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GEOLOGICAL SURVEY

Measurements of slope distances and zenith angles at Newberry and South Sister volcanoes, Oregon, 1985-1986

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ABSTRACT

Between 1980 and 1984, the U. S. Geological Survey's David A. Johnston Cascades Volcano Observatory (CVO) established baseline geodetic networks at Mount Baker, Mount Rainier, and Mount St. Helens in Washington, Mount Hood and Crater Lake in Oregon, and Mount Shasta and Lassen Peak in California. To this list of potentially active volcanoes, CVO extended its monitoring program in 1985 to include Newberry and South Sister volcanoes in central Oregon. The Newberry and South Sister networks were re-measured in 1986 and will be measured periodically in future years. Improvements since 1984 in the recording of endpoint and flightline temperatures resulted in better overall data than obtained previously. The improvements included: calibration of all the sensors and precision thermistors, installation of a new recording system for flightline data, and recording of endpoint temperatures 6 m above ground level. The data collected in 1985 and 1986 indicate little or no apparent deformation at either volcano between surveys.

INTRODUCTION

In 1985 the U. S. Geological Survey's David A. Johnston Cascades Volcano Observatory (CVO) added Newberry and South Sister volcanoes, both located in the central High Cascades Range of Oregon, to its geodetic monitoring program of Cascade volcanoes (fig. 1). Both volcanoes are potentially active and warrant monitoring similar to that which CVO has already implemented at Mount Baker, Mount Rainier, and Mount St. Helens in Washington, Mount Hood and Crater Lake in Oregon, and Mount Shasta and Lassen Peak in California. Newberry volcano is similar to Crater Lake in that both have summit calderas that contain lakes. Newberry, however, contains two lakes and was last active 1400 years ago (MacLeod and others, 1981). South Sister volcano, 3157 m high, is the tallest of the three major peaks known as the Three Sisters and was last active during two brief episodes between 2300 and 2000 yr B.P. (Scott, 1987).

The geodetic networks at Newberry and South Sister consist of Electromagnetic Distance Measurement (EDM) and leveling lines. The EDM network at Newberry lies mainly within the summit caldera and consists of 11 lines and zenith angles, all measured from one instrument station. One 8.7 km leveling line also crosses the summit caldera (Yamashita and Doukas, 1987). At South Sister are 24 EDM lines and zenith angles, measured from 5 instrument stations, and four 200-500 m long leveling lines. The leveling results at Newberry and South Sister between 1985 and 1986 showed little or no change beyond the expected leveling error. Presented here are the calculated mark-to-mark slope distances using both endpoint and flightline temperatures. Zenith angles were measured for both surveys but were used only to calculate benchmark elevations.

Monitoring of volcanoes has proven useful in helping to detect magma movement prior to eruptions (Kinoshita and others, 1974; Lipman and others, 1981). Consequently, CVO hopes to establish baseline data on all potentially hazardous volcanoes in the Cascade Range. The networks recently established at Newberry and South Sister volcanoes are designed to provide such baseline data. If future activity should occur, the networks could be expanded to meet any perceived needs. The networks are planned to be measured every 3 to 5 years as an additional precautionary measure.

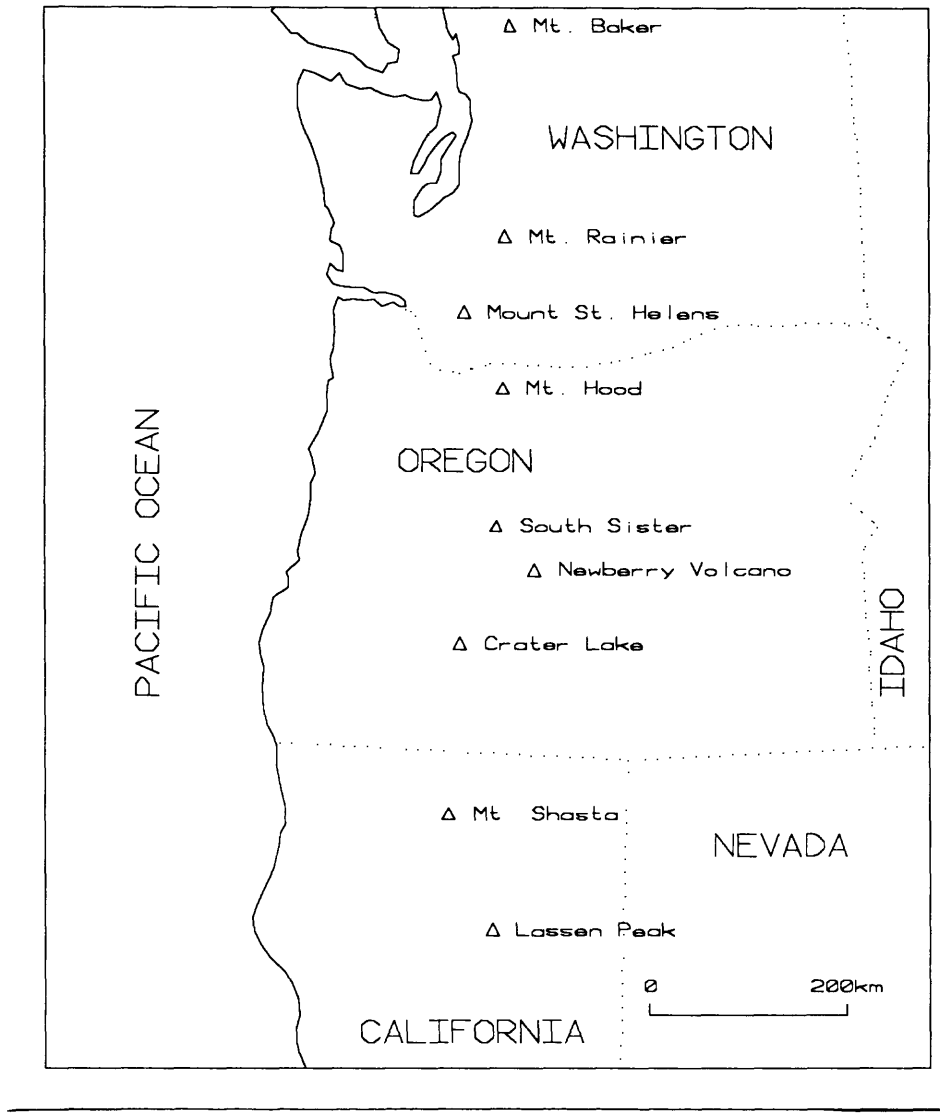

Figure 1. Map showing Cascade volcanoes monitored by the Cascades Volcano Observatory.

EQUIPMENT AND PROCEDURES

The EDM networks at Newberry and South Sister volcanoes resemble those already existing at other Cascade volcanoes (Chadwick and others, 1985). The bench mark installations, surveying equipment, and procedures followed are the same. The significant changes from the previous surveys are in the measurement of endpoint temperatures, the calibration of the temperature sensors and precision thermistors, and in the data transfer of fightline temperatures and humidities to the mainframe computer.

Endpoint temperatures are affected by ground radiation, but W. H. Prescott (1971) has shown that measuring temperatures 7 m or more above ground

level can negate this problem. Beginning in 1985, CVO devised a method to record temperatures at a height of 6 m above ground level to minimize this ground effect. CVO's EDM work involves the use of helicopters, which limit the space and restrict the size of the equipment used. The implementation of a telescoping bamboo fishing rod to hold the temperature shield enabled the sensor to be a stable 6 m high and still fit into a helicopter (Bell 206) cargo compartment. To furthur enhance the accuracy, all temperature sensors are now calibrated yearly against a highly accurate quartz thermometer in an environmental chamber at 1°C intervals between -20°C and +50°C.

The flightline temperatures were still measured using precision thermistors. Since 1985, the thermistors have been calibrated yearly, and a new heating coefficient for relatively low air speeds (less than 70 knots) has been calculated. The hygristor (humidity sensor) was new and untested in 1985. It has performed well and requires no maintenance during the day. The older hygristor had to be physically changed when saturated. It was common to change the hygristor several times a day for better data.

A new flightline recording system using an Hewlett Packard (HP) 71B handheld computer and an HP3421A data acquisition/control unit was also initiated. This allowed transferal of temperature and humidity data directly from the 71B into the VAX 11/750 mainframe computer, thus eliminating the errors inherent in the hand transferal of data.

A list of current equipment used is given in Appendix C.

RESULTS

Tables 1 and 2 list the mark-to-mark slope distance changes calculated from endpoint temperatures and pressures, and from flightline data, respectively. Table 3 lists the zenith angles and their averages for the two survey years. The large discrepency in zenith angles of line 6 at South Sister needs to be explained. In 1985, bench mark SS5 was the instrument set-up, while in 1986, bench mark SS4 was used. Therefore, angles shown for line 6 are actually reciprocal angles. To ensure the accuracy of these angles, curvature and refraction corrections were applied (Bevin, 1983) to each angle. Using either bench mark as the instrument site for both years, the difference in angles from 1985 to 1986 is 5 seconds. This confirms that the reciprocal angles are good.

Figures 2 and 3 show the network at Newberry with the endpoint and flightline mark-to-mark slope distance changes, respectively. Figures 4 and 5 show the network at South Sister with the endpoint and flightline changes, respectively. A change in the calculation of flightline data was made and is explained in Appendix D. Maps showing station locations, line numbers, station photographs, and bench mark descriptions are in Appendicies A and B.

If it is assumed that no strain occured in the two networks, precisions for 32 endpoint and 31 flown lines can be calculated. The mean precision for endpoint data is 1.57±1.57 ppm, and for flightline data is 1.79±1.55 ppm. An overall precision for all 63 lines is 1.68±1.56 ppm. Included in tables 1 and 2 are mean precisions for each volcano.

Table 1. Endpoint mark-to-mark slope distances for Newberry and South Sister.

NEWBERRY

Line #	(BM-BM)	Slope distance 1985	Slope distance 1986	Change meters	Change ppm
1	(PP-N1)	5225.819	5225.822	+.003	+0.6
2	(PP-N2)	4726.951	4726.954	+.003	+0.6
3	(PP-N3)	3985.057	3985.060	+.003	+0.8
4	(PP-N4)	4352.048	4352.057	+.009	+2.1
5	(PP-N5)	6548.740	6548.747	+.007	+1.1
6	(PP-N6)*	7989.525			
7	(PP-N7)	6494.914	6494.912	-.002	-0.3
8	(PP-N8)	5277.286	5277.284	-.002	-0.4
9	(PP-N9)	6415.770	6415.763	-.007	-1.1
10	(PP-N10)	3987.567	3987.567	.000	0.0
11	(PP-NPP)	6629.183	6629.183	.000	0.0

Mean precision = 0.70±0.63 ppm for 10 lines.
* - Bench mark N6 removed by vandals. No replacement installed.

SOUTH SISTER

Line #	(BM-BM)	Slope distance 1985	Slope distance 1986	Change meters	Change ppm
1	(SS3-SS7)	2786.239	2786.236	-.003	-1.1
2	(SS4-SS7)	3065.245	3065.243	-.002	-0.6
3	(SS4-SUMMIT)*	3328.312	3321.254		
4	(SS4-SS10)	2536.564	2636.569	+.005	+2.0
5	(SS4-SS9)	3263.211	3263.223	+.012	+3.7
6	(SS4-SS5)	4756.635	4756.626	-.009	-1.9
7	(SS5-SS10)	3752.340	3752.335	-.005	-1.3
8	(SS5-SUMMIT)*	4419.695	4426.028		
9	(SS5-SS9)	3293.252	3293.241	-.011	-3.3
10	(SS5-SS13)	3608.944	3608.946	+.002	+0.6
11	(SS5-SS6)	3304.364	3304.362	-.002	-0.6
12	(SS5-SS1)	6151.456	6151.455	-.001	-0.2
13	(SS1-SS6)	3521.068	3521.042	-.026	-7.4
14	(SS1-SS13)	4556.192	4556.192	.000	.0
15	(SS1-SS12)	5125.162	5125.174	+.012	+2.3
16	(SS1-SS16)	2614.367	2614.376	+.009	+3.4
17	(SS1-SS14)	5256.146	5256.146	.000	+0.0
18	(SS1-SS15)	4993.690	4993.686	-.004	-0.8
19	(SS2-SS12)	5085.010	5085.023	+.013	+2.6
20	(SS2-SS14)	4372.910	4372.916	+.006	+1.4
21	(SS2-SS15)	3287.013	3287.015	+.002	+0.6
22	(SS2-SS8)	5807.041	5807.068	+.027	+4.7
23	(SS3-SS14)	3329.333	3329.341	+.008	+2.4
24	(SS3-SS8)	2260.467	2260.458	-.009	-4.0

Mean precision = 2.04±1.82 ppm for 22 lines.
* - USGS SUMMIT bench mark lost. Used Reference Mark 2 (RM2) in 1986.

Table 2. Flightline mark-to-mark slope distance changes for Newberry and South Sister.

NEWBERRY

Line #	(BM-BM)	Slope distance 1985	Slope distance 1986	Change meters	Change ppm
1	(PP-N1)	5225.844	5225.847	+.003	+0.6
2	(PP-N2)	4727.007	4727.009	+.002	+0.4
3	(PP-N3)	3985.103	3985.106	+.003	+0.7
4	(PP-N4)	4352.101	4352.106	+.005	+1.1
5	(PP-N5)	6548.829	6548.829	.000	0.0
6	(PP-N6)*	7989.617			
7	(PP-N7)	6494.991	6494.989	-.002	-0.3
8	(PP-N8)	5277.349	5277.346	-.003	-0.6
9	(PP-N9)	6415.850	6415.845	-.005	-0.8
10	(PP-N10)	3987.613	3987.615	+.002	+0.5
11	(PP-NPP)	6629.260	6629.258	-.002	-0.3

Mean precision = 0.53±0.31 ppm for 10 lines.
* - Bench mark N6 removed by vandals. No replacement installed.

SOUTH SISTER

Line #	(BM-BM)	Slope distance 1985	Slope distance 1986	Change meters	Change ppm
1	(SS3-SS7)	2786.271	2786.272	+.001	+0.4
2	(SS4-SS7)	3065.285	3065.283	-.002	-0.7
3	(SS4-SUMMIT)*	3328.364	3321.296		
4	(SS4-SS10)	2536.595	2636.599	+.004	+1.6
5	(SS4-SS9)	3263.252	3263.260	+.008	+2.4
6	(SS4-SS5)	4756.689	4756.680	-.009	-1.9
7	(SS5-SS10)	3752.378	3752.370	-.008	-2.1
8	(SS5-SUMMIT)*	4419.746	4426.084		
9	(SS5-SS9)	3293.278	3293.279	+.001	-0.3
10	(SS5-SS13)	3608.979	3608.990	+.011	+3.0
11	(SS5-SS6)**	3304.390			
12	(SS5-SS1)	6151.520	6151.535	+.015	+2.4
13	(SS1-SS6)	3521.108	3521.085	-.023	-6.5
14	(SS1-SS13)	4556.241	4556.252	+.011	+2.4
15	(SS1-SS12)	5125.210	5125.229	+.019	+3.7
16	(SS1-SS16)	2614.395	2614.409	+.014	+5.4
17	(SS1-SS14)	5256.203	5256.218	+.015	+2.8
18	(SS1-SS15)	4993.740	4993.747	+.007	+1.4
19	(SS2-SS12)	5085.070	5085.081	+.011	+2.2
20	(SS2-SS14)	4372.962	4372.966	+.004	+0.9
21	(SS2-SS15)	3287.060	3287.055	-.005	-1.5
22	(SS2-SS8)	5807.118	5807.135	+.017	+2.9
23	(SS3-SS14)	3329.372	3329.378	+.006	+1.8
24	(SS3-SS8)	2260.496	2260.487	-.009	-4.0

Mean precision = 2.39±1.54 ppm for 21 lines.
* - USGS SUMMIT bench mark lost. Used Reference Mark 2 (RM2) in 1986.
** - Flight line data lost for 1986.

Table 3. Mark-to-mark zenith angles for Newberry and South Sister.

NEWBERRY

Shot (BM-BM)	Line #	Zenith angle (deg. min. sec.)		
		1985	1986	Average
PP-N1	1	97°22'51"	97°22'54"	97°22'52.5"
PP-N2	2	96°01'38"	96°01'47"	96°01'42.5"
PP-N3	3	96°38'18"	96°38'21"	96°38'19.5"
PP-N4	4	94°10'12"	94°10'17"	94°10'14.5"
PP-N5	5	93°35'31"	93°35'32"	93°35'31.5"
PP-N6*	6	91°45'15"		
PP-N7	7	93°50'41"	93°50'35"	93°50'38.0"
PP-N8	8	94°13'15"	94°13'15"	94°13'15.0"
PP-N9	9	93°14'41"	93°14'43"	93°14'42.0"
PP-N10	10	94°33'58"	94°33'44"	94°33'51.0"
PP-NPP	11	90°48'44"	90°48'45"	90°48'44.5"

* - Bench mark N6 removed by vandals. No replacement installed.

SOUTH SISTER

Shot (BM-BM)	Line #	Zenith angle (deg. min. sec.)		
		1985	1986	Average
SS3-SS7	1	79°40'03"	79°40'17"	79°40'10.0"
SS4-SS7	2	84°58'43"	84°58'38"	84°58'40.5"
SS4-SUMMIT*	3	74°54'35"		
SS4-RM2*	3		74°53'56"	
SS4-SS10	4	82°07'33"	82°07'31"	82°07'32.0"
SS4-SS9	5	81°21'40"	81°21'34"	81°21'37.0"
SS4-SS5**	6	90°59'01"	89°03'17"	
SS5-SS10	7	85°55'06"	85°55'06"	85°55'06.0"
SS5-SUMMIT*	8	79°45'21"		
SS5-RM2*	8		79°47'11"	
SS5-SS9	9	82°50'41"	82°50'36"	82°50'38.5"
SS5-SS13	10	85°27'16"	85°27'10"	85°27'13.0"
SS5-SS6	11	89°27'20"	89°27'23"	89°27'21.5"
SS5-SS1	12	92°52'30"	92°52'30"	92°52'30.0"
SS1-SS6	13	84°30'37"	84°30'42"	84°30'39.5"
SS1-SS13	14	82°32'53"	82°32'51"	82°32'52.0"
SS1-SS12	15	82°16'46"	82°16'49"	82°16'47.5"
SS1-SS16	16	88°38'38"	88°38'38"	88°38'38.0"
SS1-SS14	17	85°16'25"	85°16'26"	85°16'25.5"
SS1-SS15	18	88°25'40"	88°25'42"	88°25'41.0"
SS2-SS12	19	81°46'42"	81°46'41"	81°46'41.5"
SS2-SS14	20	83°47'57"	83°47'55"	83°47'56.0"
SS2-SS15	21	86°54'58"	86°55'06"	86°55'02.0"
SS2-SS8	22	85°06'21"	85°06'18"	85°06'19.5"
SS3-SS14	23	82°24'17"	82°24'27"	82°24'22.0"
SS3-SS8	24	78°08'57"	78°08'32"	78°08'44.5"

* - USGS SUMMIT bench mark lost. Reference Mark 2 (RM2) was used in 1986.
** - 1985 angles shot from SS5-SS4, and in 1986 angles shot from SS4-SS5.

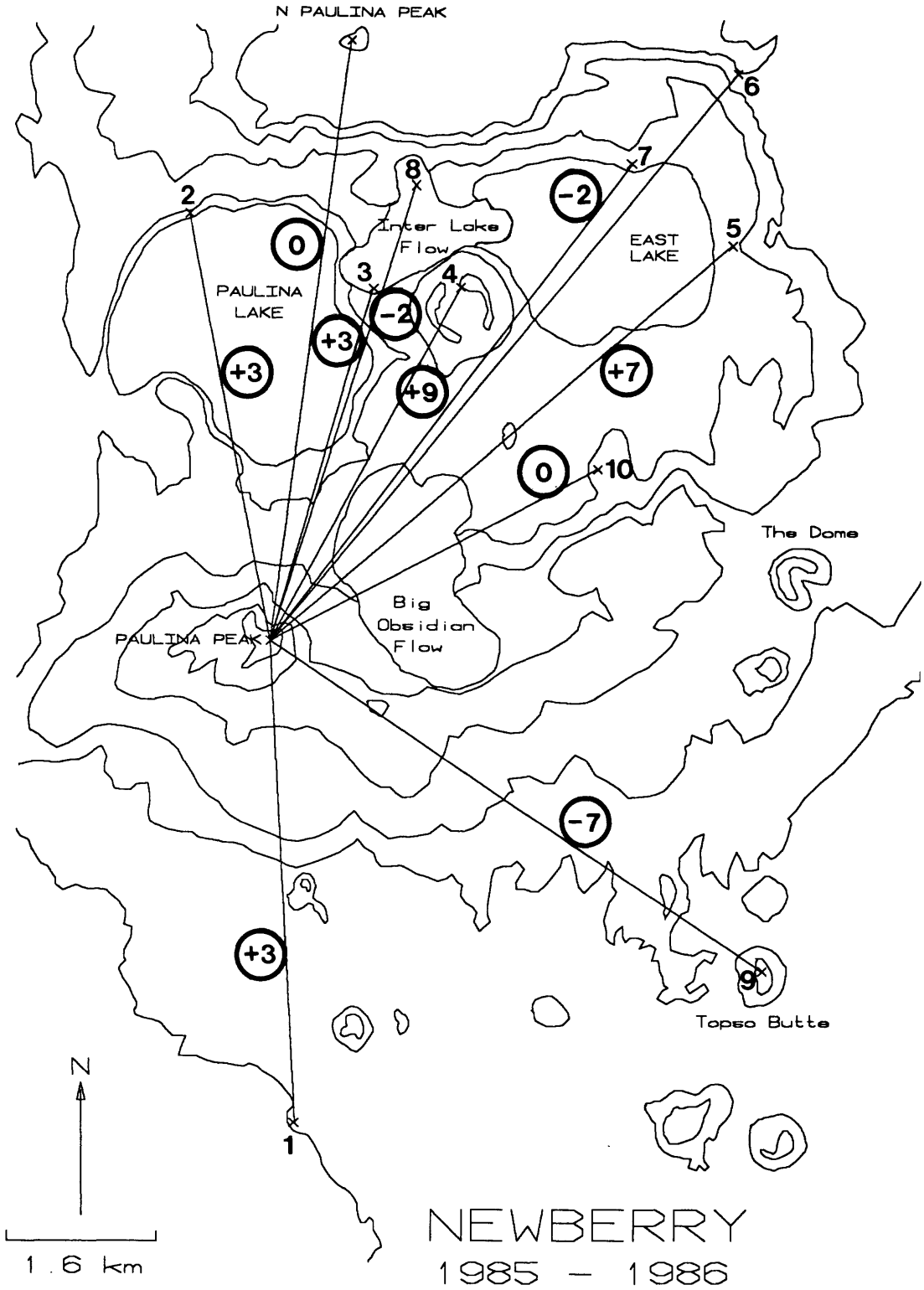

Figure 2. Schematic map showing endpoint mark-to-mark slope distance changes in millimeters at Newberry, Oregon.

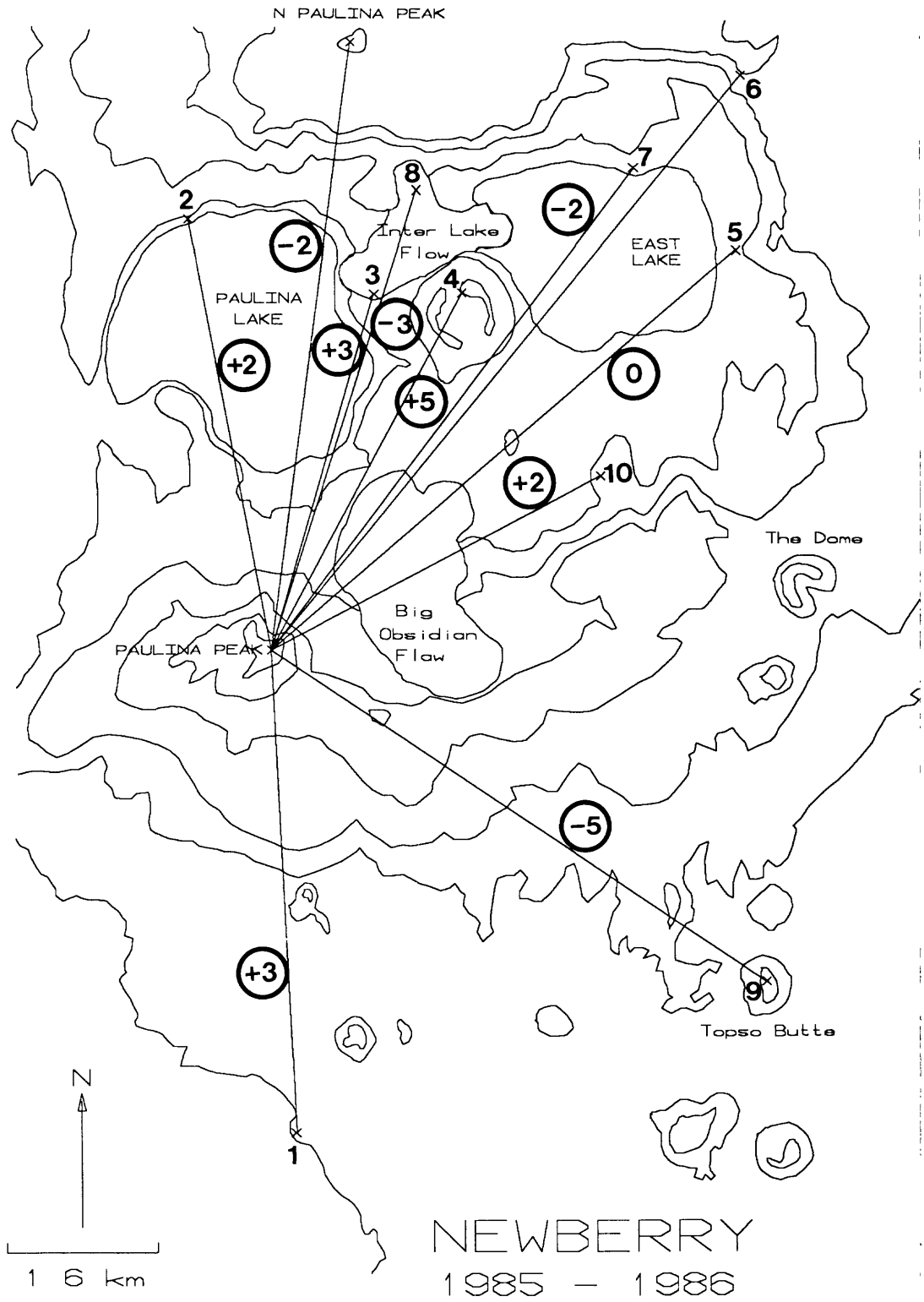

Figure 3. Schematic map showing flightline mark-to-mark slope distance changes in millimeters at Newberry, Oregon.

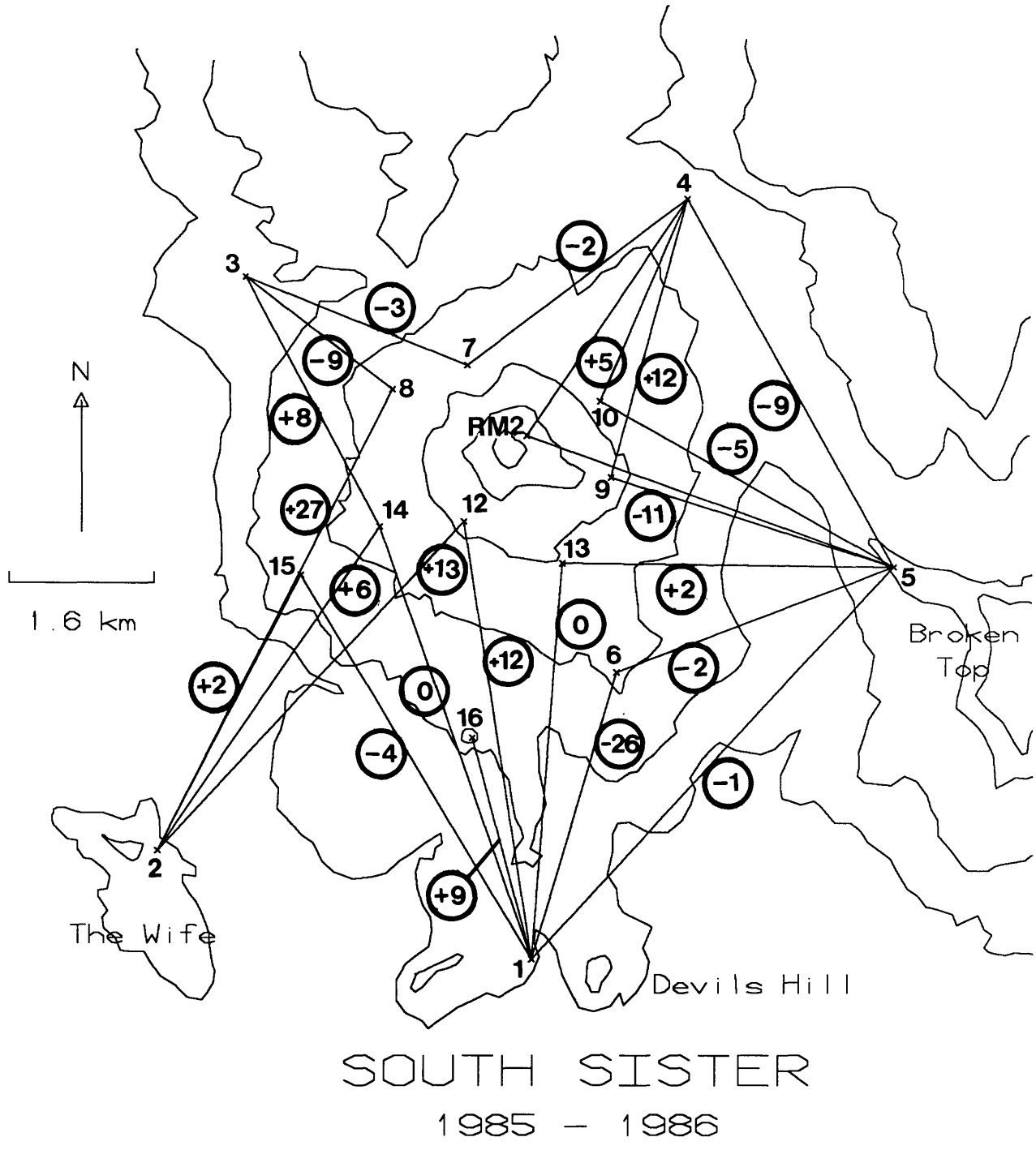

Figure 4. Schematic map showing endpoint mark-to-mark slope distance changes in millimeters at South Sister, Oregon.

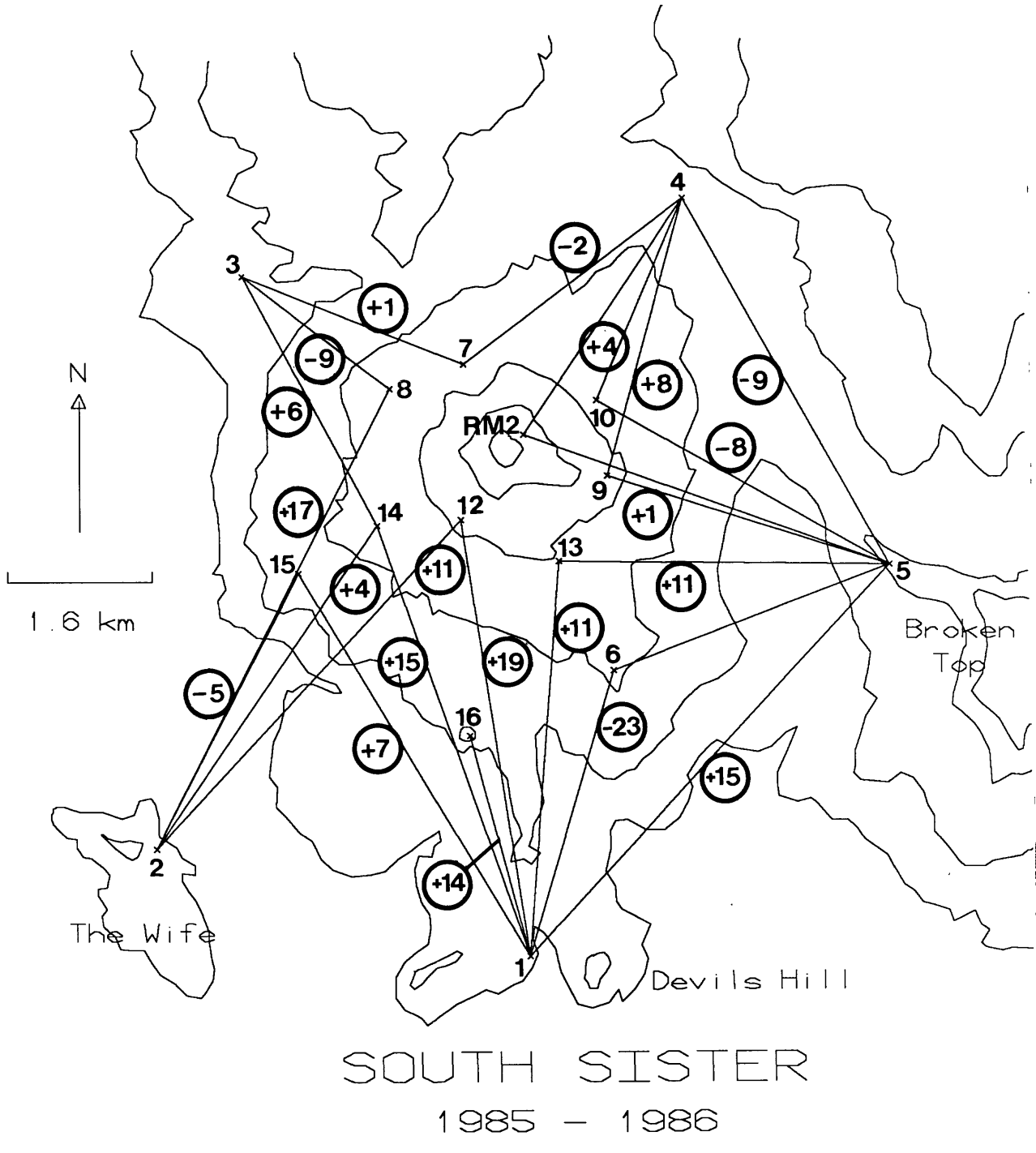

Figure 5. Schematic map showing flightline mark-to-mark slope distance changes in millimeters at South Sister, Oregon.

NEWBERRY

The Newberry EDM network is unique in the CVO system in that all measurements are made from only one instrument station, at Paulina Peak (fig. A1). Survey data indicate little or no apparent deformation between 1985 and 1986. All of the data fall well within the overall calculated precision. The endpoint and flightline mark-to-mark slope distance changes have a mean difference of 0.70±0.63 ppm, and 0.53±0.31 ppm, respectively.

In 1985, a new system for recording airborne temperatures and humidity was tested. As for many new systems, the first field test was less than completely successful. The airborne data collected appeared to be good but when reduced showed temperatures approximately 10°C cooler than the air temperature measured 6 m above the ground. A bad connector plug on the probe was found, after the fact, to be at fault. Therefore, to obtain the Newberry flightline data in Table 2, two assumptions were made. The first assumption was that the erroneous data due to the faulty plug were of constant magnitude. A plot of the 1985 raw temperature data of one flightline against its 1986 counterpart suggests that this assumption is valid (fig. 6). All other 1985 flightlines show analogous patterns when compared to their 1986 values. If the errors were intermittent, the data would be more erratic. The second assumption is based on comparisons of 90 other flightline and endpoint temperature data pairs collected in 1985 and 1986. The flightline data are consistently about 0.5°C cooler than the endpoint temperatures. With these assumptions, the flightline temperature data for 1985 were adjusted and better agree with the endpoint data than do the unadjusted data.

SOUTH SISTER

The South Sister trilateration network is shown in figure B1. The results indicate little or no apparent deformation between 1985 and 1986. Endpoint mark-to-mark slope distance changes have a mean of 2.04±1.82 ppm, and flightline distance changes have a mean of 2.39±1.54 ppm.

Four of the largest apparent changes, on lines 15, 19, 22, and 24, are associated with two bench marks, SS12 and SS8. Both the endpoint and flightline data yield similar distances, so it is unlikely that the apparent changes were caused by environmental effects. These relatively large changes may have been due either to inaccurate setups by the instrument or reflector person, unstable bench marks, anomalously bad readings, or real deformation. The most likely explanation for the apparent changes at bench mark SS12 (lines 15 and 19) was a noncentered reflector setup in either 1985 or 1986. Bench mark SS8 (lines 22 and 24), because of its location on a moraine (see appendix B), could be unstable, but a bad reflector setup cannot be ruled out.

Line 13 had the largest change (-.026 m endpoint, and -.023 m flightline), which could possibly be explained by a bad setup. Atmospheric errors are unlikely since the endpoint and flightline mark-to-mark slope distance changes are very similar. From a different instrument site to the same bench mark, SS6, line 11 showed very little change (-.002 m endpoint), thus suggesting that the bench mark is stable (line 11 was flown in 1986, but the data were lost or deleted by accident). Changes on line 16 are larger than the expected error, and no explanation for this change is apparent, as this is the only shot to bench mark SS16.

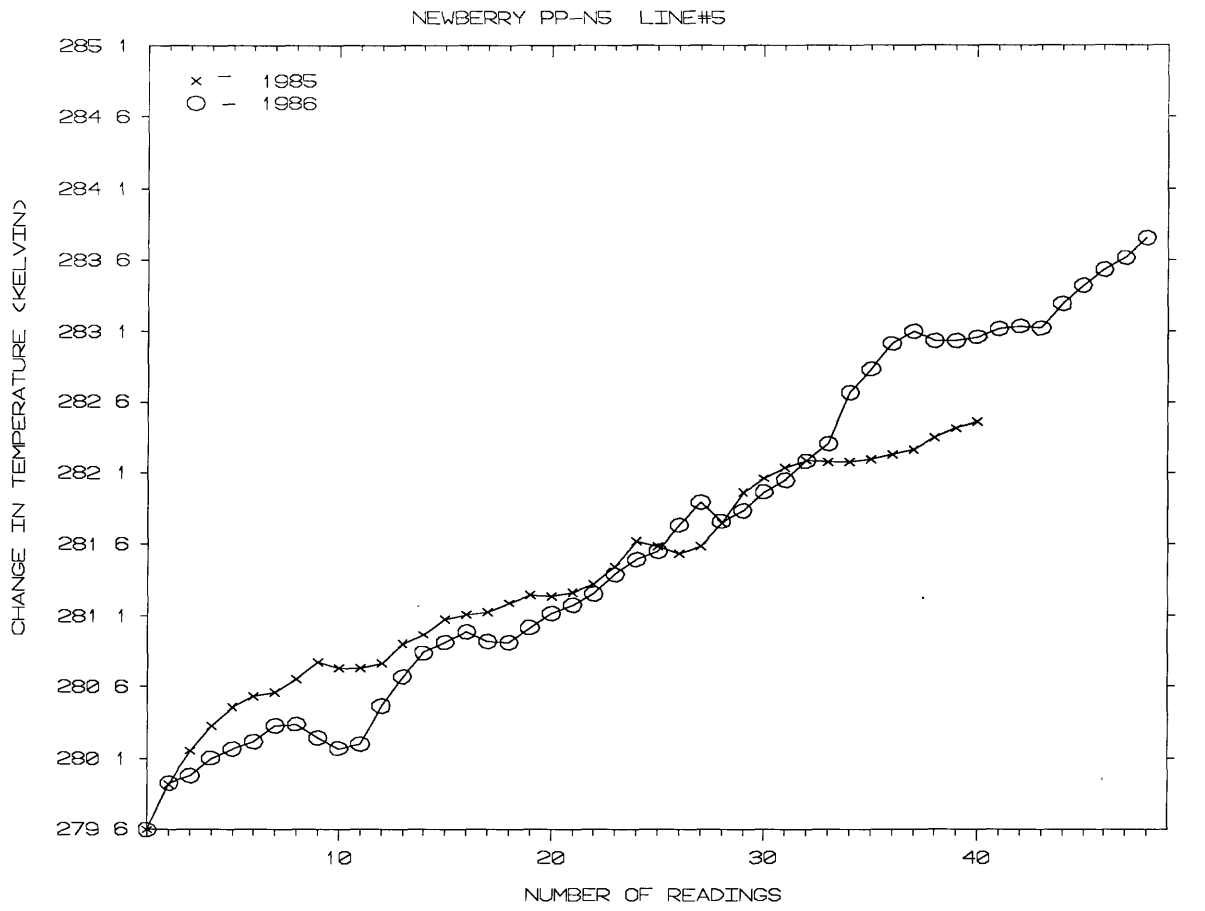

Figure 6. Raw flightline temperature data showing 1985 data similar to 1986 data. Data points are approximately 5 seconds apart. Air speed in 1986 was slower than in 1985, so that more data points were obtained.

DISCUSSION

The quality of data collected at Newberry and South Sister volcanoes is the best obtained since the CVO geodetic-monitoring program began. This is primarily due to the refinement of technique both in the field and in the laboratory. By calibrating the temperature sensors and precision thermistors at the same time, coupled with the capablity of measuring temperatures 6 m above ground, reliable endpoint temperatures were obtained that are only slightly higher than the flightline temperatures. The flightline temperature and humidity data are more accurate, as the new recording system allows direct recording from the thermistors, thus bypassing one more possible source of error. The old system used an analog-to-digital conversion board that could have induced errors due to drift or temperature changes. The new hygristor worked well and eliminated the need to change sensors when they became saturated, as was necessary in the old system.

The results of the 1985 to 1986 surveys are much more precise than those reported by Chadwick and others (1985), both for the endpoint and the flightline data. The data in tables 1 and 2 show that the endpoint mark-to-mark slope distance changes are still generally smaller, and hence probably more reliable than the corresponding flightline changes, as Chadwick and others (1985) also found. Flightine data are collected along the entire flight path and should reflect the true temperature of the line shot by the EDM; indeed, in most cases, the temperature gradient is rather linear with elevation changes (see figure 6). Occasionally, however, thermals are encountered, and the linear trend does not hold true (fig. 7). In such a case, the calculated flightline temperature is an average of all the temperatures, whether along linear or thermal (non-linear) trends. Since the temperature along the flight path is recorded by a helicopter, it is possible that the helicopter is being affected much more than the signal of the EDM: Figure 7 shows the helicopter in the thermal for a minimum of 50 seconds, which could affect the handling and air speed of the helicopter. The thermals could be an indirect cause of the error for such a line.

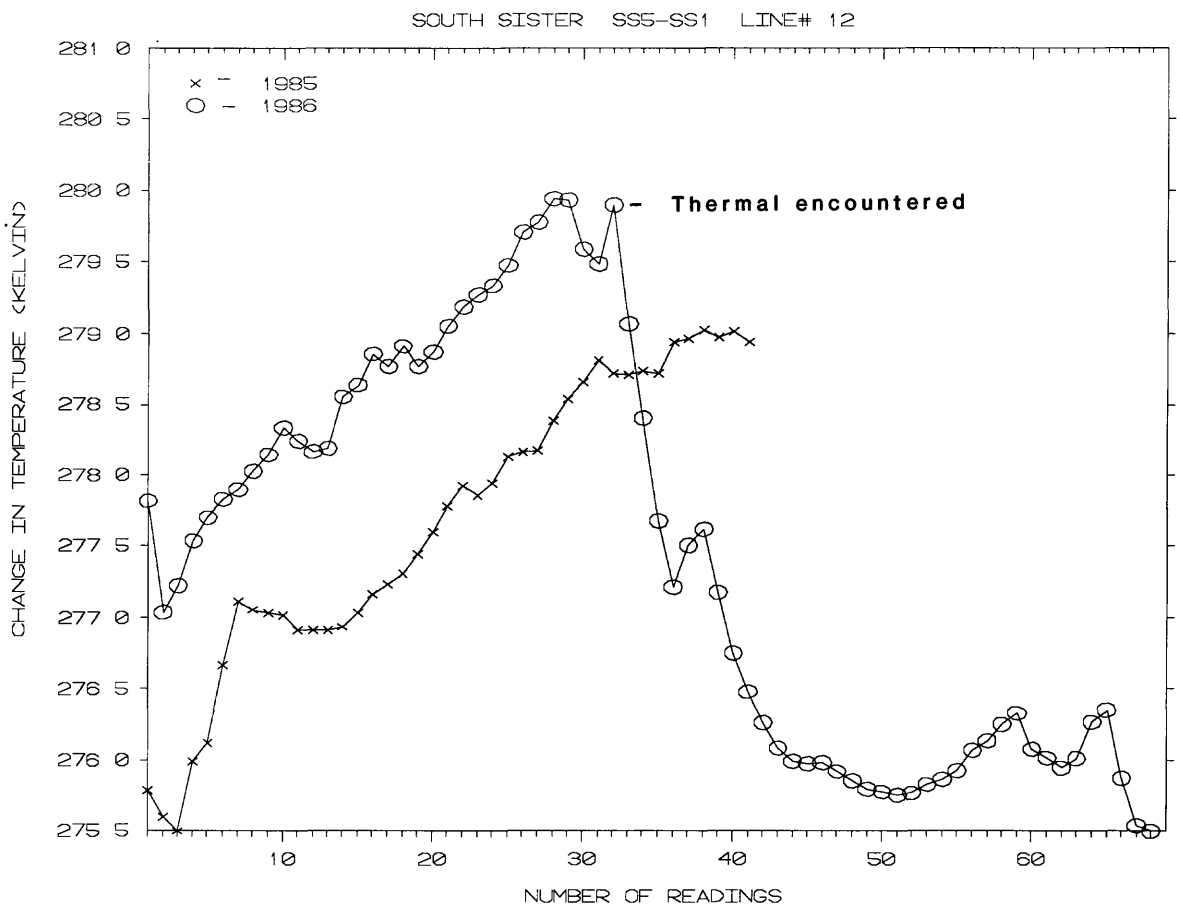

Figure 7. Raw flightline temperature data indicating thermal encounted in 1986. Data points are approximately 5 seconds apart. Air speed in 1986 was much slower than in 1985, so more data points were obtained.

We have also found that the quality of observations decline on windy days, and this is to be expected. The two major reasons are: 1) the helicopter cannot fly a true line between the reflector and instrument site due to wind convection and turbulence created by the topographic features and the steep-gradient lines, and 2) shaking of the instrument and reflectors. The EDM instrument currently used is bulky but relatively light and hence is buffeted in the wind; the problem is compounded by the fact that the EDM takes a long time to read a distance. The reflectors are also lightweight and bulky but do not catch the wind badly, so the effect of strong wind is minimal compared to that of the EDM. Strong wind along the helicopter flight path is probably the largest factor in reducing data quality, with the effect being several ppm on average for flightlines. All of the data could be improved if a smaller EDM were used to reduce wind effects, or if a shelter were built to totally protect the EDM.

SUMMARY

The data indicate little or no apparent deformation at Newberry or South Sister volcanoes between 1985 and 1986. Since the overall quality of the data is much improved over that of the previous years, it should become the standard for the existing equipment used in these surveys. The use of a smaller EDM and more careful field techniques can improve the data collected in the future. The data collected in 1985 and 1986 are adequate as a baseline for future EDM studies at either volcano.

ACKNOWLEDGEMENTS

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APPENDIX A

BENCH MARK DESCRIPTIONS, NEWBERRY VOLCANO

Elevation in feet based on assumed elevation of 7984 ft for Paulina Peak triangulation station. All stations are in area shown on USGS 7.5 minute series quadrangles Paulina Peak (1963, photorevised 1981) and East Lake (1982). Stations in the N series were established in 1985 by personnel of CVO; all are standard USGS/CVO bench marks.

PP (Paulina Peak)--Existing triangulation station on top of peak, established by USGS in 1931. This was used as the only instrument station and the elevation datum in the 1985 survey. New mortar added around mark in 1985. Can drive directly to station. Elevation is 7984 ft.

NPP (North Paulina Peak)--Existing triangulation station on top of peak, established by USGS in 1931. Land helicopter in large flat southeast of peak and climb to top. Mark was in good condition in 1986. Bench mark was used as reference for horizontal angles (Table A1). Elevation is 2342.39 m.

N1 (Surveyor's Flow)--On Surveyor's lava flow south of Surveyor's Ice Cave. From main road into crater, drive south 4.7 mi on Road 2121 to intersection with Road 300, which turns to left (east). Drive on Road 300 several miles until first clear view of Surveyor's flow. Continue short distance farther, to point where track road to right leads to edge of flow; sign at this intersection reads "Lava Casts, 1/4 mile." Park next to flow, about 100 ft from Road 300, and walk due south about 180 ft on path to a high point on flow. From there, walk to prominent large Ponderosa with crooked trunk about 150 ft to south. BM is 13-15 ft due east of tree. Elevation is 5787 ft.
Alternative route: drive on Road 2121 3.7 mi south of main road to crater to intersection with Road 2225. Turn left on Road 2225, and follow it to Surveyor's Ice Cave. Continue 0.2-0.3 mi beyond cave, then turn right at intersection with Road 300. Continue on Road 300 for about 0.1-0.2 mi to sign mentioned above and follow directions as described above. In 1985, Road 2225 was better than Road 300. Helicopter landing site is on top of high point 150 ft north of tree.

N2 (North Paulina Lake)--Drive on main road to point just east of turnoff to Paulina Peak, then turn left across dam toward Paulina Creek Campground. Park at north end of road and walk on trail 1 1/4-1 1/2 mi north along lake shore to first major outcrop, in small clearing with good views to south; this is also the last rocky point west of North Cove Campground. Bench mark is next to but about 8-10 ft above trail, approximately 2.5 ft back from edge of southeast-facing rock face. Elevation is 6360 ft.

N3 (Lower Interlake Flow)--Take Little Crater Campground road from main road. Drive along east shore of Paulina Lake to road end. Take trail upslope (rightmost of two trails--the other follows shore) to lava flow. Bench mark is directly up flow front from end of trail, on one of the near rocky mounds 50 ft from top of talus slope. It is on a flat bench about 7 ft below and 13 ft south of the top of the mound. Elevation is 6475 ft.

N4 (Central Pumice Cone)--Turn on dirt road leading north from main road into crater of Central Pumice Cone. From end of road one can look north and see two prominent cliff-forming obsidian flows in the inner crater wall, one above the other. Walk north and climb northeast inner wall of crater

shown on topo map. The bench mark is on top of the westernmost promontory on the lower flow. Approximately 10 ft more of the lower flow is exposed above this point. Elevation is 6950 ft.

N5 (Osprey)--Prominent overlook on ridge east of East Lake. Drive the main road east along East Lake and then continue north on road along east side of lake to Cinder Hill Campground. Park at south edge of campground, climb short distance to horse trail, and scramble up one of several steep way trails, all of which climb up north slope of rocky ridge. Bench mark is on relatively flat top of spur at ground level about 5 ft from southwest edge of overlook. In 1986, the bench mark had been removed by vandals. The hole for the stem of the bench mark was intact, however, as was most of the cement. A new bench mark (also stamped N5) was cemented in the hole, and rocks and cinders were piled on top to hide the mark. Elevation is 6647 ft.

N6 (Sheep's Rump)--In easternmost clear area above northeast end of East Lake, an area known locally as Sheep's Rump. Bench mark is on end of 8 ft copper rod driven into cinders. Large concrete pad surrounds mark. Land helicopter as far upslope as possible. Mark is several meters west of landing site. Elevation is 7196 ft. NOTE: BY 1986 THE MARK AND ROD HAD BEEN REMOVED BY VANDALS. NEITHER WAS REPLACED.

N7 (Eagle)--Top of cliff that forms point above northeast shore of East Lake, east of habitat for bald eagles. Drive to northwest end of Cinder Hill Campground and park. Walk northwestward (uphill) on gulleyed trail, climbing 130-200 ft in elevation. At indistinct trail junction, take left fork and walk on good trail more or less contouring to top of point, which is the most prominent point on north shore of lake from which the interlake obsidian flow can be seen. (There are smaller points to the east and west.) Descend 30-65 ft in elevation along ridge to flat area above high cliff, passing several other relatively flat areas on the way. Bench mark is on this lower flat above cliff. Elevation is 6565 ft.

N8 (Upper Interlake Flow)--On upper part of interlake obsidian flow. Very hard to find from ground, but mark is easily seen from air. Bench mark is located in central part of flow, on top of low mound (one of hundreds) about 330 ft or more south of large pine. Landing site is small flat area about 50 ft southeast of mark (bad landing if winds are strong). If landing is not possible, can walk to station from N3, hiking across and then along northwest edge of flow until reaching general area, and then being directed by helicopter to site. Eagle habitat is east of this site and should not be flown through. Elevation is 6716 ft.

N9 (Topso)--On top of Topso Butte southeast of caldera. Land on crest of butte at helispot marked with "H". Walk about 65 ft toward Paulina Peak. Bench mark is in isolated rock surrounded by cinders. Elevation is 6801 ft.

N10 (Grunt)--On hill .6 mi due south of East Lake. Land on pumice-covered floor of small crater east of hill. First climb northwest, then turn and climb southwest through dense forest to west edge of hill. Bench mark is on extreme northwest (not northernmost) point of rhyolite cliff above scree and talus slope on west side of hill. This is not the highest point on hill, which is timbered, but it is the highest point along the discontinuous ledge above the scree and talus. Elevation is 6947 ft.

Table A1. Horizontal angles shot from Paulina Peak (PP) to reflector stations, all referenced to North Paulina Peak (NPP).

Shot (BM-BM)	Line #	Horizontal angle referenced to NPP
PP-N1	1	170°41'46"
PP-N2	2	342°10'44"
PP-N3	3	8°17'35"
PP-N4	4	20°57'07"
PP-N5	5	40°57'47"
PP-N6	6	31°17'32"
PP-N7	7	29°10'07"
PP-N8	8	9°15'30"
PP-N9	9	116°42'53"
PP-N10	10	54°14'09"
PP-NPP	11	00°00'00"

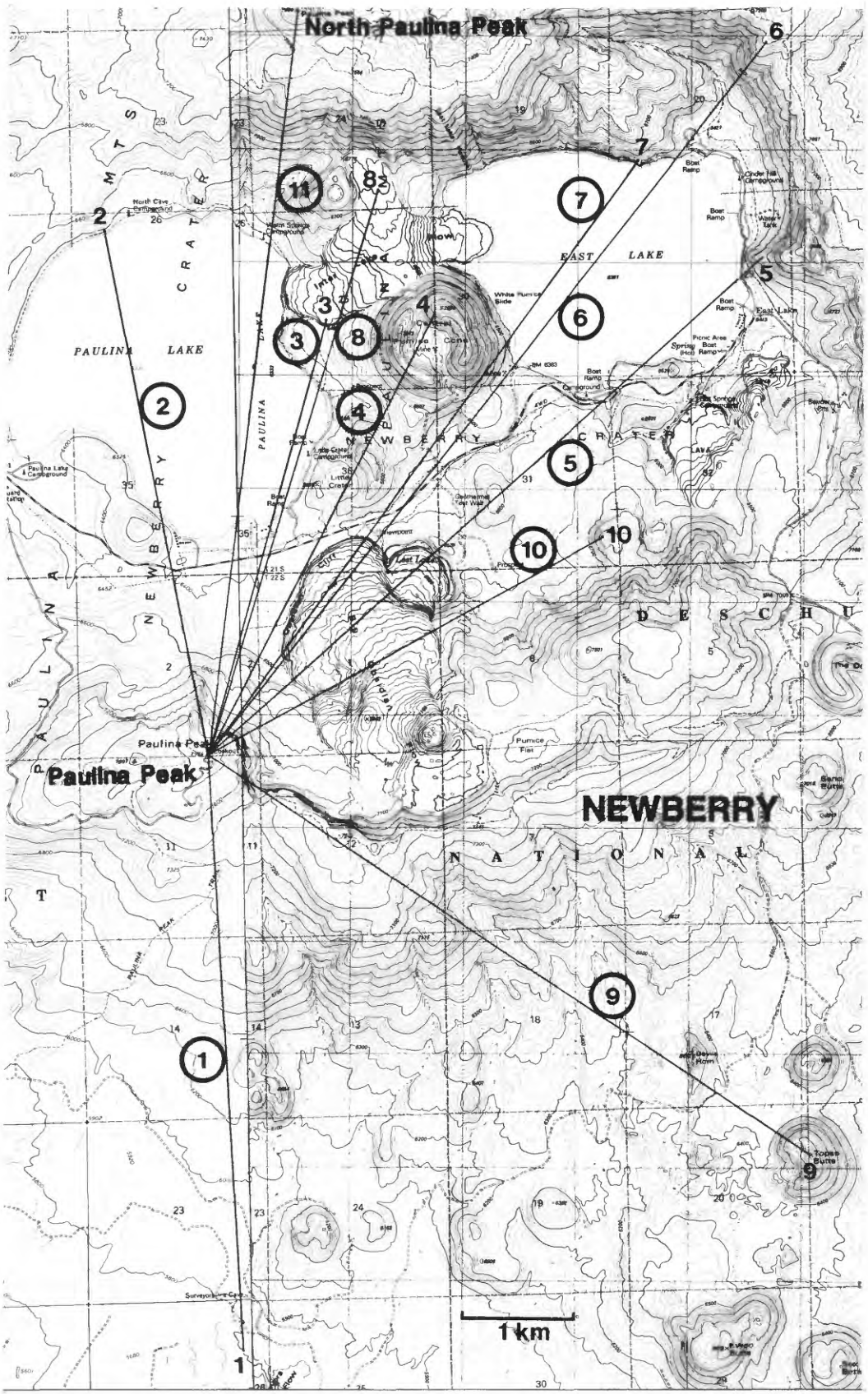


Figure A1. Map showing bench marks, line numbers (circled), and station locations for distance measuring network at Newberry, Oregon.

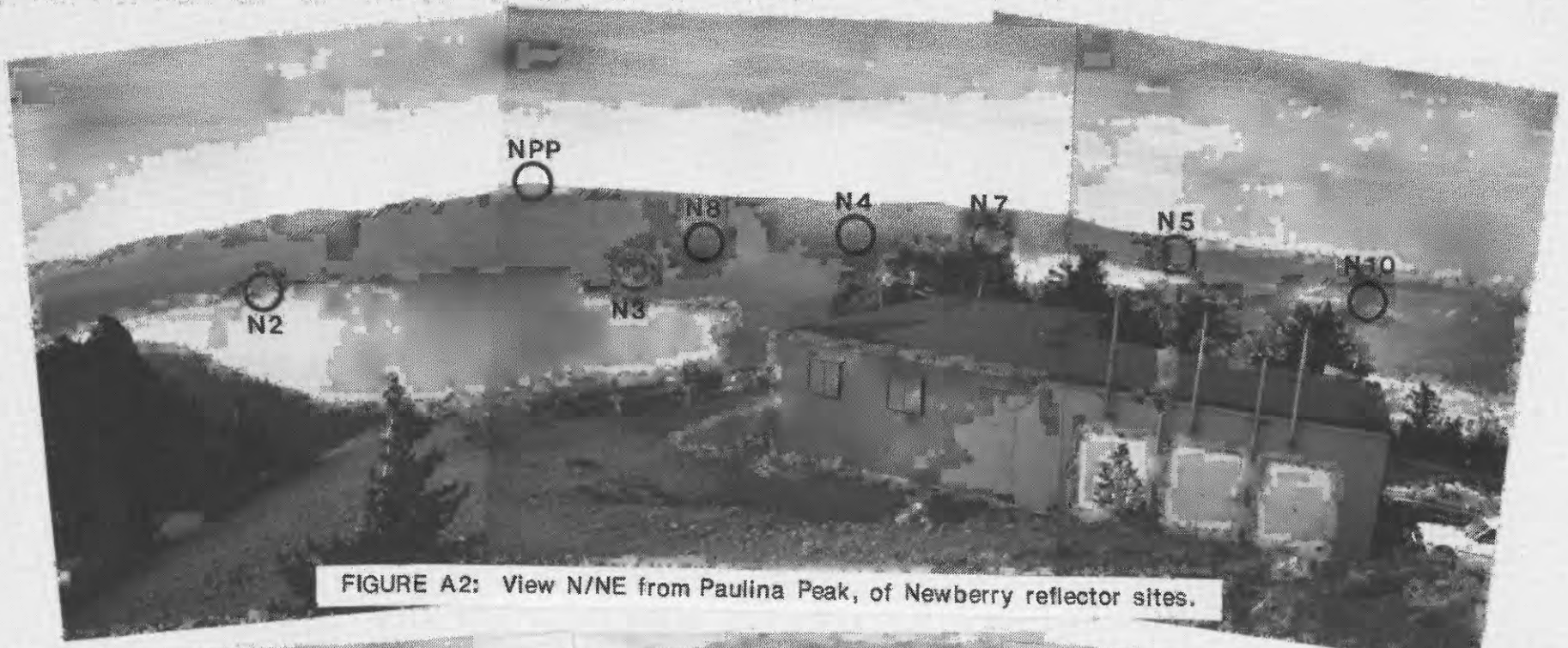


FIGURE A2: View N/NE from Paulina Peak, of Newberry reflector sites.

FIGURE A3: View S/SE from Paulina Peak, of Newberry reflector sites.

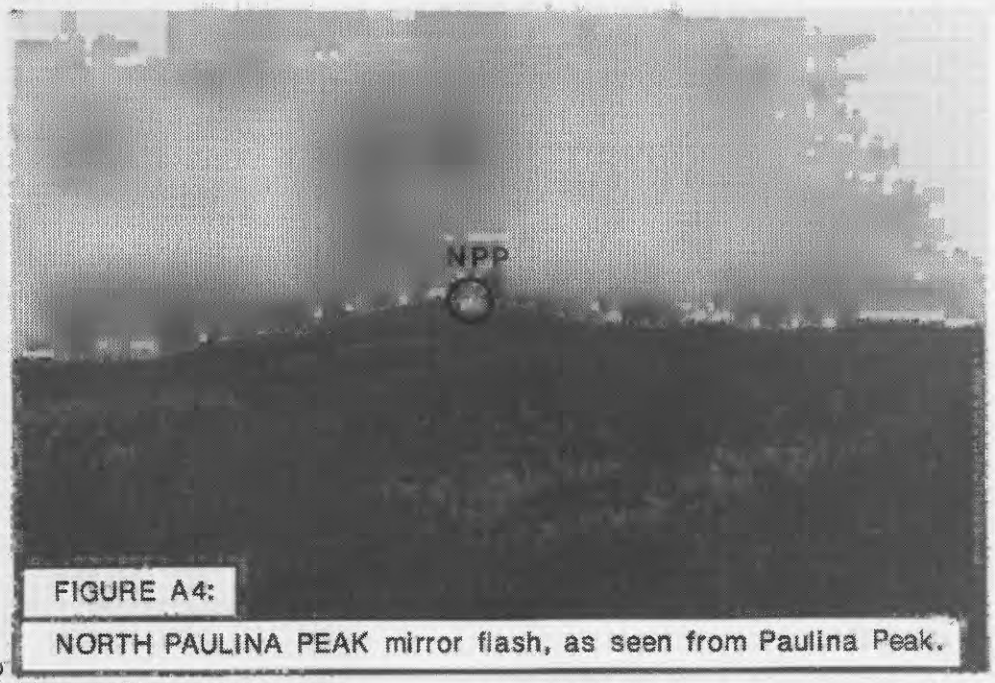


FIGURE A4:
NORTH PAULINA PEAK mirror flash, as seen from Paulina Peak.

FIGURE A5: NORTH PAULINA PEAK reflector site, from the north.

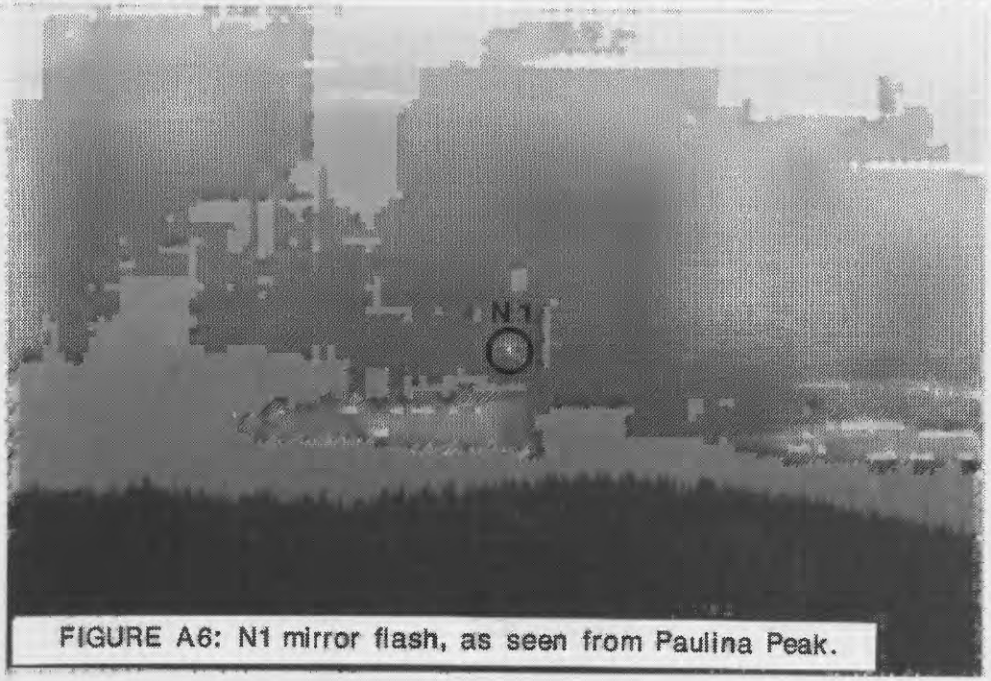


FIGURE A6: N1 mirror flash, as seen from Paulina Peak.

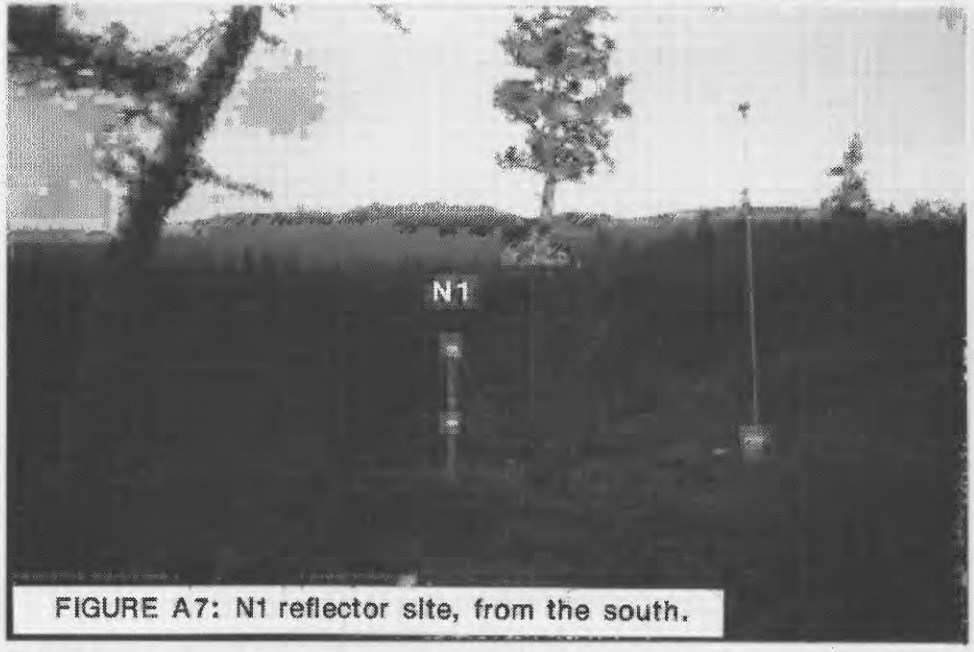


FIGURE A7: N1 reflector site, from the south.

FIGURE A8: N2 mirror flash, as seen from Paulina Peak.

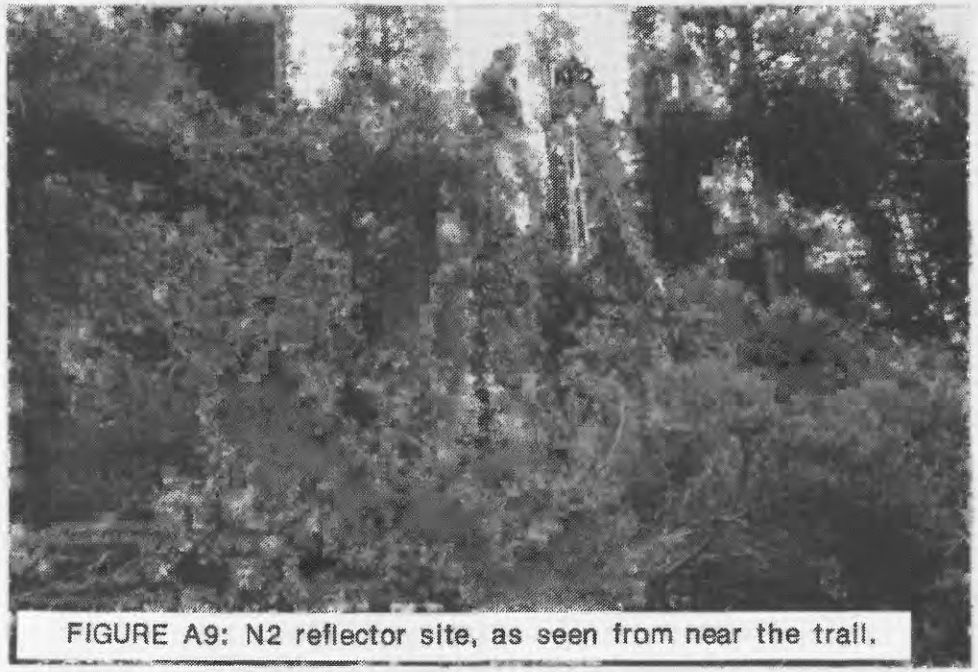


FIGURE A9: N2 reflector site, as seen from near the trail.

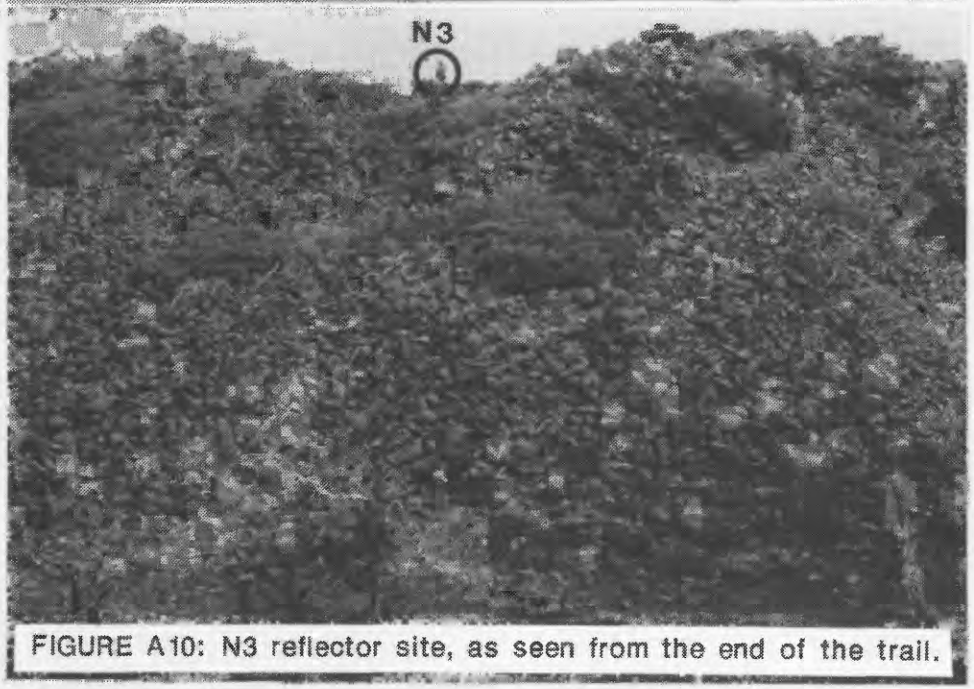


FIGURE A10: N3 reflector site, as seen from the end of the trail.

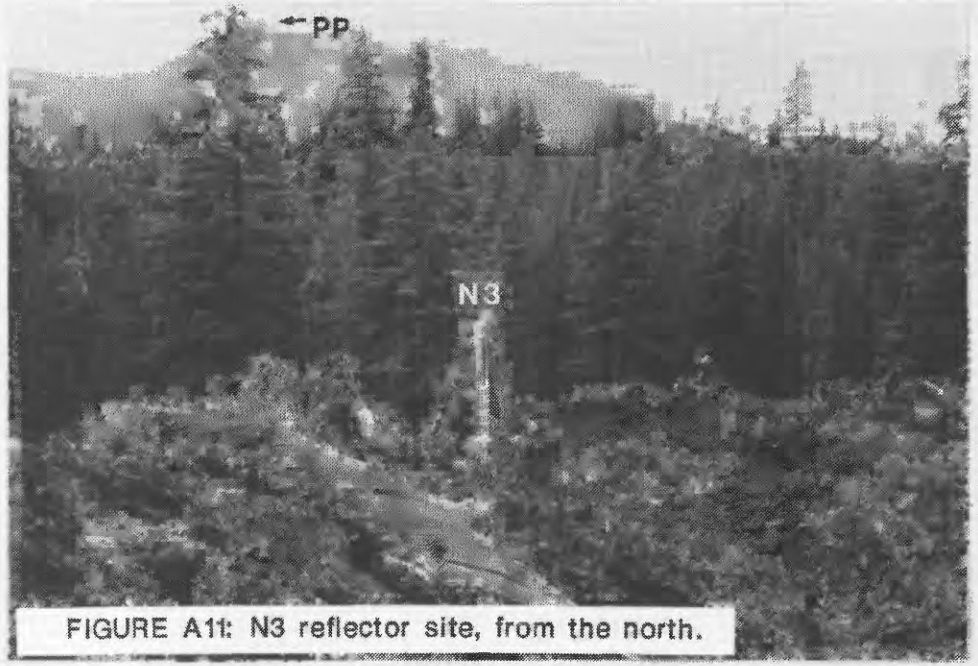


FIGURE A11: N3 reflector site, from the north.

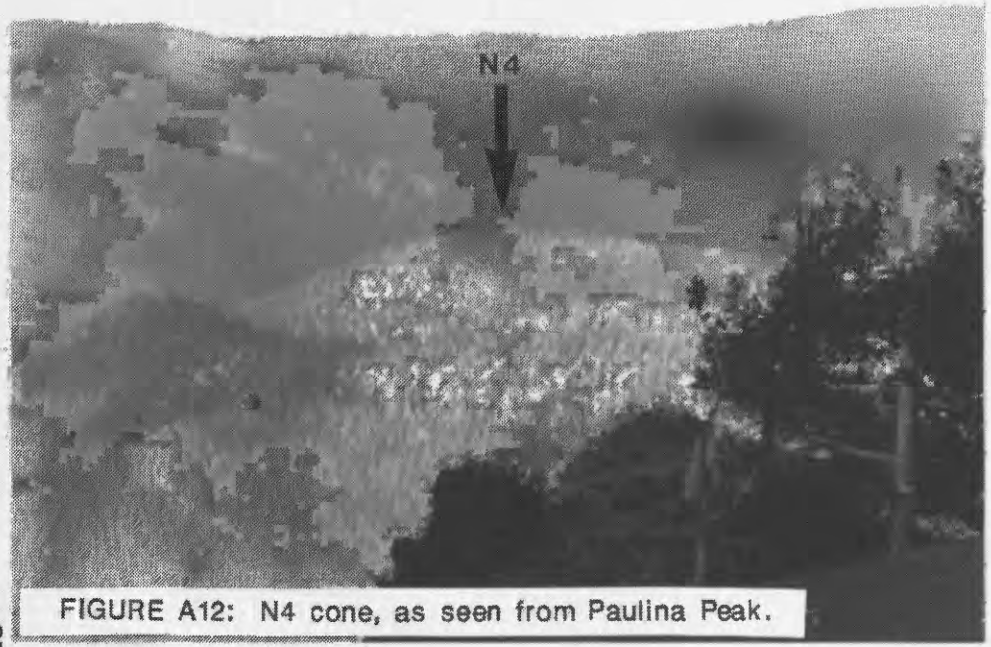


FIGURE A12: N4 cone, as seen from Paulina Peak.

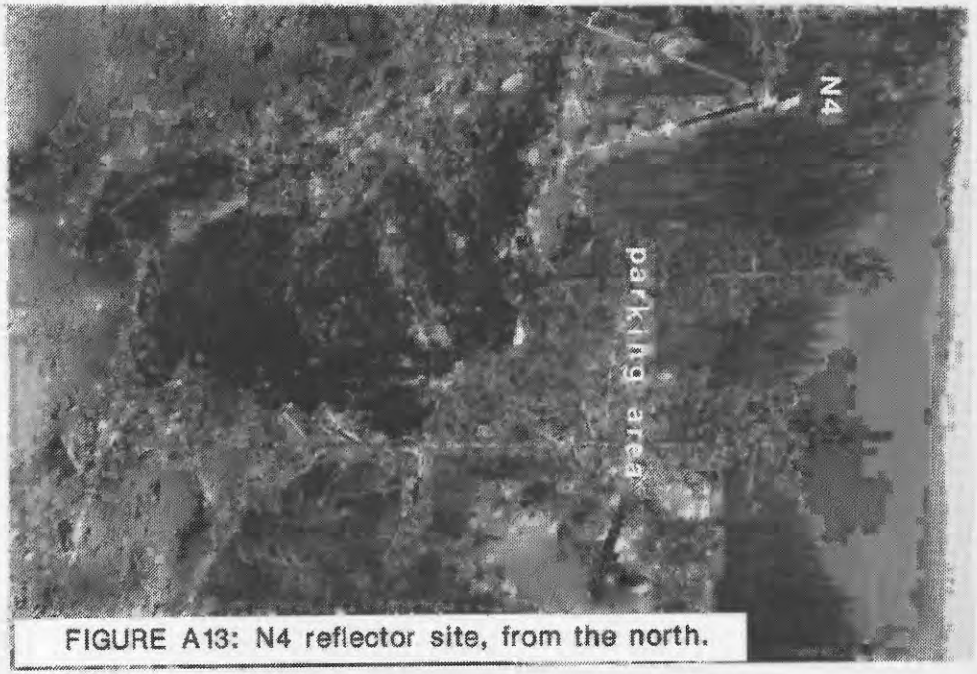


FIGURE A13: N4 reflector site, from the north.

FIGURE A14: N5 mirror flash, as seen from Paulina Peak.

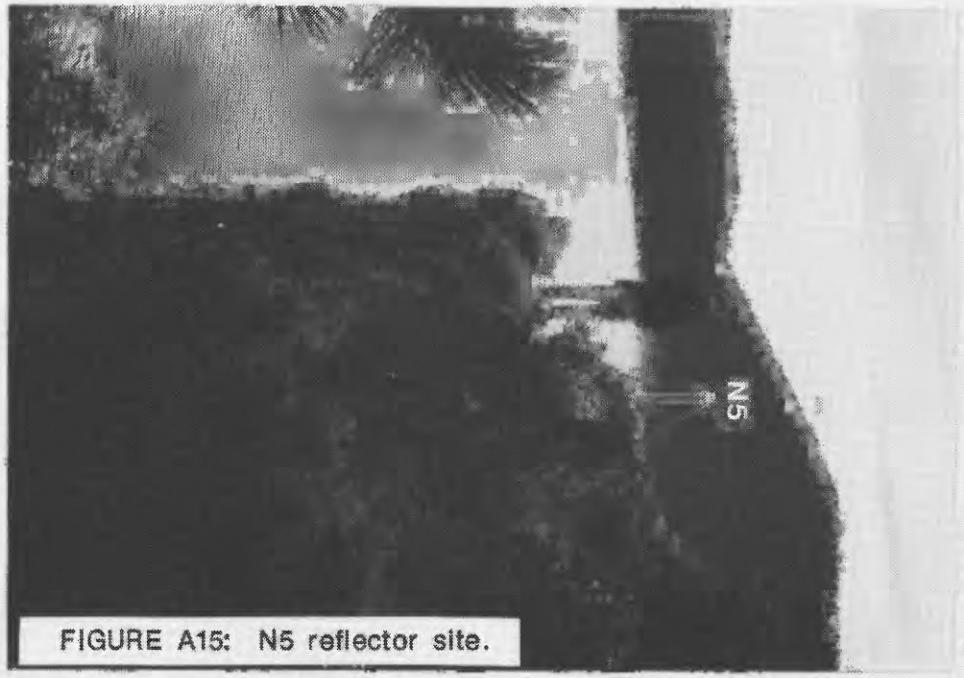


FIGURE A15: N5 reflector site.

FIGURE A16: N7 mirror flash, as seen from Paulina Peak.

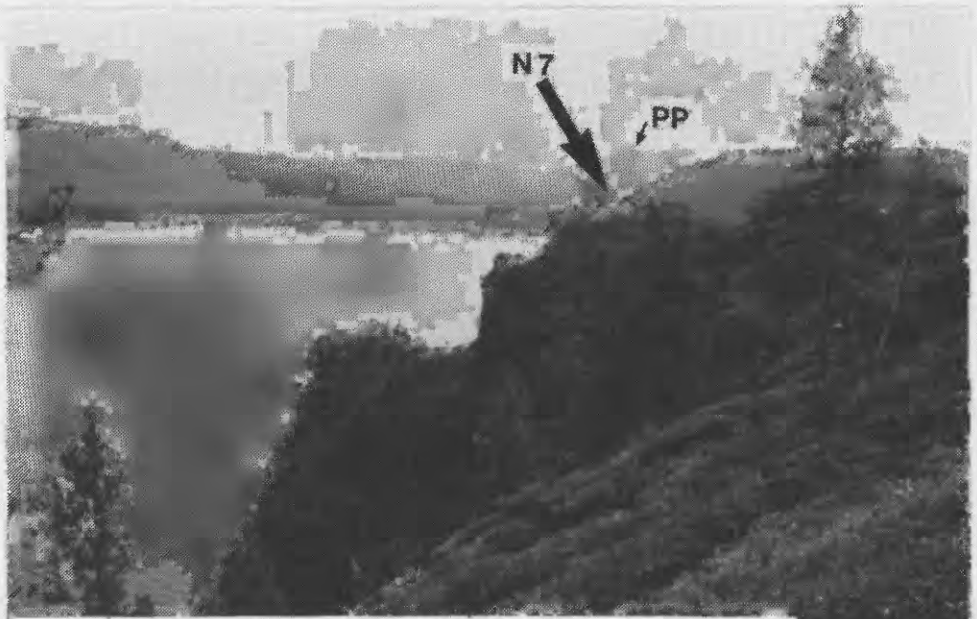


FIGURE A17: N7 reflector site, from the northeast.

FIGURE A18: N7 reflector site, from the north.

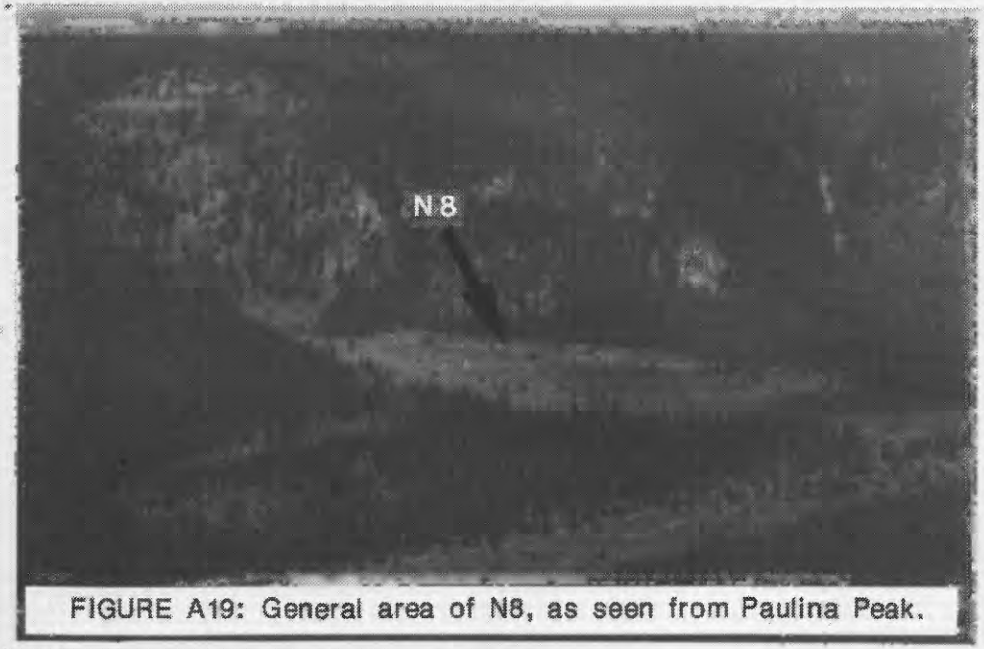


FIGURE A19: General area of N8, as seen from Paulina Peak.

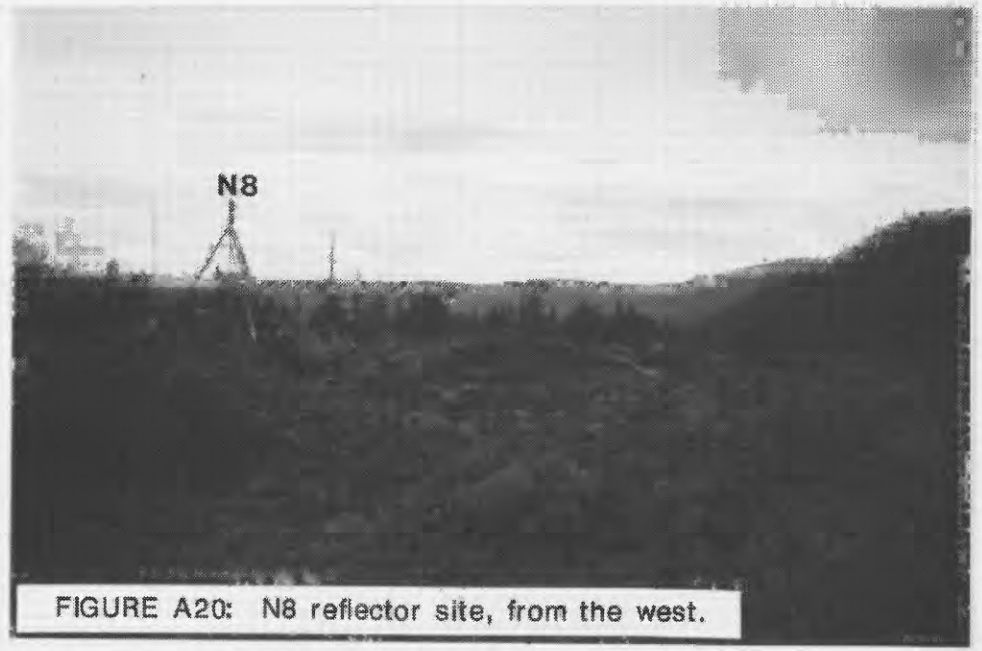


FIGURE A20: N8 reflector site, from the west.

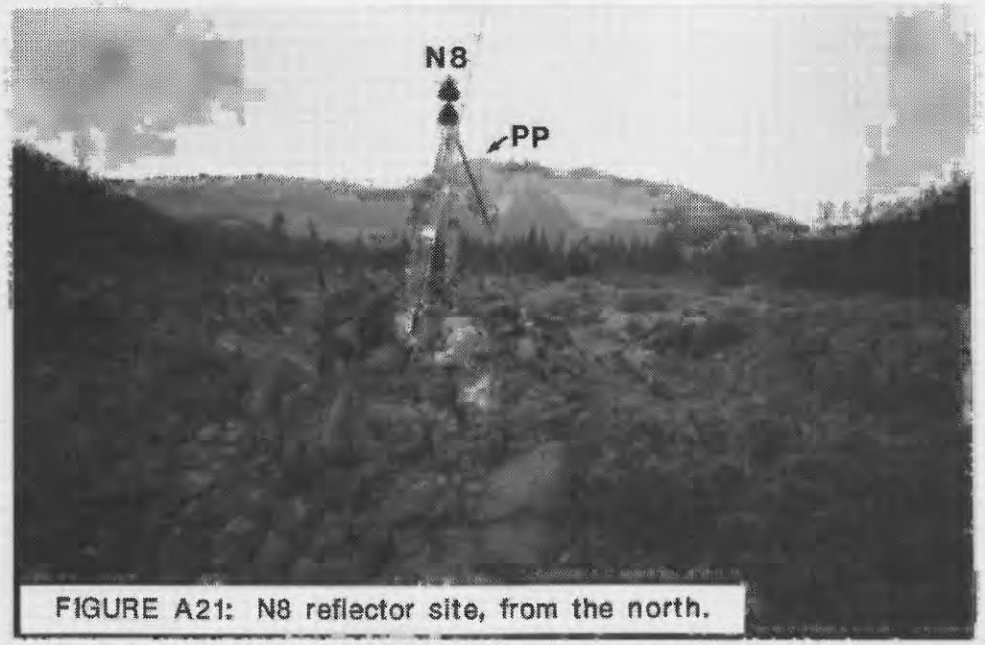


FIGURE A21: N8 reflector site, from the north.

FIGURE A22: N8 reflector site, from the east.

FIGURE A23: N9 butte, as seen from Paulina Peak.

FIGURE A24: N10 mirror flash, as seen from Paulina Peak.

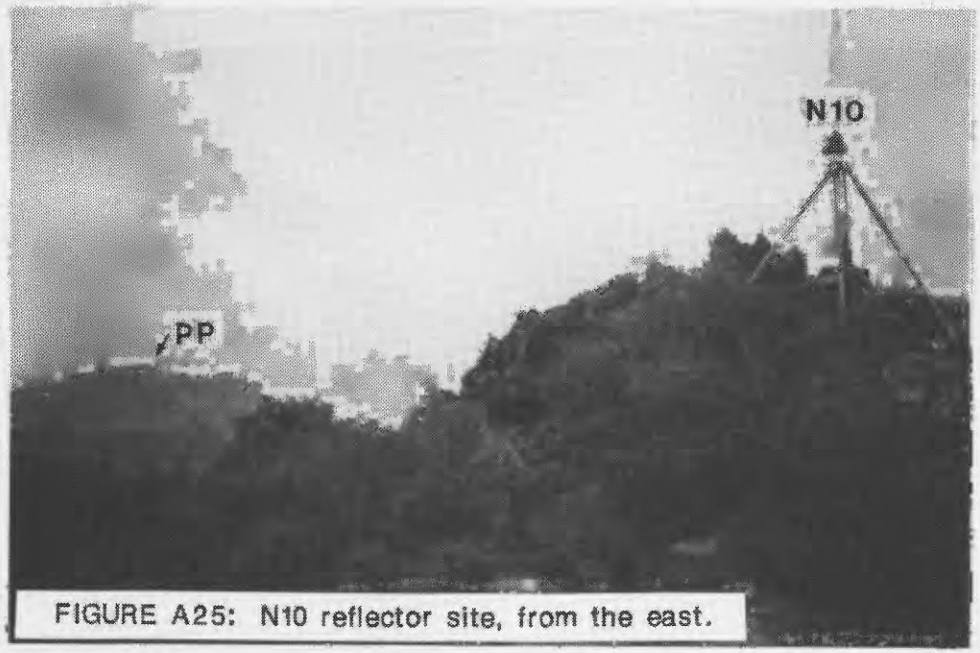


FIGURE A25: N10 reflector site, from the east.

FIGURE A26: N10 reflector site, from the north.

APPENDIX B

BENCH MARK DESCRIPTIONS, SOUTH SISTER VOLCANO

Elevations based on previously determined elevation of 10358 ft for triangulation station at summit of volcano.

SUMMIT and RM2--Preexisting USGS trig station, stamped "South Sister 1958". Located about 6.5 ft northwest of, and about 1.5 ft lower than, high point of mountain (on northeast crater rim). About 5 ft back from rim of cliff. In 1986, the mark was not found despite snow-free conditions. Either vandals removed it, or, perhaps more likely, the rock it was in fell over the cliff. Both reference marks (RM1 and RM2) remain and are in good condition. The 1986 measurements were made to RM2; a hole previously punched in top of RM2 was used as the center. Elevation of SUMMIT was 10358 ft., RM2 elevation is 10354 ft.

SS1 (Kaleetan Butte)--Land on highest mound in open area just west of bench mark location on map. From landing site, walk northeast (toward Broken Top) about 230 ft through open forest to edge of hill. Bench mark is located on a low outcrop; several large round boulders located 10-15 ft east of station. There are several outcrops on the edge of the hill, so look carefully. Elevation is 6772 ft.

SS2 (The Wife)--Land in the lower saddle due east of The Wife. Walk to top of hill just east of landing area. From top of hill, angle downslope to the north (toward South Sister). At cliff, head toward Devil's Hill. Bench mark is at break in slope at edge of cliff. It is set in a weathered, reddish outcrop. The station is on a small bench just below the top of the outcrop. From the site, you can see clearly to the north. Elevation is 6645 ft.

SS3 (Nowhere)--An elevation of 6700 ft is the key to finding this bench mark. The bench mark is located in a large flat area, 100-230 ft southeast of highest broad mound. The mark is in an elongated, east/west trending, glacially scoured outcrop at ground level. It is easily seen from the air. This outcrop is 10 ft wide and 20-33 ft long with several scrub trees growing in it. Land anywhere near the site. Elevation is 6753 ft.

SS4 (Platy)--Site location is about 330 ft east of the northern topographic high point. The area is flat and wide (50-60 ft) and landing can be anywhere. The bench mark is on the northern edge in a solid ground-level outcrop. The majority of the rocks are platy, so just check all solid outcrops. Elevation is 7513 ft.

SS5 (Shoulder)--If it is possible to see the ground (no snow), there is a contact between reddish and grey colored material; land there. If you cannot see this, land at an elevation of about 7750 ft; this will put you below the bench mark, near the contact. The bench mark is located upslope on the southern drop-off edge of the cliff, approximately 500 ft from the landing area. Walk upslope and check each outcrop; there are 3-4 noses that stick out. The mark is in a nose that has vegetation nearly to its tip and extends north toward the center of the ridge. Pick-up can be in the center of the ridge just north of the bench mark. Elevation is 7775 ft.

SS6 (Lucky)--Land at south end of ridge mantled in morainal debris just west of Newberry lava flow, at elevation of about 7850 ft. Walk upridge (northwest) about 165 ft to small rock outcrop (6.5 ft across) along ridgeline. Mark is near center of outcrop. Surface of outcrop is badly frost heaved. Elevation is 7880 ft.

SS7 (Skinner)--On ridge crest between Skinner and Eugene Glaciers on north flank of volcano. Land east of, and about 100 ft below, ridge-line on broad rocky bench in till on Skinner Glacier at elevation of about 8300 ft. This is probably the only reasonable landing site near this elevation east of ridge. Climb steeply to ridgeline. If no wind, helicopter can touch down on ridge about 30 ft upslope from bench mark (prominently visible from air.) Mark is along ridgeline, about 100-165 ft down ridge from point where shear cliff reaches ridge-crest. From mark, one can walk westward down rubble slope for 35 ft before cliff is encountered. This ridge is on skyline as seen from SS4 but not from SS3. Elevation is 8394 ft.

SS8 (Lost Creek Glacier)--Bench mark is on top of lone, 6 x 8 ft wide, 3-6 ft high, dark gray andesite block at about 8250 ft, almost directly downslope from center of Lost Creek Glacier. Station is at western edge of terminal moraine, whose high point is several tens of meters east-southeast of station. Station is located where west face of moraine steepens sharply. Landing site about 15 m north of mark. Elevation is 8277 ft.

SS9 (View)--Bench mark is on ridge just south of Prouty Glacier at elevation of about 9100 ft. It is straight down ridge from high north-facing cliff below summit. Large unnamed snowfield to south. Bench mark is about 30 ft downslope of large (6 ft high) rock that is on eastern side of landing site. Station is on skyline as seen from SS4. Elevation is 9123 ft.

SS10 (Prouty Glacier)--Bench mark is at west end of ridge that splits lower part of Prouty Glacier into two arms. Mark is on highest point of ridge, about 8650 ft, 10-13 ft west of landing site. Elevation is 8655 ft.

SS11--Not installed.

SS12 (Clark Glacier)--Land on flat area at about 9000 ft just west of southwest arm of Clark Glacier. Mark is at top of south-facing cliff, about 20 ft west of high southeast tip of bench. Elevation is 9036 ft.

SS13 (Lewis Glacier)--Land on flat bench just downridge (east) of Point 9017, at elevation of about 8700 ft. Mark is about 10 ft northeast of high point on rocky knoll at southeast edge of bench. Elevation is 8716 ft.

SS14 (Bummer)--Land in narrow, rocky saddle at about 8200 ft along prominent ridge leading southwest from north arm of Clark Glacier. Landing site is bad (flat but rocky). Bench mark is west and above landing site in jumbled pile of jagged rocks with good views to west, north, and south. Mark is about 15 ft north of high point in jumble. Elevation is 8199 ft.

SS15 (Misplaced)--Land on flat bench at about 7200 ft near west end of ridge bordering steep dropoff on south. This ridge is not the same one that SS14 is on, but instead is the next ridge to south, which extends irregularly upslope into the SS14 ridge. From landing site, walk southwest about 100 ft to station, which is on top of flat rock near edge of high cliff and almost due south of local rocky high that forms west margin of landing site. Elevation is 7227 ft.

SS16 (Little Broken Top)--On top of Little Broken Top dome. Mark is just south of flattest part of dome, on southeast side of summit area. Land on the flat spot. Elevation is 6976 ft.

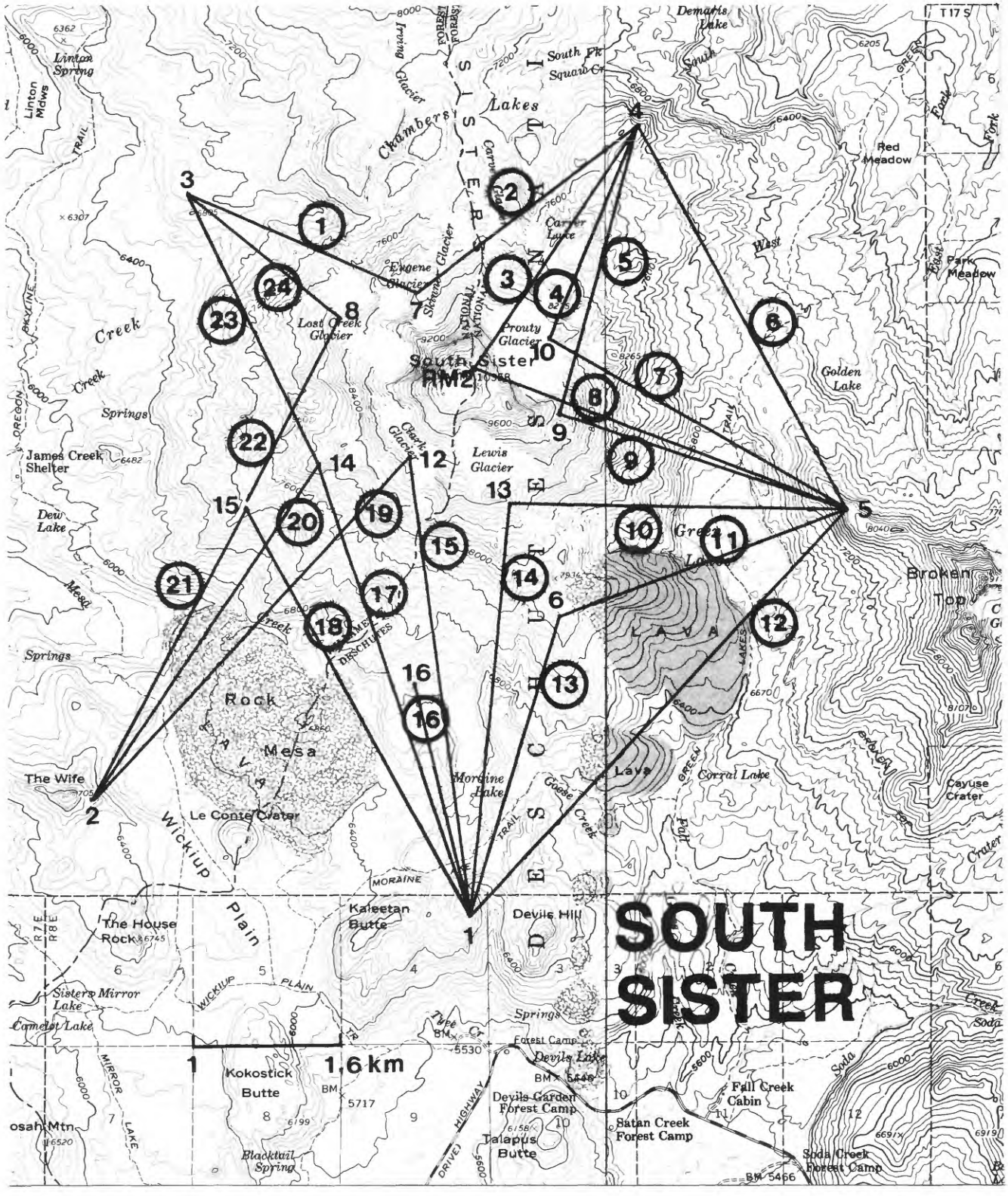


Figure B1. Map showing bench marks, line numbers (circled), and station locations of the trilateration network at South Sister, Oregon.

(SS1 mirror flash, as seen from SS13, see Figure B63.)

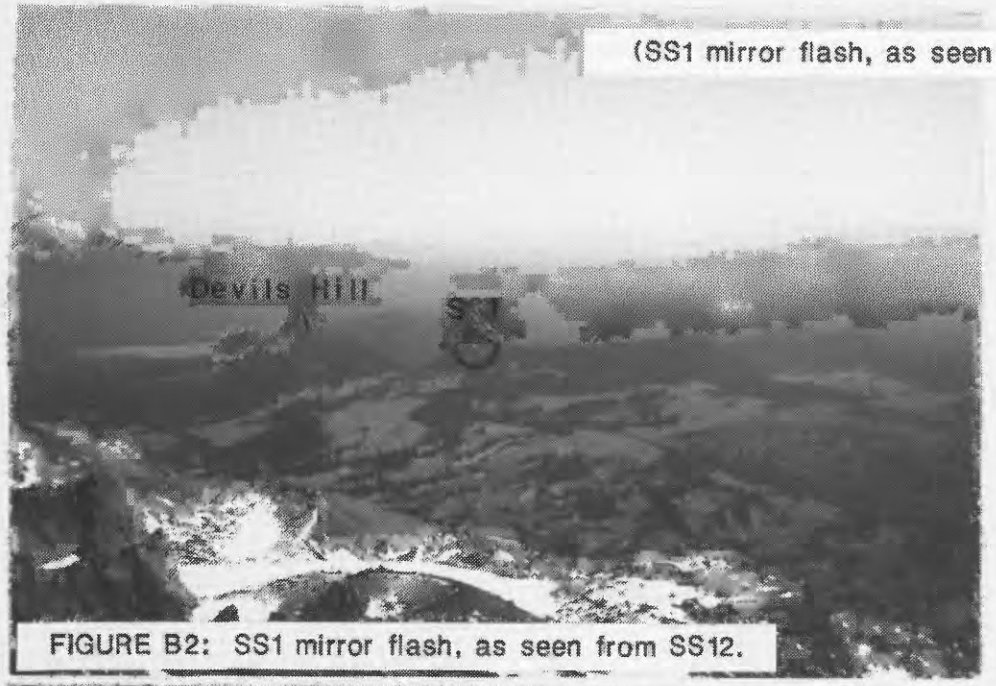


FIGURE B2: SS1 mirror flash, as seen from SS12.

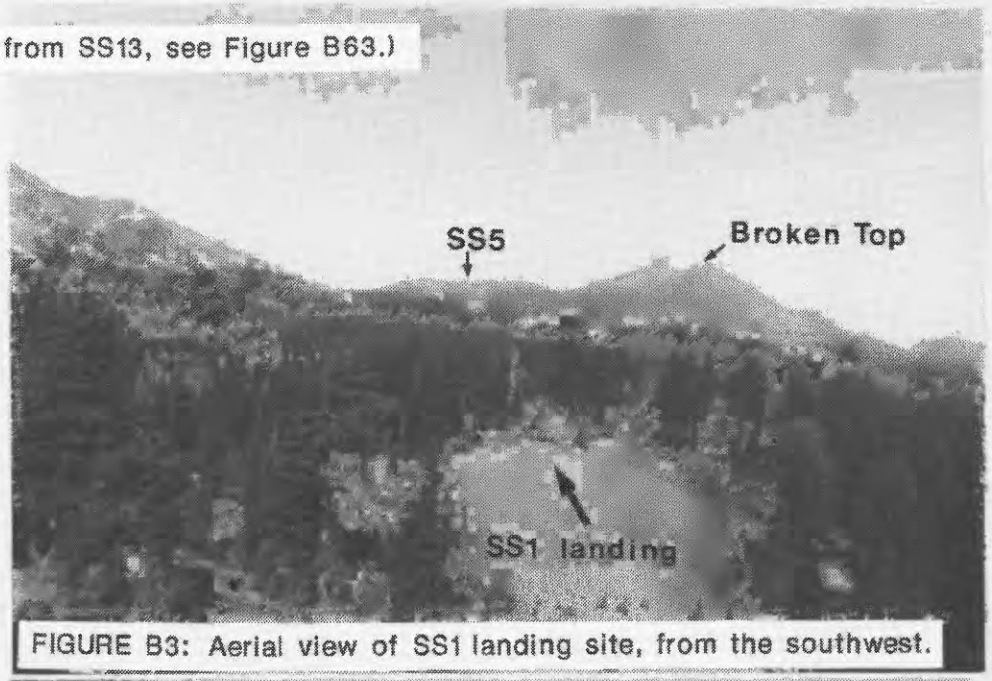


FIGURE B3: Aerial view of SS1 landing site, from the southwest.

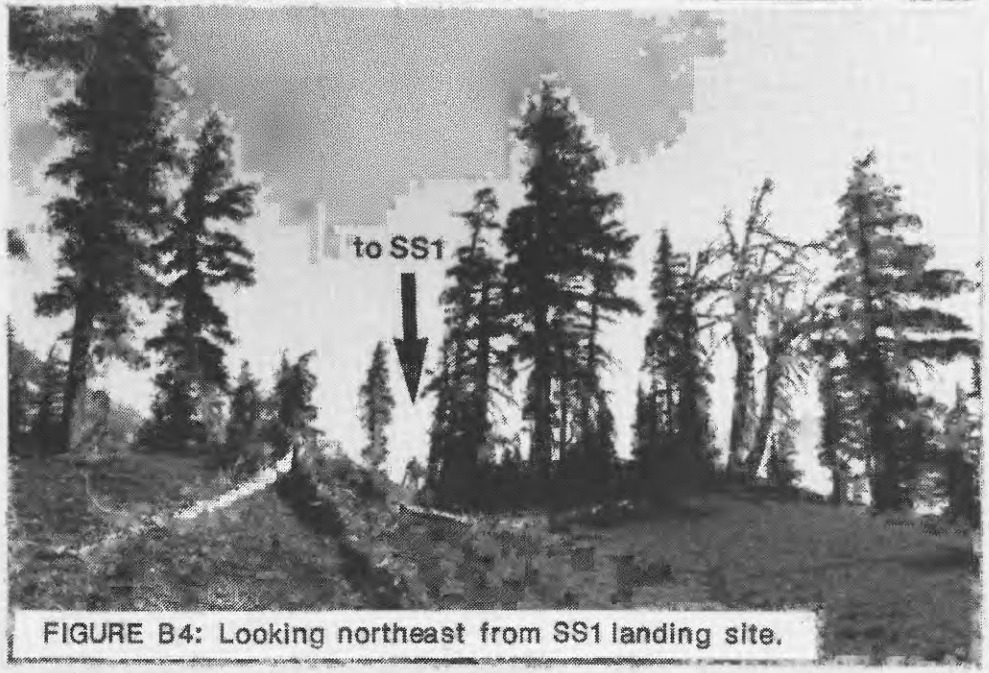


FIGURE B4: Looking northeast from SS1 landing site.

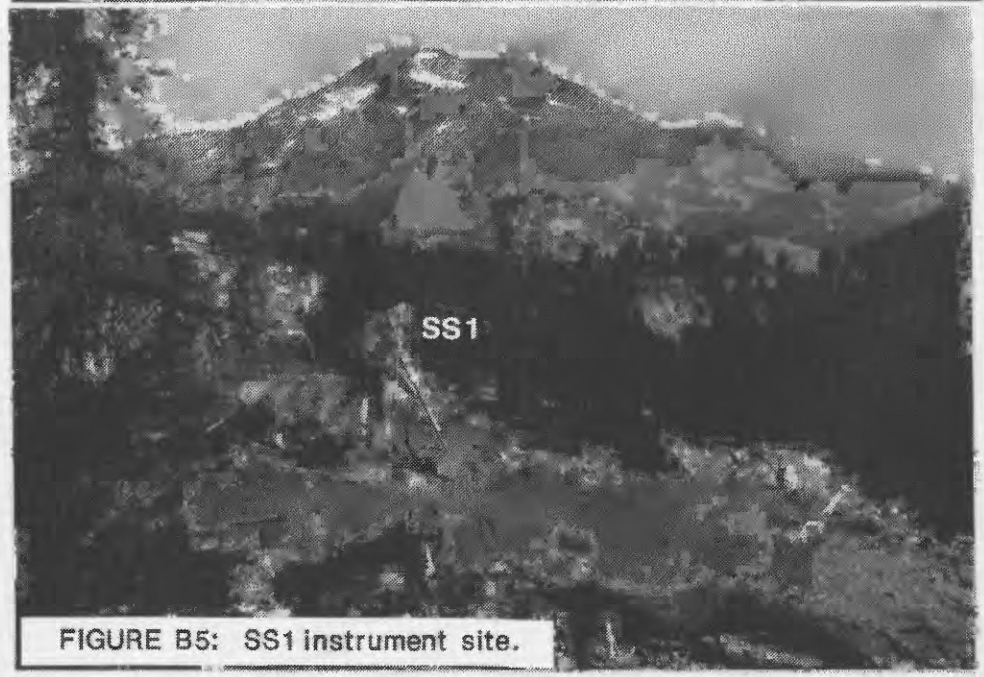


FIGURE B5: SS1 instrument site.

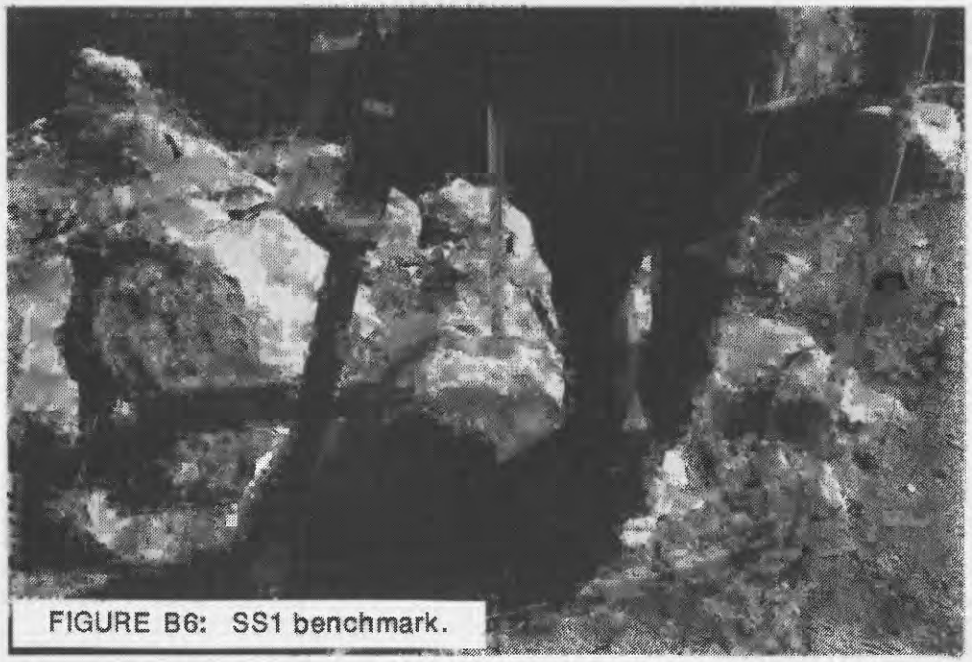


FIGURE B6: SS1 benchmark.

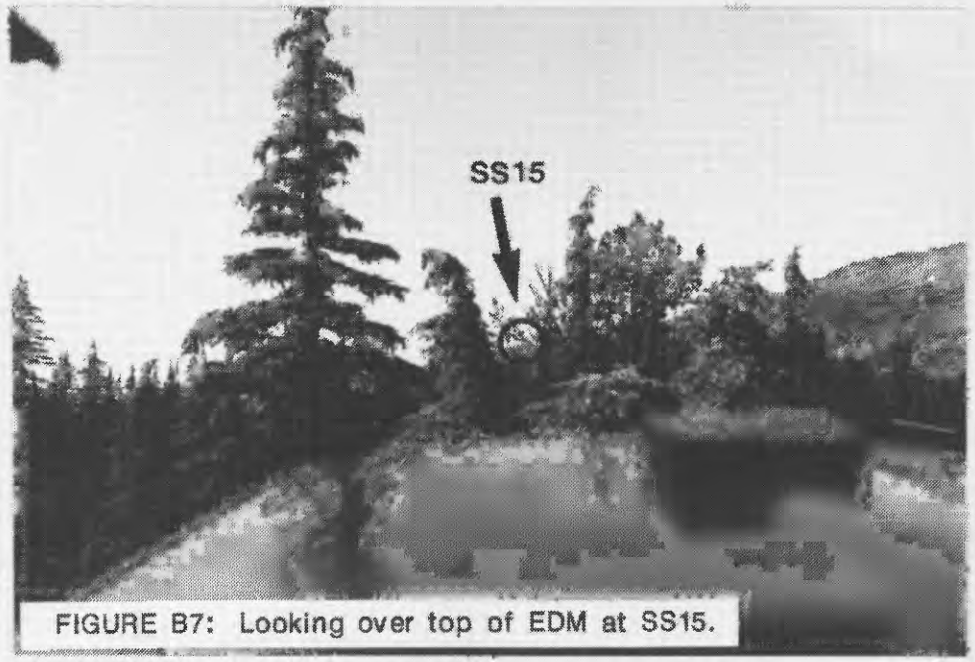


FIGURE B7: Looking over top of EDM at SS15.

FIGURE B8: South Sister from SS1, showing reflector sites.

FIGURE B9: SS2 mirror flash, as seen from SS12.

FIGURE B10: Aerial view of SS2 landing site, from the northwest.

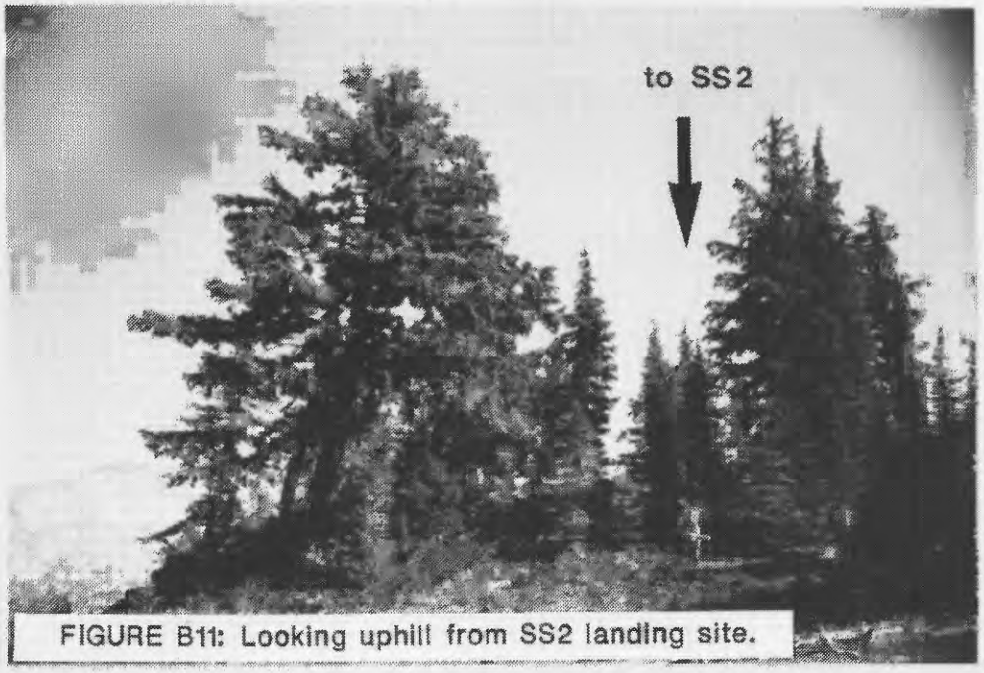


FIGURE B11: Looking uphill from SS2 landing site.

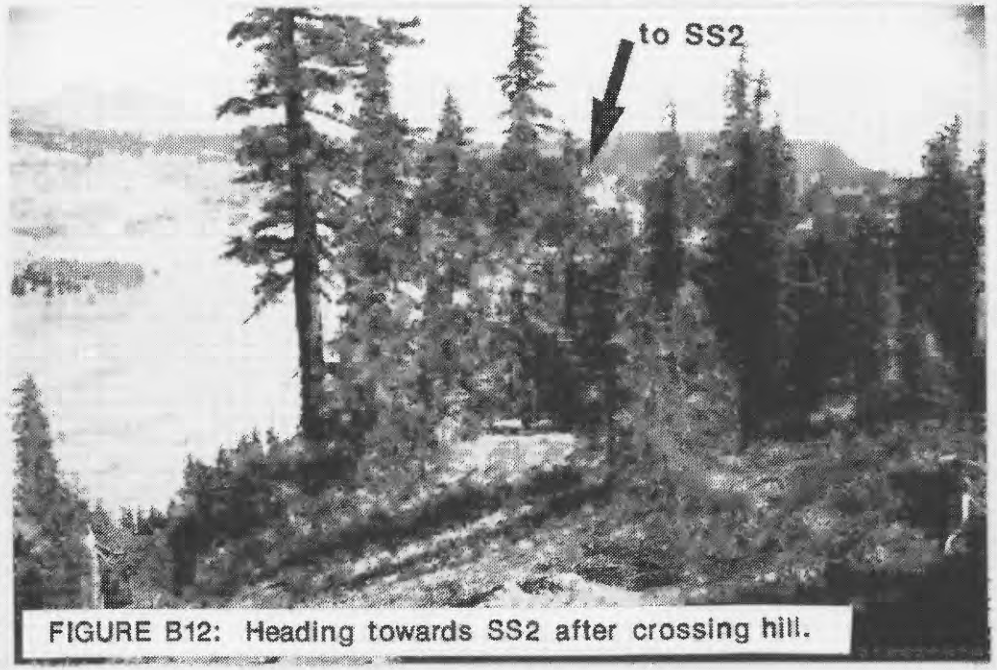


FIGURE B12: Heading towards SS2 after crossing hill.

FIGURE B13: SS2 instrument site.

FIGURE B14: SS2 benchmark.

FIGURE B15: South Sister from SS2, showing reflector sites.

FIGURE B16: SS3 mirror flash, as seen from SS7.

(SS3 location, as seen from SS8 and SS14, see Figures B47 and B67.)

FIGURE B17: Aerial view of SS3 and landing site, from the east.

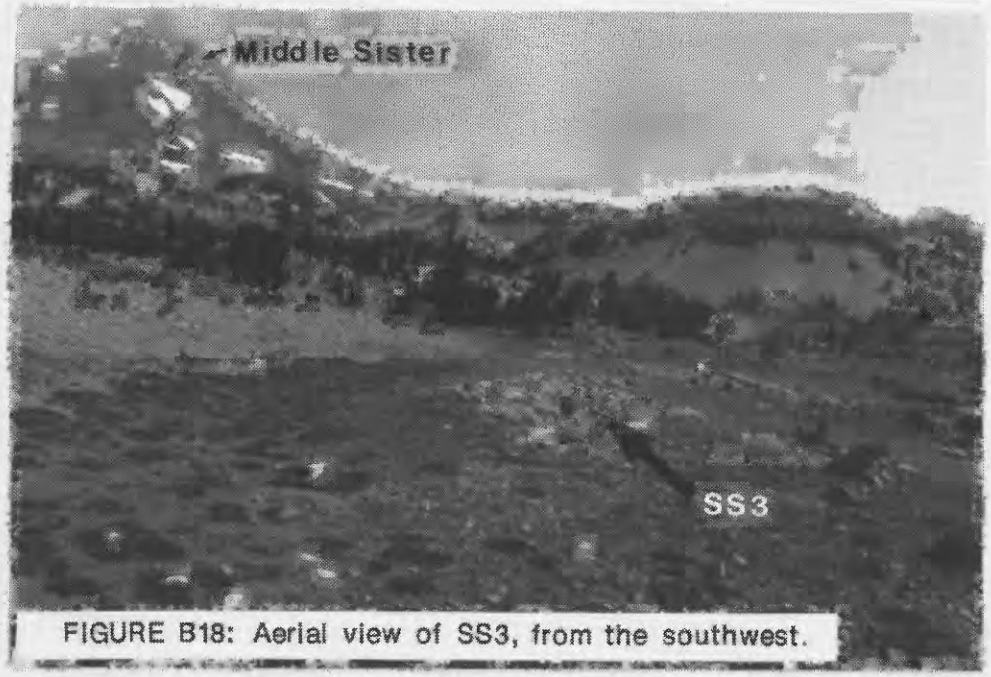


FIGURE B18: Aerial view of SS3, from the southwest.

FIGURE B19: SS3 instrument site.

FIGURE B20: SS3 instrument site and benchmark.

FIGURE B21: South Sister from SS3, showing reflector sites.

(SS4 mirror flash, as seen from SS5, see Figure B34.)

FIGURE B22: SS4 mirror flash, as seen from SS7.

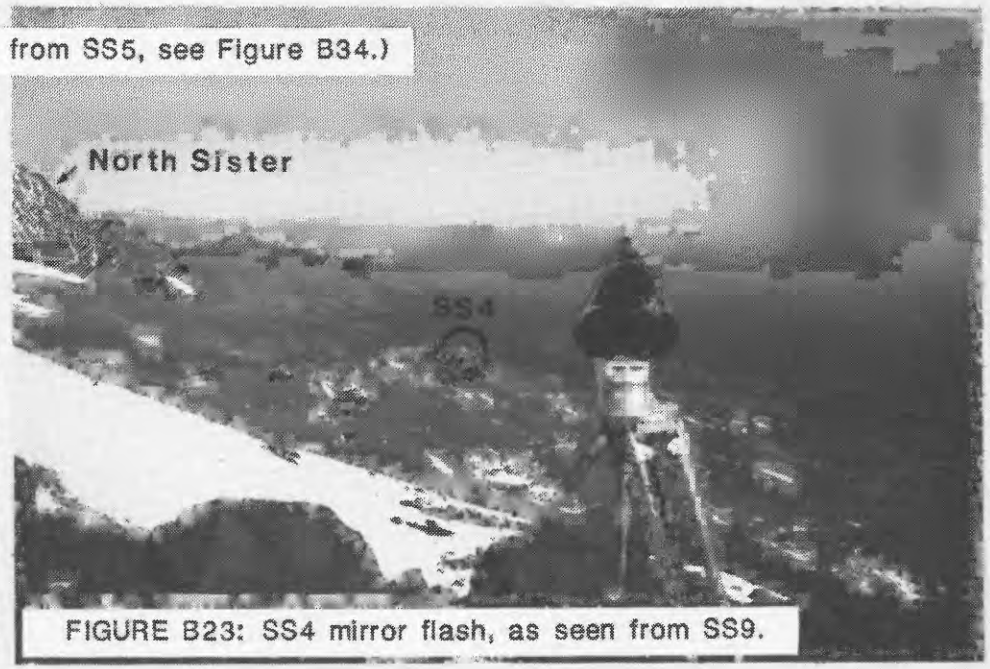


FIGURE B23: SS4 mirror flash, as seen from SS9.

FIGURE B24: SS4 mirror flash, as seen from SS10.

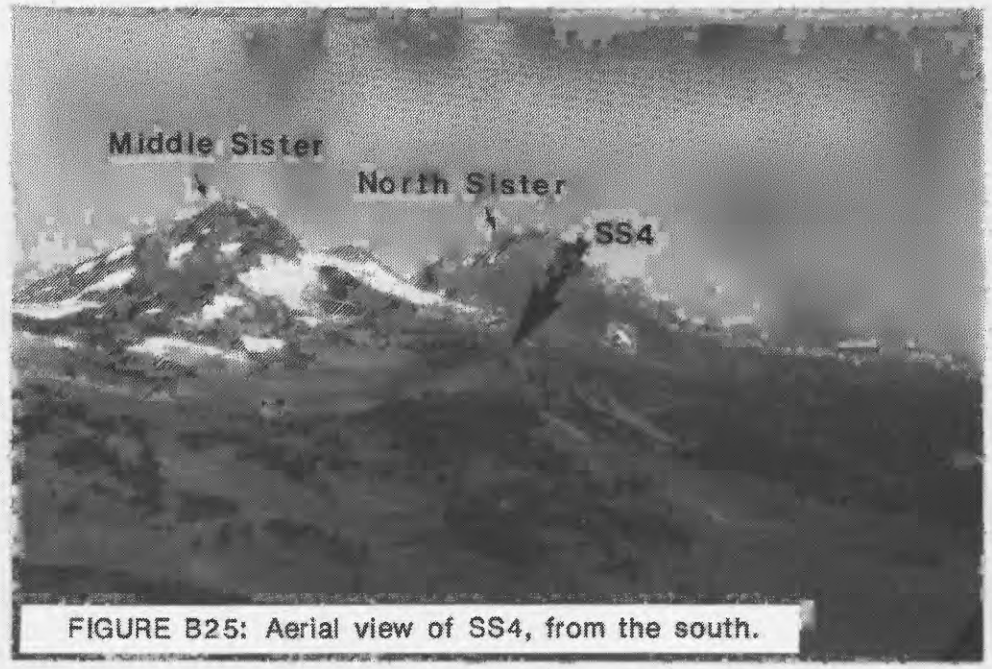


FIGURE B25: Aerial view of SS4, from the south.

FIGURE B26: SS4 from the landing site, looking northeast.

FIGURE B27: SS4 instrument site.

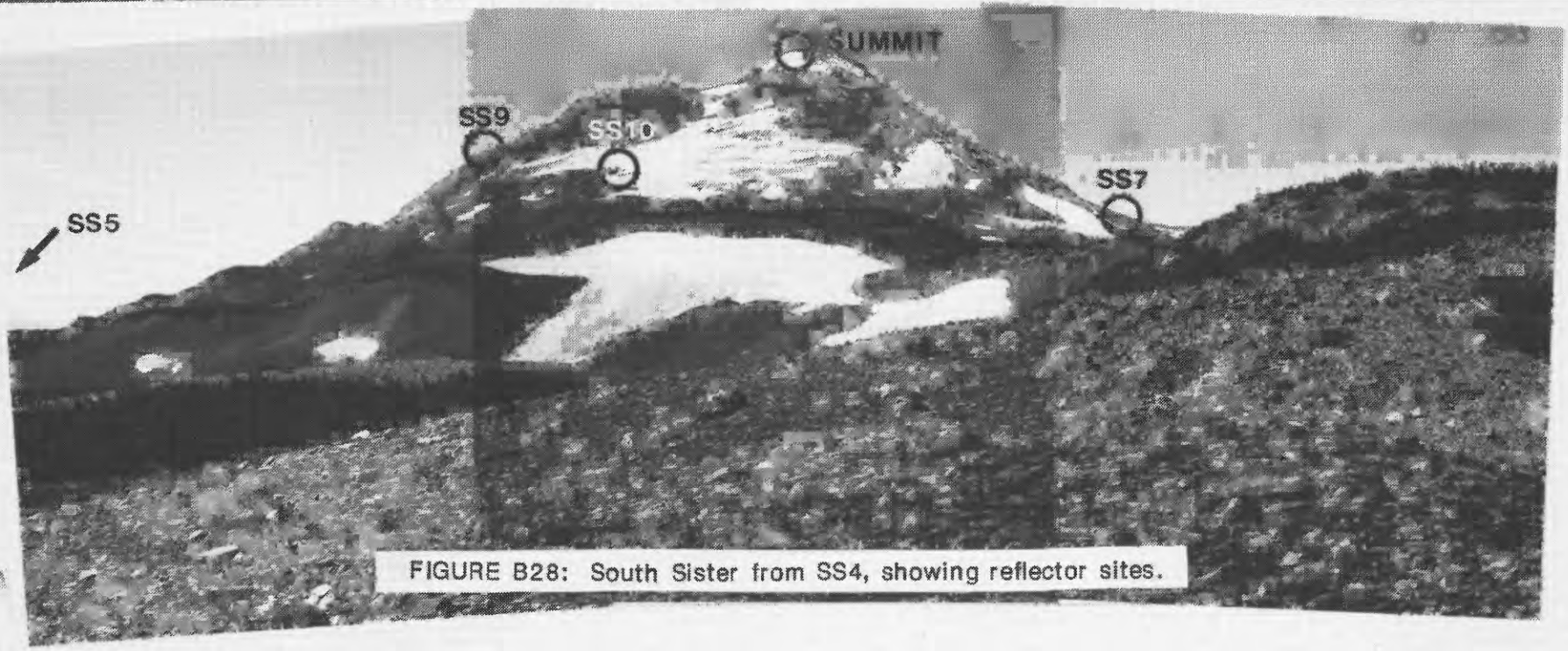


FIGURE B28: South Sister from SS4, showing reflector sites.

FIGURE B29: SS5 mirror flash, as seen from SS6.

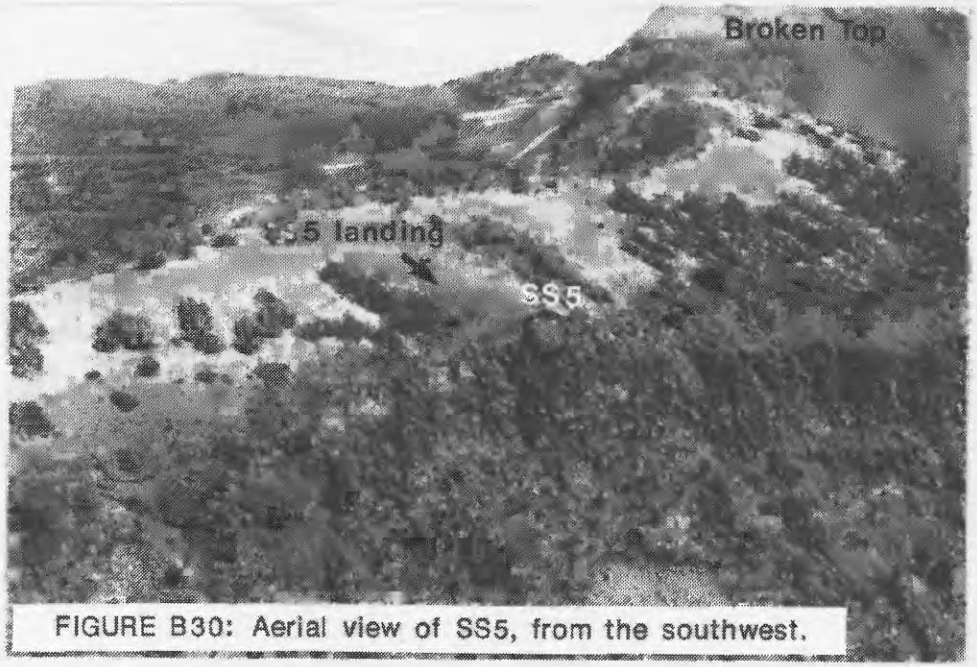


FIGURE B30: Aerial view of SS5, from the southwest.

FIGURE B31: SS5 from the landing site, looking southwest.

FIGURE B32: SS5 instrument site.

FIGURE B33: SS5 instrument site.

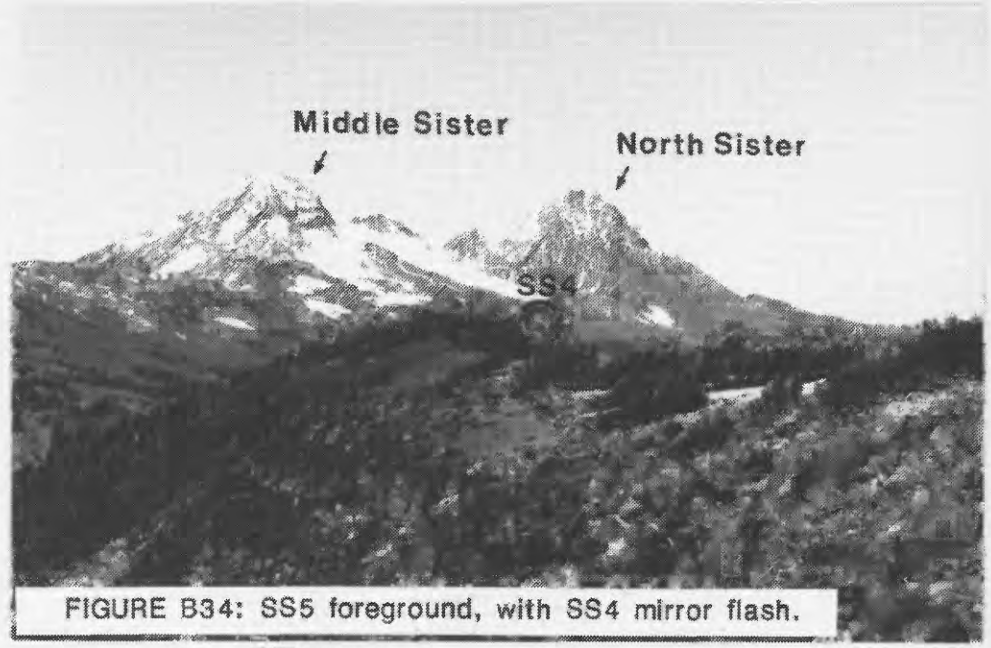


FIGURE B34: SS5 foreground, with SS4 mirror flash.

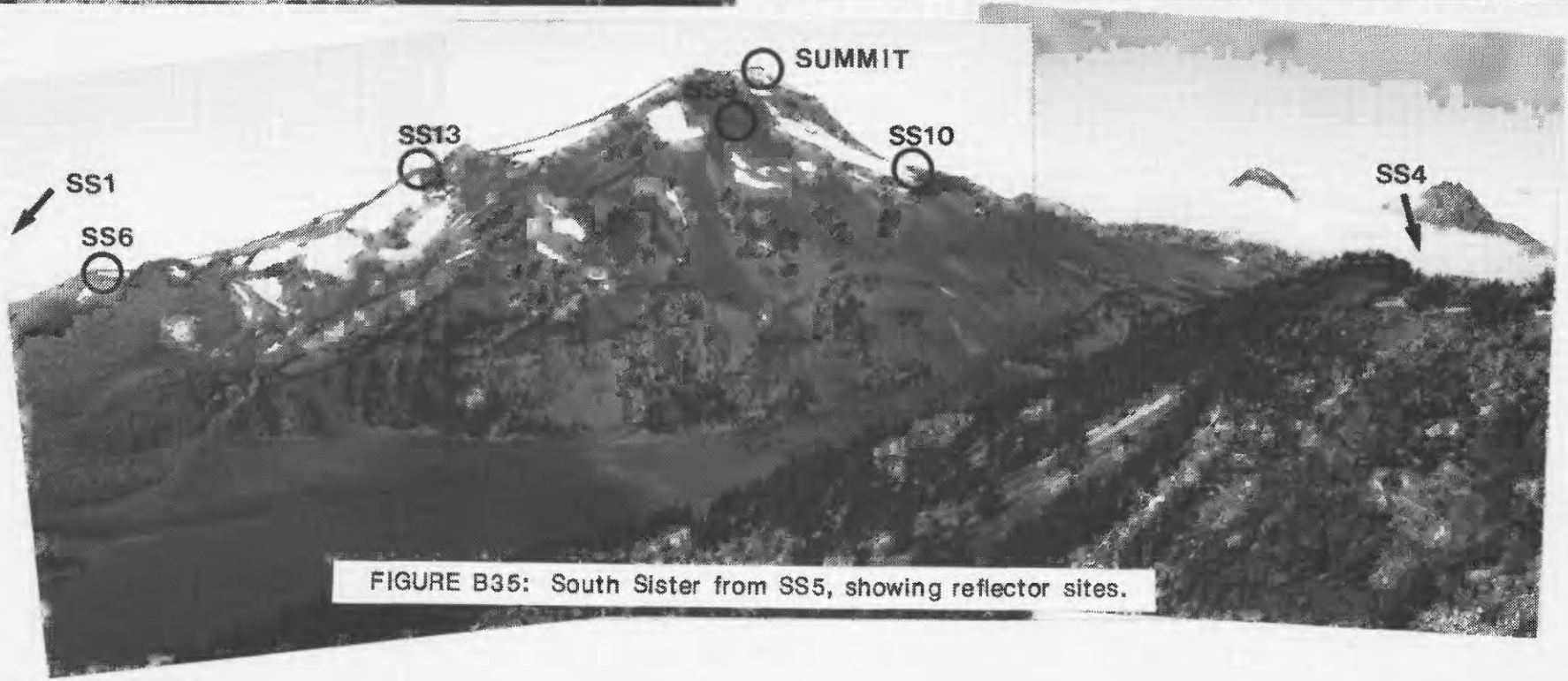


FIGURE B35: South Sister from SS5, showing reflector sites.

FIGURE B36: SS6 mirror flash, as seen from SS1.

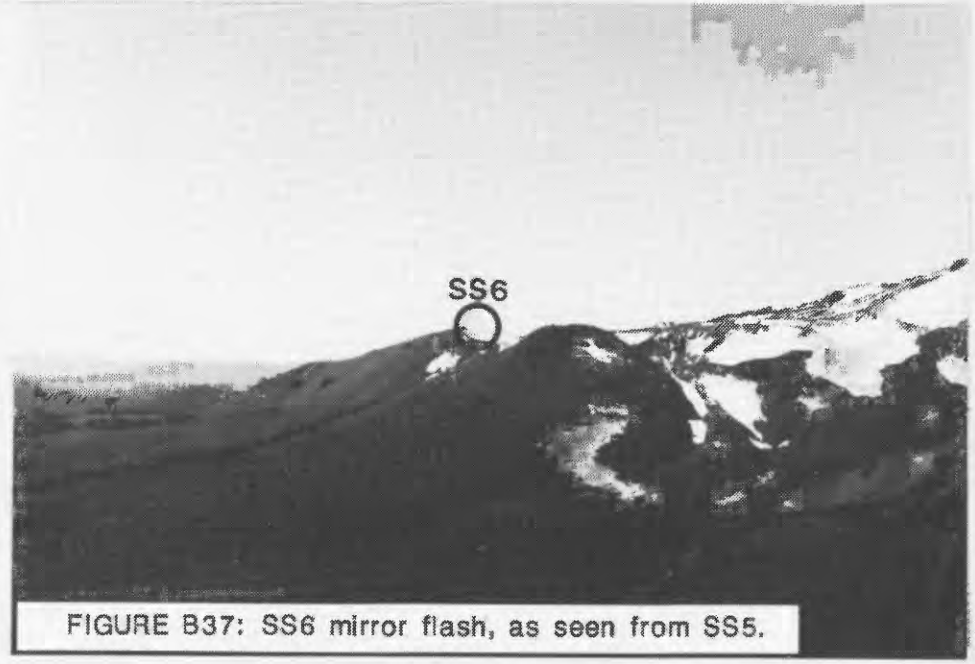


FIGURE B37: SS6 mirror flash, as seen from SS5.

FIGURE B38: SS6 reflector site, from the southeast.

FIGURE B39: SS6 reflector site, from the north.

(SS7 foreground also seen in Figures B16 and B22.)

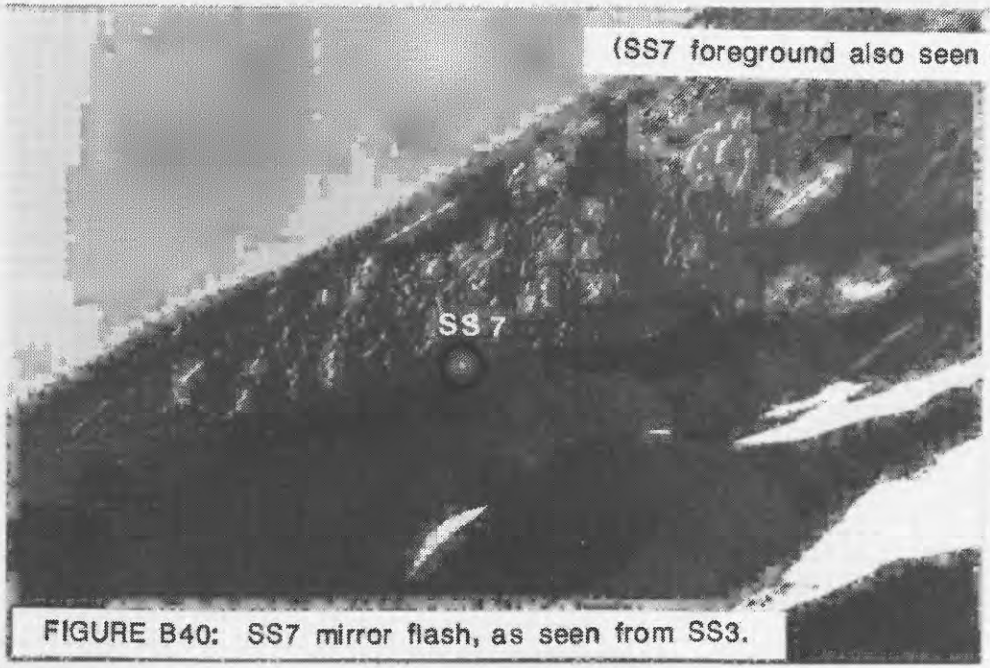


FIGURE B40: SS7 mirror flash, as seen from SS3.

FIGURE B41: SS7 mirror flash, as seen from SS4.

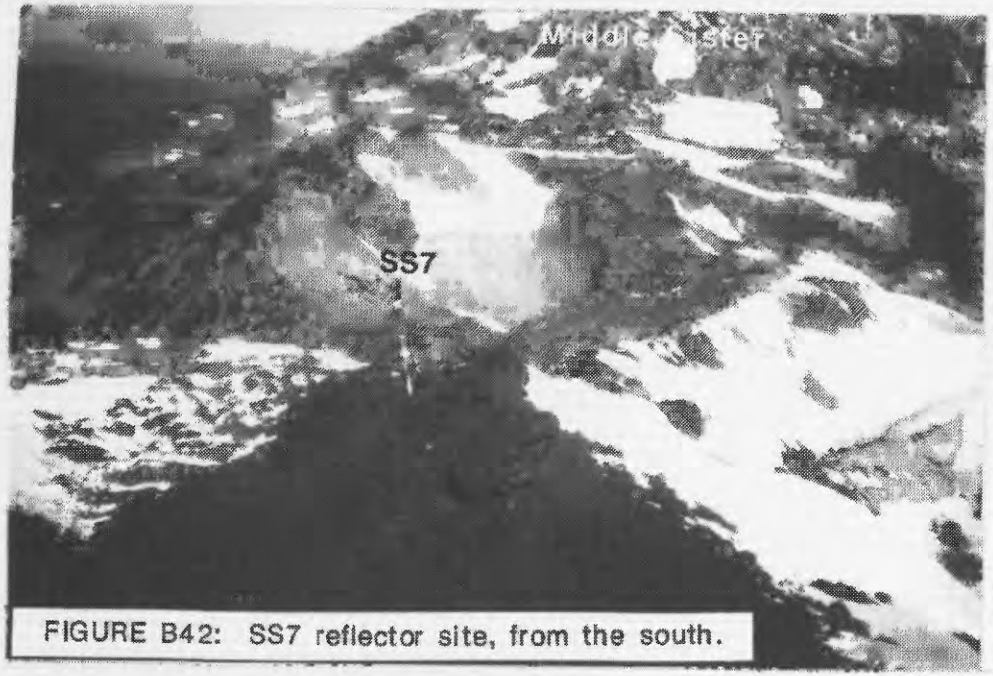


FIGURE B42: SS7 reflector site, from the south.

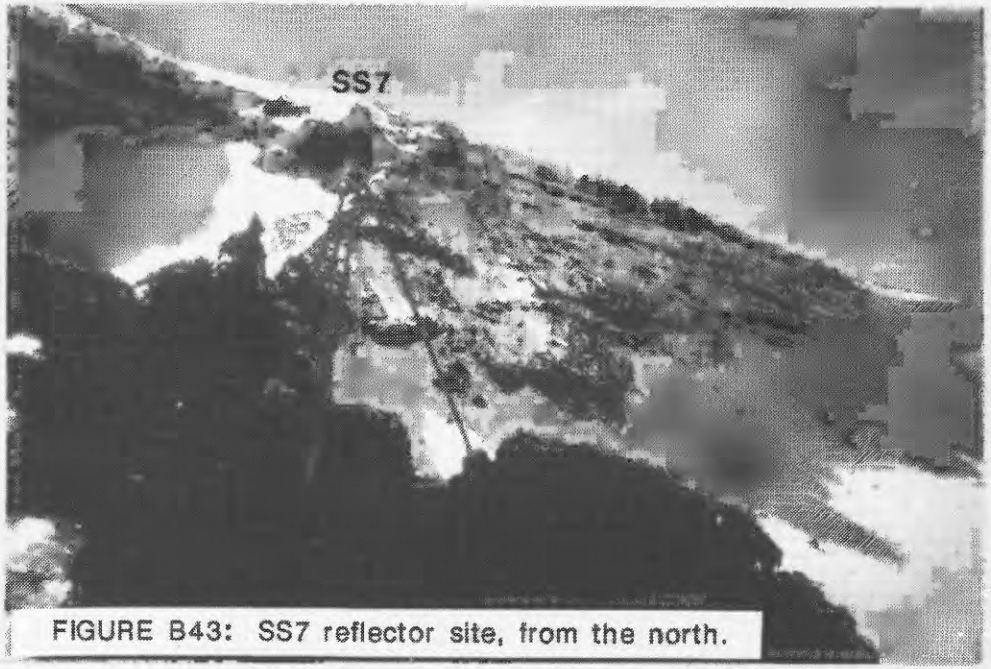


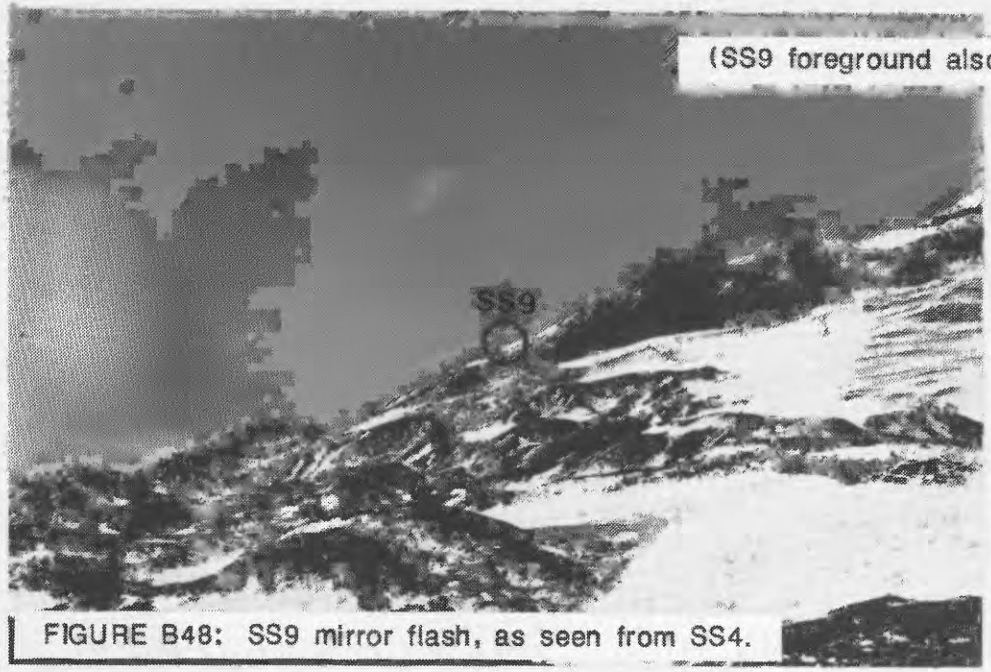
FIGURE B43: SS7 reflector site, from the north.

FIGURE B44: SS8 mirror flash, as seen from SS2.

FIGURE B45: SS8 mirror flash, as seen from SS3.

FIGURE B46: SS8 reflector site.

FIGURE B47: SS8 reflector site, looking northwest towards SS3.



(SS9 foreground also seen in Figure B23.)

FIGURE B48: SS9 mirror flash, as seen from SS4.

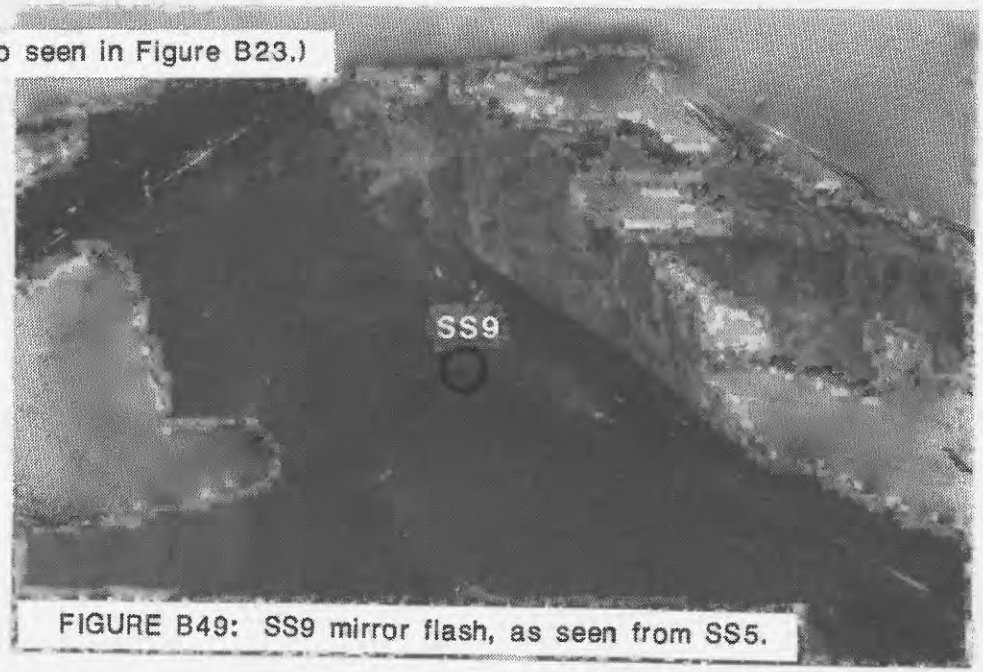


FIGURE B49: SS9 mirror flash, as seen from SS5.

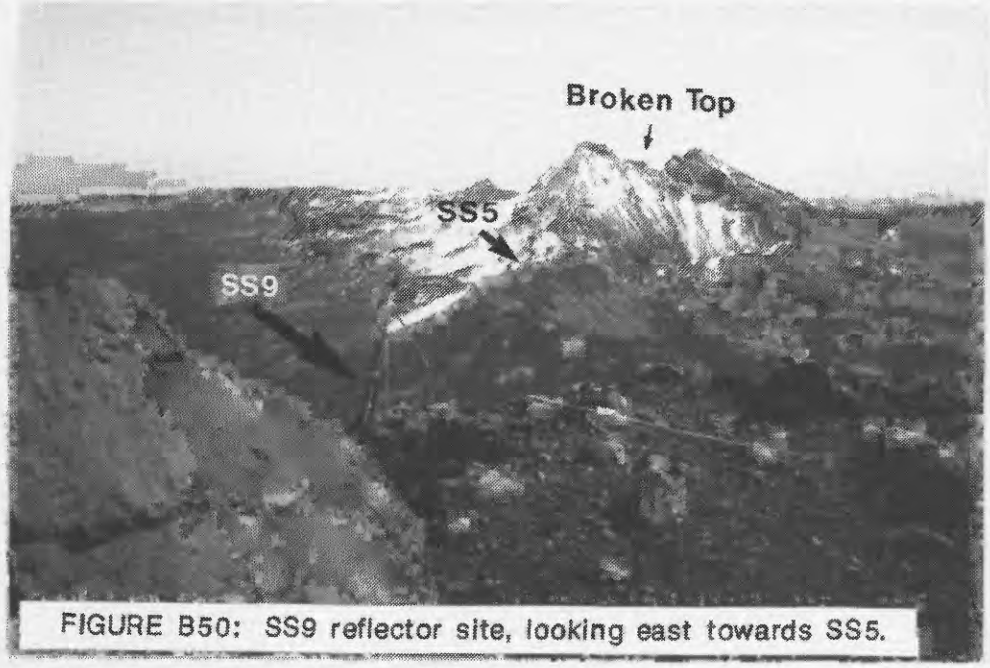
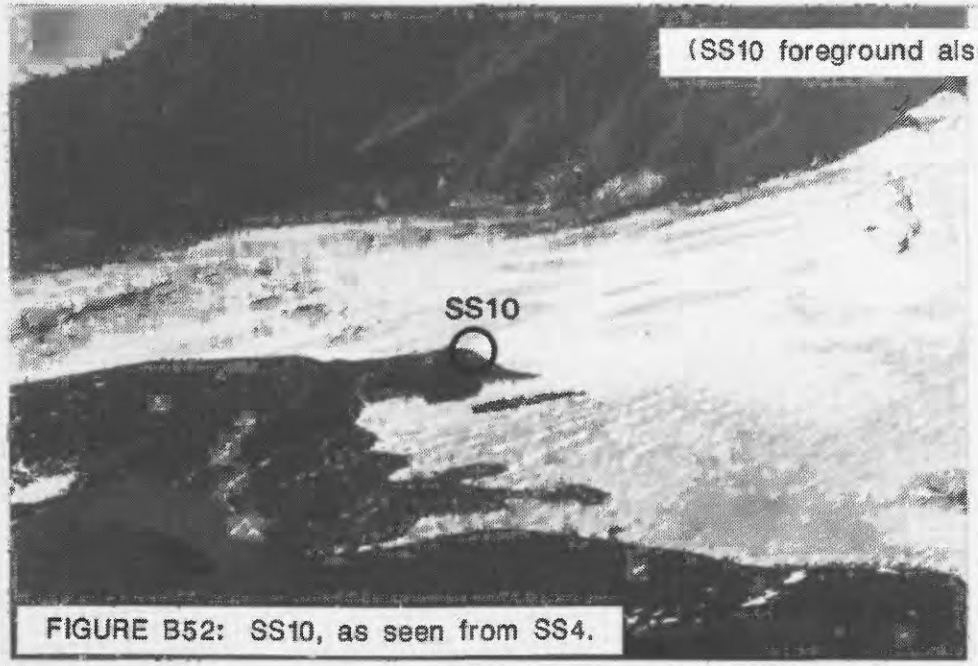


FIGURE B50: SS9 reflector site, looking east towards SS5.

FIGURE B51: SS9 reflector site.



(SS10 foreground also seen in Figure B24.)

FIGURE B52: SS10, as seen from SS4.

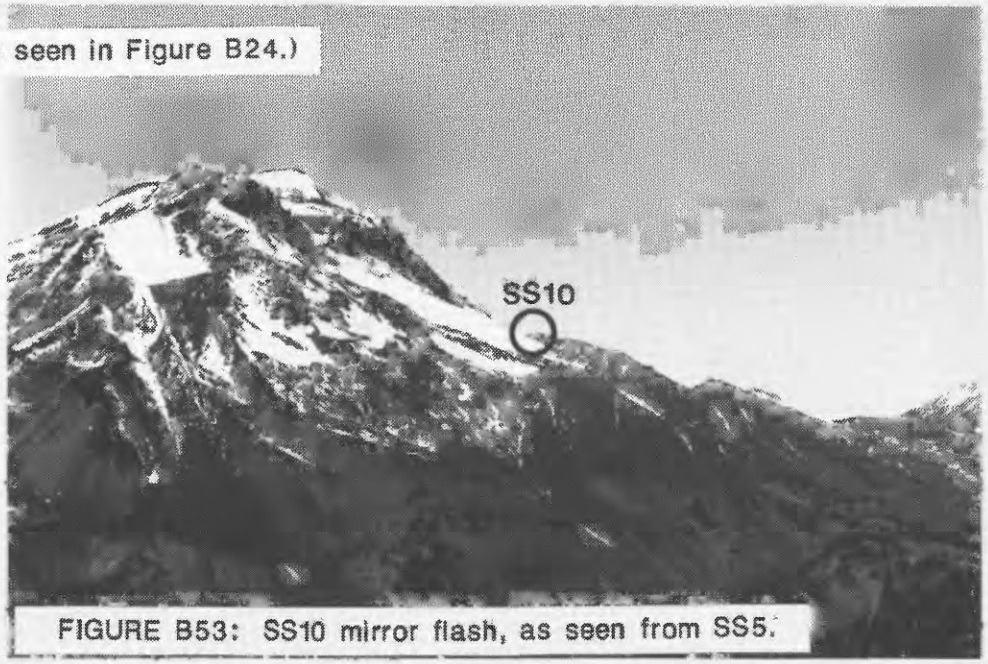


FIGURE B53: SS10 mirror flash, as seen from SS5.

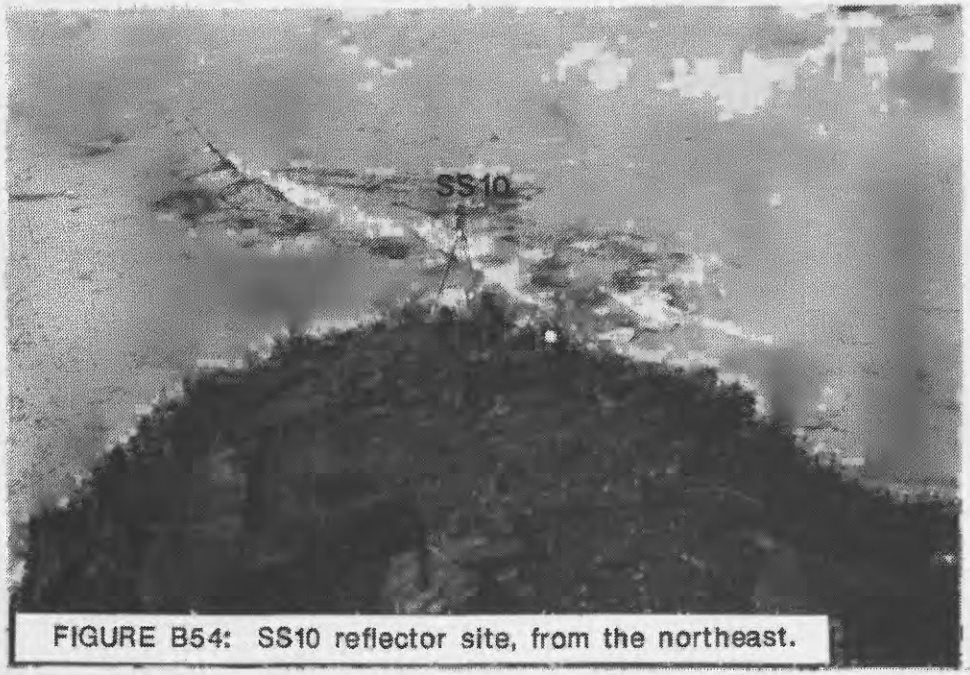


FIGURE B54: SS10 reflector site, from the northeast.

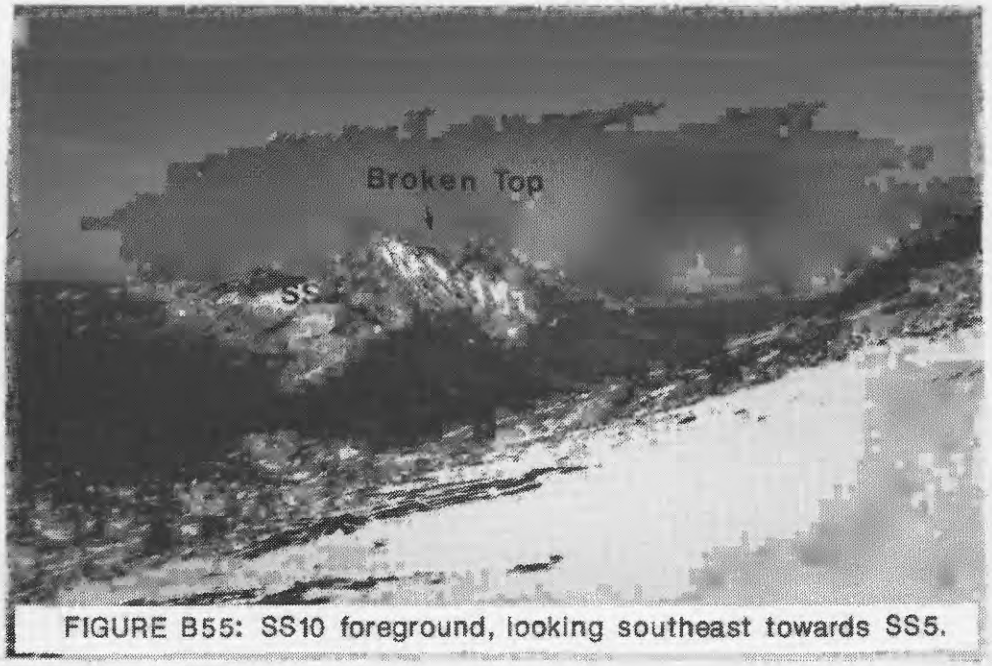


FIGURE B55: SS10 foreground, looking southeast towards SS5.

(SS12 foreground also seen in Figure B2.)

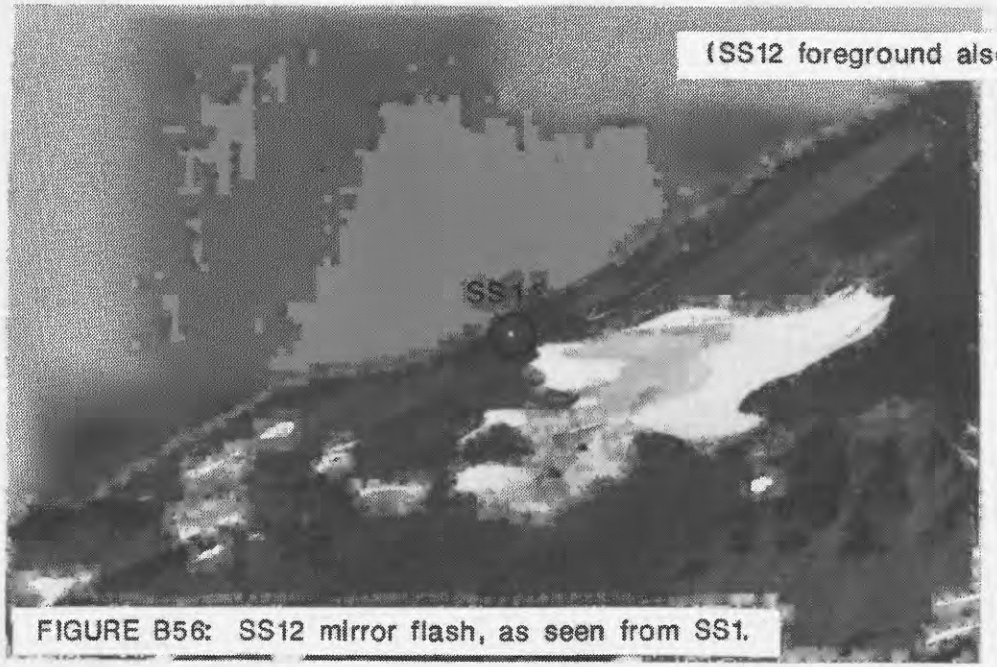


FIGURE B56: SS12 mirror flash, as seen from SS1.

FIGURE B57: SS12 mirror flash, as seen from SS2.

FIGURE B58: SS12 landing site, from the southeast.

FIGURE B59: SS12 reflector site, looking southwest towards SS2.

FIGURE B60: SS13 mirror flash, as seen from SS5.

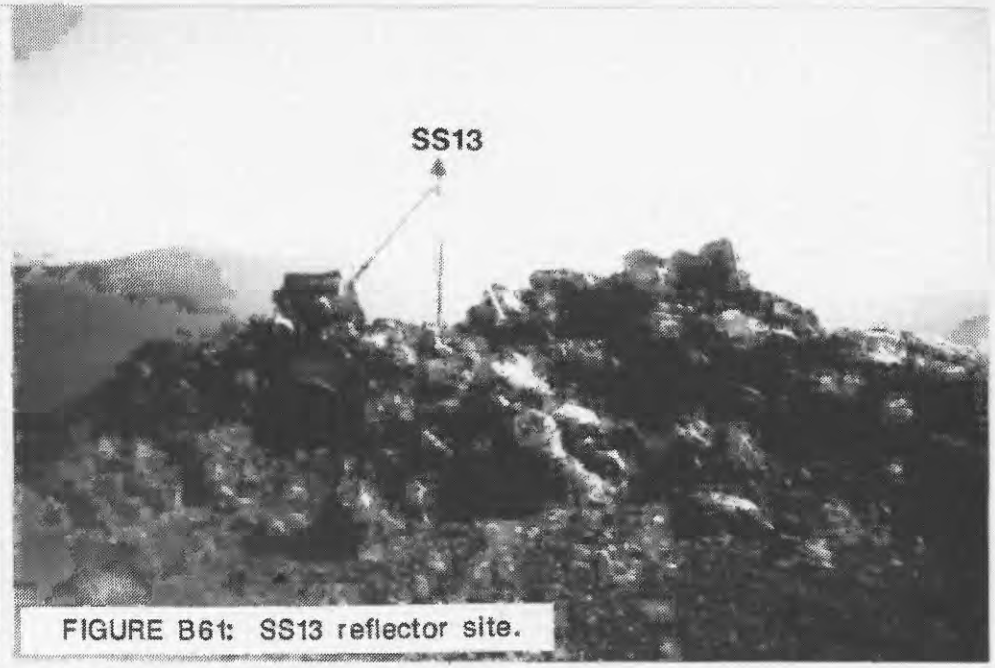


FIGURE B61: SS13 reflector site.

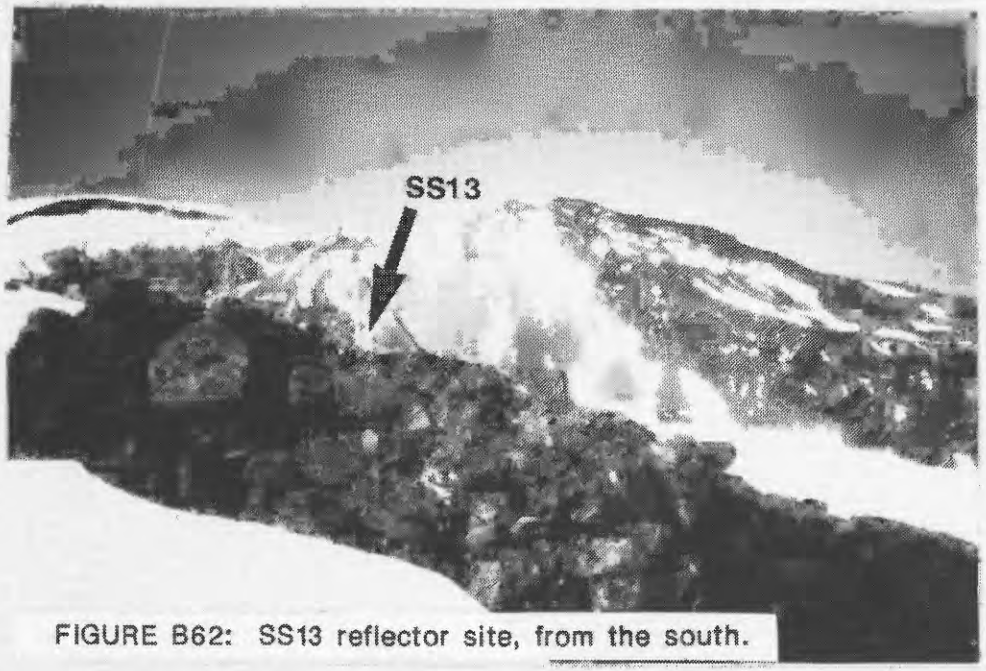


FIGURE B62: SS13 reflector site, from the south.

FIGURE B63: SS13 foreground, looking south towards SS1.

FIGURE B64: SS14 mirror flash, as seen from SS2.

FIGURE B65: SS14 reflector site, from the east.

FIGURE B66: SS14 reflector site.

FIGURE B67: SS14 foreground, looking northwest towards SS3.

FIGURE B68: SS15 mirror flash, as seen from SS2.

FIGURE B69: SS15 landing site, from the south.

FIGURE B70: SS15 reflector site.

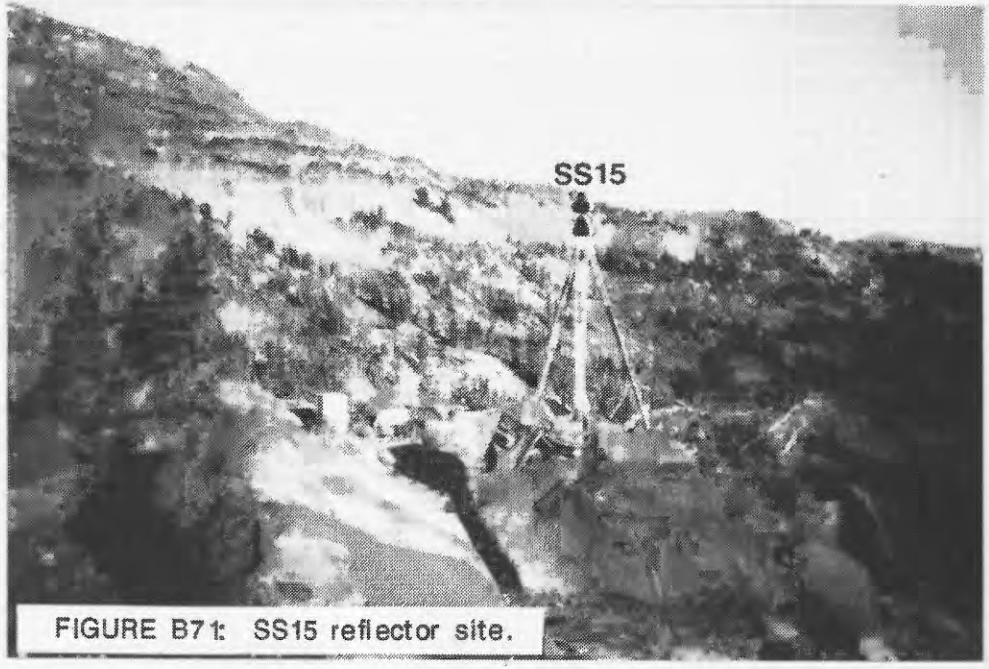


FIGURE B71: SS15 reflector site.

FIGURE B72: SS16 small dome, as seen from SS1.

FIGURE B73: SS16 reflector site, from the north.

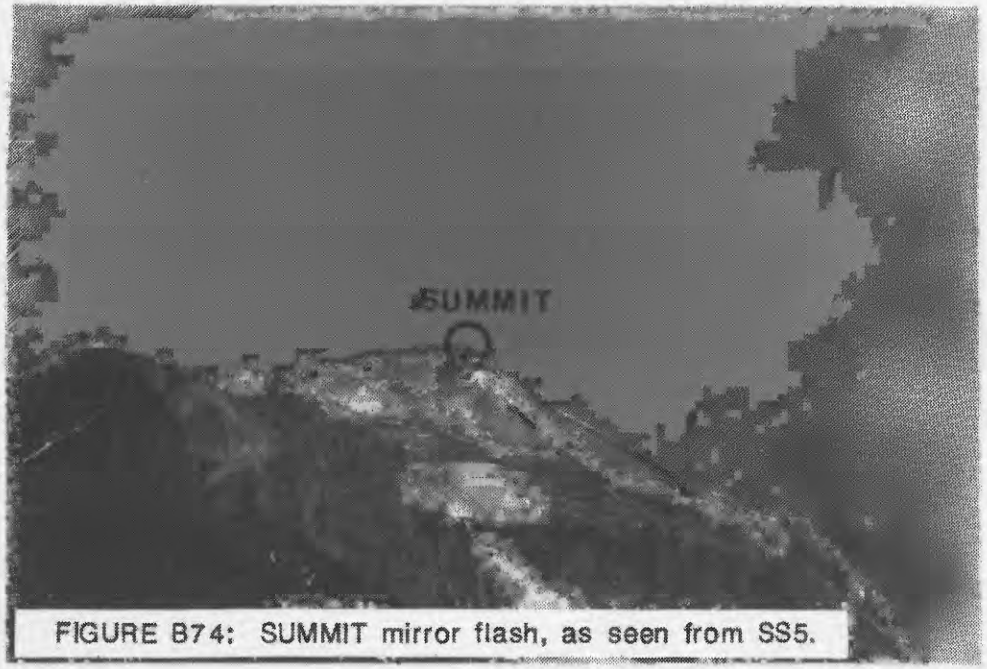


FIGURE B74: SUMMIT mirror flash, as seen from SS5.

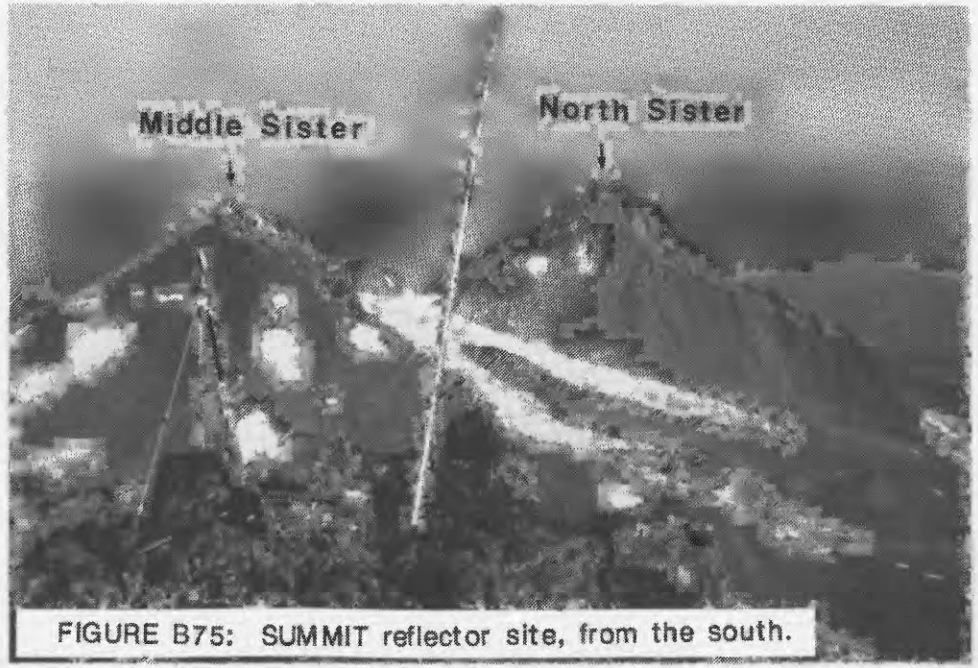


FIGURE B75: SUMMIT reflector site, from the south.

APPENDIX C

1985 and 1986 equipment list for monitoring other volcanoes.

ITEM	MANUFACTURER
Instrument site:	
EDM	Hewlett-Packard 3808A, with a Kern head adapter.
Theodolite	Wild T-2, with Kern head adapter.
Tripod	Kern, with Kern style head and stem.
Barometer	AIR, model AIR-HB-1A.
Temperature sensor	National LM335H Precision Temperature Sensor.
Temperature shield	In-house design.
Temperature holder	Hawaiian Angler, model #TPD 279 (no longer made).
Multimeter	Fluke, model 8060A.
Associated electronics	In-house design.
Reflector sites:	
All tripods and environmental equipment the same as instrument sites.	
Prisms	Two triple prism holders and prisms.
Airborne measurements:	
Data logging equipment	Hewlett-Packard: 71B hand-held computer, 3421 data acquistion/control unit, and 82162A thermal printer.
Temperature sensor	VIZ premium temperature sensor.
Hygristor	Thunder Scientific Corporation, PC-2101C.

APPENDIX D

The FORTRAN program to calculate flightline data was changed due to an error in the open-file report 85-279 (Endo and others, 1985). In the open-file report, flightline distances were calculated using two different indecies of refraction, one calculated from Bomford (1980), and the other from a Hewlitt-Packard technician (personal communication, 1985). Distances calculated using the Bomford value are correct, whereas those calculated using the Hewlitt-Packard value are incorrect.

The subroutine involved is HPINDEX (Endo and others, 1985, p. 23). Subroutine HPINDEX calculates an index of refraction for every point sampled along the flight path. Endo uses the constant $0.2899397X10^{-3}$ as the refractive index for standard atmosphere, calculated from Bomford. The standard index of refraction given by Hewlitt-Packard is $0.27926X10^{-3}$. The index of refraction given by Hewlitt-Packard was used in this report.

The actual change to the subroutine HPINDEX is as follows:

```
NO = .2899397E-3    As in the open-file report.
NO = .27926E-3      As used in this report.
```