U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Catalog of Earthquake Hypocenters at Alaskan Volcanoes: January 1, 1994 through December 31, 1999

By

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INTRODUCTION

The Alaska Volcano Observatory (AVO), a cooperative program of the U.S. Geological Survey, the Geophysical Institute of the University of Alaska - Fairbanks, and the Alaska Division of Geological and Geophysical Surveys, has maintained a seismic monitoring program at potentially active volcanoes in Alaska since 1988 (Power and others, 1993; Jolly and others, 1996). The primary objectives of this program are the seismic surveillance of active, potentially hazardous, Alaskan volcanoes and the investigation of seismic processes associated with active volcanism.

Between 1994 and 1999, the AVO seismic monitoring program underwent significant changes with networks added at new volcanoes during each summer from 1995 through 1999. The existing network at Katmai – Valley of Ten Thousand Smokes (VTTS) was repaired in 1995, and new networks were installed at Makushin (1996), Akutan (1996), Pavlof (1996), Katmai - south (1996), Aniakchak (1997), Shishaldin (1997), Katmai - north (1998), Westdahl, (1998), Great Sitkin (1999) and Kanaga (1999). These networks added to AVO's existing seismograph networks in the Cook Inlet area and increased the number of AVO seismograph stations from 46 sites and 57 components in 1994 to 121 sites and 155 components in 1999. The 1995 – 1999 seismic network expansion increased the number of volcanoes monitored in real-time from 4 to 22, including Mount Spurr, Redoubt Volcano, Iliamna Volcano, Augustine Volcano, Mount Snowy, Mount Griggs, Mount Katmai, Novarupta, Trident Volcano, Mount Mageik, Mount Martin, Aniakchak Crater, Pavlof Volcano, Mount Dutton, Isanotski volcano, Shisaldin Volcano, Fisher Caldera, Westdahl volcano, Akutan volcano, Makushin Volcano, Great Sitkin volcano, and Kanaga Volcano (Figures 1-15). The network expansion also increased the number of earthquakes located from about 600 per year in 1994 and 1995 to about 3000 per year between 1997 and 1999 (Table 1).

Highlights of the catalog period include: 1) a large volcanogenic seismic swarm at Akutan volcano in March and April 1996 (Lu and others, 2000); 2) an eruption at Pavlof

Volcano in fall 1996 (Garces and others, 2000; McNutt and others, 2000); 3) an earthquake swarm at Iliamna volcano between September and December 1996; 4) an earthquake swarm at Mount Mageik in October 1996 (Jolly and McNutt, 1999); 5) an earthquake swarm located at shallow depth near Strandline Lake; 6) a strong swarm of earthquakes near Becharof Lake; 7) precursory seismicity and an eruption at Shishaldin Volcano in April 1999 that included a 5.2 M_L earthquake and aftershock sequence (Moran and others, in press; Thompson and others, in press). The 1996 calendar year is also notable as the seismicity rate was very high, especially in the fall when 3 separate areas (Strandline Lake, Iliamna Volcano, and several of the Katmai volcanoes) experienced high rates of located earthquakes (Table 2).

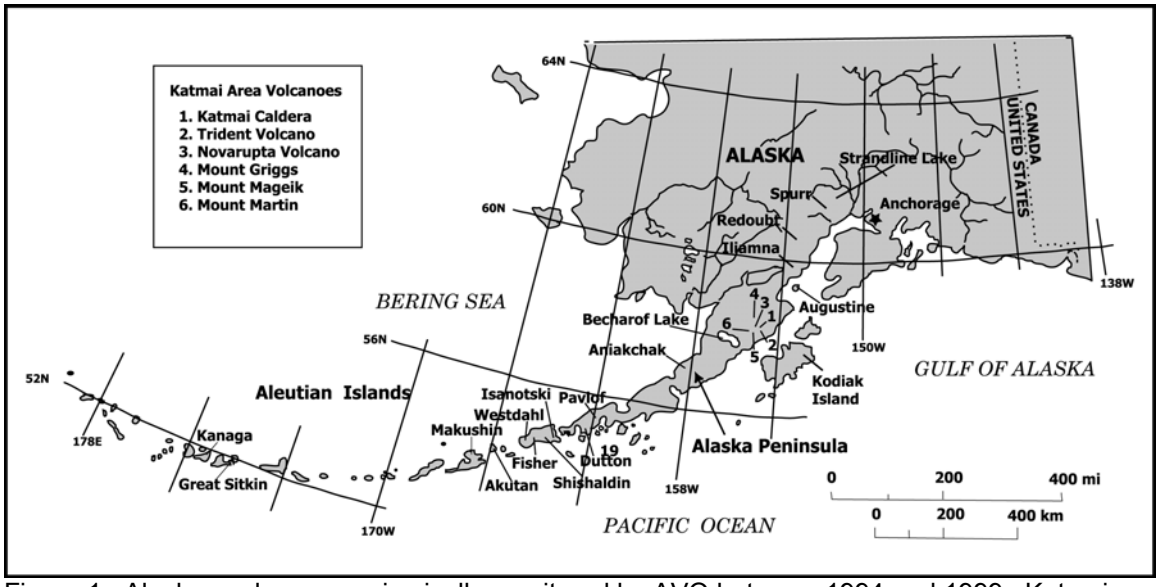

Figure 1. Alaskan volcanoes seismically monitored by AVO between 1994 and 1999. Katmai area volcanoes correspond to numbers in the inset.

Table 1: Number of earthquakes located per year by the AVO.

Year	Located Earthquakes
1994	420
1995	815
1996	6375
1997	2915
1998	2879
1999	2762

This catalog covers the period from January 1, 1994, through December 31, 1999, and includes: 1) earthquake origin times, hypocenters, and magnitudes with

summary statistics describing the earthquake location quality; 2) a description of instruments deployed in the field and their locations and magnifications; 3) a description of earthquake detection, recording, analysis, and data archival; 4) velocity models used for earthquake locations; 5) phase arrival times recorded at individual stations; and 6) a summary of daily station usage from throughout the report period. We have made calculated hypocenters, station locations, system magnifications, velocity models, and phase arrival information available for download via computer network as a compressed Unix tar file.

Table 2: Highlights of Seismicity: 1994-1999

Dates	Network	Event
Mar. 1996-Apr. 1996	Akutan	Akutan earthquake swarm
Aug. 1996-Feb. 1997	Iliamna	Iliamna earthquake swarm
Sep. 1996-Dec. 1996	Pavlof	Pavlof eruption
Oct. 1996	Katmai	Mageik earthquake swarm
Sep. 1996-Jun. 1997	Spurr	Strandline Lake swarm
May 1998	Katmai	Becharof Lake swarm
Oct. 1998-May 1999	Shishaldin	Precursory sequence, Eruptions April 19-23, 1999.

FIELD INSRUMENTATION, DATA ACQUISITION AND REDUCTION

AVO seismic instruments in operation during 1994-1999 were predominantly short-period vertical component seismometers (Mark Products L4 and Teledyne-Geotech S-13) with a one-second natural period. AVO also operated 15 three-component short-period instruments during the report period. These instruments were either Mark Products L22 seismometers with a two-second natural period or L4 horizontal instruments with a 1-second period. Two horizontal Teleydyne-Geotech S-13 instruments were operated at station AUI on Augustine Volcano throughout the report period. Guralp CGM 40T 60-second broadband instruments were operated at Mount Spurr, Augustine and Akutan volcanoes for various time periods between 1994 and 1999; however, the telemetry system limited dynamic range of the instrument at Akutan to 12 bits.

Data were telemetered using voltage-controlled oscillators (VCOs) to transform the ground motion signals from the seismometers to frequency-modulated signals suitable for transmission over a telephone circuit. AVO uses both the A1VCO (Rogers and others, 1980) and McVCO (McChesney, 1994) to modulate signals in the field. These signals were subsequently transmitted via UHF and VHF radio to communication hubs located in Anchorage, Homer, Sterling, Kasilof, King Salmon, Port Heiden, King Cove, Cold Bay, Akutan, Dutch Harbor, and Adak. Signals were then relayed via leased telephone circuits to AVO offices in Anchorage and Fairbanks.

The new seismic stations established and operated by AVO during the report period include new networks at Akutan (6 permanent stations, 8 components), Aniakchak (6 stations, 8 components), Great Sitkin (6 stations, 8 components), Kanaga (6 stations, 6 components), Katmai (18 stations, 24 components), Makushin (6 stations, 8 components), Pavlof (6 stations, 8 components), Shishaldin (6 stations, 8 components), and Westdahl (6 stations, 8 components), as well as two new seismic stations at Iliamna Volcano and one new station near Strandline Lake. AVO also added two stations to provide regional coverage of seismic activity in the Adak area. Five temporary stations were also deployed on Akutan Volcano from March 1996 to July 1997 to monitor seismicity associated with that seismic crisis (Lu and others, 2000). The station installation dates and locations (both geographic coordinates and maps) are contained in Appendix A. Time dependant station information such as changes in magnification is contained in the hypoellipse station file (stations.dat) which can be found in the accompanying Unix tar file. To provide an estimate of each station's operational status through the report period we have prepared plots showing station usage for each day. These plots are available as Appendix B, which is provided as a computer file in PDF format that can be downloaded with this report.

Data from AVO stations were digitally recorded at 100 Hz in event detection mode on PC computers in Fairbanks and Anchorage using a modified version of the computer program Xdetect (Rogers, 1993). This program allows the triggering algorithm to be tuned to individual subnets of stations on a specific volcano. The event-detected files were periodically transferred to a SUN microcomputer and converted to AH format for processing using the program Xpick (Robinson, 1990). During the transfer a one

letter code to indicate the volcano subnet that generated the trigger was added to the AH file name. These codes are summarized in Table 3. Triggered events were first visually inspected and classified as a volcano-tectonic, long-period, hybrid, explosion, regional tectonic, teleseismic, or non-seismic event. This classification system is modeled after that described by Lahr and others (1994), and is stored as an individual character in the earthquake location summary line. Events classified as volcano-tectonic, long period, or hybrid and having four or more distinct phases at three or more stations were selected for location. Most earthquakes with a P- and S-wave separation of more than four seconds on stations close to the volcanoes were assumed to come from tectonic sources and were usually discarded. Earthquake hypocenters and local magnitudes were calculated using the program Hypoellipse (Lahr, 1999).

AVO presently uses 8 seismic velocity models to locate earthquakes at selected volcanoes or within selected regions in the manner described by Lahr (1999). The models used to locate earthquakes in this report are summarized in Table 4. The quality of each hypocenter was checked using a computer algorithm that identifies events without magnitude, fewer than three P-phases, less than one S-phase, and standard hypocentral errors greater than 15 km. Events not meeting this requirement were corrected or removed from the final catalog listing.

Table 3: Volcano Designators

Volcano	Designator
Akutan	t
Aniakchak	n
Augustine	a
Dutton	d
Iliamna	i
Great Sitkin and Kanaga (Adak)	f
Katmai	k
Makushin	m
Pavlof	v
Redoubt	r
Shisaldin	h
Spurr	s
Westdahl	w

Discussion and Conclusions

Between January 1, 1994, and December 31, 1999, AVO located 16,167 earthquakes that occurred near volcanoes in the Aleutian arc. Available for download with this report is a compressed Unix tar file that contains the following: 1) a summary listing of earthquake hypocenters; 2) phase arrival information for each located event; 3) a file (stations.dat) containing information on each seismic station (location, elevation, and gain); 4) summary plots showing station usage; and 5) the text of this report. We have also included all necessary input files to relocate these hypocenters using the program Hypoellipse (Lahr, 1999) and phase arrival information collected by AVO from 1989 through 1993 (see Power and others, 1993; Jolly and others, 1996). The reader should refer to Lahr (1999) for information on file formats and instructions for configuring and running the location program Hypoellipse. Archives of waveform data in AH format are maintained on CD at AVO offices in Fairbanks and Anchorage.

Table 4: Velocity models used in AVO processing.

Velocity models for Spurr (Jolly and others, 1994)

Layer number	Vp	Top of layer	Vp/Vs
1	5.1	0.0	1.81
2	5.5	1.0	1.81
3	6.3	8.25	1.74
4	7.2	30.25	1.78

Velocity models for Redoubt and Iliamna (Lahr and others, 1994)

Layer number	Vp	Top of layer	Vp/Vs
1	2.90	0.0	1.80
2	5.10	1.3	1.80
3	6.40	4.5	1.72
4	7.00	20.0	1.78

Velocity model for Augustine (Power, 1988)

Layer number	Vp	Top of layer	Vp/Vs
1	2.3	0.0	1.80
2	2.6	2.3	1.80
3	3.4	3.0	1.80
4	5.1	4.0	1.80
5	6.3	12.0	1.78
6	8.0	47.0	1.78

Velocity model for Katmai, (Jolly, 2000)

Layer number	Vp	Top of layer	Vp/Vs
1	5.0	0.0	1.78
2	5.3	3.0	1.78
3	5.6	5.0	1.78

4	5.9	7.0	1.78
5	6.1	9.0	1.78
6	6.9	18.0	1.78
7	7.4	23.0	1.78
8	7.7	28.0	1.78
9	7.9	36.0	1.78
10	8.1	50.0	1.78
11	8.3	68.0	1.78

Velocity model for Aniakchak and Makushin

Layer number	Vp	Top of layer	Vp/Vs
1	5.3	0.0	1.78
2	5.6	7.0	1.78
3	6.2	13.0	1.78
4	6.9	18.0	1.78
5	7.4	23.0	1.78
6	7.7	28.0	1.78
7	7.9	36.0	1.78
8	8.1	50.0	1.78
9	8.3	68.0	1.78

Pavlof and Dutton (McNutt, 1986, McNutt and Jacob, 1986)

Layer number	Vp	Top of layer	Vp/Vs
1	3.05	0.00	1.78
2	3.44	3.00	1.78
3	5.56	4.79	1.78
4	6.06	6.65	1.78
5	6.72	13.18	1.78
6	7.61	25.63	1.78
7	7.90	41.51	1.78

Akutan (model is a linear increase over a half space).

1	2.30	0.0	1.80
2	0.37	1.0	1.80
3	10.0	2.0	1.80
4	6.30	3.0	1.80
5	200.00	4.0	1.80

Great Sitkin and Kanaga – Adak (Toth and Kisslinger, 1984)

Layer number	Vp	Top of layer	Vp/Vs
1	3.50	0.0	1.73
2	3.88	0.2	1.73
3	4.25	0.4	1.73
4	4.62	0.6	1.73
5	5.00	0.8	1.73
6	5.50	1.0	1.73
7	5.62	2.0	1.73
8	5.74	3.0	1.73
9	5.86	4.0	1.73
10	5.98	5.0	1.73
11	6.10	6.0	1.73
12	6.60	7.0	1.73
13	6.68	8.0	1.73
14	6.80	11.0	1.73

15	6.92	14.0	1.73
16	7.04	17.0	1.73
17	7.16	20.0	1.73
18	7.28	23.0	1.73
19	7.85	26.0	1.73
20	8.05	40.0	1.73

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APENDIX A: AVO Seismic Stations

Station	Latitude (N)	Longitude (W)	Elevation (m)	Installation date
Akutan subnet				
AKS*	54 06.624	165 41.803	213	96/07/24
AKT[B]	54 08.15	165 46.2	12	96/03/18
AHB	54 06.916	165 48.943	447	96/07/24
HSB	54 11.205	165 54.743	497	96/07/24
LVA	54 09.655	166 02.024	457	96/07/24
AKV	54 07.571	165 57.763	863	96/07/24
ZRO	54 05.494	165 58.678	446	96/07/24
AK1[T#]	54 08.15	165 46.2	12	96/03/18
AK2[T#]	54 07.45	165 46.7	90	96/03/18
AK3[T#]	54 08.15	165 46.2	12	96/03/18
AK4[T#]	54 06.6	165 43.9	135	96/03/18
AK5[T#]	54 09.31	165 51.90	225	96/03/18
12 stations - 16 components				
Aniakchak subnet				
ANIA	56 54.339	158 13.759	930	97/07/18
ANNE	56 54.763	158 03.534	705	97/07/18
ANNW	56 57.986	158 12.895	816	97/07/18
ANPB	56 48.141	158 16.847	675	97/07/18
ANPK	56 50.499	158 07.572	972	97/07/18
ANSL*	56 55.942	158 08.171	344	97/07/18
6 stations - 8 components				
Augustine subnet				
AUB[B]	59 22.93	153 26.07	360	95/12/21
AUC	59 21.596	153 25.469	1175	95/09/13
AUD[#]	59 21.759	153 25.588	1208	94/09/06
AUE[+]	59 21.531	153 22.365	168	80/10/29
AUH	59 21.833	153 26.591	890	78/12/01
AUI*	59 20.11	153 25.66	293	78/04/06
AUL	59 22.93	153 26.07	360	78/08/27
AUP	59 21.74	153 25.23	1033	77/09/22
AUR	59 21.766	153 25873	1183	95/11/01
AUS	59 21.599	153 25840	1226	90/09/01
AUW	59 22.205	153 28.249	276	76/10/17
11 stations - 15 components				
Dutton subnet				
DT1	55 06.358	162 16.709	198	91/06/21
DTN	55 09.011	162 14.985	366	88/07/16
DRR3	54 58.015	162 15.671	457	96/07/11
DOL	55 08.960	161 51.683	442	96/07/11
BLDY	55 11.67	162 47.018	259	96/07/11
BLHA	55 42.227	162 03.907	411	96/07/11
6 stations - 6 components				

AVO Stations-continued.

Station	Latitude (N)	Longitude (W)	Elevation (m)	Installation date
Great Sitkin subnet				
GSCK	52 00.712	176 09.718	384	99/09/15
GSMY	52 02.594	176 03.376	418	99/09/03
GSSP	52 05.566	176 10.541	295	99/09/15
GSTD*	52 03.356	176 08.685	873	99/09/03
GSTR	52 05.655	176 03.546	536	99/09/03
GSIG	51 59.181	175 55.502	407	99/09/03
6 stations - 8 components				
Iliamna subnet				
ILI	60 04.81	152 57.57	823	87/09/15
INE	60 03.65	153 03.75	1585	90/08/29
IVE*	60 00.972	153 00.993	1110	96/09/19
ILW	60 03.60	153 08.17	1722	94/09/09
IVS	60 00.55	153 04.85	2332	90/08/29
ILS	59 57.454	153 04.083	1107	96/08/28
6 stations - 8 components				
Kanaga subnet				
KICM	51 55.136	177 11.718	183	99/09/15
KIKV	51 52.730	177 10.223	411	99/09/15
KIMD	51 45.697	177 14.093	183	99/09/15
KINC	51 55.884	177 07.657	198	99/09/15
KIRH	51 53.976	177 05.611	309	99/09/15
KIWB	51 51.183	177 09.049	244	99/09/15
6 stations - 6 components				
Katmai subnet				
ACH*	58 12.64	155 19.56	960	96/07/25
KJL	58 03.24	155 34.39	792	96/07/25
KVT	58 22.90	155 17.70	457	88//08/01
MGLS	58 08.06	155 09.65	472	96/07/25
ANCK	58 11.93	155 29.64	869	96/07/25
CAHL	58 03.15	155 18.09	807	96/07/25
CNTC	58 15.87	155 53.02	1158	96/07/25
KABR	58 07.87	154 58.15	884	98/10/12
KAHC	58 38.94	155 00.36	1250	98/10/12
KAHG	58 29.64	154 32.78	923	98/10/12
KAIC	58 29.10	155 02.75	734	98/10/12
KAPH*	58 35.81	154 20.81	907	98/10/12
KARR	58 29.87	154 42.20	610	98/10/12
KAWH	58 23.02	154 47.95	777	98/10/12
KBM	58 16.50	155 12.10	732	91/07/22
KCE	58 14.60	155 11.00	777	91/07/22
KCG*	58 18.457	155 06.684	762	88//08/01
KEL	58 26.401	155 44.442	975	88//08/01
18 stations - 24 components				

AVO Stations-continued.

Station	Latitude (N)	Longitude (W)	Elevation (m)	Installation date
Makushin				
MCIR	53 57.08	166 53.51	800	96/07/25
MSOM	53 48.99	166 56.94	50	96/07/25
MSW*	53 54.88	166 46.96	418	96/07/25
MTLB	53 58.16	166 40.71	865	96/07/25
MGOD	53 47.68	166 52.35	695	96/07/25
MNAT	53 53.03	166 41.00	390	96/07/25
6 stations - 8 components				
Pavlof subnet				
PV6*	55 27.227	161 55.138	747	96/07/11
PN7A	55 26.009	161 59.757	838	96/07/11
PS1A	55 25.321	161 44.425	293	96/07/11
PVV	55 22.438	161 47.396	161	96/07/11
PS4A	55 20.811	161 51.233	322	96/07/11
HAG	55 19.068	161 54.150	503	96/07/11
6 stations - 8 components				
Redoubt subnet				
RDT	60 34.394	152 24.315	930	71/08/09
DFR	60 35.514	152 41.160	1090	88/08/15
NCT	60 33.789	152 55.568	1079	88/08/14
RDN	60 31.370	152 44.256	1400	88/08/13
RDW	60 28.96	152 48.57	1813	90/09/07
REF*[%]	60 29.35	152 42.10	1801	92/07/27
RSO	60 27.73	152 45.23	1921	90/03/01
RED*	60 25.192	152 46.308	1064	90/08/30
8 stations - 13 components				
Shishaldin subnet				
ISNN	54 49.925	163 46.700	546	97/07/27
ISTK	54 43.980	163 42.330	453	97/07/27
BRPK	54 38.719	163 44.475	420	97/07/27
SSLN	54 48.709	163 59.756	637	97/07/27
SSLS*	54 42.718	163 59.926	771	97/07/27
SSLW	54 46.307	164 07.282	628	97/07/27
6 stations - 8 components				
Spurr subnet				
STLK	61 29.923	151 49.979	945	97/09/01
NCG	61 24.22	152 09.40	1244	89/08/06
CGL	61 18.46	152 00.40	1082	81/09/22
CRP*	61 16.02	152 09.33	1622	81/08/26
CRB[B#]	61 16.02	152 09.33	1622	93/08/02
CP2	61 15.85	152 14.51	1981	92/10/23
BGL	61 16.02	152 23.30	1207	89/08/13
CKN	61 13.44	152 10.89	735	91/08/19

AVO Stations-continued.

Station	Latitude (N)	Longitude (W)	Elevation (m)	Installation date
CKT	61 12.05	152 12.37	975	92/09/16
SPU	61 10.90	152 3.26	800	71/08/10
10 stations - 12 components				
Westdahl subnet				
WTUG	54 50792	164 23258	636	98/08/17
WPOG	54 35776	164 44772	445	98/08/17
WESN	54 34342	164 34804	549	98/08/17
WFAR	54 31967	164 46690	640	98/08/28
WESS*	54 28795	164 43428	908	98/08/28
WESE	54 28344	164 35188	953	98/08/28
6 stations - 8 components				
Regional stations				
ADAG	51 58.812	176 36.104	286	99/09/15
CDD	58 55.79	153 38.58	622	81/08/17
ETKA	51 51.712	176 24.351	290	99/09/15
SKN*	61 58.82	151 31.78	564	72/08/08
NNL	60 02.66	151 17.36	381	72/08/24
OPT	59 39.16	153 13.78	450	74/01/01
HOM	59 39.50	151 38.60	198	76/08/01
PDB	59 47.27	154 11.55	305	78/09/09
MMN	59 11.11	154 20.20	442	81/08/22
BGM	59 23.56	155 13.76	625	78/09/08
SYI	58 36.60	152 23.45	149	90/08/27
XLV	59 27.28	151 40.30	320	87/09/16
BKG	61 04.21	152 15.76	1009	91/07/01
BGR	60 45.45	152 25.06	985	91/07/01
NAG	54 58.70	160 08.30	305	93/06/01
CNB	54 49.22	159 35.30	11	73/01/01
16 stations - 18 components				

[*] 3-componet SP station
[B] Broad-band Instrument (all have three components)
[T] Temporary station
[#] No longer in operation
[+]Station moved 97/09/06, prior coordinates 59N33.02, 153W33.02, 172 m elevation.
[%]REF also has a low-gain vertical component.

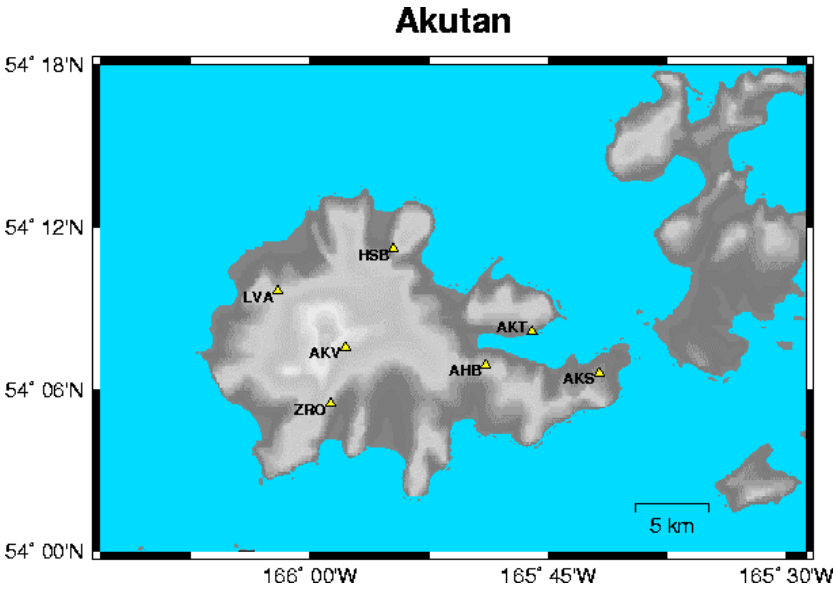

Figure 2. AVO seismic stations on Akutan Island.

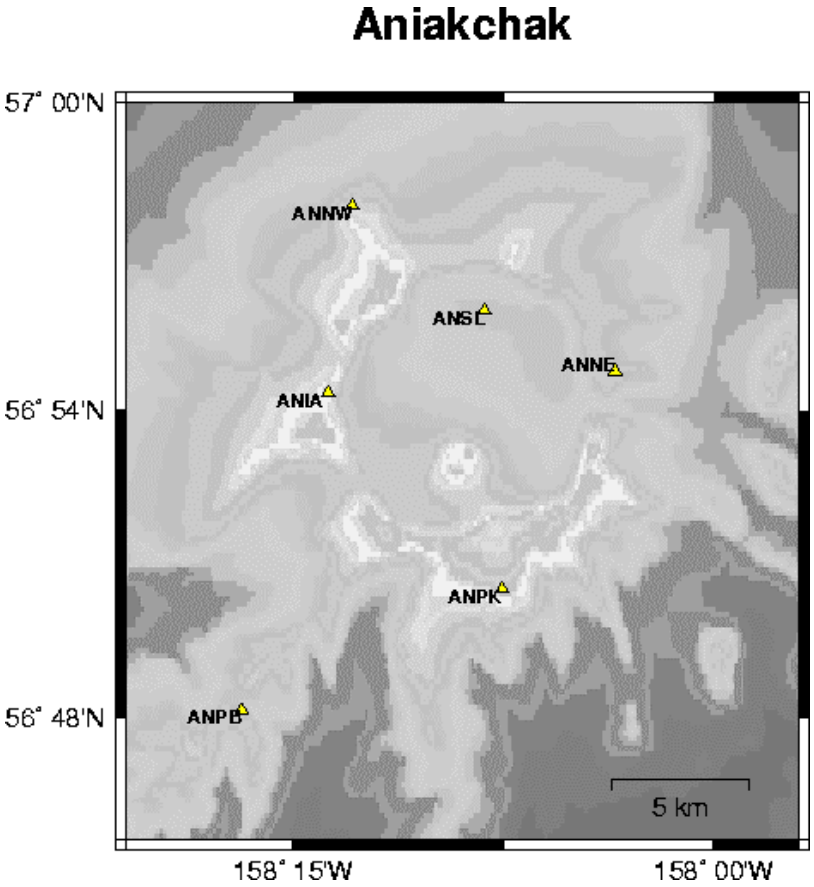

Figure 3. AVO seismic stations near Aniakchak Crater.

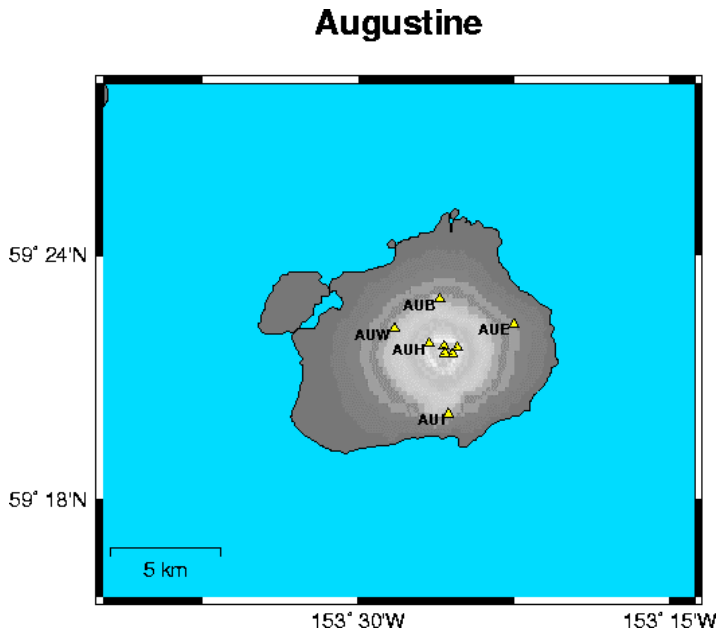

Figure 4. AVO seismic stations on Augustine Island. Stations AUS, AUC, AUP, and AUR are not labeled.

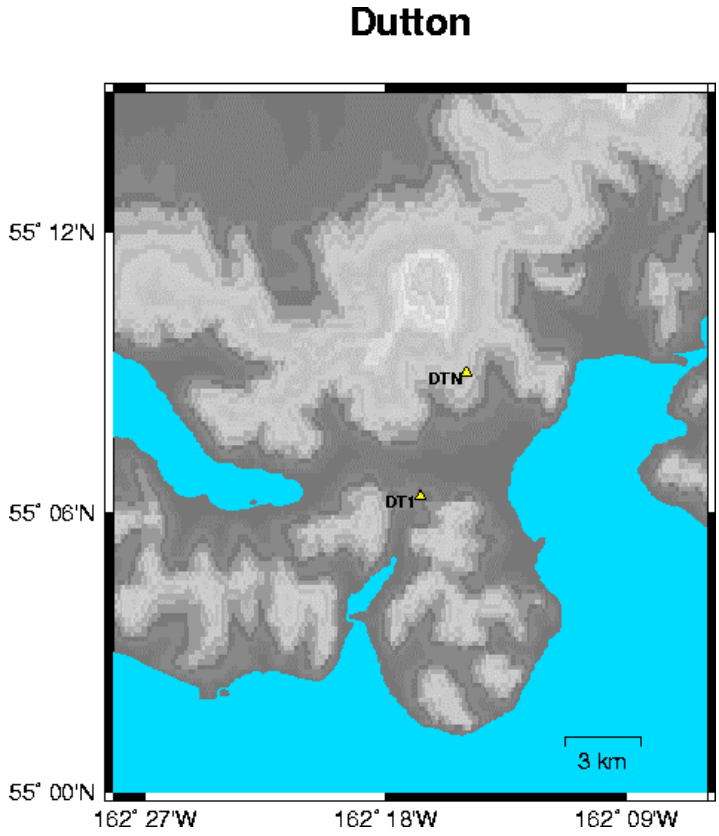

Figure 5. AVO seismic stations near Mount Dutton.

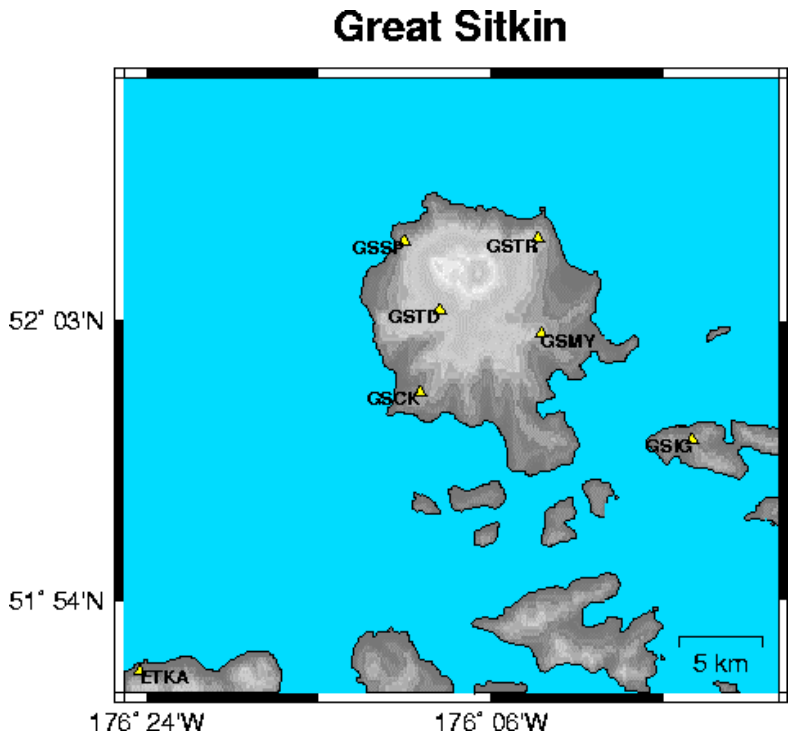

Figure 6. AVO seismic stations near Great Sitkin volcano.

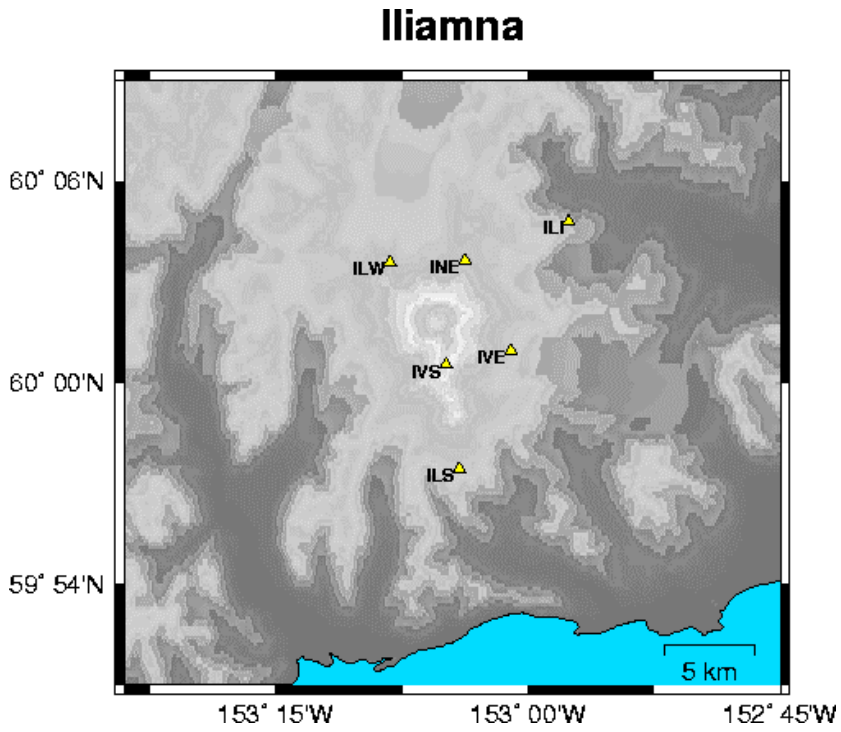

Figure 7. AVO seismic stations near Iliamna Volcano.

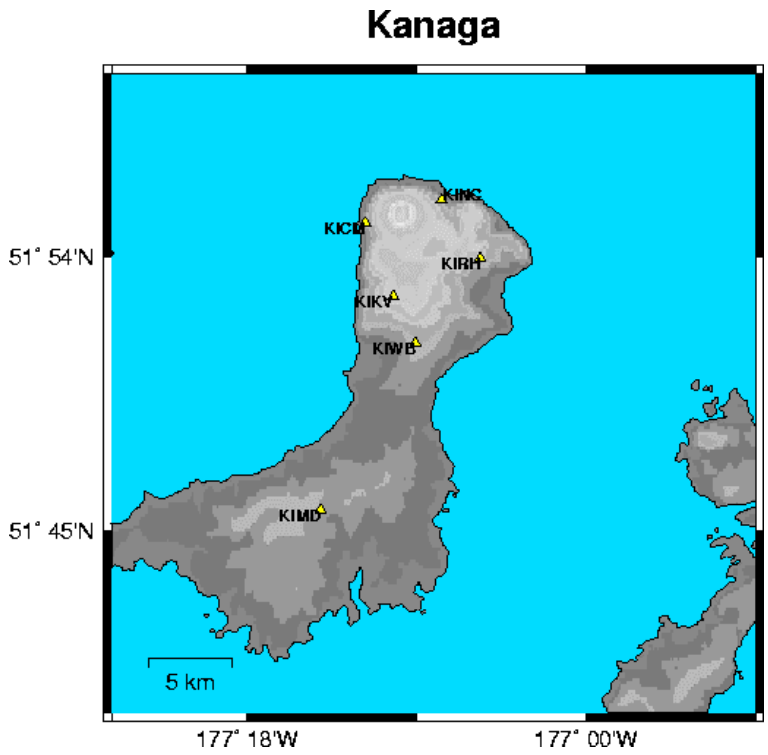

Figure 8. AVO seismic stations on Kanaga Island.

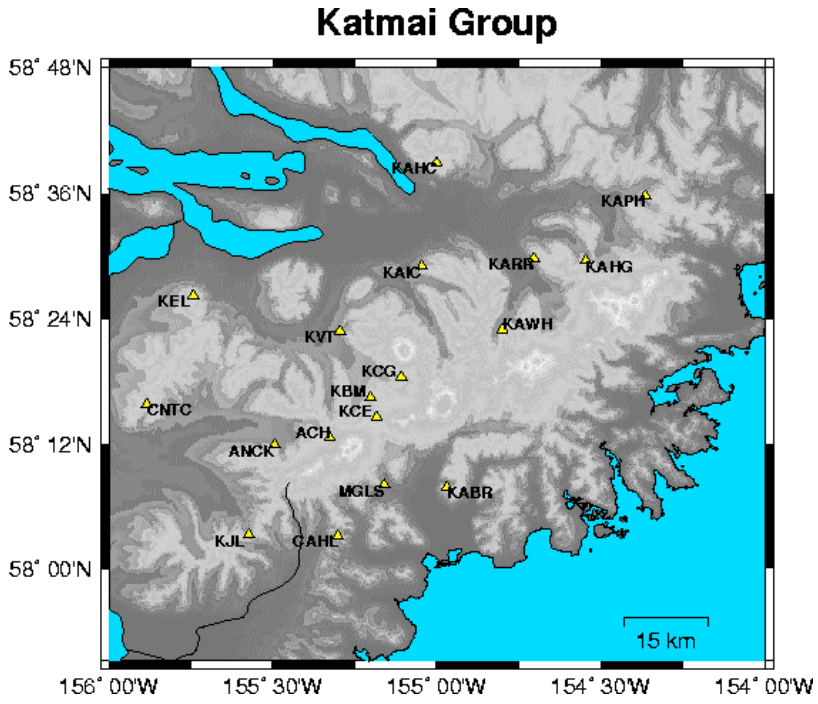

Figure 9. AVO seismic stations near the Katmai Volcanoes.

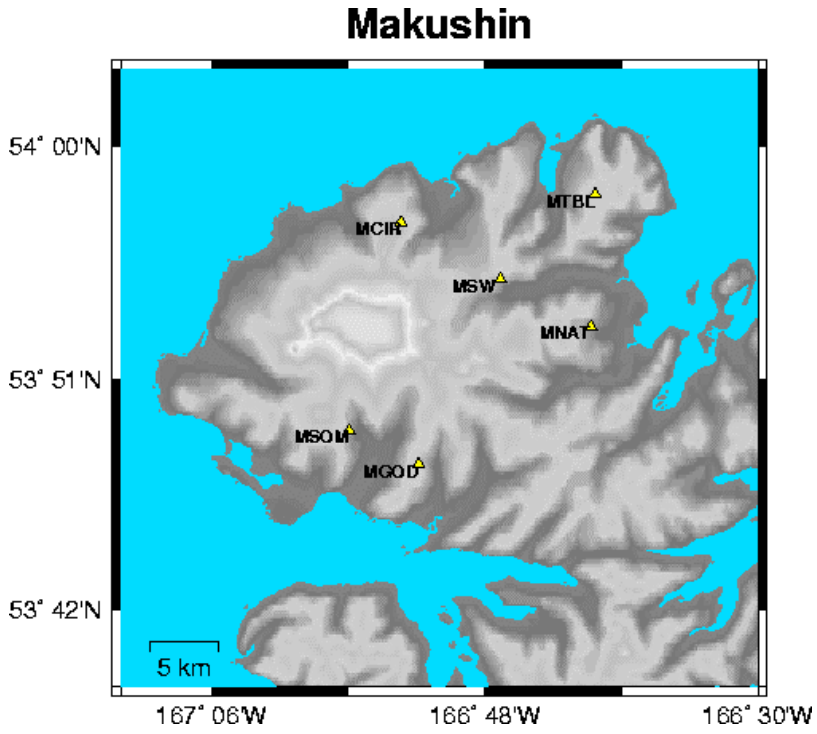

Figure 10. Seismic stations near Makushin Volcano.

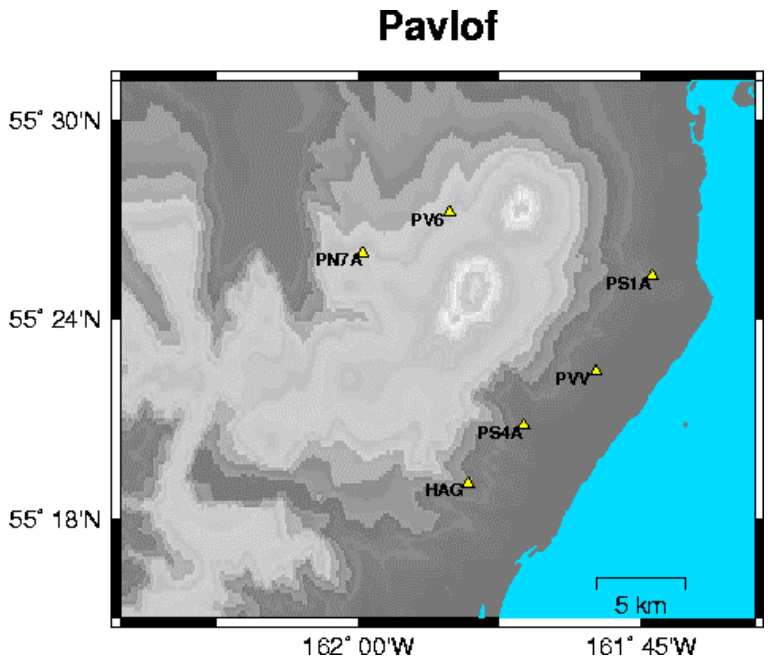

Figure 11. AVO seismic stations near Pavlof Volcano.

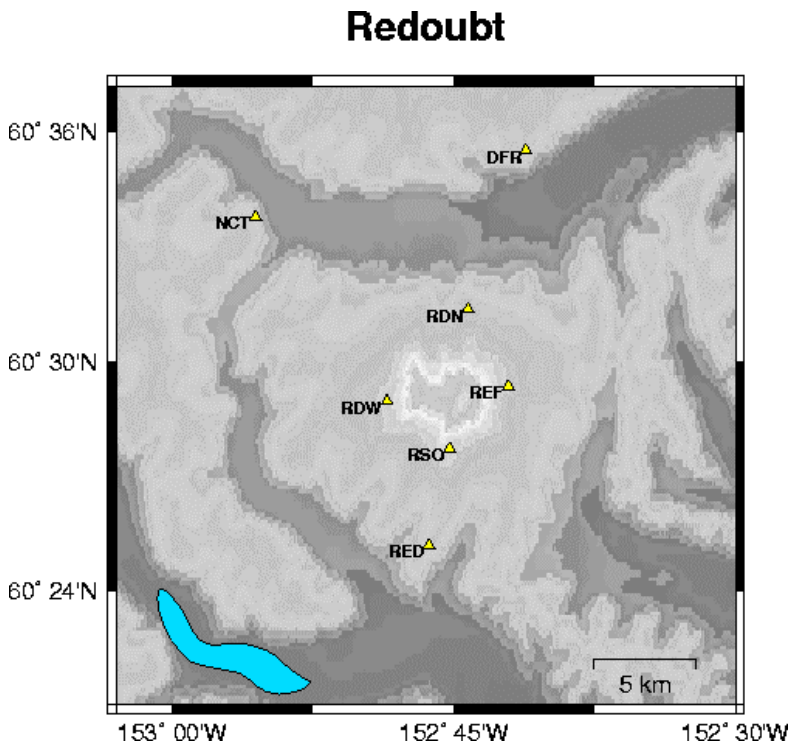

Figure 12. AVO seismic stations near Redoubt Volcano.

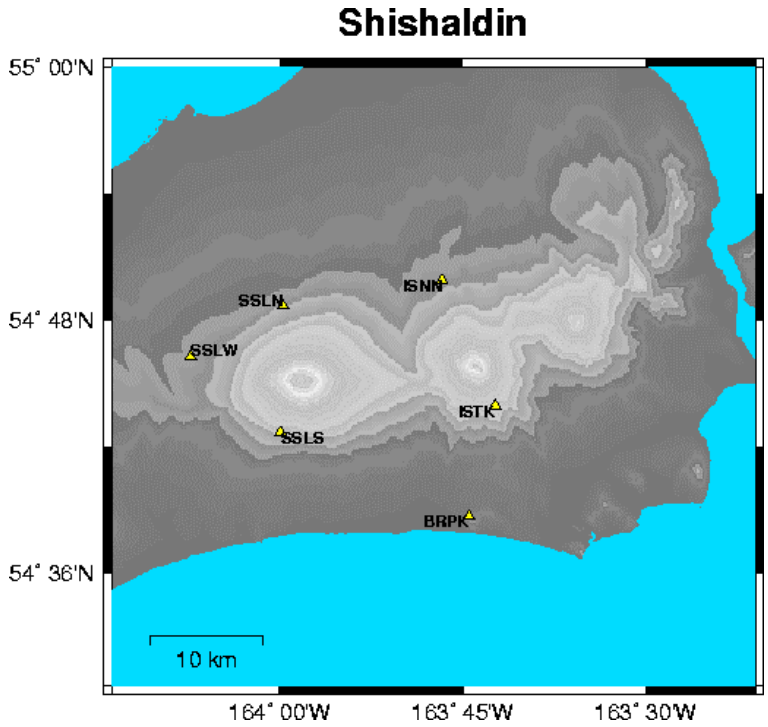

Figure 13. AVO seismic stations near Shishaldin Volcano.

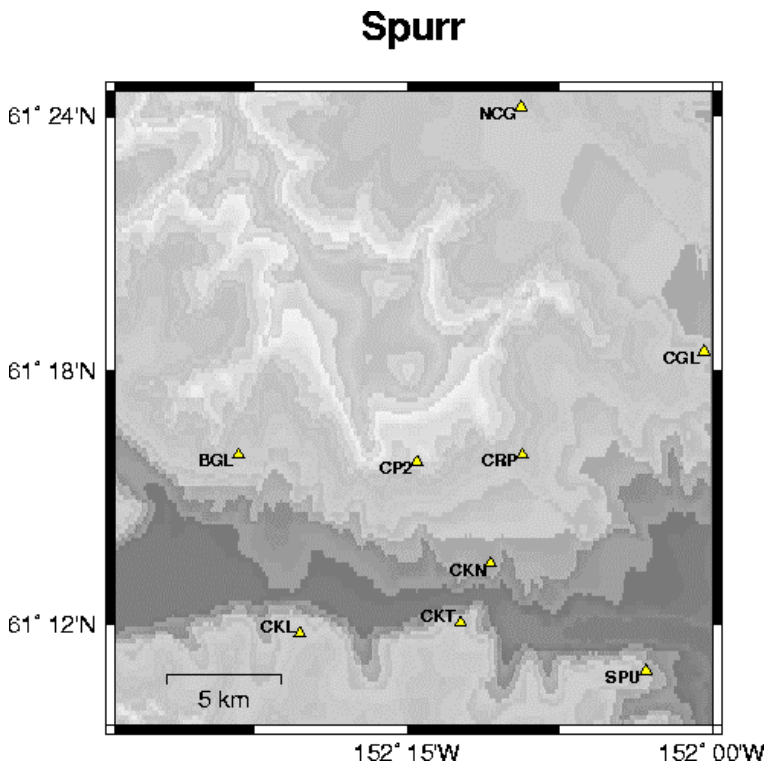

Figure 14. AVO seismic stations near Mount Spurr.

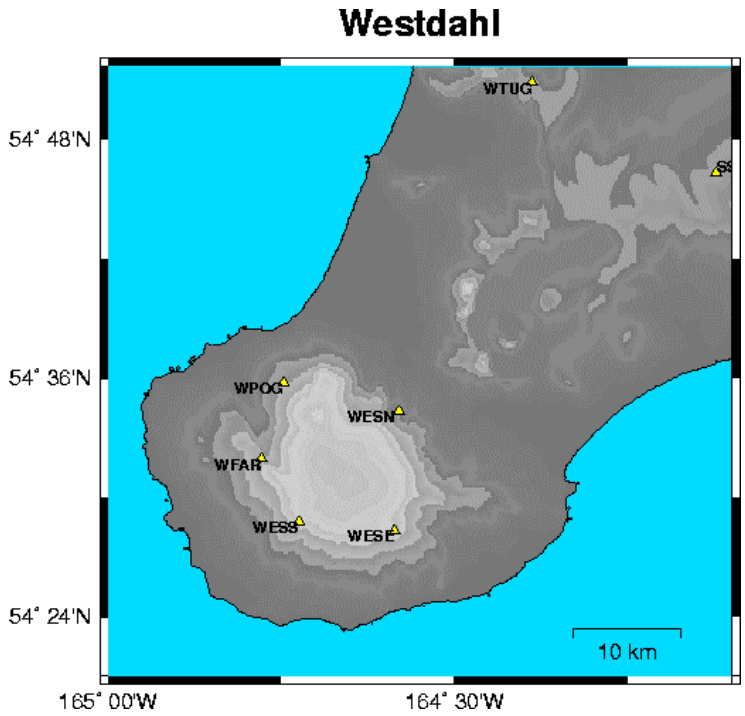

Figure 15. AVO seismic stations on Westdahl volcano.

APPENDIX B

This appendix contains monthly plots showing station usage per day for each station in each sub-network operated by AVO. These plots provide a measure of both an individual station's operational health and earthquake frequency near a given volcano. We note that an absence of seismicity at a given network might imply either a station outage or a lack of seismicity. The contents are expressed by year and subnet. These plots are in a separate PDF file that is available for download with this report. Appendix B is 180 pages in length.