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Crustal Tilt in Long Valley, California

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<u>Final Technical Report</u>

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by

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ABSTRACT

Three of 13 dry tilt records over a two-year period in Long Valley are clearly contaminated by thermoelastic expansion and contraction of the bench mark fundament where bench marks are placed on large protruding outcrops. In response to an annual temperature differential of 25°C, typical for Long Valley, thermoelastically-induced volume changes of protruding bedrock exposures produce tilts as great as 17 microradians over a 40 m baseline, equivalent in magnitude to systematic fluctuations of tilt observed in the three dry tilt arrays where one or two of the three bench marks of the array are on large, protruding outcrops of rhyolite or basalt. The overall effect generally cancels in 11 resurveys of the arrays, and a weak pattern of tilt remains for the 13 arrays as a whole. The tilt is directed outward from a northwest-southeast line nearly parallel to and coincident with the southwest perimeter of the caldera's resurgent dome. Most of the tilts are small and near the theoretical error limit of the measurement method itself. The largest are south-down tilts in three arrays in the moat of the caldera south of the resurgent dome. The tilts are uniform in time and consistent in space and magnitude with geodetic measurements of surface tilting by tiltmeters and leveling.

INTRODUCTION

The Mammoth Lakes area in east-central California has experienced increased seismicity and ground deformation since 1978, and especially since May 1980 when four M 6 earthquakes occurred in three days (Ryall and Ryall, 1981). At about the same time, a broad uplift of the caldera floor raised the possibility and concern that the area was building toward a volcanic eruption (Savage and Clark, 1982). Recurrent seismic swarms during June 1980-May 1982 heightened the concern and prompted intensified geophysical monitoring of the activity. As part of that effort, sponsored by the Volcanic Hazards Program of the U.S. Geological Survey (USGS), a network of 13 dry tilt sites were established in and around the caldera in May and July 1982 by the Cascades Volcano Observatory and by us at UCSB (Dzurisin and others, 1982). This report represents baseline data for the network together with results and interpretations pertaining to resurveys through 1984.

Initially included in the USGS Monitoring program were leveling, trilateration, seismic refraction and precision gravity measurements. The dry tilt network was established to supplement this program with an inexpensive deformation monitor which could be measured frequently, if necessary.

Dry tilt is an optical leveling technique used to monitor inflation prior to eruptions at several active volcanoes (Kinoshita et al., 1974; Fiske, 1977; Lipman et al., 1981; Yamashita, 1981; Dzurisin et al., 1982; Otway and others, 1984). The method uses a precision optical spirit level in the center of an array of three precision leveling rods set on each of three or more permanent bench marks geometrically arranged at the apices of an equilateral triangle having side lengths of from 30 to 40 m (Kinoshita et al., 1974; Sylvester, 1978; Yamashita, 1981). Tilt vectors are calculated from differential height changes among the three bench marks.

Field experience elsewhere shows that the detection limit for meaningful ground tilts by this technique under ideal conditions ranges from 5 to 10 microradians, even though greater precision may be indicated by formal error estimates (Savage et al., 1979; Decker et al., 1983; Otway and others, 1984). The variation in tilt depends to a large degree on the kind and stability of bench marks (Sylvester, 1983) as shown in this report (Appendix II).

LONG VALLEY TILT NETWORK

Locations of the dry tilt arrays are shown together in Figure 1 and individually in Figures 2 through 11. Data pertaining to the commencement of measurements and the number of surveys at each array are given in Table 1.

Each array consists of a triangular primary bench mark array from 20 m to 40 m on a side, with an associated redundancy array also triangular in geometry (Fig. 12; Appendix I). Both the primary and redundancy arrays share a common instrument point, and each is surveyed separately.

By convention the southernmost primary bench mark is designated X; bench marks Y and Z are assigned sequentially in a counterclockwise direction (Sylvester, 1978; Yamashita, 1981); in the redundancy array, A is southernmost, B and C are assigned sequentially and counterclockwise.

Three types of benchmarks have been established in the Long Valley dry tilt network:

1) Standard 10 cm diameter, 0.5 cm thick bronze tablets cemented on to available rock outcrops;

2) 10 cm long, 2 cm diameter, stainless steel rods epoxied into holes drilled into rock outcrops and boulders in glacial moraine and outwash;

3) Coupled steel rods, 1 cm diameter, driven to refusal in alluvium and volcanic pumice (class B rod mark in the terminology of Floyd, 1978).

These bench marks are set in three types of fundament:

1) Large, protruding outcrops of basalt and rhyolite;

2) Low-lying outcrops or large, low-lying boulders surrounded by unconsolidated sediment and soil;

3) Unconsolidated soil, alluvium, and volcanic pumice.

BASELINE MEASUREMENTS

The USGS dry tilt arrays were first measured on 8 May 1982, using Wild NA-2 level #459655, Wild GPM-3 optical micrometer #27826, and Wild GPLE-3 precise invar level rod pair CVD-1A/B. Initial measurements at the UCSB arrays were made on 8-9 July 1982, 15 December 1982 (REST AREA), 25 June 1983 (ESCAPE ROUTE), and 28 June 1983 (CONVICT, INYO CRATERS). Redundancy arrays were established at all 13 arrays and surveyed initially in the period 25-28 June 1983. The UCSB surveys used Wild NAK-2 level #381882, Wild GPM-3 optical micrometer #25926, and three Wild GPL-3 precise invar level rods, #2207A, 2207B and 4003A.

Equations for calculating tilt from measured height changes at each array are given in Tables 2 and 3; baseline height measurements and estimated uncertainties are listed in Tables 4 and 5.

The primary arrays have been surveyed from 4 to 11 times in the period 7 May 1982 to 12 July 1984 (Table 1). Redundancy arrays have been surveyed four times each in the period 25 June 1983 to 12 July 1984.

RESULTS

Synoptic diagrams of tilt changes from baseline measurements to July 1984 are plotted for each array in Figure 13. Study of these figures reveals some noteworthy generalizations:

1) Primary arrays south of the resurgent dome (CASA DIABLO, LAUREL, HARDING), tilt southward from 15 to 25 microradians.

2) Primary arrays on glacial moraine southwest of the resurgent dome tilt negligibly (SECTION CORNER, VOORHIS) or southwestward up to 15 microradians (SEWAGE PLANT).

3) Primary arrays in the middle of the resurgent dome (TUFF LUCK, CLAY PIT) and west of it (ESCAPE ROUTE, INYO CRATERS, REST AREA) tilt negligibly or to the southwest.

4) Primary arrays southwest of the resurgent dome up to 20 microradians.

5) Tilt vectors for redundancy arrays show reasonably good correspondence with those of primary arrays where the tilts are small (REST AREA, INYO CRATERS, SECTION CORNER, SEWAGE PLANT, VOORHIS), especially in the last two surveys when, presumably, the newer redundancy arrays have achieved environmental equilibrium (Fig. 13).

6) Primary and redundancy tilt vectors are not comparable at arrays where bench marks are diverse in type (CASA DIABLO, CONVICT, LAUREL). Disparate tilts at TUFF LUCK, HOT CREEK AND HARDING are too small to be significant.

BENCH MARK MOTIONS

The main tilt discrepancies exist between primary arrays and redundancy arrays, especially where bronze tablet bench marks are cemented on the surface of high, protruding bedrock outcrops (Fig. 13). Although some of the arrays (e.g. CASA DIABLO) are centered over the crest of the postulated intrusion and may be expected to be quite variable, and although others are located near (active?) faults (CASA DIABLO, TUFF LUCK, HOT CREEK), the tilt fluctuations from survey to survey are exactly in the direction toward and away from the bench marks on the high, protruding outcrops. Tilts are more nearly unidirectional where all bronze tablets of an array are on protruding bedrock outcrops (LAUREL, HOT CREEK). From this I conclude that the tilt records for protruding outcrops are contaminated by thermoelastic expansion and contraction from diurnal heating and cooling of the bedrock.

Analysis of the thermoelastic effects (Appendix II) shows that motion of a bench mark on a protruding outcrop may produce a tilt of 17 microradians over a 40 m baseline for a peak to peak annual temperature differential of 25^{o}C, which is typical of the Long Valley area. That is equal to some of the fluctuations we observe at the arrays having bronze tablet bench marks on large protruding outcrops. Diurnal variations produce much smaller motions which yield smaller tilts of from 1 to 2 microradians (Appendix II). A representative value for bench mark instability is 0.25 mm (Savage and others, 1979) which corresponds to 6 microradians of tilt over a 40 m baseline, if the instability is differential.

By contrast, at arrays where bench marks are short rods cemented into low boulders imbedded in glacial moraine, or class B rod marks driven to refusal in alluvium or tephra, tilt is much less variable; in fact, it is right at the error limit of the method. Unconsolidated materials, such as alluvium or moraine have a lower coefficient of expansion than bedrock (Kappelmeyer and Haenel, 1974), and therefore, are preferable materials for siting bench marks. Low boulders and class B rod marks are insulated from extreme diurnal temperature fluctuations by the unconsolidated soil, sand, gravel and vegetation. Wherever possible, it is best in an array to make each bench mark of the same type to assume homogeneity of thermoelastic response.

DISCUSSION

The dry tilt data have a relatively low signal to noise ratio in Long Valley caldera during the two year period of surveys, although records at some sites are contaminated by as much as 17 microradians of thermoelastically-induced bedrock motion. Addition of redundancy arrays complicates the interpretation of tilt in Long Valley considerably, at least at these low noise levels, because of variable kinds of ages of bench marks involved in comparison of resurveys.

A conservative conclusion is that the data are too noisy at the level close to the theoretical error level to be significant.

A more liberal interpretation is that data from the older, primary arrays show a local, asymmetric uplift centered on the southwest perimeter of the resurgent dome (Fig. 14). The location, asymmetry and size of the uplift inferred from the dry tilt data are consistent with conclusions from geodetic data drawn by other investigators (Denlinger and Riley, 1984; Rundle and Whitcomb, 1984; Savage and Cockerham, 1984) in that they indicate a trap-door mechanism of uplift about a northwest-southeast axis nearly parallel to and coincident with Highway 395 along the southwest edge of the resurgent dome (Fig. 14). Thus, according to the dry tilt data, the northeast side tilted hardly at all relative to the southwest side which has tilted southward nearly 40 microradians in two years. It must be emphasized, however, that this conclusion must be tempered with the fact that the observed tilts may be contaminated with non-tectonic thermoelastic effects of as much as 17 microradians.

The dry tilt method is not suited, nor was it ever intended, to monitor minor changes such as those in Long Valley in 1982-84. This study shows that minor, thermoelastically-induced bench mark motions may contaminate observed tilts, thus giving a questionable tilt at best and a false tilt at the worst.

The utility of the study to date and of the accumulated measurements is that they provide baseline data for the time when and if a volcanic eruption does begin to build, resulting in large and rapidly changing tilt. Then the dry tilt method will be a relatively inexpensive and frequent monitor of volcanotectonic activity.

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NOTE ADDED IN PRESS

A resurvey of all arrays was done in July 1985, and a new array was established and surveyed in Long Canyon on the south flank of the resurgent dome, nearly midway between Casa Diablo, Clay Pit, Laurel and Hot Creek arrays (Fig. 1). Station equations and baseline measurement data are given in Tables 3 and 5, respectively.

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TABLE 1.

UCSB/USGS DRY TILT ARRAYS -- LONG VALLEY

NAME	LATITUDE	LONGITUDE	QUADRANGLE	INITIAL SURVEY	MOST RECENT SURVEY	TOTAL # SURVEYS
Rest Area	37°43.88	118°58.02	Mt. Morrison	12/82	7/85	7
Tuff Luck	37°42.39	118°55.89	Mt. Morrison	5/82	7/85	12
Clay Pit	37°41.14	118°52.47	Mt. Morrison	5/82	7/85	12
Long Canyon	37°39.73	118°58.27	Mt. Morrison	7/85	7/85	1
Escape Route	37°39.72	118°59.07	Mt. Morrison	6/83	7/85	5
Casa Diablo	37°39.13	118°55.00	Mt. Morrison	5/82	7/85	12
Sewage Plant	37°38.43	118°56.25	Mt. Morrison	7/82	7/85	11
Section Corner	37°38.23	118°52.18	Mt. Morrison	7/82	7/85	11
Voorhis	37°37.50	118°56.67	Mt. Morrison	7/82	7/85	11
Harding	37°37.63	118°55.88	Mt. Morrison	7/82	7/85	11
Laurel	37°37.99	118°53.63	Mt. Morrison	5/82	7/85	12
Hot Creek	37°39.02	118°50.21	Mt. Morrison	5/82	7/85	12
Convict	37°33.83	118°47.07	Mt. Morrison	6/83	7/85	5

TABLE 2.

USGS LONG VALLEY STATION EQUATIONS

Station	Primary	Redundancy
Casa Diablo		
	(N) = +0.3275 (Y-X) - 0.0414 (X-Z)	(N) = +0.4078 (B-A) +0.1737 (A-C)
	(E) = +0.2047 (Y-X) + 0.2945 (X-Z)	(E) = +0.0719 (B-A) +0.2747 (A-C)
Tuff Luck		
	(N) = -0.1188 (Y-X) - 0.3061 (X-Z)	(N) = -0.0193 (B-A) -0.3683 (A-C)
	(E) = +0.3094 (Y-X) + 0.0707 (X-Z)	(E) = +0.3683 (B-A) +0.1759 (A-C)
Clay Pit		
	(N) = +0.1086 (Y-X) - 0.2326 (X-Z)	(N) = +0.4895 (B-A) -0.0527 (A-C)
	(E) = +0.2557 (Y-X) - 0.2494 (X-Z)	(E) = +0.2078 (B-A) +0.2990 (A-C)
Hot Creek		
	(N) = +0.2312 (Y-X) - 0.0098 (X-Z)	(N) = +0.1408 (B-A) -0.1384 (A-C)
	(E) = +0.2010 (Y-X) + 0.2814 (X-Z)	(E) = +0.3019 (B-A) +0.3260 (A-C)
Laurel		
	(N) = +0.0624 (Y-X) - 0.2631 (X-Z)	(N) = +0.2447 (B-A) -0.2286 (A-C)
	(E) = +0.4441 (Y-X) + 0.2733 (X-Z)	(E) = +0.3915 (B-A) +0.3034 (A-C)

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

TABLE 3.

UCSB LONG VALLEY STATION EQUATIONS

Station	Primary	Redundancy
Section Corner		
	(N) = +0.0547 (Y-X) - 0.0027 (X-Z)	(N) = +0.1273 (B-A) -0.2021 (A-C)
	(E) = +0.3456 (Y-X) + 0.2202 (X-Z)	(E) = +0.3151 (B-A) +0.2781 (A-C)
Voorhis		
	(N) = -0.0290 (Y-X) - 0.2981 (X-Z)	(N) = +0.0776 (B-A) -0.2587 (A-C)
	(E) = +0.3324 (Y-X) + 0.1390 (X-Z)	(E) = +0.3112 (B-A) +0.2679 (A-C)
Harding		
	(N) = -0.0299 (Y-X) - 0.2871 (X-Z)	(N) = +0.1206 (B-A) -0.2116 (A-C)
	(E) = +0.3415 (Y-X) + 0.1463 (X-Z)	(E) = +0.3314 (B-A) +0.2913 (A-C)
Sewage Plant		
	(N) = +0.1701 (Y-X) - 0.1479 (X-Z)	(N) = +0.2550 (B-A) -0.0655 (A-C)
	(E) = +0.2831 (Y-X) + 0.2902 (X-Z)	(E) = +0.2296 (B-A) +0.3368 (A-C)
Rest Area		
	(N) = 0.1390 (Y-X) - 0.1950 (X-Z)	(N) = +0.2590 (B-A) -0.0579 (A-C)
	(E) = 0.2990 (Y-X) + 0.2780 (X-Z)	(E) = +0.2251 (B-A) +0.3282 (A-C)
Convict		
	(N) = +0.1967 (Y-X) - 0.1381 (X-Z)	(N) = +0.0241 (B-A) -0.0764 (A-C)
	(E) = +0.2708 (Y-X) + 0.3102 (X-Z)	(E) = +0.2250 (B-A) +0.3309 (A-C)
Escape Road		
	(N) = +0.1783 (Y-X) - 0.1543 (X-Z)	(N) = +0.2865 (B-A)
	(E) = +0.2967 (Y-X) + 0.2902 (X-Z)	(E) = +0.1524 (B-A) +0.3485 (A-C)
Inyo Craters		
	(N) = +0.2415 (Y-X) - 0.0852 (X-Z)	(N) = +0.3233 (B-A) +0.1008 (A-C)
	(E) = +0.2252 (Y-X) + 0.3180 (X-Z)	(E) = +0.0570 (B-A) +0.3104 (A-C)
Long Canyon		
	(N) = +0.2890 (Y-X) - 0.2890 (X-Z)	(N) = +0.3286 (B-A) -0.2145 (A-C)
	(E) = +0.1669 (Y-X) + 0.1669 (X-Z)	(E) = +0.580 (B-A) +0.2557 (A-C)

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

TABLE 4.

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±.044
Hot Creek	+163.209±.010	-162.175±.006	-1.034±.013
Laurel	+21.697±.003	-82.479±.012	+60.782±.007

BASELINE MEASUREMENTS
REDUNDANCY
26-27 JUNE 1983

DATE	STATION	B-A	A-C	C-B
26 June 83	Casa Diablo	-204.843±.001 cm	+074.681±.003 cm	+130.162±.002 cm
26 June 83	Tuff Luck	+058.604±.003	+164.215±.002	-222.819±.001
27 June 83	Clay Pit	-205.844±.002	+151.660±.002	+054.184±.002
26 June 83	Hot Creek	+070.484±.005	-099.489±.003	+029.005±.004
27 June 83	Laurel	+043.176±.003	-125.834±.003	+082.658±.002

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

TABLE 5.

UCSB LONG VALLEY TILT STATIONS
BASELINE MEASUREMENTS
PRIMARY

DATE	STATION	Y-X	X-Z	Z-Y
9 July 82	Section Corner	-67.456±.002	+125.640±.001	-58.184±.002
9 July 82	Voorhis	+48.027±.003	+117.949±.002	-165.976±.003
9 July 82	Harding	+100.502±.003	+32.696±.003	-133.198±.004
9 July 82	Sewage Plant	+118.825±.002	+79.526±.004	-198.351±.002
15 Dec. 82	Rest Area	+024.027±.002	-109.503±.005	+085.476±.000
28 June 83	Convict	+217.377±.002	-056.708±.005	-160.669±.002
25 June 83	Escape Road	-195.201±.005	+014.328±.004	+180.873±.004
22 June 83	Inyo Craters	+068.594±.002	-212.992±.004	+144.398±.003
10 July 85	Long Canyon	+036.335±.001	+047.993±.002	-084.328±.002

BASELINE MEASUREMENTS
REDUNDANCY

DATE	STATION	B-A	A-C	C-B
27 June 83	Section Corner	-100.157±.003	+147.625±.004	-047.468±.002
27 June 83	Voorhis	+053.876±.005	+080.209±.001	-134.085±.001
25 June 83	Harding	+066.021±.003	+008.849±.001	-074.870±.005
27 June 83	Sewage Plant	+049.341±.002	+161.828±.002	-211.169±.003
26 June 83	Rest Area	+038.175±.004	-087.624±.005	+049.449±.002
28 June 83	Convict	+222.102±.001	-073.070±.004	-149.032±.003
25 June 83	Escape Road	-153.068±.004	-047.967±.003	+201.035±.003
22 June 83	Inyo Craters	+126.084±.005	-152.985±.005	+26.901±.005
10 July 85	Long Canyon	+017.920±.002	+067.067±.003	-084.987±.002

TABLE 6.

TILT CHANGES

BASELINE MEASUREMENTS -- 10-12 JULY 1984

PRIMARY ARRAYS

STATION	Y-X	X-Z	Z-Y	TILT	AZIMUTH
Casa Diablo	-268.278±.001	+211.119±.003	+57.159±.002	44.6 μrad	S03W
Tuff Luck	+247.848±.001	+29.249±.002	-277.097±.004	1.8 μrad	N24E
Clay Pit	-255.261±.003	+243.648±.003	+11.613±.001	7.1 μrad	S43W
Hot Creek	+163.207±.004	-162.137±.001	-1.070±.004	10.3 μrad	S85E
Laurel	+21.632±.003	-82.390±.002	+60.758±.005	27.8 μrad	S09W
Section Corner	-67.469±.002	+125.643±.003	-58.174±.006	3.9 μrad	S79W
Voorhis	+48.004±.004	+117.983±.002	-165.987±.003	9.9 μrad	S17W
Harding	+100.425±.004	+32.813±.004	-133.238±.006	32.6 μrad	S16W
Sewage Plant	+118.750±.003	+79.557±.003	-198.306±.003	21.2 μrad	S35W
Convict	+217.481±.002	-56.682±.003	-160.799±.002	40.0 μrad	N62E
Rest Area	+23.969±.005	-109.512±.002	+85.543±.005	6.8 μrad	S21W
Escape Road	-195.245±.001	+14.361±.004	+180.884±.005	13.4 μrad	S15W
Inyo Craters	+68.555±.005	-212.993±.004	+144.438±.004	13.0 μrad	S44.3W

Stated uncertainties are ± 1 standard deviation, calculated from at least 3 left/right measurements of height difference between each bench mark pair.

TABLE 7.

TILT CHANGES

BASELINE MEASUREMENTS -- 10-12 JULY 1984

REDUNDANCY ARRAYS

STATION	B-A*	A-C*	C-B*	TILT	AZIMUTH
Casa Diablo	-204.772±.003	+74.658±.002	+130.114±.001	25 μrads	N03W
Tuff Luck	+58.611±.002	+164.232±.002	-222.843±.006	9 μrads	S40E
Clay Pit	-205.876±.003	+151.668±.002	+54.208±.005	17 μrads	S15W
Hot Creek	+70.472±.003	-99.511±.003	+29.039±.003	11 μrads	S86W
Laurel	+43.234±.005	-125.827±.004	+82.593±.002	28 μrads	N63E
Section Corner	-100.172±.002	+147.622±.003	-47.550±.005	6 μrads	S79W
Voorhis	+53.853±.003	+80.240±.004	-134.093±.003	26 μrads	S03E
Harding	+65.975±.005	+8.851±.005	-74.826±.002	16 μrads	S68W
Sewage Plant	+49.314±.003	+161.833±.003	-211.147±.001	9 μrads	S32W
Convict	+222.231±.003	-73.136±.002	-149.095±.003	11 μrads	N41E
Rest Area	+38.160±.002	-87.627±.005	-49.467±.001	6 μrads	S50W
Escape Road	-153.105±.005	-47.970±.001	+201.075±.002	11 μrads	S32W
Inyo Craters	+126.090±.007	-153.003±.003	+26.913±.003	17 μrads	S18W

Stated uncertainties are ± 1 standard deviation, calculated from at least 3 left/right measurements of height difference between each bench mark pair.

TABLE 8.

TILT CHANGES

14-16 OCTOBER 1983/10-12 JULY 1984

PRIMARY ARRAYS

STATION	Y-X*	X-Z*	Z-Y*	TILT	AZIMUTH
Casa Diablo	-268.278±.001	+211.119±.003	+57.159±.002	5.3 μrad	S35E
Tuff Luck	+247.848±.001	+29.249±.002	-277.097±.004	15.0 μrad	N66E
Clay Pit	-255.261±.003	+243.648±.003	+11.613±.001	9.6 μrad	N52W
Hot Creek	+163.207±.004	-162.137±.001	-1.070±.004	2.1 μrad	S72W
Laurel	+21.632±.003	-82.390±.002	+60.758±.005	6.9 μrad	S22W
Section Corner	-67.469±.002	+125.643±.003	-58.174±.006	1.5 μrad	S80W
Voorhis	+48.004±.004	+117.983±.002	-165.987±.003	0.6 μrad	N36E
Harding	+100.425±.004	+32.813±.004	-133.238±.006	8.5 μrad	S35W
Sewage Plant	+118.750±.003	+79.557±.003	-198.306±.003	6.4 μrad	S50E
Convict	+217.481±.002	-56.682±.003	-160.799±.002	21.7 μrad	N69E
Rest Area	+23.969±.005	-109.512±.002	+85.543±.005	5.4 μrad	N74W
Escape Road	-195.245±.001	+14.361±.004	+180.884±.005	2.4 μrad	N45E
Inyo Craters	+68.555±.005	-212.993±.004	+144.438±.004	11.2 μrad	S23.3W

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

*Height differences measured 10-12 July 1984. See Tables 4 and 5 for baseline measurements.

TABLE 9.

TILT CHANGES

14-16 OCTOBER 1983/10-12 JULY 1984

REDUNDANCY ARRAYS

STATION	B-A*	A-C*	C-B*	TILT	AZIMUTH
Casa Diablo	-204.772±.003	+74.658±.002	+130.114±.001	19.6 μrad	N31W
Tuff Luck	+58.611±.002	+164.232±.002	-222.843±.006	5.3 μrad	S48W
Clay Pit	-205.876±.003	+151.668±.002	+54.208±.005	6.0 μrad	N29W
Hot Creek	+70.472±.003	-99.511±.003	+29.039±.003	26.0 μrad	N81W
Laurel	+43.234±.005	-125.827±.004	+82.593±.002	7.7 μrad	S18W
Section Corner	-100.172±.002	+147.622±.003	-47.550±.005	2.6 μrad	N28W
Voorhis	+53.853±.003	+80.240±.004	-134.093±.003	6.5 μrad	N36W
Harding	+65.975±.005	+8.851±.005	-74.826±.002	12.0 μrad	N32W
Sewage Plant	+49.314±.003	+161.833±.003	-211.147±.001	2.7 μrad	S68E
Convict	+222.231±.003	-73.136±.002	-149.095±.003	6.0 μrad	N55E
Rest Area	+38.160±.002	-87.627±.005	-49.467±.001	3.0 μrad	N70E
Escape Road	-153.105±.005	-47.970±.001	+201.075±.002	4.2 μrad	S74W
Inyo Craters	+126.090±.007	-153.003±.003	+26.913±.003	4.8 μrad	N42W

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

*Height differences measured 10-12 July 1984. See Tables 4 and 5 for baseline measurements.

FIGURE CAPTIONS

(1) Map showing locations of 13 dry tilt stations in Long Valley Caldera in 1982-83, together with locations of other tilt and strain measurement endeavors by the U.S. Geological Survey. Detailed location maps of the Long Valley tilt stations are given in Figures 2-11.

(2) Location map of CASA DIABLO tilt dry site.

(3) Location map of TUFF LUCK dry tilt site.

(4) Location map of CLAY PIT dry tilt site.

(5) Location map of HOT CREEK dry tilt site.

(6) Location map of LAUREL dry tilt site.

(7) Location map of SECTION CORNER, VOORHIS, HARDING, and SEWAGE PLANT dry tilt sites.

(8) Location map of REST AREA dry tilt site.

(9) Location map of INYO CRATERS dry tilt site.

(10) Location map of ESCAPE ROUTE dry tilt site.

(11) Location map of CONVICT dry tilt site.

(12) Dimensions and orientations of Long Valley dry tilt stations with primary array bench marks designated X, Y, Z and redundancy array bench marks designated A, B and C.

(13) Synoptic diagrams (upper) of tilt changes at Long Valley dry tilt arrays from the time the arrays were established (center of each diagram) to July 1984 (arrowheads). North is at the top of the diagrams, circles correspond to a conservative error envelope of 10 microradians. Primary arrays are shown as solid vectors, and redundancy arrays are dashed vectors. Geometry of tilt arrays is shown in lower diagrams; bench marks on high, protruding bedrock outcrops are indicated by the black dots. Note how CASA DIABLO, TUFF LUCK, and CLAY PIT tilt back and forth, perpendicular to the line connecting the black dots.

(14) Net tilt changes for Long Valley dry tilt primary arrays from the date of their establishment (Table 1) to July 1984. Arrowheads point down-tilt.

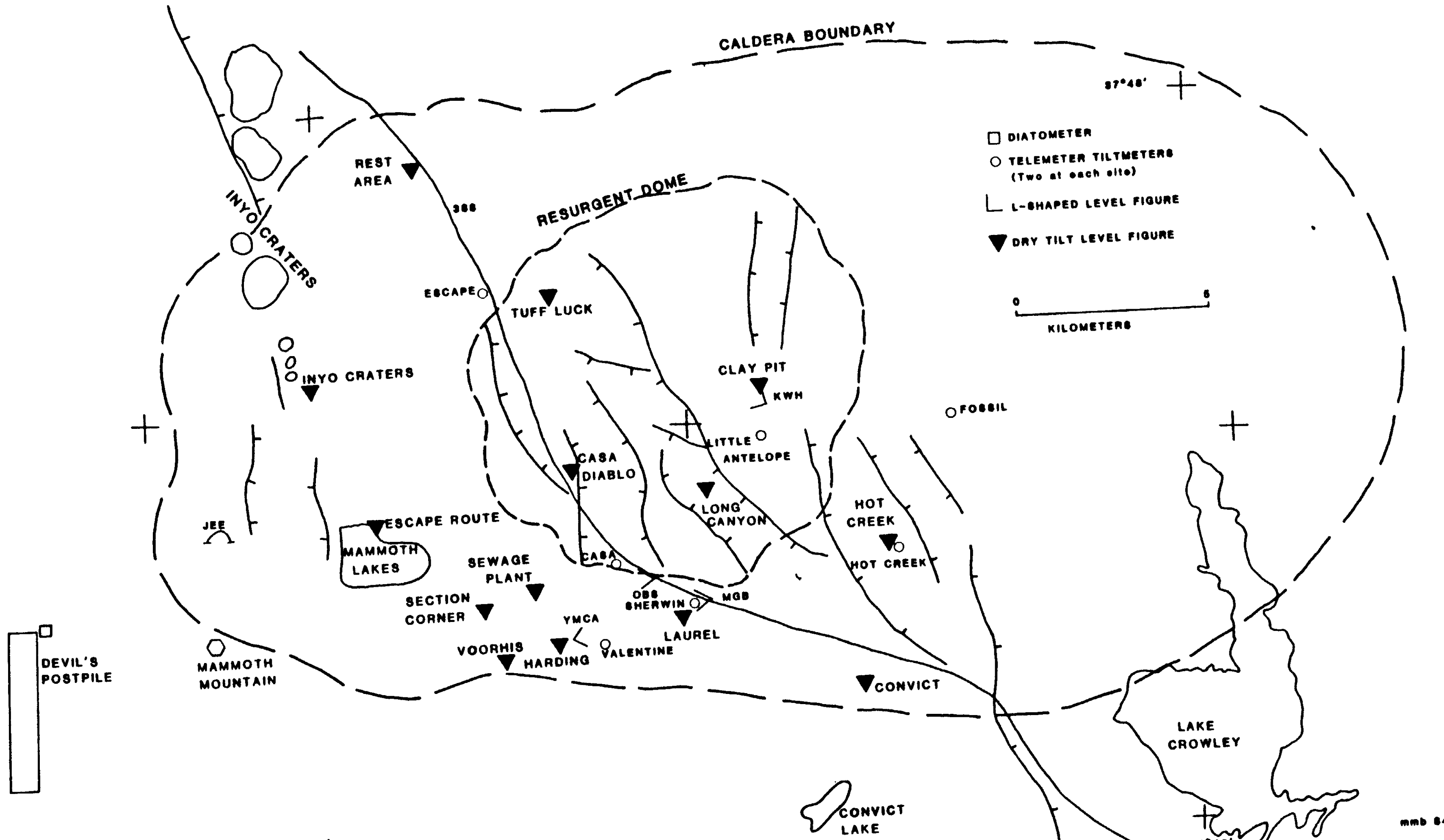

CALDERA BOUNDARY
RESURGENT DOME
37°48'
DIATOMETER
TELEMETER TILTMETERS (Two at each site)
L-SHAPED LEVEL FIGURE
DRY TILT LEVEL FIGURE
0
5
KILOMETERS
REST AREA
395
INYO CRATERS
ESCAPE
TUFF LUCK
INYO CRATERS
CLAY PIT
KWH
FOSSIL
LITTLE ANTELOPE
CASA DIABLO
LONG CANYON
HOT CREEK
HOT CREEK
JEE
ESCAPE ROUTE
MAMMOTH LAKES
SEWAGE PLANT
CASA
OBS
SHERWIN
MGB
SECTION CORNER
YMCA
LAUREL
VOORHIS
HARDING
VALENTINE
DEVIL'S POSTPILE
MAMMOTH MOUNTAIN
CONVICT
LAKE CROWLEY
CONVICT LAKE
37°36'
119°00'
118°45'
mmb 84

Fig. 1

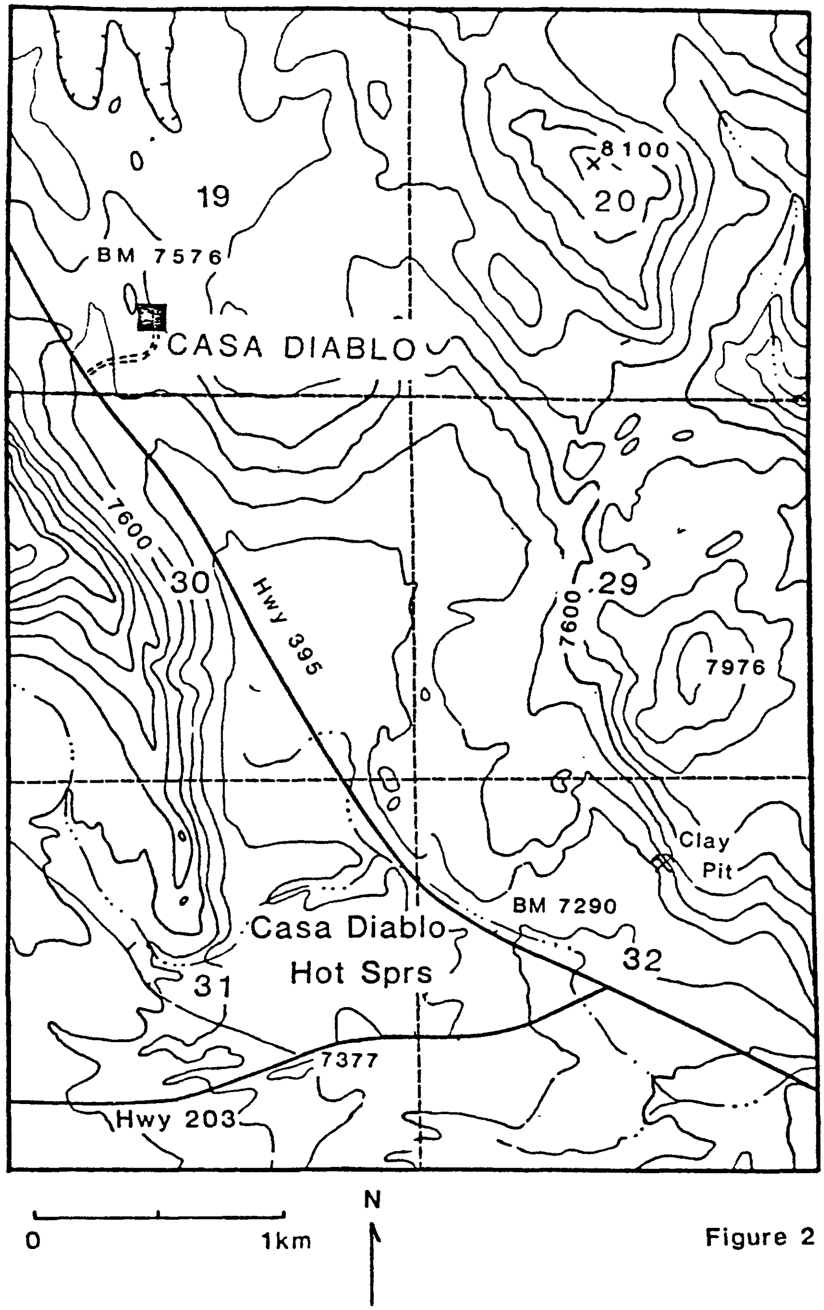
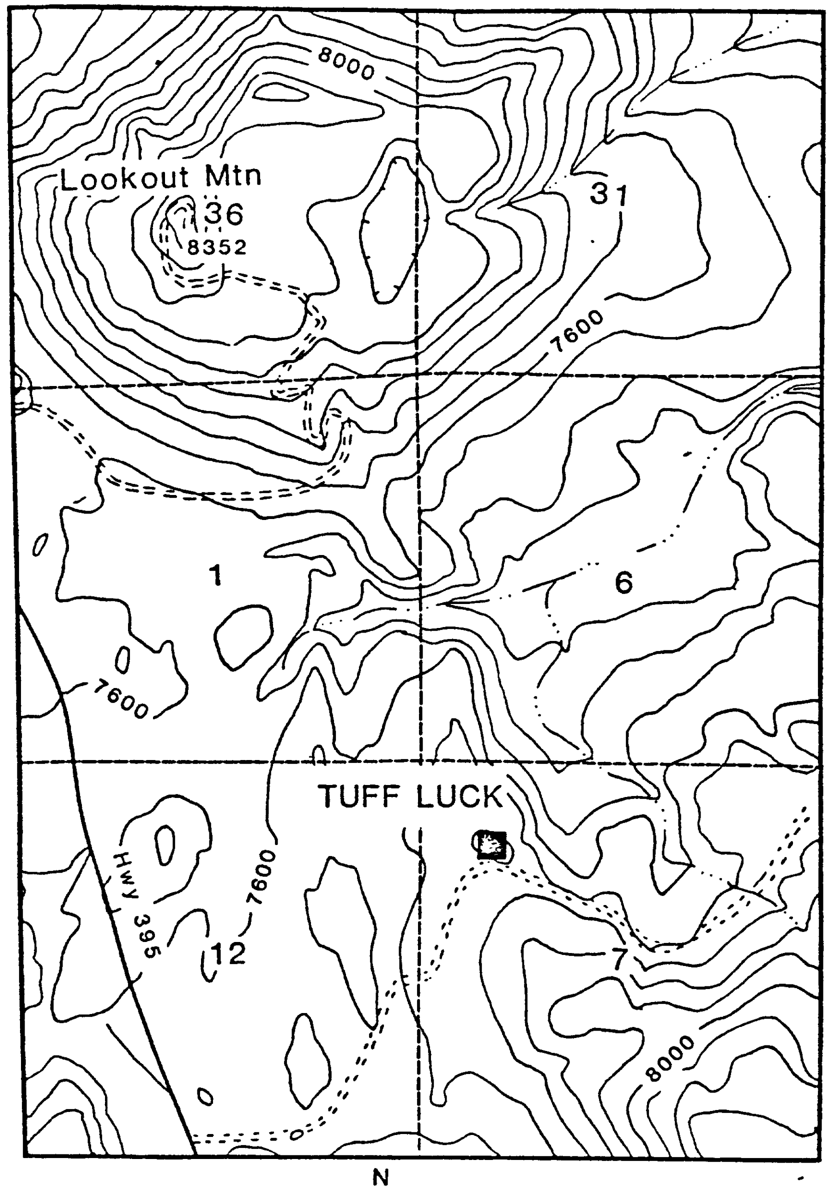

8100
19
20
BM 7576
CASA DIABLO
7600
30
Hwy 395
29
7600
7976
Clay
Pit
BM 7290
32
Casa Diablo
Hot Sprs
31
7377
Hwy 203
0
1km
N

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

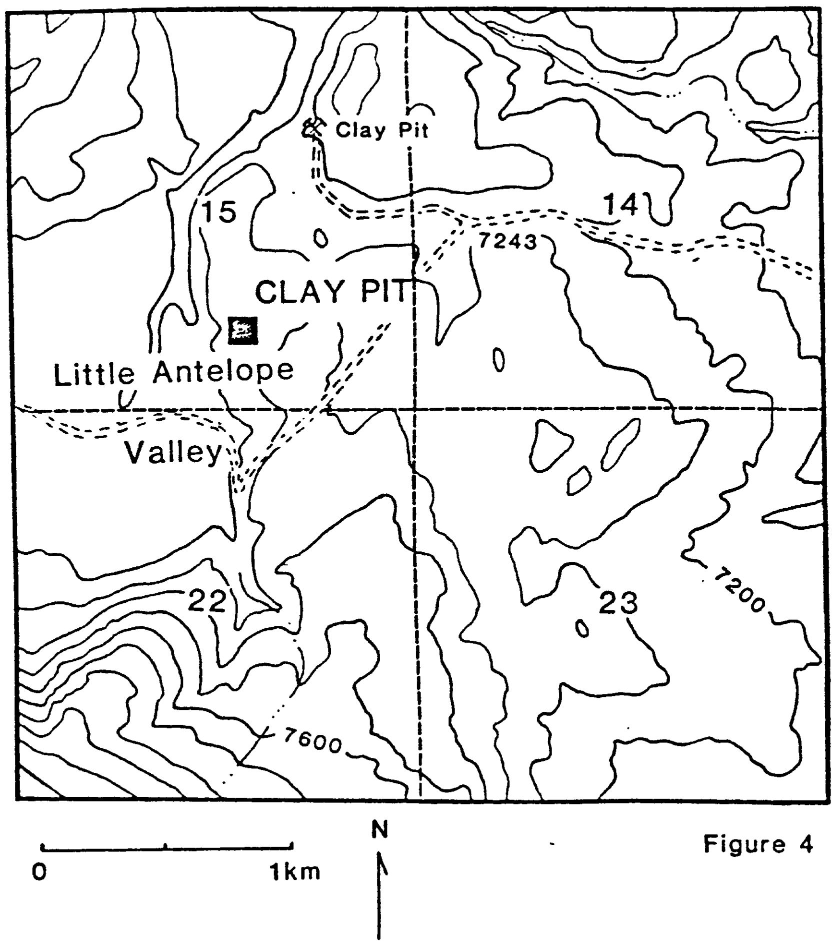

Clay Pit
15
14
7243
CLAY PIT
Little Antelope
Valley
22
23
7200
7600
0
1km
N

Figure 4

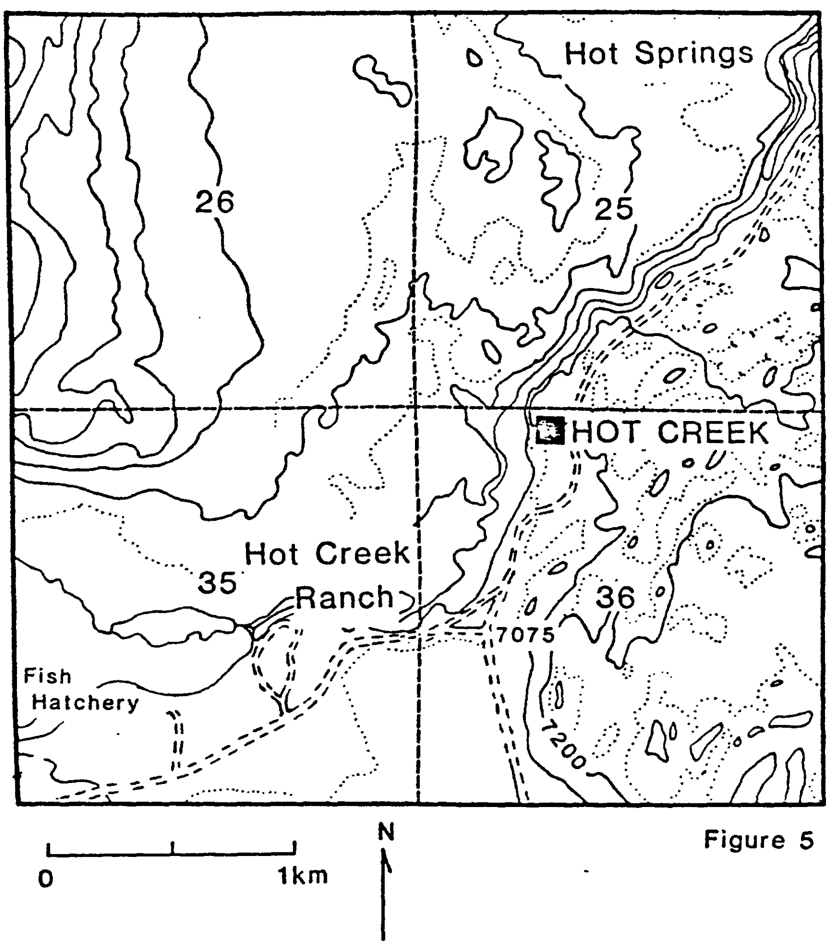

Hot Springs
26
25
HOT CREEK
Hot Creek
Ranch
35
36
7075
7200
Fish
Hatchery
0
1km
N

Figure 5

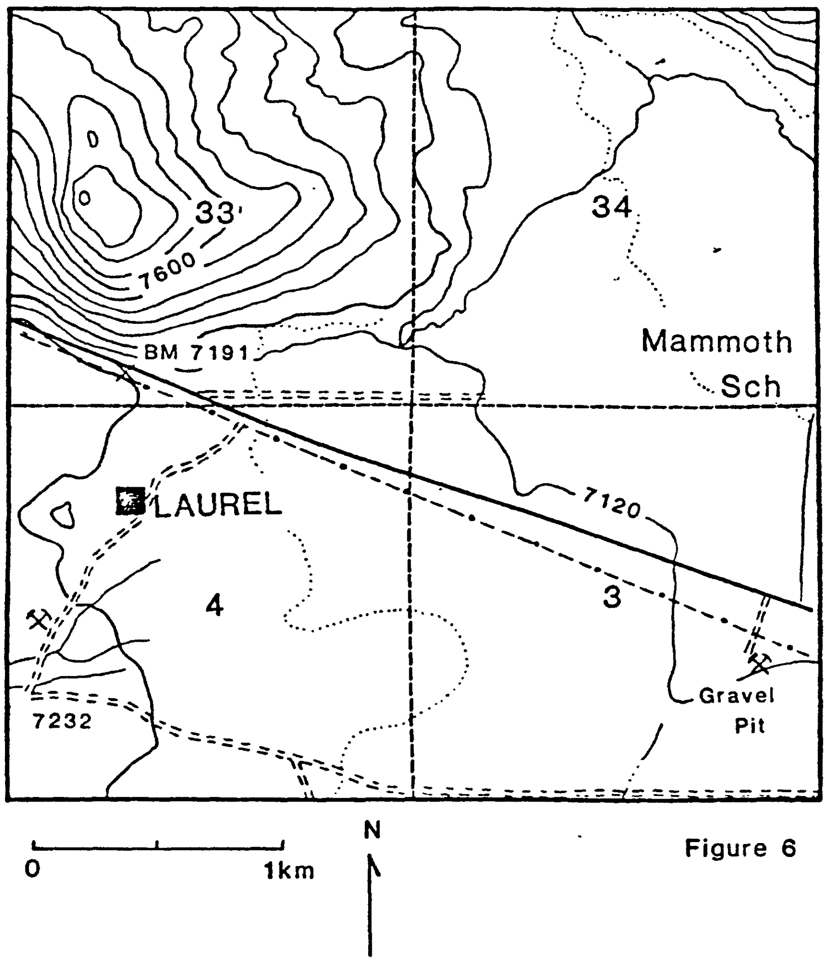

33
7600
34
BM 7191
Mammoth
Sch
LAUREL
7120
4
3
Gravel
Pit
7232
0
1km
N

Figure 6

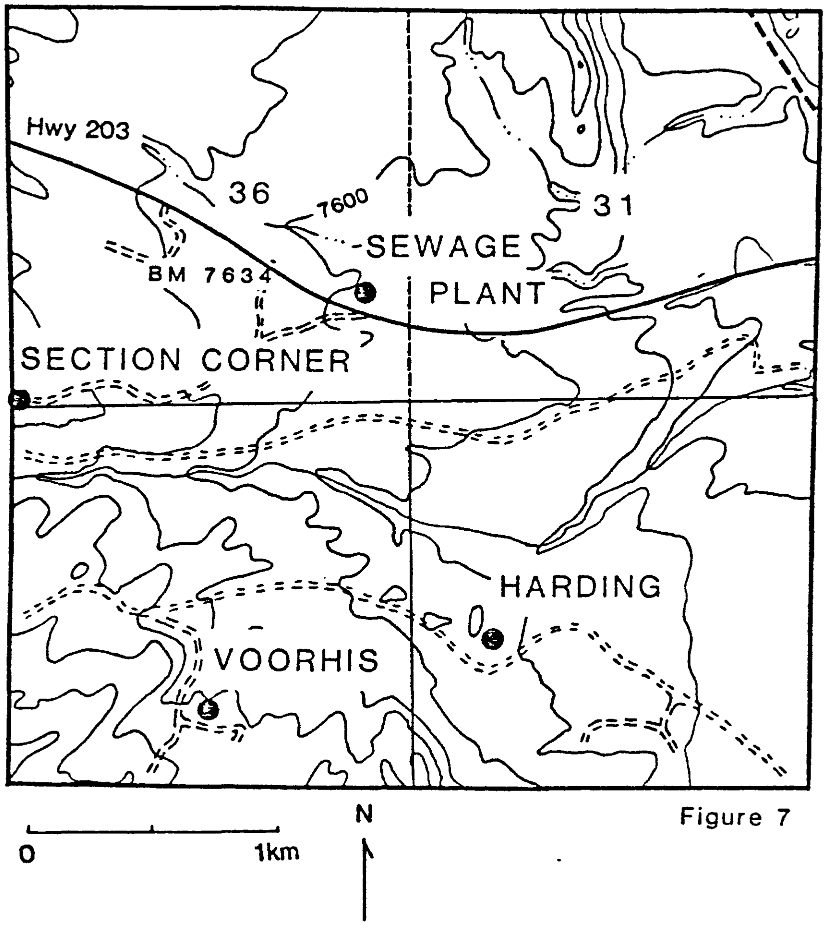

Hwy 203
36
7600
SEWAGE
PLANT
31
BM 7634
SECTION CORNER
HARDING
VOORHIS
0
1km
N

Figure 7

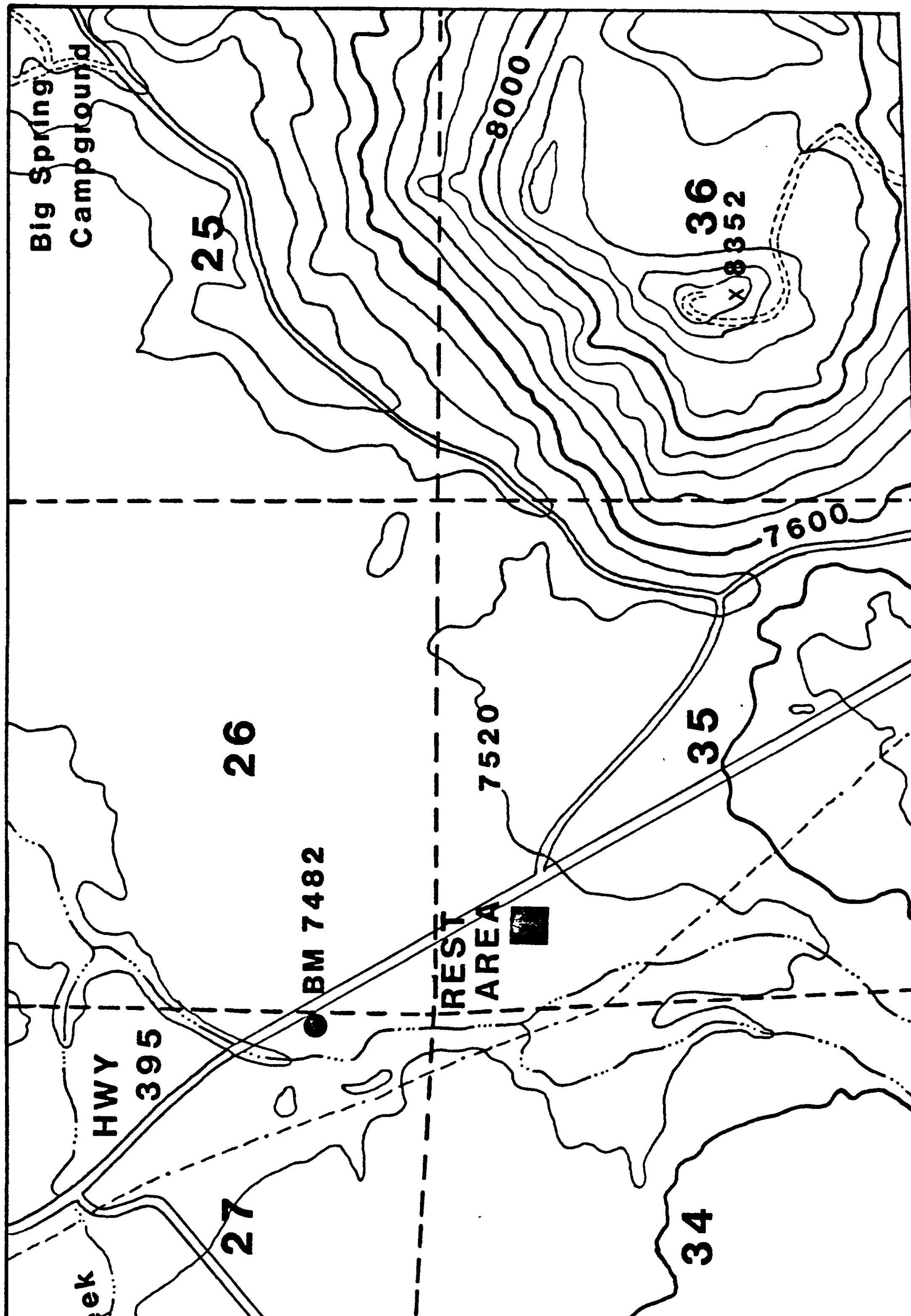

Big Spring Campground
25
26
27
34
35
36
8000
x 8352
7600
7600
7520
BM 7482
REST AREA
HWY 395
Deadman Creek
mmb 83
0
1 km
N

Fig. 8

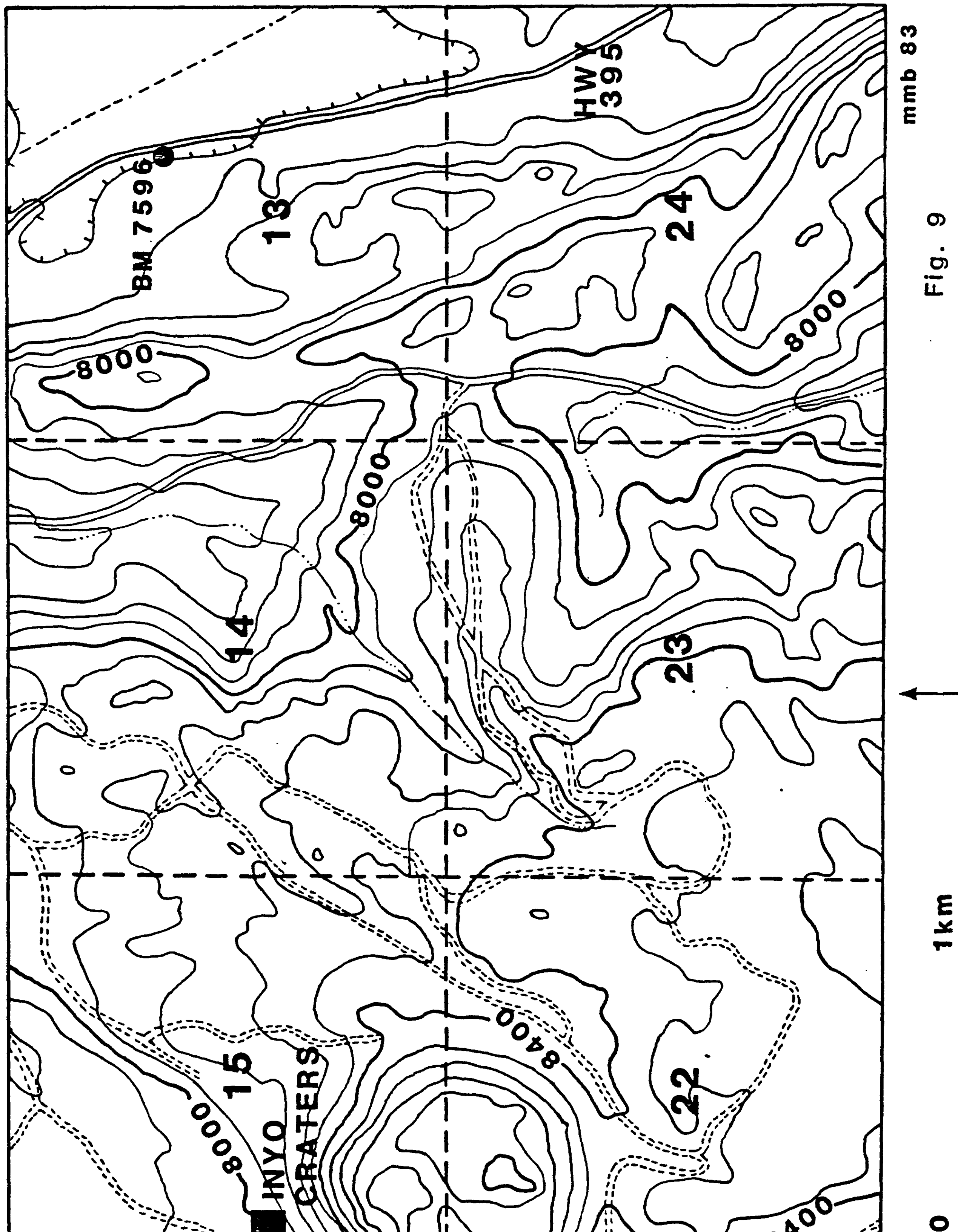

INYO CRATERS
BM 7596
HWY 395
13
14
15
22
23
24
8000
8400
N
0
1km
mmb 83

Fig. 9

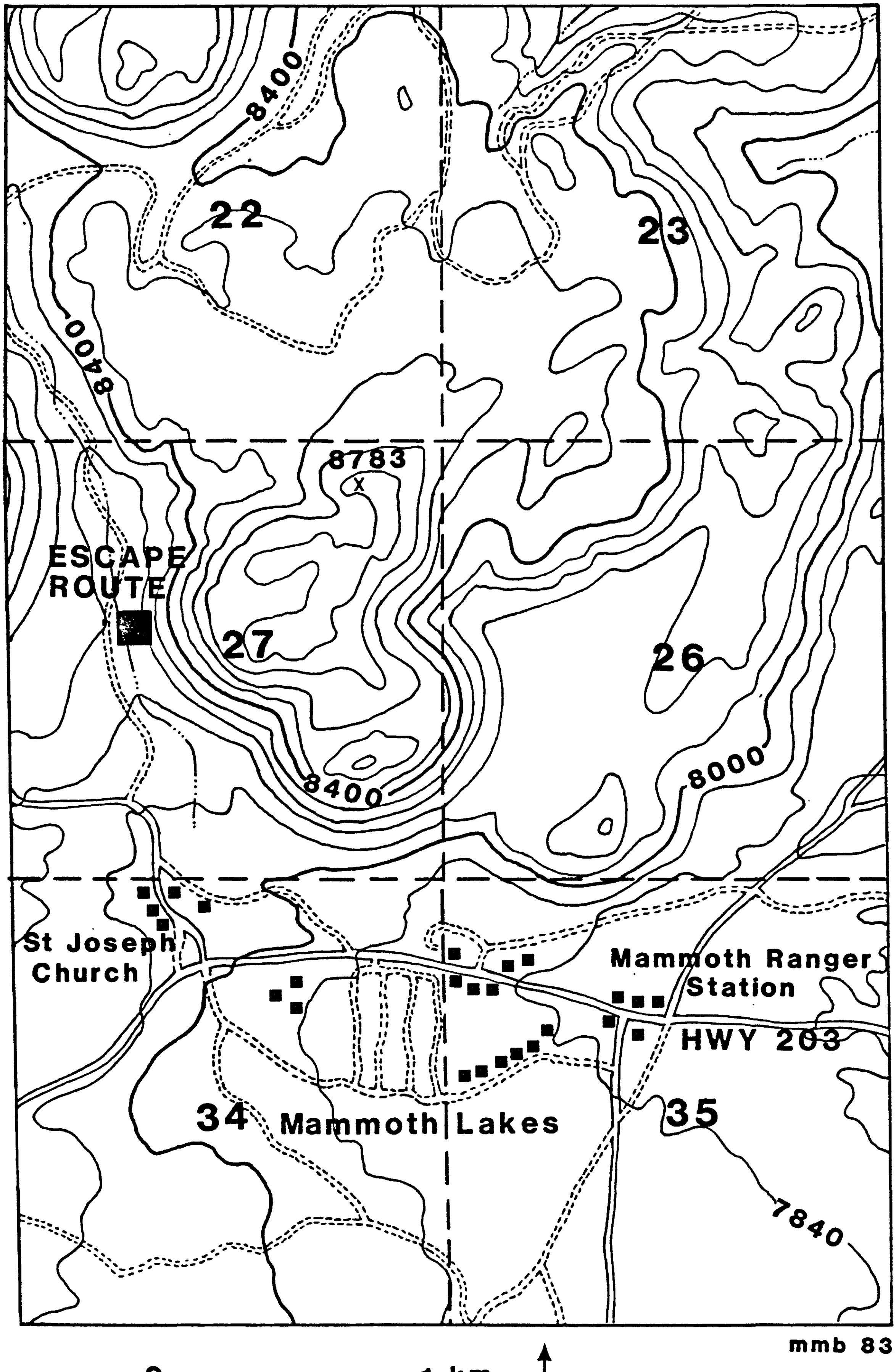

8400
22
23
8400
8783
x
ESCAPE
ROUTE
27
26
8000
8400
St Joseph
Church
Mammoth Ranger
Station
HWY 203
34
Mammoth Lakes
35
7840
mmb 83
0
1 km
N

Fig. 10

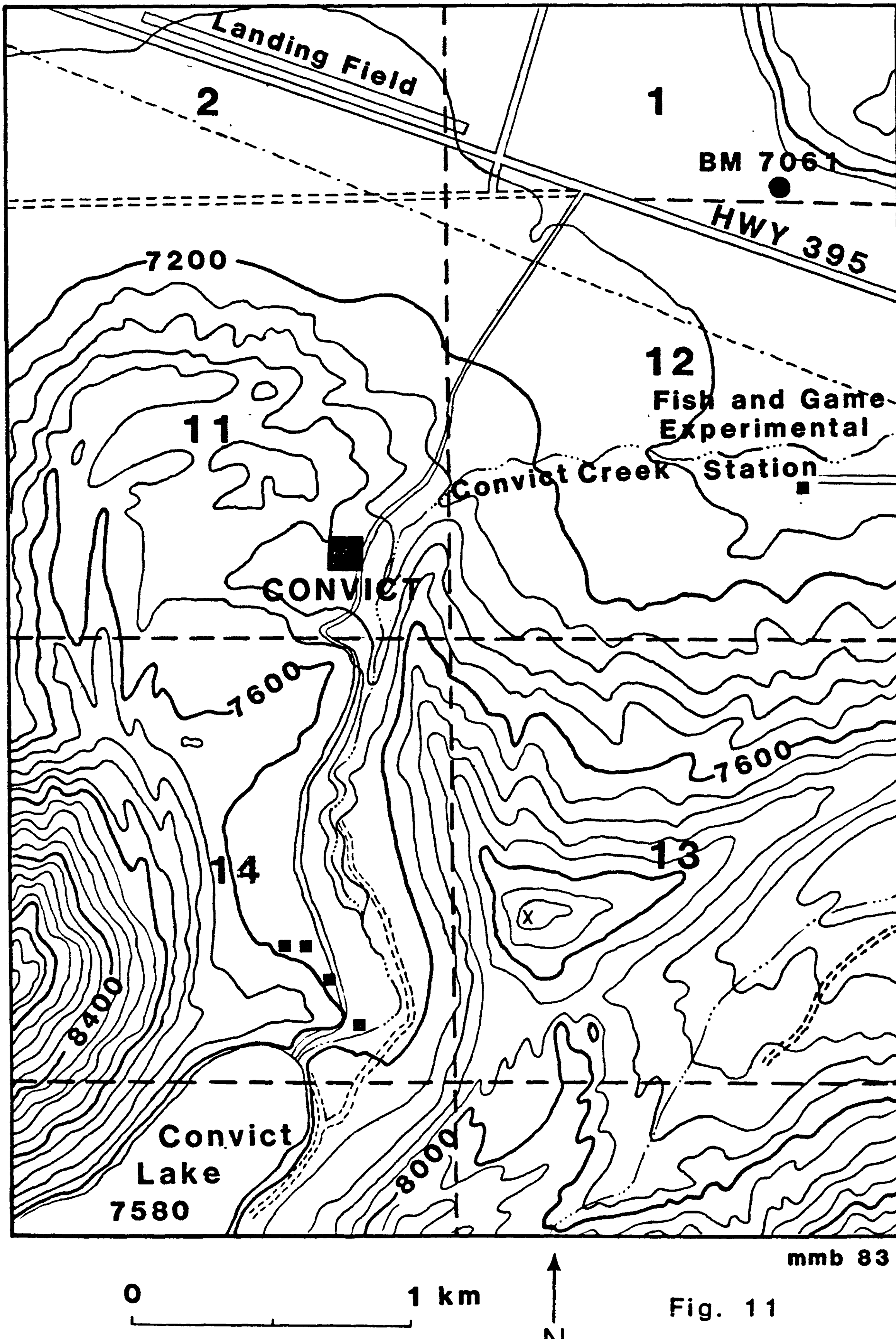

Landing Field
2
1
BM 7061
HWY 395
7200
12
Fish and Game
Experimental
Station
11
Convict Creek
CONVICT
7600
7600
14
13
8400
Convict
Lake
7580
8000
mmb 83
0
1 km
N

Fig. 11

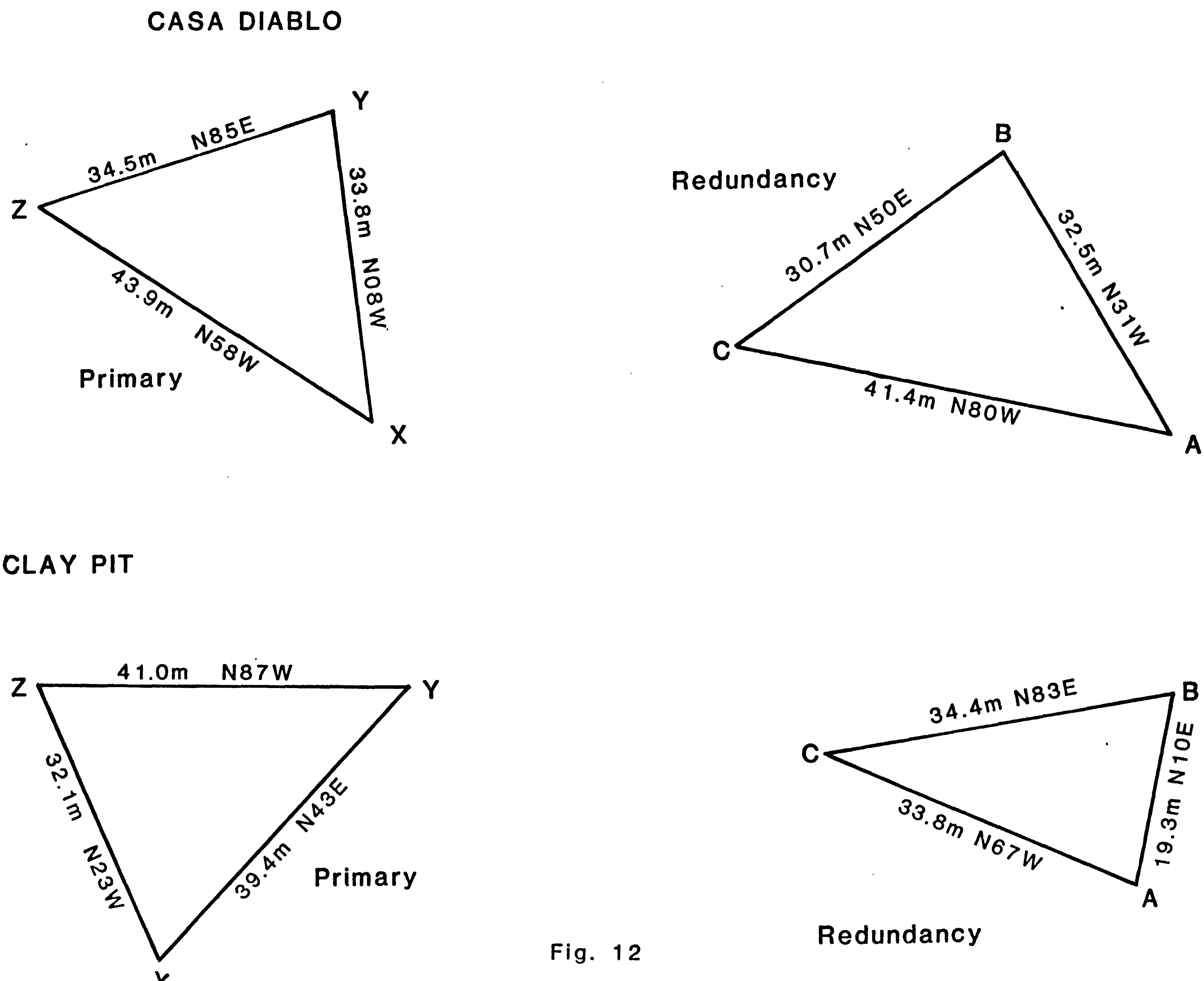

CASA DIABLO
Y
Z
X
34.5m N85E
33.8m N08W
43.9m N58W
Primary
B
C
A
Redundancy
30.7m N50E
32.5m N31W
41.4m N80W
CLAY PIT
Z
Y
X
41.0m N87W
32.1m N23W
39.4m N43E
Primary
C
B
A
34.4m N83E
19.3m N10E
33.8m N67W
Redundancy

Fig. 12

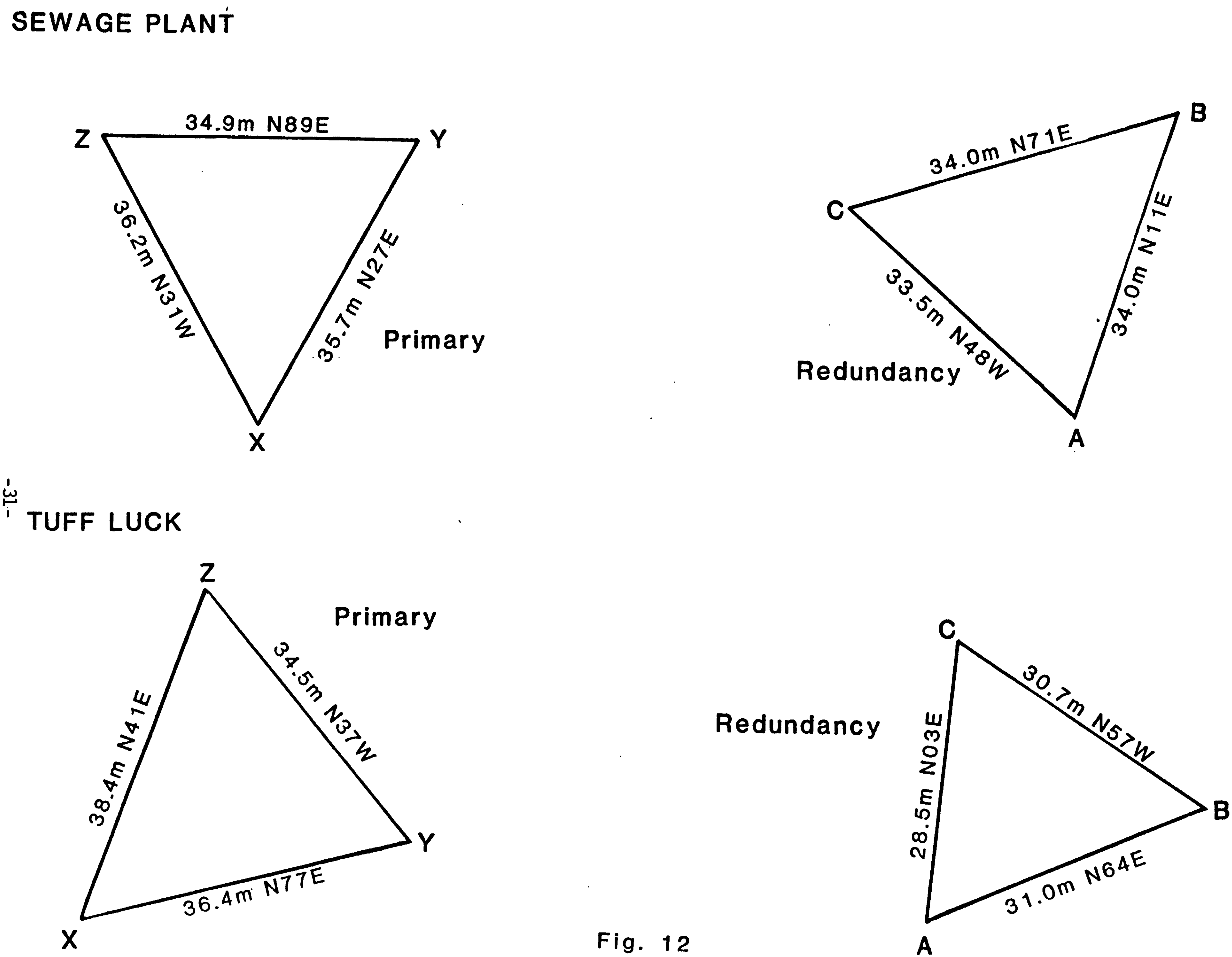

SEWAGE PLANT
Z
Y
X
34.9m N89E
36.2m N31W
35.7m N27E
Primary
B
C
A
34.0m N71E
33.5m N48W
34.0m N11E
Redundancy
TUFF LUCK
Z
Y
X
Primary
34.5m N37W
38.4m N41E
36.4m N77E
C
B
A
Redundancy
30.7m N57W
28.5m N03E
31.0m N64E

Fig. 12

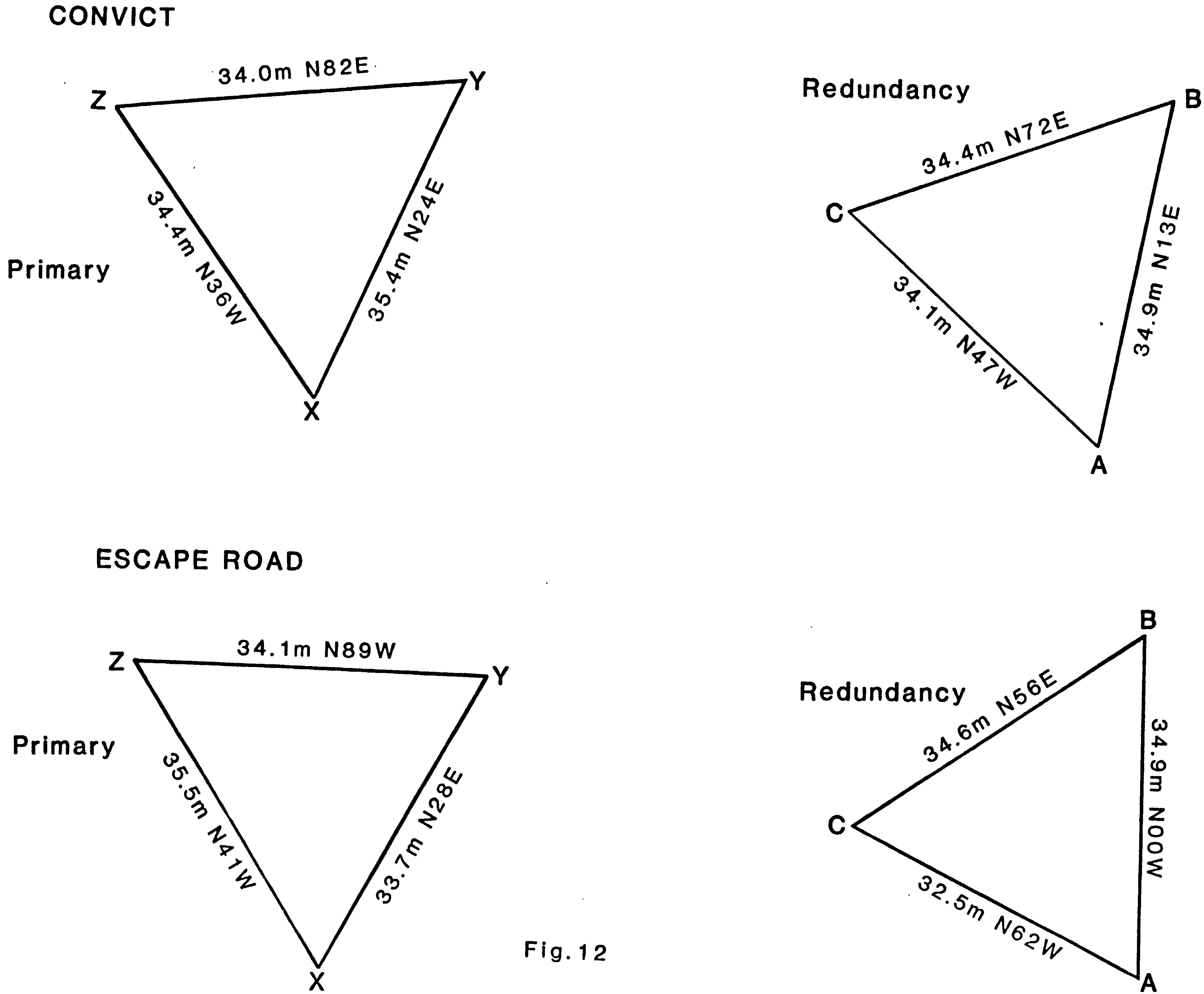

CONVICT
Primary
34.0m N82E
34.4m N36W
35.4m N24E
Z
Y
X
Redundancy
34.4m N72E
34.1m N47W
34.9m N13E
C
B
A
ESCAPE ROAD
Primary
34.1m N89W
35.5m N41W
33.7m N28E
Z
Y
X
Redundancy
34.6m N56E
32.5m N62W
34.9m N00W
C
B
A

Fig. 12

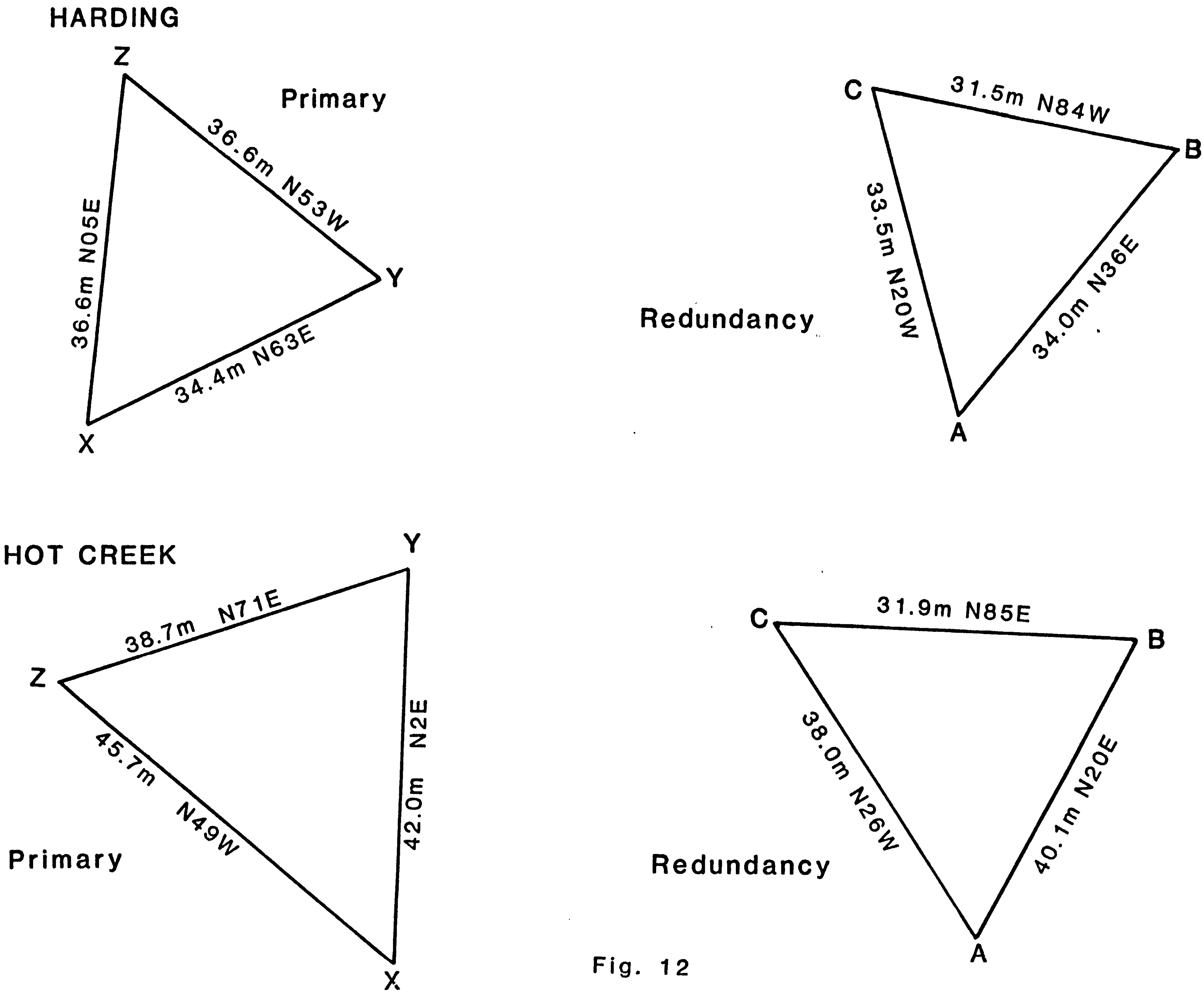

HARDING
Z
Primary
36.6m N53W
36.6m N05E
Y
34.4m N63E
X
C
31.5m N84W
B
33.5m N20W
Redundancy
34.0m N36E
A
HOT CREEK
Y
38.7m N71E
Z
45.7m N49W
N2E
42.0m
Primary
X
C
31.9m N85E
B
38.0m N26W
40.1m N20E
Redundancy
A

Fig. 12

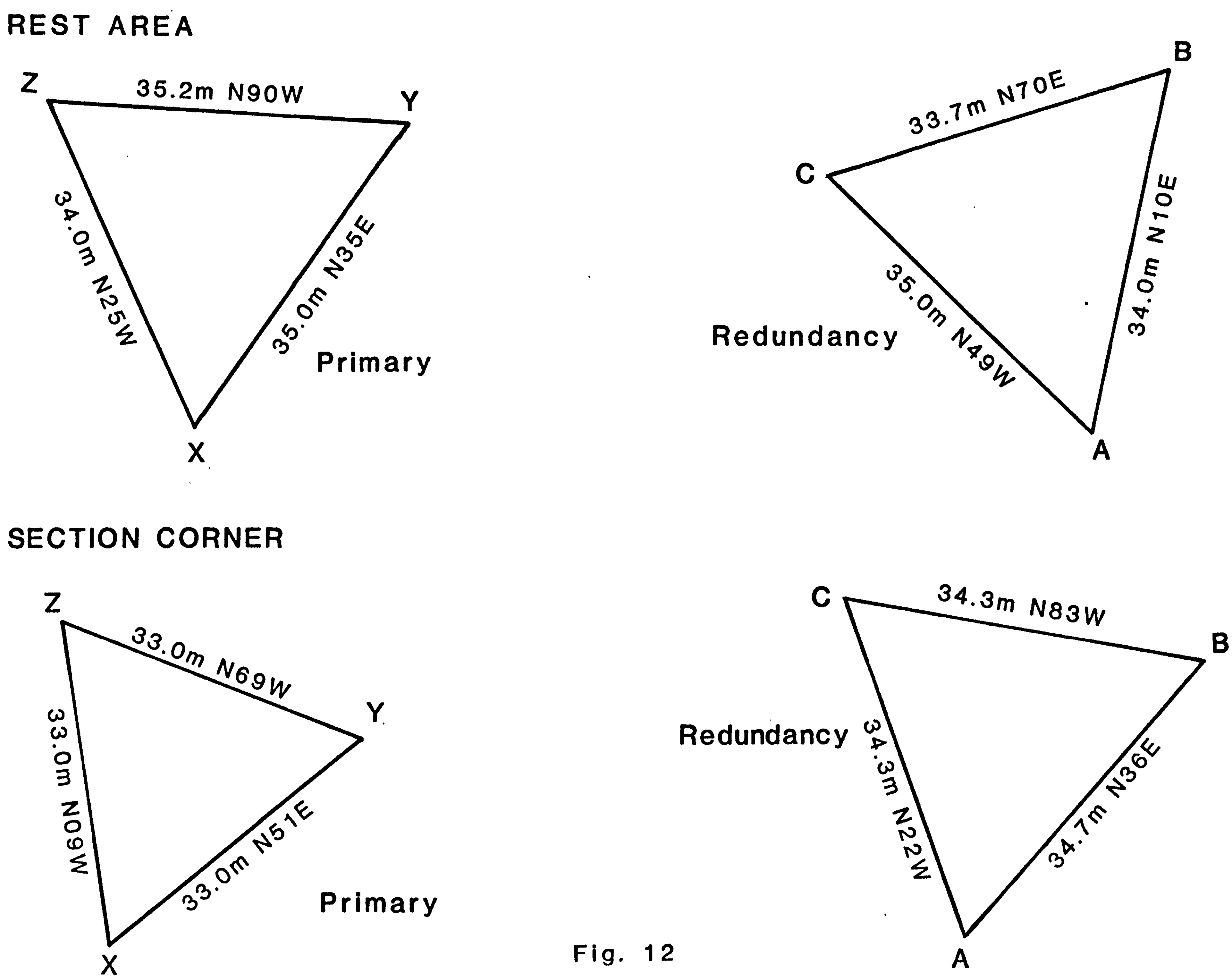

REST AREA
Z
35.2m N90W
Y
34.0m N25W
35.0m N35E
Primary
X
B
33.7m N70E
C
34.0m N10E
35.0m N49W
Redundancy
A
SECTION CORNER
Z
33.0m N69W
Y
33.0m N09W
33.0m N51E
Primary
X
C
34.3m N83W
B
Redundancy
34.3m N22W
34.7m N36E
A

Fig. 12

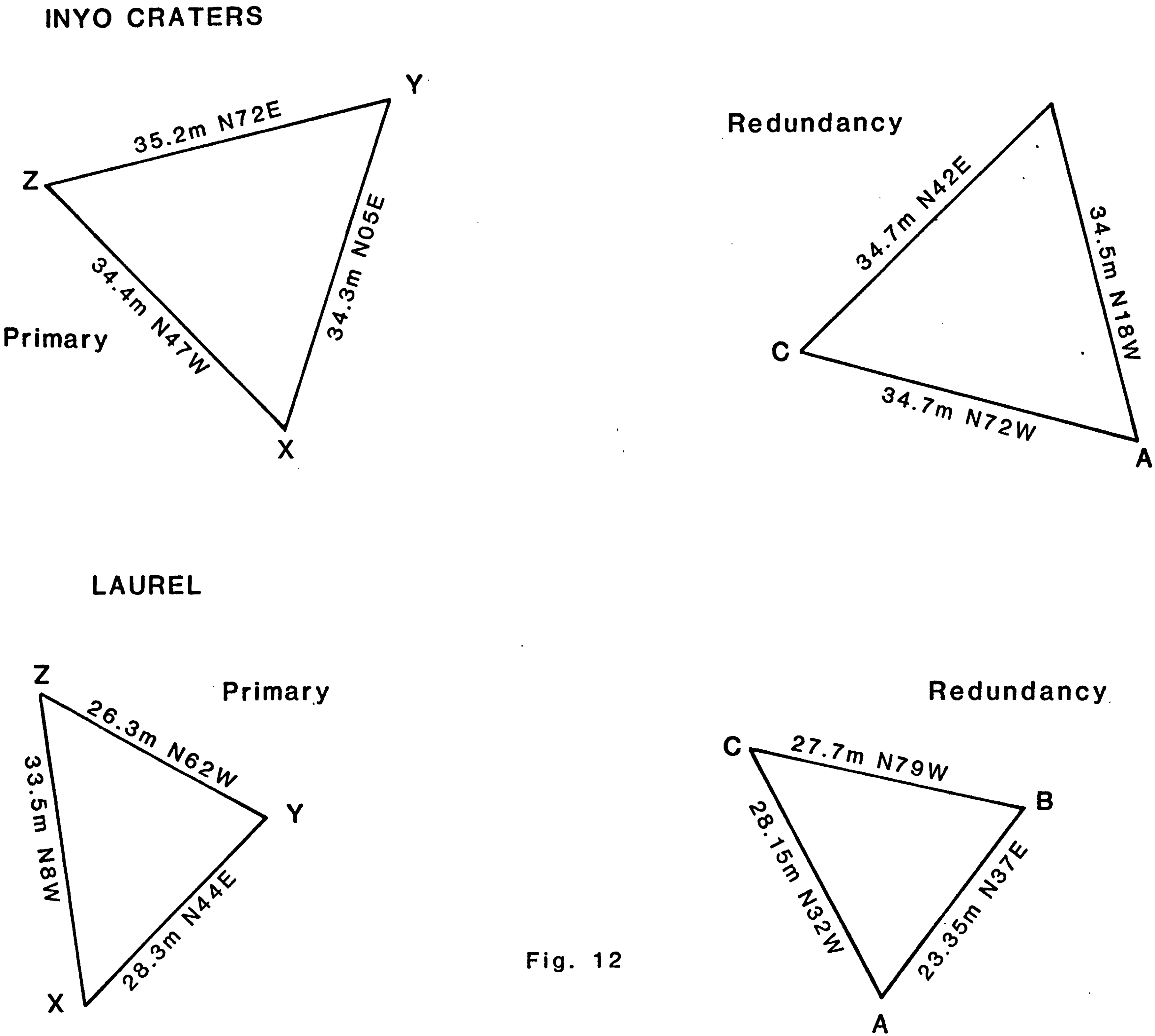

INYO CRATERS
Primary
Z
Y
X
35.2m N72E
34.4m N47W
34.3m N05E
Redundancy
C
A
34.7m N42E
34.5m N18W
34.7m N72W
LAUREL
Primary
Z
Y
X
26.3m N62W
33.5m N8W
28.3m N44E
Redundancy
C
B
A
27.7m N79W
28.15m N32W
23.35m N37E

Fig. 12

B


Primary
Z
Y
X
34.7m N55W
35.1m N05E
34.6m N65E
Redundancy
C
B
A
32.6m N84W
31.0m N14W
36.05m N44E

Fig. 12

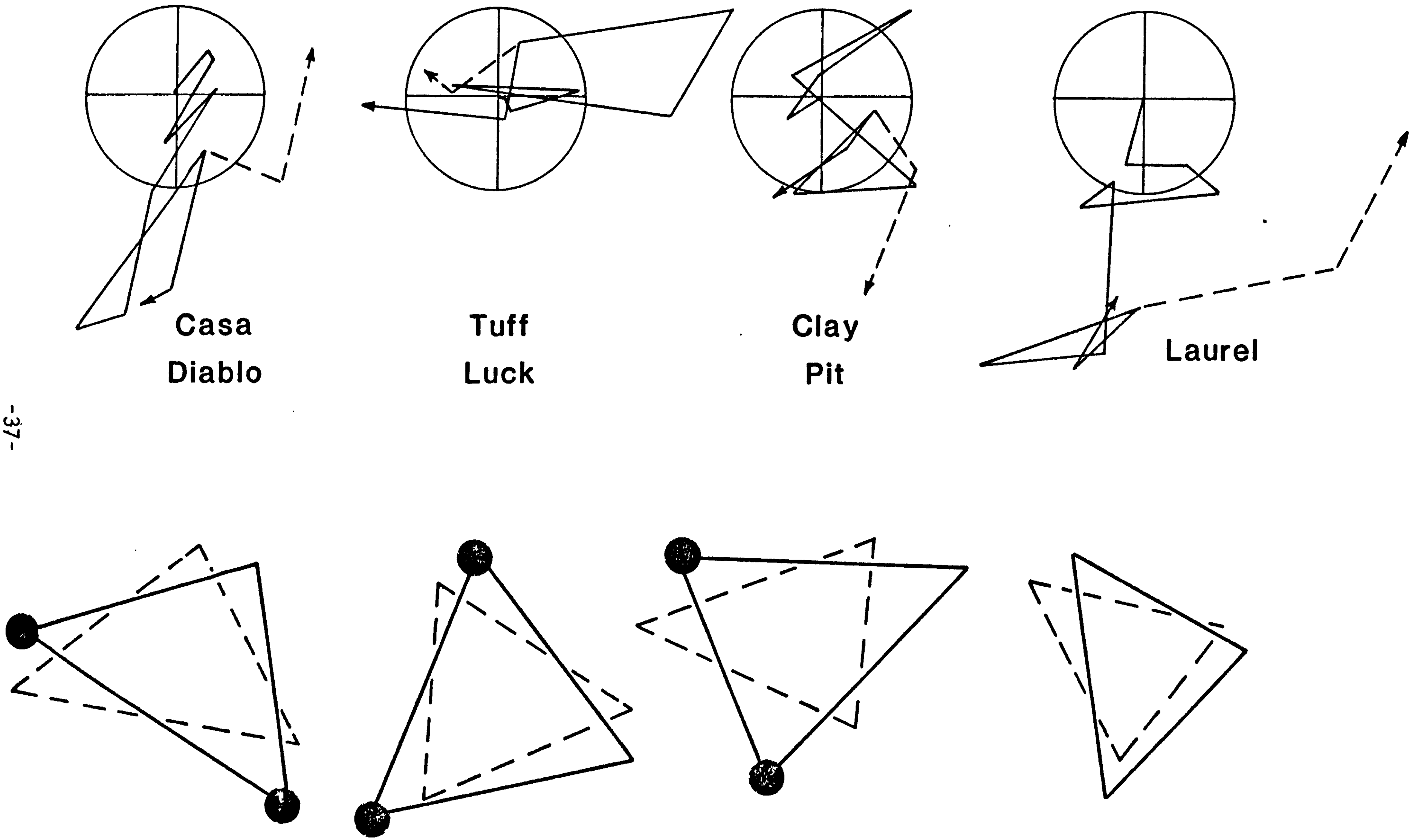
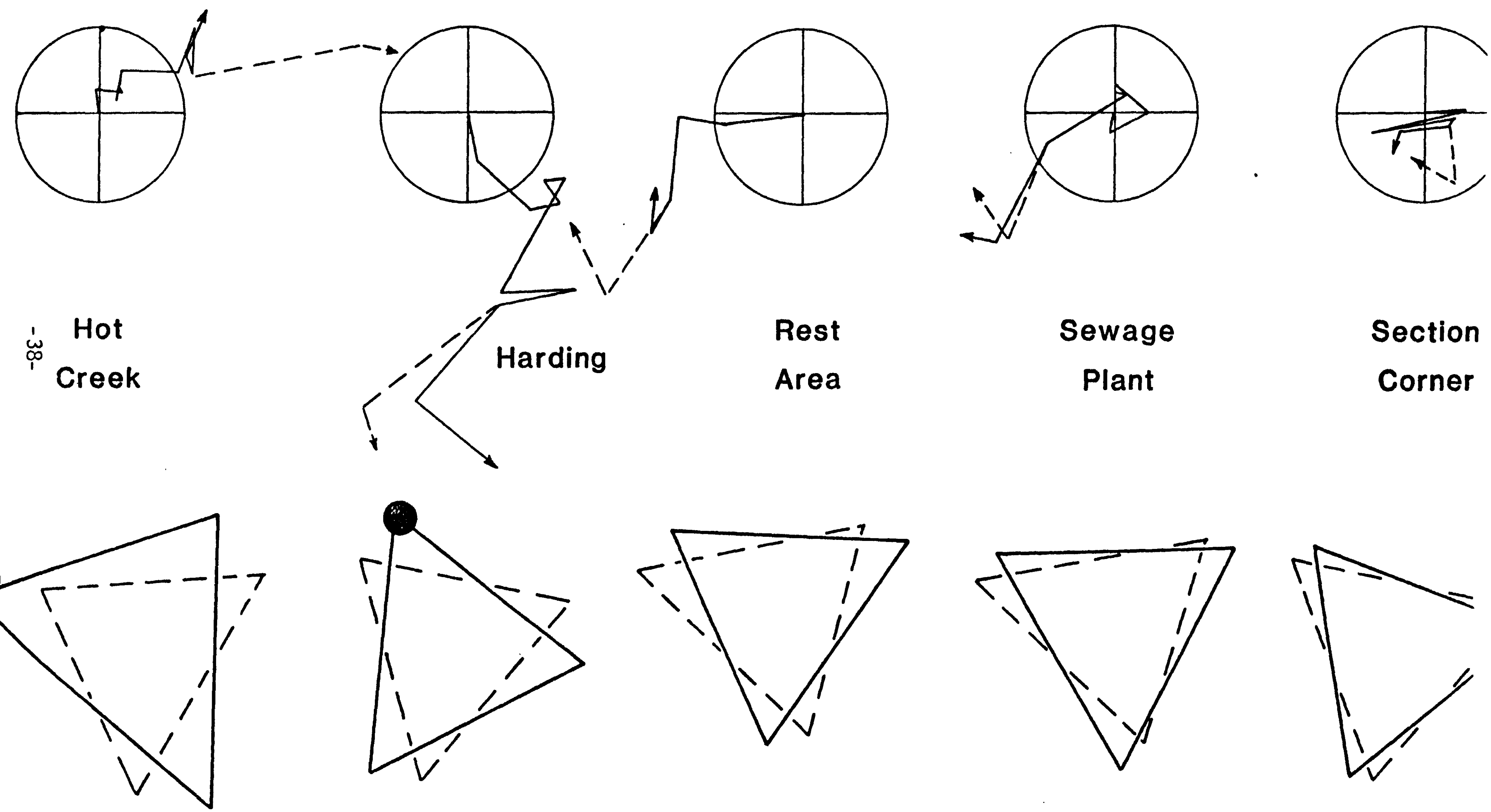
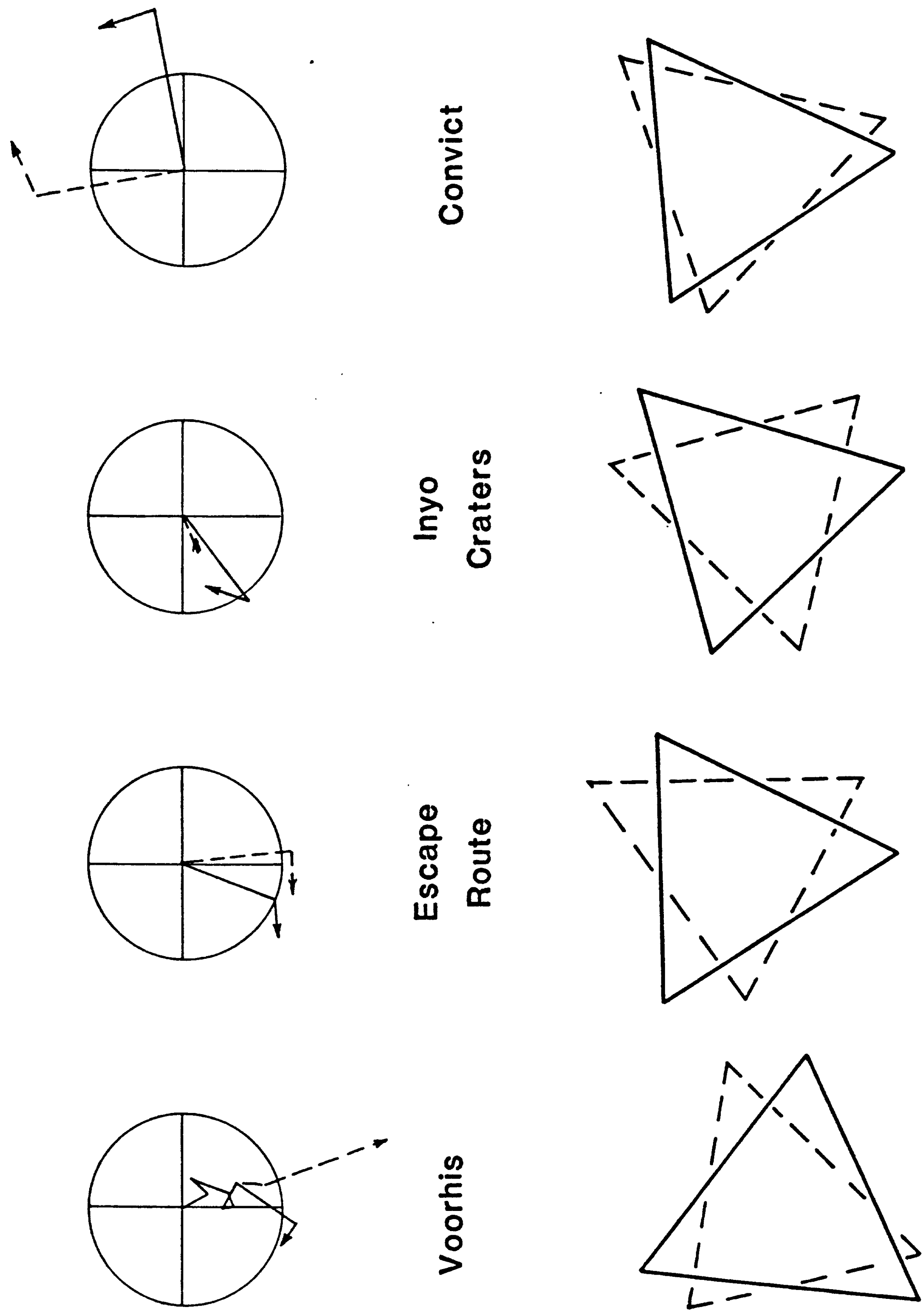


Fig. 13



Hot Creek
Harding
Rest Area
Sewage Plant
Section Corner



Convict
Inyo
Craters
Escape
Route
Voorhis

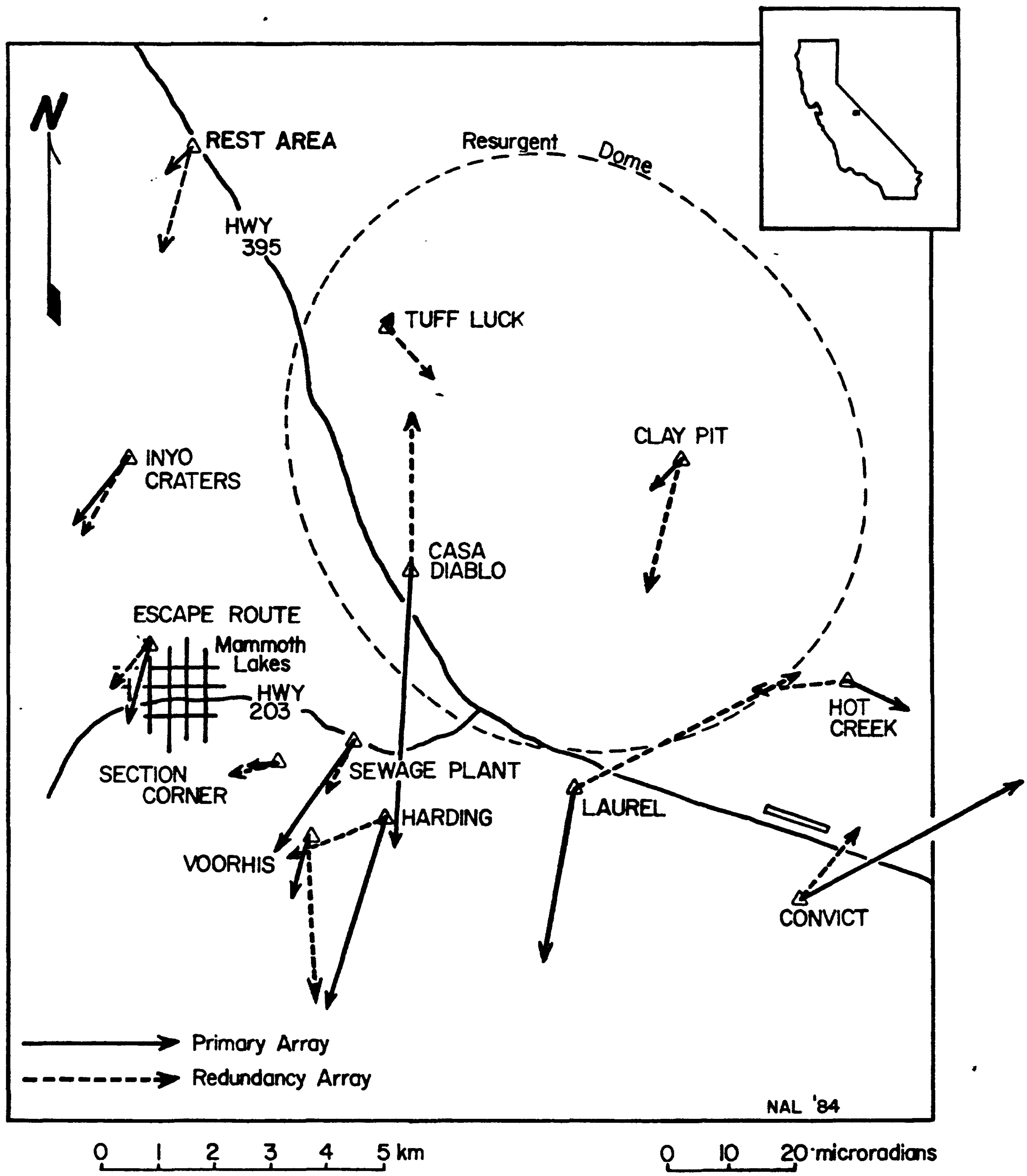

N
REST AREA
Resurgent Dome
HWY
395
TUFF LUCK
CLAY PIT
INYO
CRATERS
CASA
DIABLO
ESCAPE ROUTE
Mammoth
Lakes
HWY
203
HOT
CREEK
SECTION
CORNER
SEWAGE PLANT
LAUREL
HARDING
VOORHIS
CONVICT
Primary Array
Redundancy Array
NAL '84
0 1 2 3 4 5 km
0 10 20 microradians

Fig. 14

APPENDIX I

ARRAY DESCRIPTIONS

The Long Valley dry tilt arrays are shown on enlarged parts of the 1:62,500-scale Mt. Morrison quadrangle topographic map.

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 (1857) 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 bench marks 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. Bench mark 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.

<u>CLAY PIT</u> (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. Bench marks 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.

<u>HOT CREEK</u> (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. Bench mark 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.

<u>LAUREL</u> (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. Bench mark 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. Bench mark 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 bench mark 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 bench mark.

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. Bench mark 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 bench mark.

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; bench mark 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 bench mark.

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

The array 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. Bench mark 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 bench mark.

REST AREA (37°43'52"N, 118°59'02"W)

Access to REST AREA is from highway 395, 5.5 miles north of the intersection of highways 395 and 203. Turn left (west) at the Rest Area sign and drive about 50 m to a "stop ahead" sign. The site is located in a clearing 35 m south of the sign and south of the Rest Area road. All bench marks are class B rod marks driven to refusal in volcanic pumice. X, Y and Z and the center point are marked by 2 m high steel fenceposts, 1 m north of each mark.

CONVICT (37°36'39"N, 118°50'56"W)

Access to CONVICT is from U.S. Highway 395 on the road to Convict Lake 4.2 miles east of the intersection of Highways 395 and 203. Turn south on Convict Road and drive to a point 1.1 miles toward Convict Lake. The array is west of the road on a boulder strewn, alluvial flat. A powerline crosses from the east side of the road to the west about 80 m south of the site. Bench marks A, X and Z are short rods cemented into granite boulders in glacial outwash; C is in a metamorphic boulder; B and Y are class B rods marks driven to refusal.

INYO CRATERS (37°41'08"N, 118°59'15"W)

Access to INYO CRATERS array is from Highway 395 at a point 4.5 miles north of the intersection of Highways 395 and 203. Turn west on to Mammoth Scenic Loop, drive 2.6 miles. Park at a point 0.5 miles west of the Inyo Craters Road junction. The array is located 100 m south of the road in a clearing among tall pine trees. All bench marks are class B rod marks driven to refusal in volcanic pumice and soil, and each mark is located 1 m from a 2 m long steel fencepost.

ESCAPE ROUTE (37°39'37"N, 118°59'04"W)

Access to ESCAPE ROUTE dry tilt array is from the Ranger Station in Mammoth Lakes. Drive west on Highway 203 about one mile, follow the highway in its right turn toward the ski lift area for another mile to the Mammoth Scenic Loop. Turn right on to Mammoth Scenic Loop, drive 0.6 miles to a point where the road reaches the bottom of the canyon. The array is 100 m east of the road in a clearing among tall pine trees. All monuments are class B rods marks driven to refusal in volcanic pumice, and each is 1 m from a 2 m-high steel fencepost.

APPENDIX II

ANALYSIS OF APPARENT TILT BY THERMOELASTICALLY-INDUCED BEDROCK MOTION

by

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INTRODUCTION

Thirteen dry tilt arrays were established in the southwest part of Long Valley Caldera, California, in 1982-1983 by Dr. Dan Dzurisin and Kathy Cashman of the Cascades Volcano Observatory, and by Dr. Arthur G. Sylvester of the University of California, Santa Barbara. These arrays were established to monitor and document volcanotectonic ground deformation associated with a broad uplift of the caldera floor after 1979 and a sharp increase in seismic activity since May 1980. Repeated surveys of primary arrays since May 1982 and associated redundancy arrays established in June 1983 reveal an unusually high signal to noise ratio in arrays containing a mixture of bench mark types and fundaments. Sylvester (1983) postulated that the erratic nature of the tilts in those arrays may be due to the thermoelastic behavior of the bedrock or of the bench mark itself.

ANALYSIS

The depth to which a given temperature variation will penetrate and thermoelastically affect a given medium depends on the amplitude of the variation, the frequency of the oscillation and the thermal diffusivity, κ ($mm^2 sec^{-1}$), of the medium according to the equation (Turcotte and Schubert, 1982):

$$(1)\quad T = T_O + \Delta T \exp\left(-y\sqrt{\omega/2\kappa}\right)\cos(\omega t - \phi)$$

where T is the temperature ($^O K$) at a given depth y(m), ω(rad sec^{-1}) is the frequency of temperature variation, T($^O K$), and ϕ is the time it takes for a temperature variation to reach a depth y (Turcotte and Schubert, 1982):

$$(2)\quad \phi = y\sqrt{\omega/2\kappa}$$

The skin depth (equation 3) is the depth where the amplitude of the surface temperature variation (ΔT) has decreased to $1/e$ or approximately 36 percent of its original value (Turcotte and Schubert, 1982):

$$(3) \quad \delta_\omega = \left(\frac{2\kappa}{\omega}\right)^{1/2}$$

The skin depth gives a good estimation of a thermoelastic "cutoff" depth used in thermal expansion calculations. By holding the temperature differential, ΔT, constant and by confining all thermoelastic behavior to a zone between the surface and the skin depth, the exponential decay (equation 1) of ΔT is compensated by the thermoelastic behavior of a medium below the skin depth.

Assuming $\kappa = 1\ mm^2 sec^{-1}$, a valid estimate for the thermal diffusivity of bedrock outcrops considered in this study, the skin depth for a diurnal temperature variation is approximately 0.17 m, and for the annual variation it is about 3.1 m. The time lag (ϕ) for diurnal variation is approximately four hours and about two months for annual variations.

Linear thermal expansion (or contraction) is a function of the original length of the medium (L_o), the magnitude of temperature variation (ΔT) and the coefficient of linear thermal expansion, α_L ($°K^{-1}$):

$$(4) \quad \Delta L = L_o \Delta T \alpha_L$$

Average daily ambient air temperatures for Long Valley caldera from May 1982 to April 1983 have a sinusoidal variation with a peak to peak temperature differential of approximately 25°C (Fig. 1). Diurnal temperature data for the same time period has a maximum temperature differential of 33.2°C.

Three types of bench marks have been established in Long Valley dry tilt arrays, depending on the nature of the site:

(1) Type I - 10 cm diameter, 0.5 cm thick bronze tablets cemented with mortar onto available rock outcrops;

(2) Type II - 10 cm long, 2 cm diameter stainless steel rods with beleveled top, cemented with epoxy into holes drilled into rock outcrops and boulders;

(3) Type III - 2 cm diameter, coupled steel rods driven to refusal (class B rod mark in the terminology of Floyd, 1978).

The bench marks are set in three types of fundament:

(1) Type A - large, protruding outcrops of basalt and rhyolite;

(2) Type B - low-lying outcrops or large, low-lying boulders surrounded by unconsolidated sediments;

(3) Type C - unconsolidated alluvium and volcanic ash.

RESULTS

The parameters and results of thermal expansion calculations are summarized in Tables 1 and 2. The rock or bench mark material is given in each instance together with its associated coefficient of expansion, α_L. L_O, the original length of the rock or bench mark, is determined by the height by which the bench mark protrudes above its fundament in Table 1, and by the skin depth for a given period T in Table 2. The results of these expansion calculations are listed in the last two columns titled L and $\Delta°$. ΔL is the maximum variation in length resulting from exposure to a temperature variation of ΔT, $\Delta°$ is the "thermal tilt" of an array and is determined by calculating the angle subtended by raising one (or two) bench mark(s) by ΔL and holding the other(s) constant in an heterogenous array with 40 m bench mark spacings.

Results in Table 1 show that insignificant tilt ranging from 0.18 to 1.50 microradians may be associated with all types of bench marks themselves in response to diurnal and annual temperature fluctuations typical of those at Long Valley. The diurnal thermoelastic response of the bedrock also produces relatively insignificant tilt, well within the noise range of the method; however, the response of bedrock fundaments to annual temperature variations is surprisingly large and very significant, yielding a thermoelastic contribution to the tilt of up to 17 microradians. Thus the non-tectonic, thermal contamination in tilt records for some kinds of dry tilt arrays yields tilts comparable in size to directionally systematic seasonal tilt at 3 dry tilt arrays in Long Valley (Sylvester, this report).

CONCLUSION

Theoretical calculations and field experience shows that a conservative detection limit for tectonic tilt in homogeneous arrays of bench marks in a typical dry tilt array is from 5 to 10 microradians (Savage et al., 1979; Decker et al., 1983; Sylvester, 1983; Otway et al., 1984). But calculations of thermoelastic effects on bench marks and their fundaments show that bench marks on high, protruding outcrops in heterogeneous arrays produce tilts which are as much as a factor of three greater than those in homogeneous arrays. Further calculations indicate that an annual temperature variation as small as 14.5°C will produce a tilt of 10 microradians in a heterogeneous array with at least one bench mark set in a high, protruding outcrop and at least one bench mark set in any other kind of fundament.

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TABLE 1 -- Thermal behavior of bench marks:

Material	Coefficient of Linear Expansion α_L*	Thickness (meters) L_o	Period τ	Temperature Range ΔT_o C	ΔL (meters)	$\Delta°$ μrad
Bronze	$17.5 \cdot 10^{-6}$	.02	annual	25	$7.5 \cdot 10^{-6}$	.18
Bronze	$17.5 \cdot 10^{-6}$	.02	diurnal	33.2	$9.9 \cdot 10^{-6}$	.24
Steel	$11.0 \cdot 10^{-6}$	.10	annual	25	$2.75 \cdot 10^{-5}$	.68
Steel	$11.0 \cdot 10^{-6}$	.10	diurnal	33.2	$3.65 \cdot 10^{-5}$	.91
Steel	$11.0 \cdot 10^{-6}$	.20	annual	25	$5.5 \cdot 10^{-5}$	1.3
Steel	$11.0 \cdot 10^{-6}$	.20	diurnal	33.2	$6.2 \cdot 10^{-5}$	1.5

*Thermal coefficients of linear expansion from Razunjevic (1976)

TABLE 2 -- Thermal behavior of Type A bench mark fundaments.

Material	Coefficient of Linear Expansion α_L*	Skin Depth (meters) L_o	Period τ	Temperature Range ΔT_o C	ΔL (meters)	$\Delta°$ μrad
Rhyolite	$8.9 \cdot 10^{-6}$	= 3.1	annual	25	$6.89 \cdot 10^{-4}$	17
Rhyolite	$8.9 \cdot 10^{-6}$	= .17	diurnal	33.2	$.02 \cdot 10^{-5}$	1.2
Basalt	$8.0 \cdot 10^{-6}$	= 3.1	annual	25	$6.2 \cdot 10^{-4}$	15.5
Basalt	$8.0 \cdot 10^{-6}$	= .17	diurnal	33.2	$4.5 \cdot 10^{-5}$	1.12

*Thermal coefficients of linear expansion for rhyolite from Best (1982). Thermal coefficients of linear expansion for basalt from Razunjevic (1976).

Figure 1.

Average 5-day temperatures at Mammoth Ranger Station,
May 1982-April 1983 (Bob Grom, U.S. Forest Service, written communcation, 1984).

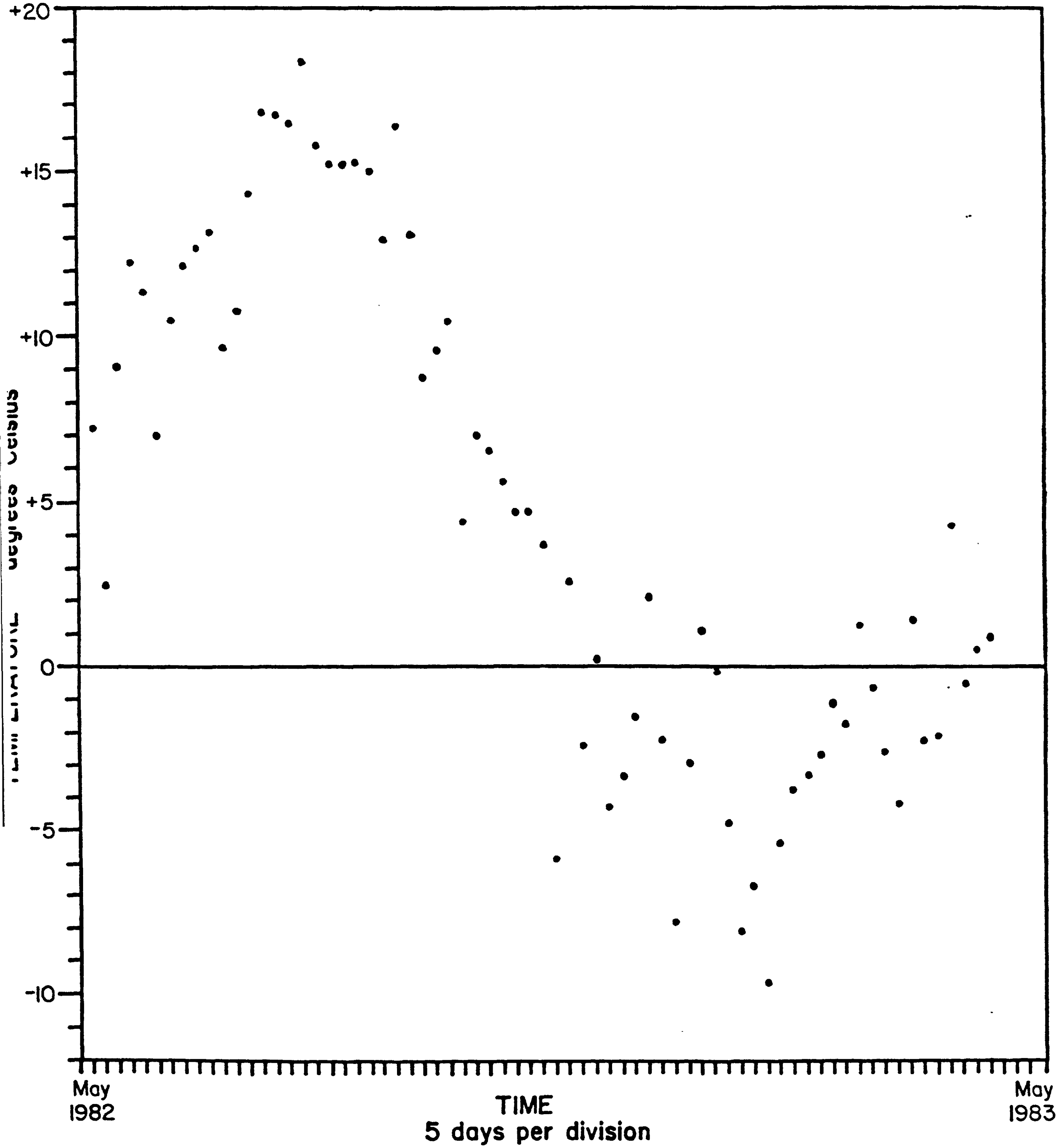

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Fig. 1