TILT MEASUREMENTS AT LONG VALLEY CALDERA, CALIFORNIA, MAY-AUGUST 1982

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ABSTRACT

The Mammoth Lakes area in east-central California has experienced unusual seismicity and ground deformation since 1978, highlighted by four M >6 earthquakes in May 1980 and by the discovery soon thereafter of a broad uplift within Long Valley caldera. Recurrent seismic swarms during June 1980-May 1982 raised concern over the possibility of renewed volcanic activity in the foreseeable future, prompting a USGS Notice of Potential Volcanic Hazard on 28 May 1982. As part of an intensified Long Valley monitoring effort sponsored by the USGS Volcanic Hazards Program, a network of nine tilt sites was established near Mammoth Lakes in May and July 1982. This report describes those stations and presents results from three tilt resurveys during July-August 1982.

INTRODUCTION

Mammoth Lakes is a ski resort community nestled along the eastern front of the Sierra Nevada, 6 km northeast of Mammoth Mountain in east-central California. The town is situated on the southwestern floor of Long Valley caldera, a 17 km x 32 km depression formed roughly 700,000 years ago when 600 km^3 of rhyolitic magma were erupted to form the Bishop Tuff. Caldera collapse was followed by roughly 100,000 years of resurgence and dome growth in the western part of the caldera. Since then, a series of relatively small eruptions have occurred along the caldera rim and within the enclosed moat.

Products of these sporadic eruptions include rhyolite and quartz latite domes with associated pyroclastic rocks, and basaltic lava flows. Recent eruptions produced a series of basalt flows 60,000-150,000 years ago along the south caldera margin and added a summit dome to Mammoth Mountain about 50,000 years ago (Bailey, Dalrymple, and Lanphere, 1976). Since at least 40,000 years ago, the Inyo and Mono craters immediately north of Long Valley caldera have been frequently active, erupting domes and/or pyroclastic deposits every few centuries during the past 1500 years (Miller and others, 1982). Until recently, though, there was no geophysical monitoring evidence to suggest that volcanic activity might resume in the Mono/Inyo/Long Valley chain in the foreseeable future.

However, a distinct increase in seismicity along the eastern Sierran front immediately south of Long Valley caldera began in October 1978, and four $M > 6$ earthquakes occurred near the southeast caldera rim during 25-27 May 1980 (Ryall and Ryall, 1981). As a result, the U.S. Geological Survey issued an Earthquake Hazards Watch for the area on 27 May 1981, alerting public officials to the possibility of additional large earthquakes in the foreseeable future.

The rate of seismic energy release has generally decreased since May 1980, but numerous earthquake swarms with associated spasmodic tremor occurred about 3 km southeast of Mammoth Lakes during June 1980-May 1982 (A. Ryall and R. Cockerham, oral commun., 1982). Although the average depth of these swarms has fluctuated, the shallowest quakes have moved generally upward from 8-9 km to 3-4 km depth. The epicentral area is near the intersection of the south caldera rim and the Laurel Canyon fault, a structural setting which elsewhere in Long Valley has produced post-caldera rhyolite or quartz latite eruptions (R. Bailey, oral commun., 1982).

Concern over the possibility of renewed volcanic activity at Long Valley was heightened in 1981 by the recognition of a broad uplift and associated horizontal displacements, possibly from a pressure source about 10 km beneath the resurgent dome. Savage and Clark (1982) attributed these geodetic changes to reinflation of the remnant Long Valley magma chamber and speculated that the May 1980 earthquake swarm was triggered by magma intrusion beneath the caldera. Although the relative timing and, therefore, the causal relationship between uplift and the May 1980 earthquakes remain open to debate, dome resurgence and spasmodic tremor during upward-migrating earthquake swarms strongly suggest that magma has risen toward the surface at Long Valley since June 1980. For this reason, the U.S. Geological Survey on 28 May 1982 issued a Notice of Potential Volcanic Hazard stating that "The discovery in recent months of ground deformation and new fumarolic activity, apparently associated with (increased) seismicity, indicates that the outbreak of volcanic activity is a possibility but by no means a certainty."

Long Valley monitoring plans for summer 1982 initially included leveling, trilateration, precision gravity measurements, and a seismic refraction study. To supplement this program with an inexpensive deformation monitor which could be frequently measured, Dzurisin and Cashman installed five tilt stations on the floor of Long Valley caldera during May 1982. Two months later, the network was augmented with four additional stations by Sylvester and student crew from the University of California at Santa Barbara.

Our surveying technique has informally been called "dry tilt", "telescopic spirit level tilt", "tilt leveling", and more, but in our opinion none of these is entirely satisfactory (see Dzurisin and others, 1982). The procedure involves precision leveling of a small array of benchmarks, typically arranged in a 35-40 m equilateral triangle, to determine relative elevation changes and resultant tilt between successive surveys (Sylvester, 1978). It has been used to monitor inflation prior to eruptions at several active volcanoes (Kinoshita, Swanson, and Jackson, 1974), and may eventually earn a name befitting its considerable utility. In the meantime, we will refer here simply to "tilt stations" and "tilt measurements", and invite the reader to invent a more satisfying terminology.

LONG VALLEY TILT NETWORK

Stations CASA DIABLO, TUFF LUCK, CLAY PIT, HOT CREEK, AND LAUREL (hereafter called USGS stations) were established by Dzurisin and Cashman during 6-8 May 1982, primarily to monitor the resurgent dome and south caldera floor. SECTION CORNER, VOORHIS, HARDING, and SEWAGE PLANT (hereafter called UCSB stations) were added during 8-9 July 1982 by Sylvester to better monitor the site of recurrent seismic swarms since June 1980.

Each station consists of a triangular benchmark array 25-40 m on a side. By convention, the southernmost benchmark in each array is labelled X; benchmarks Y and Z are assigned sequentially in a counterclockwise direction (see Yamashita, 1981). USGS benchmarks are specially cast 10 cm diameter brass caps with 2 x 2-cm rounded nipples. UCSB benchmarks are either 1-cm-diameter copper-jacketed steel rods cemented and epoxied into boulders, or 1-cm-diameter coupled steel rods driven to refusal and capped with a 2 x 5 cm stainless steel nipple. All USGS stations were placed on bedrock; UCSB stations except HARDING are situated in glacial till. One benchmark at HARDING is in basaltic bedrock; the other two are in alluvial boulders of a kipuka.

STATION DESCRIPTIONS

The Long Valley tilt stations are shown on the 1:62,500-scale Mt. Morrison quadrangle topographic map in figure 1. More specific station locations are given below and in figures 2-7; a road log to the USGS stations is provided in the Appendix. Bearings and distances between benchmarks are shown in figures 8 and 9.

CASA DIABLO (37°39.13'N, 118°55.00'W)

Access to the station is from U.S. Highway 395, roughly 2.4 km (1.5 mi) north of its intersection with State Highway 203 to Mammoth Lakes (figure 2, Appendix). Turn east (right) from Hwy 395 near USCGS BM W911 (1957) onto a dirt road, then north (left) onto the powerline road and continue 150 m (0.1 mi) to pole A366. The station is adjacent to the powerline road, roughly 100 m east of Hwy 395 and immediately east of a prominent fault scarp. Three benchmarks are arranged in a triangular array on rhyolite outcrops. BM Y is 2.9 m S31°E of pole A366; BM X is roughly 60 m N23°E of BM W911. The instrument site is marked by a stone cross; it must be chosen carefully owing to visibility and elevation limitations.

TUFF LUCK (37°42.39'N, 118°55.89'W)

Access to TUFF LUCK is along a well-maintained U.S. Forest Service road from Smokey Bear Flat, 5.6 km (3.5 mi) north-northwest of CASA DIABLO (figure 3, Appendix). The triangular station is situated atop a prominent knob 100 m north of the road (marked by an aluminum tag on tree), just west of a major drainage. Benchmark Y is closest to the road on a small boulder near the top of the knob. BM X is near the western end of a prominent rhyolite outcrop along the first crest of the knob; BM Z lies 38.4 m N41°E of X, behind two tall pine trees. The knob flattens out north of the station, before climbing again to the top. The instrument site is marked by a stone cross. It could not be placed in the center of the station owing to visibility problems, but is instead between X and Z.

CLAY PIT (37°41.14'N, 118°52.47'W)

Access to the station is along Little Antelope Valley Road, atop a prominent fault scarp which forms the eastern margin of the valley (Figure 4, Appendix). The triangular tilt station lies approximately 0.5 km (0.3 mi) south of a large, actively-mined clay pit shown on most maps and approximately 0.3 km (0.2 mi) west of the road. Park near a bulldozer pit on the left side of the road, marked with a P-K masonry nail in a large tree ringed at its base with stones. Benchmarks X and Z are located on large rhyolite outcrops near the head of the fault scarp; BM Y is east of the scarp (toward the road) on a low rhyolite outcrop. The instrument site is marked by a stone cross at the center of the array.

HOT CREEK (37°39.02'N, 118°50.21'W)

This triangular station straddles a small bedrock knob near the intersection of Hot Creek Road and a private dirt road (Figure 5, Appendix). Turn west onto the ranch road 1.6 km (0.95 mi) south of Hot Creek parking lot, and park in front of the NO TRESPASSING sign. Benchmark Y is closest to the private road, on the first good outcrop to the south. BM X and Z are further south, also on low rhyolite outcrops. The instrument site is marked by a stone cross at the center of the array.

LAUREL (37°37.99'N, 118°53.63'W)

Access to LAUREL is south along Sherwin Creek Road 1.2 km (0.75 mi) from Hwy 395 (Figure 6, Appendix). The station straddles a basalt outcrop immediately west of a small dirt road, roughly 0.4 km (0.25 mi) north of the quarry shown on most maps. Benchmark Y is within 20 m of the road, on a small knob. BM X is at the southwest end of a small ridge striking roughly southwest; BM Z is on a low outcrop to the northwest. The instrument site is marked by a stone cross at the center of the array.

SECTION CORNER (37°38.23'N, 118°57.18'W)

Access to SECTION CORNER is from the Mammoth traffic light at the intersection of Highway 203 and Old Mammoth Road, thence south on Old Mammoth Road 1.4 km (0.85 mi; see Figure 7). Take left fork onto dirt road before Motocross road and drive 0.5 km (0.3 mi); bear left and drive 0.6 km (0.35 mi) to the corner of sections 35, 36, 2 and 1. Benchmark X is in a 1-m-diameter white boulder which protrudes 25 cm above the surface, 29.5 m due north of the section corner benchmark in a flat area north of the gravel road. BM Y is in a 1-m-diameter black boulder which protrudes 30 cm above the surface. BM Z is a capped stainless steel rod driven to refusal and surrounded by a white plastic pipe. The instrument site is marked by a stone cross in the center of the array, equidistant from each benchmark.

VOORHIS (37°37.50'N, 118°56.67'W)

Access to VOORHIS is from the Mammoth traffic light at the intersection of Highway 203 and Old Mammoth Road, thence south on Old Mammoth Road 1.4 km (0.9 mi) to Sherwin Creek Road (Figure 7). Proceed southeast (left) 2.2 km (1.4 mi) on Sherwin Creek Road. At turnoff to Motocross area and Sherwin Creek Trailhead, go right 0.6 km (0.35 mi) to Voorhis Camp turnoff, then left at gate 0.2 km (0.1 mi) to trailhead parking area. Benchmark X is 40 m N20°W of the trailhead in a flat north of the parking area. The instrument site is marked by a stone cross in the center of the array, equidistant from each benchmark.

HARDING (37°37.63'N, 118°55.88'W)

Access to HARDING is from the Mammoth traffic light at the intersection of Highway 203 and Old Mammoth Road, south on Old Mammoth Road 1.4 km (0.9 mi) to Sherwin Creek Road (Figure 7). Proceed southeast (left) on Sherwin Creek Road 3.8 km (2.4 mi) to a large flat on the west side of the road. The road and flat are surrounded by basalt flows. The array is approximately halfway between Sherwin Creek Campground and Harding Camp; benchmark Y is located 12 m west of the road. The instrument site is marked by a basalt stone cross in the center of the array, equidistant from each benchmark.

SEWAGE PLANT (37°38.43'N, 118°56.25'W)

The station is along State Highway 203, 0.2 km (0.15 mi) east of the entrance to the Mammoth Waste Water Treatment facility (Figure 7). Park on the north side of the road next to a large isolated granite boulder 0.2 km (0.15 mi) east of the plant entrance. Benchmark X is in a white boulder 10 m north of the large isolated boulder. The instrument site is marked by a stone cross in the center of the array, equidistant from each benchmark.

BASELINE MEASUREMENTS

The USGS stations were first measured on 8 May 1982, using Wild NA-2 level #459655, Wild GPM-3 optical micrometer #27826, and Wild GPL-3 level rod pair CVO-1A/B. Initial measurements at the UCSB stations were made on 8-9 July 1982 with Wild NAK-2 level #381882, Wild GPM-3 optical micrometer #25926, and three Wild GPL-3 level rods #2207A, 2207B, and 4003A. Equations for calculating tilt from measured elevation changes at each station are provided in tables 1 and 2; baseline elevation measurements and estimated uncertainties are listed in tables 3 and 4.

REPEAT SURVEYS

The five USGS tilt stations were remeasured by a UCSB crew on 7 July 1982; all nine stations were measured again by a UCSB crew on 3-5 August, and by Dzurisin and Cashman on 22-25 August. Results are summarized in Tables 5-8. Field experience elsewhere suggests that the detection limit for meaningful ground tilts with this technique under ideal conditions is about 5 microradians, even though greater precision may be indicated by formal error estimates.

RESULTS

Net changes during summer 1982 exceeded 5 microradians at all stations except HOT CREEK, VOORHIS, and SEWAGE PLANT (table 8), but the resulting tilt pattern is complex (figure 10). There was a tendency for the most active stations to tilt consistently during July-August (e.g., CLAY PIT tilted progressively to the northeast, HARDING to the southeast), and in some cases nearby stations tilted together (e.g., LAUREL and HARDING tilted southeast). On the other hand, the result at HARDING was not confirmed by nearby stations SECTION CORNER, SEWAGE PLANT, or VOORHIS.

The data do not yet discriminate between the following interpretations, which we subjectively rank in order of decreasing plausiblity.

1. Measured tilt changes are "noise" inherent in the technique, and do not reflect regional crustal deformation. Factors which may contribute to larger than expected errors include instability of individual benchmarks or stations, systematic differences between USGS

and UCSB results, and diurnal or seasonal tilt fluctuations. Lack of a consistent overall tilt pattern and disagreements between adjacent stations are the strongest argument for this conclusion.

2. Measured tilts were caused by continuing uplift and extension of the resurgent dome, but the effects of local structures complicate the resultant tilt pattern. This interpretation is consistent with tilts to the ENE measured on the resurgent dome, given the NNW-SSE structural trend within the dome. The recent appearance of warm ground and tree kill along a graben fault on the dome suggests that resurgence has re-activated at least some pre-existing structures since 1980, which may have caused complex local tilting.

3. Measured tilt changes reflect real crustal deformation which is not centered on the resurgent dome. If we ignore tilt changes less than 5 microradians, four of five remaining stations suggest a center of uplift between Casa Diablo and the June 1980 - May 1982 epicentral area, perhaps along Highway 203 near SEWAGE PLANT (figure 10). This interpretation is consistent with an apparent northeastward migration of seismicity toward Casa Diablo since May 1982 (R. Cockerham, oral commun., 1982), but does not explain the lack of appreciable tilt at SECTION CORNER and VOORHIS, unless they, too, are situated on the crest of the uplifting area.

Additional measurements are thus required to separate the possible effects of continuing deformation in a structurally complex setting from uncertainties inherent in our technique. We plan to remeasure our Long Valley stations in late September, and again this winter in the event of a seismic swarm or other indication of increased activity.

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REFERENCES

Bailey, R.A., Dalrymple, G.B., and Lanphere, M.A., 1976, Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California: Journal of Geophysical Research, 81, 725-744.

Dzurisin, Daniel, Johnson, D.J., Murray T.L., and Myers, Barbara, 1982, Tilt networks at Mount Shasta and Lassen Peak, California: U.S. Geological Survey Open-File Report 82-670, 42 p.

Kinoshita, W.T., Swanson, D.A., and Jackson, D.B., 1974, The measurement of crustal deformation related to volcanic activity at Kilauea volcano, Hawaii: in Civetta et al., eds., Physical Volcanology, Elsevier Publishing Company, pp. 87-115.

Miller, C.D., Mullineaux, D.R., Crandell, D.R. and Bailey, R.A., 1982, Potential hazards from future volcanic eruptions in the Long Valley-Mono Lake area, east-central California and southwest Nevada - A preliminary assessment: U.S. Geological Survey Circular 877, 10 p.

Ryall, Alan and Ryall, Floriana, 1981, Spatial-temporal variations in seismicity preceding the May 1980, Mammoth Lakes, California, earthquakes: Bulletin of the Seismological Society of America, 71, no.3, 747-760.

Savage, J.C. and Clark, M.M., 1982, Magmatic resurgence in Long Valley caldera, California: Possible cause of the 1980 Mammoth Lakes earthquakes: Science, 217, 531-533.

Sylvester, A.G., 1978, The dry tilt method of measuring crustal tilt, in Evernden, J.F., convener, Stress and strain measurements related to earthquake prediction: U.S. Geological Survey Open-File Report 79-370.

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 81-523, 21 p.

APPENDIX
ROAD LOG TO USGS LONG VALLEY TILT STATIONS

0.0 miles		Traffic light at intersection of State Highway 203 and Old Mammoth Highway in Mammoth Lakes.
2.9		Intersection of State Highway 203 and U.S. Highway 395; proceed north on Hwy 395.
4.4		Turn right onto a dirt road, less than 0.1 miles beyond where the divided highway narrows to a single road.
4.55		Turn left (north) onto powerline road.
4.65		Park at power pole A366 - station CASA DIABLO.
4.65	0.0	Proceed north along powerline road from DIABLO.
6.4	1.75	Take right fork of powerline road.
6.75	2.1	Bear right onto somewhat better dirt road.
7.2	2.55	Bear right onto main Smokey Bear Flats Rd.
7.8	3.15	Take right fork; stay on main road.
8.25	3.6	Park by tree on left with aluminum tag; station TUFF LUCK is on top of knob left of road.
8.25	0.0	Continue northeast from TUFF LUCK
8.45	0.2	Bear left.
8.65	0.4	Bear left.
9.3	1.05	Continue straight.
9.45	1.2	Bear right at junction
10.6	2.35	Bear right at junction
11.5	3.25	4-way intersection - continue on by staying left
11.7	3.45	Bear left, continuing on main road.
13.1	4.85	Cross powerline and continue past Chalk Bluffs.
14.45	6.2	Sharp left at intersection toward Antelope Valley.
15.2	6.95	Take upper road on left toward clay pit; station is on prominent cliff visible to the left.
15.65	7.4	Park at small pit and P-K nail in large tree left of road; walk west roughly 0.2 mile to cliff and station CLAY PIT.
15.65	0.0	Continue northeast on dirt road.
15.95	0.3	Go straight at Clay Pit intersection.
19.5	3.85	Turn right at intersection.
20.2	4.55	Turn right at intersection onto main road.
20.75	5.1	Turn right at intersection toward Hot Creek.
21.85	6.2	Pass Hot Creek parking lot.
22.9	7.25	Park on dirt road on right with NO TRESPASSING sign; HOT CREEK station is on left (south).
22.9	0.0	Continue south on Hot Creek road.
23.5	0.6	Take main road to right (not road to cabins).
24.8	1.9	Turn left toward Highway 395.
25.3	2.4	Turn right onto Highway 395 toward Mammoth Lakes.
27.0	4.1	Turn left onto Sherwin Creek Rd.
27.8	4.9	Park at small dirt road on right; station LAUREL is on toe of basalt flow, between main road and small dirt road.

TABLE 1

USGS LONG VALLEY STATION EQUATIONS

Casa Diablo

$\tau(N) = +0.3275\ \Delta(Y-X) - 0.0414\ \Delta(X-Z)$

$\tau(E) = +0.2047\ \Delta(Y-X) + 0.2945\ \Delta(X-Z)$

Tuff Luck

$\tau(N) = -0.1188\ \Delta(Y-X) - 0.3061\ \Delta(X-Z)$

$\tau(E) = +0.3094\ \Delta(Y-X) + 0.0707\ \Delta(X-Z)$

Clay Pit

$\tau(N) = +0.1086\ \Delta(Y-X) - 0.2326\ \Delta(X-Z)$

$\tau(E) = +0.2557\ \Delta(Y-X) + 0.2494\ \Delta(X-Z)$

Hot Creek

$\tau(N) = +0.2312\ \Delta(Y-X) - 0.0098\ \Delta(X-Z)$

$\tau(E) = +0.2010\ \Delta(Y-X) + 0.2814\ \Delta(X-Z)$

Laurel

$\tau(N) = +0.0624\ \Delta(Y-X) - 0.2631\ \Delta(X-Z)$

$\tau(E) = +0.4441\ \Delta(Y-X) + 0.2733\ \Delta(X-Z)$

Tilts are expressed in microradians, elevation changes in thousanths of a centimeter.

TABLE 2

UCSB LONG VALLEY STATION EQUATIONS

Section Corner

$$\tau(N) = +\,0.0547\ \Delta(Y-X) - 0.0027\ \Delta(X-Z)$$
$$\tau(E) = +\,0.3456\ \Delta(Y-X) + 0.2202\ \Delta(X-Z)$$

Voorhis

$$\tau(N) = -\,0.0290\ \Delta(Y-X) - 0.2981\ \Delta(X-Z)$$
$$\tau(E) = +\,0.3324\ \Delta(Y-X) + 0.1390\ \Delta(X-Z)$$

Harding

$$\tau(N) = -\,0.0299\ \Delta(Y-X) - 0.2871\ \Delta(X-Z)$$
$$\tau(E) = +\,0.3415\ \Delta(Y-X) + 0.1463\ \Delta(X-Z)$$

Sewage Plant

$$\tau(N) = +\,0.1701\ \Delta(Y-X) - 0.1479\ \Delta(X-Z)$$
$$\tau(E) = +\,0.2831\ \Delta(Y-X) + 0.2902\ \Delta(X-Z)$$

Tilts are expressed in microradians, elevation changes in thousanths of a centimeter.

TABLE 3

USGS LONG VALLEY TILT STATIONS
BASELINE MEASUREMENTS
8 MAY 1982

STATION	Y-X	X-Z	Z-Y
Casa Diablo	-268.152±.006 cm	+211.040±.006	+57.112±.002
Tuff Luck	+247.844±.006	+29.256±.005	-277.100±.004
Clay Pit	-255.233±.013	+243.639±.015	+11.594±.004
Hot Creek	+163.209±.010	-162.175±.006	-1.034±.013
Laurel	+21.697±.003	-82.479±.012	+60.782±.007

Stated uncertainties are ± 1 standard deviation, calculated from 3 left/right measurements of elevation difference between each benchmark pair.

TABLE 4

UCSB LONG VALLEY TILT STATIONS
BASELINE MEASUREMENTS
8-9 JULY 1982

STATION	Y-X	X-Z	Z-Y
Section Corner	-67.456±.002	+125.640±.001	-58.184±.002
Voorhis	+48.027±.003	+117.949±.002	-165.976±.003
Harding	+100.502±.003	+32.696±.003	-133.198±.004
Sewage Plant	+118.825±.002	+79.526±.004	-198.351±.002

Stated uncertainties are ± 1 standard deviation, calculated from 3 left/right measurements of elevation difference between each benchmark pair.

TABLE 5
LONG VALLEY TILT CHANGES
8 MAY - 7 JULY 1982

STATION	Y-X*	X-Z*	Z-Y*	TILT	AZIMUTH
Casa Diablo	-268.148±.004 cm	+211.035±.003 cm	+57.113±.002 cm	1.4 μrad	N23°W
Tuff Luck	+247.848±.003	+29.256±.002	-277.104±.003	1.3	S69°E
Clay Pit	-255.251±.004	+243.642±.002	+11.609±.002	4.7	S55°W
Hot Creek	+163.220±.004	-162.184±.002	-1.036±.005	2.7	N 7°W
Laurel	+21.679±.001	-82.457±.000	+60.778±.001	7.2	S16°W

Stated uncertainties are ± 1 standard deviation, calculated from 3 left/right measurements of elevation difference between each benchmark pair.

*Elevation differences measured 7 July 1982. See Table 3 for baseline measurements.

TABLE 6
LONG VALLEY TILT CHANGES
7 JULY - 3-5 AUGUST 1982

STATION	Y-X*	X-Z*	Z-Y*	TILT	AZIMUTH
Casa Diablo	-268.166±.002 cm	+211.038±.002 cm	+57.128±.001 cm	4.0 μrad	East
Tuff Luck	+247.848±.004	+29.259±.002	-277.107±.005	1.0	S13°E
Clay Pit	-255.228±.002	+243.632±.001	+11.596±.003	5.9	N35°E
Hot Creek	+163.219±.003	-162.177±.004	-1.042±.002	1.8	S80°E
Laurel	+21.692±.002	-82.453±.004	+60.761±.004	6.9	S88°E
Section Corner	-67.545±.003	+125.646±.004	-58.192±.001	2.0	N87°E
Voorhis	+48.028±.004	+117.958±.003	-165.986±.004	3.1	S30°E
Harding	+100.498±.002	+32.714±.002	-133.212±.002	5.4	S14°E
Sewage Plant	+118.818±.002	+79.532±.002	-198.350±.001	2.1	S07°W

Stated uncertainties are ± 1 standard deviation, calculated from 3 left/right measurements of elevation difference between each benchmark pair.

*Elevation differences measured 3-5 August 1982. See Tables 3 and 4 for baseline measurements.

TABLE 7
LONG VALLEY TILT CHANGES
3-5 AUGUST - 22-25 AUGUST 1982

STATION	Y-X*	X-Z*	Z-Y*	TILT	AZIMUTH
Casa Diablo	-268.128±.008	+211.045±.006	+57.083±.008	15.6 μrad	N39°E
Tuff Luck	+247.881±.011	+29.239±.005	-277.120±.007	9.1	N76°E
Clay Pit	-255.178±.004	+243.623±.003	+11.555±.006	12.9	N54°E
Hot Creek	+163.218±.010	-162.172±.013	-1.046±.010	1.2	S77°E
Laurel	+21.693±.010	-82.443±.007	+60.750±.008	4.1	S51°E
Section Corner	-67.445±.006	+125.646±.007	-58.201±.010	3.1	N81°E
Voorhis	+48.038±.004	+117.948±.009	-165.986±.006	3.3	N36°E
Harding	+100.507±.008	+32.732±.012	-133.239±.013	7.9	S46°E
Sewage Plant	+118.820±.008	+79.532±.010	-198.352±.010	0.7	N59°E

Stated uncertainties are ± 1 standard deviation, calculated from 3 left/right measurements of elevation difference between each benchmark pair.

*Elevation differences measured 22-25 August 1982. See Tables 3 and 4 for baseline measurements.

TABLE 8
NET LONG VALLEY TILT CHANGES
SUMMER 1982*

STATION	TILT	AZIMUTH
Casa Diablo**	10.0 μrad	N40°E
Tuff Luck**	10.3	N85°E
Clay Pit**	14.0	N46°E
Hot Creek**	3.4	N52°E
Laurel**	12.6	S40°E
Section Corner***	5.2	N83°E
Voorhis***	3.5	East
Harding***	12.6	S34°E
Sewage Plant***	1.8	S11°E

Stated uncertainties are ± 1 standard deviation, calculated from 3 left/right measurements of elevation difference between each benchmark pair.

*See Tables 3, 4 and 7 for measured elevation differences.

**Net changes during 8 May - 22-25 August 1982

***Net changes during 7 July - 22-25 August 1982.

FIGURE CAPTIONS

Figure 1. Map showing locations of 9 tilt stations installed in Long Valley during May and July 1982. Squares mark USGS stations installed by Dzurisin and Cashman; circles mark UCSB stations installed by Sylvester. Bold dashed line indicates approximate margin of Long Valley resurgent dome; hachured area in lower left has been site of recurrent seismic swarms since June 1980. Also shown are section boundaries (thinner dashed lines) and section numbers (29-32). More detailed maps of Long Valley tilt stations are provided in Figures 2-7.

Figure 2. Sketch map of CASA DIABLO tilt station. Solid lines indicate two principal access roads in the area, U.S. Highway 395 and State Highway 203. See Road Log given in Appendix A for specific directions to site.

Figure 3. Sketch map of tilt site TUFF LUCK. Solid line marks U.S. Highway 395; dashed line shows U.S. Forest Service access road to station.

Figure 4. Sketch map of tilt site CLAY PIT, showing access road and actively-mined pit shown on most maps of the area.

Figure 5. Sketch map of tilt site HOT CREEK, with access road shown as dashed line.

Figure 6. Sketch map of tilt site LAUREL along Sherwin Creek Road, between U.S. Highway 395 (solid line) and active gravel pit shown in lower left.

Figure 7. Detailed map showing UCSB tilt stations SECTION CORNER, VOORHIS, HARDING, and SEWAGE PLANT. Access to each station is described in the text.

Figure 8. Dimensions and orientations of USGS Long Valley tilt stations, with benchmark locations denoted X,Y,Z.

Figure 9. Dimensions and orientations of UCSB Long Valley tilt stations, with benchmark locations denoted X,Y,Z.

Figure 10. Net tilt changes at Long Valley stations during summer 1982. The measurement interval for the USGS stations (squares) was 8 May-25 August; the UCSB stations were measured on 7 July and 25 August. Arrow heads point down-tilt; i.e., the vector in the legend indicates 10 microradians tilt down to the northeast.

LONG VALLEY TILT NETWORK

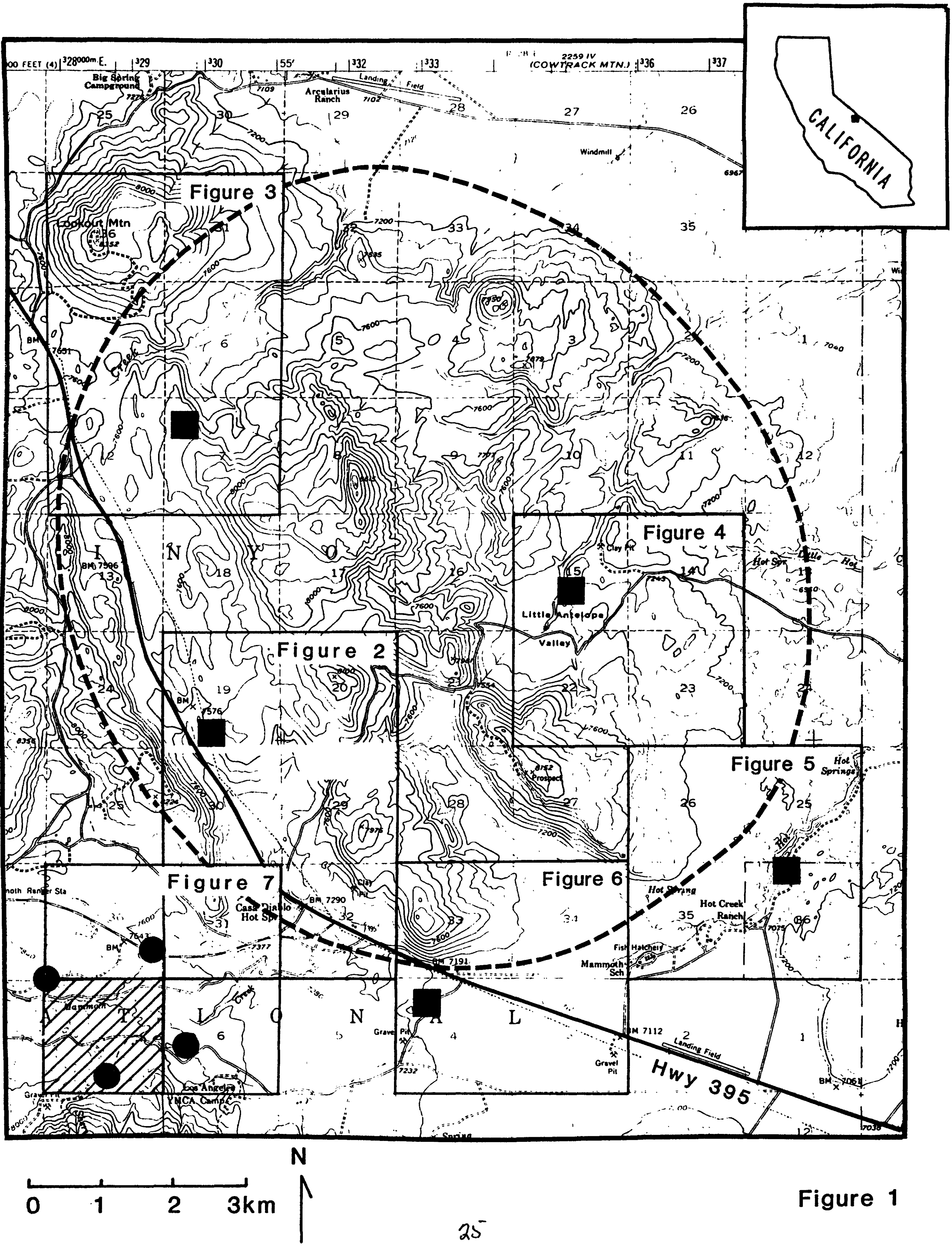
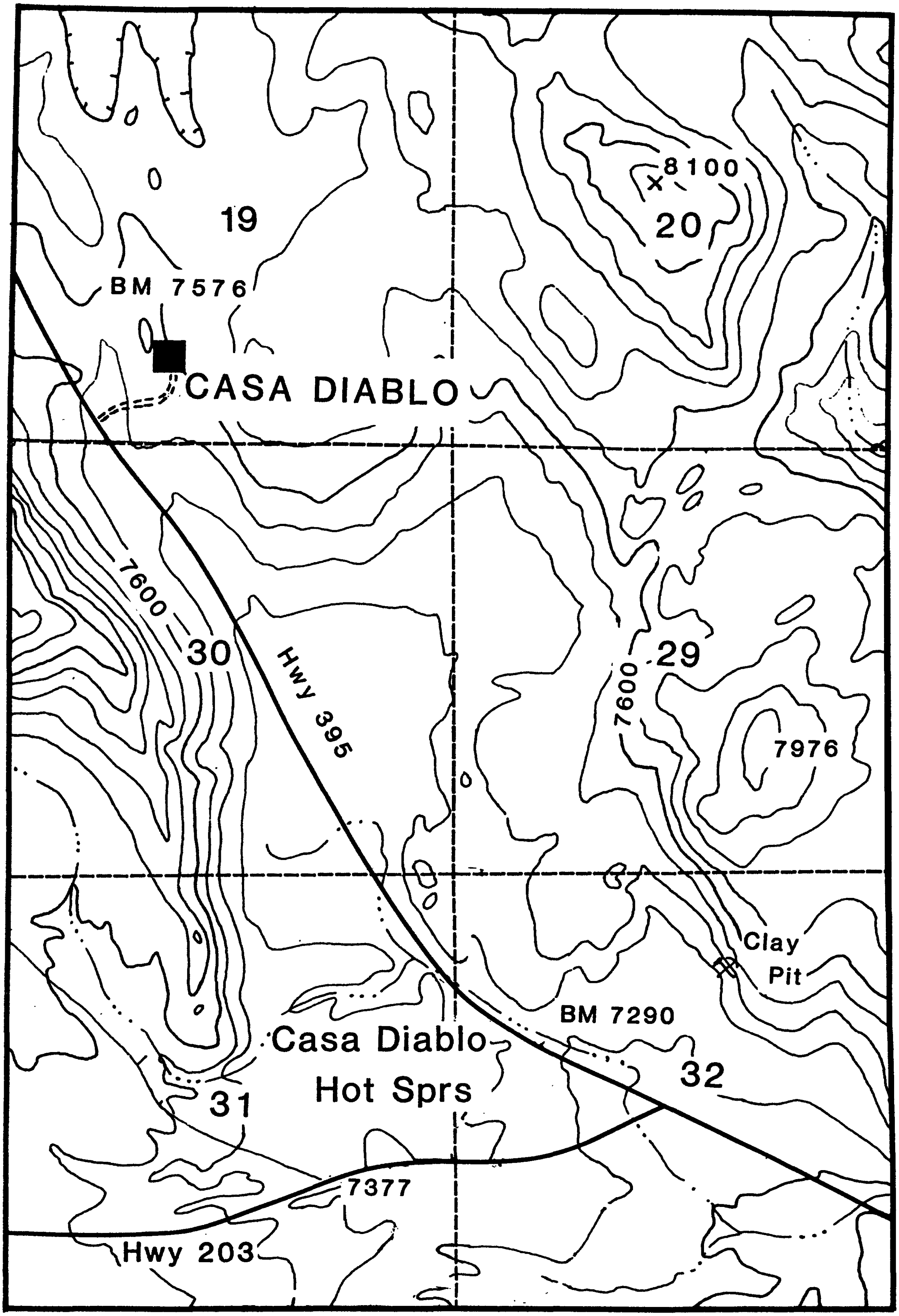


Figure 1



0 1km

Figure 2

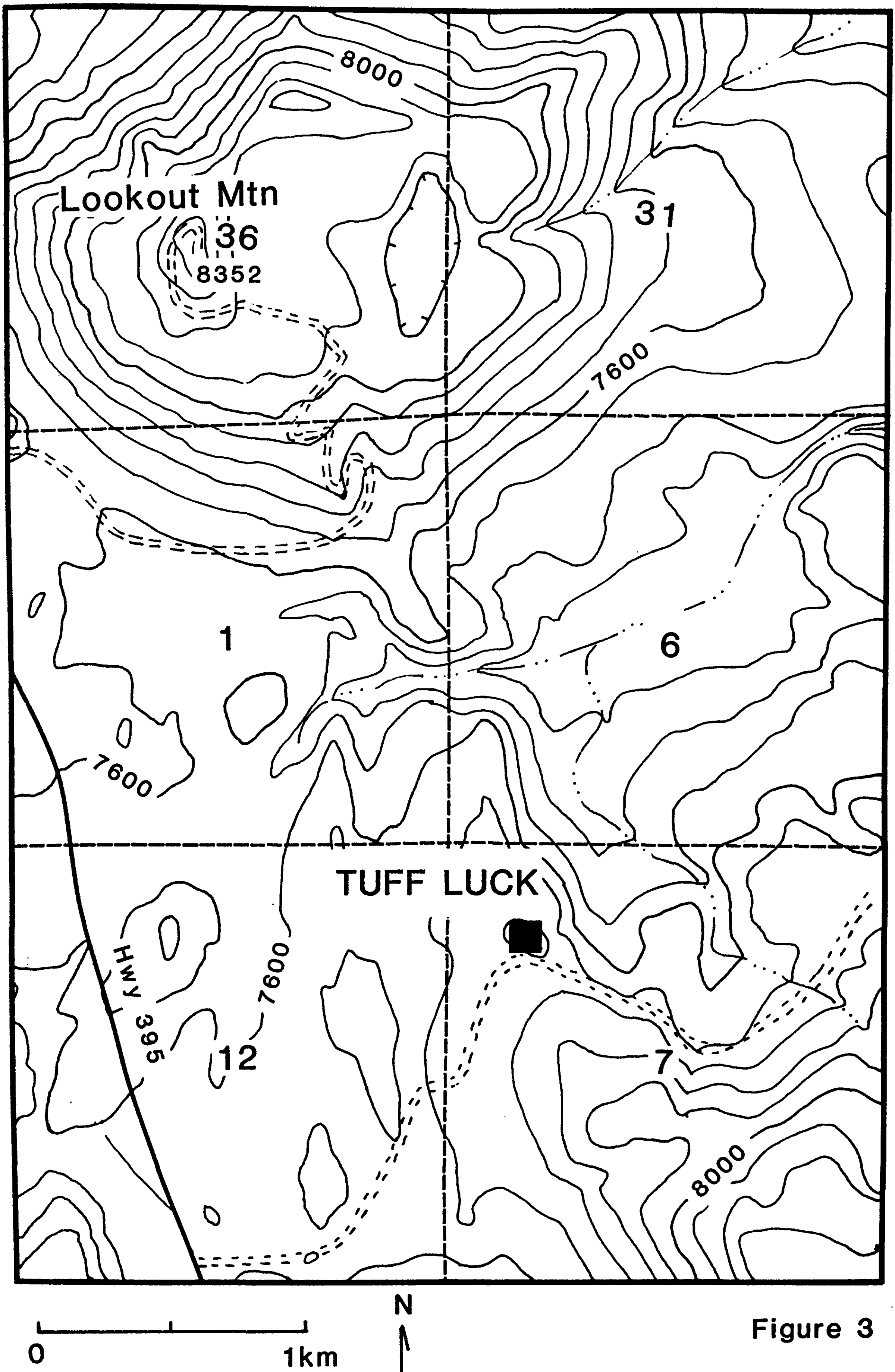

8000
Lookout Mtn
36
8352
31
7600
1
6
7600
TUFF LUCK
Hwy 395
7600
12
7
8000
0
1km
N

Figure 3

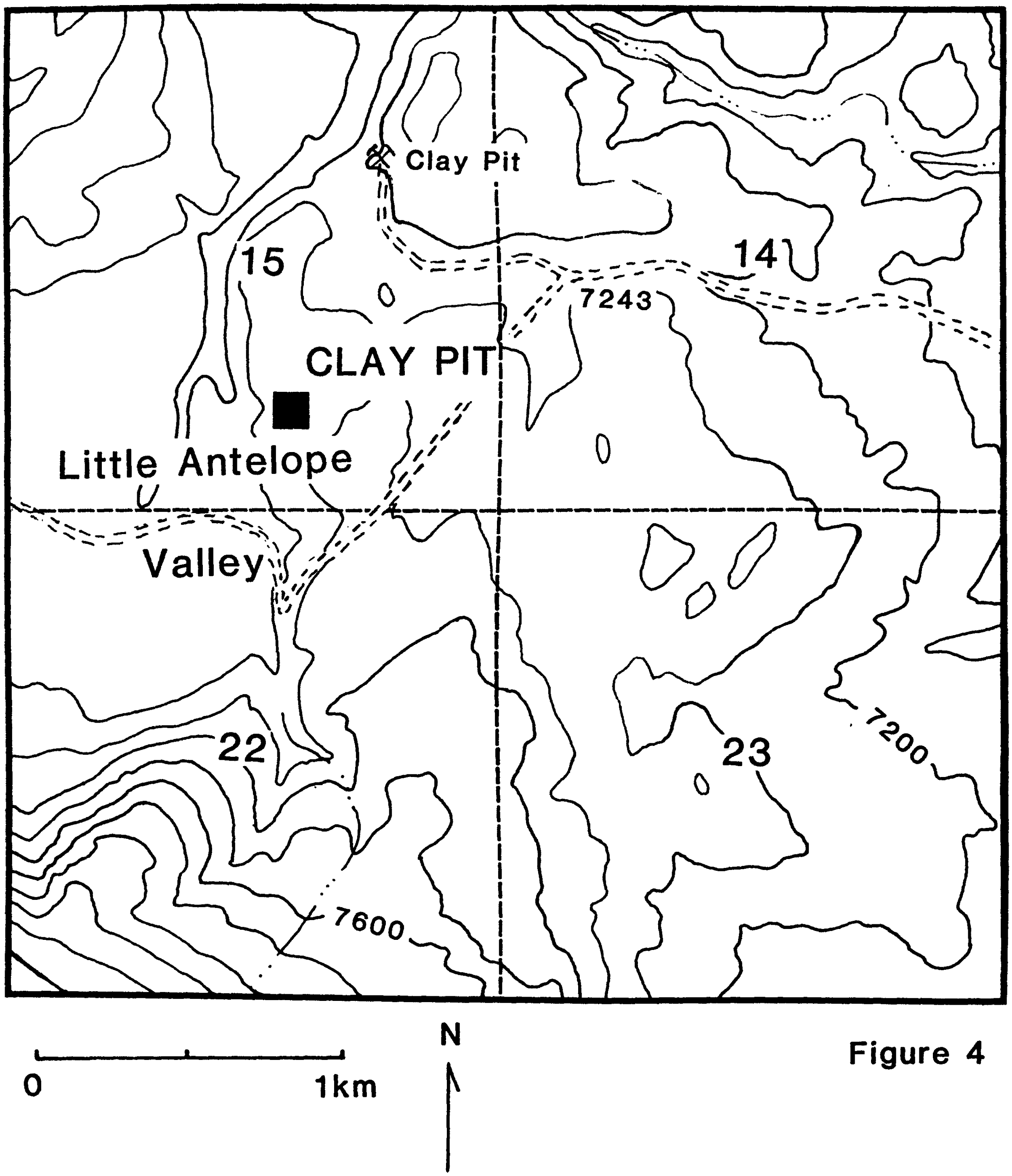

Clay Pit
15
14
7243
CLAY PIT
Little Antelope
Valley
22
23
7200
7600
0
1km
N

Figure 4

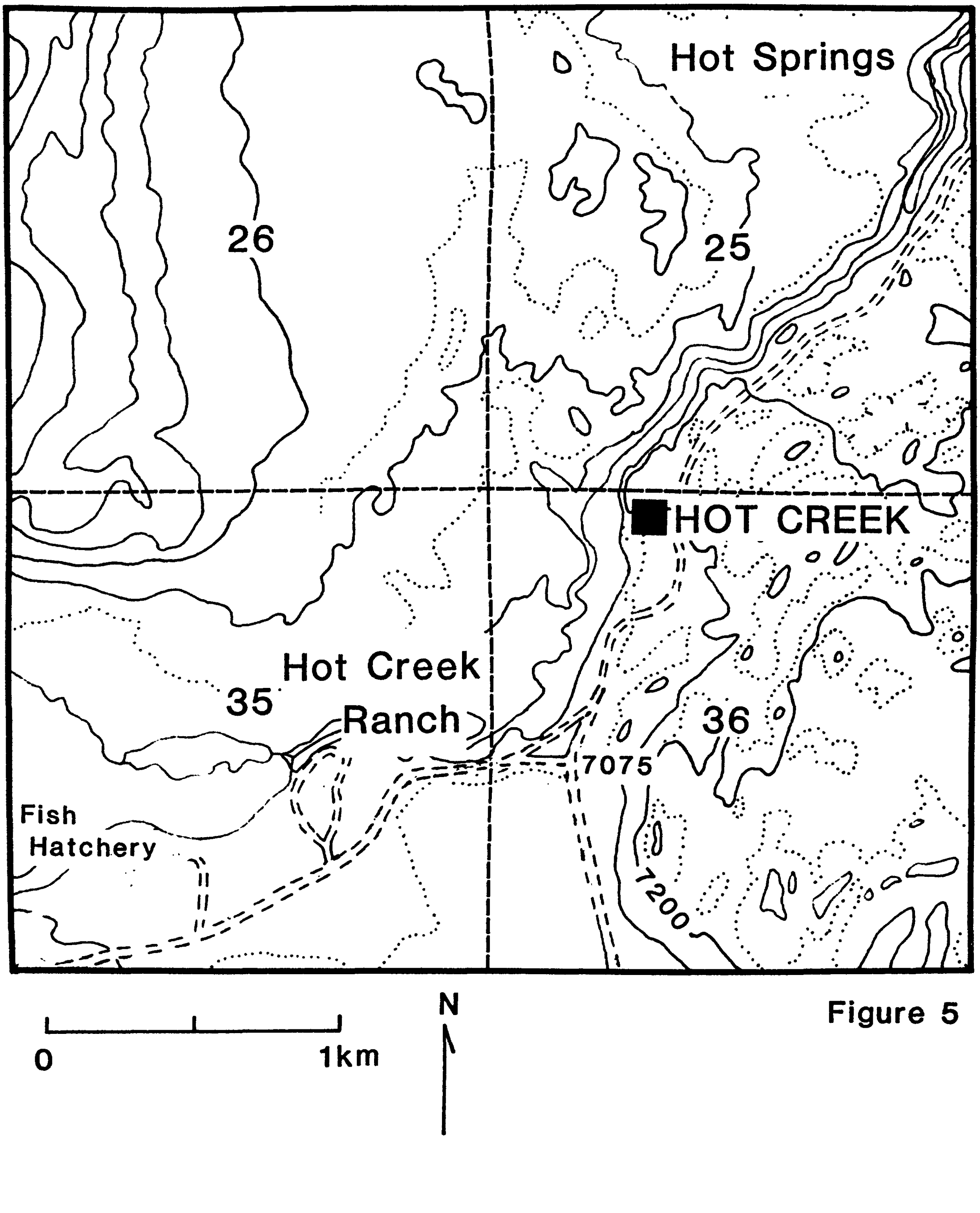
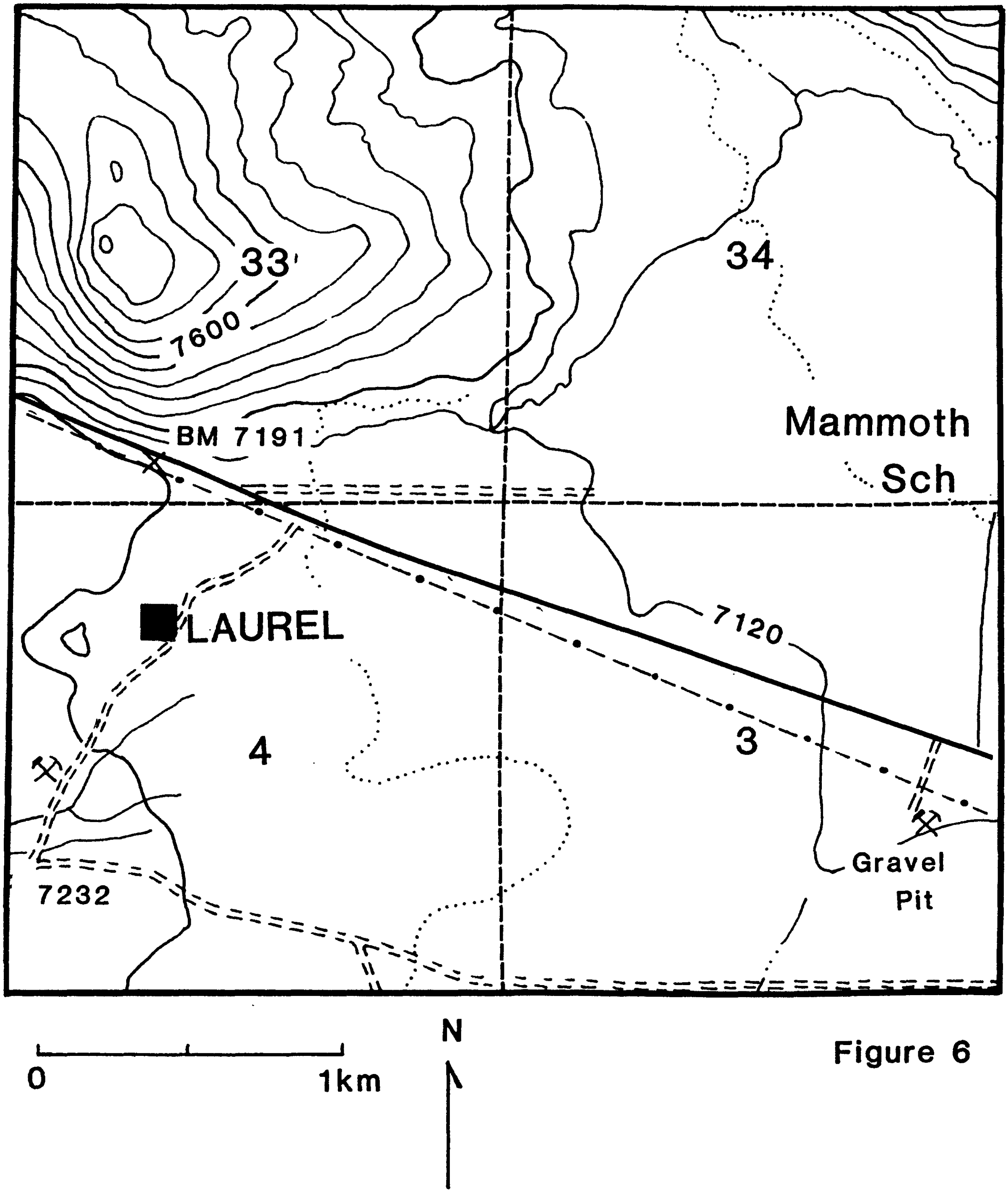

Hot Springs
26
25
HOT CREEK
Hot Creek
Ranch
35
36
7075
7200
Fish
Hatchery
0
1km
N

Figure 5



33
7600
34
Mammoth
Sch
BM 7191
LAUREL
7120
4
3
Gravel
Pit
7232
0
1km
N

Figure 6

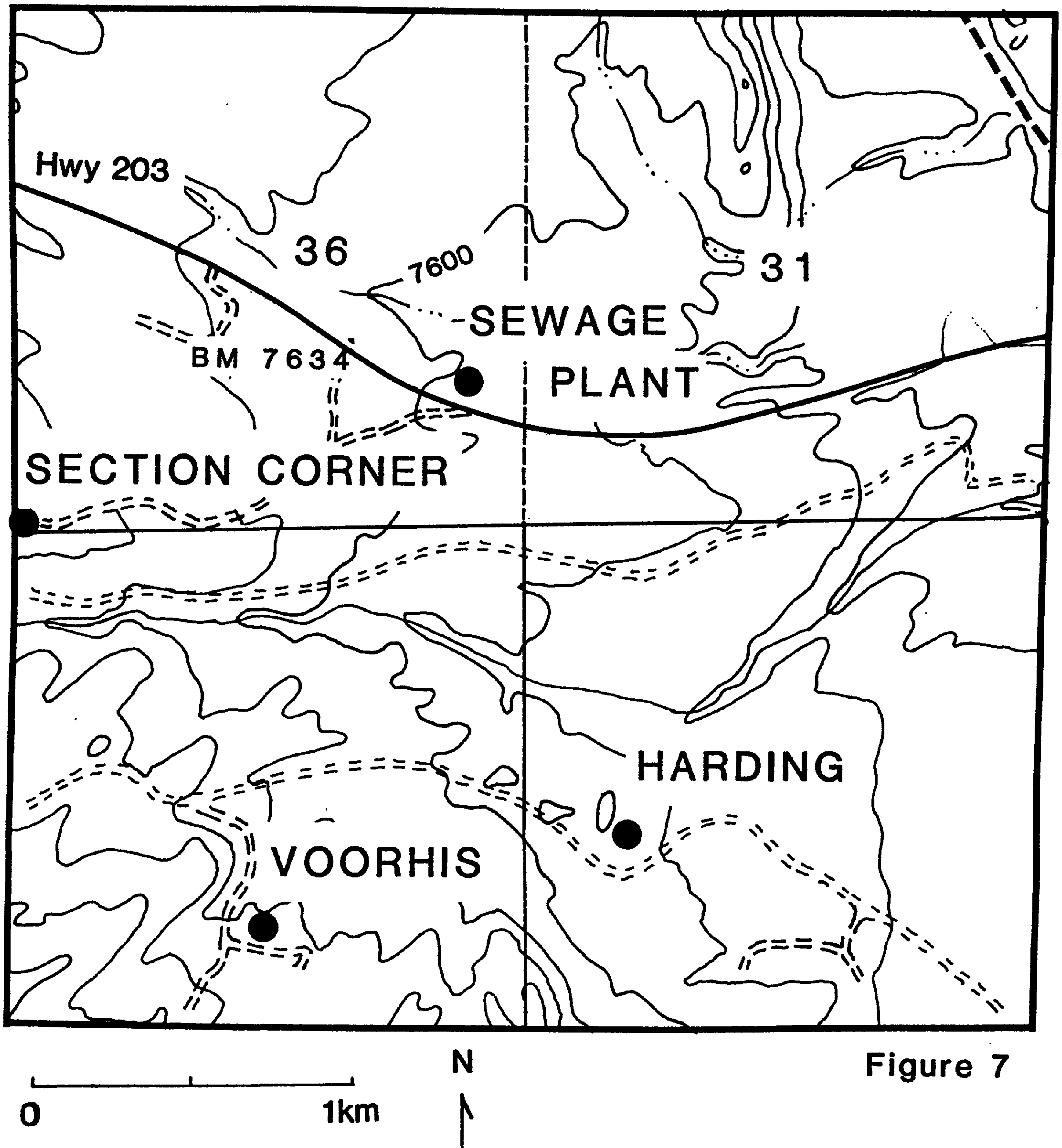

Hwy 203
36
7600
31
SEWAGE
PLANT
BM 7634
SECTION CORNER
HARDING
VOORHIS
0
1km
N

Figure 7

LONG VALLEY TILT STATIONS

(USGS)

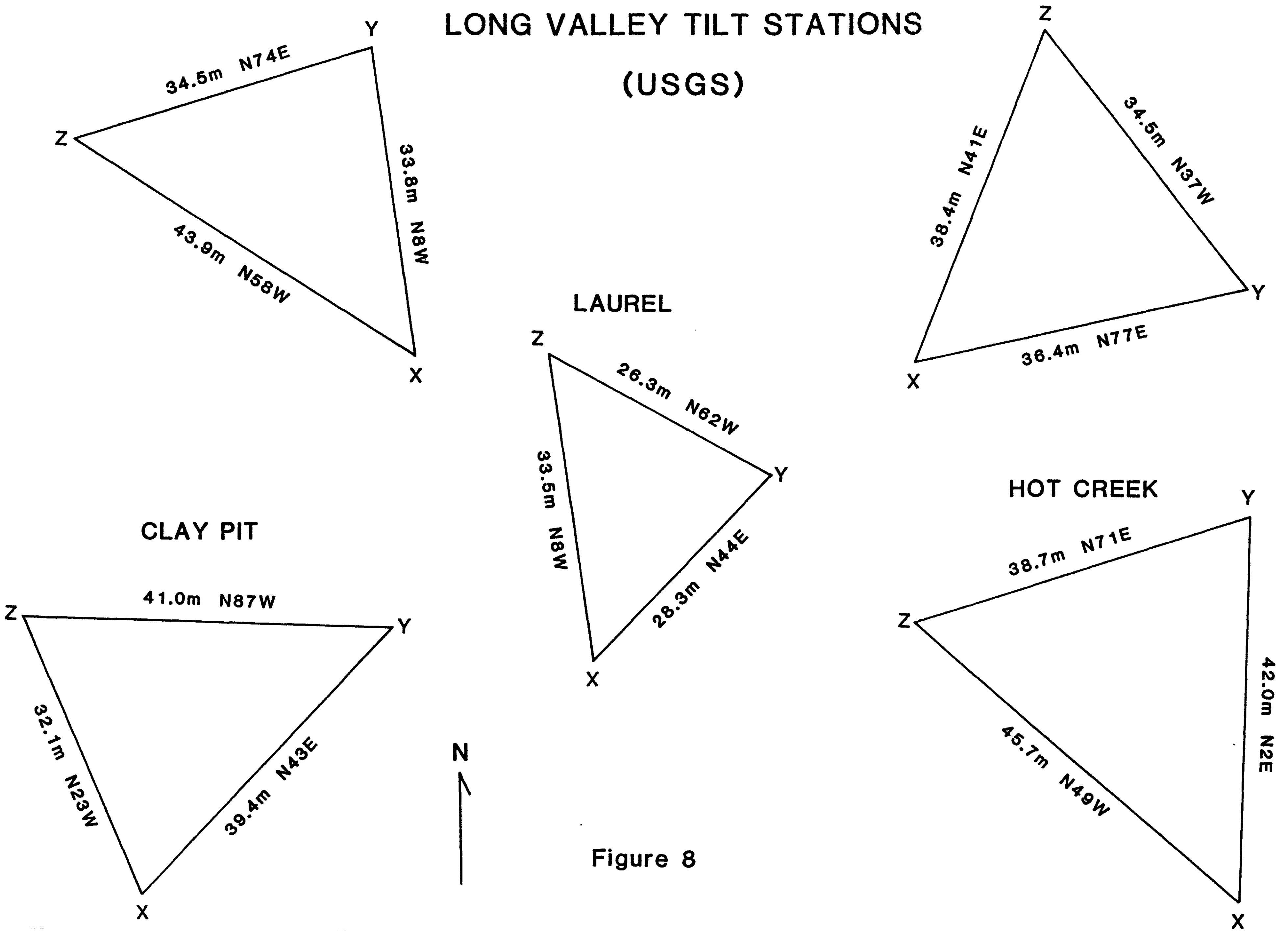


Figure 8

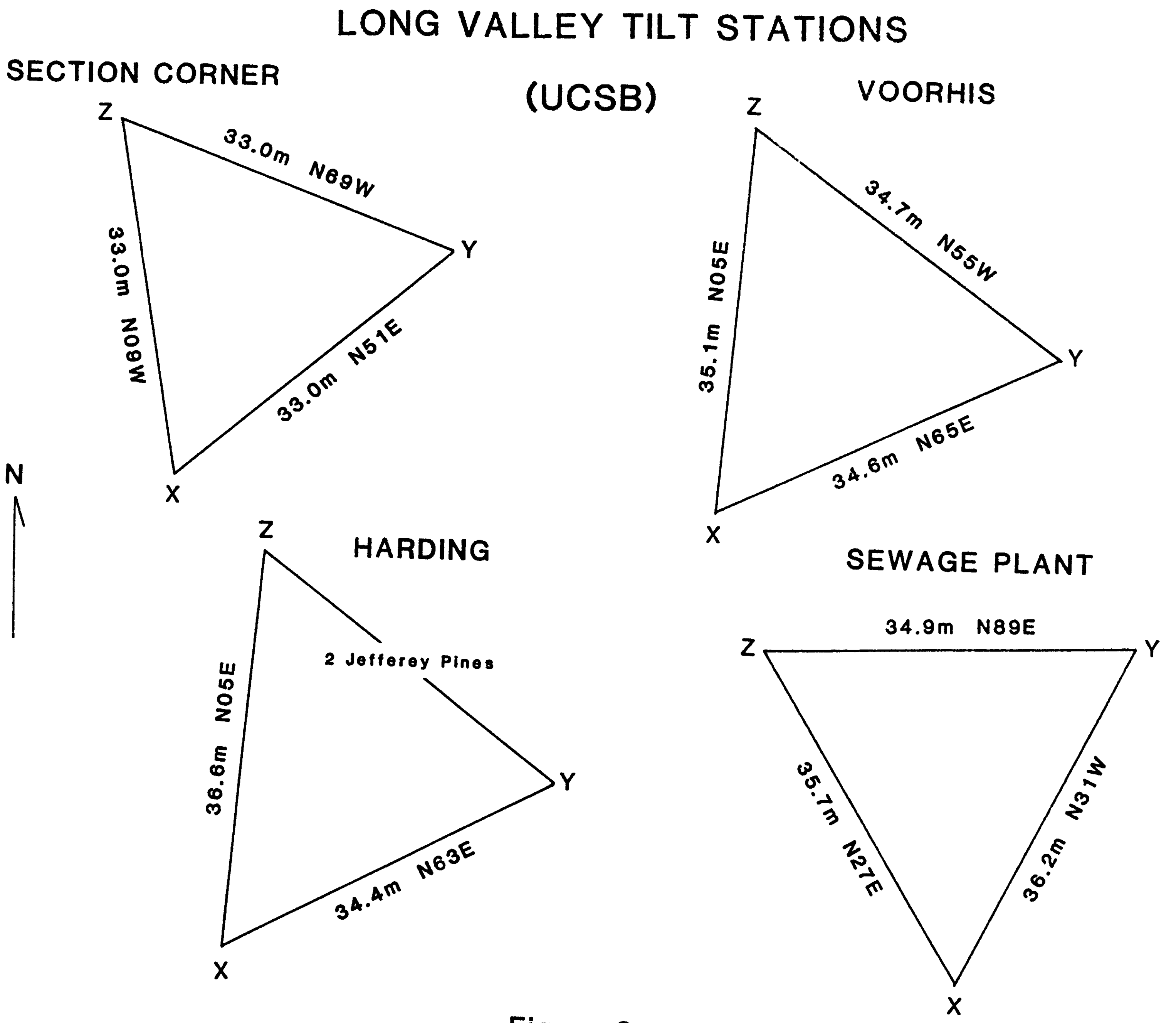

LONG VALLEY TILT STATIONS
(UCSB)
SECTION CORNER
33.0m N69W
33.0m N09W
33.0m N51E
VOORHIS
34.7m N55W
35.1m N05E
34.6m N65E
HARDING
2 Jefferey Pines
36.6m N05E
34.4m N63E
SEWAGE PLANT
34.9m N89E
35.7m N27E
36.2m N31W
N
Z
Y
X

Figure 9

LONG VALLEY TILT NETWORK

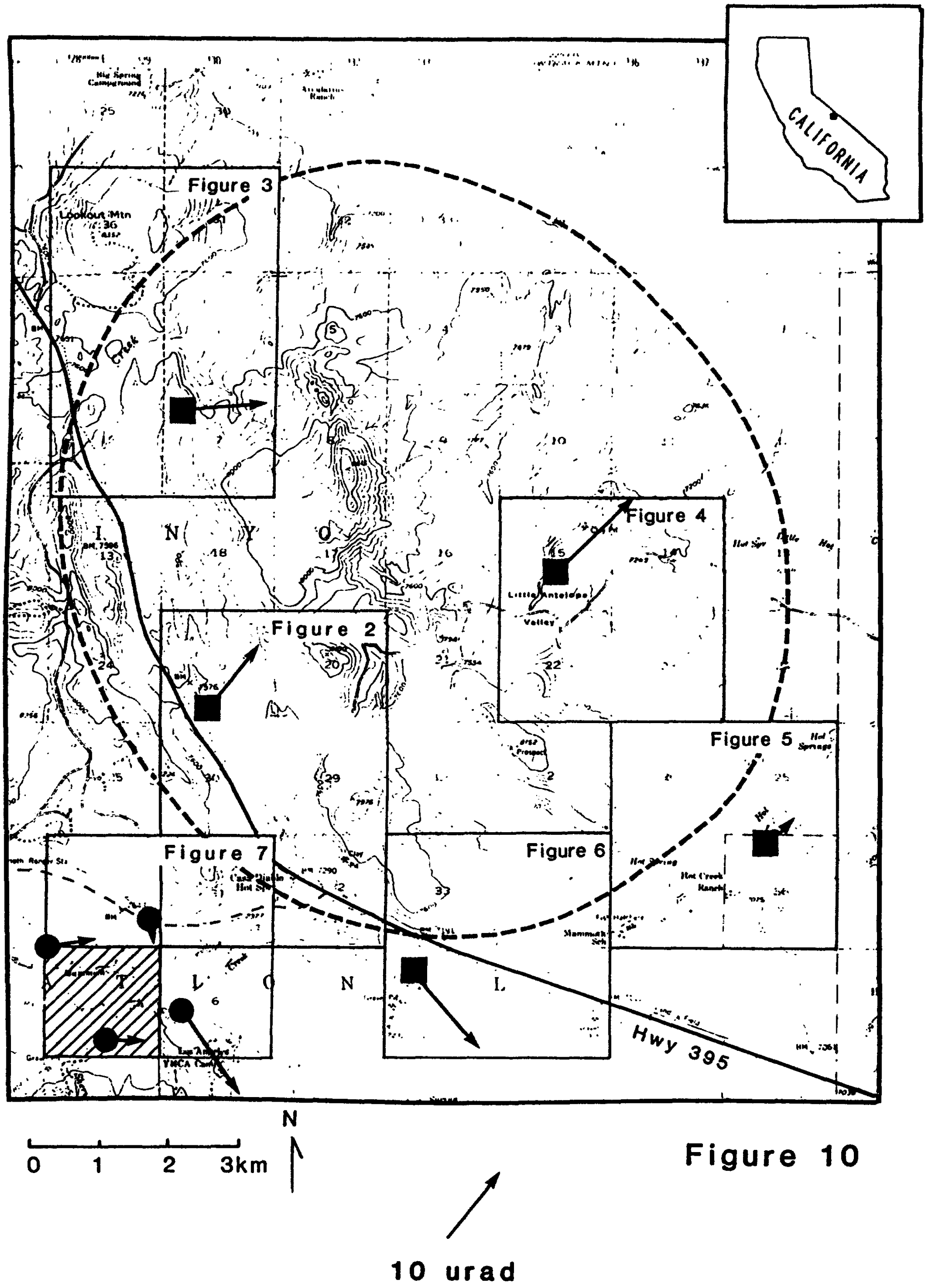


Figure 10