13.82	3.48	6.20	7.10	0.19	9.00	5.76	0.71	2.68	0.48	NW/4	09	10N	02W
BP0115853	TGV	49.14	14.82	2.71	5.69	6.51	0.18	11.37	6.20	0.45	2.58	0.35	NE/4	30	10N	02W
BP0116851	TGV	49.48	13.21	3.21	6.18	7.08	0.19	9.97	6.70	0.69	2.65	0.65	NW/4	09	10N	02W
BP0425851	TGV	49.50	14.42	3.24	5.96	6.82	0.20	10.56	5.23	0.66	2.90	0.51	SW/4 SE/4	19	09N	02W
BP0604851	TGV	50.30	13.94	3.78	6.48	7.42	0.20	9.30	4.75	0.49	2.84	0.50	NE/4 SE/4	27	10N	02W
BP0131851	TGV	50.08	13.77	3.43	6.60	7.56	0.20	9.17	4.85	0.85	2.85	0.64	NW/4 NW/4	17	07N	02W
BP0115852	TGV	49.67	15.20	3.49	5.86	6.72	0.18	10.26	4.60	0.87	2.65	0.50	NW/4	30	10N	02W
BP0710842	TGV	50.68	14.61	3.66	2.00	11.09	0.19	8.84	5.18	0.69	2.62	0.43	CENTER	16	10N	02W
BP0710844	TGV	49.46	14.22	3.43	2.00	11.40	0.23	10.27	5.28	0.50	2.66	0.56	CENTER	09	11N	02W
BP0226854	TIA	58.50	16.44	1.35	4.38	5.02	0.15	7.81	2.18	0.85	3.06	0.27	NW/4 NW/4	30	08N	01W
BP0222852	TIA	60.44	16.04	1.65	3.90	4.47	0.16	5.74	2.42	0.97	3.73	0.48	SW/4	25	09N	02W
BP0117856	TIB	53.40	16.25	1.88	4.99	5.71	0.17	8.98	4.47	0.58	3.29	0.28	NW/4	14	09N	02W
BP0814856	TVA_1	53.38	16.84	1.08	4.50	5.15	0.14	9.49	6.44	0.24	2.57	0.16	SE/4 NE/4	07	08N	04E
BP0814854	TVA_1	58.11	15.93	1.22	3.99	4.57	0.16	7.52	4.26	1.06	2.92	0.25	NW/4	24	08N	03E
BP0619851	TVA_1	55.03	16.07	1.06	4.05	4.64	0.15	9.12	6.42	0.86	2.43	0.18	CENTER	10	10N	04E
BP0516851	TVB_3	53.86	17.56	1.50	4.40	5.04	0.16	9.23	4.60	0.42	2.96	0.27	CEN. NE/4	33	12N	05E

Analyses by XRF, Department of Geology, Washington State University
All analyses normalized to 100% on a volatile-free basis.

Samples with Fe2O3=2.00% analyzed with Columbia River Basalt Group standards and a single-fusion sample preparation method.

All other samples analyzed with international standards and a double-fusion sample preparation method. Fe2O3/FeO set at 0.87 for these samples.

Table 3: Whole-rock trace-element analyses. See Table 2 for location of samples.

SAMPLE	UNIT	SC	V	BA	RB	SR	ZR	Y	NB	GA	CU	ZN	NI	CR
BP0610851	TGO_2	28	201	94	3	403	111	19	9	17	135	108	109	173
BP1004842	TGO_2	23	177	286	32	379	207	25	13	16	230	156	43	62
BP0712844A	TGO_2	30	218	100	10	390	88	17	5	20	389	231	53	116
BP0710844	TGV	28	305	176	12	470	227	37	35	25	35	114	30	59
BP0710842	TGV	31	321	228	14	467	234	35	37	22	27	121	24	51
BP0131851	TGV	30	339	250	22	458	284	41	48	24	61	150	32	43
BP0116851	TGV	26	328	193	10	423	239	36	40	20	57	139	110	180
BP0710841	TGV	29	305	209	16	530	248	38	38	26	16	129	9	33
BP1205841	TGV	23	320	185	14	431	230	36	35	23	38	125	62	95
BP0604851	TGV	28	311	193	13	468	245	36	38	25	77	168	14	25
BP0115852	TGV	28	367	251	20	539	264	36	44	26	55	125	59	77
BP0516851	TVB_3	26	237	177	8	318	178	30	12	20	165	88	75	131

Analyses by XRF, Department of Geology, Washington State University
All analyses in parts per million (ppm)

Table 4: K-Ar age determinations for the Mount St. Helens quadrangle.

Locality Number	Sample Number	Map Unit Dated	Latitude North	Longitude West	Material Dated	K_2O Analysis First	K_2O Analysis Second	Rad. Ar (mol/gm) First	Rad. Ar (mol/gm) Second	% Rad. Ar First	% Rad. Ar Second	Age (my)	Std. Dev.	REF	LAB
K-AR 1	BP0604851	TGV	46°19'10"	122°54'34"	wr,hf,nit	0.643	0.671	3.643E-11	3.455E-11	46.6	44.1	37.3	2.2	1	1
K-AR 2	BP1004842	TGO$_2$	46°21'03"	122°48'42"	plag,hf	0.243		1.219E-11		63.2		34.5	0.5	1	3
K-AR 3		TGO$_2$	46°04'36"	122°48'42"	plag,hf	0.180		1.115E-11		27.2		42.8	1.2	2	3
K-AR 4	4338	TGO$_2$	46°02'10"	122°51'18"								37.4	0.7	3	4
K-AR 5A	77-37B	TGO$_2$	46°10'12"	122°45'	wr							45.0	1.4	4	3
K-AR 5B	77-37B	TGO$_2$	46°10'12"	122°45'								41.4	1.3	4	3
K-AR 6A	77-07B	TGO$_2$	46°22'48"	122°37'48"								32.2	0.3	4	3
K-AR 6B	77-07B	TGO$_2$	46°22'48"	122°37'48"								35.9	0.4	4	3
K-AR 7	MK8589	TVA$_1$	46°17'21"	122°33'11"	wr,hf,nit	1.324	1.329	6.195E-11	6.845E-11	65.1	70.1	33.9	1.7	1	1
K-AR 8	BP0814851	TGO$_2$	46°10'17"	122°25'00"	wr,hf,nit	0.646	0.648	3.050E-11	3.505E-11	49.3	23.1	36.3	2.2	1	1
K-AR 9	BP0814856	TVA$_1$	46°11'36"	122°21'12"	wr,hf,nit	0.380	0.380	1.740E-11	1.883E-11	29.7	47.7	32.9	2.6	1	1
K-AR 10	BP0619851	TVA$_1$	46°21'44"	122°17'31"	wr,hf,nit	0.989		5.130E-11		93.8		35.7	1.6	1	3
K-AR 11	S81-A5-R48	TVA$_2$	46°16'11"	122°13'44"	plag	0.201	0.202	8.103E-12		3.3		27.7	3.7	7	2
K-AR 12	MK8586	TVA$_2$	46°02'30"	122°02'03"	wr,hf,nit	0.756	0.729	3.073E-11	3.063E-11	54.3	56	28.5	1.8	1	1
K-AR 13	S78-A1-E209A	TVC2	46°27'02"	122°13'21"	hbl	0.270	0.256	1.040E-11		10		27.1	2.0	7	2
K-AR 14A	S82-A3-E32	TVB$_2$	46°23'44"	122°14'22"	plag	0.274	0.279	1.406E-11		13		35.0	2.0	7	2
K-AR 14B	S82-A3-E32	TVB$_2$	46°23'44"	122°14'22"	plag	0.274	0.279	1.144E-11		11		28.5	1.1	7	2
K-AR 15	S80-A1-SO$_2$	TVC2	46°27'56"	122°13'26"	plag	0.306	0.307	1.265E-11		14		28.5	0.9	7	2
K-AR 16	S78-B2-E49A	TVA$_3$	46°24'45"	122°09'20"	plag	0.253	0.256	9.117E-12		2.8		24.7	3.5	7	2
K-AR 17A	S82-D1-E106	TVB$_3$	46°28'31"	122°00'08"	plag	0.529	0.533	1.819E-11		46°		23.6	1.2	7	2
K-AR 17B	S82-D1-E106	TVB$_3$	46°28'31"	122°00'08"	plag	0.529	0.533	1.787E-11		41		23.2	0.7	7	2
K-AR 18	S77-D3-R12	TVA$_3$	46°23'21"	122°02'16"	plag	0.310	0.313	1.020E-11		14		22.6	0.7	7	2
K-AR 19	S78-C5-E123A	TVA$_3$	46°17'23"	122°05'28"	hbl	0.478	0.484	1.387E-11		15		19.9	0.7	7	2
K-AR 20A	S78-D5-E199A	TVC$_3$	46°15'23"	122°03'43"	plag	0.208	0.206	7.296E-12		15		24.3	0.9	7	2
K-AR 20B	S78-D5-E199A	TVC$_3$	46°15'23"	122°03'43"	plag	0.208	0.206	7.129E-12		16		23.8	0.8	7	2
K-AR 21	84CG-V29	TVA$_1$	46°07'43"	122°15'58"	wr,nit	1.248	1.254	2.778E-11		24		15.4	0.5	7	2
K-AR 22	72	QVMA	46°04'21"	122°08'51"	wr	1.566		3.654E-13		24.7		0.162	0.006	6	3
K-AR 23		TIQD	46°19'48"	122°12'12"	hbl	0.578	0.580	1.830E-11		17.3		21.4	0.3	7	2
K-AR 24	S79-A4-R128	TIQD	46°20'55"	122°12'06"	biot	9.18	9.25	2.811E-10		63		21.1	0.6	7	2
K-AR 25	S80-A4-R06	TIQD	46°19'04"	122°12'02"	biot	8.82	8.96	2.681E-10		62		20.8	0.6	7	2
K-AR 26	S80-A4-R08	TIQD	46°18'43"	122°12'08"	biot	9.07	9.15	2.923E-10		65		22.2	0.7	7	2
K-AR 27	S81-B5-E43	TIGD	46°15'05"	122°08'33"	hbl	0.218	0.224	7.789E-12		8.1		24.3	1.3	7	2
K-AR 28	S78-D5-E168A	TIA5	46°16'06"	122°02'50"	wr,nit,hf	0.704	0.704	8.817E-12		15		8.7	0.3	7	2
K-AR 29	S78-D5-M88A	TIA5	46°15'07"	122°09'55"	wr,nit	1.259	1.267	1.704E-11		21		9.3	0.3	7	2
K-AR 30	S78-A2-R128	TIA5	46°26'18"	122°12'45"	wr,nit	0.852	0.856	1.059E-11		14		8.6	0.3	7	2
K-AR 31A	SH4141	QTIG	46°09'48"	122°18'36"	hbl	0.637	0.645	2.920E-12		4.5		3.1	0.3	5	2
K-AR 31B	SH4141	QTIG	46°09'48"	122°18'36"	biot	8.33	8.33	1.272E-11		8.8		1.0	0.06	5	2
K-AR 31C	SH4141	QTIG	46°09'48"	122°18'36"	biotite	8.32	8.30	9.050E-12		10.2		0.7	0.06	5	2
K-AR 32A		EARL*	46°21'	122°05'	biotite	7.134		1.710E-10		66		16.2	0.6	8	5
K-AR 32B	MOH7 684/687	EARL*	46°21'25"	122°04'52"	sec. ser.	10.52	10.52	2.572E-10		57		16.9	0.5	7	2
K-AR 33		TGO$_2$										30.0		9	
K-AR 34	BP0516851	TVB$_3$	46°29'07"	122°10'52"	wr,hf	0.518	0.530	1.874E-11	1.829E-11	53	62.3	24.4	1.2	1	6

REFERENCES:
1. Phillips and others (1986)
2. K. McElwee, written communication (1985)
3. Armentrout and others (1980)
4. Beck and Burr (1979)
5. Engels and others (1976)
6. Hammond and Korosec (1983)
7. Evarts and others (1987)
8. Armstrong and others (1978)
9. Armentrout and others (1983)

CONSTANTS: λ_β=4.962 x 10^{-10} yr^{-1}, λ_ε=0.581 x 10^{-10} yr^{-1}
$^{40}K/K_{total}$=1.167 x 10^{-4} atom percent

TREATMENTS: hf=hydrofluoric acid
nit=nitric acid

MATERIALS: wr=whole rock
biot=biotite
hbl=hornblende
plag=plagioclase

LABS:
1. Geochron
2. U. S. Geological Survey, Menlo Park
3. Oregon State University
4. Mobil Research Laboratories
5. University of British Columbia
6. Teledyne

* Earl porphyry copper deposit within the Spirit Lake pluton

Glacial Deposits

During the Pleistocene, glaciers repeatedly advanced from Mount Rainier, Mount Adams, Mount Saint Helens, and adjacent alpine areas. In the Mount St. Helens 1:100,000-scale quadrangle, outwash, till, and morainal deposits document these alpine glacial events. The thickest and most extensive glacial sediments are present along the Cowlitz River in the vicinity of Toledo where at least six distinct outwash deposits underlie loess-covered terraces. This sequence may be the best-preserved record of alpine glacial events in the Pacific Northwest (Dethier and Bethel, 1981). Significant exposures of alpine glacial deposits are also found in the Spirit Lake 15-minute quadrangle north of Mount St. Helens (Evarts and Ashley, 1984), and in the Elk Rock 15-minute quadrangle, between the North Fork Toutle and Green rivers. Elsewhere in the map area, alpine glacial deposits are restricted to small cirque-basin accumulations in the highlands west and southwest of Mount St. Helens (Hammond, 1985a), or to exposures of interstratified drift, pyroclastic flows, and lahars on the south flank of Mount St. Helens (Hyde, 1975; these units are not mappable at the 1:100,000 scale and are not shown).

Stratigraphic nomenclature and correlation of the deposits generally follows that of Crandell and Miller (1974). Named drifts recognized in the map area, from oldest to youngest, include the Logan Hill Formation, Wingate Hill, Hayden Creek, and Evans Creek. The Evans Creek Drift corresponds to the alpine stade of the Fraser (late Wisconsin) Glaciation. Along the Cowlitz River, Dethier and Bethel (1981) have subdivided the Hayden Creek and Evans Creek deposits; however, these subunits were not used in this report as they are nearly unmappable at a 1:100,000 scale. Low terrace deposits correlative with the Holocene and latest Pleistocene drifts of Mount Rainier (for example, Garda and Burroughs Mountain drifts and the McNeely Drift, respectively) are mapped by Dethier and Bethel (1981, p. 4) along the Cowlitz River as undivided Holocene outwash (unit Qou below).

Precise dating of the alpine drifts, especially those older than Evans Creek, remains a significant and difficult problem. Evans Creek deposits in the Mount St. Helens quadrangle are dated by Dethier and Bethel (1981, p. 5) at between 22,000 to 13,000 yr B.P. Tentative appraisals of the age of the Hayden Creek Drift range from about 70,000 to about 140,000 yr B.P.; it is possible that deposits of both ages are present in the map area (Dethier and Bethel, 1981, p. 6). No datable materials have been found in the Wingate Hill Drift or Logan Hill Formation. Dethier and Bethel (1981, p. 6-7) speculate that the Wingate Hill Drift is "several hundred thousand years old, and possibly older," and that the Logan Hill Formation is "older than 630,000 years, and may be as much as 1 to 1.5 million years old."

Qou

Alpine glacial outwash, younger than Evans Creek stade (upper Pleistocene (?) to Holocene)--Sand and gravel deposits along the Cowlitz River near Toledo; thickness unknown, mantled with less than 0.3 m of fine sand and silt (loess) and oxidized to a depth of about 0.5 m (Dethier and Bethel, 1981).

Qoe

Evans Creek outwash (upper Pleistocene)--Gravel deposits along the Cowlitz River generally 3 to 8 m thick; mantled with 0.3 to 2.0 m of fine sand and silt (loess); deposits oxidized to a depth of about 1 m (Dethier and Bethel, 1981).

Qdet

Evans Creek till (upper Pleistocene)--Till and moraine deposits confined to north-facing cirques or cirque-headed valleys at elevations above about 750 m in the highlands north, west and southwest of Mount St. Helens; correlated by Hammond (1985a) and Evarts and Ashley (1984) with Evans Creek Drift.

Qdem

Evans Creek moraine deposits (upper Pleistocene)--Unconsolidated poorly-sorted detritus forming lateral and end moraines, chiefly along the Cowlitz River, Green River, and Coldwater Creek in the Spirit Lake 15-minute quadrangle north of Mount St. Helens (Evarts and Ashley, 1984); the deposits in the upper Cowlitz River drainage are ascribed by Crandell and Miller (1974) to the Evans Creek Drift.

Qohe

Pre-Evans Creek, post-Hayden Creek outwash (upper Pleistocene)--Gravel deposits generally 3 to 5 m thick; mantled with about 0.5 to 1.5 m of silt and fine sand (loess); deposits form isolated terrace remnants near Toledo; oxidation extends to a depth of about 1.0 to 1.5 m (Dethier and Bethel, 1981).

Qoh

Hayden Creek outwash (upper Pleistocene)--Gravel deposits along the Cowlitz River generally 5 to 16 m thick; mantled with about 0.5 to 2.0 m of fine sand and silt (loess); oxidation extends to a depth of about 1.5 m (Dethier and Bethel, 1981).

Qdht

Hayden Creek till (upper Pleistocene)--In the upper Cowlitz River valley, till covered with 1.5 to 3.0 m of weathered silt (loess) and thin sand and gravel deposits (Dethier and Bethel, 1981); in the Elk Rock area, silt-rich bouldery till covered with 1 to 9 m of yellow-brown, massive reworked volcanic ash and, locally, colluvium; interbedded with thinly laminated glacial-lacustrine sediments and deltaic outwash gravels at Hoffstadt Creek (3E-10N); locally, distinguished with difficulty from high-elevation lahar deposits; characterized by striated and faceted clasts, and by clasts of granitic composition derived from the Spirit Lake pluton; basaltic to andesitic cobbles from till have weathering rinds of 0 to 2 mm; locally, includes older till unit with weathering rinds greater than 2 mm which may be of Wingate Hill age.

The base is not generally exposed, but where visible, the unit directly overlies Tertiary bedrock units; oxidized to a depth of about 2.5 to 3.5 m; glaciers producing the tills had at least two distinct accumulation areas--The Mount Rainier and Mount Adams drainage basins (Crandell and Miller, 1974), and the highlands north of Spirit Lake and/or Mount St. Helens (Evarts and Ashley, 1984); the Spirit Lake-area glaciers produced the till and thin outwash and glacial-lacustrine deposits present along the Green River and between the Green River and North Fork of the Toutle River; the age and correlation of these deposits is uncertain; placement within unit Qdht is based upon the elevation reached by the deposits (lower than the Evans Creek-age terminal moraines) and upon relatively widespread distribution (as opposed to cirque-basin-bounded character of most Evans Creek-age tills).

Qow

Wingate Hill outwash (lower (?) Pleistocene)--Gravel deposits more than 30 m thick near Salkum, 3.2 km north of the Mount St. Helens quadrangle; unit of unknown thickness elsewhere; unit mantled with about 1.0 to 3.0 m of weathered silt; oxidation commonly extends to depths of 5.0 to 10.0 m.

Qlh

Logan Hill Formation (lower (?) Pleistocene)--Weakly consolidated, deeply weathered, pale-yellow to reddish-brown gravel, sand and till; at the surface, gravels of the formation can easily be cut with a knife; distinguished with difficulty from portions of the Miocene Wilkes Formation (Roberts, 1958); mantled with 2.0 to 4.0 m of silt and clay in many exposures; oxidized to depths of more than 15.0 m; the original texture of the upper 5 m of the unit often obscured by weathering (Bethel and Dethier, 1981); thickness variable, from greater than 45 m near Chehalis north of the Mount St. Helens quadrangle (Snavely and others, 1958), to 75 m near Castle Rock and Toledo (Roberts, 1958); apparently thins south of the Cowlitz River (Bethel and Dethier, 1981) where the relationship to the partly coeval (?) Troutdale Formation (unit QTtd) is uncertain.

Till within the Logan Hill Formation is a compact mixture of boulders, cobbles, and pebbles in a sandy clay matrix; according to Roberts (1958, p. 38) clasts in both tills and outwash gravels consist of porphyritic basalt or andesite, rhyolite, diorite, gabbro, pyroclastic rocks (pumice and scoria), and "metamorphic rock"; except for the metamorphic rock, which is not described further, a source area typical of the southern Washington Cascade Mountains is suggested by clast composition; this is supported by the occurrence of Logan Hill Formation at progressively higher elevations eastward along the Cowlitz River valley (Roberts, 1958, p. 37); based on these data and upon the presence of till within the formation, the Logan Hill Formation is interrupted as outwash and till from a lower (?) Pleistocene Cascade alpine glacier.

Near the type section in the Centralia-Chehalis coal district (Snavely and others, 1958), the Logan Hill Formation is overlain by gravels of the Vashon Drift, hence the unit is pre-Fraser (late Wisconsin) Glaciation; no fossils or datable materials have been located and paleomagnetic studies are hampered by the degree of weathering and by the absence of fine-grained interbeds (Dethier and Bethel, 1981).

The unit includes terraced deposits in the vicinity of Hoffstadt Mountain (3E-10N) which consist of poorly to semiconsolidated, grayish-green to brown, matrix-supported cobble conglomerate and breccia rich in poorly preserved wood fragments; from geomorphic evidence, this unit appears to be too old for a Mount St. Helens-derived lahar, and too young for Hayden Creek-age glacial till. The material contrasts sharply with the zeolitized and firmly lithified character of the otherwise similar Tvc_1.

Quaternary Volcanic Deposits

Deposits of Mount St. Helens

Products of Mounts St. Helens dominate the Quaternary volcanic geology of the map area. More than 35 lahars have inundated flood plains up to 50 km away from the mountain in the Toutle-Cowlitz river system. At least six of the largest of these lahars probably inundated flood plains over 100 km downstream to the Columbia River (Scott, 1986). Tephras from the volcano (which are not shown on the map in order to clearly portray Tertiary bedrock geology) record more than 100 explosive eruptive events at Mount St. Helens and are widely distributed throughout Washington State. Several of these tephras form important marker beds at distances of hundreds of kilometers downwind from the volcano (Mullineaux, 1986).

Classification and mapping of these products have been conducted in a variety of ways over the last 50 years. Verhoogen (1937, p. 268) informally divided Mount St. Helens volcanic deposits into an "old Mount St. Helens series" and a "recent" assemblage making up the modern cone of the volcano. The "old" Mount St. Helens eruptive center was characterized by dominantly dacitic to andesitic explosive volcanism which produced voluminous pyroclastic flows and lahars, as well as lava or plug domes. Characteristic lithologies of the "old Mount St. Helens" eruptive center are pale-red hornblende dacite and gray hornblende-hypersthene andesite. The "recent" lithologies record a shift to more mafic lava flow volcanism interspersed with explosive and dome-building dacitic events. Characteristic of "recent" units are olivine basalt and olivine basaltic-andesite lava flows, hypersthene-augite andesite flows, and dacitic to andesitic domes, pyroclastic flows, and lahars.

Crandell and Mullineaux (1973) described a portion of the "old Mount St. Helens series" in Pine Creek on the south flank of the volcano. Their work established a stratigraphic sequence and late Pleistocene to Holocene age for the dominantly dacitic pyroclastic flows and lahars of the "Pine Creek volcanic assemblage."

Hyde (1975) characterized another thick section of Mount St. Helens-derived pyroclastic flows, lahars and alluvium in Swift Creek on the south flank of the volcano. Hyde's (1975) "Swift Creek volcanic assemblage" consists of units ranging in age from about 36,000 yr B.P. to 12,000 yr B.P.

Hopson (1980) mapped the volcano in the greatest detail to date, breaking out four chronologic groups which also represent distinctive stages in the mountain's petrologic evolution and eruptive history. The stages are:

"1. Prolonged evolution of an older Mount St. Helens volcanic center, characterized by explosive domes of hornblende-rich dacite, abundant pumiceous tephras and voluminous valley-filling assemblages of pyroclastic flows and lahars;"

"2. Early development of the modern Mount St. Helens volcano, marked by change to cone-building lava flows of pyroxene andesite and streams of olivine basalt, with hypersthene dacite domes and pyroclastic flows but restricted tephras;"

"3 and 4. Episodic eruptions of tephra and dacite domes, usually with flank eruptions of pyroxene andesite" (Hopson, 1980).

Stages 3 and 4 represent A.D. 800-1650 and historic (A.D. 1800-1857) eruption cycles, respectively.

Mullineaux and Crandell (1981) divided the eruptive history of Mount St. Helens into nine informal eruptive "periods" separated by eight dormant intervals. The eruptive periods are defined as "clusters of eruptions distinguished by close association in time, by similarity of rock units, or both (Mullineaux and Crandell, 1981, p. 61)." Somewhat confusingly, the terms "Swift Creek" and "Pine Creek" (Crandell and Mullineaux, 1973; Hyde, 1975) were incorporated into the eruptive period terminology even though both "volcanic assemblages" contain lithologies other than Pine or Swift Creek eruptive periods.

Based upon the apparent concentrations of eruptive activity over time, Crandell (1983, written commun. in Scott, 1986, p. 51) further grouped the eruptive periods into four eruptive "stages." Mullineaux (1986) refined the eruptive period geochronology and summarized tephra sets associated with each eruptive period. Table 5 summarizes the eruptive period nomenclature.

While the eruptive period terminology of Mullineaux and Crandell (1981) has been widely used in the literature, no geologic map depicting the distribution of volcanic deposits associated with the eruptive periods or stages is presently available. The best mapping of the cone and vicinity is from

Hopson (1980). In Hopson (1980), deposits of the Pine Creek, Smith Creek, Swift Creek, Cougar, and Ape Canyon eruptive periods are grouped into a "stage 1" or "older Mount St. Helens volcanic center" unit. Although younger units on the map can readily be correlated with eruptive periods, lumping of the older units prohibits use of the eruptive period terminology.

Table 5: Correlation of map units with Mount St. Helens eruptive periods.

General Group	Map Unit	Eruptive Periods*
Deposits of A.D. 1980 and post-1980 eruptions	$Qshp_3$ $Qshu_3$ $Qshda_3$ $Qshd_3$	none defined
Mixed pyroclastic and flow deposits (about 100-2000 yr B.P.)	$Qshu_2$ $Qshb_2$ $Qshd_2$	Goat Rocks Kalama Sugar Bowl Castle Creek
Dominently pyroclastic deposits (older than 2500 yr B.P)	$Qshu_1$ $Qsha_1$ $Qshd_1$	Pine Creek Smith Creek Swift Creek Cougar Creek Ape Canyon
Mount St. Helens deposits, undivided	Qshu Qshc	all eruptive periods

* after Mullineaux and Crandell, 1981

A similar problem exists for the Mount St. Helens lahar deposits found outside of Hopson's (1980) map area in the Toutle-Cowlitz, Kalama, and Lewis river drainages. Scott (1986) describes vertical sections for these deposits and correlates them with eruptive periods and stages, but supplies no map showing the distribution of units assigned to each eruptive period.

In this report, the eruptive period nomenclature of Mullineaux and Crandell (1981) and the "stage" terminology of Hopson (1980) has been combined and simplified into three chronostratigraphic groups:

1. Dominantly dacitic pyroclastic deposits and plug or lava domes of the Ape Canyon, Cougar, Swift Creek, Smith Creek, and Pine Creek eruptive periods (older than about 2,500 yr B.P.);

2. Mixed dacitic pyroclastic deposits and andesitic to basaltic lava flows of the Castle Creek, Kalama, and Goat Rocks eruptive periods (2,500 to 100 yr B.P.);

3. Deposits of the A.D. 1980 and post-1980 eruptions. Table 5 illustrates the correlation of the eruptive periods of Mullineaux and Crandell (1981) with the generalized groups of this report.

It was also necessary to define a "lahar, undivided" unit and "core of cone exposed by the 1980 eruption" unit. The lahar, undivided unit consists of lahars of probable Kalama through Pine Creek age in the North and South Fork Toutle river drainages. Available mapping or stratigraphic descriptions (for example, Hammond, 1985a, 1985b; Scott, 1986) does not permit distinguishing between the various-aged lahars upstream of the confluence of the North and South Fork Toutle rivers. Downstream of the confluence, the lahars are dominantly Pine Creek age or older (Scott, 1986).

Detailed examination of the crater wall stratigraphy following the 1980 eruptions revealed units of both "old Mount St. Helens" and "modern" or "recent" Mount St. Helens making up the cone (Hopson and Melson, 1982). Therefore, an undivided unit for the "core of the cone" was required.

Deposits of A.D. 1980 and post-1980 eruptions

The following account of 1980 and post-1980 eruptive activity at Mount St. Helens is modified from Peterson (1986).

On March 20, 1980, after more than 100 years of quiet, Mount St. Helens resumed activity with an earthquake swarm. By March 27, 1980, phreatic eruptions occurred. An east-west, arcuate graben formed on the north side of the summit, within which two craters formed and eventually merged. The graben was the head of a 1-by-2-km block on the north flank of the volcano. This block or "bulge" moved laterally as much as 2 m/day, apparently in response to intrusion of a dacitic magma body or cryptodome into the volcanic edifice.

At 8:32 am on May 18, 1980, a magnitude 5.1 earthquake apparently triggered a catastrophic chain of events leading to the deposits described below.

The block forming the "bulge" failed in several huge landslides, resulting in a debris avalanche (unit $Qshda_3$) which flowed northward into Spirit Lake and Coldwater Creek and westward down the North Fork Toutle River.

Abrupt depressuring of magmatic and hydrothermal systems in the volcano produced a minutes-long laterally-directed "blast" that devastated about 600 km^2 in a 180° sector north of the mountain. The relatively thin deposits of pyroclastic material produced by the lateral blast have been lumped with pyroclastic deposits (unit $Qshp_3$) on the map.

As the blast declined, vertically-directed eruptions produced a tephra column about 25 km high. During some 9 hours of vigorous eruptive activity, about 1.1 km^3 of tephra was produced, blanketing with ash thousands of square kilometers east and northeast of the volcano. The tephra deposits, typically less than 1 m in thickness, are not shown on the map in order to clearly portray Tertiary bedrock geology.

Pumiceous pyroclastic flows (unit $Qshp_3$) accompanied the vertical tephra column, accumulating on debris avalanche deposits on the north side of the volcano. Pyroclastic flows also occurred on the north flank on May 25, June 12, July 22, August 7, and October 16-18, 1980. All of these flows are also mapped as unit $Qshp_3$.

Slumping and flowing of water-saturated parts of the debris avalanche, pyroclastic surges mixing with surface water and possibly hydrothermal water, and melting of debris-laden snow or ice, generated lahars in nearly all streams draining the cone of Mount St. Helens (Janda and others, 1981). Deposits of the lahars are indicated by unit $Qshu_3$ on the map. The character and effect of the lahars reflects in large part the directional nature of the initial eruption. The largest lahar--the North Fork Toutle River lahar--was formed hours after the initial blast by dewatering of debris avalanche deposits in response to harmonic tremors (Fairchild, 1984). Other lahars, such as those on the South Fork Toutle River, Muddy River, or Pine Creek formed within minutes of the initial eruption as water and lithic debris within initially gas- and air-rich pyroclastic surges separated to form water-rich basal lahars and overriding turbulent surge clouds (Major and Voight, 1986).

Mount St. Helens was greatly affected by these volcanic events. The summit was lowered by 400 m and a new 600 m deep crater exposing the core of the cone was formed. About 2.5 km^3 of mountain avalanched, and more than 0.5 km^3 of new magma and preexisting rock was deposited by the lateral blast, tephra column, and pyroclastic flows.

Since 1981, eruptive activity at Mount St. Helens has been limited to minor steam and tephra eruptions, generation of small lahars, and the emplacement of a composite dacite dome (unit $Qshd_3$). By late 1985, the dacite dome had a volume of approximately 60 x 10^6 m^3.

Erosion of sediment from tephra deposited by the lateral blast, the debris avalanche, and the lahars has modified these deposits and in some cases (that is, along the lower Toutle and Cowlitz Rivers), produced a significant, continuing hazard that has been expensive to mitigate (Collins, 1986).

$Qshu_3$

Lahar deposits--In North and South Fork Toutle rivers, 2-9 m of clast-supported sandy gravel sharply overlain by 2 m to less than 20 cm of matrix-supported, unstratified mixtures of gravel and sand; along the center of channels, overlain by thin (less than 0.5 m) stratified and crossbedded sands with gravel lenses (Gilkey, 1983); on the southwest flank of Mount St. Helens, 0.5 m brown, massive, gravely diamictons with a sand-rich matrix and clasts up to 2.5 m in diameter (Major and Voight, 1986); on the eastern flank of Mount St. Helens in the Pine and Muddy Creek drainages, 2.5 to less than 0.5 m of poorly sorted, nonstratified, and generally ungraded mixtures of clay-sized to boulder-sized particles (Pierson, 1985).

$Qshda_3$

Rockslide-debris avalanche deposits--Unconsolidated, poorly sorted, chaotic debris derived from the catastrophic landsliding of the north flank of Mount St. Helens; surface of deposit characterized by irregular to conical hummocks as much as 170 m wide and 6 to 30 m high, and closed depressions as much as 130 m across and 40 m deep; deposit typically 20 to 70 m thick; consists dominantly of multicolored heterolithologic breccia with blocks ranging from 1 to 170 m in diameter; lithologies derived from the pre-1980 volcano dominate as clasts and include dacite dome fragments (units $Qshd_2$ and $Qshd_1$), and andesite and basalt lava flow fragments (units $Qsha_2$ and $Qshb_2$); also present are distinctive small, gray, prismatically jointed dacite clasts of the 1980 cryptodome, disaggregated masses of colluvium, jumbled masses of wood debris in a matrix of organic-rich soil, manmade objects, and clasts of altered Tertiary bedrock (Voight and others, 1981).

The 2.5-km^3 deposit consists of rubble divisible into block facies and matrix facies. The block facies consists of unconsolidated pieces of the old mountain transported relatively intact; matrix facies is a mixture of all rock types from the old mountain, material incorporated during transport, and juvenile dacite of the cryptodome (Glicken, 1986).

$Qshp_3$

Pyroclastic flow and lateral blast deposits--The pyroclastic flow deposits consist of nonwelded and mostly poorly sorted ash and clasts of pumice and dense (lithic) dacite; multiple sheets, tongues, and lobes of flows deposited May 18, May 25, June 12, July 22, August 7, and October 16-18, 1980, form a large (15.5 km^2) composite fan on the north flank of the volcano and also cover the floor of the crater; most individual flows are less than 4 m thick, but locally much thicker where ponded; each flow unit consists of poorly sorted glass shards, pumice fragments, and lithic dacite fragments that are generally normally graded with respect to dense lithic clasts and reversely graded with respect to light pumice clasts; locally, a thin (2 cm or less) fine-grained ash layer, reversely graded with respect to pumice, occurs at the base of flow units (Rowley and others, 1981).

Pumice lapilli and blocks in the pyroclastic-flow deposits consist of a glassy matrix (vesiculated glass and microlithic crystals of plagioclase and opaque minerals) and phenocrysts of plagioclase, orthopyroxene, amphibole (hornblende), and iron-titanium oxide minerals; each successive eruption (May 18 to October 16-18) topped a deeper level in a thermally and compositionally zoned magma chamber resulting in the following general trends in pyroclastic flow character (Kuntz and others, 1981):

1. Anorthite content of plagioclase from An_{41} (May 18) to An_{44} (October 16-18);

2. Increase in modal plagioclase, orthopyroxene, and iron-titanium minerals;

3. Decreased glass content;

4. Decreased amphibole content;

5. Decrease in vesicularity of pumice;

6. Major element data (Logan, 1983) becoming more mafic for example, May 18 mean SiO_2=64%, October 16-18 mean SiO_2=62.5%).

Lateral-blast deposits consist of two stratigraphically complex units produced by the directed volcanic blast of May 18 (Lipman and Mullineaux, 1981, plate 1). The first unit, present above the treeline on the cone, is made up of unconsolidated, texturally and compositionally variable pyroclastic material ranging from fine ash to clasts as much as 1 cm across; includes distinctive dense gray dacite of the 1980 cryptodome; deposit mantles terrain without major change in thickness and becomes finer grained upward in section and outward from volcano; thickness ranges from a few mm at margins to more than 1 m close to the volcano; locally divisible into three subunits: a block-sized, massive to slightly normally graded basal subunit, a finer grained, thin-bedded or cross-stratified subunit of ash to lapilli, and a thin, capping subunit of air-fall ash.

The second unit of blast-related pyroclastic-flow deposits consists of ash, abundant clasts of cryptodome dacite and fragments of older Mount St. Helens rocks, and locally, abundant wood fragments (in places consisting of large log jams); forms valley bottom deposits as thick as 20 m; represents dense concentrations of fine material within the blast cloud.

Qshd$_3$

Dacite to andesite lava dome--Medium-gray, crystal-rich, plagioclase-hypersthene-hornblende dacite to andesite (SiO_2 62-63.5%) forming steep-sided dome-shaped mass on crater floor; consists of multiple lobes with rough, fragmented, scoriaceous carapaces, and flow banded, dense interiors; cracked, breadcrust-like surface contains local accumulations of ash tephra and yellowish sulphur and iron hydroxide sublimates; gas and minor tephra emissions common from fumaroles on or near base of dome; dome lobes broken by smooth-walled radial cracks and thrust faults; talus blocks produced by lobe collapse fringe the dome (Moore and others, 1981).

Average dome lavas consist of 32% zoned, euhedral plagioclase (An_{45-55}), 4.5% prismatic hypersthene, 1.5% corroded reaction-rimmed hornblende, 2% cubes and octahedra of magnetite ilmenite, and minor corroded crystals of clinopyroxene; remaining 60% of rock consists of microlites of plagioclase and minor orthopyroxene and opaque minerals in glassy groundmass (Cashman and Taggart, 1983).

Growth of dome results from both extrusion of lava and injection of magma into dome; episodic dome growth preceded by increased displacement rates of the crater floor near vent and by increase of spreading rates of the dome itself (Swanson, 1986); five episodes of explosive magmatic activity destroyed portions of the dome between May 25, 1980, and January 1981 (Moore and others, 1981).

Trends in major-element chemistry, crystallinity, and mineral ratios suggest dome fed from a zoned magma chamber with initial (1980) eruption of volatile-rich crystal-poor material from top of chamber, followed by production of volatile-poor crystal-rich dome rock from deeper in the magma body (Cashman and Taggart, 1983).

Mixed Pyroclastic and Lava Flow Deposits
of the Castle Creek, Kalama, and Goat Rocks
Eruptive Periods (2,500-100 yr B.P.)

Qshu$_2$

Lahar and pyroclastic flow deposits, undivided--Unconsolidated lahar, pyroclastic flow and glacial deposits; chiefly lahar deposits on lower flanks of the cone and in adjacent stream valleys, and pyroclastic and glacial deposits higher on the cone; contains characteristic black andesite and basalt clasts; youngest deposits contain hornblende-hypersthene dacite clasts from the "summit dome" (blown apart by the 1980 eruption) (Hopson, 1980); in the Toutle River system, lahars of Castle Creek through Kalama eruptive age are lumped with older units in Qshu; a rubbly lahar of probable Castle Creek age is present at Camp Baker; lahars of Kalama age occur in nearly every watershed draining Mount St. Helens; lahar deposits of Sugar Bowl or Goat Rock ages have not been identified (Scott, 1986).

Qsha$_2$

Andesite lava flows--Augite-hypersthene andesite of Kalama eruptive age that forms complex of thin, narrow, "shoestring" flows on south flank of cone; older than set T tephra (A.D. 1800) but younger than set W tephra (A.D. 1482); also includes aphyric pyroxene andesite lava flow of Kalama Springs area which appears to be slightly older than Cave Basalt (unit $Qshb_2$); also contained within this unit are hypersthene-augite andesite flows on northwest flank of cone which are younger than tephra T, and an equally youthful olivine-pyroxene andesite flow on southwest flank of the cone (Hopson, 1980).

$Qshb_2$

Basalt lava flows, including Cave Basalt--Olivine basalt and lesser olivine basaltic-andesite lava flows erupted from the flanks or base of the cone; Cave Basalt is a light gray to dark gray, pahoehoe basalt lava flow, vesicular to massive with phenocrysts of olivine and plagioclase; euhedral 1-2-mm plagioclase is slightly zoned and ranges from An_{70} to An_{40}; olivine phenocrysts 0.5 to 1 mm are generally broken along curved fractures into several fragments; spherical vesicles make up 20% of the rock (Greeley and Hyde, 1972).

The flow surface of Cave Basalt is generally hummocky or flat over broad areas with ropy texture, pressure ridges, and tumuli; commonly broken into large, tilted slabs; vertical and horizontal tree molds are common near flow margins; at least 14 lava tubes are present in the flow, with one (Ape Cave) possessing a passage length of 3,400 m (Greeley and Hyde, 1972).

Cave Basalt was erupted from the southwest base of Mount St. Helens about 1,900 yr B.P. (carbon 14 dates on charcoal of 1,860 +/- 250 yr B.P. and 1,925 +/- 95 yr B.P.; Greeley and Hyde, 1972) during the Castle Creek eruptive period. The flow is the longest erupted from Mount St. Helens, traceable 13 km south to the Lewis River, and about 17 km to the southwest in the Kalama River drainage.

Unit $Qshb_2$ also includes unnamed olivine basalt and lesser olivine basaltic-andesite flows erupted during the Kalama eruptive period; the sequence includes flows on the northeast side of the cone heavily mantled by pumice, and a group of thin (1-3 m) flows on the flank and thicker aa flows near the base of the cone (Hopson, 1980).

$Qshd_2$

Dacite lava dome--Hypersthene dacite of Abraham Flat dome (eastern flank of Mount St. Helens); probably formed about 2,200-1,600 yr B.P. during Castle Creek eruptive period (Hopson, 1980); hornblende-hypersthene dacite of Sugar Bowl dome, and hornblende-hypersthene dacite of Goat Rocks dome were destroyed by the 1980 eruption.

Dominantly Pyroclastic Deposits of the
Ape Canyon, Cougar, Swift Creek, Smith Creek,
and Pine Creek Eruptive Periods
(older than about 2,500 yr B.P.)

$Qshu_1$

Lahar and pyroclastic flow deposits, undivided--Unconsolidated lahar and pyroclastic flow deposits characterized by gray, pink, and red hornblende-hypersthene dacite and andesite clasts (Hopson, 1980), and absence or near-absence of mafic lithic clasts; consists entirely of lahar deposits in the Toutle-Cowlitz and lower Kalama River systems; elsewhere contains mixed pyroclastic flow, lahar, glacial, and alluvial deposits; includes the Pine Creek volcanic assemblage of Crandell and Mullineaux (1973), and the Swift Creek volcanic assemblage of Hyde (1975).

West of the confluence of the South and North Fork Toutle rivers, more than 20 lahar units of Ape Canyon through Pine Creek age are present (Scott, 1986). Ape Canyon-age lahars are as much as 3 m thick and light-colored, with relatively highly weathered biotite dacite and pumice clasts impregnated with secondary clay; soils more than 3 m thick mantle the deposits. Contains pumice-rich alluvium in part consisting of glacial outwash (Scott, 1986).

A lahar at least 1.3 m thick and of Cougar age is exposed in a quarry west of Castle Rock in NE/4 sec. 4 (9N-2W).

Swift Creek-age deposits present in the upper South Fork Toutle river in NW/4 sec. 3 (8N-4E) and SE/4 sec. 32 (9N-4E), and near Toutle in SE/4 sec. 19 (10N-1E) consist of multiple lahar units interbedded with fluvial silty sands. Pumice present contains phenocrysts of hypersthene and hornblende. Total unit thickness is as much as 20 m. The lahars are commonly matrix-supported granule to boulder gravels, commonly graded, with brownish-gray silty sand matrix. Clay content of the lahars is higher than other Qshu1 lahar units. Soils as much as 1.6 m thick overlie or are interbedded with the deposits (Scott, 1986).

Near the volcano, Smith Creek-age lahar and pyroclastic deposits make up much of the apron extending from the cone into the valley of the North Fork Toutle River. Much of these deposits are covered by unit $Qshda_3$ in 1980.

Pine Creek-age deposits constitute the largest Mount St. Helens-derived lahars in the history of the Toutle River watershed. The largest lahar occurred about 2,500 yr B.P. when a natural dam of ancestral Spirit Lake failed. The lahar consists of as much as 10 m of cobbles, or locally, boulders in a light gray to tan silty sand matrix; framework-supported in coarser part of the unit; inversely graded at base becoming normally graded upward; contains megaclasts of hydrothermally altered dacite breccia (eroded debris avalanche deposits) and tree molds; distinctive "ball-bearing bed" of marble-sized, commonly abraded and fractured, framework-supported pebbles forms sole layer of unit. The Pine Creek age lahar units form the uppermost lahar units in the lower Toutle River-Cowlitz river area (Scott, 1986).

$Qsha_1$

Andesite lava flows--Opacitic hornblende-augite-hypersthene andesite forming thick lava lobes and flows in the Swift and Pine Creek drainages on the southern flank of the cone (Hopson, 1980); probably of Swift Creek eruptive period age (D. A. Swanson, oral commun., 1986).

$Qshd_1$

Dacite to andesite lava and plug domes--Light gray to pink, vesicular, seriate hornblende-hypersthene dacite and andesite forming Kalama River dome, Butte Camp dome, and other smaller domes or plugs (Hopson, 1980; Evarts and others, 1987) older than Castle Creek units, they petrographically resemble old domes of Mount St. Helens now exposed in crater walls (Hopson and Melson, 1982) and may be as young as Swift Creek age (circa 12,000 yr B.P.) (Evarts and others, 1987).

Mount St. Helens Deposits, Undivided

Qshu

Lahar deposits, undivided--Unconsolidated deposits in the South Fork of the Toutle River of Pine Creek through Kalama age (Scott, 1986); also includes undivided lahar deposits in sec. 20 (3E-7N) along the upper Kalama River.

Qshc

Deposits exposed in crater walls--Heterogeneous lithologies making up cone; consist of remnants of hornblende-hypersthene dacite domes from early growth stages of Mount St. Helens eruptive center (circa 40,000-2,500 yr B.P.), andesite pyroclastic flows and thin lavas of Castle Creek age, proximal end of Cave Basalt (unit $Qshb_2$), distinctive red to black olivine basalt or basaltic-andesite scorias and thin lavas, andesite lavas, scoria, and breccia of Kalama age, and dacite talus from former Summit dome (destroyed in the 1980 eruption); basalt, andesite, and dacite dikes cut portions of the crater wall assemblage (Hopson and Melson, 1982).

Lava flows exclusive of
Mount St. Helens

Qvmm

Basalt flows of Marble Mountain (Pleistocene)--Gray microphyric olivine basalt; forms bulk of Marble Mountain shield volcano north of Swift Reservoir; composed of vesicular, block-jointed lava flows 1-3 m thick; maximum unit thickness is about 200 m; much of the area underlain by Qvmm covered with Mount St. Helens tephras; vent areas shown on map marked by accumulations of cinders and bombs; age uncertain; appears to be associated with unit Qvma which has a K-Ar age of 0.16 m.y., lies below tephra set C (about 36,000 yr B.P.), and has normal magnetic polarity (Hammond, 1980, p. 19; Hopson, 1980; Hammond and Korosec, 1983).

Qvma

Andesite flows of Marble Mountain (upper Pleistocene)--Gray aphyric to microporphyritic hornblende andesite; erupted from vent on south side of Marble Mountain in NW/4 sec. 13 (7N-5E); forms block lava flows, 10 to 15 m thick with top and bottom breccia zones; platy jointed; maximum thickness about 40-60 m (Hammond, 1980); normal magnetic polarity with a K-Ar age of 0.16 +/- 0.01 m.y. (Hammond and Korosec, 1983, p. 16).

Qvtp

Andesite flows of Timbered Peak (upper Pleistocene ?)--Medium gray, porphyritic augite-olivine basaltic-andesite; forms thick (about 31 m) intracanyon flows; massive, with smooth glaciated surface; phenocrysts consist of subhedral to euhedral olivine and lesser plagioclase and augite in a fine-grained pilotaxitic groundmass of plagioclase and pyroxene; unit named for proximity to Timbered Peak (sec. 35, 6N-6E) located south of the map area in the Vancouver 1:100,000-scale quadrangle; age uncertain but clearly preglacial or older than about 10,000 yr B.P. (Polivka, 1984, p. 23-24).

Qvb

Basalt flows, unnamed (Pleistocene ?)--Poorly known, dark to medium gray basalt or basaltic-andesite lava flows in highlands south of Swift Reservoir and east of Merrill Lake (sec. 18, 7N-4E); recognized by geomorphic character and fresh, unaltered appearance of generally dense, microphyric basalt or basaltic-andesite; age uncertain but most flows appear to have been glaciated.

Tertiary Sedimentary and Volcanic Rocks

Pleistocene-Pliocene Sedimentary Deposits

QTtd

Troutdale Formation (upper Miocene to lower Pleistocene)--Moderately to weakly consolidated conglomerate, sandstone, and sandy siltstone; conglomerate crossbedded and channeled, with well-rounded, dominantly basaltic pebbles and cobbles, distinctive light orange quartzite cobbles and pebbles forming 5-15% of all clasts, and rare schist and granite clasts; lenticular, crossbedded, coarse-grained sandstone beds are intercalated with conglomerate; sand grains consist of angular quartz, feldspar, rock fragments, and mica; siltstone is light gray, very weakly consolidated, and mineralogically similar to the sandstone except that more clay is present; degree of cementation and consolidation is variable; locally the terms "gravel," "sand," or "silt" are appropriate for the Troutdale; thickness of the unit ranges from a few meters plastered on valley walls to about 150 m at Kelso (Livingston, 1966).

The Troutdale Formation is a valley-fill unit in the Mount St. Helens quadrangle and represents ancient deposits of the Columbia River system. Based upon data within the map area, age of the unit is limited to post-early Oligocene and pre-late Pleistocene. Eocene to Oligocene bedrock units (Tcz, Tgv, Tgo_1, Tgo_2) are unconformably overlain by the Troutdale; along the Coweeman River east of Kelso, the unit is incised and in unconformable contact with terraced deposits (Qtr) of probable late Pleistocene age.

In the Vancouver 1:100,000-scale quadrangle south of the map area (Phillips, 1987), the Troutdale contains an early Pliocene fossil flora (Trimble, 1963, p. 35) and is interbedded with a lava flow with a K-Ar isotopic age of 1.53 +/- 0.20 m.y. (Hammond and Korosec, 1983, p. 16). In the Columbia River Gorge east of Portland, Tolan and Beeson (1984) report Troutdale conglomerate beneath the 12-m.y.-old Pomona member of the Saddle Mountain Basalt. Therefore, an upper Miocene age through early Pleistocene range is conservatively assigned to the unit, although the age range within the map area may be much less.

Livingston (1966) divided the Troutdale exposed near Kelso into a lower conglomeratic member and an upper sandy silt member. This division appears only locally relevant because descriptions of more complete Troutdale sections in the Vancouver quadrangle (Trimble, 1963; Mundorff, 1964) cannot be correlated with the Kelso-area members.

Tolan and Beeson (1984) subdivided the Troutdale in the Columbia River Gorge into two facies. "Ancestral Columbia River" facies are characterized by fluvial conglomerates containing clasts (for example, quartzite, schist, or granite) for which no local source can be found. The "Cascadian" facies consists of conglomerates with high percentages of locally derived volcanic clasts (for example, high-alumina basalts from the Boring Basalts or Simcoe Volcanics) that represent local Cascade streams draining into the Columbia River.

Sandstone lithofacies demonstrate similar differences in provenance. Micaceous feldspathic beds reflect distant source areas, while sands rich in hyaloclastic (vitric) fragments and pumice clasts typify deposits of Cascadian side streams.

Both lithofacies appear to be present in the Mount St. Helens quadrangle. Vitric sandstone together with possible laharic conglomerate and breccia deposits are exposed in the quarry in SE/4 sec. 6 (6N-1W). Other good exposures of the Troutdale can be viewed in the quarry in SE/4 SE/4 sec. 23 (8N-2W) and in the many other localities described by Livingston (1966, p. 43-44).

Middle to Upper Miocene Sedimentary and Volcanic Rocks

Twk

Wilkes Formation (middle to upper Miocene)--Semiconsolidated, rust-colored to greenish-gray tuffaceous siltstone and sandstone, with interbedded conglomerate, claystone, and minor fibrous lignite; siltstone is thin bedded with varve-like sets of sandy or clay-rich layers, or massive and mottled with indistinct bedding and abundant plant fossils and carbonized wood; sandstone is generally medium- to coarse-grained, poorly sorted, massive to cross-bedded, in many places mottled and iron-stained with lenses of siltstone intraclasts, wood fragments, and pebbles; pebbly conglomerate is commonly iron-stained, partly decomposed to clay, and has a very coarse grained sandy matrix; claystone is tuffaceous, indurated and flint-like, or semi-plastic; in the type area in the Wilkes Hills, the formation is about 120 m thick (Roberts, 1958).

A massive blue-gray tuffaceous clay exposed near the base of the Wilkes in Cedar Creek (secs. 30 and 31, 11N-1E) contains numerous siderite concretions with coprolitic forms. The coprolite-like bodies range from tiny irregular and elongate masses 2.5 cm or less in length and 3 mm to 12 mm in diameter, up to masses 30 cm or more in length and 5-8 cm in diameter. Shape of the masses has suggested possible origin as the excrement of carnivores, turtles, or large fishes (Roberts, 1958, p. 36). However, none of the 500 concretions examined by Danner (1968) contained visible seeds, plant fibers, hair, or bones, and no vertebrate fossils have ever been found in the Wilkes. Spencer and Tuttle (1980) suggest that the bodies were formed by extrusion of altered tephra through knot holes in hollow logs. Roberts (1958) advances extrusion through clumps of reeds, algal nodules, or "inorganic accumulations" as possible modes of origin for the features.

Sandstone mineralogy in the Wilkes consists of volcanic lithic fragments, quartz, feldspar, hornblende, chlorite minerals, magnetite, muscovite, augite, volcanic glass, biotite, and zircon; conglomerate clasts or pebbles within sandstone beds are pumice, andesite, rhyolite, basalt, chert, and metamorphic rock.

Fossil leaves found within the lower portion of the Wilkes indicate a late Miocene age for the unit (Roberts, 1958, p. 36). The Wilkes is correlative with as much as 330 m of nonmarine strata exposed north of the Mount St. Helens quadrangle along the Newaukum River (Snavely and others, 1958). These rocks contain a fossil flora assigned to the Homerian (middle to upper Miocene) megafloral stage (J. A. Wolfe, USGS, oral commun., 1985).

The Wilkes Formation is restricted to the axial region of a broad, shallow, northwest-southeast elongate depression, the Napavine Syncline. Deposition of the unit probably was synchronous with folding (Roberts, 1958, p. 42).

Distinction of the Wilkes from overlying glacial-fluvial sediments of the Logan Hill Formation (unit Qlh) is difficult due to general lithologic similarity and deep weathering (Roberts, 1958, p. 42).

Tgr

Grande Ronde Basalt of the Columbia River Basalt Group (middle Miocene)--Dark-gray to black, dense, aphyric basaltic-andesite; commonly deeply weathered and laterized; in the Kelso area and southwest of Rainier, Oregon, forms reddish ferruginous bauxite deposits averaging about 4 m thick (Livingston, 1966).

At Cathlamet, west of the map area on the Columbia River, the units consists of a least one reversed polarity (R_2) low-MgO flow overlain by three normal polarity (N_{2S}) low-MgO flows or flow lobes, and three normal polarity (N_2) high-MgO flows (Wells and others, 1983). Magnetic polarity measurements have not been published for the Grande Ronde in the Mount St. Helens quadrangle but five geochemical analyses (Table 2) indicate that both high-MgO and low-MgO chemical types are present.

The Grand Ronde Basalt was erupted from vents in southeastern Washington and adjacent Idaho and Oregon. The rocks exposed in the Mount St. Helens quadrangle are the eastern edge of a huge sheet of flows which filled channels of the ancestral Columbia River, reached the Pacific Ocean, and invaded soft marine sediments of middle Eocene to Miocene age (Beeson and others, 1979; Wells and Niem, 1987). North of the Longview-Kelso area, Grande Ronde Basalt typically consists of isolated outcrops made up of only one or two flows.

The age of the Grande Ronde Basalt is usually reported as between 14 and 16.5 m.y., following the K-Ar isotopic data of Watkins and Baksi (1974). However, more recent $^{40}Ar/^{39}Ar$ determinations on basalts (Long and Duncan, 1983; Lux, 1981) indicate that the top of the Grande Ronde is about 15.6-15.3 m.y. old.

Earlier investigators, working without the advantage of current geochemical data, miscorrelated two flow sequences within the Mount St. Helens quadrangle with the Columbia River Basalt Group. Henriksen (1956) mapped the flows in the west half of T. 10 N., R. 2 W. as "Astoria Basalt" (that is, Columbia River Basalt Group). Geochemical analyses presented in this report (Table 2) indicate these flows belong to the Eocene Grays River volcanics. (See unit Tgv.) Roberts (1958) mapped the porphyritic two-pyroxene andesites of the Toutle Mountain Range (unit Tva_1) as "Middle (?) Miocene volcanic sequence" and tentatively correlated the rocks with Columbia River Basalt Group (Roberts, 1958, p. 33). Geochemical data and a K-Ar isotopic age determination rule out this correlation (see discussion under unit Tva_1).

Lower to Middle Miocene Sedimentary Rocks

Tso

Scappoose Formation of Van Atta and Kelty (1985) (lower to middle Miocene)--Fluvial micaceous, lithofeldspathic sandstone, conglomerate, and carbonaceous to coal-bearing mudstone, intertongued with shallow neritic to estuarine siltstone, mudstone, and minor sandstone; conglomerate clasts derived from low-MgO Grande Ronde Basalt (see unit Tgr) which interfingers with and overlies the Scappoose; about 460 m thick. Southwest of the map area, the Scappoose disconformably overlies the Keasey (late Eocene through early Oligocene) and Pittsburg Bluff (Oligocene) formations; the unit was previously assigned to the late Oligocene through early Miocene (Warren and others, 1945); as mapped, may include some strata of Pittsburg Bluff or Keasey formations.

Lower Miocene to Upper Oligocene Volcanic Rocks

A stratigraphically complex and lithologically heterogeneous volcanic and volcaniclastic section several km thick is present in the eastern third of the map area. Lithologies present are lava flows, plug and lava domes, lapilli tuff, lithic tuff-breccia, hypabyssal intrusive rock, and zones of hydrothermal alteration. Minor stratigraphic discontinuities are common, but significant unconformities have not been detected. Widespread stratigraphic marker horizons are rare or absent in the section, probably because the sequence represents near-vent depositional environments in which abrupt facies changes are the rule. In terms of mineralogy or major element geochemistry, little compositional variation related to stratigraphic position is evident in the volcanic pile (Evarts and others, 1987).

The K-Ar age determinations reported by Evarts and others (1987) have been used to subdivide the volcanic section into a dominantly upper Oligocene sequence (units Tvc_2, Tvt_2, Tvd_2, Tva_2, Tvb_2), and a dominantly lower Miocene sequence (units Tvc_3, Tvt_3, Tvd_3, Tva_3, Tvb_3). Zeolite-facies burial metamorphism, which probably reached a peak during emplacement of the lower Miocene Spirit Lake pluton, has affected all of the volcanic pile. This complicates interpretation of K-Ar isotopic results, hence age assignments must be considered provisional (Evarts and others, 1987). However, most of the K-Ar results fit regional stratigraphic and structural constraints.

Because K-Ar ages, rather than lithological contrasts, have been used to divide the volcanic pile, unit descriptions for the lower Miocene and upper Oligocene strata are grouped together.

Hammond (1980) assigned these strata to the late Eocene through Oligocene Ohanapecosh Formation of Fiske and others (1963). This terminology was not used for the following reasons: the Ohanapecosh Formation consists dominantly of well-bedded, subaqueously deposited, distal facies of volcaniclastic sedimentary rocks (Fiske and others, 1963) in contrast to the near-vent character of the heterogeneous section; it cannot be continuously traced from the type area near Mount Rainier to the Mount St. Helens quadrangle (Walsh and others, in press); and, the Ohanapecosh does not include rocks as youthful as lower Miocene (Vance and others, in press). While these data do not preclude a partial correlation of the heterogeneous volcanic section with the Ohanapecosh, use of "generic" or informal time-lithology units avoids possible miscorrelation and signals to the map user that further stratigraphic work is required.

Tsm

Andesite of Smith Creek Butte (lower Miocene?)--Pyroxene andesite and olivine-pyroxene andesite lava flows (Hopson, 1980); possibly equivalent to lower Miocene units--for instance, andesite of Council Bluff or andesite of Three Corner Rock, found east of the map area in the Mount Adams and Vancouver quadrangles (Korosec, 1987; Phillips, 1987), or to unit Tva_3.

Tvd_3 and Tvd_2

Dacite flows, plugs or lava domes (lower Miocene and upper Oligocene)--White to light greenish gray, sparsely-phyric, commonly flow-banded dacite flows, flow breccia, or hypabyssal, chaotically jointed plugs or lava domes; typically contains less than 10% plagioclase and 5% pyroxene phenocrysts in a groundmass of devitrified glass which now consists of fine-grained granular to spherulitic quartz and feldspar; contains rare hornblende; quartz and biotite not present; secondary alteration more common than in interbedded, more mafic volcanic rocks; commonly contains alteration resulting from supergene oxidation of minor but widespread pyrite (Evarts and Ashley, 1984).

Tvc_3 and Tvc_2

Volcaniclastic rocks (lower Miocene and upper Oligocene)--Subaerial pyroclastic and sedimentary rocks including andesitic to dacitic, typically lithic-rich, ash-flow and air-fall tuff, tuff breccia, volcanic siltstone, sandstone, conglomerate, minor coal beds, and many poorly sorted volcanic breccia beds of uncertain origin; dominantly pumiceous pyroclastic rocks in eastern portion of outcrop area where closely associated with thick accumulations of dacite; volcanic glass altered to smectite, quartz, feldspar, and zeolites (Evarts and Ashley, 1984).

Tvt_3 and Tvt_2

Tuff (lower Miocene and upper Oligocene)--Tuff-breccia and lapilli-tuff with angular volcanic-lithic fragments in matrix of pumice lapilli and ash; pumice-lapilli tuff in beds several centimeters to tens of meters thick; typically lithic-rich with eutaxitic foliation; includes air-fall tuff, nonwelded to poorly welded ash-flow tuff, reworked pyroclastic material, and pumiceous mudflow deposits; quartz-phyric tuff not present; massive poorly sorted tuff-breccia and lapilli-tuff several hundred meters thick northeast of the Spirit Lake pluton may represent caldera-fill deposits (Evarts and others, 1987).

Tvb_3 and Tvb_2

Basalt lava flows (lower Miocene and upper Oligocene)--Black to dark gray-green aphyric to sparsely porphyritic, massive to vesicular basalt and basaltic-andesite lava flows and flow breccia; locally includes interbedded mafic tuff, lahar, and minor sedimentary rocks; porphyritic flows contain phenocrysts of plagioclase, olivine, and augite in intergranular to intersertal groundmass of plagioclase, clinopyroxene, magnetite, and rare brown to green glass; slightly to completely altered to zeolite or prehnite-pumpellyite facies assemblages; within contact aureole of Spirit Lake pluton, recrystallized to fine-grained hornblende- and pyroxene-hornfels facies assemblages (Evarts and Ashley, 1984).

Tva_3 and Tva_2

Basaltic-andesite and andesite lava flows (lower Miocene and upper Oligocene)--Porphyritic pyroxene andesite and basaltic-andesite flows and flow breccia, locally includes minor basalt and dacite flows, breccia, and interbedded volcaniclastic rocks; typically consists of plagioclase, augite, and hypersthene phenocrysts in pilotaxitic groundmass of plagioclase, pyroxene, magnetite, quartz, and interstitial glass (usually altered to fine-grained smectite); includes hypabyssal sills or dikes in areas where contacts could not be observed (Evarts and Ashley, 1984).

Lower Oligocene Volcanic Rocks

Tvd_1

Dacite (lower Oligocene)--Light gray pyroxene dacite; forms complex of plugs, flows, interstratified tuff-breccia, and hypabyssal intrusive rocks in sec. 25 (2E-11N); elsewhere consists of platy pyroxene dacite which weathers to form bright red soils; locally includes small zones of argillic hydrothermal alteration consisting of country rock altered to white, soft, crumbly mass of clay minerals and finely disseminated pyrite.

Tva_1

Andesite lava flows (lower Oligocene)--Porphyritic two pyroxene andesite, clinopyroxene basaltic-andesite, and associated flow breccia forming two major flow complexes at Toutle Mountain Range (9N-2E) and near Big Bull Mountain (8N-3 and 4E).

At the Toutle Mountain Range, the unit consists of platy, light-to-medium-gray, porphyritic andesite with abundant medium-grained hypersthene, plagioclase, and clinopyroxene phenocrysts; ground-mass hypocrystalline with trachytic, intersertal texture composed of dark brown glass, tabular plagioclase, and equant clinopyroxene; about 600 m thick (Roberts, 1958); a flow at Signal Peak in the Toutle Mountain Range yielded a K-Ar whole rock age of 33.9 +/- 1.7 m.y. (Table 4, sample MK8589); the flows of the Toutle Mountain Range were erroneously considered by Roberts (1958) to be correlative with flows of the Columbia River Basalt Group (middle to upper Miocene); the Toutle Mountain flows overlie the Toutle Formation (Tto), unit Tvc_1, and the Goble Volcanics with minor, and possibly local unconformity (Roberts, 1958); Oligocene tuff (Tvt_1) overlies and is interbedded with the Toutle Mountain Range flows.

Northeast of Big Bull Mountain, sparsely porphyritic clinopyroxene basaltic-andesite, and abundantly porphyritic augite-hypersthene andesite flows and flow breccia form a complex several hundred meters thick; andesite flows consist of at least two or three flows or flow lobes 9 to 12 m thick with lava tube structures; numerous basaltic-andesite flows are blocky to platy jointed and very well exposed in the glaciated headwaters of Trouble Creek, secs. 1, 12, and 13 (8N-3E); a basaltic-andesite flow capping the Big Bull section yielded a whole-rock K-Ar date of 32.9 +/- 2.6 m.y. (Table 4; sample BP0814856).

Also included in Tva1 are andesites of Cinnamon Peak (Oligocene ?); porphyritic hypersthene-clinopyroxene andesite lava flows and flow breccia, with minor intercalated andesite- clast conglomerate in 7N-4E; the unit rests with slight angular discordance on lower Oligocene volcaniclastic rocks (unit Tvc_1); uniform in chemical composition and chemically indistinguishable from other Oligocene-Miocene andesitic flow units; yielded a whole rock K-Ar age of 15.4 +/- 0.5 m.y. (Evarts and others, 1987); a plagioclase K-Ar age of about 26 m.y., and an $^{40}Ar/^{39}Ar$ date of about 32 m.y. B.P. (Russ Evarts, oral commun., 1987); regional correlations with similar lithologies suggest the unit is late Oligocene to early Miocene in age.

Finally, Tva_1 includes clinopyroxene basaltic-andesite flows, flow breccia, and interbedded tuff in the Elk Rock 15-minute quadrangle; consists of sparsely to abundantly porphyritic, plagioclase-clinopyroxene-olivine-phyric basaltic-andesite with holocrystalline, intergranular groundmass of plagioclase, clinopyroxene, opaque minerals, and chloritic alteration products; yielded a K-Ar whole rock age of 35.7 +/- 1.6 m.y.; this late Eocene age may reflect a regional unconformity (see Structural Features), unrecognized faulting, or the effect of zeolite-facies alteration on the K-Ar method; the sample (BP0619851 in Table 4) had an unusually high radiogenic argon yield of 93.8%.

Tvc_1

Volcaniclastic sedimentary and volcanic rocks (lower Oligocene)--Diverse lithologies including dark green-gray boulder conglomerate and breccia, and light-colored pumiceous lapilli tuff and tuffaceous sediments; major accumulations include the beds of Fossil Creek (8N-3,4E) consisting of about 120 m of well-bedded pumice-vitric-crystal tuff of andesitic to dacitic composition; contains fossil flora of Goshen (early Oligocene) age (Wolfe, 1961, sample 9758); at Hoffstadt Mountain, sec. 24 (10N-2E), consists of massive to thick-bedded, poorly sorted boulder to cobble conglomerate or breccia with abundant fossil wood fragments and a dark-colored, andesitic to basaltic clast composition.

At Elk Rock and Spud Mountain, the unit includes vent breccia composed of dark black, glassy-appearing rock with vitreous plagioclase phenocrysts and abundant clasts of lapilli tuff, porphyritic volcanic rocks, and phaneritic intrusive rocks; vent breccia forms resistant, cliff-forming dikes or roughly circular plugs.

Elsewhere in the map area, the unit consists of tuffaceous sedimentary rocks or tuff, with interbedded lava flows, hypabyssal intrusive rocks, and pyroxene dacite plugs; typically separates major flow complexes (units Tgo_2, Tva_1); may be in part correlative with Toutle Formation (Tto) or unit Tgo_1 in Elk Rock 15-minute quadrangle.

Eocene-Oligocene Sedimentary and Volcanic Rocks

Tto

Toutle Formation (upper Eocene through lower Oligocene)--Poorly sorted basaltic to andesitic conglomerate and sandstone with interbedded tuffaceous siltstone, high-alumina clay, lignite, pumiceous lapilli tuff, and locally, basalt or basaltic-andesite lava flows; volcanic-lithic sandstone is olive-gray and composed of basalt, andesite, red scoria, pumice, plagioclase, magnetite, and small amounts of quartz, biotite, augite, and hornblende; tuffaceous siltstone usually carbonaceous; about 173 m (570 ft) thick (Roberts, 1958, p. 24-31).

May (1980) subdivided the unit into a lower, dominantly marine member, and an upper member composed of continental deposits; according to May (1980), most of the lower member probably was deposited in a cooling subtropical to warm temperate sea in shallow nearshore waters in depths no greater than 40 m, while the upper member accumulated in swamps, lakes, and rivers on an adjacent low-lying coastal plain.

The base of the Toutle is described as being in unconformable contact with both the Cowlitz Formation (Tcz) and the Hatchet Mountain Formation (placed within unit Tgo_2 and Tgo_1) by Roberts (1958); however, outcrop patterns and exposed contacts suggest that the Toutle overlies the Cowlitz with only local unconformity, and that it is interbedded with the Hatchet Mountain Formation.

Carbonaceous, tuffaceous siltstone of the lower Toutle contains a Kummerian (upper Eocene) fossil flora (Wolfe, 1966, p. 6-7; Wolfe, 1981, p. 42-43). An extensive Galvinian (upper Eocene through lower Oligocene) molluscan fauna also is present in the lower Toutle (Roberts, 1958, p. 25-27; May, 1980). Apatite from a tuff in the nonmarine upper portion of the Toutle produced an anomalously youthful fission track age of 8.3 +/- 1.7 m.y. (May, 1980, p. 39 and 110). A K-Ar age determination from the porphyritic two-pyroxene andesite flows (unit Tva_1) which unconformably cap the Toutle gave an age of 33.9 +/- 1.7 m.y. (Table 4). A basalt flow interbedded in the Cowlitz Formation yielded a K-Ar age of 37.3 +/- 2.2 m.y. (Table 4). Thus the Toutle probably spans the Refugian Stage (upper Eocene through lower Oligocene, from approximately 38 to 35.7 m.y.B.P.

The Toutle is correlated with and probably a proximal equivalent of the basaltic sandstone member of the Lincoln Creek Formation (Snavely and others, 1958). It was not possible to trace with certainty the Toutle outside of Roberts' (1958) map area because volcaniclastic sediments are present at multiple stratigraphic levels within the generally flow-dominated Goble sequence, and because critical biostratigraphic or geochronologic control is absent.

Tlc

Lincoln Creek Formation (upper Eocene through Oligocene)--Light-gray, fine-grained sandstone and sandy siltstone, partly tuffaceous; generally poorly exposed in stream beds, stream banks, and roadcuts along Olequa Creek near Winlock; greater than about 455 m thick (Henriksen, 1956, p. 16).

The unit contains a molluscan fauna assigned to the Echinophoria dalli zone, middle Galvinian Stage (uppermost Eocene) by Armentrout (1975, p. 23; 1973, fig. 12). The Lincoln Creek overlies unconformably the Olequa Creek member of the Cowlitz Formation (unit Tcz). The contact represents transgressive overlap of the Cowlitz Formation by the Lincoln Creek and is locally a disconformity rather than an angular unconformity (Henriksen, 1956, p. 58). The Lincoln Creek Formation exposed in the map area is correlative with the "basaltic sandstone" member of the type Lincoln Creek of Beikman and others (1967). It is correlative and probably gradational to the Toutle Formation (unit Tto).

Tgo_2

Basaltic-andesite lava flow member of the Goble Volcanics (upper Eocene through lower Oligocene)-- Porphyritic pyroxene basaltic-andesite lava flows and flow breccia with thin interbeds of red-brown siltstone, sandstone, conglomerate, and tuff; also contains lesser olivine basalt, pyroxene andesite, and platy to irregularly jointed dacite; flows are typically thin (1-4 m) and lenticular or lozenge-shaped, with wavy top and bottom contacts; thin (5-50 cm) siltstone or sandstone layers often separate flows; dense flow centers typically blocky jointed to platy; well-developed columnar-jointing or colonnade-entablature sets rare; locally, scoriaceous flow breccia forms bulk of unit, enveloping small,lenticular dense flow-centers in block rubble; vugs and fractures contain characteristic assemblage of calcite and complex suite of zeolite minerals (Tschernich, 1986); total unit thickness exceeds 1500 m in the type area between Woodland, Washington and Kelso (Wilkinson and others, 1946).

In thin section, the unit is most commonly plagioclase-augite phyric with trachytic groundmass of plagioclase microlites, clinopyroxene, opaque minerals, and murky, green to brown, microcrystalline mixtures of zeolite minerals, chlorite, and volcanic glass; olivine phenocrysts also present in a few flows.

The Goble Volcanics were first described by Wilkinson and others (1946) for flows and pyroclastic rocks exposed at Goble, Oregon (sec. 12, 6N-2W), and on the Washington side of the Columbia River between Woodland and Kelso. In this report, unit Tgo_2 includes flow lithologies of the Hatchet Mountain Formation of Roberts (1958). Flows of the type Goble are traceable directly and continuously into the Hatchet Mountain type area (Phillips and Kaler, 1985).

The unit does not include most strata mapped as Goble Volcanics by Livingston (1966), Wells (1981), and Wells and Coe (1985), or as Goble Volcanic Member of the Cowlitz Formation by Henriksen (1956). These rocks are assigned to the informal unit Grays River volcanics (Tgv) in this report.

Major element geochemistry of flows from the Goble Volcanics is summarized in Table 2. As noted by Beck and Burr (1979), the unit is calc-alkalic and similar to many volcanic arc assemblages. X-Y major element plots discriminating between Tgo_2 and Tgv are shown in Figures 3 and 4.

The Goble Volcanics of Wilkinson and others (1946) are informally subdivided here into two members: a lower, volcaniclastic and pyroclastic unit (Tgo_1); and an upper, lava-flow dominated unit (Tgo_2).

Basal portions of Tgo_2 are interbedded with the regionally extensive volcaniclastic unit, Tgo_1.

The top of the flow member is variably defined depending on location within the quadrangle. In northwestern Oregon, in the southwestern corner of the map sheet, the flow member is unconformably overlain by marine sediments of "Gries Ranch, Pittsburg Bluff, and possibly Blakely" age (Wilkinson and others, 1946). These sediments are labeled Tso or Scappoose Formation on the map; recent work by Van Atta and Kelty (1985) indicates that the Scappoose is, at least in part, early to middle Miocene in age.

In the Toledo-Castle Rock area, Tgo_2 (Hatchet Mountain Formation of Roberts, 1958) is conformably overlain, and in some instances, clearly interbedded with volcaniclastic sediments of the Toutle Formation (Tto). Where the Toutle is thin or absent, distinction between Tgo_2 and the overlying porphyritic andesite of the Toutle Mountain Range (Tva_1) is sometimes made with difficulty. In this area, volcanism during the latest Eocene through early Oligocene produced lava flow, pyroclastic, and epiclastic facies which are complexly interbedded.

Elsewhere in the map area, Tgo_2 is overlain with apparent conformity by light-colored pumiceous pyroclastic volcanic rocks and volcaniclastic sediments of unit Tvc_1. This contact is well-exposed northwest of Merrill Lake in (8N-3E).

Age of Tgo_2 ranges from about 38 to about 35 m.y. (latest Eocene to early Oligocene). This age range is constrained by K-Ar analyses (Table 4). Biostratigraphic control is provided by the underlying Cowlitz Formation (upper Narizian foraminifers, Cowlitz-Coaledo mollusks; see unit Tcz), and overlying to interbedded Toutle Formation (Refugian foraminifers, Galvinian mollusks, Kummarian flora; see unit Tto) and unit Tvc_1 (Goshen flora, see unit Tvc_1). K-Ar age determinations by other workers for this unit include 45 and 32 m.y., and 30 m.y. (Beck and Burr, 1978; Armentrout and others, 1983, p. 49). However, these K-Ar ages appear to reflect the sensitivity of the K-Ar method to rocks containing zeolite-facies alteration rather than true geologic ages.

The unit correlates with the Cole Mountain Volcanics of northwestern Oregon (Niem and Niem, 1985), the basal portions of the Ohanapecosh Formation (Fiske and others, 1963), and with basal portions of the volcanic rocks of Huckleberry Mountain (Frizzell and others, 1984) north of the White River. Portions of the Northcraft Formation of Hagen (1987) and unit Tva of this report may be correlative with Tgo_2, but further mapping is required to demonstrate this.

Tgo_1

Volcaniclastic sedimentary and volcanic rock member of the Goble Volcanics (upper Eocene-lower Oligocene)--Light-colored volcanic-lithic sandstone, siltstone, and conglomerate, lapilli and ash tuff, breccia, and minor coal and carbonaceous shale; locally contains interbedded lava flows similar to unit Tgo_2; thin-bedded to massive with coarser grained strata commonly cross-bedded; tuff commonly normally graded; upon weathering, unit produces characteristic brilliant red, sticky, clay-rich soils; thickness variable; at least 180 m thick in the vicinity of Mount Brynion (8N-1W), about 50 m thick north of Castle Rock in secs. 11-12 (10N-2W) (Roberts, 1958, p. 20); gradationally overlies the Cowlitz Formation (Tcz) and breccia of the Grays River volcanics south of Kelso (7N-1,2W) and near Castle Rock; overlain and interbedded with flows of unit Tgo_2; impossible to distinguish from the nonmarine member of the Toutle Formation (Tto) where unit Tgo_2 is absent; see unit Tgo_2 for discussion of unit age and correlation.

Eocene Sedimentary and Volcanic Rocks

Stratigraphic nomenclature presently in use for several Eocene units in the Mount St. Helens quadrangle is confusing. This is primarily a result of two factors: (1) miscorrelation of volcanic units; and (2) imprecise definition of type sections. To alleviate these problems, several stratigraphic revisions are proposed in this report. Since this is an open-file document, these revisions are informal and conflict with nomenclature shown in U.S. Geological Survey lexicons.

Tcz

Cowlitz Formation (middle to upper Eocene)--Massive to thin-bedded, light-gray to rust-colored, micaceous feldspathic sandstone with interbedded siltstone, shale, carbonaceous shale, and lignite to subbituminous coal; locally contains basalt lava flows and volcaniclastic rocks (where mappable, assigned to the Grays River volcanics, unit Tgv); interbedded molluscan fossil fauna and coal suggest mixed nearshore marine and nonmarine deposition in river-dominated deltaic environment (Nesbitt, 1982); sandstone commonly massive as result of bioturbation; unit thins and is interbedded with basaltic-andesite to andesite lava flows to the northeast (Northcraft Formation of Hagen, 1987; unit Tva of this report); measured thickness exceeds 1,100 m; contains upper Narizian benthic foraminifers

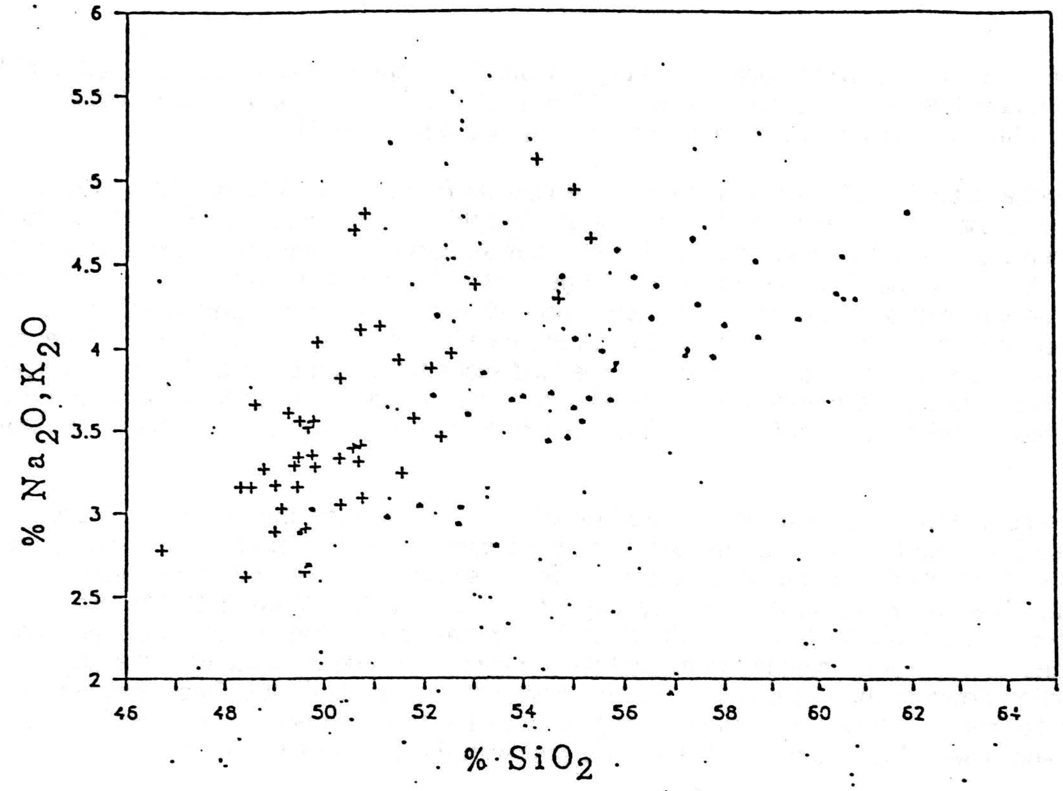


Figure 3: Plot of Na_2O+K_2O vs. SiO2 for the Grays River volcanics (+) and the Goble Volcanics (*).

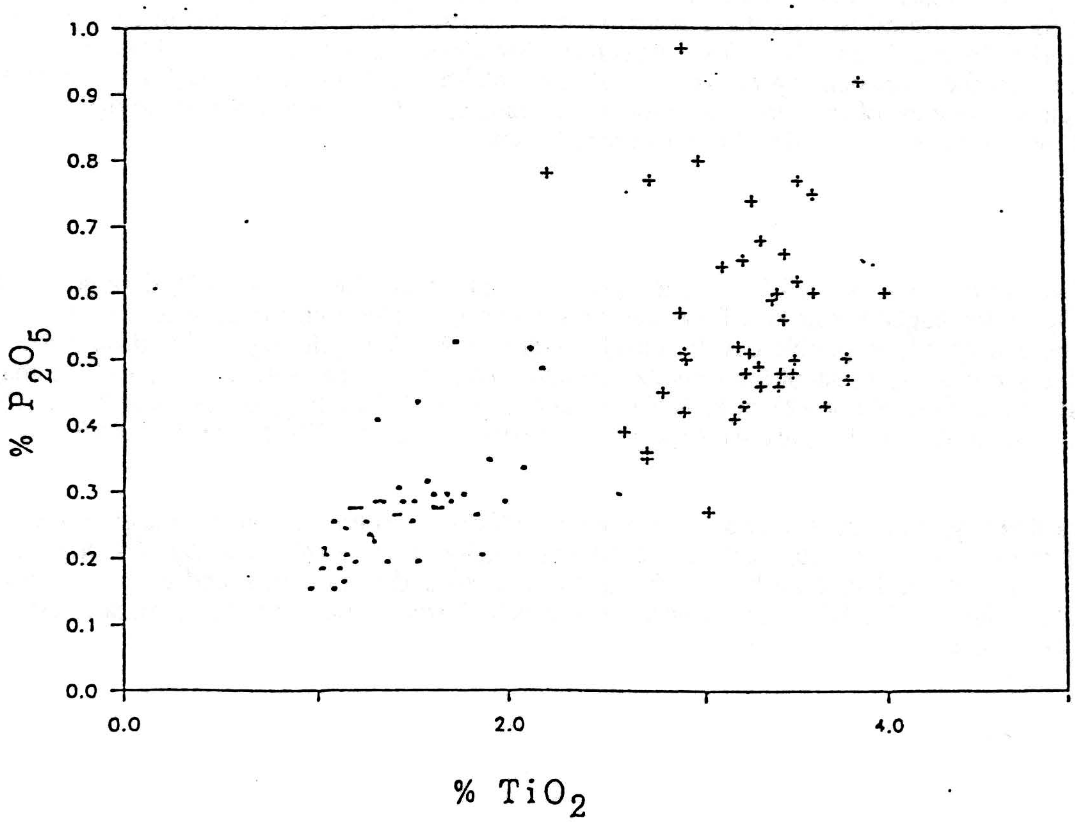


Figure 4: Plot of P_2O_5 vs. TiO_2 for the Grays River volcanics (+) and the Goble Volcanics (*).

(Henriksen, 1956) and Cowlitz-Coaledo molluscan fauna (Armentrout, 1981), both assigned a middle to late Eocene age; interbedded basalt lava flow of Tgv yielded a K-Ar age of 37.9 m.y. (Table 4); correlated with the Skookumchuck Formation (Snavely and others, 1958).

Imprecise definition of the type section of the Cowlitz Formation by Weaver (1912; 1937; 1944) has prompted use of two distinct and conflicting stratigraphic nomenclatures for the unit. In the first, championed by Henriksen (1956), the Cowlitz includes all Eocene marine and estuarine deposits above the pillow basalts of the Crescent Formation and below basaltic sandstone and tuffaceous shales of the Lincoln Creek Formation. Four members based upon lithofacies and stratigraphic position are recognized, at least locally. From bottom to top, the members include marine siltstone, shale, and sandstone of the Stillwater Creek member, interbedded mafic tuff and breccia of the Pe Ell volcanics member, mixed nearshore marine and terrestrial sandstone, siltstone, mudstone, and coal of the Olequa Creek member, and basalt lava flows and flow breccia of the Goble Volcanics member (Henriksen, 1956).

The second approach, most recently used by Wells (1981), restricts the Cowlitz Formation to the mixed nearshore marine and terrestrial, sandstone-dominated facies (the facies represented by the Olequa Creek member). Marine siltstone and sandstone sections are assigned to the McIntosh Formation. This nomenclature has the advantage of clearly including Weaver's (1912; 1937) original Cowlitz type section (although it is equally clear that, at least toward the end of his career, Weaver [in Weaver and others, 1944] intended to expand the Cowlitz to include all strata from the original Olequa Creek section down to the Crescent Formation). Assignment of the Stillwater Creek member to the McIntosh Formation is based on arguments of priority as the McIntosh was first defined in 1951 (Snavely and others, 1951) and specifically correlated with the Stillwater Creek section.

A more detailed treatment of the Cowlitz nomenclatural problem is given in Walsh (1987). In the present report, the Cowlitz Formation consists solely of mixed nearshore marine and terrestrial facies typified by the Olequa Creek member of Henriksen (1956). The Goble Volcanics member and other volcanic rocks interstratified with the Cowlitz (Livingston, 1966) have been placed in an informally named and defined unit, the Grays River volcanics. (See discussion for unit Tgv.) This usage is consistent with the nomenclature of Wells (1981) and Walsh (1987) in the Astoria 1:100,000-scale quadrangle to the west of the Mount St. Helens quadrangle, and also with the terminology of Niem and Niem (1985) in the Astoria Basin of northwestern Oregon.

Tgv

Grays River volcanics [informal] (middle to upper Eocene)--Porphyritic and aphyric, dark gray to black, high TiO_2 olivine-augite basalt lava flows and flow breccia, basaltic tuff, hyaloclastic breccia, basaltic sandstone, and cobble to pebble basaltic conglomerate; interbedded with light-colored quartzo-feldspathic sedimentary rocks of the Cowlitz Formation (Tcz) along the western margin of the map area; thickness varied, from about 425 m at Beebe Mountain (10N-2W) to 30 m or less near Kelso (8N-2W); unit thickness appears to increase west toward the headwaters of the Grays River in 10N-6W (Walsh, 1987).

Lava flows typically consist of 5-15 m of dense, blocky- to columnar-jointed, massive flow-centers, with 1-2 m of basal or flow-top scoriaceous breccia; locally, flows consists entirely of scoriaceous block breccia; flow tops and bases are hummocky, often oxidized and rust-colored, and are commonly intercalated with massive feldspathic sandstone or sandy siltstone, coal, or basaltic volcaniclastic sedimentary rocks.

In hand specimen, many fresh samples of basalt contain vitreous green augite phenocrysts set in a microphyric to very fine grained groundmass; very fine grained equigranular to aphyric textures are also present; a slight greenish sheen probably caused by secondary chlorite is commonly present on joint surfaces; vesicles and fractures are commonly filled with calcite and/or zeolite minerals.

In thin section, most basalts are seriate to glomeroporphyritic with phenocrysts of calcic andesine to calcic labradorite (Livingston, 1966, p. 23), augite, magnetite, olivine, and alteration products of olivine; the groundmass is typically intersertal with abundant opaque minerals, microlites of plagioclase, clinopyroxene, and cloudy, dark brown devitrified glass consisting of microcrystalline mixtures of opaque minerals, chlorite, zeolites, and calcite.

Good exposures of lava flow lithologies are present in roadcuts along state highway 411 south of Vader in 10N-2W; in quarries on Beebe Mountain in sec. 30, T. 10N-2W and sec. 25, 10N-3W; and in the very large quarry and roadcuts at the southeast end of the Longview (state highway 433) bridge in secs. 17-18, 7N-2W.

Volcaniclastic sedimentary rocks within the unit typically consist of very coarse grained sandstone and pebble to cobble-sized conglomerate; clast lithologies are limited to basalt and clay or sandstone intraclasts derived from the Cowlitz Formation; the roadcut visible from southbound lanes of Interstate 5 in SE/4 sec. 22, 10N-2W exposes dark, greenish-gray thick-bedded basaltic sandstone and conglomerate overlaid by feldspathic sandstone and lignite; these lithologies probably represent detritus eroded from locally erupted basalt lava flows and tuff mixed with fluvial-deltaic sedimentary rocks of the Cowlitz Formation.

Dark gray, massive breccia composed dominantly of plagioclase and pyroxene crystals, and coarse-ash to lapilli-sized, dark brown hyaloclastite (altered basaltic glass) and basalt lithic fragments comprise the unit from Kelso south to the junction of Interstate 5 and Highway 432 (the "Kelso Y") in sec. 12 7N-2W); the breccia is brittle, crumbles easily, shows a great deal of shearing, and has a well-developed spheroidal weathering habit. Livingston (1966, p. 49) mapped the breccia lithology as an "intrusive plug;" however, the breccia is closely associated with and gradational to both a lava flow and basaltic sandstone and conglomerate at Rocky Point (SE/4, sec. 14, 7N-2W); a hyaloclastic origin resulting from sudden contact of a hot lava flow with water appears more likely.

Geochemical analyses of fresh samples from massive flow centers (Table 2) indicates that the Grays River volcanics possesses distinctive major element concentrations relative to other volcanic rocks of the map area. Flow rocks are enriched in P_2O_5, total alkalies (Na_2O+K_2O), and especially TiO_2 (Figures 3 and 4). As a group, they are more mafic (lower SiO2) than the other Tertiary volcanic units (units Tgo_2 and Tgr) in the map area in contact with the Cowlitz Formation. In addition, Tgv has a dramatically lower Cu content than Tgo_2 (Table 3).

Following a suggestion by R. E. Wells of the U.S. Geological Survey, the informal term "Grays River volcanics" is applied to the above-described basaltic lava flows, breccia, and volcaniclastic sediments interbedded with the Cowltiz Formation. This basaltic sequence is well-exposed in quarries and along logging roads west of the map area in the headwaters of Grays River, 10N and 11N-6W (Walsh, 1987).

The Grays River volcanics include the unit B volcanics of Wolfe and McKee (1968, 1972), most of the Goble Volcanics of Livingston (1966), the Goble Volcanic Member of the Cowlitz Formation (Henriksen, 1956), and the Goble Volcanics of Wells (1981) and Wells and Coe (1985).

Tertiary Volcanic Rocks, Undivided

Tvc

Volcaniclastic sedimentary and pyroclastic rocks (upper Eocene-lower Oligocene ?)--Thick-bedded boulder to cobble volcanic-lithic conglomerate, breccia, and andesitic tuff near Riffe (Davisson) Lake; cliffs on south shore of Riffe Lake expose several hundred meters of unit; age uncertain, but probably older in part than unit Tgo_1; overlies andesite flows which yielded K-Ar age of 38.3 +/- 1.9 m.y. (Phillips and others, 1986, sample HS0117851A).

Tva

Andesite and basaltic-andesite lava flows (middle ? to upper Eocene through lower Oligocene)--Porphyritic basaltic-andesite and andesite lava flows, flow breccia and locally, interbedded andesitic volcaniclastic conglomerate and sandstone; flows commonly contain vesicles and fractures filled with chalcedony, calcite, and zeolite minerals; correlated with the middle Eocene Northcraft of Snavely and others (1958) by Roberts (1958); however, regional mapping (Hagen, 1987; Schasse, 1987) north of the Mount St. Helens quadrangle and K-Ar age determinations (Phillips and others, 1986) suggest a late Eocene to early Oligocene age; oil and gas exploration wells (McFarland, 1983) also demonstrate the presence of several thick volcanic sections interbedded with Cowlitz or correlative sedimentary rocks; the volcanics may be unit Tva or unit Tgv or both; upper portion of unit may be correlative to the Goble Volcanics (units Tgo_1 and Tgo_2) of this report.

Tertiary Igneous Intrusive Rocks

Pleistocene-Pliocene Intrusive Igneous Rocks

QTid

Dacite porphyry of Goat Mountain (lower Pleistocene to Pliocene ?)--Biotite-hornblende-quartz dacite porphyry forming 850-m high plug dome; consists of about 50% plagioclase, quartz, biotite, and hornblende phenocrysts as much as 1 cm in length, and 50% light gray friable glass groundmass; also found in two other plugs low on the southwestern flank of Mount St. Helens; yielded discordant K-Ar ages of 3.0 m.y. (hornblende) and 0.74 and 1.0 m.y. (biotite) (Hammond, 1980).

Lower Miocene Igneous Intrusive Rocks

Intrusive Rocks of the Spirit Lake Pluton

The Spirit Lake pluton is the largest intrusive complex present in the Mount St. Helens quadrangle. It is part of a northeast-trending belt of large, generally intermediate composition intrusions stretching from near the Columbia River to north of Mount Rainier. These plutons (from south to north, the Silver Star, Spirit Lake, Bumping Lake, and Tatoosh) share a dominantly early Miocene age and shallow emplacement depths (Evarts and others, 1987).

The Spirit Lake pluton consists of a complex, multiphase, epizonal body ranging in composition from quartz diorite to granite. For mapping at a 1:48,000 scale, Evarts and Ashley (1984) divided the pluton into three readily distinguishable phases: from oldest to youngest, early granodiorite, main quartz diorite, and latest granite (or quartz monzonite) phases. These divisions are also used in this report (units Tigd, Tiqd, and Tiqm, respectively).

Multiple K-Ar (biotite) and fission-track (zircon) ages obtained from the quartz diorite main phase (Tiqd) range from 20.6 to 22.0 m.y. (Evarts and others, 1987).

Tiaa

Argillic alteration (lower Miocene ?)--Areas of argillic alteration within the Spirit Lake pluton; protolith rocks totally replaced by fine-grained quartz, rutile, limonite, and sericite or pyrophyllite, locally accompanied by diaspore, andalusite, topaz (?), and clay minerals; vague brecciated texture usually visible in hand specimen; protolith generally obscure, but includes porphyritic volcanic and hypabyssal plutonic rocks and possibly volcaniclastic rocks; post-dates main phase of pluton; may be related to Earl porphyry copper-molybdenum deposits, dated at about 17 m.y. B.P. (Evarts and Ashley, 1984; Evarts and others, 1987).

Tipb

Pebble breccia (middle to upper Miocene ?)--Bodies of pale green, poorly sorted, coarse-grained breccia within "main phase" quartz diorite near Ryan Lake (secs. 17-18, 10N-6E); consists of angular to subrounded clasts of porphyritic dacite and andesite in a fine tuff matrix; thoroughly altered to carbonate and clay minerals; probably post-dates Earl porphyry copper-molybdenum deposit dated at about 17 m.y. B.P. (Evarts and Ashley, 1984).

Tigd

Granodiorite--In the Spirit Lake area, forms "early phase" of the Spirit Lake pluton (lower Miocene); consists of complex of dikes and irregular intrusions of fine-grained porphyritic to seriate pyroxene-quartz diorite, together with numerous screens of thoroughly recrystallized (hornfelsed) country rock; extensive to complete deuteric alteration characteristic; contact with main phase (Tiqd) poorly exposed, but dikes probably part of the main phase locally cut granodiorite (Evarts and Ashley, 1984; Evarts and others, 1987).

Elsewhere in the map area, consists of small, poorly known dikes, sills, and irregular intrusive bodies with fine- to medium-grained phaneritic texture or porphyritic texture with phaneritic groundmass and granodioritic to quartz dioritic mineralogy (that is, plagioclase, pyroxene, quartz, orthoclase, magnetite, and rare hornblende or biotite); age uncertain, but possibly related to or coeval with the Spirit Lake pluton.

Tiqd

Quartz diorite "main phase" of the Spirit Lake pluton (lower Miocene--Dark to light gray to pale pink-gray, medium- to coarse-grained quartz diorite, quartz monzodiorite, granodiorite, and quartz monzodiorite; consists of numerous small, irregular bodies with complex, commonly gradational contacts, typically contains plagioclase phenocrysts as much as 1 cm, prismatic augite and hypersthene phenocrysts, and groundmass of anhedral to granophyric quartz and alkali feldspar; also, minor late magmatic biotite and light-brown hornblende; most lithologies moderately to extensively deuterically altered; coarse-grained hypidiomorphic granular textures predominate in southwest portion of unit and porphyritic textures elsewhere; unit is similar to "granitic phase" (Tiqm) except for common secondary biotite; K-Ar ages range from 20.6 to 22 m.y. (Evarts and Ashley, 1984; Evarts and others, 1987).

Tiqm

Quartz monzonite "granite (latest) phase" of the Spirit Lake pluton (lower Miocene)--Light gray to pale pinkish gray, fine- to medium-grained, generally sparsely porphyritic and miarolitic pyroxene-hornblende-quartz monzonite, granite, and aplite; phenocrysts of plagioclase, clinopyroxene, orthopyroxene, magnetite, and hornblende; groundmass of quartz, alkali feldspar, and minor biotite; pervasive deuteric alteration with primary mafic minerals uralitized or chloritized and plagioclase variably altered to albite, epidote, and sericite; widespread fine-grained black secondary tourmaline; abundant tourmaline in vicinity of Mount Margaret, north of Spirit Lake; not shown on the map are small dikes and irregular bodies of the unit occurring throughout the main phase (Tiqd) of the pluton (Evarts and Ashley, 1984).

Tertiary Igneous Intrusive Rocks, Undivided

Tia

Intrusive andesite dikes, sills, or plugs (lower Oligocene to upper Miocene)--Dark gray to black, porphyritic to aphyric pyroxene basaltic-andesite or basalt with lesser pyroxene andesite and hornblende andesite; typically blocky jointed to platy; often sheared; may contain vesicles but lack flow structures such as flow breccia; commonly resistant, forms cliffs or waterfalls in streams; locally, altered to chlorite and zeolite minerals; age generally unknown but may often be comagmatic with intruded volcanic section; small, poorly known hypabyssal intrusions very numerous in eastern one-third of map area; distinguished with difficulty from lava flows of similar composition unless contacts observed; easiest to observe cutting volcaniclastic or tuff units.

Tidi

Diorite dike, sill, or plug (lower Miocene?)--In the Spirit Lake area, black to medium gray, orange-weathering, medium- to coarse-grained hypidiomorphic to subophitic dikes and sills; composed of plagioclase, augite, orthopyroxene, and magnetite, with or without olivine, ilmenite, minor interstitial quartz, or traces of orthoclase; unaltered to extensively altered to zeolite, smectite, and carbonate; age uncertain, but cuts upper Oligocene to lower Miocene volcanic rocks; may be associated with lower Miocene Spirit Lake pluton (Evarts and Ashley, 1984).

Elsewhere in the map area, such as in Bear Creek west of Elk Rock (sec. 36 10N-2E), the unit consists of poorly known, small dikes, sills, or irregular plugs with fine- to medium-grained phaneritic texture, or porphyritic texture with fine-grained groundmass; contains dioritic to gabbroic mineralogy (plagioclase, pyroxene, and magnetite); age uncertain, but cuts Oligocene to lower Miocene sections and may be related to Spirit Lake plutonism (lower Miocene).

STRUCTURAL FEATURES

Fold Structures

Tertiary strata in the Mount St. Helens quadrangle are folded by two major, variably trending and plunging folds, the Lakeview Peak anticline and the Napavine syncline (Plate 1).

The Lakeview Peak anticline, informally named here, is an asymmetric, doubly plunging structure. The fold or elongate dome is most easily viewed near Lakeview Peak in 7N-3E where a plunge of 20°-30° to the southeast causes the structure to be especially obvious. The fold continues southeast well into the Vancouver 1:100,000-scale quadrangle (Phillips, 1987). To the northwest, the fold either dies out or becomes very subtle in the poorly exposed and thickly bedded lava flows of Tgo_2. In this area southeast of Silver Lake, the plunge is gently northwest. The youngest units folded by the anticline are late Oligocene flows in the Vancouver quadrangle; however, if the structure is the same age as the adjoining Napavine syncline, it could be as young as post-late Miocene.

The Napavine syncline (Roberts, 1958) is a broad, doubly plunging structure traceable from the Napavine area in the Centralia 100,000-scale quadrangle to some 20 km west of Mount St. Helens. Regional stratigraphic data, poorly constrained south of the volcano, suggest that the syncline may continue beneath Mount St. Helens, then trend north-south through Swift Reservoir into the Vancouver quadrangle. Abrupt changes in fold trends near the Cascade crest, from northwest to north-south, are characteristic of folds in southwestern Washington (Walsh and others, in press).

The Napavine syncline controls the outcrop distribution of the upper Miocene Wilkes Formation, and hence it may be as young as post-late Miocene. Roberts (1958) suggests that the Wilkes was deposited in a basin formed by the subsiding syncline. A 15-to-20-m.y. age of folding is suggested by Evarts and others (1987) for rocks in the Spirit Lake 15-minute quadrangle.

Oil and gas exploration wells (McFarland, 1983) and some strike and dip data (Plate 1) suggest that a major northwest-trending anticline is located to the northeast of the Napavine structure. Other strike and dip data and geomorphology suggest that the region lying from Riffe (Davisson) Lake south and west toward the North Fork Toutle River contains several small, variously trending anticlines and synclines. These structures are not well located because of poor exposures and the difficulty of obtaining bedding estimates in thickly bedded volcanic units.

The northeast corner of the map area is characterized by uniform, generally eastward dips of strata complicated locally by the Spirit Lake pluton (Evarts and Ashley, 1984). Regionally, these rocks lie on the west limb of a major north-south trending syncline (Walsh and others, in press; Korosec, 1987).

A major unconformity may exist between upper Eocene-lower Oligocene (?) strata exposed in the Elk Rock 15-minute quadrangle, and the upper Oligocene units mapped in the Spirit Lake quadrangle by Evarts and Ashley (1984). If present, the unconformity separates variably folded flows and hypabyssal intrusives from the east-dipping, structurally simple strata.

Fault Structures

Faults are probably more numerous than depicted on Plate 1. Lack of stratigraphic control in units Tgo_2 and Tgo_1 defeated attempts to map fault structures over the large outcrop area of those units. Wells and Coe (1985, fig. 19) show numerous photolineaments or topographic linears in the map area. These features may be similar to fault structures mapped in the adjoining Astoria 1:100,000-scale quadrangle by Wells (1981).

According to Evarts and others (1987), Mount St. Helens is located at the intersection of a N25°-trending structure and a second feature defined by the east-northeast array of Pleistocene plug domes (units QTig and $Qshd_1$) west of the volcano. The plug domes may be controlled by an active fault.

REFERENCES CITED

Aguirre, Emiliano; Pasini, Giancarlo, 1985, The Pliocene-Pleistocene boundary: Episodes, v. 8, no. 2, p. 116-120.

Armentrout, J. M., 1973, Molluscan paleontology and biostratigraphy of the Lincoln Creek Formation, late Eocene-Oligocene, southwestern Washington: University of Washington Ph.D dissertation, 478 p.

Armentrout, J. M., 1975, Molluscan biostratigraphy of the Lincoln Creek Formation, southwest Washington. In Weaver, D. W.; Hornaday, G. R.; Tipton, Ann, editors, 1975, Paleogene symposium and selected technical papers--Conferences on future energy horizons of the Pacific Coast: American Association of Petroleum Geologists Pacific Section, 50th Annual Meeting, p. 14-48.

Armentrout, J. M., 1981, Correlation and ages of Cenozoic chronostratigraphic units in Oregon and Washington. In Armentrout, J. M., editor, 1981, Pacific Northwest Cenozoic biostratigraphy: Geological Society of America Special Paper 184, p. 137-148.

Armentrout, J. M.; Hull, D. A.; Beaulieu, J. D.; Rau, W. W., 1983, Correlation of Cenozoic stratigraphic units of western Oregon and Washington: Oregon Department of Geology and Mineral Industries Oil and Gas Investigation 7, 90 p., 1 plate.

Armentrout, J. M.; McDougall, K. A.; Jefferis, P. T.; Nesbitt, Elizabeth, 1980, Geologic field trip guide for the Cenozoic stratigraphy and late Eocene paleoecology of southwest Washington. In Oles, K. F.; Johnson, J. G.; Niem, A. R.; Niem, W. A., editors, 1980, Geologic field trips in western Oregon and southwestern Washington: Oregon Department of Geology and Mineral Industries Bulletin 101, p. 79-120.

Armstrong, R. L., 1978, Cenozoic igneous history of the U. S. cordillera from lat 42° to 49° N. In Smith, R. B.; Eaton, G. P., editors, 1978, Cenozoic tectonics and regional geophysics of the western cordillera: Geological Society of America Memoir 152, p. 265-282.

Beeson, M. H.; Perttu, Rauno; Perttu, Janice, 1979, The origin of the Miocene basalts of coastal Oregon and Washington--An alternative hypothesis: Oregon Geology, v. 41, no. 10, p. 159-166.

Beck, M. E.; Burr, C. D., 1979, Paleomagnetism and tectonic significance of the Goble Volcanic Series, southwestern Washington: Geology, v. 7, p. 175-179.

Beikman, H. M.; Rau, W. W.; Wagner, H. C., 1967, The Lincoln Creek Formation, Grays Harbor Basin, southwestern Washington: U. S. Geological Survey Bulletin 1244-I.

Cashman, K. V.; Taggart, J. E., 1983, Petrologic monitoring of 1981 and 1982 eruptive products of Mount St. Helens: Science, v. 221, no. 4618, pp. 1385-1387.

Collins, B. D., 1986, Erosion of sediments released by the 1980 eruption: Volcano News, no. 24, p. 6.

Crandell, D. R.; Miller, R. D., 1974, Quaternary stratigraphy and extent of glaciation in the Mount Rainier region, Washington: U.S. Geological Survey Professional Paper 847, 59 p., 2 plates.

Crandell, D. R.; Mullineaux, D. R., 1973, Pine Creek volcanic assemblage at Mount St. Helens, Washington: U. S. Geological Survey Bulletin 1383-A, 23 p.

Crandell, D. R.; Mullineaux, D. R., 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U. S. Geological Survey Bulletin 1383-C.

Danner, W. R., 1968, Origin of the siderite coprolite-like bodies of the Wilkes Formation, late Miocene, of southwestern Washington: University of British Columbia, Department of Geological Sciences Report No. 9, 6 p.

Dethier, D. P.; Bethel, J. P., 1981, Surficial deposits along the Cowlitz River near Toledo, Lewis County, Washington: U.S. Geological Survey Open-File Report 81-1043, 10 p., 1 plate.

Engels, J. C.; Tabor, R. W.; Miller, F. K.; Pbradovich, J. D. 1976, Summary of K-Ar, Rb-Sr, U-Pb, Pba, and fission-track ages of rocks from Washington State prior to 1975 (exclusive of Columbia River Plateau basalts): U. S. Geological Survey Miscellaneous Field Studies Map MF-710, 2 sheets, scale 1:1,000,000.

Evarts, R. C.; Ashley, R. P., 1984, Preliminary geologic map of the Spirit Lake quadrangle, Washington: U.S. Geological Survey Open-File Report 84-480, 1 sheet, scale 1:48,000.

Evarts, R. C.; Ashley, R. P.; Smith, J. G., 1987, Geology of the Mount St. Helens area--Record of discontinuous volcanic and plutonic activity in the Cascade arc of southwestern Washington: Journal of Geophysical Research, v. 92, no. B10, p. 10,155-10,169

Fairchild, L. H., 1984, Initiation of the North Fork Toutle River lahar by liquefaction of debris avalanche deposits during the May 18, 1980 Mt. St. Helens eruption: EOS (Transactions American Geophysical Union), v. 65, no. 17, p. 329.

Fiske, R. S.; Hopson, C. A.; Waters, A. C., 1963, Geology of Mount Rainier National Park, Washington: U. S. Geological Survey Professional Paper 444, 93 p.

Frizzell, V. A., Jr.; Tabor, R. W.; Booth, D. B.; Ort, K. M.; Wait, R. B., Jr., 1984, Preliminary geologic map of the Snoqualmie Pass 1:100,000 quadrangle, Washington: U. S. Geological Survey Open File Report 84-693, 43 p., 1 plate, scale 1:100,000.

Gilkey, K. E., 1983, Sedimentology of the North Fork and South Fork Toutle River mudflows generated during the 1980 eruption of Mount St. Helens: University of California at Santa Barbara Master of Arts thesis, 254 p., 2 plates.

Glicken, Harry, 1986, Mt. St. Helens rockslide-debris avalanche: Volcano News, no. 24, p. 4.

Greeley, Ronald; Hyde, J. H., 1972, Lava tubes of the Cave Basalt, Mount St. Helens, Washington: Geological Society of America Bulletin v. 83, no. 8, p. 2397-2418.

Hagen, R. L., 1987, The geology and petrology of the Northcraft Formation: University of Oregon Master of Science thesis, 252 p., 1 plate.

Hammond, P. E., 1980, Reconnaissance geologic map and cross sections of southern Washington Cascade Range, latitude 45 degrees 30 minutes - 47 degrees 15 minutes N., longitude 120 degrees 45 minutes - 122 degrees 22.5 minutes W.: Portland State University Department of Earth Sciences, 31 p., 2 sheets.

Hammond, P. E., 1985a, Preliminary geologic map of the Cougar 15-minute quadrangle, Washington: unpublished map, 1 sheet, scale 1:62,500.

Hammond, P. E., 1985b, Preliminary geologic map of the Elk Rock 15-minute map, Washington: unpublished map, 1 sheet, scale 1:62,500.

Hammond, P. E., 1985c, Preliminary geologic map of the Pigeon Springs 15-minute quadrangle, Washington: unpublished map, 1 sheet, scale 1:62,500.

Hammond, P. E., 1985d, Preliminary geologic map of the Toutle 15-minute quadrangle, Washington: unpublished map, 1 sheet, scale 1:62,500.

Hammond, P. E.; Korosec, M. A., 1983, Geochemical analyses, age dates, and flow-volume estimates for Quaternary volcanic rocks, southern Cascade Mountains, Washington: Washington Division of Geology and Earth Resources Open-File Report 83-13, 36 p., 1 plate.

Henriksen, D. A., 1956, Eocene stratigraphy of the lower Cowlitz River-eastern Willapa Hills area, southwestern Washington: Washington Division of Mines and Geology Bulletin 43, 122 p., 2 plates.

Hopson, C. A., 1980, Geology of the Mount St. Helens area, Washington: unpublished report, 2 sheets, scale 1:32,250.

Hopson, C. A.; Melson, W. G., 1982, Stratigraphy of Mount St. Helens crater walls: Eos (Transactions American Geophysical Union), v. 63, no. 45, p. 1144.

Hyde, J. H., 1975, Upper Pleistocene pyroclastic-flow deposits and lahars south of Mount St. Helens volcano, Washington: U. S. Geological Survey Bulletin 1383-B, 20 p.

Janda, R. J.; Scott, K. M.; Nolan, K. M.; Martinson, H. A., 1981, Lahar movement, effects, and deposits. In Lipman, P. W.; Mullineaux, D. R., editors, the 1980 eruptions of Mount St. Helens, Washington: U. S. Geological Survey Professional Paper 1250, p. 461-478.

Korosec, M. A., compiler, 1987, Geologic map of the Mount Adams quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-5, 39 p., 1 pl., scale 1:100,000.

Kuntz, M. A.; Powley, P. D.; MacLeod, N. S.; Reynolds, R. L.; McBroome, L. A.; Kaplan, A. M.; Lidke, D. A., 1981, Petrography and particle-size distribution of pyroclastic-flow, ash-cloud, and surge deposits. In The 1980 Eruptions of Mount St. Helens, Washington: U. S. Geological Survey Professional Paper 1250, p. 525-539.

Lipman, P. W.; Mullineaux, D. R., editors, 1981, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p., 1 plate.

Livingston, V. E., Jr., 1966, Geology and mineral resources of the Kelso-Cathlamet area, Cowlitz and Wahkiakum Counties, Washington: Washington Division of Mines and Geology Bulletin 54, 110 p., 2 plates.

Logan, R. L., 1983, Temporal trends in the geochemistry and petrology of the Mount St. Helens pyroclastic flow deposits: Western Washington University Master of Science thesis, 109 p.

Long, P. E.; Duncan, R. A., 1983, 40Ar/39Ar ages of Columbia River Basalt from deep boreholes in southcentral Washington: EOS, v. 64, no. 9, p. 90.

Lux, D. R., 1981, Geochronology, geochemistry and petrogenesis of basaltic rocks from the western Cascades, Oregon: Ohio State University Ph.D dissertation, 171 p.

Major, J. J.; Voight, Barry, 1986, Sedimentology and clast orientations of the 18 May 1980 southwest-flank lahars Mount St. Helens, Washington: Journal of Sedimentary Petrology, v. 56, no. 5, p. 691-705.

May, D. J., 1980, The paleoecology and depositional environment of the late Eocene-early Oligocene Toutle Formation, southwestern Washington: University of Washington Master of Science thesis, 110 p.

McFarland, C. R., 1983, Oil and gas exploration in Washington 1900-1982: Washington Division of Geology and Earth Resources Information Circular 75, 119 p.

Montanari, Alessandro; Drake, Robert; Bice, D. M.; Alvarez, Walter; Curtis, G. H.; Turrin, B. D.; DePaolo, D. J., 1985, Radiometric time scale for the upper Eocene and Oligocene based on K/Ar and Rb/Sr dating of volcanic biotites from the pelagic sequence of Gubbio, Italy: Geology, v. 13, no. 9, p. 596-599.

Moore, J. G.; Lipman, P. W.; Swanson, D. A.; Alpha, T. R., 1981, Growth of lava domes in the crater, June 1980-January 1981. In Lipman, P. W.; Mullineaux, D. R., editors, The 1980 eruptions of Mount St. Helens, Washington: U. S. Geological Survey Professional Paper 1250, p. 541-547.

Mullineaux and Crandell, 1981, The eruptive history of Mount St. Helens. In Lipman, P. W.; Mullineaux, D. R., editors, 1981, The 1980 eruptions of Mount St. Helens, Washington: U. S. Geological Survey Professional Paper 1250, p. 3-15.

Mullineaux, D. R., 1986, Summary of pre-1980 tephra-fall deposits erupted from Mount St. Helens, Washington State, USA: Bulletin of Volcanology, v. 48, no. 1, p. 17-26.

Mundorff, M. J., 1964, Geology and groundwater conditions of Clark County, Washington, with a description of a major alluvial aquifer along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 268 p., 1 plate.

Myers, D. A., 1970, Availability of groundwater in western Cowlitz County, Washington: Washington Department of Ecology Water-Supply Bulletin 35, 63 p., 2 plates.

Nesbitt, E. A., 1982, Paleoecology and biostratigraphy of Eocene marine assemblages from western North America: University of California at Berkeley Doctor of Philosophy thesis, 215 p.

Niem, A. R.; Niem, W. A., 1985, Geologic map of the Astoria Basin, Clatsop and northernmost Tillamook Counties, northwest Oregon: Oregon Department of Geology and Mineral Industries Oil and Gas Investigations 14, 2 sheets, scale 1:100,000, with 8 p. text.

Pacific Power and Light Company, 1958, Board of consultants' meeting, August 5-6, 1958, Swift hydroelectric project, Lewis River, Washington: Pacific Power and Light Company, Portland, p. IV-1.

Peterson, D. S., 1986, Summary of Mount St. Helens activity, 1980-1986: Volcano News, no. 24, p. 2.

Pierson, T. C., 1985, Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington: Geological Society of America Bulletin, v. 96, P. 1056-1069.

Phillips, W. M., compiler, 1987, Geologic map of the Vancouver quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open-File Report 87-10, 32 p., 1 pl., scale 1:100,000.

Phillips, W. M.; Kaler, K. L., 1985, Chemical variation in upper Eocene volcanic rocks, southwestern Washington [abstract]: Geological Society of America Abstracts with Programs, v. 17, no. 6, p. 400.

Phillips, W. M.; Korosec, M. A.; Schasse, H. W.; Anderson, J. L.; Hagen, R. A., 1986, K-Ar ages of volcanic rocks in southwest Washington: Isochron/West, v. 47, p. 18-24.

Polivka, D. R., 1984, Quaternary volcanology of the West Crater-Soda Peaks area, southern Washington Cascade range: Portland State University master of science thesis, 78 p., 1 plate, scale 1:24,000.

Prothero, D. R.; Armentrout, J. M., 1985, Magnetostratigraphic correlation of the Lincoln Creek Formation, Washington--Implications for the age of the Eocene/Oligocene boundary: Geology, v. 13, no. 3, p. 208-211.

Roberts, A. E., 1958, Geology and coal resources of the Toledo-Castle Rock district, Cowlitz and Lewis Counties, Washington: U.S. Geological Survey Bulletin 1062, 71 p., 6 plates.

Rowley, P. D.; Kuntz, M. A.; MacLeod, N. S., 1981, Pyroclastic-flow deposits. In Lipman, P. W. and Mullineaux, D. R., editors, 1981, The 1980 eruptions of Mount St. Helens: U. S. Geological Survey Professional Paper 1250, p. 489-512.

Salvador, Amos, 1985, Chronostratigraphic and geochronometric scales in COSUNA stratigraphic correlation charts of the United States: American Association of Petroleum Geologists Bulletin, v. 69, no. 2, p. 181-189.

Schasse, H. W., compiler, 1987, Geologic map of the Centralia quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87-11, 27 p., 1 pl., scale 1:100,000.

Scott, K. M., 1986, Lahars and lahar-runout flows in the Toutle-Cowlitz River system, Mount St. Helens, Washington--Magnitude and frequency: U.. S. Geological Survey Open-File Report 86-500, 95 p.

Snavely, P. D., Jr.; Rau, W. W.; Hoover, Linn, Jr.; Roberts, A. E., 1951, McIntosh Formation, Centralia-Chehalis coal district, Washington: American Association of Petroleum Geologists Bulletin, v. 35, no. 5, p. 1052-1061.

Snavely, P. D., Jr.; Brown, R. D., Jr.; Roberts, A. E.; Rau, W. W., 1958, Geology and coal resources of the Centralia-Chehalis district, Washington, with a section on Microscopical character of Centralia-Chehalis coal, by M. M. Schopf: U.S. Geological Survey Bulletin 1053, 159 p., 6 plates.

Spencer, P. K.; Tuttle, F. H., 1980, Coprolites or pseudo-coprolites--New evidence concerning the origin of Washington coprolites: Geological Society of America Abstracts with Programs, v. 12, no. 3, p. 153.

Swanson, D. A., 1986, Predicting dome growth at Mt. St. Helens using non-seismic techniques: Volcano News, no. 24, p. 3-4.

Tabor, R. W.; Waitt, R. B., Jr.; Frizzell, V. A., Jr.; Swanson, D. A.; Byerly, G. R.; Bentley, R. D., 1982, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington: U. S. Geological Survey Miscellaneous Investigation Series Map I-1311, 1 sheet, scale 1:100,00, 20 p.

Tolan, T. L.; Beeson, M. H., 1984, Intracanyon flows of the Columbia River Basalt Group in the lower Columbia River Gorge and their relationship to the Troutdale Formation: Geological Society of America Bulletin, v. 95, no. 4, p. 463-477.

Travis, R. B., 1955, Classification of rocks: Colorado School of Mines Quarterly, v. 50, no. 1, p. 98 p.

Trimble, D. E., 1963, Geology of Portland, Oregon and adjacent areas: U. S. Geological Survey Bulletin 1119, 119 p., 1 plate.

Tschernich, R. W., 1986, Zeolite collecting at Goble, Oregon--revisited: Micro Probe [Northwest Micro Mineral Study Group Newsletter], v. VI, no. 3, 6 p.

Van Atta, R. O.; Kelty, K. B., 1985, Scappoose Formation, Columbia County, Oregon--New evidence of age and relation to Columbia River Basalt Group: American Association of Petroleum Geologists Bulletin, v. 69, no. 5, p. 688-698.

Vance, J. A.; Clayton, g. A.; Mattinson, J. M.; Naeser, C. W, in press, Early and middle Cenozoic stratigraphy of the Mount Rainier-Tieton River area, southern Washington Cascades. In Schuster, J. E., editor, Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin.

Verhoogen, Jean, 1937, Mount St. Helens--A recent Cascade volcano: University of California Publications in Geological Sciences, v. 24, no. 9, p. 263-302.

Voight, Barry; Glicken, Harry; Janda, R. J.; Douglass, P. M., 1981, Catastrophic rockslide avalanche of May 18. In Lipman, P. W.; Mullineaux, D. R., editors, 1981, The 1980 eruptions of Mount St. Helens: U. S. Geological Survey Professional Paper 1250, p. 347-377.

Waitt, R. B., Jr., 1985, Case for periodic, colossal jokulhlaups from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin v. 96, no. 10, p. 1271-1286.

Walsh, T. J.; Korosec, M. A.; Phillips, W. M.; Logan, R. L.; Schasse, H. W., in press, Geologic map of Washington--southwest quadrant: Washington Division of Geology and Earth Resources GM-34, scale 1:250,000.

Walsh, T. J., 1987, Geologic map of the Astoria and Ilwaco quadrangles, Washington: Washington Division of Geology and Earth Resources Open File Report 87-2, 1 sheet, scale 1:100,000.

Walsh, T. J., compiler, 1986, Geologic map of the west half of the Toppenish quadrangle, Washington: Washington Division of Geology and Earth Reports Open File Report 86-3, 7 p., l pl., scale 1:100,000.

Walsh, T. J., compiler, 1986, Geologic map of the west half of the Yakima quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 86-4, 9 p., l pl., scale 1:100,000.

Warren, W. C.; Grivetii, R. M.; Norbisrath, Hans, 1945, Geology of northwestern Oregon, west of Willamette River and north of latitude 45°15': U. S. Geological Survey Oil and Gas Investigations Preliminary Map [OM 42], scale 1:145,728.

Watkins, N. D.; Baksi, A. K., 1974, Magnetostratigraphy and oroclinal folding of the Columbia River, Steens and Owyhee Basalts in Oregon, Washington and Idaho: American Journal of Science, v. 274, p. 148-189.

Weaver, C. E., 1912, A preliminary report on the Tertiary paleontology of western Washington: Washington Geological Survey Bulletin 15, 80 p.

Weaver, C. E., 1937, Tertiary stratigraphy of western Washington and northwestern Oregon: University of Washington Publications in Geology, v. 4, 266 p.

Weaver, C. E., 1944, Correlation of the marine Cenozoic formations of western North America: Geological Society of America Bulletin v. 55, no. 5.

Weigle, J. M.; Foxworthy, B. L., 1962, Geology and ground-water resources of west-central Lewis County, Washington: Washington Division of Water Resources Water Supply Bulletin 17, 248 p., 5 plates.

Wells, R. E., 1981, Geologic map of the eastern Willapa Hills, Cowlitz, Lewis, Pacific, and Wahkiakum Counties, Washington: U.S. Geological Survey Open-File Report 81-674, 1 sheet, scale 1:62,500.

Wells, R. E.; Coe, R. S., 1985, Paleomagnetism and geology of Eocene volcanic rocks of southwest Washington, implications for mechanisms of tectonic rotation: Journal of Geophysical Research, v. 90, no. B2, p. 1925-1947.

Wells, R. E.; Niem, A. R., 1987, Geology of the Columbia River Basalt Group in the Astoria Basin, Oregon and Washington [abstract]: Geological Abstracts with Programs v. 19, no. 6, p. 462-463.

Wells, R. E.; Simpson, R. W.; Kelley, M. M.; Beeson, H. M.; Bentley, R. D., 1983, Columbia River Basalt Group stratigraphy and rotational in southwest Washington: EOS, v. 64, no. 45, p. 687.

Wilkinson, W. D.; Lowry, W. D.; Baldwin, E. M., 1946, Geology of the St. Helens quadrangle, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 31, 39 p., 1 plate.

Wolfe, E. W.; McKee, E. H., 1968, Geology of the Grays River quadrangle, Wahkiakum and Pacific Counties, Washington: Washington Division of Mines and Geology Geologic Map GM-4, 6 p., 1 plate.

Wolfe, E. W.; McKee, E. H., 1972, Sedimentary and igneous rocks of the Grays River quadrangle, Washington: U.S. Geological Survey Bulletin 1335, 70 p.

Wolfe, J. A., 1961, Age of the Keechelus andesitic series of the Cascade Range, Washington. In Short papers in the geologic and hydrologic sciences; Geological Survey Research 1961: U. S. Geological Survey Professional Paper 424-C, article 232, p. 228-230.

Wolfe, J. A., 1968, Paleogene biostratigraphy of nonmarine rocks in King County, Washington: U.S. Geological Survey Professional Paper 571, 33 p.

Wolfe, J. A., 1981, Chronologic framework for Cenozoic megafossil floras of northwestern North America and its relation to marine geochronology. In Armentrout, J. M., editor, Pacific Northwest Cenozoic Biostratigraphy: Geological Society of America Special Paper 184, p. 39-47.

Zanettin, Bruno, 1984, Proposed new chemical classification of volcanic rocks: Episodes, v. 7, no. 4, p. 19-20.

*Note: Text reformatted by sd on 4/90

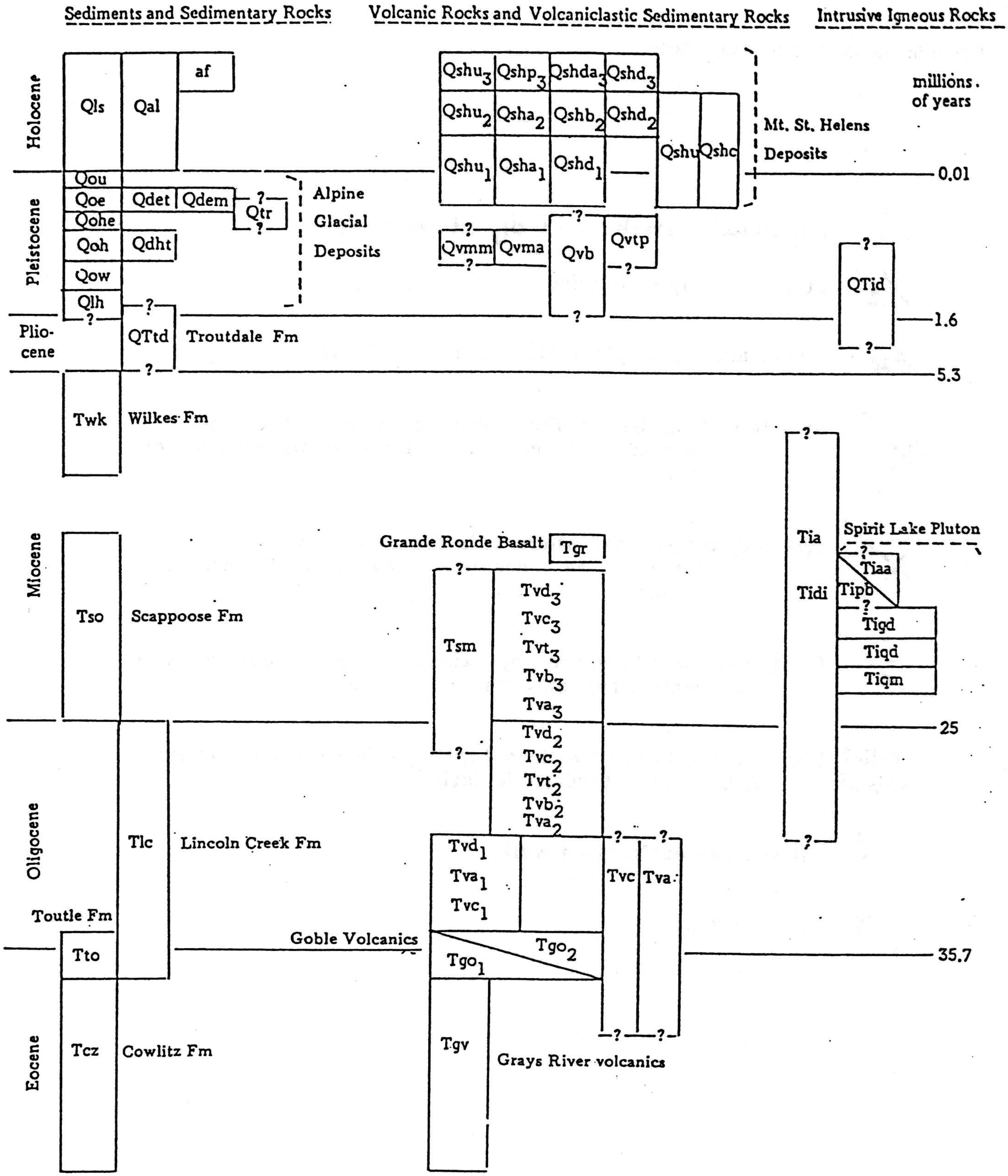


Figure 5: Stratigraphic Correlation Chart

Figure 6: Explanation of map symbols

approximate strike and dip of bedding

12 strike and dip of bedding

20 strike and dip of platy jointing in lava flows

anticline, long-dashed where axis approximately located, dotted where concealed; arrow shows direction of plunge

syncline, long-dashed where axis approximately located, dotted where concealed; arrow shows direction of plunge

fault, long-dashed where approximately located, dotted where concealed; ball on downthrown side

K-Ar2
13.5+/-1.1 K-Ar sample locality with isotopic age determination in my B.P. +/- one standard deviation

Oil and gas exploration well

Volcanic vent