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

EARTHQUAKE HYPOCENTERS IN WASHINGTON AND OREGON — 1982-1986

by
ANTHONY QAMAR, RUTH LUDWIN, ROBERT S. CROSSON,
and STEPHEN D. MALONE

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
INFORMATION CIRCULAR 84

1987

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

This report is available from:

Publications
Washington Department of Natural Resources
Division of Geology and Earth Resources
Mail Stop PY-12
Olympia, WA 98504

The printing of this report was supported by U.S. Geological Survey Earthquake Hazards Reduction Program Agreement No. 14-08-0001-A0509.

This publication is free, but please add $1.00 to each order for postage and handling. Make checks payable to the Department of Natural Resources.

Printed in the United States of America.

CONTENTS

APPENDICES

ILLUSTRATIONS

TABLES

EARTHQUAKE HYPOCENTERS IN WASHINGTON AND NORTHERN OREGON—1982-1986

by

Anthony Qamar, Ruth Ludwin, Robert S. Crosson, and Stephen D. Malone*

INTRODUCTION

The Geophysics Program at the University of Washington operates a continuously recording, telemetered seismograph network in Washington and northern Oregon (Figs. 1 and 2). This report is the eleventh in a series designed to provide a chronological compilation of earthquake locations. Beginning with the report describing earthquakes in 1980 (Qamar and others, 1986), these reports cover the whole state of Washington and northern Oregon; previous reports treated earthquakes in western Washington only. Appendices I and II list hypocentral locations for 3,126 earthquakes and blasts having coda-length magnitudes equal to or exceeding M_c 1.8 that occurred from January 1982 through December 1986; 2,482 of these were earthquakes. "Hypocenter" refers to the subsurface point where the earthquake occurs, while "epicenter" indicates the point on the Earth's surface directly above the hypocenter. The distribution of earthquake epicenters in Washington and northern Oregon for 1982 through 1986 is shown in Figures 3 and 4. Epicenters of smaller earthquakes, with magnitudes $1.0 \leq M_c < 1.8$, are shown in Figure 5 and those for blasts in Figure 6. Figure 7 shows epicenters of earthquakes that were reported as felt, and Figure 8 is a detailed map showing earthquake epicenters near Seattle.

The number of seismic events located each year depends on four basic factors: the number of stations operating, the locations of earthquakes relative to recording stations, earthquake magnitudes, and the number of earthquakes in the area monitored. Ignoring the inherent variability of the data may lead to incorrect interpretations. When used carefully, the data in this report may enhance evaluations of seismic hazard potential, as well as contribute to basic studies in seismology, structure of the Earth, and tectonics.

Compilations of earthquakes covering western Washington only have been published by the Washington Department of Natural Resources for the years 1970-79 (Crosson, 1974, 1975; Crosson and Millard, 1975; Crosson and Noson, 1978a, 1978b, 1979; Noson and Crosson, 1980; Noson and others, 1985). Data for eastern Washington earthquakes from 1969-79 are covered in annual technical reports to the U.S. Department of Energy and are available at the University of Washington library (Malone, 1975, 1976, 1977, 1978, 1979). Eastern Washington earthquakes that occurred during the period 1969-74 are summarized in an appendix of the 1979 annual report (Malone, 1979). A list of large historical earthquakes in Washington from 1840 to 1965 was compiled by Rasmussen (1967). Qamar and others (1986, 1987) describe earthquakes in Washington and northern Oregon in 1980 and 1981.

The Seismograph Network

The seismograph network in Washington and northern Oregon operated by the University of Washington from 1982 through 1986 consisted of more than 100 short-period, vertical-component, telemetered seismograph stations, a three-component (both short and long period) World Wide Standardized Seismograph Network (WWSSN) station at Longmire (LON), and two horizontal-component Wood-Anderson seismographs at Seattle (SEA). Stations operating at the end of 1986 are shown in Figures 1 and 2. Locations of all stations operating during the period 1982-86 are given in Table 1. Each station, except LON and SEA, consisted of a single vertical seismometer, an amplifier, a voltage-controlled oscillator and, at some stations, radio-telemetry equipment to

* The authors are members of the Geophysics program, University of Washington.

Table 1. Stations operating from 1982 through 1986. (See Figures 1 and 2)

Station designator	Dates*	Latitude(N) (dg mn sec)	Longitude(W) (dg mn sec)	Elevation (km)	Station name
APW	23456	46 39 06.0	122 38 51.0	0.457	Alpha Peak
ASR	23456	46 09 02.4	121 35 33.6	1.280	Mount Adams - Stagman Ridge
AUG	23456	45 44 10.0	121 40 50.0	0.865	Augspurger Mt.
BDG	234__	46 13 59.1	119 19 03.9	0.430	Badger Mt.
BHW	__456	47 50 12.6	122 01 55.8	0.198	Bald Hill
BLN	23456	48 00 26.5	122 58 18.6	0.585	Blyn Mt.
BLS	___5_	48 34 21.0	121 40 00.0	1.341	Mount Baker, Lake Shannon
BOW	23456	46 28 30.0	123 13 41.0	0.870	Boistfort Mt.
BRV	_3456	46 29 07.2	119 59 29.4	0.925	Black Rock Valley
BVW	____6	46 48 37.8	119 52 54.1	0.707	Beverly
CBW	23456	47 48 25.5	120 01 57.6	1.160	Chelan Butte
CDF	23456	46 06 58.2	122 02 51.0	0.780	Cedar Flats
CHO	____6	45 35 27.0	118 34 45.0	1.076	Cabbage Hill, OR
CMM	23456	46 26 07.0	122 30 21.0	0.620	Crazy Man Mt.
CMW	____6	48 25 25.3	122 07 08.4	1.190	Cultus Mtns.
COW	23456	46 29 27.6	122 00 43.6	0.305	Cowlitz River
CPW	23456	46 58 25.8	123 08 10.8	0.792	Capitol Peak
CRF	23456	46 49 30.6	119 23 18.0	0.260	Corfu
DAV	23___	47 38 18.0	118 13 33.6	0.758	Davenport
DIG	___5_	46 12 45.0	122 11 09.0	1.800	Mount St. Helens crater 3-comp
DIO	____6	46 12 03.0	122 11 21.0	2.102	Mount St. Helens, dome
DPW	____6	47 52 14.3	118 12 10.2	0.892	Davenport
DY2	___56	47 59 06.9	119 46 13.0	0.884	Dyer Hill
DYH	2345_	47 57 37.8	119 46 09.6	0.820	Dyer Hill
EDM	23456	46 11 50.4	122 09 00.0	1.609	East dome, Mount St. Helens
ELK	23456	46 18 20.0	122 20 27.0	1.270	Elk Rock
ELL	23456	46 54 35.0	120 34 06.0	0.805	Ellensburg
EPH	23456	47 21 12.8	119 35 46.2	0.628	Ephrata
EST	23456	47 14 16.8	121 12 21.8	0.756	Easton
ETP	23456	46 27 53.4	119 03 32.4	0.250	Eltopia
ETT	23456	47 39 18.0	120 17 36.0	0.439	Entiat
ETW	____6	47 36 16.2	120 19 51.6	1.475	Entiat
EUK	2____	46 23 45.0	118 33 43.5	0.350	Eureka
FL2	__456	46 11 47.0	122 21 01.0	1.378	Flat Top
FLT	234__	46 11 21.3	122 21 22.5	1.387	Flat Top
FMW	23456	46 55 54.0	121 40 19.2	1.890	Mount Fremont
FOR	___56	45 58 14.0	121 45 30.0	1.152	Forlorn Lakes
FOX	___56	48 19 50.0	119 42 29.0	0.896	Fox Mountain
FPW	2345_	47 58 09.0	120 12 46.5	0.352	Fields Point
GBL	23456	46 35 51.6	119 27 35.4	0.330	Gable Mountain
GHW	23456	47 02 30.0	122 16 21.0	0.268	Garrison Hill
GL2	__456	45 57 35.0	120 49 22.5	1.000	Goldendale
GLD	23___	45 50 13.0	120 48 46.0	0.610	Goldendale
GLK	23456	46 33 50.2	121 36 30.7	1.320	Glacier Lake
GMW	23456	47 32 52.5	122 47 10.8	0.506	Gold Mt.
GRO	____6	45 21 04.5	123 39 43.0	0.945	Grindstone Mt., OR
GSM	23456	47 12 11.4	121 47 40.2	1.305	Grass Mt.
GUL	____6	45 55 27.0	121 35 44.0	1.189	Guler Mt.
HDW	23456	47 38 54.6	123 03 15.2	1.006	Hoodsport
HHW	__456	46 10 59.0	119 22 59.0	0.415	Horse Heaven Hills

Table 1. (Continued)

Station designator	Dates*	Latitude(N) (dg mn sec)	Longitude(W) (dg mn sec)	Elevation (km)	Station name
HOE	_3___	46 15 24.0	122 12 00.0	1.115	Elliot Sta., Mount St. Helens
HSR	___56	46 10 22.2	122 10 58.2	1.774	South Ridge, Mount St. Helens
HTW	23456	47 48 12.5	121 46 08.6	0.829	Haystack Lookout
JBO	23456	45 27 41.7	119 50 13.3	0.645	Jordan Butte, OR
JCW	23456	48 11 36.6	121 55 46.2	0.616	Jim Creek
JUN	23456	46 08 48.0	122 09 10.8	1.049	June Lake
KIT	__4__	46 37 13.0	120 21 25.0	1.000	Kittitas
KMO	23456	45 38 07.8	123 29 22.2	0.975	Kings Mt., OR
KOS	23456	46 27 40.8	122 11 25.8	0.828	Kosmos
LMW	23456	46 40 04.8	122 17 28.8	1.195	Ladd Mt.
LNO	____6	45 52 15.8	118 17 06.0	0.768	Lincton Mt., OR
LON	23456	46 45 00.0	121 48 36.0	0.853	Longmire (WWSSN and DWWSSN)
LVP	23456	46 04 06.0	122 24 30.0	1.170	Lakeview Peak
LYW	234__	48 32 07.2	122 06 06.0	0.107	Lyman
MAS	2____	46 08 41.0	121 35 30.7	1.370	Mount Adams South
MBW	23456	48 47 02.4	121 53 58.8	1.676	Mount Baker
MCW	23456	48 40 46.8	122 49 56.4	0.693	Mount Constitution
MDW	23456	46 36 48.0	119 45 39.0	0.330	Midway
MEW	___56	47 12 07.0	122 38 45.0	0.097	McNeil Island
MFW	23456	45 54 10.8	118 24 21.0	0.395	Milton-Freewater, OR
MOW	234__	47 50 46.9	122 02 52.9	0.180	Monroe
MOX	__456	46 34 38.0	120 17 35.0	0.540	Moxie City
MTM	23456	46 01 31.8	122 12 42.0	1.121	Mount Mitchell
NAC	23456	46 44 03.8	120 49 33.2	0.738	Naches
NEL	___56	48 04 41.8	120 20 17.7	1.490	Nelson Butte
NEW	23456	48 15 50.0	117 07 13.0	1.000	Newport Observatory (USGS)
NLO	23456	46 05 18.0	123 27 00.0	0.900	Nicolai Mt., OR
NSP	___5_	46 12 04.0	122 11 13.0	2.062	New Spider, Mount St. Helens
OBC	23456	48 02 07.1	124 04 39.0	0.938	Olympics - Bonidu Creek
OBH	23456	47 19 34.5	123 51 57.0	0.383	Olympics - Burnt Hill
OCP	23___	48 17 58.5	124 37 37.5	0.487	Cheela Peak
OCT	234__	47 44 57.0	124 10 25.8	0.743	Mount Octopus
ODS	23456	47 18 24.0	118 44 42.0	0.523	Odessa
OEM	234__	48 07 46.5	124 18 13.5	0.712	Tyee Ridge
OFK	23456	47 57 00.0	124 21 28.1	0.134	Olympics - Forks
OHW	23456	48 19 24.0	122 31 54.6	0.054	Oak Harbor
OLQ	23456	47 30 58.1	123 48 31.5	0.121	Olympics - Lake Quinault
OMK	2345_	48 28 49.2	119 33 39.0	0.421	Omak
ONR	23456	46 52 37.5	123 46 16.5	0.257	Olympics - North River
OOW	__456	47 44 12.0	124 11 22.0	0.743	Octopus West
OSD	__456	47 49 15.0	123 42 06.0	2.010	Olympics - Snow Dome
OSP	_3456	48 17 05.5	124 35 23.3	-	Olympics - Sooes Peak
OTH	23456	46 44 20.4	119 12 59.4	0.260	Othello
OTR	__456	48 05 00.0	124 20 39.0	0.712	Olympics - Tyee Ridge
PAT	23456	45 52 50.1	119 45 40.1	0.300	Paterson
PEN	23456	45 36 43.2	118 45 46.5	0.430	Pendleton, OR
PGO	23456	45 28 00.0	122 27 10.0	0.237	Gresham, OR
PGW	___56	47 49 18.8	122 35 57.7	0.122	Port Gamble
PHO	23456	45 37 07.8	122 49 50.2	0.299	Portland Hills, OR
PLN	23456	47 47 04.8	120 37 58.8	0.700	Plain

Table 1. (Continued)

Station designator	Dates*	Latitude(N) (dg mn sec)	Longitude(W) (dg mn sec)	Elevation (km)	Station name
PRO	23456	46 12 45.6	119 41 09.0	0.552	Prosser
RED	2345_	45 56 13.2	121 49 10.8	1.510	Red Mt.
RMW	23456	47 27 34.9	121 48 19.2	1.024	Rattlesnake Mt. (West)
ROA	2____	46 12 15.1	122 11 19.1	1.790	Roach Rock
RPK	__456	45 45 42.0	120 13 50.0	0.330	Roosevelt Peak
RPW	23_56	48 26 54.0	121 30 49.0	0.850	Rockport
RSW	23456	46 23 28.2	119 35 19.2	1.037	Rattlesnake Mt. (East)
RVC	_3456	46 56 34.5	121 58 17.3	1.000	Mount Rainier - Voight Creek
RVW	23456	46 08 58.2	122 44 37.2	0.460	Rose Valley
SAW	23456	47 42 06.0	119 24 03.6	0.690	St. Andrews
SBL	234__	46 20 25.2	122 02 19.8	1.665	Strawberry Lookout
SBO	_34__	45 01 42.0	120 03 33.5	1.390	Squaw Butte,OR
SEA	23456	47 39 18.0	122 18 30.0	0.030	Seattle (Wood Anderson)
SHW	23456	46 11 33.0	122 14 12.0	1.423	Mount St. Helens
SLH	__4__	46 37 55.0	120 32 28.0	1.000	Selah
SMW	23456	47 19 10.2	123 20 30.0	0.840	South Mt.
SOS	23456	46 14 38.5	122 08 12.0	1.270	Source of Smith Creek
SPW	23456	47 33 13.3	122 14 45.1	0.008	Seward Park, Seattle
STD	23456	46 14 16.0	122 13 21.9	1.268	Studebaker Ridge
STW	23456	48 09 02.9	123 40 13.1	0.308	Striped Peak
SUG	_345_	46 12 52.2	122 10 29.4	1.859	Sugar Bowl
SYR	23456	46 51 46.8	119 37 04.2	0.267	Smyrna
TBM	23456	47 10 10.1	120 35 54.0	1.064	Table Mt.
TDH	23456	45 17 23.4	121 47 25.2	1.541	Tom,Dick,Harry Mt., OR
TDL	_3456	46 21 03.0	122 12 57.0	1.400	Tradedollar Lake
TWW	____6	47 08 17.2	120 52 04.5	1.046	Teanaway
VBE	23456	45 03 37.2	121 35 12.6	1.544	Beaver Butte, OR
VBP	234__	44 39 37.8	121 41 20.4	1.876	Bald Peter, OR
VCP	23___	44 40 16.2	122 05 22.2	1.161	Cooper's Ridge, OR
VFP	23456	45 19 05.0	121 27 54.3	1.716	Flag Point, OR
VG2	___56	45 09 20.0	122 16 15.0	0.823	Goat Mt., OR
VGB	23456	45 30 56.4	120 46 39.0	0.729	Gordon Butte, OR
VGT	2345_	45 08 59.4	122 15 55.2	0.993	Goat Mt., OR
VHE	23___	45 19 45.0	121 39 57.0	1.646	Mount Hood East, OR
VHH	2____	45 15 09.0	123 18 34.2	0.553	High Heaven, OR
VHO	2345_	45 13 09.0	123 43 31.2	0.951	Mount Hebo, OR
VIP	23456	44 30 29.4	120 37 07.8	1.731	Ingram Pt., OR
VJY	23___	44 54 07.8	120 58 27.0	0.951	Jersey, OR
VLL	23456	45 27 48.0	121 40 45.0	1.195	Laurance Lk., OR
VLM	23456	45 32 18.6	122 02 21.0	1.150	Little Larch, OR
VLO	234__	44 52 46.2	122 23 34.8	1.351	Lookout Mt., OR
VMN	23___	45 11 12.6	121 03 10.8	0.555	Maupin, OR
VNM	2____	46 05 18.0	123 27 00.0	0.900	Nicolai Mt., OR
VSM	23___	44 57 37.2	123 07 39.0	0.290	Salem, OR
VTD	2____	45 32 42.0	121 18 48.0	0.365	The Dalles, OR
VTG	23456	46 57 28.8	119 59 14.4	0.208	Vantage
VTH	23456	45 10 52.2	120 33 40.8	0.773	The Trough, OR
VWC	2____	45 14 29.0	121 48 47.0	1.457	Wolf Camp, OR
WA2	23456	46 45 24.2	119 33 45.5	0.230	Wahluke Slope
WAT	23456	47 41 55.0	119 57 15.0	0.900	Waterville

Table 1. (Continued)

Station designator	Dates*	Latitude(N) (dg mn sec)	Longitude(W) (dg mn sec)	Elevation (km)	Station name
WBW	23456	48 01 04.2	119 08 13.8	0.825	Wilson Butte
WEN	23456	47 31 46.2	120 11 39.0	1.061	Wenatchee
WGE	____6	46 03 09.0	118 48 08.0	0.262	Wallula Gap East
WGW	23456	46 02 40.8	118 55 57.6	0.158	Wallula Gap
WIW	23456	46 25 48.8	119 17 13.4	0.130	Wooded Island
WNS	__456	46 42 37.0	120 34 30.0	1.000	Wenas
WPO	____6	45 34 24.0	122 47 22.4	0.334	West Portland, OR
WPW	23456	46 41 53.4	121 32 48.0	1.250	White Pass
WRD	23456	46 58 11.4	119 08 36.0	0.378	Warden
WTP	23___	48 28 16.2	120 14 52.2	0.855	Winthrop
YAK	23456	46 31 15.8	120 31 45.2	0.619	Yakima
YEL	23456	46 12 35.0	122 11 16.0	1.750	Yellow Rock, Mount St. Helens

* Digits in Dates column indicate individual years when the station operated from 1982 through 1986. For example, the entries "SBO _34__" show that station SBO operated during 1983 and 1984.

transmit the data to the central recording laboratory at the University of Washington.

Until the end of 1984, signals from many of the seismograph stations in the network were recorded on 16-mm film by three Geotech Develocorders, at a speed of 15 mm/min. A few selected stations were recorded continuously on paper at 30 or 60 mm/min. Since 1980, we have digitally recorded all stations in the network using a Digital Equipment Corp. PDP-11/34 computer. This has been our principal method of recording data after Develocorder recording was discontinued in 1985. The computer operates in an "event triggered" mode, recording data at 100 samples per second, only when a seismic event is detected. The digital recording system is closely modeled after the CEDAR system developed at the California Institute of Technology by Johnson (1979).

Earthquake Analysis Procedure

Most of the earthquakes in the period 1982-86 were located from digital data recorded by our online PDP-11/34 computer. The reading of arrival times, first motion polarities, and signal durations was done using interactive computer programs on a PDP-11/70 computer. For a small number of earthquakes, data were taken from analog Develocorder films or paper records. These earthquakes are designated as type H in the appendices.

Detected events were classified and entered into a processing list in the following categories: teleseisms (epicentral distance greater than 1,000 km), regional events (distance less than 1,000 km), and local events (epicenter within the network). Local events recorded on at least three stations were analyzed. Earthquake and blast locations determined for 1982 through 1986 are given in Appendices I and II.

Earthquakes were located with the computer program "spong", a modification of the program "FASTHYPO" from St. Louis University (Herrmann, 1979). It is based on the standard non-linear least-squares inversion scheme of Geiger (Geiger, 1910; Lee and Stewart, 1981) and has been optimized for use with data from the Washington seismograph network. The accuracy of locations determined with this program depends on the accuracy of the crustal model, station distribution around the epicenter, station spacing, number of stations used, and quality of arrival time data.

In the earthquake location procedure, we have used a different velocity model and set of station corrections for each of five regions in Washington and Oregon. The regions are shown in the inset on Figure 1. As a general rule, we locate earthquakes by giving full weight to P-wave arrival times at stations within (50+d) km of the epicenter (where d = the distance from the epicenter to the nearest station) and reduced weight to P readings at more distant stations. Usually P readings at stations farther than (150+d) km are not used. Readings from well recorded S waves are also used from stations within 50 km of the epicenter. These guidelines may be relaxed for very deep earthquakes or earthquakes near the edge of the seismograph net.

In the computer location procedure the hypocentral parameters (that is, location and origin time) are modified until arrival time residuals (the observed minus the predicted P- or S-wave arrival times) are minimized.

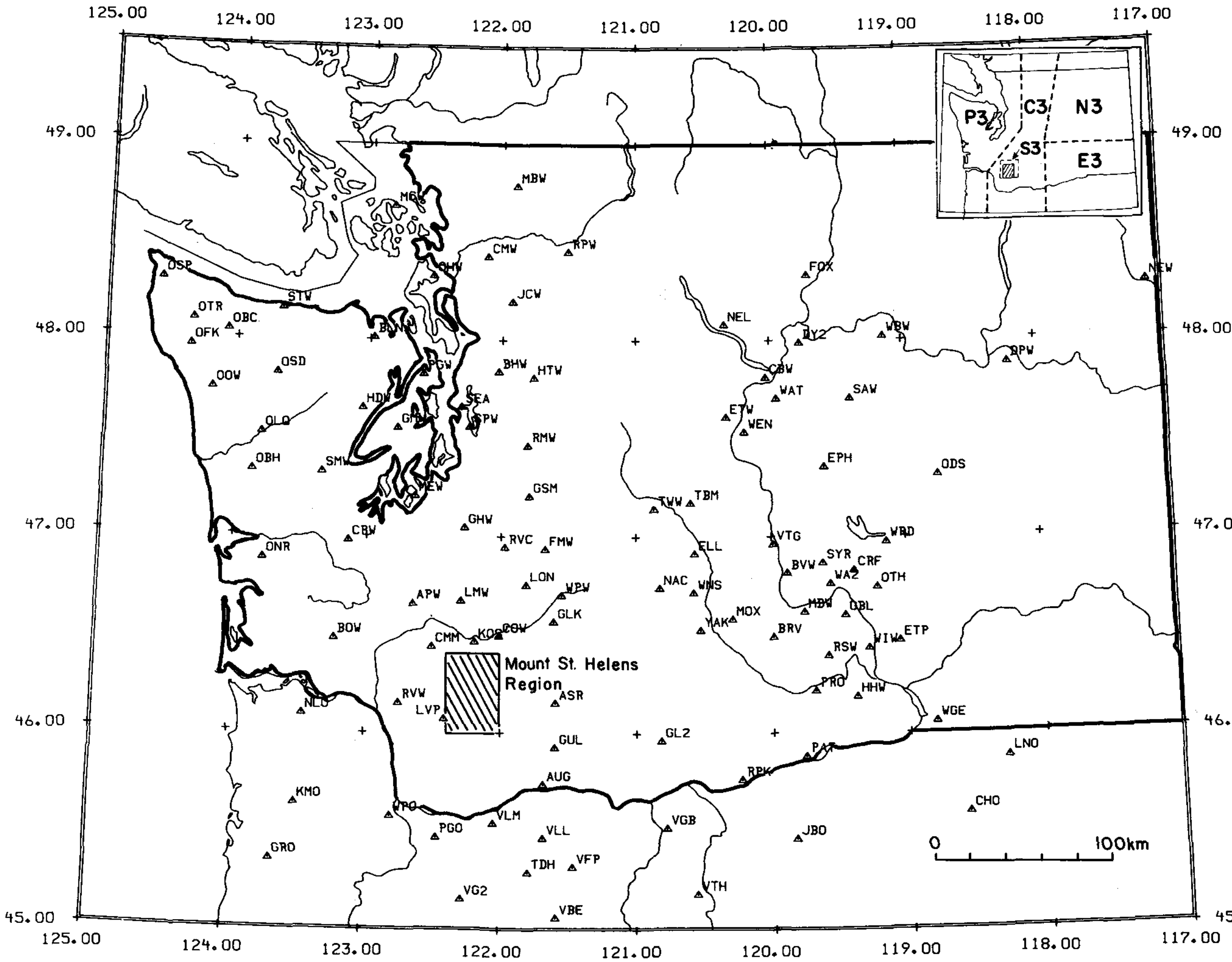


Figure 1.—Location of stations operating at the end of 1986. Other stations operating during 1982-1986 are listed in Table 1. Stations in the Mount St. Helens region (hachured box) are shown in Figure 2. Station VIP, in Oregon, lies south of the region shown. The inset shows the five regions for which different crustal velocity models (P3, C3, N3, E3, and S3) are used to locate hypocenters.

The root mean square (RMS) residual is one indicator of the overall quality of the solution. It is obtained by squaring each residual, summing the squares, dividing by the number of observations minus 4, and taking the square root of that quantity. A RMS residual is included with each event solution in Appendices I and II. Values less than 0.1 sec indicate a solution that fits the observed arrival-time data very well. Values greater than 0.5 sec usually indicate a poor solution. Earthquakes located with only three or four readings (in column labeled NS/NP in the Appendices) have RMS values set to zero. The RMS does not indicate the quality of the location unless more than four P or S readings are available. In addition, two quality factors, each rated A to D, are assigned to every event. The first factor is based on the RMS residual and estimates of uncertainty in horizontal and vertical location. The second factor depends on number of stations read, largest angular gap between stations, and distance from the epicenter to the nearest station. In each case, A is the highest and D the lowest quality.

Explosions are identified in the data set wherever possible. Criteria useful in distinguishing explosions are: shallow depths, positive P-wave polarity, clustering of epicenters, time of day of occurrence, spectral content of signals, and, of course, direct verification. When explosions occur in unusual locations and are nonrepetitive, positive identification is difficult. Suspected or possible explosions are indicated in Appendices I and II as type P. Confirmed or highly probable explosions are indicated as Type X.

The magnitude of an earthquake is determined using a coda or signal duration technique. The method used is described by Crosson (1972), and the magnitude is

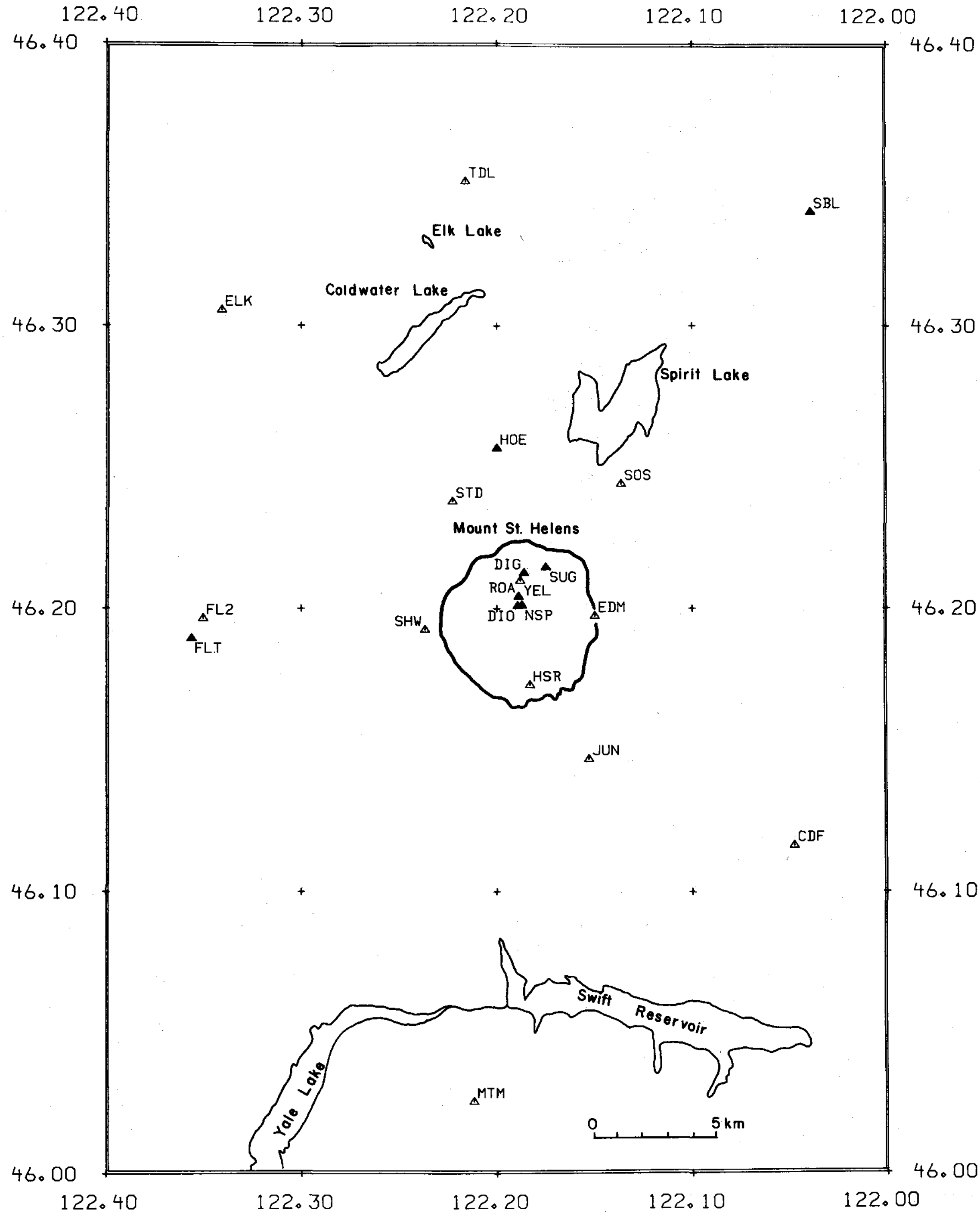


Figure 2.—Locations of seismograph stations in the Mount St. Helens region operating from 1982 through 1986. Open triangles show stations still operating at the end of 1986. Filled triangles show other stations that operated from 1982 through 1986. Most of the stations have been installed since 1980. Station SHW has operated on the flank of Mount St. Helens since 1972. The solid line around Mount St. Helens is the 1,500-m elevation contour.

referred to as coda magnitude or M_c to distinguish it from magnitudes determined by other methods. We refer occasionally to M_L, the local or Richter magnitude determined from Wood-Anderson seismograph records; M_s, surface wave magnitude; and M_b, body wave magnitude (Richter, 1958).

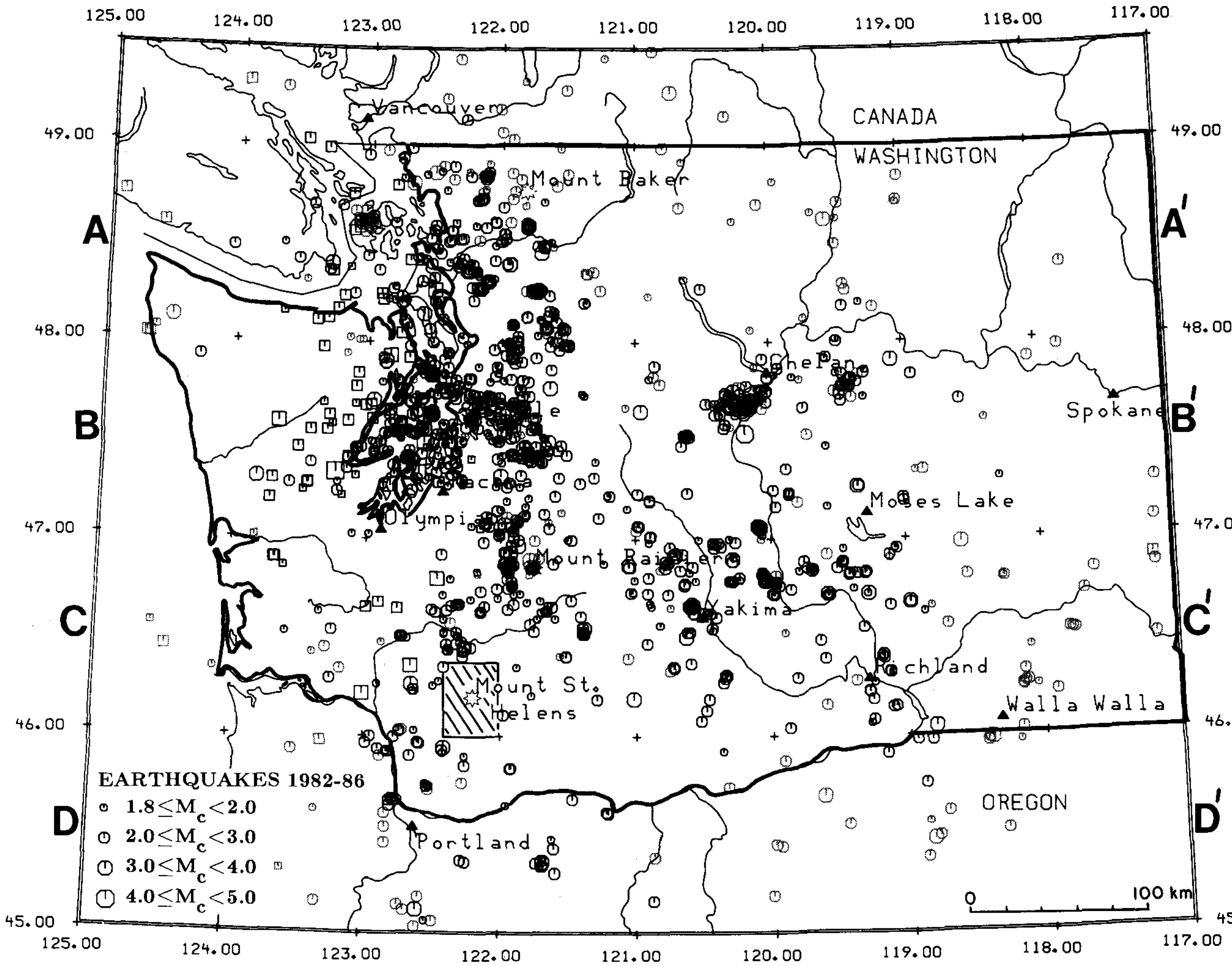


Figure 3.—Locations of earthquake epicenters for Washington and northern Oregon from 1982 through 1986, $M_c \geq 1.8$. Earthquakes deeper than 30 kilometers are shown as squares. Earthquakes near seattle are shown in more detail in Figure 8. Earthquakes in the hachured Mount St. Helens region are shown in Figure 4. Four earthquakes are listed in Appendix I that occurred in western Oregon between latitudes 44° and 45°, just to the south of the area shown here; they had magnitudes from 1.9 to 2.8 and occurred on June 21, 1982, June 22, 1985, and July 14, 1986 (two earthquakes). Gray symbols indicate less reliable earthquake hypocenters. These correspond to earthquakes with at least one D quality factor. (See Description of Appendices.) As an example, the depths indicated for the earthquakes at the extreme western edge of the map are not reliable. The east-west end points of cross sections A-A', B-B', C-C', and D-D', shown in Figure 9, are indicated at the edges of the map.

DISCUSSION OF EARTHQUAKE ACTIVITY

From 1982 through 1986 we located 9,453 earthquakes and blasts having $M_c \geq 0.0$. Locations for the largest of these are listed in Appendix I, except for locations of events near Mount St. Helens, which are listed in Appendix II. Figure 3 shows epicenters of earthquakes in Washington and northern Oregon, and Figure 4 shows epicenters of earthquakes near Mount St. Helens. Epicenters of minor earthquakes are shown in Figure 5, those for blasts in Figure 6, and those for earthquakes reported felt in Figure 7. Epicenters of earthquakes near Seattle are shown in more detail in Figure 8.

Figures 3 and 4 and Appendices I and II include only earthquakes having magnitudes $M_c \geq 1.8$. We located 1,399 earthquakes having $M_c \geq 1.8$ outside of the Mount St. Helens region (Fig. 3), and 1,083 tectonic and volcanic earthquakes in the Mount St. Helens region (Fig. 4). In addition to these, there were 1,645 minor earthquakes ($1.0 \leq M_c < 1.8$) in the Mount St. Helens

Table 2. Comparison of numbers of earthquakes and blasts, 1980 through 1986

	1980	1981	1982	1983	1984	1985	1986
All events processed	4573	5115	4419	4489	3144	3560	2555
Events, lat. 44°-50° N., long. 117°-125° W.							
Blasts $M \geq 1$	289	511	237	302	350	230	139
Deep earthquakes $M \geq 1$	33	35	23	34	42	45	27
Felt earthquakes $M \geq 1$	17	29	17	15	11	15	20
Earthquakes $M \geq 1$, except St. Helens region	459	686	585	652	639	799	500
Earthquakes $M \geq 1$, St. Helens region only	1353	404	400	359	616	793	560

region, not shown, and 1,776 elsewhere (Fig. 5). A total of 644 blasts in Washington and northern Oregon (Fig. 6) were recorded.

In the 1980 and 1981 catalogs (Qamar and others, 1986, 1987), locations for all earthquakes with magnitudes $M_c \geq 1.0$ were reported. Similar reporting for the period 1982-86 would have required tabulating 5,903 earthquakes and 1,258 blasts, as indicated in Table 2. For brevity we have chosen to list only earthquakes and blasts having $M_c \geq 1.8$. Our record of these earthquakes is nearly complete; the present seismograph network will detect and record virtually all earthquakes in Washington and northern Oregon having magnitudes above 1.8. We can consistently record and locate earthquakes of much smaller magnitudes in the few places where seismographs are closely spaced, such as in the Mount St. Helens region.

The largest earthquakes during 1982-86 were a magnitude M_c 4.4 earthquake in the southern Cascades on March 1, 1982; a M_c 4.3 earthquake in the Puget Sound on October 31, 1983; and a M_c 4.3 earthquake just east of the Cascades on April 11, 1984. The most seismically active areas were the Puget Sound, the west side of the Cascades, Mount St. Helens, the Entiat region, and a broad zone to the east and west of Yakima. There was scattered activity elsewhere, including earthquakes in southern Washington and northern Oregon.

As shown in Figure 3, shallow earthquakes occur over much of Washington and northern Oregon. Deep earthquakes are confined mainly to western Washington; occasional deep ones occur in western Oregon. The deepest earthquakes occur under the Cascade mountains. The largest (M_c 4.3) deep earthquake during 1982-86 occurred northwest of Olympia at a depth of 43 km on October 31, 1983. The three deepest ones occurred at depths of 86 to 87 km on April 21, 1983 (M_c 1.7), October 30, 1983 (M_c 1.3), and November 25, 1986 (M_c 1.0). These earthquakes are too small to be shown as epicenter symbols on Figures 3 and 8, but their locations are indicated by "A" in Figure 8. All three earthquakes occurred a few kilometers west of Skykomish at the same spot a similar 87-km-deep earthquake (M_c 1.3) occurred on October 25, 1981 (Qamar and others, 1987).

In Figure 9 are four cross sections showing the depth distribution of earthquakes in Washington and northern Oregon for 1982 through 1986. The separation of earthquakes into two distinct groups, shallow and deep, with an intervening zone between depths of 25 and 35 km that is relatively free of earthquakes, is clearly shown. The zone of deep earthquakes is thought to lie near the top of the subducting Juan de Fuca plate (Taber and Smith, 1985). Section D-D' in Figure 9 shows that deep earthquakes were very rare south of latitude 46°. The hypocenters of shallow earthquakes in eastern Washington do not attain the depths reached by hypocenters in western Washington. Shallow earthquakes in western Washington occur at noticeably smaller depths near the crest of the Cascades.

FELT EARTHQUAKES

From 1982 through 1986 there were 78 earthquakes reported felt. These are listed in Table 3, and their epicenters are shown in Figure 7. A detailed description of damage reported for some of these earthquakes can be found in the annual U.S. Geological Survey publication "United States Earthquakes" (for example, Stover, 1985). The Modified Mercalli (MM) Intensity scale used in Table 3 is described in "United States Earthquakes" and in Richter (1958). Intensities given in Table 3 are taken from published and unpublished data obtained by the U.S. Geological Survey or are estimated from reports received by the University of Washington (intensities in parentheses) if that is the only available source. Where data are insufficient to estimate intensity, the earthquakes are listed as "felt". In this section of the report, we discuss those earthquakes with magnitudes $M_c \geq 3.5$.

The largest earthquake in 1982-86 occurred on March 1, 1982, near Elk Lake, about 17 km north of Mount St. Helens. This earthquake was one of the largest aftershocks (M_c 4.4) of the February 14, 1981, earthquake

(M_L 5.5), and it occurred at nearly the same location as the mainshock. The March 1982 earthquake was 5 km deeper than the mainshock and was accompanied by numerous smaller earthquakes. It was felt most strongly in Glenoma and Silver Creek, where objects were overturned or thrown from shelves.

On March 22, 1983, a M_c 3.8 earthquake occurred near Walla Walla, in the same region as the 1936 magnitude-5.8 Milton-Freewater earthquake. P-wave first-motion polarities for the March 22 earthquake are consistent with strike-slip faulting and a direction of maximum principal stress (compression) oriented northwest-southeast. The earthquake had no detectable aftershocks.

Five more earthquakes having magnitudes $M_c \geq 3.5$ occurred in 1983. In August two were felt on the Olympic peninsula—one north of Forks on August 17 (M_c

Table 3. Felt earthquakes, 1982 through 1986

DAY gives year, month and day of earthquake. TIME is hour and minute in Coordinated Universal Time (subtract 8 hours for Pacific Standard Time or 7 hours for Pacific Daylight Time). M is coda magnitude of earthquake. INT is an estimate of the maximum Modified Mercalli Intensity, from earthquake felt reports. Intensities in parentheses are estimated from reports received by the University of Washington. Other intensities are taken from the annual publication United States Earthquakes (Stover, 1985) or from Stover (written commun., 1987).

DAY	TIME	M	INT	Some localities where earthquake was reported felt
82/01/21	16:05	2.2	felt	Skagit River. Felt at Van Horn
82/01/21	17:12	2.0	felt	Same as above
82/01/30	02:37	3.1	felt	Near Bellingham. Felt in San Juan and Vancouver Islands
82/03/01	17:40	4.4	V	Elk Lake area. Felt as far as Portland, OR
82/03/03	05:27	2.1	felt	Southwest of St. Helens. Felt at Chelatchie
82/03/10	14:27	2.9	felt	Felt near Tacoma
82/04/14	07:22	3.4	IV	Felt on Bainbridge Is., Kitsap peninsula, and in Seattle
82/05/31	05:10	3.0	felt	Elk Lake. Felt in Glenoma and Randle
82/06/04	07:44	2.8	IV	Kirkland, Redmond, Woodinville
82/06/04	16:10	3.0	IV	Bothell and Redmond
82/06/05	09:24	2.7	felt	Same as above
82/07/15	03:02	2.3	IV	Northwest of Moses Lake. Felt at Quincy
82/08/18	11:50	3.4	felt	Felt near Mount Hood, OR
82/09/15	17:32	2.9	III	Duvall, Bremerton
82/09/26	10:09	3.4	felt	Northwest of Yakima. Felt in Naches area
82/10/15	09:56	3.0	felt	Bremerton
82/11/21	04:57	2.7	felt	North of Portland, OR. Felt in Woodland
83/01/24	13:31	3.0	IV	Carbonado
83/02/23	05:39	2.7	II	Timberline Lodge at Mount Hood, OR
83/03/03	15:38	2.9	III	Fall City
83/03/22	12:47	3.8	IV	Walla Walla, College Place; Milton-Freewater, OR.
83/05/11	20:20	2.6	felt	West Hills area of Portland
83/05/25	04:20	3.0	IV	Sultan, Goldbar, Skykomish
83/08/12	01:12	3.1	III	North Bend
83/08/17	10:54	3.7	IV	Beaver, Forks. Felt also in Soleduck valley
83/08/28	12:47	3.9	IV	Bremerton, Port Townsend, Oak Harbor, Seattle, Vancouver Is.
83/09/14	09:03	2.5	III	Entiat
83/09/14	10:51	2.6	felt	Entiat
83/10/05	03:46	3.0	felt	North Bend
83/10/31	21:47	4.3	IV	Shelton, Olympia, Belfair, Hoodsport
83/11/14	11:19	3.8	IV	Yakima, Selah, Cowiche
83/12/05	07:24	3.8	III	Vantage, Ellensburg, Wenas valley

Table 3. (Continued)

DAY	TIME	M	INT	Some localities where earthquake was reported felt
84/03/16	02:35	2.6	felt	Rockport, Concrete
84/03/16	17:16	3.4	felt	Rockport, Concrete
84/04/11	03:07	4.3	V	Chelan, Entiat, Wenatchee, Grand Coulee, Yakima
84/04/27	23:06	2.9	IV	Fall City
84/06/02	12:57	3.6	IV	Port Orchard
84/06/04	04:46	3.7	IV	Kelso, Longview, Centralia
84/07/10	12:43	2.9	III	Mount Vernon, Lyman
84/08/24	04:42	3.0	felt	Fish Lake area west of Cle Elum
84/10/10	03:24	3.0	V	Grand Coulee, Electric City, Elmer City
84/12/02	16:17	3.1	III	West of Concrete, Hamilton
84/12/03	19:03	3.2	III	West of Concrete
84/12/11	06:34	2.5	felt	Portland, OR
85/01/11	13:07	3.3	IV	Keyport, Quilcene
85/02/10	20:29	3.9	IV	Hermiston and Umatilla, OR
85/02/28	17:02	3.7	IV	Seattle, Tacoma
85/03/05	14:14	3.1	felt	Mount Vernon
85/03/18	17:15	3.5	(IV)	Seattle, Tacoma
85/03/21	02:39	3.0	felt	Mercer Island
85/03/24	16:55	2.7	felt	Mercer Island
85/04/26	10:32	3.0	felt	Mount Vernon
85/04/30	01:13	3.3	felt	Mount Vernon
85/06/16	10:22	3.1	felt	North Bend
85/07/06	23:46	3.1	felt	Mercer Island
85/07/29	21:05	3.2	felt	Darrington
85/07/30	17:01	3.3	(IV)	Victoria, B.C.
85/09/25	19:28	2.2	felt	Issaquah
85/11/01	19:37	2.6	felt	Northeast of Bellingham
86/02/10	17:12	3.1	(IV)	Concrete
86/02/10	18:05	3.9	IV	Concrete, Sedro Woolley, Mount Vernon, Lyman
86/03/11	07:23	2.9	IV	Dockton, Gig Harbor
86/03/11	10:48	3.1	V	Ariel, Cougar, Vancouver WA
86/03/27	12:10	2.9	(III)	Darrington
86/03/28	03:48	3.1	felt	Darrington
86/03/28	04:12	3.6	IV	Darrington, Concrete, Duvall
86/03/28	05:40	2.4	felt	Darrington
86/03/28	12:11	2.1	felt	Darrington
86/03/29	13:09	3.3	felt	Darrington
86/03/31	07:11	2.3	felt	Darrington
86/04/08	10:57	3.3	felt	Chelan
86/04/20	16:40	3.0	III	Bellingham, Lynden
86/07/08	05:16	3.5	IV	Lyman, Freeland, Mukilteo, Oak Harbor, Silvana, Mount Vernon, Marysville
86/08/28	04:34	2.7	felt	Carson (near Columbia river)
86/09/16	23:19	1.6	felt	Darrington
86/09/16	23:38	2.8	felt	Darrington
86/09/16	23:49	2.4	felt	Darrington
86/09/26	23:34	2.4	felt	Sedro Woolley
86/09/29	19:37	2.2	felt	Sedro Woolley

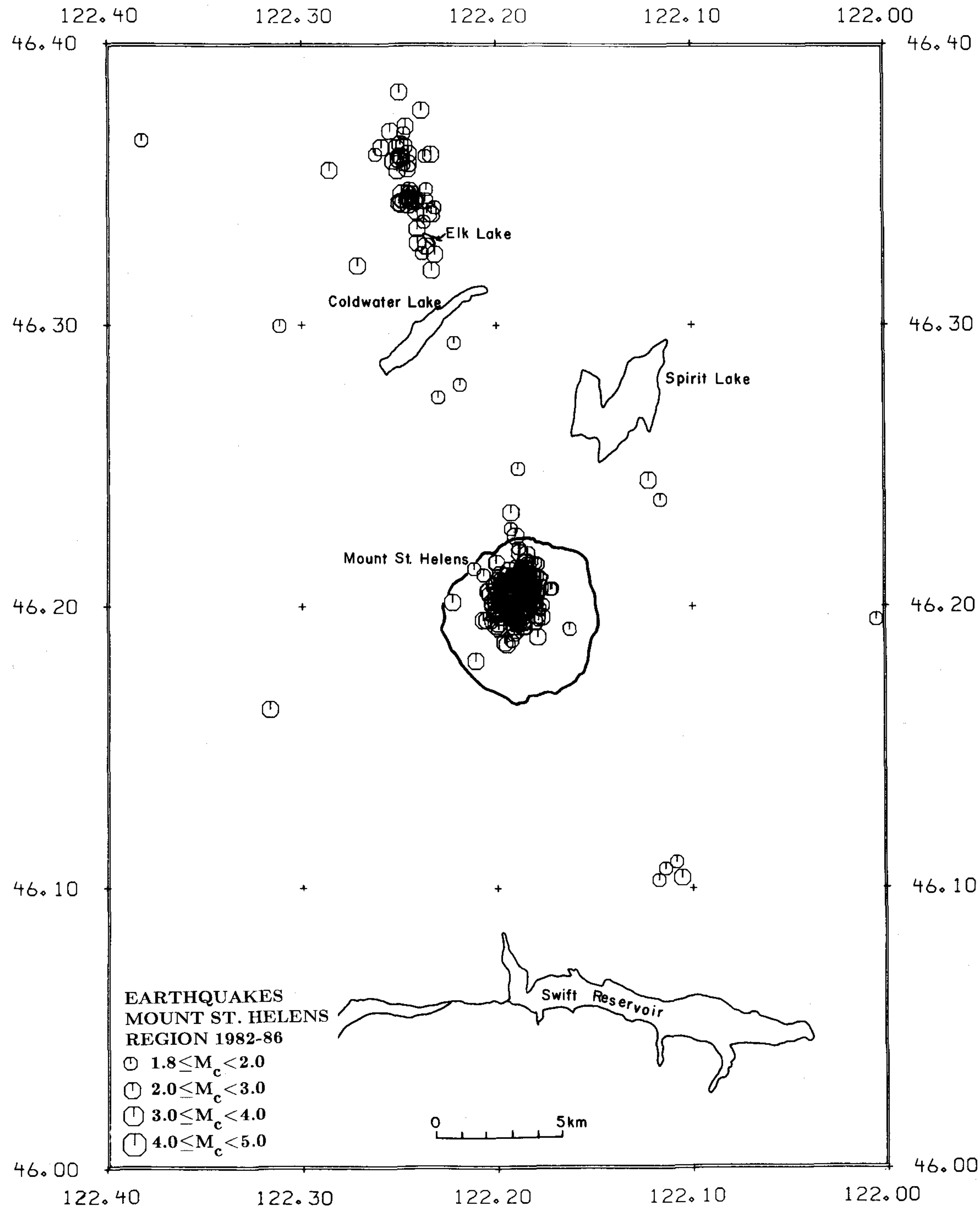


Figure 4.—Epicentral locations of earthquakes in the Mount St. Helens region in 1982 through 1986 having $M_c \geq 1.8$. The solid line around Mount St. Helens is the 1,500-m elevation contour.

3.7), and the other on the northeast part of the peninsula on August 28 (M_c 3.9). The largest earthquake (M_c 4.3) in 1983 occurred near Hood Canal at a depth of 43 km on October 31. It was reported felt in Shelton and Olympia, and the first-motion P-wave pattern indicates that it had a normal-fault mechanism caused by tension in a northwest-southeast direction. Two M_c 3.8 earthquakes were felt immediately east of the Cascades at the end of 1983. The first, near Yakima, occurred on November 14 and was widely felt. It was preceded by three small foreshocks with magnitudes less than 2 and was followed by several aftershocks. The second earthquake, near Ellensburg on December 5, had no foreshocks or aftershocks.

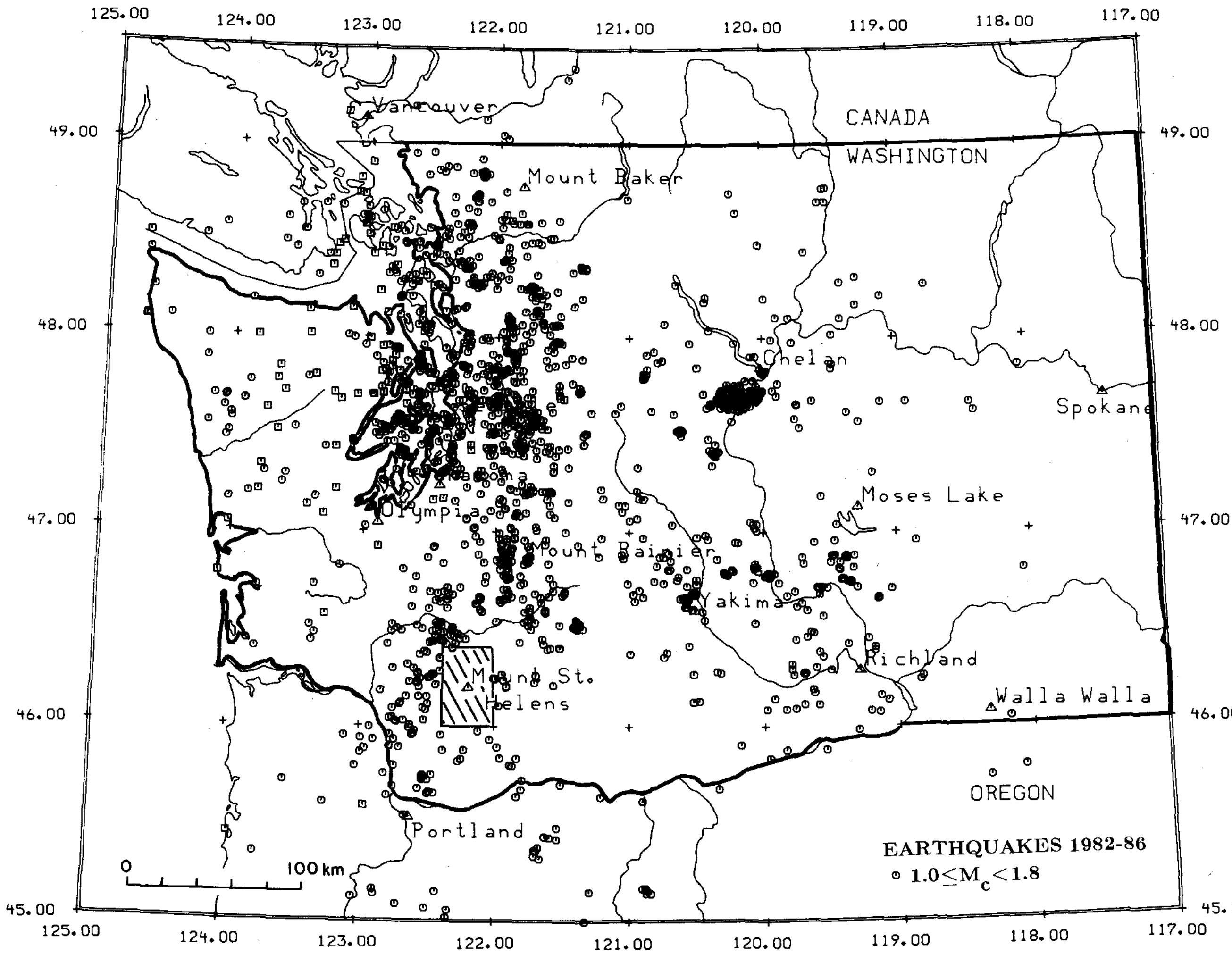


Figure 5.—Epicenters of small earthquakes in Washington and northern Oregon during 1982-1986, 1.0 <M_c < 1.8. Small earthquakes in the hachured Mount St. Helens region are not shown. Earthquakes deeper than 30 km are shown as squares.

Three significant earthquakes occurred in 1984: a shallow magnitude 4.3 earthquake near Wenatchee on April 11, a magnitude 3.6 earthquake southwest of Bremerton on June 2, and a magnitude 3.7 earthquake near Longview on June 4. The Wenatchee earthquake caused slight damage near Grand Coulee and occurred 20 km south of Chelan. Its epicentral location was just south of the region where about 40 earthquakes per year ($M_c \geq 1.0$) have occurred since local recording began in 1969. The Bremerton earthquake occurred at a depth of 21 km and was reported felt in Port Orchard. The Longview earthquake occurred below the Earth's crust at a depth of 50 km and had a first-motion P-wave pattern consistent with strike-slip faulting and a north-south direction of maximum principal stress.

On February 10, 1985, a moderate (M_c 3.9) earthquake was felt on the Washington-Oregon border near Umatilla. On February 28 and March 18 two earthquakes (M_c 3.7 and M_c 3.5) were felt between Seattle and Tacoma. Both hypocenters were about 50 km deep.

All significant earthquakes in the study area in 1986 occurred in northwest Washington. On February 10, a shallow M_c 3.9 earthquake occurred 15 km south of Concrete in the mountains between the Skagit River valley and the North Fork of the Stillaguamish River. The earthquake was part of a swarm of 11 events in an area that has not had earthquake activity in recent years. The first-motion P-wave pattern indicates a combination of thrust and strike-slip motion on a fault striking either northwest-southeast or northeast-southwest. On March 28, a magnitude 3.6 earthquake was felt; it was part of a swarm of 25 earthquakes near Darrington that occurred between March 24 and April 30. On July 8, a 68-km-deep M_c 3.5 earthquake occurred below Saratoga Passage between Whidbey and Camano Islands. It was felt on both islands and on the mainland at Mount Vernon and Marysville.

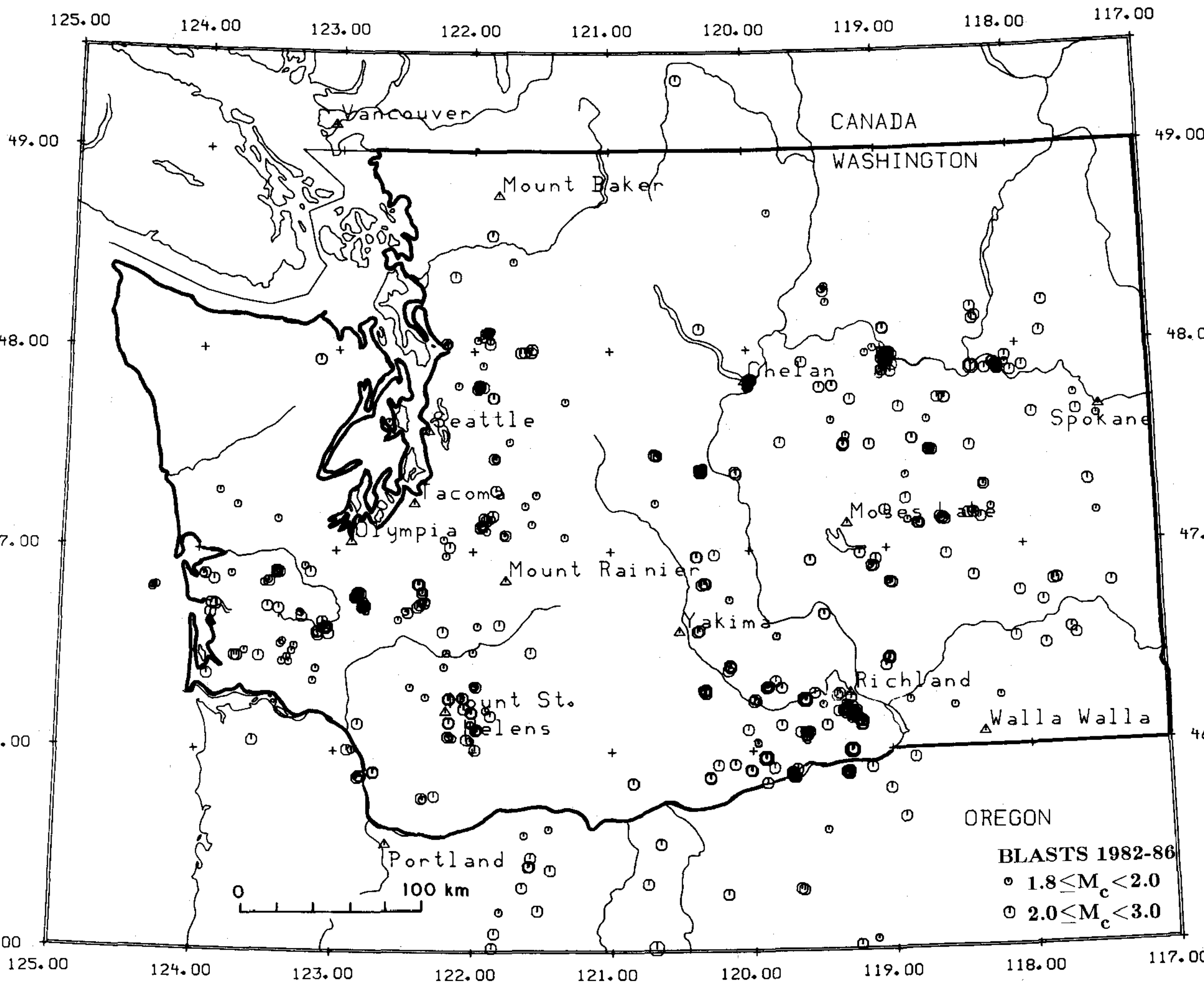


Figure 6.—Locations of blasts and probable blasts in Washington and northern Oregon during 1982-1986, $M_c \geq 1.8$.

MOUNT ST. HELENS

After lying dormant since 1857, Mount St. Helens signaled its renewed activity with swarms of earthquakes which began in March 1980. Since its cataclysmic explosion on May 18, 1980, the volcano has had frequent eruptions. All of these eruptions have been accompanied by an elevated rate of earthquake activity as seen in Figure 10. Since 1980, we have analyzed and located 6,000 representative volcanic earthquakes at Mount St. Helens. Many additional thousands have occurred. Although most of the earthquakes occur within 3 km of the surface, deeper ones (4-24 km) have followed and sometimes preceded some of the eruptions. Deep earthquakes preceded both the explosive May 18, 1980, eruption and the dome-building eruption of March 19, 1982; a few deep earthquakes also preceded the May 8, 1986, eruption. Deep earthquakes followed the 1980 eruptions of May 18, May 25, June 13, July 22, August 7, and October 16. Weaver and others (1983), Zollweg and Jonientz-Trisler (1984), Scandone and Malone (1985), and Shemeta and others (1984) have used the shallow and deep earthquakes as evidence of two distinct magma chambers under Mount St. Helens. In this interpretation, the deep earthquakes accompany the transport of magma or volatile gases from the deeper chamber to the shallow one. However, the seismicity during most of the explosive and dome-building eruptions of Mount St. Helens has been dominated by shallow earthquakes.

From 1982 to 1986 there have been 11 dome-building eruptions at Mount St. Helens during which new lobes of molten dacite have been extruded onto the dome that began growing in December 1980. The eruptions have been accompanied by swarms of earthquakes indicated in Table 4 and Figure 10. Generally, a short-term prediction of the eruptions was possible from the rapid increase of seismic energy release from 12 to 24 hours before magma was actually extruded at the surface (Malone and others, 1983; Swanson and others, 1983). Most of the eruptions have lasted only a few days or weeks, but in 1983 the dome grew rather steadily for most of the year.

Although eruptions have become less frequent since 1980, the earthquakes accompanying each eruption have tended to become more energetic. Data in Table 4 and Figure 10 show that many recent eruptions from 1984 to 1986 have been accompanied by greater numbers of large earthquakes than those which occurred from May 25, 1980, to December 1983. The largest earthquakes during recent eruptions have had magnitudes of 3.0 to 3.2.

Table 4. Number of Mount St. Helens earthquakes located, 1980-1986

Total number of events includes earthquakes with negative magnitudes. The smallest earthquakes located had magnitude -1.1. Note also that the number of events in magnitude range 3-4, for example, means the number of events located having $3 \leq M_c < 4$.

Year	Month	Total number of events	Number of events in selected magnitude ranges 0-1	1-2	2-3	3-4	4-5	5-6	Maximum magnitude for month	Eruption date
1980	Jan	0	0	0	0	0	0	0	0	
	Feb	1	0	0	0	1	0	0	3.2	
	Mar	121	0	0	16	46	59	0	4.9	
	Apr	349	0	3	18	171	145	12	5.2	
	May	1000	405	215	66	189	101	1	5.7	May 18 May 25
	Jun	83	69	13	1	0	0	0	2.0	Jun 12
	Jul	58	29	9	14	1	0	0	3.7	Jul 22
	Aug	33	25	4	0	0	0	0	1.9	Aug 7
	Sep	13	7	4	0	0	0	0	1.9	
	Oct	32	11	16	4	0	0	0	2.8	Oct 16
	Nov	14	9	2	0	0	0	0	1.4	
	Dec	71	11	57	3	0	0	0	2.7	Dec 27
1981	Jan	9	1	8	0	0	0	0	1.7	
	Feb	28	2	6	18	2	0	0	3.1	Feb 5
	Mar	17	9	6	1	0	0	0	2.7	
	Apr	51	8	34	9	0	0	0	2.5	Apr 10
	May	5	0	2	0	0	0	0	1.6	
	Jun	55	16	26	10	0	0	0	2.5	Jun 18
	Jul	2	1	1	0	0	0	0	1.1	
	Aug	78	39	18	0	0	0	0	1.7	
	Sep	70	50	17	0	0	0	0	1.9	Sep 6
	Oct	12	7	5	0	0	0	0	1.6	Oct 30
	Nov	3	3	0	0	0	0	0	0.7	
	Dec	7	5	1	0	0	0	0	1.0	
1982	Jan	1	1	0	0	0	0	0	0.3	
	Feb	93	45	9	0	0	0	0	1.9	
	Mar	417	228	86	20	0	0	0	2.6	Mar 19
	Apr	18	4	10	3	1	0	0	3.3	
	May	86	25	34	21	1	0	0	3.0	May 14
	Jun	4	3	1	0	0	0	0	1.6	
	Jul	31	21	8	0	0	0	0	1.5	
	Aug	140	87	48	5	0	0	0	2.8	Aug 18
	Sep	7	3	4	0	0	0	0	1.9	
	Oct	31	24	7	0	0	0	0	1.5	
	Nov	48	9	38	1	0	0	0	2.2	
	Dec	33	20	12	1	0	0	0	2.1	

Table 4. (Continued)

Year	Month	Total number of events	Number of events in selected magnitude ranges 0-1	1-2	2-3	3-4	4-5	5-6	Maximum magnitude for month	Eruption date
1983	Jan	66	45	20	1	0	0	0	2.3	
	Feb	32	18	11	2	0	0	0	2.8	Feb 4
	Mar	68	32	32	2	0	0	0	2.1	
	Apr	109	20	86	2	0	0	0	2.1	
	May	78	14	47	16	0	0	0	2.4	
	Jun	48	7	33	5	0	0	0	2.2	
	Jul	24	8	15	1	0	0	0	2.1	
	Aug	6	2	3	1	0	0	0	2.2	
	Sep	5	1	1	1	0	0	0	2.2	
	Oct	14	4	10	0	0	0	0	1.7	
	Nov	20	4	13	3	0	0	0	2.1	
	Dec	19	0	16	3	0	0	0	2.2	
1984	Jan	18	6	11	1	0	0	0	2.0	
	Feb	172	17	130	25	0	0	0	2.8	Feb 10
	Mar	274	13	188	72	1	0	0	3.0	Mar 29
	Apr	8	0	4	4	0	0	0	2.2	
	May	13	1	11	1	0	0	0	2.0	
	Jun	22	4	15	3	0	0	0	2.4	Jun 18
	Jul	28	3	17	8	0	0	0	2.5	
	Aug	35	3	22	10	0	0	0	2.4	
	Sep	53	4	36	12	0	0	0	2.5	Sep 10
	Oct	11	2	7	2	0	0	0	2.3	
	Nov	11	3	6	2	0	0	0	2.4	
	Dec	13	4	9	0	0	0	0	1.7	
1985	Jan	4	3	1	0	0	0	0	1.2	
	Feb	8	1	6	1	0	0	0	2.1	
	Mar	11	6	5	0	0	0	0	1.5	
	Apr	11	3	8	0	0	0	0	1.6	
	May	712	122	335	252	3	0	0	3.0	May 28
	Jun	123	1	25	95	2	0	0	3.0	
	Jul	3	1	2	0	0	0	0	1.9	
	Aug	11	4	7	0	0	0	0	1.7	
	Sep	8	1	7	0	0	0	0	1.6	
	Oct	7	1	5	1	0	0	0	2.1	
	Nov	4	2	1	1	0	0	0	2.0	
	Dec	9	3	5	1	0	0	0	2.2	
1986	Jan	7	2	4	0	0	0	0	1.6	
	Feb	13	6	6	1	0	0	0	2.1	
	Mar	26	9	15	2	0	0	0	2.6	
	Apr	68	29	31	8	0	0	0	2.8	
	May	216	53	129	32	2	0	0	3.2	May 8
	Jun	4	2	1	1	0	0	0	2.2	
	Jul	14	7	6	1	0	0	0	2.0	
	Aug	15	6	9	0	0	0	0	1.5	
	Sep	56	25	27	4	0	0	0	2.2	
	Oct	417	155	160	81	19	0	0	3.2	Oct 22
	Nov	2	0	2	0	0	0	0	1.2	
	Dec	2	2	0	0	0	0	0	0.4	

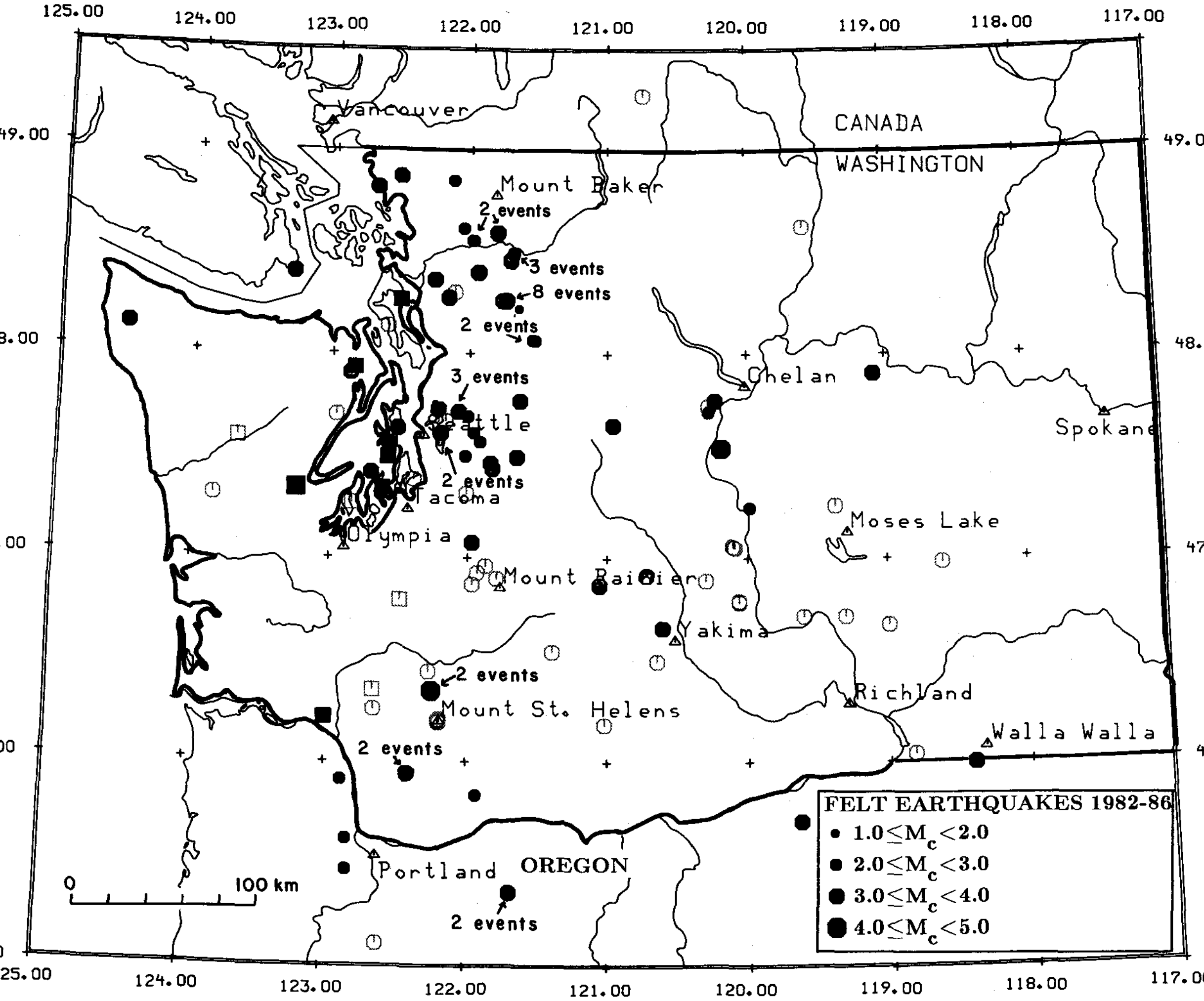


Figure 7.—Epicenters of felt and other important earthquakes in Washington and northern Oregon during 1982-1986. Felt earthquakes are shown as filled symbols. Earthquakes not felt, having $M_c \geq 3.0$, are shown as open gray symbols. Earthquakes deeper than 30 km are shown as squares.

The epicenters of tectonic earthquakes that occurred at Elk Lake, 17 km north of Mount St. Helens (Fig. 4), represent continued activity in the aftershock zone of the M_L 5.5 earthquake of February 14, 1981. See Grant and others (1984) and Qamar and others (1987) for discussion of this event. Most of the Elk Lake aftershocks from 1982 through 1986 occurred in 1982. The largest aftershock, on March 1, 1983, had a magnitude of 4.4. A few small earthquakes occurred southeast of Mount St. Helens near Marble Mountain, an area which was active in 1980 (Qamar and others, 1986). Hypocenters of the Marble Mountain and Elk Lake earthquakes are believed to lie on a north- to northwest-trending zone of strike-slip faulting called the St. Helens seismic zone (Weaver and Smith, 1983).

ACKNOWLEDGMENTS

The agencies that funded the University of Washington seismograph network and the earthquake research partially summarized in this report are the U.S. Geological Survey (contracts 14-08-0001-19274, 14-08-0001-19848, 14-08-0001-21192, 14-08-0001-21861, 14-08-0001-21862, 14-08-0001-21978, 14-08-0001-22007, and 14-08-0001-A0266, and Joint Operating Agreement 14-08-0001-G1080), the U.S. Department of Energy (contract DE-AM06-76RL02225, task agreement 39), and the U.S. Nuclear Regulatory Commission (contract NRC-04-81-177).

In addition to the authors mentioned in the text, many students and other staff members have contributed to this document. Processing of the digital data ("pinging") was done initially by Susan Carson-Sanger with assistance from Wendy Grant and Jim Zollweg. Processing was later done by Julie Shemeta, Christina Boyko, and Rick Benson. Zollweg served as Network Operations Manager, and Judy Terreberry was Seismic Data Manager. Barbara Bogaert was manager of Seismic Analysis. A. B. Adams, Bob Norris, Boyko, and Chris

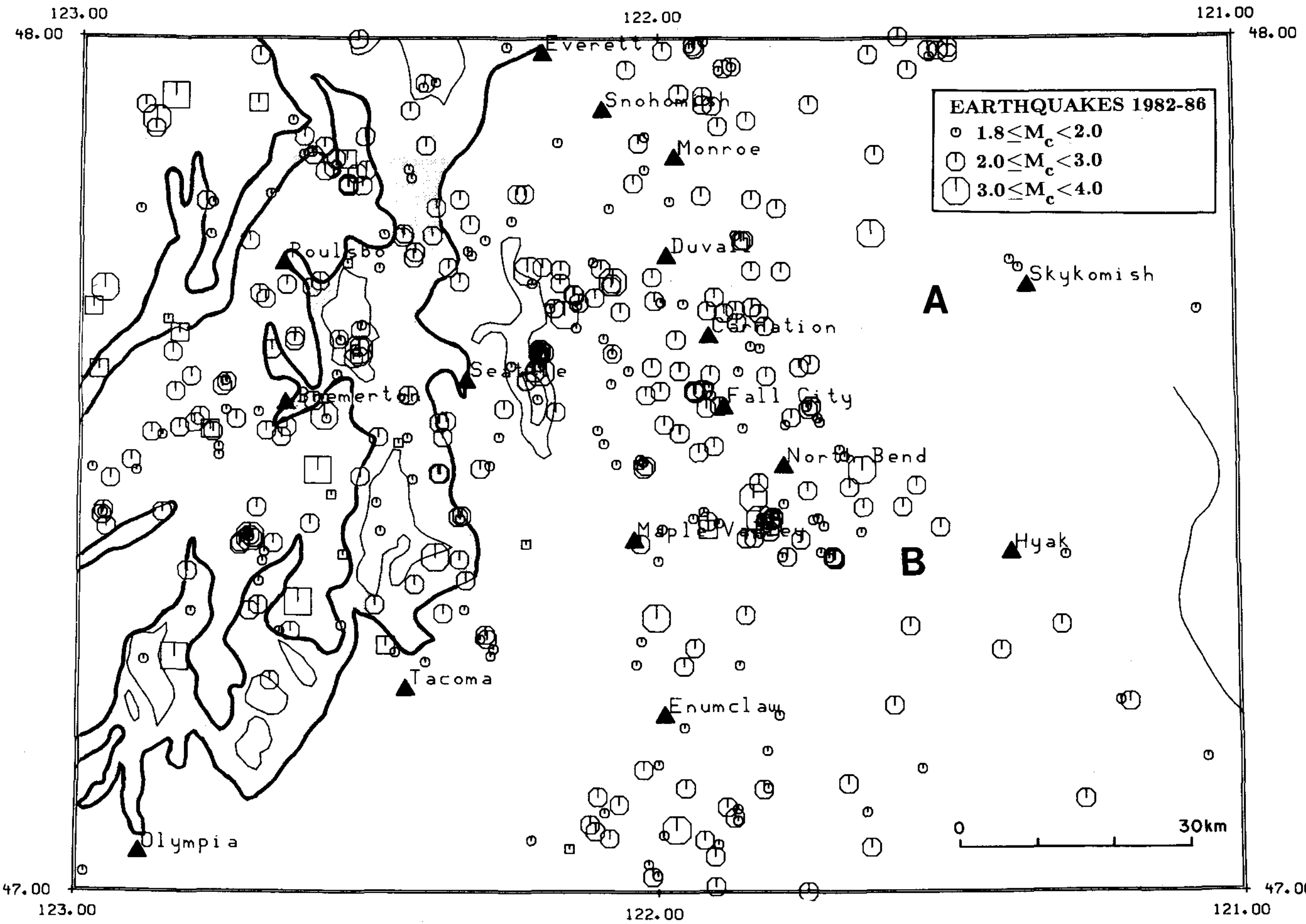


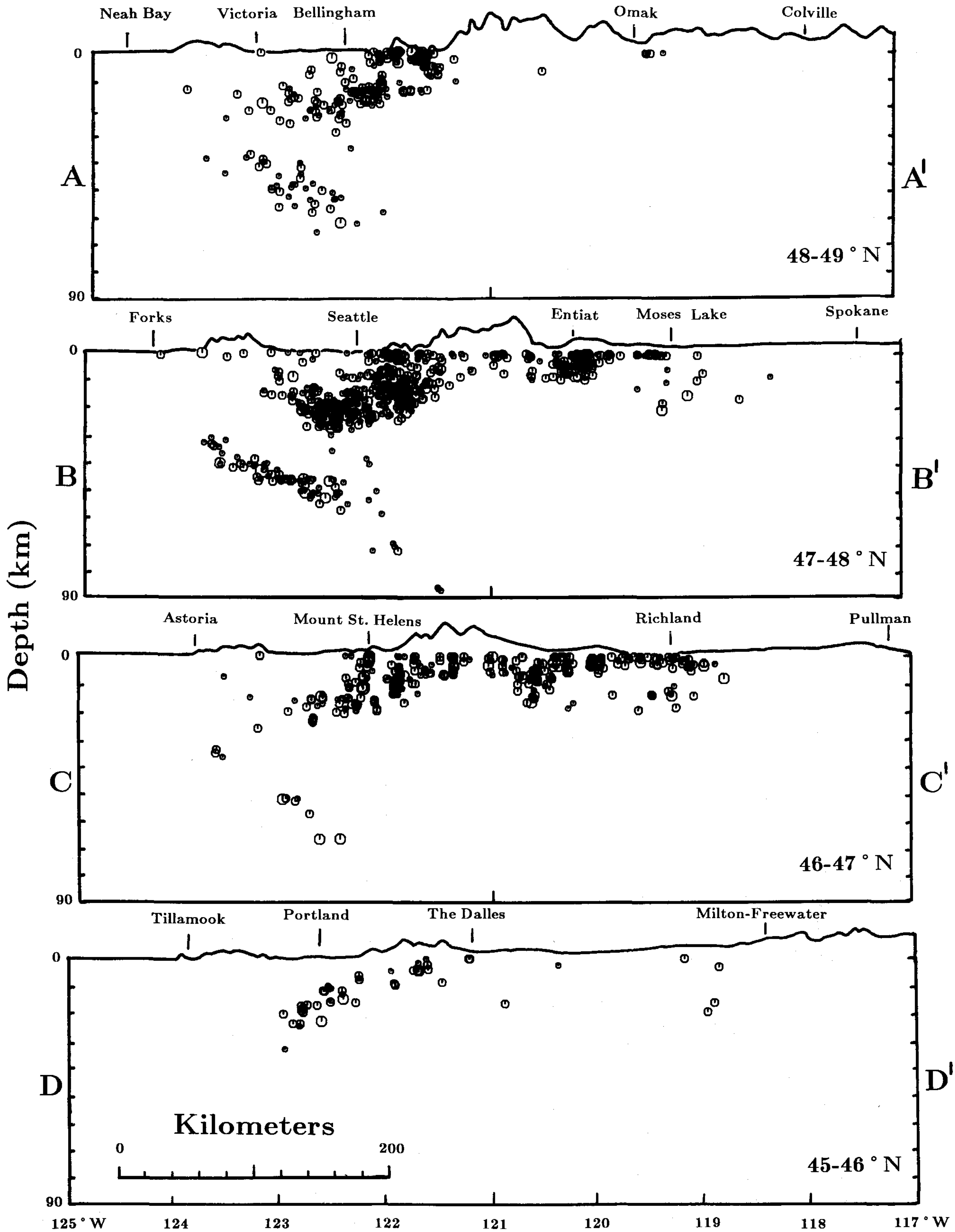
Figure 8.—Epicenters of earthquakes near Seattle during 1982 through 1986 having Mc ≥ 1.8. Earthquakes deeper than 30 km shown as squares. The symbol "A" is the location of four small, 87-km-deep earthquakes (M_c < 1.8) described in the text. The symbol "B" is the location of the deepest known earthquake in Washington (M_c 2.4, depth 96 km), which occurred in 1980 (Qamar and others, 1986).

Jonientz-Trisler, Anne Rathbun, and Cindy Roe served as analysts, "captains", or "night captains". Our technicians were Laurens Engel, Jim Ramey, and Jim Hudspeth. They were assisted by John Power, Jeff McClean, and Dawn Mullen. Don Leaver and Duane Hesser developed a number of computer programs to facilitate seismic processing. Linda Noson, Elliot Endo, and John Taber contributed other valuable assistance.

DESCRIPTION OF APPENDICES

Earthquake locations for 1982-86 have been divided into two catalogs, Appendices I and II. Appendix I lists all earthquakes and blasts (M_c ≥ 1.8) that occurred between latitudes 44° and 50° N., and longitude 117° and 125° W., but excluding the Mount St. Helens region, latitude 46.0° to 46.4° N., longitude 122.0° to 122.4° W.

Figure 9.—East-west cross sections showing depths of earthquakes between longitude 117° W. and 125° W. during 1982-86. Only earthquakes with quality C or better (described in Description of Appendices) are plotted. Above a depth of 30 km only earthquakes having M_c ≥ 1.8 are shown. Below 30 km all earthquakes having M_c ≥ 1.0 are shown. Section A-A' shows earthquakes between north latitudes 48° and 49°; B-B' between 47° and 48°; C-C' between 46° and 47°; and D-D' between 45° and 46°. In each section earthquakes are projected from the north or south onto a vertical plane. The locations of cross section end point A, A', B, B', etc., are shown on Figure 3. There is 2 to 1 vertical exaggeration below sea level; above sea level the topography is exaggerated 12 to 1. →


Neah Bay
Victoria
Bellingham
Omak
Colville
0
90
A
A'
48-49 ° N
Forks
Seattle
Entiat
Moses Lake
Spokane
B
B'
47-48 ° N
Astoria
Mount St. Helens
Richland
Pullman
C
C'
46-47 ° N
Tillamook
Portland
The Dalles
Milton-Freewater
D
D'
Kilometers
0
200
45-46 ° N
Depth (km)
125 ° W
124
123
122
121
120
119
118
117 ° W

Appendix II contains data for the earthquakes and blasts in the Mount St. Helens region only. There are 2,019 earthquakes and blasts listed in Appendix I, and 1,107 earthquakes and blasts are listed in Appendix II. Epicenters of smaller earthquakes having magnitudes $1.0 \le M_c < 1.8$ are not listed but are plotted in Figure 5.

In Appendices I and II the following information is given:

TIME—Origin time, calculated for each earthquake on the basis of multi-station arrival times. Time is given in Coordinated Universal Time (UTC), in hours:minutes:seconds. To convert to Pacific Standard Time, subtract 8 hours, or to Pacific Daylight Time, subtract 7 hours.

LAT—North latitude, in degrees and minutes, of the epicenter.

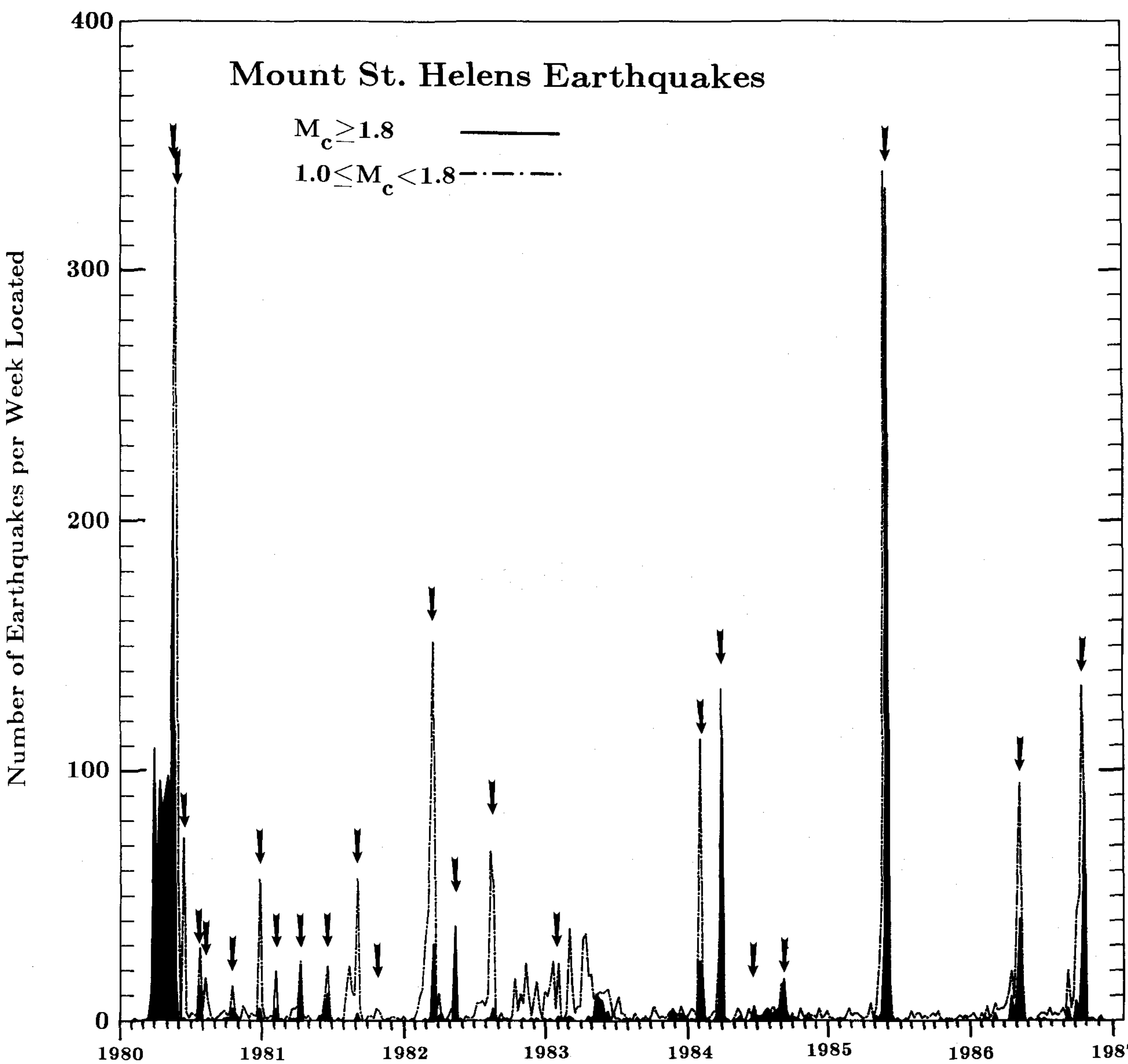


Figure 10.—Numbers of earthquakes located under the Mount St. Helens volcano each week from 1980 through 1986. Solid line with black shading shows numbers of earthquake having $M_c \ge 1.8$. Dashed line shows numbers of earthquakes having $1.0 \le M_c < 1.8$. The beginnings of eruptions listed in Table 4 are indicated by arrows. Not all of the earthquakes at Mount St. Helens have been located, particularly the small ones. (See Qamar and others, 1986, for a partial discussion of this.) Therefore, comparing eruptions using the numbers shown here must be done in combination with an analysis of the completeness of the data.

LON—West longitude, in degrees and minutes, of the epicenter.

DEPTH—The depth, given in kilometers, usually freely calculated from the arrival-time data. In some instances, the depth must be fixed arbitrarily to obtain a convergent solution. Such depths are noted by an asterisk (*) in the column immediately following the depth. A $ or a # following the depth means that the maximum number of iterations has been exceeded without meeting convergence tests and both the location and depth have been arbitrarily fixed.

M—Coda magnitude, M_c (Crosson, 1972). For tectonic earthquakes in Washington, M_c is an estimate of local Richter magnitude, M_L (Richter, 1958). Magnitude values may be revised as we improve our analysis procedure.

NS/NP—NS, the number of station observations, and NP, the number of P and S phases used to calculate the earthquake location. A minimum of three stations and four phases is required. Generally, more observations improve the quality of the solution.

GAP—Azimuthal gap. The largest angle (relative to the epicenter) containing no stations.

RMS—The root mean square residual taken about the mean of the station first-arrival residuals. It is only useful as a measure of the quality of the solution when five or more well distributed stations are used in the solution. Good solutions are normally characterized by **RMS** values less than about 0.3 sec.

Q—Two **Quality factors** indicating the general reliability of the solution (**A** is the best quality, **D** is the worst). Similar quality factors are used by the U.S. Geological Survey for events located with the computer program HYPO71. The first letter is a measure of the hypocenter quality based on travel time residuals. For example: **A** quality requires an **RMS** less than 0.15 sec, while an **RMS** of 0.5 sec or more is **D** quality. (Estimates of the uncertainty in hypocenter location also affect this quality parameter.) The second letter of the quality code depends on the spatial distribution of stations around the epicenter, that is, number of stations, their azimuthal distribution, and the minimum distance (**DMIN**) from the epicenter to a station. Quality **A** requires a solution with eight or more phases, **GAP** $\leq 90°$ and DMIN ≤ 5 km or calculated depth of earthquake, whichever is greater). If the number of phases, NP, is five or less, or GAP $> 180°$, or DMIN > 50 km, the solution is assigned quality D; the depths of such earthquakes are poorly defined.

MOD—The crustal velocity model used in location calculations (refer to Fig. 1).

P3— Puget Sound model
C3—Cascade model
S3— Mount St. Helens model including Elk Lake
N3—northeastern model
E3— southeastern model

TYP—Earthquake classification.

F—earthquakes reported to have been felt
P—probable explosion
L—low-frequency earthquakes
H—handpicked from helicorder records
X—known explosion

REFERENCES CITED

Crosson, R. S., 1972, Small earthquakes, structure, and tectonics of the Puget Sound region: Seismological Society of America Bulletin, v. 62, p. 1133-1171.

Crosson, R. S., 1974, Compilation of earthquake hypocenters in western Washington–1972: Washington Division of Geology and Earth Resources Information Circular 53, 25 p.

Crosson, R. S., 1975, Compilation of earthquake hypocenters in western Washington–1973: Washington Division of Geology and Earth Resources Information Circular 55, 14 p.

Crosson, R. S.; Millard, R. C., 1975, Compilation of earthquake hypocenters in western Washington–1974: Washington Division of Geology and Earth Resources Information Circular 56, 14 p.

Crosson, R. S.; Noson, L. L., 1978a, Compilation of earthquake hypocenters in western Washington–1975: Washington Division of Geology and Earth Resources Information Circular 64, 12 p.

Crosson, R. S.; Noson, L. L., 1978b, Compilation of earthquake hypocenters in western Washington–1976: Washington Division of Geology and Earth Resources Information Circular 65, 13 p.

Crosson, R. S., Noson, L. L., 1979, Compilation of earthquake hypocenters in western Washington–

1977: Washington Division of Geology and Earth Resources Information Circular 66, 12 p.

Geiger, Ludwig, 1910, Herdbestimmung bei Erdbeben aus den Ankunftszeiten: Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen, math.-phys. kl. 1910, [v.] 4, p. 331-349.

Grant, W. C.; Weaver, C. S.; Zollweg, J. E., 1984, The February 1981 Elk Lake, Washington earthquake sequence: Seismological Society of America Bulletin, v. 74, p. 1289-1309.

Herrmann, R., 1979, The FASTHYPO location program: Earthquake Notes, v. 50, p. 25-37.

Johnson, C. E., 1979, I, CEDAR--An approach to the computer automation of short-period local seismic networks; II. Seismotectonics of the Imperial Valley of southern California: California Institute of Technology Doctor of Philosophy thesis, 343 p.

Lee, W. H. K.; Stewart, S. W., 1981, Principles and applications of microearthquake networks; Advances in Geophysics, supplement 2: New York, Academic Press Inc., 293 p.

Malone, S. D., 1975, 1976, 1976, 1977, 1978, 1979, Earthquake monitoring of the Hanford region, eastern Washington; Annual technical report: University of Washington Geophysics Program, 1 v., annual.

Malone, S. D.; Boyko, Christina; Weaver, C. S., 1983, Seismic precursors to the Mount St. Helens eruptions in 1981 and 1982: Science, v. 221, no. 4618, p. 1376-1378.

Noson, L. L.; Crosson, R. S., 1980, Compilation of earthquake hypocenters in western Washington–1978: Washington Division of Geology and Earth Resources Information Circular 72, 18 p.

Noson, L. L.; Ludwin, R. S.; Crosson, R. S., 1985, Compilation of earthquake hypocenters in western Washington–1979: Washington Division of Geology and Earth Resources Information Circular 79, 19 p.

Qamar, Anthony; Rathbun, Anne; Ludwin, R. S.; Crosson, R. S.; Malone, S. D., 1986, Earthquake hypocenters in Washington and northern Oregon–1980: Washington Division of Geology and Earth Resources Information Circular 82, 64 p.

Qamar, Anthony; Rathbun, Anne; Ludwin, R. S.; Noson, L. L.; Crosson, R. S.; Malone, S. D., 1987, Earthquake hypocenters in Washington and northern Oregon–1981: Washington Division of Geology and Earth Resources Information Circular 83, 50 p.

Rasmussen, H. H., 1967, Washington State earthquakes 1840 through 1965: Seismological Society of America Bulletin, v. 57, p. 463-467.

Richter, C. F., 1958, Elementary Seismology: San Francisco, W. H. Freeman and Co., 768 p.

Scandone, Roberto; Malone, S. D., 1985, Magma supply, magma discharge and readjustment of the feeding system of Mount St. Helens during 1980: Journal of Volcanology and Geothermal Research, v. 23, p. 239-262.

Shemeta, J. E.; Weaver, C. S.; Grant, W. C., 1984, Details of the May 18, 1980 post-eruption seismicity at Mount St. Helens, Washington [abstract]: EOS (American Geophysical Union Transactions), v. 65, no. 45, p. 1001.

Stover, C. W., 1985, United States Earthquakes, 1982: U.S. Geological Survey Bulletin 1655, 141 p.

Swanson, D. A.; Casadevall, T. J.; Dzurisin, Daniel; Malone, S. D.; Newhall, C. G.; Weaver, C. S., 1983, Predicting eruptions at Mount St. Helens, June 1980 through December 1982: Science, v. 221, no. 4618, p. 1369-1376.

Taber, J. J., Jr.; Smith, S. W., 1985, Seismicity and focal mechanisms associated with subduction of the Juan de Fuca plate beneath the Olympic peninsula, Washington: Seismological Society of America Bulletin, v. 75, no. 1, p. 237-249.

Weaver, C. S.; Smith, S. W., 1983, Regional tectonic and earthquake hazard implications of a crustal fault zone in southwestern Washington: Journal of Geophysical Research, v. 88, p. 10371-10383.

Weaver, C. S.; Zollweg, J. E.; Malone, S. D., 1983, Deep earthquakes beneath Mount St. Helens—Evidence for magmatic gas transport?: Science, v. 221, no. 4618, p. 1391-1394.

Zollweg, J. E.; Jonientz-Trisler, C., 1984, A swarm of deep earthquakes at Mount St. Helens, Washington, prior to the eruption of 18 May 1980 [abstract]: EOS [American Geophysical Union Transactions], v. 65, no. 45, p. 1001.