DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Precise Level Lines at Crater Lake, Newberry Crater, and South Sister, Oregon

by

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SUMMARY

A magnitude 4.0 earthquake centered beneath Mount St. Helens, Washington on March 20, 1980, signaled the beginning of activity within the volcano and prompted scientists of the U.S. Geological Survey to initiate geodetic measurements (EDM lines) on the flanks of the volcano. As a result of daily measurements of these lines, the growth of a bulge on the northern side of the mountain was effectively tracked until May 18 (Lipman and others, 1981) when a large landslide and devastating lateral blast destroyed the northern flank of the mountain, killing 57 people, including U.S.G.S. geologist David A. Johnston. The destructive nature of the explosion, like that of Lassen Peak, California in 1912, poignantly re-emphasised the need to better monitor other volcanoes in the continental United States. That is one of the missions of the David A. Johnston Cascades Volcano Observatory (C.V.O.), established in Vancouver, Washington in 1980 and dedicated formally in 1982.

It is the responsibility of C.V.O. to study Mount St. Helens and other volcanoes in the Cascade Range. Accordingly, monitoring efforts were implemented on Lassen Peak, and Mount Shasta, California, Mount Baker, Mount St. Helens and Mount Rainier, Washington, and Mount Hood, Oregon, between 1981 and 1984. During August and September 1985, short (200 m to 9 km) precise level lines were surveyed at Newberry Crater, Crater Lake, and South Sister, Oregon as part of C.V.O.'s continuing program to implement baseline geodetic control and to expand and upgrade its monitoring techniques on potentially active volanoes in the Cascade Range.

INTRODUCTION

With the re-awakening of Mount St. Helens during March 1980, and the establishment of the David A. Johnston Cascades Volcano Observatory in 1980, special attention has been given to the Cascade Range of the western United States by members of the United States Geological Survey.

"Dry-tilt" (Yamashita, 1981) stations were installed at Mount Baker, Washington in 1975 (Frank and others, 1977). Additional stations were installed in 1981-84 at Mount Shasta and Lassen Peak, California (Dzurisin and others, 1982), Mt. Rainier (Dzurisin and others, 1983), Mount Baker, and Mount St. Helens, Washington (Yamashita, unpublished report), and Mt. Hood, Oregon (Dzurisin, unpublished report), in an effort to detect vertical displacements that might signal the intrusion of magma beneath those volcanos. Such intrusions have been documented by this technique on Hawaiian volcanoes (Fiske and Kinoshita, 1969; Kinoshita and others, 1974). Repeat measurements of dry-tilt stations at Lassen Peak and Mount Shasta in 1984, however, showed random tilt changes inconsistent with tilt patterns observed on Hawaiian volcanoes by members of the Hawaiian Volcano Observatory. Analysis of the data led us to conclude that the anomalous tilt vectors were a product of benchmark instability; thus we have redesigned our method of monitoring for vertical displacements.

In the dry-tilt method of determining vertical changes, three benchmarks are placed in a nearly equilateral triangle with sides of 30 to 40 m long, and the relative elevation difference between the three benchmarks measured. By knowing the azimuth and length of each leg of the triangle and the elevation changes between the vertices, a vector and magnitude of tilt can be calculated. The simplicity of the system and its proven track record in Hawaii seemed to make it an ideal method for detecting vertical changes on Cascade volcanoes. However, because of the short base used, subtle benchmark instability (due to frost heaving or thermal expansion and contraction) appears to make the system unreliable in the Cascades (a change of only 0.5 mm on a base line of 35 m would give a tilt change of 14 microradians).

In order to continue monitoring the Cascades for vertical displacements and to overcome the shortcomings of the dry-tilt technique, it was decided that a longer base was needed (a change of 0.5 mm at 200 m is only 2.5 micoradians) and that precise level lines would be the best method for measuring vertical changes.

This report presents benchmark descriptions and corrected data for the 1985 and 1986 surveys as well as maps, photos and the names of persons to contact for access to level lines at Crater Lake, Newberry Crater, and South Sister, Oregon.

Level Procedure

The level lines were observed using a Wild (magnetically shielded) NA2 pendulum level with micrometer plate and two 3-m precise invar level rods supported with detachable stays. All baseline surveys during 1985 were double run and only closures less than first-order standards accepted ((3mm x (2d))$^{1/2}$, where d is distance in km between benchmarks) (Rappleye, 1948). The 1986 resurvey was only single run, but every other benchmark interval was run in opposing direction to eliminate the effects of pin settling. Balance between rod and instrument was maintained for all surveys. A collimation test was performed on the instrument at the beginning of each day. All turning points were established using hardened "concrete" nails, and benchmarks were "nippled" die-cast red brass cemented into bedrock, large boulders, or permanently attached to rods driven into the ground. On the South Sister level lines, 2.5 x 5 cm stamped aluminum tags were attached to the nails to be used as intermediate "benchmarks" between standard benchmarks. First-order procedures were mostly observed by using only the middle 2 m of the level rod and by measuring temperatures at 0.5 and 2.5 m above ground level at each instrument set-up.

Data Reduction

All data have been corrected for rod error as determined by the National Bureau of Standards in Gaithersburg, Maryland, for the paired rods used. A temperature correction has been applied to correct for changes in length of the invar strip, as well as a refraction correction using the Kukkamaki formula as presented in NOAA publication NOS NGS 34 (Balazs and Young, 1982).

CRATER LAKE

Crater Lake, located in southwestern Oregon (fig. 1), is a 700 m (2,000 ft) deep lake created by the removal of magma and subsequent collapse of ancestral Mt. Mazama during the cataclysmic eruption 6800 years ago (Bacon, 1983). Although no lava flows younger than the post-caldera volcanism of about 6800 years are found outside the caldera, eruptions within the crater are evident by Wizard Island on the west side and by Merriam cone, a small andesite vent on the north caldera floor (Bacon, 1983). Level lines were implemented at Crater Lake to compliment an EDM network established by Chadwick and others (1985) in 1983.

Level lines (fig. 2) were established along existing roads in areas where they form an "L" shape to allow calculation of a tilt vector (Fig. 2a & 2b). All turning points were established by hammering hardened "concrete" nails into the asphalt pavement. Balance between rod and instrument was maintained between benchmarks, and all benchmarks were cemented into bedrock.

BENCHMARK DESCRIPTIONS: CRATER LAKE

The benchmarks lie along three short, first-order level lines designed to detect crustal tilts associated with future unrest of the Crater Lake magmatic system (see fig. 2).

STATION WATCHMAN
CVO85-206: In road cut along crater rim road, 5.7 km (3.55 miles) NW of Rim Village intersection, 0.7 km (0.45 miles) WSW of Watchman trailhead; in lava flow on lake side of road, 7 m S45°E of centerline, 0.5 m above road level.

CVO85-207: Near NE end of large road cut along crater rim road, 5.9 km (3.7 miles) NW of Rim Village intersection, 0.4 km (0.25 miles) W of Watchman trailhead; in lava flow on lake side of road, 5 m S20°E of centerline, 1 m above road level.

CVO85-208: Near Watchman trailhead, 6.3 km (3.95 miles) NW of Rim Village intersection, 0.2 km (0.15 miles) SW of paved viewpoint; 2 m S of trail about 40 m beyond trailhead, 5 m beyond "No Pets" sign, 1 m above trail level, 15 m S10°E of centerline, 4 m above road level.

CVO85-209: Near SE end of road cut, 6.7 km (4.2 miles) NW of Rim Village intersection, 0.2 km (0.15 miles) NW of paved viewpoint; in lava flow on lake side of road, 50 m N of NW end of paved pullout, 5 m N35°E of centerline, 0.5 m above road level.

CVO86-1: In bedrock roadcut 7.2 km (4.5 miles) NW of rim Village intersection, about 20 cm above road level, 5.25 m east of centerline, near south end of roadcut.

BENCHMARK ID	1985 SURVEY ELEVATION BETWEEN BM'S (m)	CUMULATIVE ELEVATION DIFFERENCE(m)	1986 SURVEY ELEVATION BETWEEN BM'S (m)	CUMULATIVE ELEVATION DIFFERENCE(m)	1985-1986 CHANGE (mm)	CUMULATIVE CHANGE(mm)
CVO85-206	0.0	0.0	0.0	0.0	0.0	
CVO85-207	16.45963	16.45963	16.46023	16.46023	0.60	0.60
CVO85-208	25.42316	41.88279	25.42335	41.88358	0.19	0.79
CVO85-209	5.09308	46.97587	5.09344	46.97702	0.36	1.15

The changes of 0.79 mm between CVO85-206 and CVO85-208 and 0.36 mm between CVO85-208 and CVO85-209, convert to a tilt of 1.91 microradians N67°W down (fig. 2c). This is within the expected uncertainty of the technique (± 5 microradians).

STATION PALISADE

CVO85-210: In road cut through pumice ridge, 2.9 km (1.8 miles) E of Cleetwood Cove trailhead; on flank side of road, 36 m N45°E of centerline, in small bedrock knob (not visible from road), about 1 m above road level.

CVO85-211: At small pullout on lake side of crater rim road, 3.6 km (2.3 miles) SE of Cleetwood Cove trailhead; in Wineglass Tuff along crater rim, 32 m S75°W of centerline, about 4 m below road level; 8.6 m N63°W of BM CL1.

CVO85-212: Near SE end of paved viewpoint along crater rim road, 3.9 km (2.45 miles) SE of Cleetwood Cove trailhead; in Wineglass Tuff 3 m beyond overlook wall, 20 m S40°W of centerline, about 1 m below road level.

CVO86-2: At small turnout about 50 m north of north end of small stone wall 4.5 km (2.8 miles) SE of Cleetwood Cove trailhead; in Wineglass tuff at rim, 29.6 m WSW of centerline.

BENCHMARK ID	1985 SURVEY ELEVATION BETWEEN BM'S(m)	CUMULATIVE ELEVATION DIFFERENCE(m)	1986 SURVEY ELEVATION BETWEEN BM'S (m)	CUMULATIVE ELEVATION DIFFERENCE(m)	1985-1986 CHANGE (mm)	CUMULATIVE CHANGE(mm)
CVO85-210	0.0	0.0	0.0	0.0	0.0	0.0
CVO85-211	-39.78108	-39.78108	-39.77943	-39.77943	1.65	1.65
CVO85-212	-5.17495	-44.95603	-5.17553	-44.95496	-0.58	1.07

The changes of -1.07 mm between CVO85-212 and CVO85-210 and -0.58 mm between CVO85-212 and CVO85-211, convert to a tilt of 3.26 microradians, N68°E down (fig. 2c).

STATION KERR

CVO85-213: Near NE end of road cut along crater rim road, 4.0 km (2.5 miles) SW of Cloudcap Road intersection; in lava flow on lake side of road, 5 m N75°W of centerline, 0.5 m above road level.

CVO85-214: Near W end of road cut along crater rim road, 4.5 km (2.8 miles) SW of Cloudcap Road intersection; in lava flow on lake side of road, 5 m N15°W of centerline, 1 m above road level (Destroyed in 1985).

CVO86-3: 4.5 km (2.8 miles) SW of Cloudcap Road intersection, 5.6 m S of centerline in 3 m diameter rounded boulder about 1 m above road level, and about 70 m West of West end of lava flow exposed in road cut (replaces CVO85-214).

CVO85-215: At NW end of road cut along crater rim road, 5.4 km (3.4 miles) SW of Cloudcap Road intersection; in lava flow on lake side of road, opposite NW end of pullout, 7 m N65°E of centerline, 4 m above road level.

	1985 SURVEY		1986 SURVEY		1985-1986
BENCHMARK ID	ELEVATION BETWEEN BM'S (m)	CUMULATIVE ELEVATION DIFFERENCE(m)	ELEVATION BETWEEN DIFFERENCE(m)	CUMULATIVE ELEVATION(m) BM'S (m)	CHANGE(mm)
CVO85-213	0.0	0.0	0.0	0.0	0.0
CVO85-214	-32.74622	-32.74622	DESTROYED BY ROAD WORK		
CVO86-3			-39.28913	-39.28913	0.0
CVO85-215	-56.18225	-88.92847	-49.63750	-88.92663	1.84

Computation of a tilt vector is not possible for this line because of the destruction of benchmark CVO85-214. The magnitude of tilt between CVO85-213 and CVO85-215 is 1.7 microradians, west up.

Permission should be obtained in advance from the National Park Service before engaging in any activity within Crater Lake National Park. Coordination for the 1985-86 survey was made through Mr. John Jarvis, Parks Resource Management Specialist. Mr Jarvis can be reached by writing:

National Park Service
P.O. BOX 7
Crater Lake, Oregon 97604
or by calling (503)594-2211 ext. 251

NEWBERRY CRATER

Newberry Crater (fig. 1), like Crater Lake, Oregon and Mount St. Helens, Washington, is a product of cataclysmic volcanism and as such deserves special attention.

Although the age of the most recent collapse of Newberry Crater is not known, many rhyolite lava flows have been extruded in the past 7,000 years and as recently as 1,300 years ago (MacLeod and others, 1982). Newberry was added to the list of volcanoes for CVO'S expanding network of precise level lines because it is "capable of future eruptions" (MacLeod and others, 1982).

All turning points were established by hammering hardened "concrete" nails into the asphalt pavement, all sights were kept to 40 meters or less, and balance between foresight and backsight was maintained between benchmarks.

Unlike the lines at Crater Lake, the Newberry survey crossed the center of the caldera nearly from rim to rim (fig. 3). Benchmarks were placed approximately 1 km apart on bedrock where possible. Where no suitable bedrock was found, copper-coated rods were driven to refusal (7.6 m for CVO85-203) and a benchmark attached to the rod.

BENCHMARK DESCRIPTIONS: NEWBERRY CALDERA

The benchmarks lie along a first-order level line across Newberry caldera, along the paved road from the entrance station at Paulina Lake Campground eastward to Cinder Hill Campground (fig. 3).

BM A1 6330.6: At bridge over headwaters of Paulina Creek, along spur road to Paulina Creek Campground; on bedrock along S bank of creek, 5.6 m N6°W of SW corner of bridge, 6 m WSW of centerline, 2 m below road level.

CVO85-190: In roadcut through lava flow, N side of paved road, 1.4 km (0.9 miles) SE of entrance station, 0.6 km (0.4 miles) W of Chief Paulina Horse Camp road; between paved road and abandoned dirt road, 45 m SE of pullout at intersection, 15.6 m N37°E of centerline, near road level.

CVO85-200: In trees on N side of paved road, 2.5 km (1.55 miles) east of entrance station, 45 m W of dirt road to Paulina Lake summer homes; on 1.5 m diameter boulder projecting 1 m above ground level, 34 m N7°W of centerline, about 3.5 m below road level.

CVO85-201: At large pullout on S side of paved road, 3.9 km (2.45 miles) east of entrance station, 0.3 km (0.2 miles) east of intersection of Obsidian Flow viewpoint road. Benchmark about 0.4 m above ground level, on 2 m diameter boulder projecting 1 m above ground level, 53 m S31°E of centerline, about 0.4 m above road level.

CVO85-202: In roadcut through lava flow, N side of paved road, 5.1 km (3.2miles) east of entrance station, 40 m west of dirt road to mine, 16.4 m N35°W of centerline, about 2 m above road level.

CVO85-203: In trees on S side of paved road, 6.5 km (4.05 miles) east of entrance station, 0.1 km (0.05 miles) NE of entrance to East Lake Campground; 27.3 m S16°E of centerline, on a 25 foot long, 5/8 inch diameter copperweld rod driven to refusal, surrounded by an 8 inch diameter white plastic pipe projecting 10 cm above ground level.

CVO85-204: In roadcut through lava flow, SE side of paved road, 7.8 km (4.9 miles) east of entrance station, about 20 m SW of point where powerline crosses road, opposite pullout; 9.2 m S36°E of centerline, about 2 m above road level.

CVO85-205: At Cinder Hill Campground, 8.7 km (5.45 miles) NE of entrance station, 0.8 km (0.5 miles) N of China Hat Road intersection; on NE side of 2 m diameter boulder projecting 1 m above ground level, 60 m N74°E of first split in road within campground, about 0.4 m above ground level, 2.5 m above road level.

NEWBERRY CRATER

BENCHMARK ID	1985 SURVEY ELEVATION BETWEEN BM'S (m)	1985 SURVEY CUMULATIVE ELEVATION DIFFERENCE(m)	1986 SURVEY ELEVATION BETWEEN BM'S (m)	1986 SURVEY CUMULATIVE ELEVATION DIFFERENCE(m)	1985-1986 CHANGE (mm)	1985-1986 CUMULATIVE CHANGE(mm)
A1 6330.6	0.0	0.0	0.0	0.0	0.0	
CVO85-190	28.46462	28.46462	28.46482	28.46482	0.20	0.20
CVO85-200	20.44086	48.90548	20.44089	48.90571	0.03	0.23
CVO85-201	7.30636	56.21184	7.30678	56.21249	0.42	0.65
CVO85-202	10.23018	66.44202	10.22971	66.44220	-0.47	0.18
CVO85-203	1.26768	67.70970	1.26738	67.70958	-0.30	-0.12
CVO85-204	2.39201	70.10171	2.39179	70.10137	-0.22	-0.34
CVO85-205	2.02446	72.12617	2.02405	72.12542	-0.41	-0.75

All changes measured during 1985-86 are less than the expected uncertainty for first-order leveling.

Permission should be obtained in advance from the U.S Forest Service in Bend, Oregon, before engaging in any activity within the National Forest. Coordination for the 1985-86 survey was made through Mr. Roger King, Resources Assistant for the Fort Rock Ranger District. Mr. King can be contacted by writing:

U.S. Forest Service
Fort Rock Ranger District
1645 Highway 20 East
Bend, Oregon 97701
or by calling (503) 388-5674

SOUTH SISTER

The numerous lava flows and lava domes around South Sister, and its relatively recent eruption 2300 years ago (Scott, 1987), made South Sister (Fig. 1) another ideal subject for CVO's monitoring program. Working on South Sister, however, proved to be more diffcult than on either Crater Lake or Newberry Crater, owing to its status as a wilderness area. At Newberry Crater, copper-coated rods were driven into the ground with a gas-powered jack hammer. Operation of this device was prohibited at South Sister, so only those areas where bedrock was exposed were considered for the level lines. The lack of roads meant that all sites required the use of a helicopter (special permission required), and working near trails or intensive-use areas was discouraged. Fortunately, sufficient bedrock was found to install four short level lines radial to the summit of South Sister Volcano, with the installation of all benchmarks on bedrock and the placement of intermediate "benchmarks" using numbered aluminum tags attached to hardened "concrete" nails. The steep terrain prohibited us from following the first-order standard of using only the middle 2 meters of the level rods, but because most shots were only 6-20 meters long and temperatures at the elevations of the level lines (2200 - 2500 m) were low, refraction error due to heat shimmer should not be a factor.

In order to minimize the impact of our activity on South Sister, no attempts was made to mark the landing sites or the level line with paint or flagging. Small rock cairns were built at all turning points, instrument set-ups, and benchmarks, although these rock cairns are not expected to survive the spring snow melt. Recovery of the turning points in future years will therefore be a slow and difficult process.

Only a radial component of tilt can be calculated, because all lines on Sisters are radial (fig. 4). In all cases, the benchmark farthest from the summit will be assumed to be "fixed", and changes along the line will be referenced to that point.

SOUTH SISTER - SOUTH LINE

The south line on South Sister (fig. 5 & 5a) is located at the 2511 m (8,240 ft) level (elevation determined by altimeter reading) on a north-south trending ridge with exposed weathered rock cropping out at an approximate latitude of 44° 05' 12" and an approximate longitude of 121° 45' 54".

At the southern end of the ridge is a clear flat area approximately 12 by 12 m in diameter, surrounded by 1 meter-tall scrub pine, suitable for use as a landing site. From the helipad, bearings of 116 degrees to a distinct notch on Broken Top and 154 degrees to Bachelor Butte were obtained.

The level line was started from the southern end of the line, beginning on benchmark CVO85-300, located approximately 40 meters south of the helipad on the northern part of a large 2 X 2 m boulder.

From benchmark CVO85-300, the level line runs along the ridge on a bearing of 003 degrees and ends at benchmark CVO85-302 located on the northern most part of exposed bedrock 2 m east of the west edge of rock outcropping.

SOUTH LINE

	1985 SURVEY				1986 SURVEY	1985-1986
BENCHMARK ID	DISTANCE BETWEEN POINT(m)	CUMULATIVE DISTANCE	ELEVATION DIFFERENCE (m)	CUMULATIVE ELEVATION (m)	CUMULATIVE ELEVATION (m)	CUMULATIVE CHANGE(mm)
CVO85-300	0		0.0	0.0	0.0	0.0
1st nail	12	12	-2.1	-2.1		
2nd nail	34	46	2.0	0.1		
TAG SS-2	28	74	1.3	1.25742	1.25801	0.59
4th nail	14	88	2.2	3.5		
5th nail	8	96	2.7	6.2		
CVO85-301	6	102	0.9	7.09008	7.09094	0.86
6th nail	9	111	2.6	9.4		
7th nail	8	119	2.5	11.9		
8th nail	12	131	2.5	14.4		
TAG SS-3	10	141	2.6	17.38391	17.38536	1.55
10th nail	8	149	2.6	19.9		
11th nail	24	173	2.4	22.3		
12th nail	12	185	2.6	24.9		

CVO85-302	11	196	1.5		26.46761	26.46888	1.27

The tilt along this line during 1985-86 is 6.48 microradians, north up.

SOUTH SISTER - WEST LINE

The west line (fig. 6 & 7) on South Sister is located at about the 2252 m (7,390 ft.) level (elevation determined by altimeter) on an east-west trending ridge with exposed rock cropping out at an approximate latitude of 44° 05' 42" and an approximate longitude of 121° 47' 54".

On the extreme western end of the ridge is a clear flat area approximately 12 by 12 m in diameter suitable for use as a landing site. To the north of the landing site is a 35 by 50 m depression approximately 15 m deep.

The level line was started from CVO85-306, located on the west end of a east-west ridge approximately 13 m east of the depression just described.

Benchmark CVO85-306 is cemented on a 0.75 m by 2 m long rock outcrop 0.75 meter higher then the ground level, bordered on the north and south by 2 m tall scrub pine and open to the east and west sides. About 2.5 m away on a bearing of 227 degrees is a large solitary boulder in the approximate direction to which the level line runs.

From CVO85-306, the level line follows the ridge toward the east along the north side of the depression and up the ridge to benchmark CVO85-305. CVO85-305 is approximately 10 m east of where the "platy" ridge temporarily narrows to about 3 m wide, and is on a prominent rock outcrop protruding 1 m into the north side of the 18 m-deep depression and approximately 18 m south of a 3 m-high outcrop with a 2 m-tall mature tree growing nearly parallel to the ground.

Beyond CVO85-305 is benchmark CVO85-304 on a bearing of 78 degrees. CVO85-304 is on the northwest side of a large 3 by 4 m rock outcrop and 3.5 m higher than west-sloping ground. Beyond CVO85-304 is benchmark CVO85-303 at the crest of a steep incline, cemented on a 5 by 10 m rock outcrop, 30 m south of a steep 30 m drop and 7 m north of the south edge, in a flat 3 by 3 m area.

	1985 SURVEY				1986 SURVEY	1985-1986
BENCHMARK ID	DISTANCE BETWEEN POINT(M)	CUMULATIVE DISTANCE (m)	ELEVATION DIFFERENCE (m)	CUMULATIVE ELEVATION (m)	CUMULATIVE ELEVATION (m)	CUMULATIVE CHANGE(mm)
CVO85-306	0	0	0.0	0.0	0.0	
1st nail	31	31	0.9	0.9		
2nd nail	26	57	2.8	3.7		
3rd nail	14	71	2.3	6.0		
4th nail	14	85	2.4	8.4		
CVO85-305	6	91	2.1	10.37716	10.37747	0.31
5th nail	24	115	2.1	12.5		
TAG SS-4	22	137	2.6	15.11778	15.11820	0.42

7th nail	14	151	2.5	17.7		
8th nail	20	171	2.6	20.3		
CVO85-304	14	185	2.8	23.00424	23.00521	0.97
9th nail	24	209	2.3	25.4		
10th nail	11	220	2.9	28.3		
11th nail	9	229	2.4	30.7		
TAG SS-5	10	239	2.8	33.38066	33.38164	0.98
13th nail	12	251	2.7	36.2		
14th nail	11	262	2.8	39.0		
15th nail	12	274	2.7	41.7		
TAG SS-6	14	288	2.8	44.35896	44.36019	1.23
CVO85-303	7	295	0.9	45.21232	45.21371	1.39

The tilt along this line during 1985-86 is 4.7 microradians, east up.

SOUTH SISTER - NORTH LINE

The north line (fig. 8) on South Sister is located at about the 2316 m (7,600 ft.) level (elevation determined by altimeter) on a north-south trending ridge with exposed rock cropping out at an approximate longitude of 44° 07' 06" and an approximate latitude of 121° 464' 06".

At the north end of the level line is a large circular flat area suitable for a landing site, and at the southern end of the line is a broad clear area also suitable for a landing site.

From the south landing site a bearing of 343 degrees was obtained to the top of Middle Sister, 001 degrees to the top of North Sister and 180 degrees to the highest point on South Sister.

The level line was started on benchmark CVO85-308, located on the southern part of the ridge on a large rock outcrop on the west side of a broad ridge. Following the ridge on a bearing of 357 degrees, BM309 was cemented on a 1 by 2 m boulder, 1 m higher than ground level in the approximate middle of a bouldery ridge. Just beyond this benchmark, the rock outcrop narrows noticeably and the ridge becomes extremely steep.

At this point, the level line veers to the northeast and follows the east side of the ridge among the rubble of large boulders and down into the flat area at the north end of the ridge (north landing area). 60 m north of this point is a prominent rock outcrop bounded on the west and north by scrub pine. In the middle of this outcrop is a 1.5 by 3.5 m rock outcrop, 0.75 m higher than ground level on which benchmark CVO85-310 is cemented. CVO85-310 is at the southern end of a 1 km-long north-south ridge, densely covered with scrub pine. Northwest and northeast of the level line are a number of moraine-dammed lakes.

NORTH LINE

BENCHMARK ID	1985 SURVEY DISTANCE BETWEEN POINT(m)	CUMULATIVE DISTANCE (m)	ELEVATION DIFFERENCE (m)	CUMULATIVE ELEVATION (m)	1986 SURVEY CUMULATIVE ELEVATION (m)	1985-1986 CUMULATIVE CHANGE(mm)
CVO85-310	0		0	0.0	0.0	
1st nail	20	20	-2.1	-2.1		
2nd nail	26	46	-2.4	-4.5		
3rd nail	23	69	1.6	-2.9		
4th nail	18	87	2.8	-0.1		
5th nail	14	101	2.7	2.6		
6th nail	7	108	2.7	5.3		
7th nail	9	117	2.7	8.0		
8th nail	12	129	1.8	9.8		
9th nail	13	142	2.6	12.4		
10th nail	12	154	2.6	15.0		
11th nail	24	178	2.5	17.5		
12th nail	9	187	2.8	20.3		
TAG SS-9	11	198	2.7	23.04578	23.04541	-0.37
14th nail	9	207	2.4	25.4		
BM309	13	220	2.7	28.16028	28.16023	-0.05
15th nail	12	232	1.5	29.6		
16th nail	17	249	1.8	31.5		
TAG SS-8	8	257	2.0	33.41697	33.41676	-0.21
18th nail	14	271	2.4	35.8		
19th nail	14	285	1.6	37.4		
TAG SS-7	22	307	2.9	40.22544	40.22550	0.06
CVO85-308	10	317	2.2	42.44845	42.44870	0.25

The tilt along this line during 1985-86 is 0.79 microradians, north up.

SOUTH SISTER - EAST LINE

The east line (fig. 9 & 10) on South Sister is located at about the 2310 m (7,580 ft.) level (elevation determined by altimeter) on a northeast-trending low area at an approximate longitude of 44° 06' 42" and an approximate longitude of 121° 44' 48", approximately 200 m south of a prominent ridge running east-west and 0.6 km S45°E of Carver lake. At the western end of the level line is a clear, flat 8 by 10 m landing site among 1-m tall scrub pine.

A bearing of 340 degrees was obtained from the landing site to North Sister, 137 degrees to the south peak of Broken Top, and 239 degrees to the highest point on South Sister.

The level line was started from benchmark BM312, approximately 45 m west of the landing site and approximately 18 m N22°E of a large west-trending rock ridge in a rock outcrop 4 m by 8 m long. Bearings taken from BM312 are S247°W to the highest point on South Sister, and S143°E to the south peak at Broken Top. Bearing of level line begins at about N81°E. However, the level line skirts along the north edge of the pine-covered ridge used as a landing site and follows a small wash to a short bottle neck in the wash, then down the middle of a 100 m wide wash, and across a small snow-melt stream toward an outcrop of rocks in the middle of the wash. Benchmark CVO85-307 (not surveyed during the 1985 level survey, because it was installed just prior to the survey and the cement had not yet hardened) is cemented on a 2 by 7 m outcrop 1.5 m above the wash bed and approximately 12 m east of the stream. From CVO85-307, the line continues on a bearing of N61°E up a small rise among 2 m tall scrub pine and to benchmark BM311, cemented on a rock outcrop at the edge of a large valley.

	1985 SURVEY				1986 SURVEY	1985-1986
BENCHMARK ID	DISTANCE BETWEEN POINT(M)	CUMULATIVE DISTANCE (m)	ELEVATION DIFFERENCE (m)	CUMULATIVE ELEVATION (m)	CUMULATIVE ELEVATION (m)	CUMULATIVE CHANGE(mm)
BM311	0.0		0.0	0.0	0.0	
1st nail	8	8	1.8	1.8		
2nd nail	10	18	2.4	4.2		
3rd nail	23	41	0.7	4.9		
4th nail	12	53	2.3	7.2		
BM NAIL	30	83	-0.72	6.47546	6.47506	-0.40
CVO85-307	2	85	1.3	7.8		
7th nail	17	102	2.4	10.2		
8th nail	15	117	2.0	12.2		
9th nail	19	136	2.4	14.6		
10th nail	17	153	2.2	16.8		
11TH NAIL	17	170	2.3	19.1		
12TH NAIL	9	179	2.6	21.7		
13th nail	12	191	1.9	23.6		
14th nail	15	206	2.1	25.7		
15th nail	12	218	2.4	28.1		
16th Nail	12	230	2.4	30.5		
BM312	12	254	2.5	33.04684	33.04791	1.07

The tilt along this line during 1985-86 is 4.21 microradians, west up.

All level lines on South Sister lie within the boundary designated as Wilderness Area in the Deschutes and Willamette National Forest. All activity must be cleared through the U.S. Forest Service. Permission to work in the Wilderness Area requires advance notice, and it is advisable that arrangements be made 6 months or more in advance. Coordination for the 1985-86 survey was made through Mr. David Mohla, Forest Supervisor, Deschutes National Forest; Mr. Harold D. Siegworth, Lands and Mineral Staff Officer; and Mr. Mike Kerrick, Forest Supervisor, Willamette National Forest.

Mr. Mohla and Mr. Siegworth can be contacted by writing:

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Deschutes National Forest
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Bend, Oregon 97701
or by calling (503) 388-5674.

Mr. Kerrick can be contacted by writing:
U.S. Forest Service
Willamette National Forest
P.O.Box 10607
Eugene, Oregon 97440
or by calling (503) 687-6521.

CONCLUSION

Comparison of 1985-1986 data indicates that the stability of the benchmarks along the level lines is well within the tolerance of the system, and that the changes measured are well within error limits, an indication of no change on any of the three volcanoes. The reproducibility of the data suggests that the error limits are approximately 1-6.5 microradians between adjacent benchmarks less than 0.5 km apart and about 2 microradians over lines at least 1 km long.

Although the closure error on some of the short lines appears to exceed first order standards, National Geodetic Survey Special Publication No. 239, page 8, paragraph 26, states "... on all sections of first order leveling which are 0.25 km or less in length, a discrepency of not more than 2.0 mm between foward and backwards measurment will be considered a satisfactory check".

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REFERENCES

Bacon, C. R., 1983, Eruptive history of Mount Mazama and Crater Lake Caldera, Cascade Range U.S.A.: Journal of Volcanology and Geothermal Reasearch. v 18, p. 57-115.

Balazs, E. I., and Young, G. M., 1982, Corrections applied by the National Geodetic Survey to precise leveling observations: NOAA Technical Memorandum NOS NGS 34, 11 pages, p. 5.

Chadwick, W. W., Iwatsubo, E. Y., Swanson, D. A, and Ewert, J. W., 1985, Measurement of slope distance and vertical angles at Mt. Baker and Mount Rainier, Washington, Mount Hood and Crater Lake, Oregon and Mount Shasta and Lassen Peak, California, 1980-1984: U.S. Geological Survey Open-File Report 85-205, 8 p.

Dzurisin, D., Johnson, D. J., Murray, T. L. and Meyers, B., 1982, Tilt Network at Mount Shasta and Lassen Peak, California: U.S. Geological Survey Open-File Report 83-277, 9 p.

Dzurisin, D., Johnson, D. J. and Symonds R.B., 1983, Dry-Tilt Network at Mount Rainier, Washington: U. S. Geological Survey Open-File Report 83-277. 9 p.

Eaton, J. P., 1959, A portable water-tube tiltmeter: Bull. Seismological Society of America, 49 pages, p 301-316.

Frank, D., Meier, M. M., and Swanson, D. A., 1977, Assessment of increased thermal activity at Mount Baker, Washington, March 1976: U.S. Geological Survey Prof. Paper, 49 P.

Fiske, R. S., and Kinoshita, W. T., 1969, Inflation of Kilauea Volcano prior to its 1967-1968 Eruption: Science, 25 July 1969, Volume 165, Number 3891, p. 341-349.

Kinoshita, W. T., Swanson, D. A., and Jackson, D. B., 1974, The Measurement of crustal deformation related to Volcanic activity at Kilauea Volcano, Hawaii; Physical Volcanology: Ed. Civetta et al, 9 p.

Lipman, P. W., Moore, J. G. and Swanson, D. A., 1981, Bulging of the North flank before the May 18 eruption - Geodetic data. The 1980 eruption of Mount St. Helens, Washington: U.S. Geological Survey Professional paper. p 143-157.

MacLeod, N. S., Sherrod, D. R. and Chitwood, L. A.; Geologic Map of Newberry Volcano, Deschutes, Kalamath and Lake Counties, Oregon: U.S. Geological Survey Open-File Report 82-847, Sept 1982, 23 p.

MacLeod, N. S., Sherrod, D.R., Chitwood l. A. and McKee, E. H., 1981, Newberry Volcano, Oregon, <u>in</u> Johnston, D. A., and Donnelly-Nolan, editors, Guides to Some Volcanic Terranes in Washington, Idaho, Oregon and Northern California: Geological Survey Circular 838. P. 85-91.

Rappleye, H. S., Manual of Geodetic leveling: U.S. Department of Commerce, National Geodetic survey (NOAA) Special Publication No. 239, 1948, pg 2.

Scott, W. E., 1987, Holocene rhyodacite eruptions on the flanks of South Sister Volcano, Oregon, in Fink, J. H., editor, The emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p.35-53.

Yamashita, K. M., 1981, Dry Tilt: A Ground Deformation Monitor as Applied to the Active Volcanoes of Hawaii: U.S. Geological Survey Open-File Report. 20 P.

TABLE 1

CRATER LAKE

BENCHMARK ID FROM TO	DIST BETWEEN BENCHMARK (km)	CLOSURE ERROR BETWEEN BM (mm)	ERROR PER KILOMETER(mm)
CVO85-210 TO CVO85-211	0.7	0.35	0.50
CVO85-211 TO CVO85-212	0.3	-0.38	-1.27

	ROUND TRIP DISTANCE BETWEEN BM'S (km)	TOTAL CLOSURE ERROR FOR LINE (mm)
CVO85-210 TO CVO85-212	2.0	-0.03

BENCHMARK ID FROM TO	DIST BETWEEN BENCHMARK (km)	CLOSURE ERROR BETWEEN BM (mm)	ERROR PER KILOMETER(mm)
CVO85-213 TO CVO85-214	0.5	0.03	0.06
CVO85-214 TO CVO85-215	0.9	0.77	0.86

	ROUND TRIP DISTANCE BETWEEN BM'S (km)	TOTAL CLOSURE ERROR FOR LINE (mm)
CVO85-213 TO CVO85-215	2.8	0.80

BENCHMARK ID FROM TO	DIST BETWEEN BENCHMARK (km)	CLOSURE ERROR BETWEEN BM (mm)	ERROR PER KILOMETER(mm)
CVO85-206 TO CVO85-207	0.2	0.50	2.50
CVO85-207 TO CVO85-208	0.4	-0.78	-1.95
CVO85-208 TO CVO85-209	0.4	-0.64	-1.60

	ROUND TRIP DISTANCE BETWEEN BM'S (km)	TOTAL CLOSURE ERROR FOR LINE (mm)
CVO85-206 TO CVO85-209	2.0	-0.92

NEWBERRY CRATER

BENCHMARK ID FROM TO	DIST BETWEEN BENCHMARK (km)	CLOSURE ERROR BETWEEN BM (mm)	ERROR PER KILOMETER(mm)
BMA1 6306 TO CVO85-190	1.4	1.40	1.00
CVO85-190 TO CVO85-200	1.1	0.36	0.33
CVO85-200 TO CVO85-201	1.4	2.12	1.51
CVO85-201 TO CVO85-202	1.2	1.94	1.62
CVO85-202 TO CVO85-203	1.4	0.59	0.42
CVO85-203 TO CVO85-204	1.3	-0.30	-0.23
CVO85-204 TO CVO85-205	0.9	1.00	1.11

	ROUND TRIP DISTANCE BETWEEN BM'S (km)	TOTAL CLOSURE ERROR FOR LINE (mm)
BMA1 6306 TO CVO85-205	17.4	7.41

TABLE 1 (continued)

SOUTH SISTER

BENCHMARK ID FROM		TO	DIST BETWEEN BENCHMARK (km)	CLOSURE ERROR BETWEEN BM (mm)	ERROR PER KILOMETER(mm)
CVO85-300	TO	CVO85-301	0.10	0.32	3.20
CVO85-301	TO	CVO85-302	0.06	-0.02	-0.33
CVO85-300	TO	CVO85-302	0.20	0.30	1.5

BENCHMARK ID FROM		TO	ROUND TRIP DISTANCE BETWEEN BM'S (km)	TOTAL CLOSURE ERROR FOR LINE (mm)
CVO85-300	TO	CVO85-302	0.40	0.60

BENCHMARK ID FROM		TO	DIST BETWEEN BENCHMARK (km)	CLOSURE ERROR BETWEEN BM (mm)	ERROR PER KILOMETER(mm)
CVO85-306	TO	CVO85-305	0.09	0.32	3.56
CVO85-305	TO	CVO85-304	0.09	0.18	2.00
CVO85-304	TO	CVO85-303	0.11	0.00	0.00

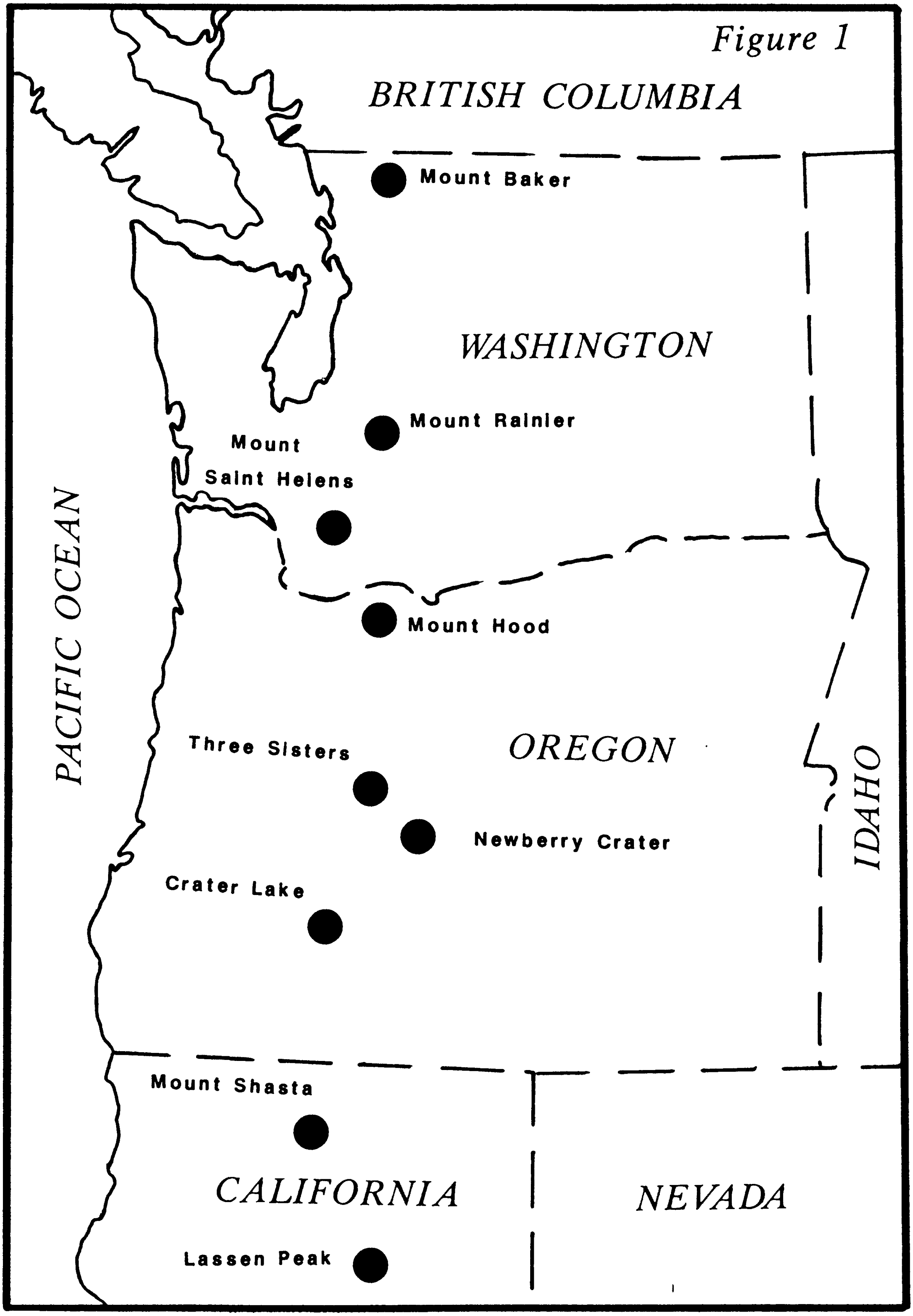
BENCHMARK ID FROM			ROUND TRIP DISTANCE BETWEEN BM'S (km)	TOTAL CLOSURE ERROR FOR LINE (mm)
CVO85-306	TO	CVO85-303	0.58	0.50

BENCHMARK ID FROM		TO	DIST BETWEEN BENCHMARK (km)	CLOSURE ERROR BETWEEN BM (mm)	ERROR PER KILOMETER(mm)
CVO85-310	TO	BM309	0.22	-0.26	1.18
BM309	TO	CVO85-308	0.10	-0.04	-0.40

BENCHMARK ID			ROUND TRIP DISTANCE BETWEEN BM'S (km)	TOTAL CLOSURE ERROR FOR LINE (mm)
CVO85-310	TO	CVO85-308	0.64	-0.30

BENCHMARK ID FROM		TO	DIST BETWEEN BENCHMARK (km)	CLOSURE ERROR BETWEEN BM (mm)	ERROR PER KILOMETER(mm)
BM312	TO	BM311	0.25	-0.96	-3.84

			ROUND TRIP DISTANCE BETWEEN BM'S (km)	TOTAL CLOSURE ERROR FOR LINE (mm)
BM312	TO	BM311	0.50	-0.96



Location of Cascade Volcanoes

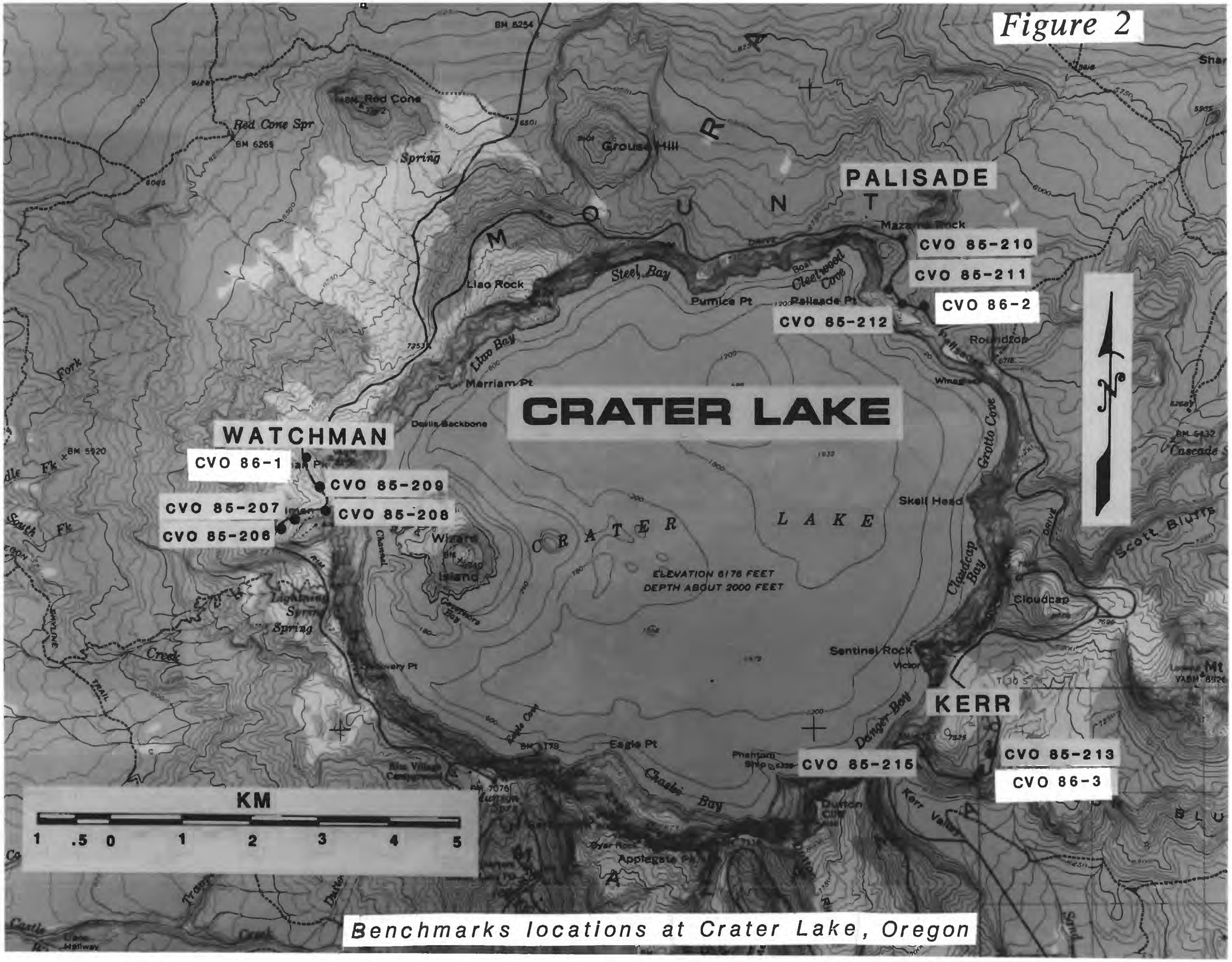
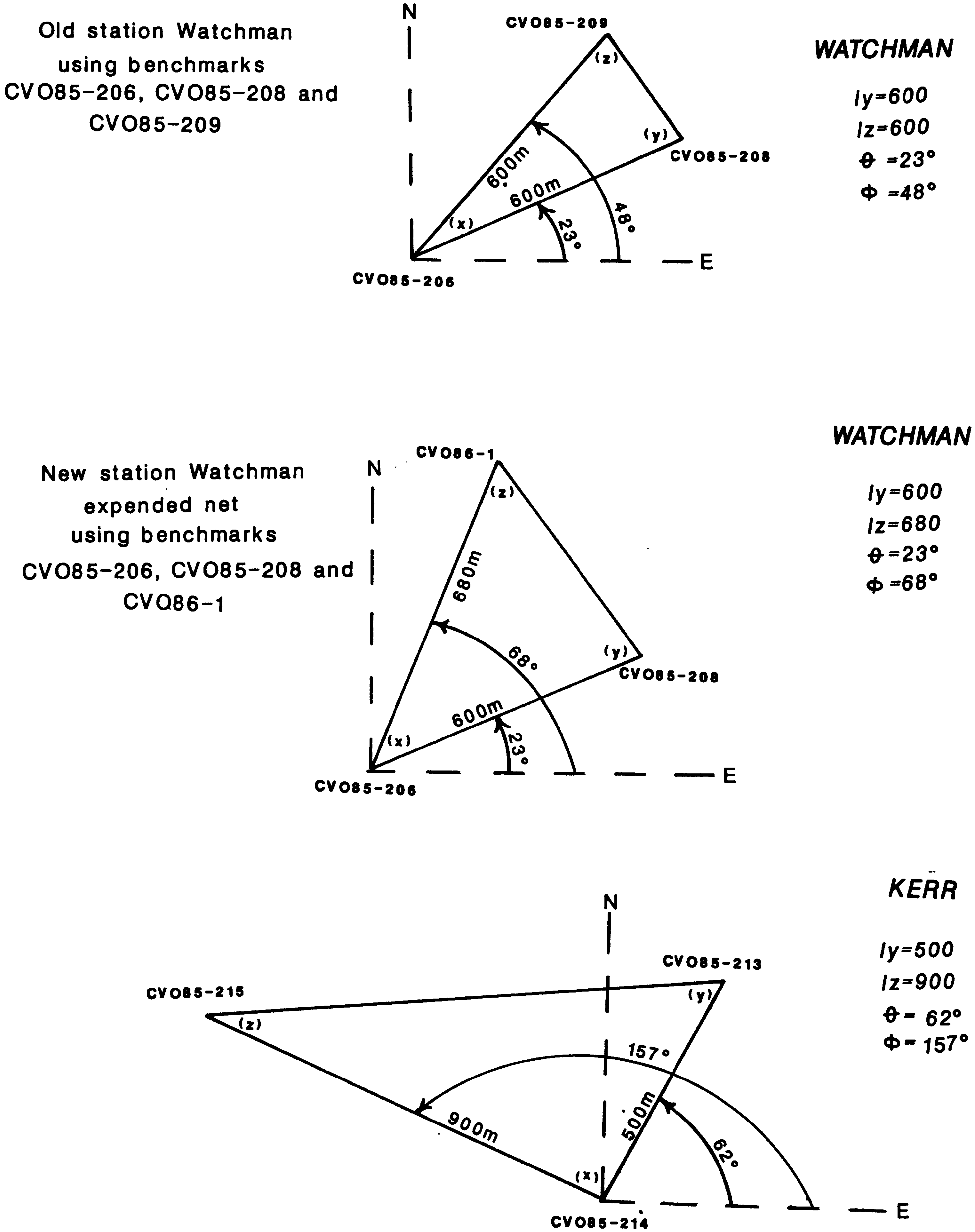


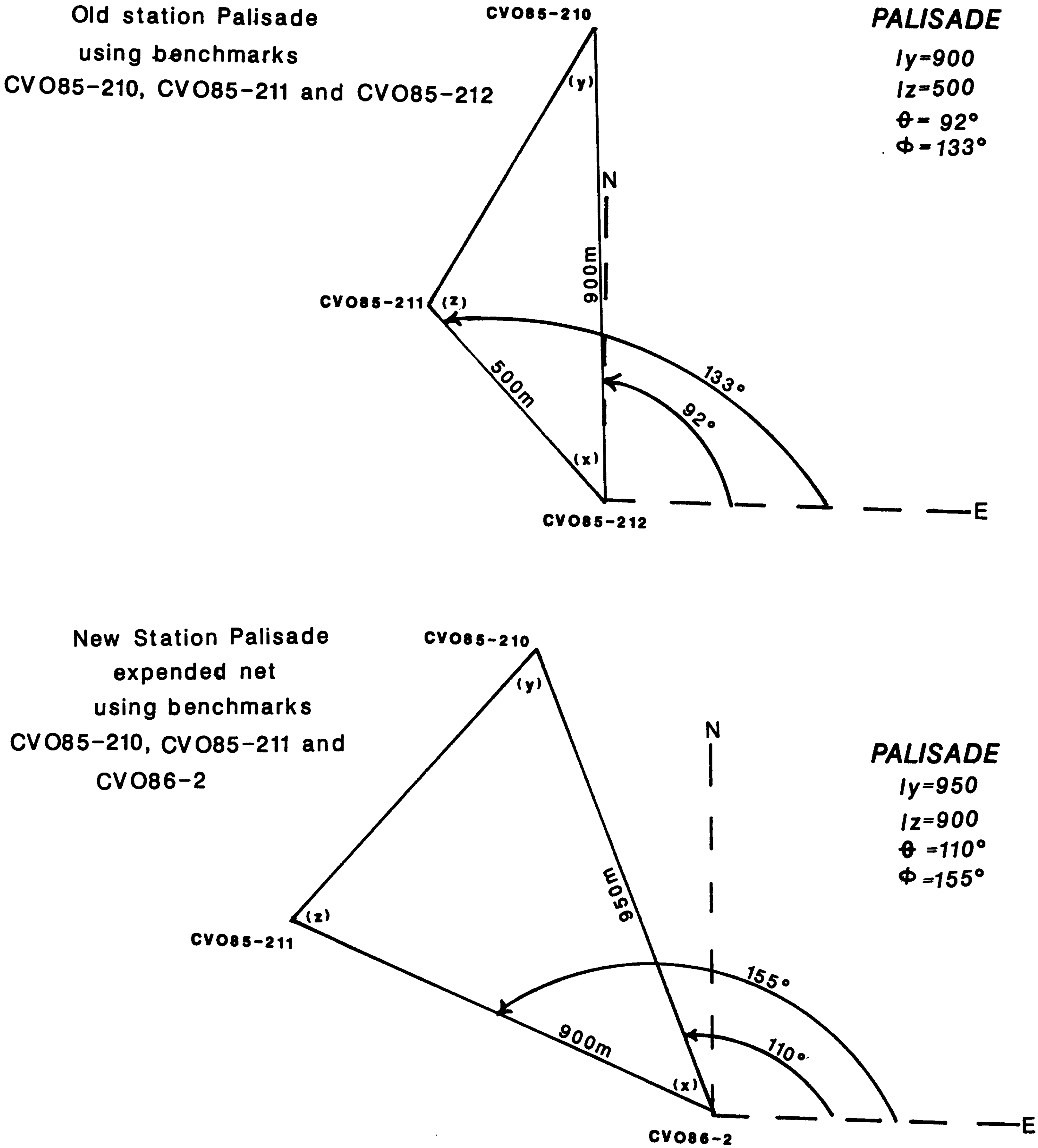
Figure 2

Benchmarks locations at Crater Lake, Oregon

Figure 2a



Tilt configuration at Crater Lake, Oregon



Tilt configuration at Crater Lake, Oregon

Figure 2c ***Formula to calculate tilt vector and magnitude***

General formula (modified from J.P. Eaton, 1959)

$$t(N)= \left[\frac{10\ -\cos\phi}{l_y\sin(\phi-\theta)}\right]((y-x)1000) - \left[\frac{10\ \cos\theta}{l_z\sin(\phi-\theta)}\right]((x-z)1000)$$

$$t(E)= \left[\frac{10\ \sin\phi}{l_y\sin(\phi-\theta)}\right]((y-x)1000) + \left[\frac{10\ \sin\theta}{l_z\sin(\phi-\theta)}\right]((x-z)1000)$$

If t(N) is positive, tilt vector is to the north, if negative, tilt is to the south.
If t(E) is positive, tilt vector is in the east, if negative, tilt is to the west.

Magnitude of tilt in Urads= $(t(N)^2 + t(E)^2)^{\frac{1}{2}}$

Azimuth of tilt in degrees= $\mathrm{Tan}^{-1}\left[\frac{t(E)}{t(N)}\right]$

Old Station Watchman CV085-209, CV085-208, CV085-206

t(N)= (-0.026 (y-x) - 0.036 (x-z))
t(E)= (0.029 (y-x) + 0.015 (x-z))

t(N)= (-0.026 (79) - 0.036 (-36))= -0.758
t(E)= (0.029 (79) + 0.015 (-36))= 1.751

l_y=600
l_z=600
θ=23°
ϕ=48°

$((0.758)^2 + (1.751)^2)^{\frac{1}{2}}$ = 1.91 Urads
tan-1 (1.751/0.758) = -66.67
Tilt is 1.91 Urads N67°W

New Station Watchman CV085-206, CV085-208, CV086-1

t(N)= (-0.009 (y-x) - 0.019 (x-z))
t(E)= (0.022 (y-x) + 0.008 (x-z))

l_y=600
l_z=680
θ=23°
ϕ=68°

Station Kerr CV085-213, CV085-215, CV085-214
in future years CV086-3 should be substituted for CV085-214

t(N)= (0.018 (y-x) - 0.005 (x-z))
t(E)= (0.008 (y-x) + 0.010 (x-z))

l_y=500
l_z=900
θ=62°
ϕ=157°

Old Station Palisade CV085-210, CV085-212, CV085-211

t(N)= (0.012 (-107) - 0.001 (-58)) =-1.226
t(E)= (0.012 (-107) + 0.030 (-58)) =-3.024
change is 3.26 Urads, N68°E

l_y=900
l_z=500
θ=92°
ϕ=133°

New Station Palisade CV085-210, CV085-211, CV086-2

t(N)= (0.013 (y-x) + 0.005 (x-z))
t(E)= (0.006 (y-x) + 0.015 (x-z))

l_y=950
l_z=900
θ=110°
ϕ=155°

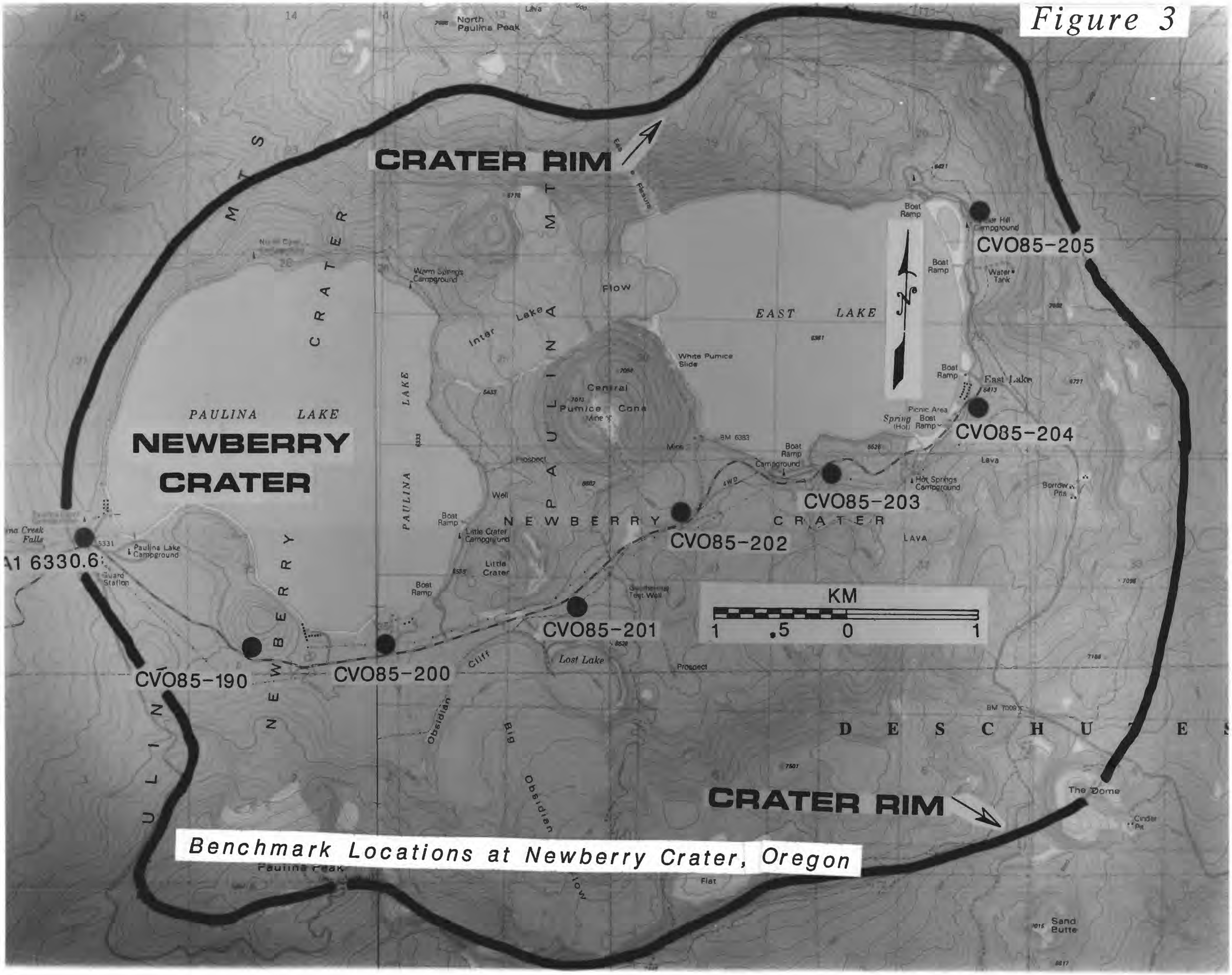


Figure 3
CRATER RIM
CRATER RIM
NEWBERRY CRATER
PAULINA LAKE
EAST LAKE
KM
1 .5 0 1
CVO85-190
CVO85-200
CVO85-201
CVO85-202
CVO85-203
CVO85-204
CVO85-205
A1 6330.6
Central Pumice Cone
Lost Lake
The Dome
Sand Butte
North Paulina Peak
Paulina Peak
NEWBERRY CRATER
PAULINA MTS
DESCHUTES
Benchmark Locations at Newberry Crater, Oregon

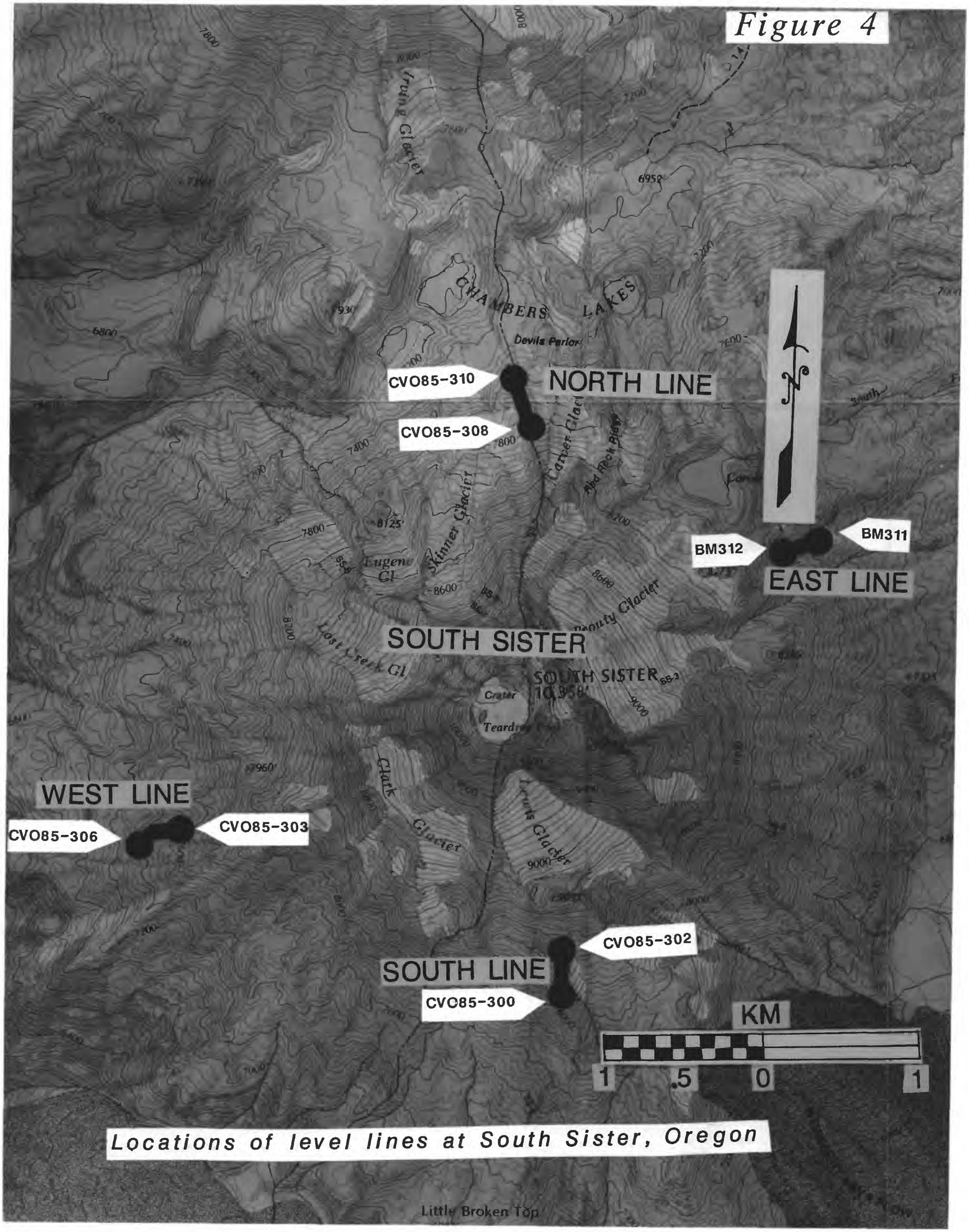


Figure 4

Locations of level lines at South Sister, Oregon

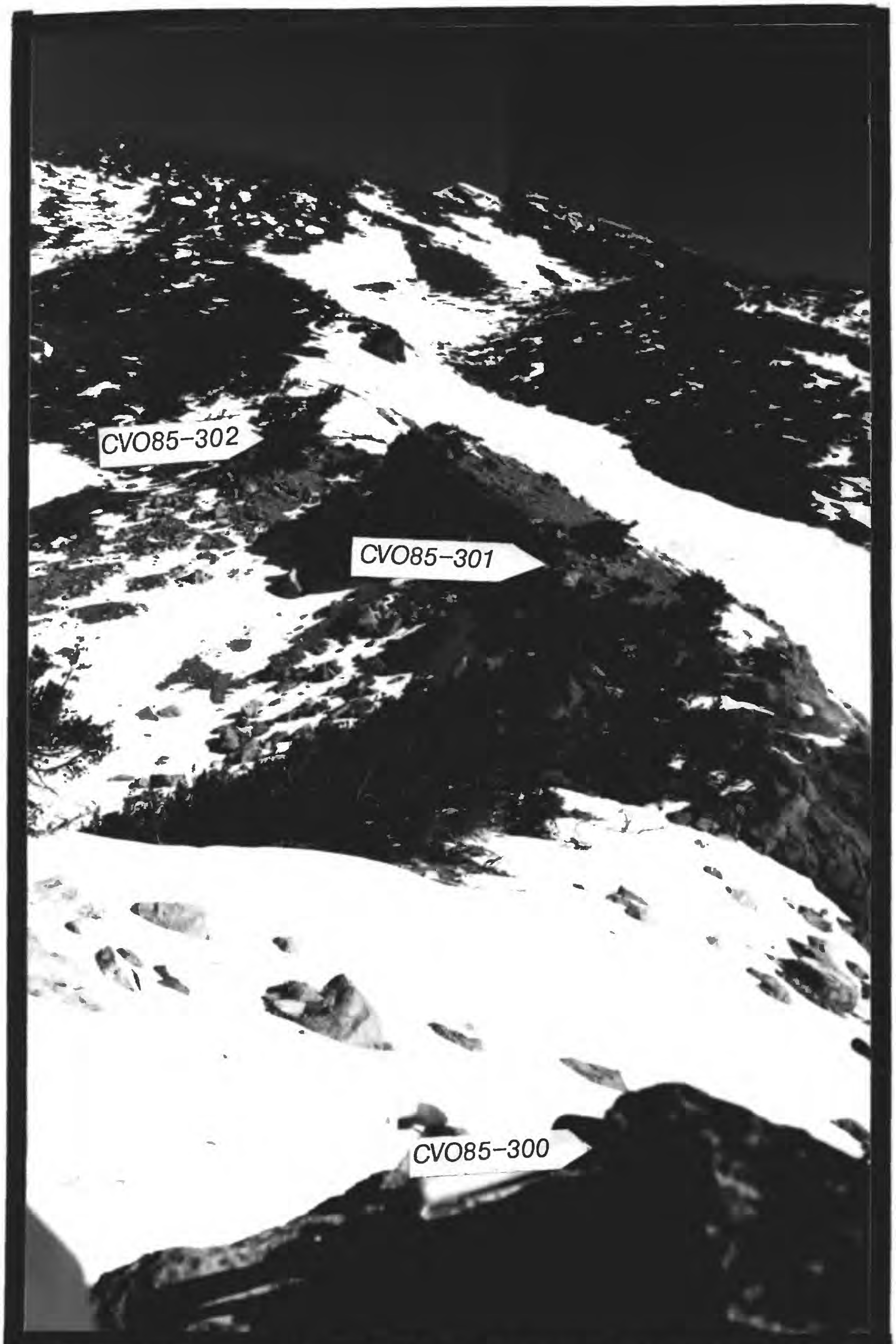


Figure 5. South line of South Sister looking northeast

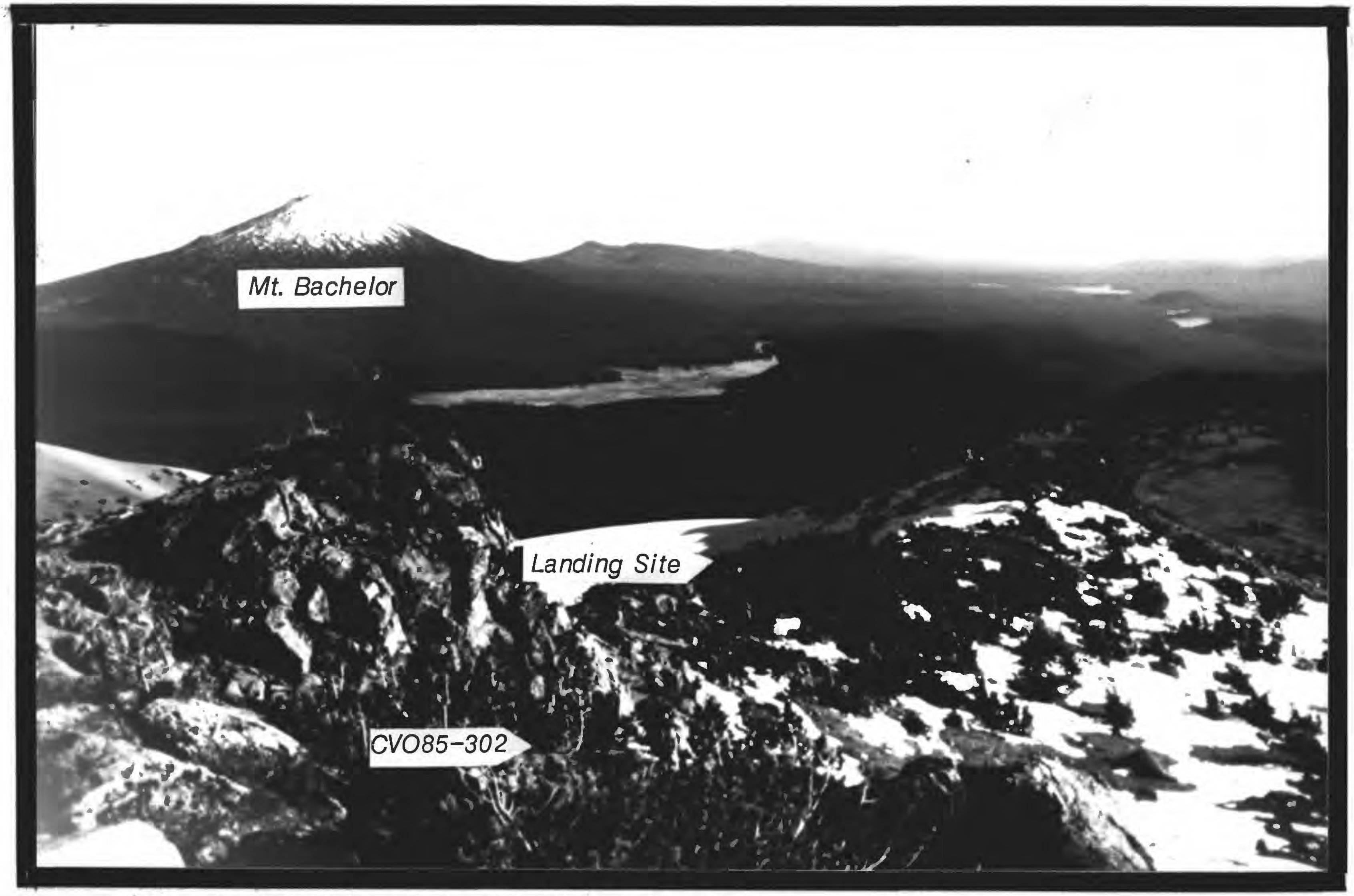


Figure 5a. South line of South Sister looking southwest.

Figure 6. West line of South Sister looking northeast.

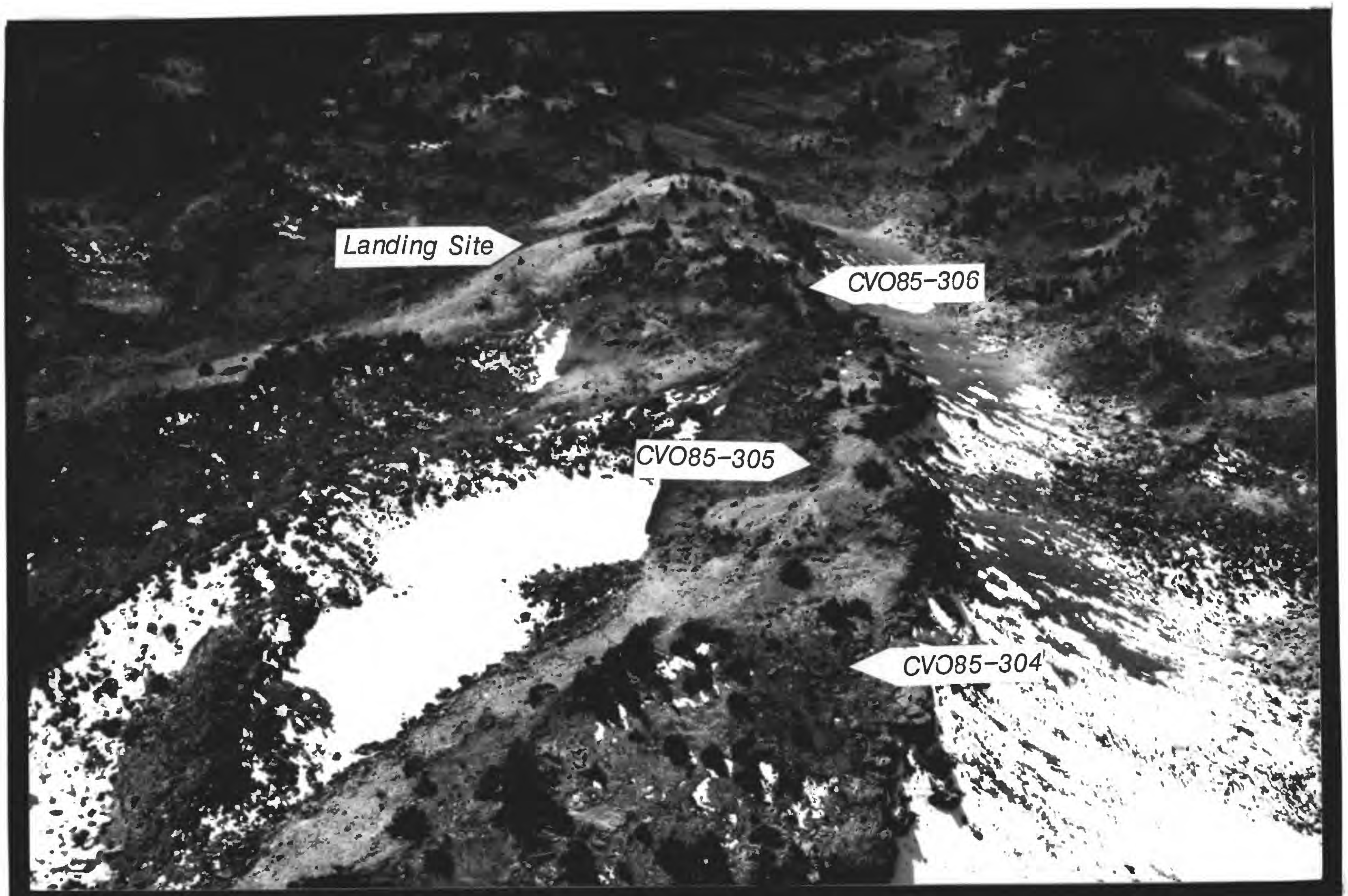


Figure 7. West line of South Sister looking southwest.

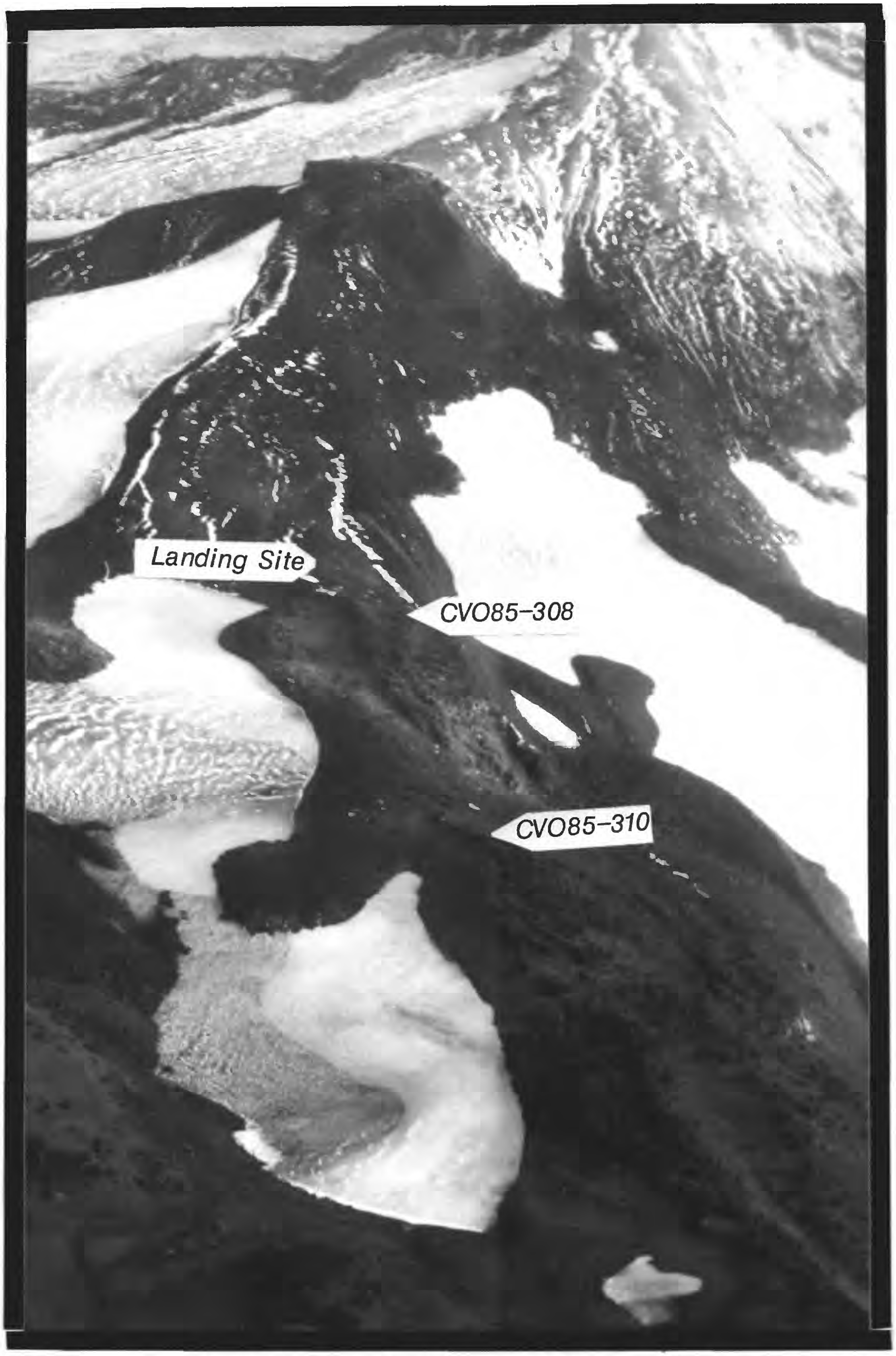


Figure 8. North line of South Sister looking south.

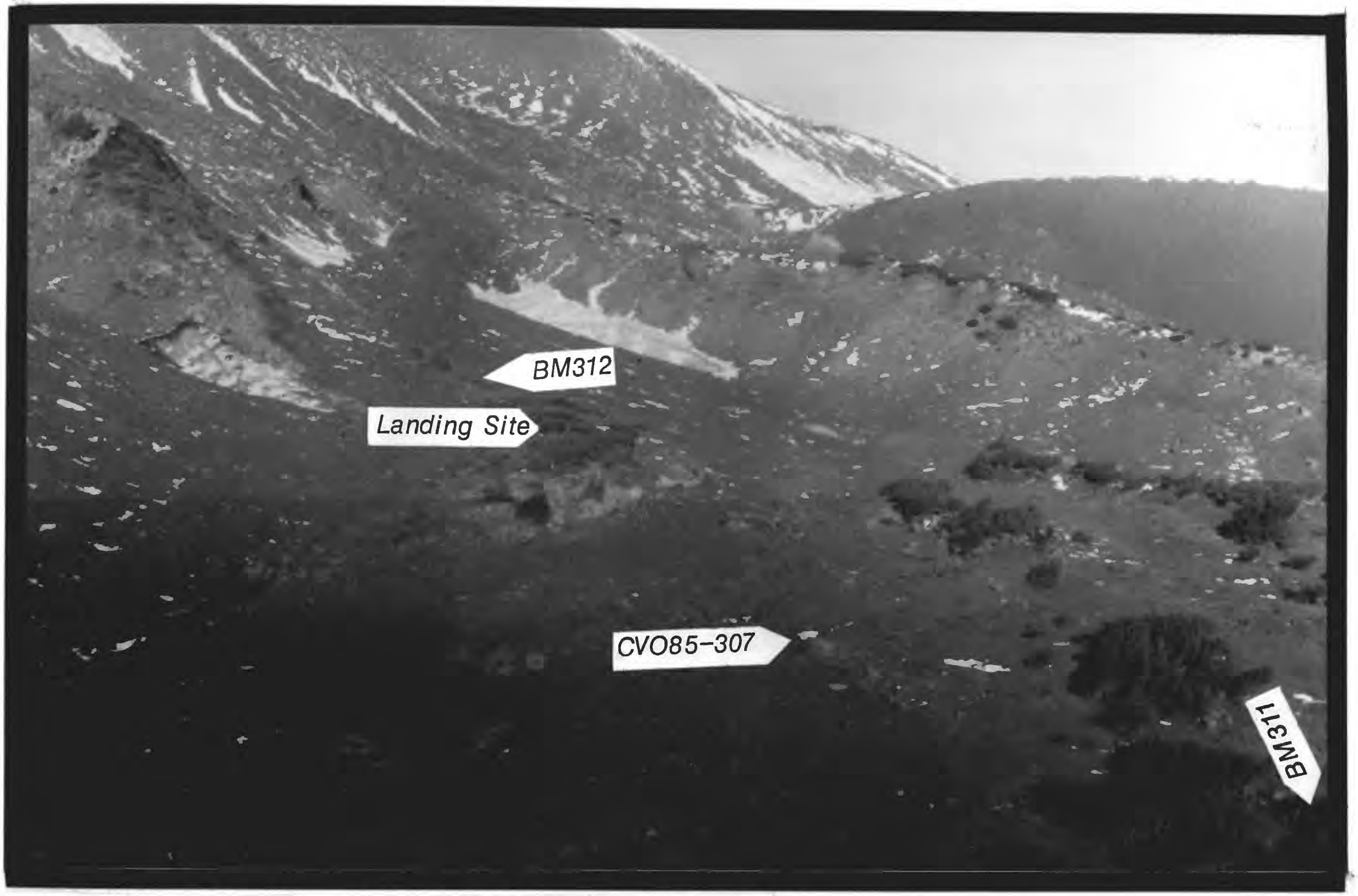


Figure 9. East line of South Sister looking west.

Figure 10. East line of South Sister looking east.