DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Leveling, EDM, and Crack-Monitoring Networks in the Koa'e Fault System, Kīlauea Volcano, Hawai'i

By

Victoria F. Avery
U.S. Geological Survey
Reston, VA 22092

Richard S. Fiske
Smithsonian Institution
Washington, D.C. 20560

Donald A. Swanson
U.S. Geological Survey
Hawaiian Volcano Observatory
Hawai'i National Park, HI 96718

Open-File Report 02-129

TABLE OF CONTENTS

Metric Conversions*

1 m = 3.28 feet

1 cm = 0.3937 inches

*Some historic English System measurements are retained in this report

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

The Koa'e fault system, a 2-3 km wide zone of normal faults, graben, and open cracks, extends from Kīlauea's upper east rift zone to the middle part of its southwest rift zone, a distance of about 17 km (Fig. 1). The Koa'e marks the boundary between the comparatively stable main mass of Kīlauea and its mobile south flank, which is being displaced toward the southern, unbuttressed side of the island (Duffield, 1975; Swanson et al., 1976; Delaney et al., 1998). The extensional structures within the Koa'e are a consequence of this displacement.

Recent motions in the Koa'e fault system have been large. Measured cracks cutting 650-year old lava flows document cumulative horizontal extension of as much as 32 m (Duffield, 1975), and intrusions into the Koa'e at the time of the December 1965 eruption on the upper east rift zone reactivated numerous faults and produced hundreds of new cracks (Fiske and Koyanagi, 1968). Because seaward motion and detachment of Kīlauea's south flank is a longstanding process (Swanson et al., 1976; Dieterich, 1988; Denlinger and Okubo, 1995; Owen et al., 2000), future motions in the Koa'e fault system can be expected.

Purpose

The purpose of this Open File Report is to provide future workers with the documentation necessary to locate benchmarks and stainless steel carriage bolts we have used to establish leveling, electronic distance measuring (EDM), and crack monitoring networks in the Koa'e fault system. Future measurements will yield valuable information about the magnitude and style of motions within this area of active deformation.

General Comments

The leveling and EDM networks and the crack-monitoring stations described in this report were established piecemeal over the past 35 years. Collectively they have provided, and will continue to provide, a reasonably good monitor of horizontal and vertical motions in the central and western parts of the Koa'e fault system. We surveyed parts of the network at various times over the past 35 years, and we measured the entire network in January–February 1998. We plan to resurvey the leveling and EDM networks in 2003, and we will allow 10-12 working days for this work. Maps of the various networks are shown in Figs. 2 to 10. Additional information about individual segments of the network accompanies the tables in this Report.

More than 300 marks, each cemented into rock, define our Koa'e monitoring networks. Thirteen are standard aluminum benchmarks, installed for other purposes over the past few decades but used by us because of proximity to our networks. Nine consist of hardened steel masonry nails (PK nails) set into 1-inch square rebars that are cemented into rock; these were installed in 1966-1967 and are in remarkably good condition. The great majority of marks, 292 in all, are stainless steel carriage bolts (and tags) installed by us in 1986 and in the 1990's. These bolts, which have smooth, rounded tops, are ideal for leveling surveys. Each bolt in the EDM network, and at the crack stations, has a small hole drilled into its top to facilitate mark-to-mark distance measurements. The stainless steel bolts and tags have remained virtually rust-free for the past 10 years, and, barring burial by lava flows or disruption by structural events, should last for many decades.

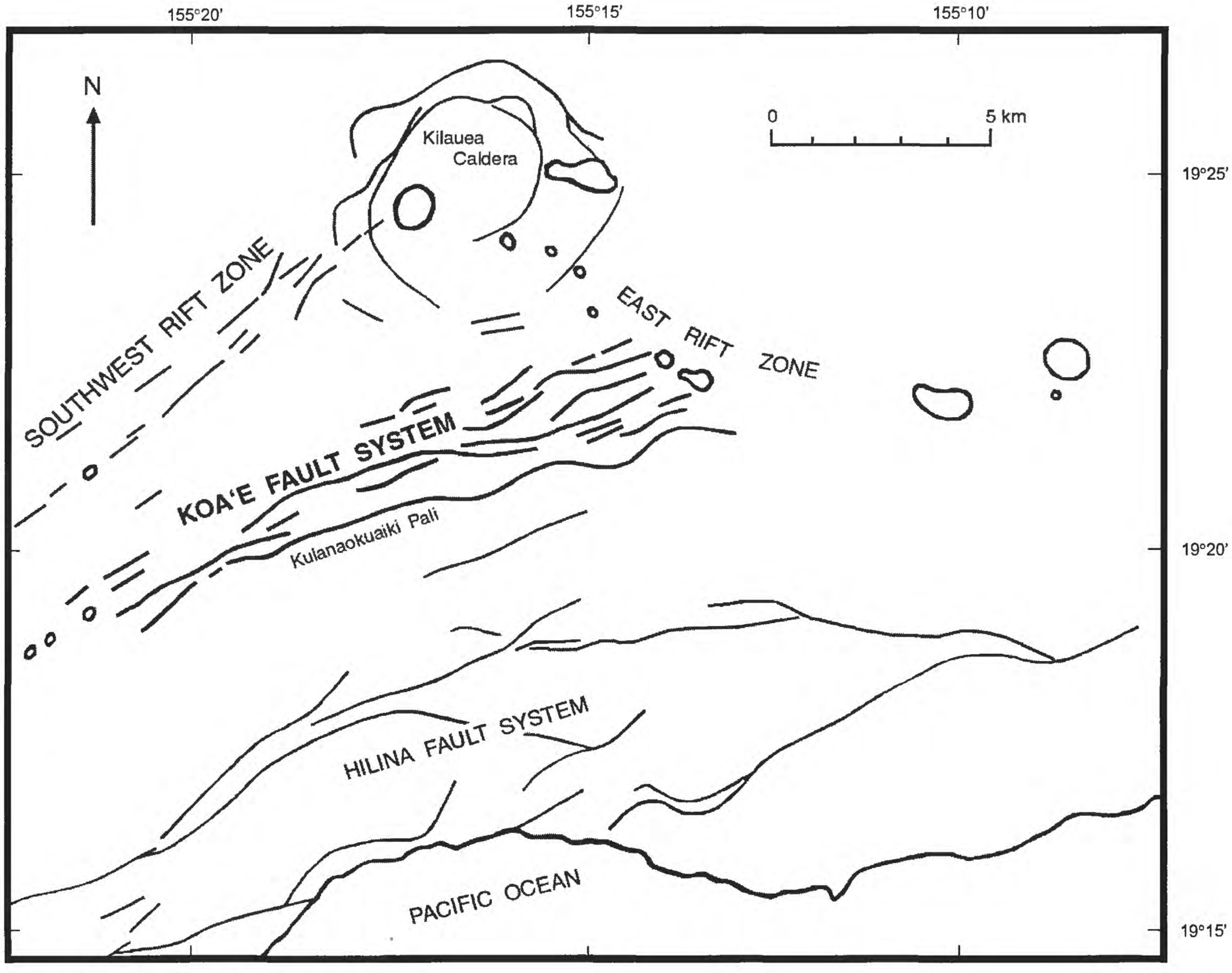


Figure 1. Koa'e Fault System.

We used hand-held Garmin GPS 12CX receivers to determine the latitude and longitude of each mark. We made these measurements in August 2000, 3 months after the elimination of the Selective Availability (SA) that had previously degraded all such measurements. We estimate that each mark is located to within 5 m of its stated position. Latitude and longitude of all marks are referenced to the Old Hawaiian datum, the datum in use at the time the networks were developed. The same datum was used to prepare the locator maps. Coordinates referenced to the NAD83 zone 5 datum are also presented in italics in the tables.

LEVEL LINES

General Statement

Six level lines (Fig. 2) are described in this report. Five of these, the Central, Western, Pali-Nēnē, Lacy, and Crossline, were established by us over the past 35 years. The sixth, a segment of the Hawaiian Volcano Observatory's (HVO) leveling line along the Mauna Iki trail, is included because it links the Lacy line with other lines of our leveling network. All six lines can then be tied to the HVO summit leveling network, so that elevations relative to HVO 23, a reference benchmark in Bird Park (Kīpuka Puaulu) used by HVO for the last several decades, can be determined. Since the early 1990's, the Koa'e level lines were surveyed with a Wild NA2 automatic level and Wild 3-m invar rods, using procedures that approximated second-order leveling.

The inscriptions on the stainless steel tags affixed to (or near) the carriage-bolt marks are exactly as shown in the tables below. To distinguish marks along the Central and Western level lines having the same numbers, C's and W's were stamped into all tags of these two lines in March 2001. This was done with some difficulty, because the tags had already been firmly wired to the ground; as a result, the C's and W's are not always aligned with the rest of the inscription on the tags.

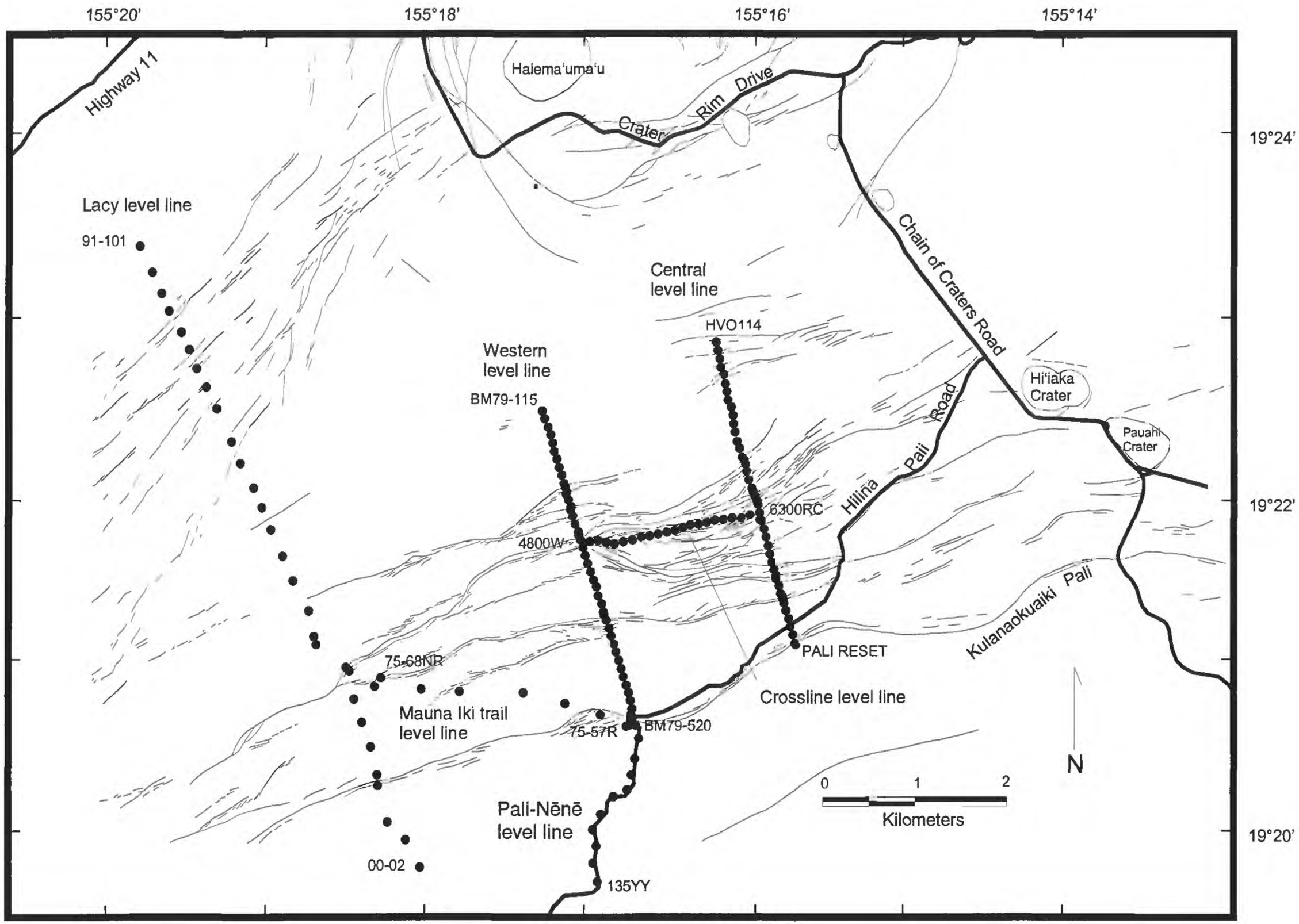


Figure 2. Koa'e level lines overview. Tic mark positions are approximate. As with this and all succeeding maps, map projection is Latitude/Longitude referenced to the Old Hawaiian datum.

Central Level Line

Established in 1966 by R.S. Fiske and J.P. Judd, the Central level line (Fig. 3) extends along an azimuth of about 165° from Āhua Kamokukōlau triangulation station to the base of the Kulanaokuaiki Pali (misspelled as Kalanaokuaiki on all existing quadrangle maps), a distance of about 3.4 km. Initially consisting of marks at 300-foot intervals, intermediate marks were added in the 1990's, so that elevation changes across specific cracks and pali can be measured. Note that, unlike the marks placed at 300-foot intervals, the names of these intermediate marks often do not accurately reflect their position along the line. See the comments box for their true distance from the previous 300-foot mark. This line can be leveled in one full day, but it should be preceded by a day or two of line clearing (machete needed!) and benchmark location in the increasingly thick faya forest between HVO 114 and 6000RC.

Table 1. Central level line station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	**OHD Lat. (°N)** *NAD83*	**OHD Long. (°W)** *NAD83*	**Comments**
HVO 114	19.38224 *2144345.85*	155.26880 *261990.79*	Standard aluminum benchmark about 1 m N of continuously operating GPS station; about 3 m S of Āhua Kamokukōlau triangulation station
300RC	19.38145 *2144258.16*	155.26864 *262006.45*	Difficult to find. From HVO 114, walk 300 feet along an azimuth of 180° (a naturally occurring corridor in the thick vegetation). Two rocks wrapped in aluminum foil have been placed at this point, which is about 1 m south of a gaping crack. 300RC is located about 10 m east of this point and will likely be concealed by dense vegetation
600RC	19.38065 *2144169.32*	155.26844 *262026.29*	On W-sloping pāhoehoe outcrop, at boundary between an open area to the east and a vegetated area to the west
900RC	19.37981 *2144076.17*	155.26833 *262036.63*	On low rise in center of clearing
1200RC	19.37909 *2143996.03*	155.26802 *262068.16*	In SE corner of open area, at bottom of shallow hole dug through tephra to bedrock; vegetation adjacent. The adjacent tephra washes in and tends to conceal the mark.
1500RC	19.37817 *2143893.95*	155.26786 *262083.63*	On S side of open area
1800RC	19.37744 *2143812.90*	155.26770 *262099.39*	On pāhoehoe outcrop on W side of line; apt to be covered by thick grass
2100RC	19.37659 *2143718.63*	155.26758 *262110.76*	In pāhoehoe; apt to be buried by wind-blown tephra
2400RC	19.37590 *2143641.77*	155.26724 *262145.48*	In S-sloping pāhoehoe outcrop at W edge of large open area
2700RC	19.37511 *2143554.06*	155.26706 *262163.24*	On S side of N-S trending tumulus

3000RC	19.37428 *2143462.07*	155.26699 *262169.39*	On small pāhoehoe outcrop 1 m S of track road to Āhua seismometer station
3300RC	19.37347 *2143372.20*	155.26685 *262182.92*	In small outcrop surrounded by extensive tephra
3600RC	19.37253 *2143267.82*	155.26663 *262204.68*	In small outcrop surrounded by tephra
3900RC	19.37186 *2143193.29*	155.26637 *262231.02*	In ʻaʻa (or spatter) on S-facing slope
4200RC	19.37100 *2143097.73*	155.26612 *262256.04*	2-3 m N of crack in area that can be badly overgrown
4350C	19.37064 *2143057.56*	155.26589 *262279.69*	3 m N of S-facing pali and associated crack. 54 m S of 4200RC.
4500RC	19.37029 *2143018.61*	155.26575 *262293.89*	In low ʻaʻa outcrop that is likely obscured by brush, 20-30 m S of S-facing pali
4800RC	19.36959 *2142940.97*	155.26565 *262303.38*	In an unfortunate place low on the W side of large tumulus; difficult to find
5100RC	19.36878 *2142850.98*	155.26542 *262326.38*	In slightly jumbled crack zone
5400RC	19.36795 *2142758.68*	155.26512 *262356.70*	On S slope of broad low tumulus mostly covered by tephra
5450RC	19.36753 *2142711.93*	155.26494 *262374.99*	2 m N of top of steep S-facing pali that forms N boundary of the Doughnut graben. 50 m S of 5400RC.
5700RC	19.36714 *2142668.53*	155.26478 *262391.25*	In pāhoehoe about 6 m S of crack
5800RC	19.36682 *2142632.86*	155.26461 *262408.65*	On pāhoehoe surface about 6 m N of base of N-facing pali and ramp. 37 m S of 5700RC.
5850C	19.36660 *2142608.40*	155.26453 *262416.73*	10 m S of N-facing pali, small outcrop in grass and ʻaʻaliʻi.
6000RC	19.36635 *2142580.61*	155.26445 *262424.77*	At N edge of sandy area
6300RC	19.36553 *2142489.62*	155.26430 *262439.35*	In open and flat pāhoehoe surface. Eastern terminus of the Crossline level line
6530C	19.36487 *2142416.55*	155.26430 *262438.39*	About 5 m W of 6550RC; installed as a back-up for 6550RC which is close to unstable ramp. 75 m S of 6300RC.
6550RC	19.36487 *2142416.47*	155.26424 *262444.70*	At base of large N-facing ramp. 76.5 m S of 6300RC.
6600RC	19.36477 *2142405.20*	155.26410 *262459.26*	Half-way up large N-facing ramp
6900RC	19.36397 *2142316.23*	155.26381 *262488.57*	In pāhoehoe outcrop
7200RC	19.36319 *2142229.59*	155.26360 *262509.51*	In pāhoehoe outcrop
7500RC	19.36234 *2142135.17*	155.26338 *262531.39*	In pāhoehoe outcrop

7800RC	19.36152 *2142044.14*	155.26320 *262549.12*	In pāhoehoe outcrop about 1 m N of 30 cm-wide crack
8100RC	19.36071 *2141954.19*	155.26300 *262568.96*	In pāhoehoe outcrop
8400RC	19.35998 *2141873.04*	155.26276 *262593.13*	On W side of large tumulus
8630C	19.35944 *2141812.98*	155.26256 *262613.36*	In pāhoehoe outcrop about 5 m N of 8650RC; installed as back-up for 8650RC which is close to unstable ramp. 60 m S of 8400RC.
8650RC	19.35938 *2141806.35*	155.26257 *262612.22*	In pāhoehoe, at base of N-facing, informally named White Rabbit pali ramp. 67 m S of 8400RC.
8700RC	19.35921 *2141787.53*	155.26257 *262611.98*	At top of N-facing pali ramp that marks the S margin of the White Rabbit graben. Mark is located 1 m N of large gaping crack at head of ramp
8750RC	19.35908 *2141773.14*	155.26257 *262611.79*	About 3 m S of large gaping crack described above. 13 m S of 8700RC.
9000RC	19.35838 *2141695.18*	155.26224 *262645.45*	In pāhoehoe outcrop
9300RC	19.35764 *2141613.05*	155.26209 *262660.14*	In pāhoehoe outcrop
9450RC	19.35728 *2141572.88*	155.26186 *262683.79*	About 10 m N of N-facing, informally named Ohale pali. 49 m S of 9300RC.
9500RC	19.35709 *2141551.79*	155.26183 *262686.67*	In pāhoehoe outcrop about 6 m S of N-facing Ohale pali. 68 m S of 9300RC.
9600RC	19.35674 *2141512.94*	155.26175 *262694.57*	In ropy pāhoehoe outcrop
9900RC	19.35597 *2141427.39*	155.26153 *262716.57*	On side of pāhoehoe tumulus
10200RC	19.35516 *2141337.33*	155.26125 *262744.82*	In pāhoehoe outcrop. Hilina Pali Road is between this mark and 10500RC
10500RC	19.35440 *2141252.96*	155.26109 *262760.54*	In pāhoehoe outcrop
10800RC	19.35360 *2141164.02*	155.26082 *262787.76*	In pāhoehoe outcrop
11100RC	19.35277 *2141071.84*	155.26061 *262808.62*	In pāhoehoe outcrop
PALI RESET	19.35263 *2141056.21*	155.26052 *262817.88*	In face of Kulanaokuaiki Pali. Carriage bolt is cemented horizontally into steep rock face, but a 3-m leveling rod can be held in a near-vertical position on the edge of the bolt. It helps to be tall!

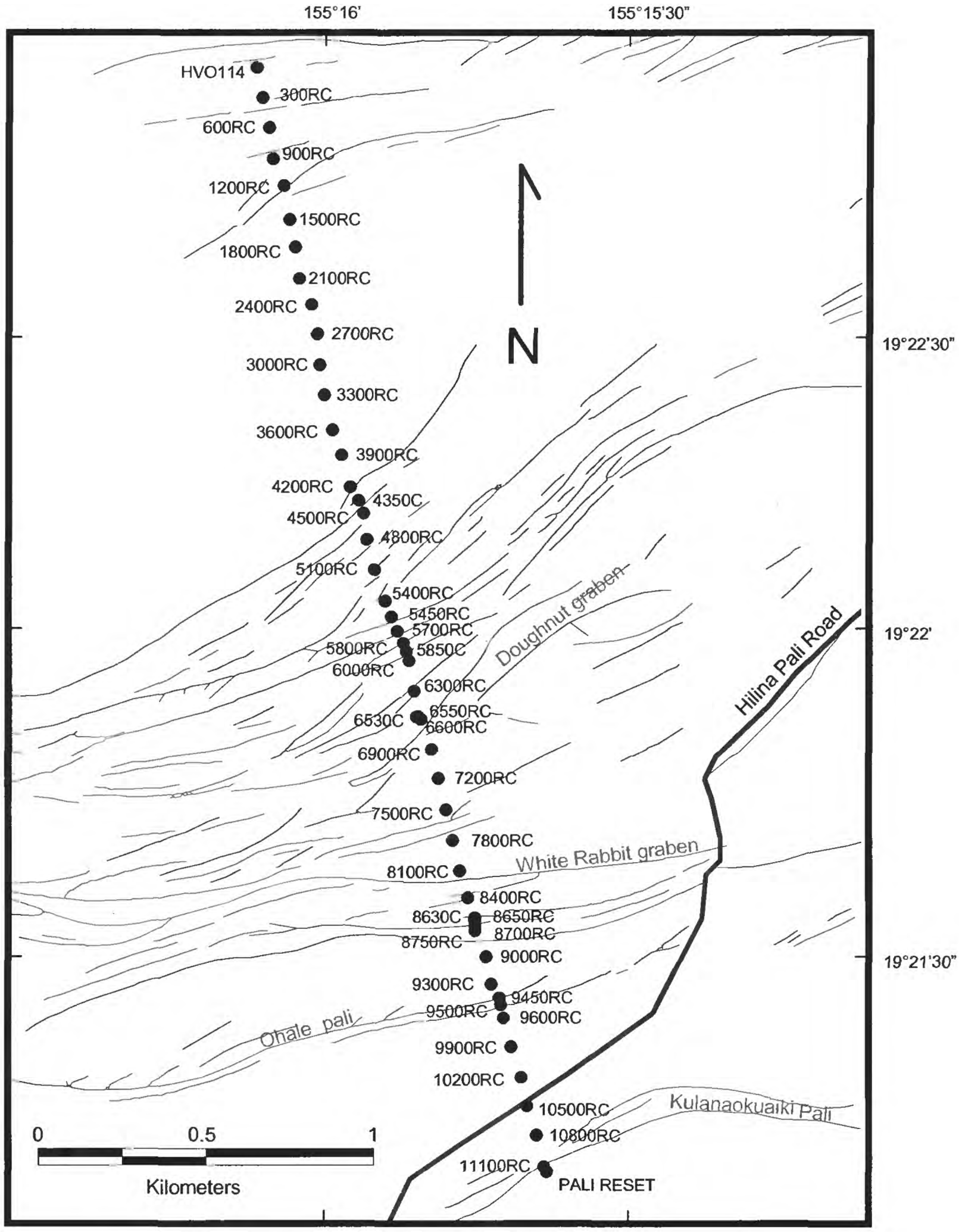


Figure 3. Central level line.

Western Level Line

Established in 1966 by R.S. Fiske and J.P. Judd, the Western level line (Fig. 4) extends from a point 3 km south of Halema'uma'u to the northern edge of the volcano's south flank, a distance of about 3.6 km. As with the Central level line, the original 300-foot spacing between marks was modified by the addition of intermediate marks in the 1990's, so that elevation changes across specific cracks and pali can be measured. Again, for these intermediate marks, the true distance from the previous 300-foot mark is shown in the comments box of the table below. This line can be leveled in one full day and needs no clearing. A subset of benchmarks along the line is occupied every year or two by HVO.

Table 2. Western level line station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	**OHD Lat. (°N)** *NAD83*	**OHD Long. (°W)** *NAD83*	**Comments**
BM79-115	19.37551 *2143625.71*	155.28681 *260088.55*	Standard aluminum benchmark 8 m N of track road and about 20 m south of wide sand wash
300RW	19.37477 *2143543.44*	155.28656 *260113.73*	In small pāhoehoe outcrop next to ōhi'a
600RW	19.37395 *2143452.17*	155.28621 *260149.31*	In small pāhoehoe outcrop
900RW	19.37319 *2143367.63*	155.28593 *260177.62*	At S base of small tumulus
1200RW	19.37237 *2143276.57*	155.28573 *260197.42*	In small pāhoehoe outcrop along narrow drainage
1500RW	19.37156 *2143186.68*	155.28558 *260212.00*	In pāhoehoe outcrop near E margin of small sand flat
1800RW	19.37080 *2143102.15*	155.28530 *260240.31*	In pāhoehoe at N end of small sand flat
2100RW	19.36996 *2143008.80*	155.28505 *260265.35*	On N side of low tumulus
2400RW	19.36921 *2142925.38*	155.28478 *260292.62*	At W end of extensive pāhoehoe high
2700RW	19.36840 *2142835.40*	155.28456 *260314.56*	On top of tumulus at N side of S-facing fault, about 12 m N of rubble ridge
2850W	19.36807 *2142798.70*	155.28444 *260326.69*	At N brow of uplifted fault block, gentle rise to S. 38 m S of 2700RW.
3000W	19.36757 *2142743.12*	155.28428 *260342.76*	In pāhoehoe 30 N of open crack
3100W	19.36733 *2142716.64*	155.28434 *260336.11*	In flat pāhoehoe. 28 m S of 3000W.
3300W	19.36680 *2142657.64*	155.28411 *260359.50*	At W base of tumulus on which EDM station 68-16 is located
3550W	19.36615 *2142585.28*	155.28383 *260387.97*	5 m N of open crack, on high overlooking broad low area to S. 82 m S of 3300W.
3600W	19.36601 *2142569.84*	155.28387 *260383.57*	In crack zone, about 3 m N of largest crack

3700W	19.36577 *2142543.25*	155.28386 *260384.27*	At N edge of broad sandy flat, S of crack zone. 24 m S of 3600W.
3900W	19.36520 *2142479.85*	155.28365 *260405.50*	At N edge of broad pāhoehoe outcrop
4200W	19.36441 *2142391.97*	155.28335 *260435.87*	In middle of flat pāhoehoe area
4500W	19.36365 *2142307.40*	155.28304 *260467.33*	On top of E-W sharp linear tumulus well N of high area to S
4700W	19.36328 *2142266.37*	155.28299 *260472.04*	At base of steep N-facing slope. About 16 m N of Crack Station bolt 15-B. 40 m S of 4500W.
4800W	19.36286 *2142219.60*	155.28280 *260491.40*	On flat pāhoehoe surface S of crack zone. Area still slopes to N. Western terminus of the Crossline level line.
5100W	19.36212 *2142137.33*	155.28256 *260515.53*	S of several cracks and nearly on top of broad flat area
5400W	19.36134 *2142050.67*	155.28234 *260537.51*	In pāhoehoe outcrop in large flat area
5700W	19.36053 *2141960.64*	155.28208 *260563.65*	In pāhoehoe outcrop near S end of broad flat
6000W	19.35974 *2141872.78*	155.28180 *260591.92*	On ooze-out toe on small tumulus
6300W	19.35893 *2141782.70*	155.28151 *260621.21*	In tumuli-studded terrain
6600W	19.35827 *2141709.20*	155.28120 *260652.83*	On top of small tumulus
6900W	19.35737 *2141609.32*	155.28103 *260669.37*	In ropy pāhoehoe outcrop
7200W	19.35659 *2141522.45*	155.28066 *260707.12*	In fractured pāhoehoe outcrop near sandy area
7500W	19.35579 *2141433.63*	155.28048 *260724.86*	In smooth pāhoehoe outcrop
7650W	19.35549 *2141400.30*	155.28040 *260732.83*	In pāhoehoe outcrop in sandy area 5 m N of Ohale pali. 29 m S of 7500W.
7800W	19.35498 *2141343.57*	155.28020 *260753.10*	In fairly flat pāhoehoe
8100W	19.35418 *2141254.57*	155.27990 *260783.46*	In pāhoehoe in low spot between tumuli
8400W	19.35344 *2141172.34*	155.27968 *260805.51*	Near top of tumulus with prominent knob; azimuth is 237° from Ohale and 57° to Ohale
8700W	19.35264 *2141083.44*	155.27944 *260829.56*	In ropy pāhoehoe outcrop
9000W	19.35187 *2140997.86*	155.27920 *260853.65*	At top of E-W tumulus
9300W	19.35106 *2140907.77*	155.27891 *260882.95*	On tumulus, about 15 m N of more prominent tumulus with cave on its N side

9600W	19.35023 *2140815.53*	155.27866 *260908.01*	On side of tumulus in tumulus-studded terrain
9900W	19.34944 *2140727.77*	155.27844 *260929.98*	At top of small tumulus with ooze-outs
10200W	19.34861 *2140635.44*	155.27813 *260961.34*	In fractured pāhoehoe outcrop
10500W	19.34787 *2140553.17*	155.27788 *260986.54*	In hummocky pāhoehoe flow
10800W	19.34708 *2140465.45*	155.27770 *261004.30*	At top of small E-W tumulus
11100W	19.34627 *2140375.54*	155.27753 *261020.99*	In relatively flat pāhoehoe
BM79-518	19.34573 *2140315.90*	155.27764 *261008.64*	Standard aluminum benchmark about 4 m N of center of Hilina Pali Road; in level pāhoehoe
11400W	19.34544 *2140283.55*	155.27746 *261027.14*	On broad ramp N of Kulanaokuaiki Pali, about 30 m S of center of Hilina Pali Road. Partly concealed behind circle of rocks
BM79-520	19.34466 *2140197.82*	155.27791 *260978.70*	Standard aluminum benchmark about 11 m W of center of Hilina Pali Road at hairpin turn; about 30 m S of Kulanaokuaiki Pali; at start of Mauna Iki trail

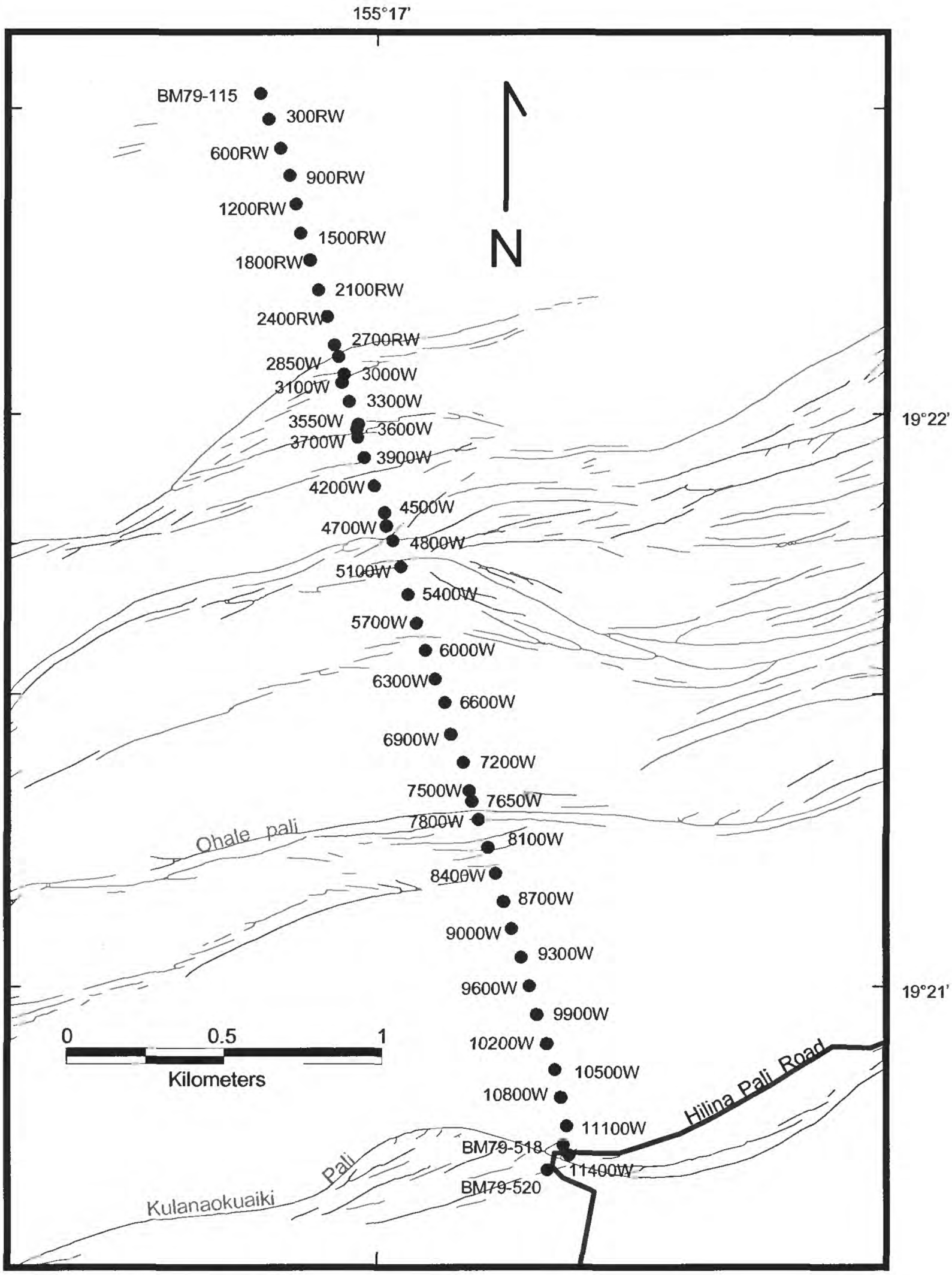


Figure 4. Western level line.

Pali-Nēnē Level Line

Established in February 1986 by E. Nielson and R.S. Fiske, the Pali-Nēnē line (Fig. 5) is located along the Hilina Pali Road and extends from the Kulanaokuaiki Pali southward to Kīpuka Nēnē, a distance of about 1.7 km (as projected onto the 165° azimuth). This line serves as an extension of the Western level line and was established to monitor vertical motions in this part of the volcano's south flank. Nine of the 11 marks consist of large, non-tagged stainless steel carriage bolts (with heads 3.8 cm in diameter) cemented into pāhoehoe on either side of the Hilina Pali Road. Station numbers are scribed on the head of each bolt, but these are difficult to read. Two pre-existing roadside benchmarks (134YY and 135 YY) are included in the line. This line, located in a lightly forested area with little breeze, can be extremely difficult to level on hot, sunny afternoons. It should be surveyed in the early morning or on cloudy days. The line can be leveled in slightly more than 2 hours.

Table 3. Pali-Nēnē level line station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	**OHD Lat. (°N)** *NAD83*	**OHD Long. (°W)** *NAD83*	**Comments**
BM79-520	19.34466 *2140197.82*	155.27791 *260978.70*	Standard aluminum benchmark about 11 m W from center of Hilina Pali Road at hairpin turn; about 30 m S of Kulanaokuaiki Pali
HVO 86-52	19.34341 *2140057.96*	155.27685 *261088.29*	In pāhoehoe, 7 m E of road center
134YY	19.34142 *2139838.23*	155.27728 *261040.19*	Standard aluminum benchmark on flat pāhoehoe bluff 7 m W of road center
HVO 86-53	19.33985 *2139664.83*	155.27758 *261006.37*	In flat pāhoehoe 6 m W of road center
HVO 86-54	19.33836 *2139500.47*	155.27802 *260957.95*	In flat pāhoehoe 7 m W of road center
HVO 86-55	19.33771 *2139430.49*	155.27945 *260806.71*	In flat pāhoehoe 9 m S of road center
HVO 86-56	19.33597 *2139239.64*	155.28075 *260667.54*	In flat pāhoehoe 6 m W of road center
HVO 86-57	19.33448 *2139075.85*	155.28159 *260577.08*	In grassy area about 4 m W of road centerline; bolt is on north side of small, grassy topographic low
HVO 86-58	19.33292 *2138902.63*	155.28123 *260612.63*	At edge of low bluff 5 m E of road center. In area of small trees.
HVO 86-59	19.33126 *2138719.31*	155.28156 *260575.53*	In flat grassy pāhoehoe area 7 m W of road center
135YY	19.32945 *2138518.28*	155.28110 *260621.24*	Standard aluminum benchmark in flat pāhoehoe 9 m W of road center. The site of the former Kīpuka Nēnē campground is located on the opposite side of the road.

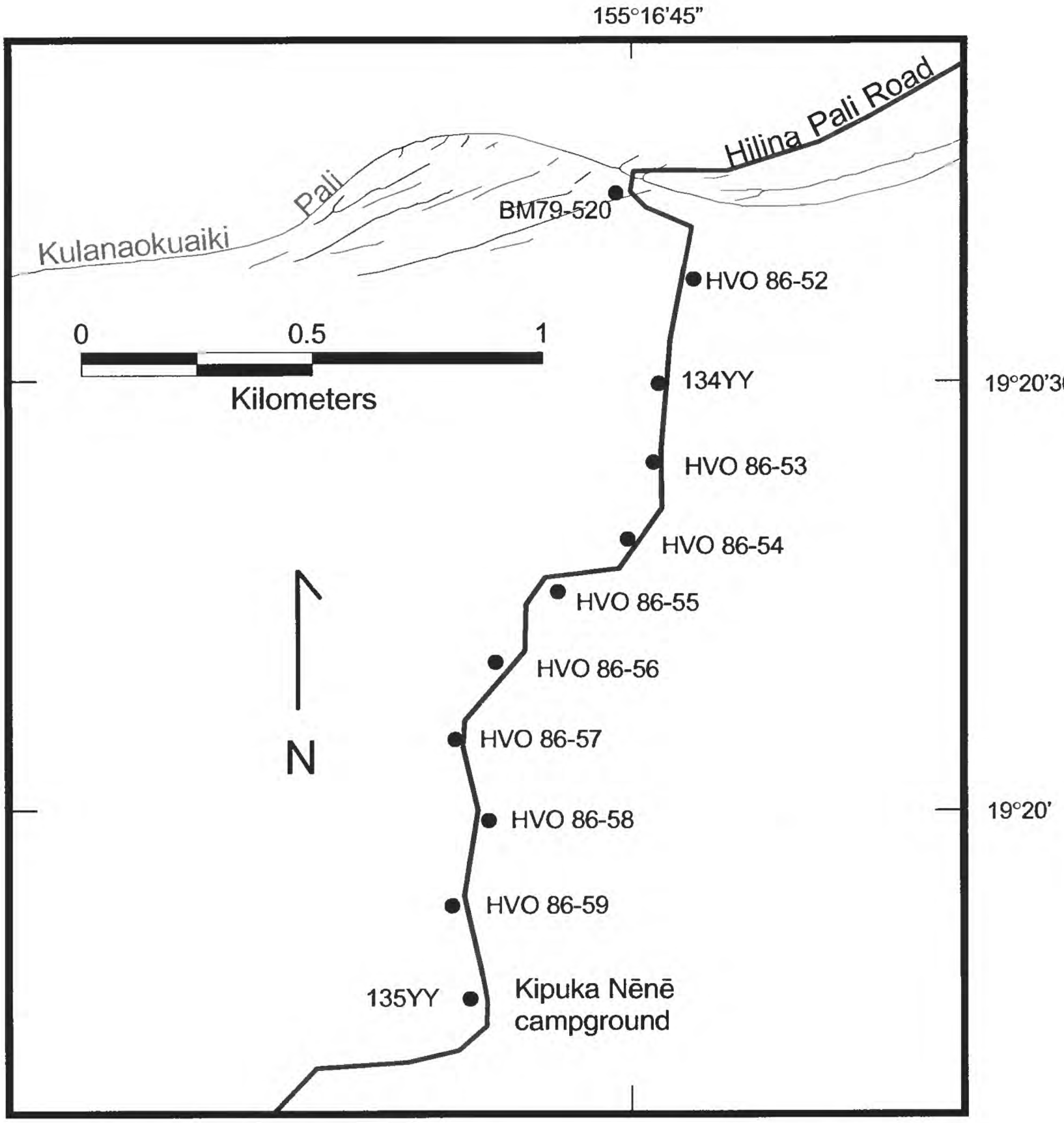


Figure 5. Pali-Nēnē level line, a southern extension of the Western level line.

Lacy Level Line

The Lacy level line (Fig. 6) was originally established in January 1991 by R.S. Fiske, D.A. Swanson, and E. O'Leary and was extended about 500 m farther southeastward by R.S. Fiske and V.F. Avery in August 2000. The line extends along an azimuth of about 155° and is 7.4 km long. It crosses the southwest rift zone and Koa'e fault system, ending about 800 m south of Kulanaokuaiki Pali on the volcano's south flank. The Lacy level line receives its name from the Lacy Ranch on the lower slopes of Mauna Loa, where an EDM base station was established for the Upper Southwest Rift Zone Monitor (Hanatani, 1988). Our level line was established to coincide with this now-abandoned linear array of EDM reflectors. This array consisted of corner-prism reflectors affixed to 1-inch diameter rebars; several "Lacy rebars" remain in place and are referred to in the descriptions below. About 1.5 days are required to level this line, although we have found it more efficient to spend one day leveling the northern two thirds of the Lacy line (from 91-101 to 75-70NR) and a second full day leveling the Mauna Iki trail line (BM79-520 to 75-68NR) and the southern third of the Lacy line (75-68NR to 00-02).

Table 4. Lacy level line station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	**OHD Lat. (°N)** *NAD83*	**OHD Long. (°W)** *NAD83*	**Comments**
91-101	19.39167 *2145473.54*	155.32855 *255726.68*	On top of craggy 'a'a high 2–3 m above surrounding area. Ahu and small stick are about 8 m to southwest
91-102	19.38911 *2145188.24*	155.32724 *255860.51*	On broken pāhoehoe; about 60–cm–high ahu of flat rocks (no stick) is about 5 m to SW
91-103	19.38707 *2144960.99*	155.32626 *255960.43*	In jumbled pāhoehoe with much sand in surrounding flat area. Ahu and small stick about 1 m north of bolt. Blowing sand easily conceals bolt and tag. Exact location of bolt marked by circle of small rocks
91-104	19.38532 *2144766.12*	155.32547 *256040.83*	In jumbled pāhoehoe with much surrounding sand. Bolt is in smooth sand-free surface about 8 m west of ahu made of flat rocks. No stick. Lacy rebar is about 1 m W of ahu
91-105	19.38327 *2144537.40*	155.32423 *256168.06*	In smooth pāhoehoe rise 3–4 m above surrounding area. Windswept ohia 3–4 m high is on S side of rise. About 15 m W of Ka'ū Desert Trail. Small ahu, no stick
91-106	19.38152 *2144342.48*	155.32341 *256251.61*	In pāhoehoe rise southeast of sandy area. About 10 m from EDM station 95-9 (which has its own ahu and tall stick). Both are on crest of ridge. Ahu and short stick
91-107	19.37968 *2144137.69*	155.32265 *256328.73*	In flat pāhoehoe, much sand around. About 40 m northwest of 1971 lava flow (and lots of spatter). Ahu, no stick

91-108	19.37785 *2143933.66*	155.32165 *256431.08*	On pāhoehoe surface, about 40 m southeast of Lacy rebar. Ahu, no stick
91-109	19.37574 *2143698.52*	155.32057 *256541.42*	On top of smooth pāhoehoe tumulus rising 3-4 m above surroundings. Should be silhouetted against sky when coming from the SE. About 40–cm–high ahu and short stick
91-110	19.37252 *2143339.85*	155.31904 *256697.41*	On smooth pāhoehoe saddle between low tumuli. About 40 m W of very wide sandy area. Broad stocky ahu and short stick
91-11	19.37036 *2143099.41*	155.31812 *256790.88*	In small outcrop in ʻaʻa flow surrounded by much sand. About 3 m W of Lacy rebar. A 1.2–m–high ahu made of flat slabs is 35 m to the SE. This ahu is easily seen on the W side of the broad sand wash when driving southward toward Puʻu Koaʻe
91-111	19.36796 *2142831.79*	155.31678 *256928.12*	In flat pāhoehoe surface with much surrounding sand; about 40 m SE from edge of large sand wash and track road toward Puʻu Koaʻe. Ahu and short stick
91-112	19.36603 *2142616.92*	155.31593 *257014.58*	In flat pāhoehoe surrounded by much sand. About 2 m NW of 1974 lava flow margin. About 30 cm from Lacy rebar. Ahu about 50–cm–high made of rock slabs, no stick
91-12	19.36390 *2142379.63*	155.31490 *257119.65*	In flat sandy pāhoehoe surface, about 2 m SW of Lacy rebar. Ahu and long stick
91-113	19.36128 *2142087.77*	155.31363 *257249.23*	In featureless 1974 pāhoehoe. Station is difficult to locate. Azimuth to Cone Crater summit is 215°. Ahu and short stick
91-114	19.35888 *2141820.60*	155.31260 *257353.91*	In featureless 1974 pāhoehoe, difficult to locate. Azimuth to Cone Crater summit is 270°. Low slabby ahu and short stick about 5 m to SE
91-15	19.35592 *2141490.59*	155.31097 *257520.82*	In crusty 1974 pāhoehoe, about 1.5 m S of Lacy rebar. Ahu and long stick
91-115	19.35338 *2141208.58*	155.31041 *257575.92*	In 1974 pāhoehoe, low rolling terrain. Very difficult to locate. About 30-35 m NE of Mauna Iki trail. Do not make the mistake of looking for this station in the older pāhoehoe to the E. Ahu and small stick
75-70NR	19.35261 *2141123.02*	155.31019 *257597.90*	In pāhoehoe along Mauna Iki trail. Small ahu, no stick. Also on the Mauna Iki Trail line.

pali nail	19.35035 *2140868.47*	155.30710 *257919.30*	Badly rusted PK nail in large block at foot of pali. On W side of trail where it begins to climb up the pali. No ahu or stick
75-69R	19.35002 *2140831.48*	155.30678 *257952.44*	In flat pāhoehoe about 3 m W of trail and about 3 m S of break in trail slope. Also on the Mauna Iki Trail line.
75-68NR	19.34935 *2140752.71*	155.30350 *258296.16*	On W side of low tumulus, about 4 m E of Mauna Iki trail; no ahu or stick. Also on the Mauna Iki Trail line.
91-116	19.34848 *2140657.30*	155.30415 *258226.57*	In area of relatively flat pāhoehoe; ahu and stick nearby
91-5	19.34721 *2140519.63*	155.30625 *258003.99*	At top of broad 5 m-high tumulus; ahu and stick nearby
91-117	19.34494 *2140267.19*	155.30546 *258083.67*	In broken pāhoehoe among scattered tumuli; ahu and stick nearby
91-118	19.34258 *2140004.66*	155.30457 *258173.72*	In S-sloping pāhoehoe surface; broken tumulus with entrail ooze-outs to N may obscure mark when coming from N
91-119	19.33983 *2139699.18*	155.30385 *258245.34*	In pāhoehoe in moat about 15 m N of broken ramp at base of N-facing Kulanaokuaiki Pali; ahu with stick
91-7	19.33882 *2139587.29*	155.30380 *258249.10*	Near crest of large tumulus 150-200 m S of wide crack on top of Kulanaokuaiki pali. About 200 m W of rebar and EDM reflector. Ahu with stick
91-120	19.33524 *2139189.53*	155.30280 *258348.93*	On low tumulus. Ahu and stick
00-01	19.33351 *2138995.36*	155.30092 *258543.98*	On S side of 2 m-high tumulus, not visible from the N; ahu on top of tumulus; no stick
00-02	19.33085 *2138698.82*	155.29946 *258693.52*	About 10 m E of jagged 2 m-high tumulus, on azimuth 157° from 91-7; ahu about 4 m NE of bolt; no stick

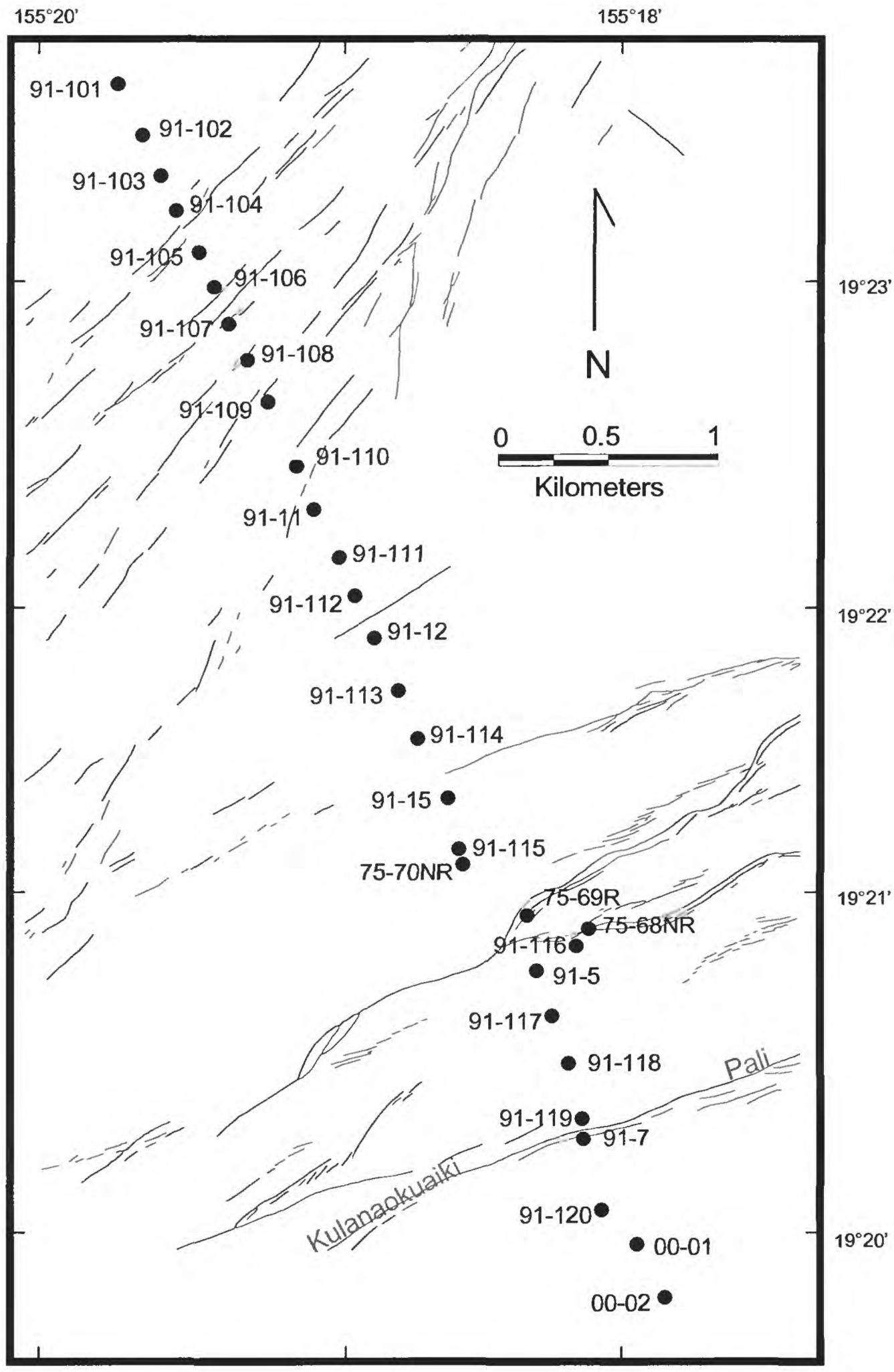


Figure 6. Lacy Level Line.

Crossline Level Line

Established in November 1997 by R.S. Fiske and D.A. Swanson and first leveled in March 1998, this 1.96–km line (Fig. 7) connects the Central and Western level lines and was established to pass through the anomalous area of curved Koa'e faults and associated closed-contour subsidence noted by Duffield (1975). The line is linked to the Central level line at 6300RC and the Western level line at 4800RW. If care is taken when positioning the level at each set-up point, and if 3–m rods are used, the gentle topography permits this line to be surveyed bolt-to-bolt, with no intervening turning points. This line can be leveled in 2 hours.

Table 5. Crossline level line station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	OHD Lat. (°N) *NAD83*	OHD Long. (°W) *NAD83*	Comments
6300RC	19.36553 *2142489.62*	155.26430 *262439.35*	Carriage bolt and tag of the Central Koa'e level line; in open and flat pāhoehoe
97-1	19.36533 *2142468.83*	155.26528 *262336.07*	In open and flat pāhoehoe
97-2	19.36504 *2142437.96*	155.26618 *262241.08*	In open and flat pāhoehoe
97-3	19.36501 *2142435.94*	155.26713 *262141.21*	In pāhoehoe at top of W-facing monocline
97-4	19.36486 *2142420.63*	155.26806 *262043.26*	In pāhoehoe
97-5	19.36478 *2142413.00*	155.26895 *261949.62*	In pāhoehoe
97-6	19.36458 *2142391.94*	155.26974 *261866.32*	At top of pāhoehoe tumulus
97-7	19.36440 *2142373.21*	155.27060 *261775.68*	In pāhoehoe
97-8	19.36432 *2142365.51*	155.27144 *261687.29*	In pāhoehoe
97-9	19.36403 *2142334.50*	155.27224 *261602.80*	In pāhoehoe
97-10	19.36380 *2142310.16*	155.27305 *261517.34*	In pāhoehoe
97-11	19.36363 *2142292.48*	155.27388 *261429.88*	In pāhoehoe
97-12	19.36344 *2142272.73*	155.27480 *261332.93*	In pāhoehoe at edge of tumulus
97-13	19.36324 *2142251.80*	155.27568 *261240.16*	In pāhoehoe
97-14	19.36315 *2142243.04*	155.27655 *261148.61*	In pāhoehoe
97-15	19.36285 *2142211.10*	155.27747 *261051.49*	In pāhoehoe near top of tumulus
97-16	19.36268 *2142193.59*	155.27842 *260951.41*	In pāhoehoe at edge of tumulus

97-17	19.36246 *2142170.52*	155.27934 *260854.40*	In pāhoehoe
97-18	19.36260 *2142187.15*	155.28016 *260768.44*	In pāhoehoe near top of tumulus
97-19	19.36281 *2142211.62*	155.28104 *260676.27*	In pāhoehoe
97-20	19.36269 *2142199.49*	155.28187 *260588.88*	In pāhoehoe
4800W	19.36286 *2142219.60*	155.28280 *260491.40*	Carriage bolt and tag of the Western level line. Local flat area S of crack zone; broader local area slopes to N

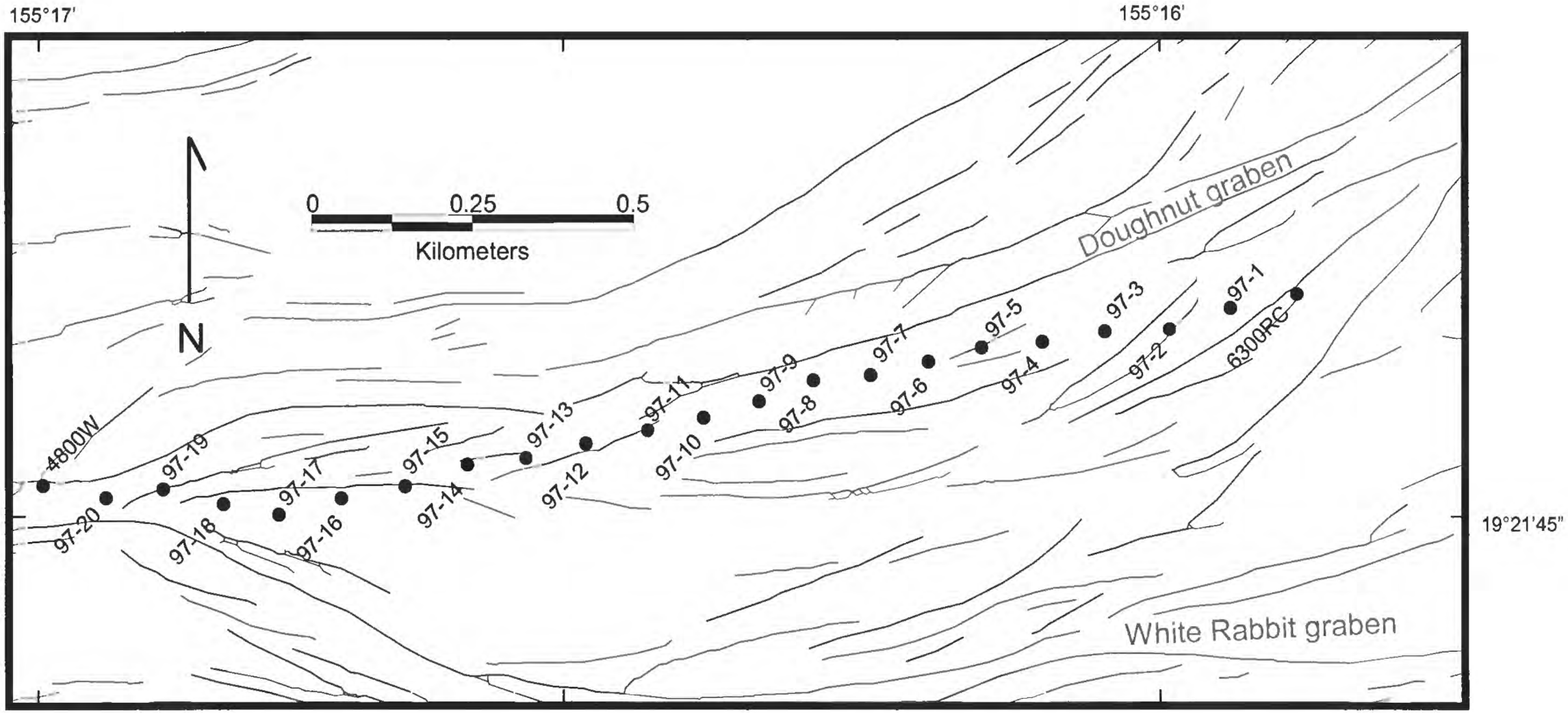


Figure 7. Crossline Level Line.

Mauna Iki Trail Level Line

This series of marks, part of HVO's summit leveling network located along the national park's Mauna Iki trail, connects the Western level line with the Lacy level line, a distance of 2.7 km (Fig. 8). This line can be leveled in 2.5 hours.

Table 6. Mauna Iki Trail level line station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	**OHD Lat. (°N)** *NAD83*	**OHD Long. (°W)** *NAD83*	**Comments**
BM79-520	19.34466 *2140197.82*	155.27791 *260978.70*	Standard aluminum benchmark about 11 m W of center of Hilina Pali Road at hairpin turn; about 30 m S of Kulanaokuaiki Pali. The Mauna Iki Trail line connects with the Central level line at this point
75-57R	19.34459 *2140190.37*	155.27813 *260955.48*	In pāhoehoe about 1 m S of trail and about 35 m W of center of Hilina Pali Road
75-62R	19.34571 *2140320.84*	155.28280 *260466.31*	In uneven pāhoehoe terrain, about 2 m N of trail
75-63R	19.34679 *2140442.67*	155.28442 *260297.64*	At top of small low tumulus about 10 m S of trail; no ahu
75-64	19.34783 *2140563.80*	155.28873 *259846.19*	In pāhoehoe about 0.5 m S of trail; no ahu
75-65			A rusted, non-tagged PK nail is here, but no bolt or tag was ever installed
75-66	19.34795 *2140586.34*	155.29537 *259148.54*	In flat pāhoehoe about 4 m N of trail
75-67R	19.34824 *2140623.98*	155.29933 *258732.78*	In pāhoehoe about 1 m S of trail; no ahu, no stick
75-68NR	19.34935 *2140752.71*	155.30350 *258296.16*	Carriage bolt and tag on W side of low tumulus, about 4 m E of trail; no ahu or stick. The Mauna Iki Trail line connects with the Lacy level line at this point
75-69R	19.35002 *2140831.48*	155.30678 *257952.44*	In flat pāhoehoe about 3 m W of trail and about 3 m S of break in trail slope
75-70NR	19.35261 *2141123.02*	155.31019 *257597.90*	In pāhoehoe along Mauna Iki trail. Small ahu, no stick

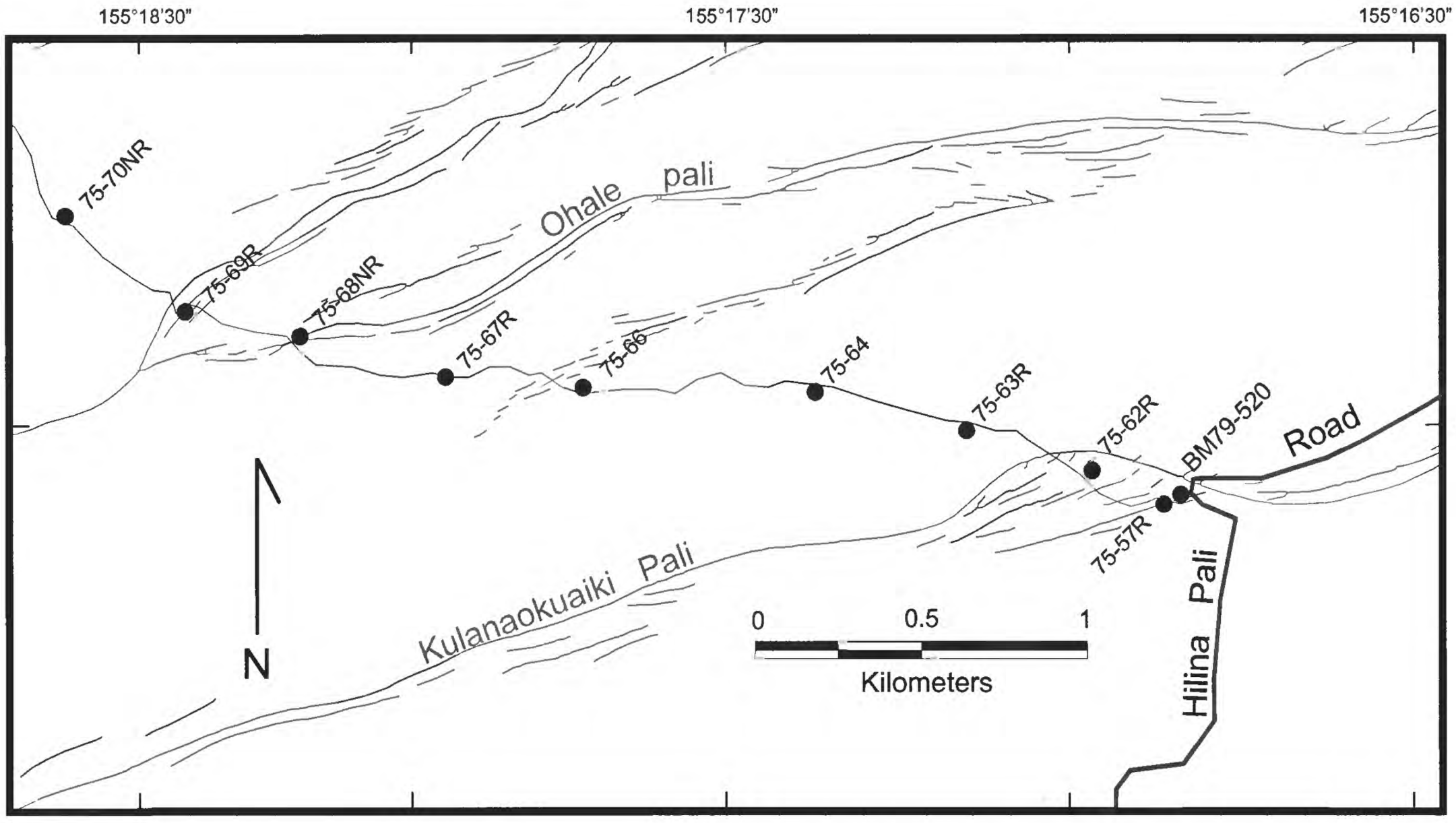


Figure 8. Mauna Iki trail level line.

EDM NETWORK

General Statement

We established and first measured the Koa'e EDM network (Fig. 9) in three stages: 1970 (established by D.A. Swanson and W.A. Duffield using tags stamped in 1968), 1991 (established by D.A. Swanson, R.S. Fiske, and E. O'Leary), and 1995 (established by D.A. Swanson, R.S. Fiske, and T.R. Rose). We describe these as the 1970, 1991, and 1995 EDM sub-networks. Mark-to-mark visibility is generally excellent, but eight lines in the forested northeastern part of the network will likely be blocked by vegetation and will require pre-survey clearing. These specific problems are noted in the tables below. However, if future measurements are made with instruments employing GPS technology, mark-to-mark intervisibility will be irrelevant. Only two of our EDM stations are sited at or near stations of HVO's island-wide GPS network (as configured in 2001). HVO-111, on top of Kulanaokuaiki Pali, is shared by both networks; HVO-114 is located 1 m north of a continuously recording GPS instrument maintained by HVO at Āhua Kamokukōlau. Since 1990, we used a "Lietz Red 1A" EDM and tripod-mounted corner-cube reflectors in our surveys. Extensive experience has shown that the precision of this instrument is 3-5 mm (with no ppm error for short distances) from one survey period to the next. All stations, unless otherwise noted, are stainless steel carriage bolts marked by a rock pile (ahu) built around a nearly vertical stick 50–70 cm high. In good weather, the entire EDM network can be measured in 6 days.

1970 EDM Sub-network

Table 7. 1970 EDM sub-network station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	**OHD Lat. (°N)** *NAD83*	**OHD Long. (°W)** *NAD83*	**Comments**
G-1	19.36721 *2142672.04*	155.26170 *262715.00*	About 2 m S of cracked zone at head of N-facing pali. About 150–200 m W of high point along pali rim.
113YY	19.38290 *2144430.69*	155.27730 *261098.63*	Standard aluminum benchmark cemented in large rock 2 m W of track road
HVO 111	19.35364 *2141163.12*	155.25694 *263195.56*	Standard aluminum benchmark in broad open area about 70 m S of Kulanaokuaiki Pali.
HVO 114	19.38224 *2144345.85*	155.26880 *261990.79*	Standard aluminum benchmark about 1 m N of HVO's continuously recording GPS station, AHUP; on top of prominent pāhoehoe tumulus. About 3 m S of Āhua Kamokukōlau trig station. Lines from this station to 133YY, 68-17, 68-13, 68-12, and 68-11 will be blocked by vegetation and need extensive clearing for EDM work.
HVO 131	19.38089 *2144221.13*	155.28664 *260114.30*	Standard aluminum benchmark on crest of tephra-covered, E -W trending spatter rampart W of track road.
HVO 132	19.39034 *2145265.09*	155.28499 *260301.53*	Standard aluminum benchmark, in rock protruding from tephra surface about 8 m E of track road.

HVO 134	19.38897 *2145119.80*	155.28958 *259817.25*	Standard aluminum benchmark on flat, broad ridge about 100 m W of major gully.
HVO 144	19.37894 *2144017.70*	155.29558 *259172.06*	Standard aluminum benchmark in small kīpuka in 1974 lava flow.
68-1	19.34474 *2140205.42*	155.27700 *261074.46*	In flat, bare pāhoehoe about 10 m S of Kulanaokuaiki Pali and about 50 m E of hairpin turn in the Hilina Pali Road where it crosses the pali. Care should be taken to confirm the tag number of this station, because two other bolts are located nearby.
68-2	19.35478 *2141313.30*	155.27434 *261368.65*	About 6 m S of, and on top of, N-facing Ohale pali. A good place to climb up this pali (when coming from the N) is about 50 m to the W.
68-3	19.35606 *2141445.22*	155.26724 *262116.64*	About 7 m S of, and on top of, N-facing Ohale pali. On top of fairly prominent rise as seen from the W.
68-4	19.35910 *2141774.64*	155.26205 *262666.46*	Broad high area about 6 m S of N-facing pali marking the S margin of the White Rabbit graben. Not a particularly conspicuous location.
68-5	19.36202 *2142124.94*	155.28160 *260616.27*	About 15 m SE of high point on rim of N-facing pali. About 50-75 m E of 5100RW in the Western level line.
68-6	19.36016 *2141913.58*	155.27769 *261024.44*	Station in cracked area, about 5 m S of largest crack and on top of high ramped area.
68-7	19.36288 *2142203.41*	155.26951 *261888.01*	On top of 3-m pali on steep N-facing slope, about 65 m S of topographic S rim of broad shallow graben.
68-11	19.37455 *2143490.30*	155.26578 *262296.93*	On top of tumulus about 15 m E of Āhua seismometer shed. Visibility to G-1 and 68-12 will be blocked by vegetation.
68-12	19.37503 *2143551.81*	155.27184 *261660.85*	On top of broad low tephra-covered pāhoehoe tumulus N of track road to Āhua seismometer station.
68-13	19.37512 *2143569.44*	155.27738 *261078.85*	On top of low pāhoehoe tumulus about 100-150 m S of track road to Āhua seismometer station.
68-14	19.36980 *2142980.17*	155.27719 *261091.06*	On top of steep, prominent tumulus surrounded by flat pāhoehoe and sand washes.
68-15	19.36697 *2142676.27*	155.28398 *260373.41*	On low tumulus about 100 m E of broad sand wash, and 10-15 m E of Western level line.
68-16	19.37465 *2143527.40*	155.28458 *260321.61*	On low tumulus with good view to W, about 200-250 m NW of W end of a small vegetated area

68-17	19.37817 *2143910.90*	155.28011 *260796.46*	On top of low pāhoehoe tumulus 20 m S of track road.
68-19R	19.34876 *2140635.54*	155.26618 *262217.44*	About 5 m S of top of Kulanaokuaiki Pali. Accessible from the N by climbing up rubble ramp constructed in the 1960's for herding feral goats. On top of the pali about 25 m W of the climb-up ramp, but one must pass through a fairly dense thicket to get there. On small pāhoehoe outcrop in grassy clearing.

1991 EDM Sub-network

Table 8. 1991 EDM sub-network station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	**OHD Lat. (°N)** ***NAD83***	**OHD Long. (°W)** ***NAD83***	**Comments**
NOSE	19.38679 *2144899.39*	155.30456 *258240.08*	Standard aluminum benchmark on prominent point with good views to the S.
Ohale Offset	19.35391 *2141223.63*	155.27914 *260862.94*	Carriage bolt set in triangular concrete pad, offset 64 cm from trig station metal flag. At top of broad and very prominent tumulus.
91-1	19.36632 *2142618.10*	155.29388 *259332.13*	On top of fairly prominent tumulus in hummocky pāhoehoe area; about 100-150 m E of narrow tongue of 1974 'a'a and slabby pāhoehoe.
91-2	19.37007 *2143042.53*	155.30050 *258642.00*	On high knob in small kīpuka surrounded by 1974 flow.
91-3	19.36116 *2142055.95*	155.30042 *258637.27*	On top of long N-S tumulus, with 1974 flow only 50 m or less to N. SE of large NE-SW trending kīpuka in 1974 flow
91-4	19.37057 *2143111.07*	155.30989 *257656.01*	About 20 m W of 1974 flow and about 50 m SW of conspicuous 1974 spatter rampart.
91-5	19.34721 *2140519.63*	155.30625 *258003.99*	On top of broad, 5 m-high tumulus about 200 m S of highly cracked N-facing pali.
91-6	19.35443 *2141307.42*	155.29798 *258883.77*	On low tumulus in generally high area about 100 m S of prominent N-facing pali. About 10 m E of entrance to lava tube.
91-7	19.33882 *2139587.29*	155.30380 *258249.10*	Near crest of large tumulus 150 m S of wide crack at top of Kulanaokuaiki Pali.
91-8	19.34085 *2139796.36*	155.29257 *259432.38*	On top of low tumulus in hummocky area, about 250 m SE of subdued Kulanaokuaiki Pali. Can be difficult to find.

91-9	19.37671 *2143792.90*	155.31134 *257512.75*	In flat area about 4 m S of small tumulus with thick entrail ooze-outs. 500 m NNW of large sand wash.
91-10	19.38379 *2144584.95*	155.31714 *256913.81*	In 1971 lava flow, about 30 m SE of vent fissure of conspicuous 1971 spatter cone.
91-11	19.37036 *2143099.41*	155.31812 *256790.88*	In small outcrop of ʻaʻa surrounded by much sand. About 3 m W of rebar. A 1.2 m high ahu made of flat pāhoehoe slabs is 35 m to the SE. Ahu is easily seen on W side of the broad sand wash while driving southward on track road toward Puʻu Koaʻe.
91-12	19.36390 *2142379.63*	155.31490 *257119.65*	Carriage bolt and tag in flat sandy pāhoehoe surface.
91-13	19.36080 *2142000.62*	155.28934 *259801.11*	On top of NW-facing pali at highest point for some distance along pali top. Located within topographic contour labeled 3327 on the Kaʻū Desert quadrangle. Ahu and stick.
91-14	19.34738 *2140514.67*	155.28923 *259792.99*	On SE summit of large compound tumulus; elevation of 3321 is labeled on the Kaʻū Desert quadrangle.
91-15	19.35592 *2141490.59*	155.31097 *257520.82*	In crusty 1974 pāhoehoe at top of broad NE-SW-trending ridge.
91-16	19.34296 *2140010.74*	155.27873 *260890.04*	Top of prominent tumulus; relatively large ʻōhiʻa trees nearby. About 240 m WSW of hairpin curve where the Hilina Pali Road crosses the Kulanaokuaiki Pali.

1995 EDM Sub-network

Table 9. 1995 EDM sub-network station descriptions. The coordinates for each mark are referenced both to the Old Hawaiian datum (OHD) and the NAD83 zone 5 datum (in italics).

Mark	**OHD Lat. (°N)** *NAD83*	**OHD Long. (°W)** *NAD83*	**Comments**
95-1	19.38759 *2145008.51*	155.31915 *256708.27*	On top of low tumulus 150–200 m SE of Kaʻū Desert Trail.
95-2	19.39583 *2145925.82*	155.32269 *256348.60*	On sand-covered pāhoehoe along an azimuth of about 159° from station 95-1. Difficult to find.
95-3	19.38520 *2144753.50*	155.32594 *255991.26*	About 35 m SW of the Lacy Level Line and BM79-104. NW of Kaʻū Desert trail and just W of large sand-filled fissure.

95-4	19.39400 *2145735.91*	155.33165 *255404.45*	On low tumulus in area of many low tumuli. Station is on one of the higher tumuli in scrub ʻōhiʻa area where all the trees look very much alike. Located NW of large sand flat. Difficult to find.
95-5	19.40281 *2146703.70*	155.32627 *255982.88*	On very top of sharp-peaked, dark driblet cone that stands prominently above surroundings. No rock pile or wood stick here.
95-6	19.39382 *2145685.81*	155.31031 *257646.34*	On E side of Cone Peak structure on knife-edge ridge near its southern high point. SSE of Cone Peak trig station. Marked with small ahu built in 2000 that may not survive high winds.
95-7	19.40310 *2146717.22*	155.31312 *257364.89*	On EW-trending linear ash-covered ʻaʻa ridge in slabby pāhoehoe flow about 100 m from S edge of flow
95-8	19.40753 *2147211.26*	155.31565 *257105.67*	In pāhoehoe near SW end of long, narrow, fairly prominent NE-SW trending tumulus. Nineteenth century trail is 50-75 m further W
95-9	19.38146 *2144335.92*	155.32347 *256245.22*	On cracked tumulus several meters SW of 91-106 of the Lacy Level Line.

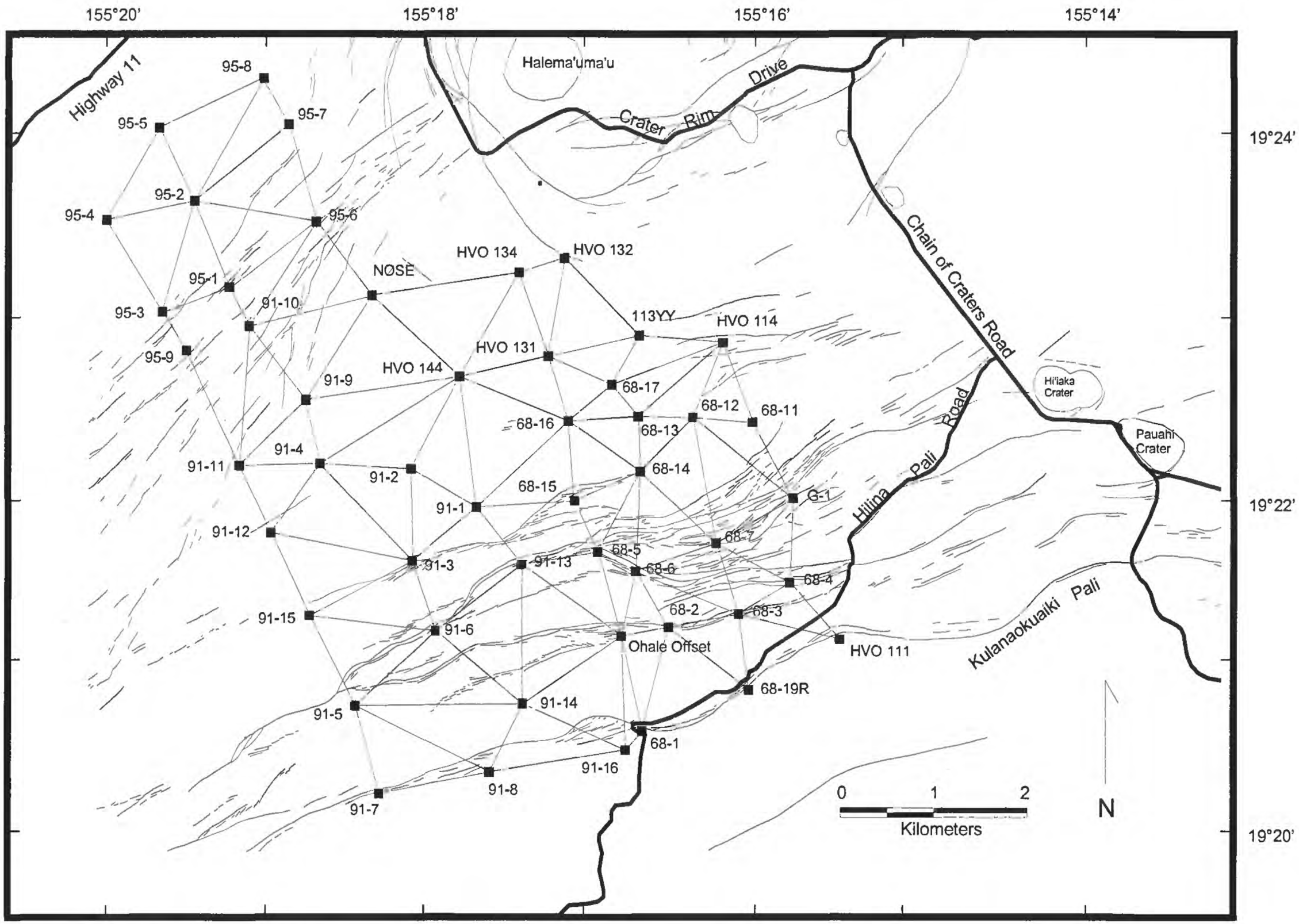


Figure 9. Koa'e EDM network.

CRACK STATIONS

General Statement

R.S. Fiske and D.A. Swanson installed more than 30 crack-monitoring stations in 1966–1971, but only nine of these have survived (stations 1, 2, 9R, 10R, 11R, 12R, 14R, 15R, and 16R). We established 12 new stations in 1998 and one in 2000, making a total of 22 that are documented in this open file report (fig. 10).

We established the crack stations with simplicity in mind. All mark-to-mark distances can be measured by two people with a 30–m steel tape, excepting line A-B at 98-10 (which is 30.8 m long), and line A-B at 98-11 (which is about 84 m long and must be measured electronically). Unless otherwise noted in the crack station sketches, the tape does not touch (skim) the ground when held taut during measurement. Repeat taping shows measurement precision to be ±7 mm at the 98% confidence level. Much of this error can be attributed to differences in tension applied to the tape and to the precision with which the rulings on the tape are held above the reference marks on the carriage bolts. Taped measurements will probably be of questionable value in monitoring low rates of creep on Koa'e structures, but they will provide a rapid and reasonably precise measure of centimeter-scale (or greater) changes associated with specific structural events.

We also leveled mark to mark (on select marks) at each station to obtain relative differences in elevation. Two people can do the leveling, but it is a relatively slow process requiring the person holding the leveling rod to be involved with both backsight and foresight readings. Preferably, a 3– or 4–person crew should do the leveling.

It takes 30–90 minutes to level and tape individual crack stations, depending on the complexity of the site. Measurement of the entire 22–station network, including walking time to and from the stations, takes 3-4 very full days. An important advantage of the crack-monitoring network is that any one or more stations can be spot checked if localized motion in the Koa'e fault system is suspected. The entire crack-monitoring network need not be surveyed unless widespread deformation has taken place.

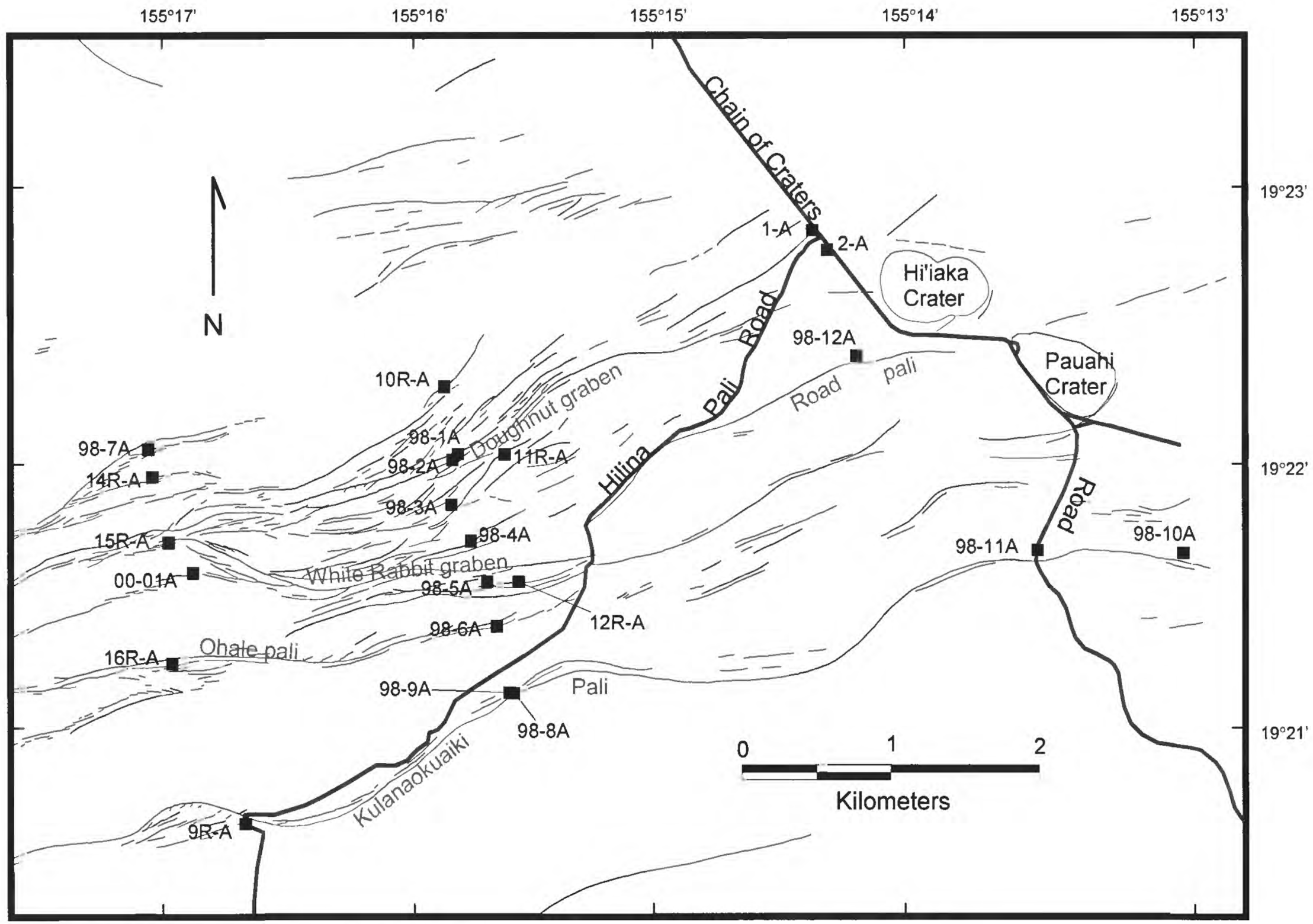


Figure 10. Koa'e Crack Monitoring Network.

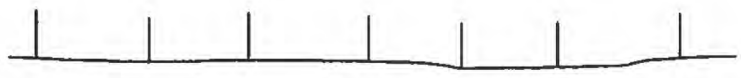
Crack Station Sketches

Figures 11-30 show sketches and descriptions of each station, and GPS coordinates of Bolt A referenced to both the Old Hawaiian datum (top) and the NAD83 zone 5 datum (bottom, in italics). The line distances shown on each sketch have been rounded to the nearest tenth of a meter and are presented for station recovery purposes only. The data tables accompanying each sketch show measurements made in May 1998 (except station 00-01, which shows measurements made in August 2000). Height differences in parentheses were not measured directly but are calculated from nearby measurements for closed circuits. Local structural features are depicted as follows:

- **Narrow cracks** not associated with a larger structure are shown as single lines, though some may be labeled as wider cracks

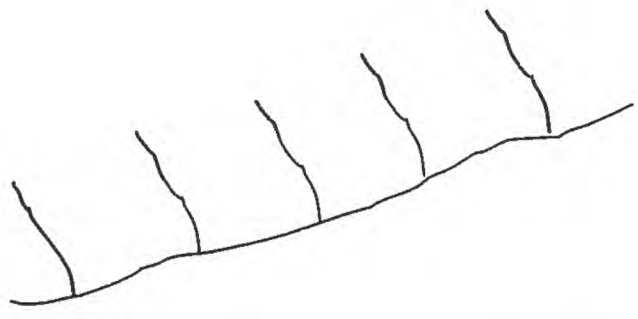
- **Wide cracks** are shown as either parallel lines with hachures pointing toward the crack center or as enclosed lines without hachures. If a wide crack is drawn by a single line, it is labeled as wide.

- A **Pali** is shown as a single line denoting the pali top, with hachures pointing toward the pali face.



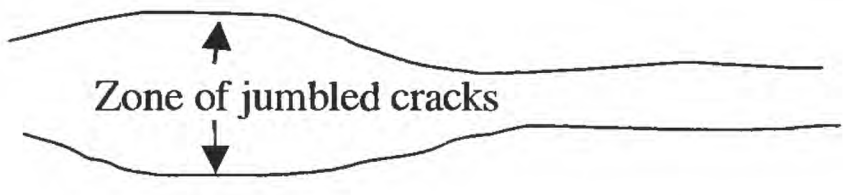
N-facing pali

- **Ramps and thrusts** are portrayed similar to palis but with longer perpendicular lines. In complex sketches, they may be denoted only by a label with arrows defining the ramp boundaries



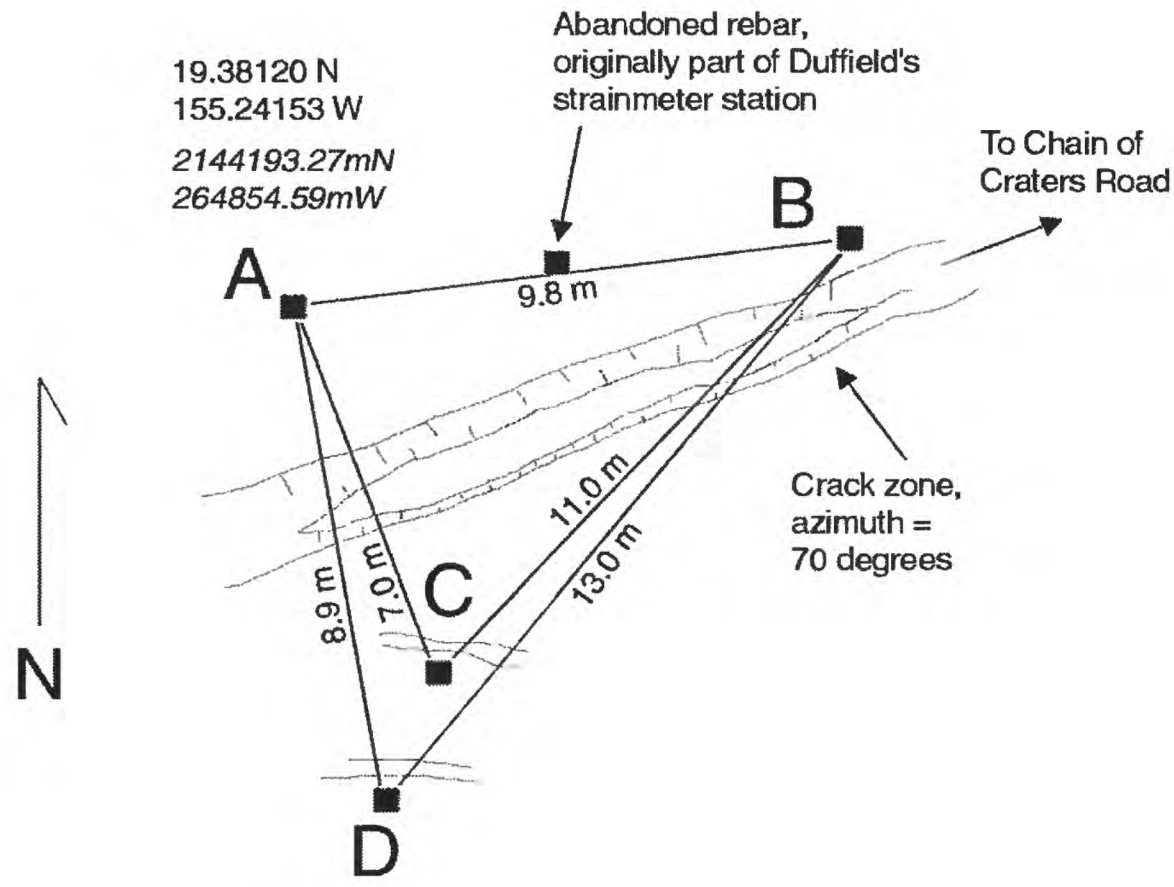
NW-facing thrust

- **Zones of cracks or jumbled rocks** are denoted by arrows, with or without drawn boundaries



Station 1

Spans gaping cracks at a site about 15 m SW of Chain of Craters Road and about 75 m NW of junction with Hilina Pali Road. Area is moderately brushy. All marks are 1966 vintage PK nails set into top of 1-inch square rebars cemented into rock. Note: An identical rebar, with affixed PK nail, is located near the midpoint of A-B. This was installed by W.A. Duffield in 1970 as part of a continuously operating strainmeter. This strainmeter has been abandoned, and the rebar is not part of this crack station.

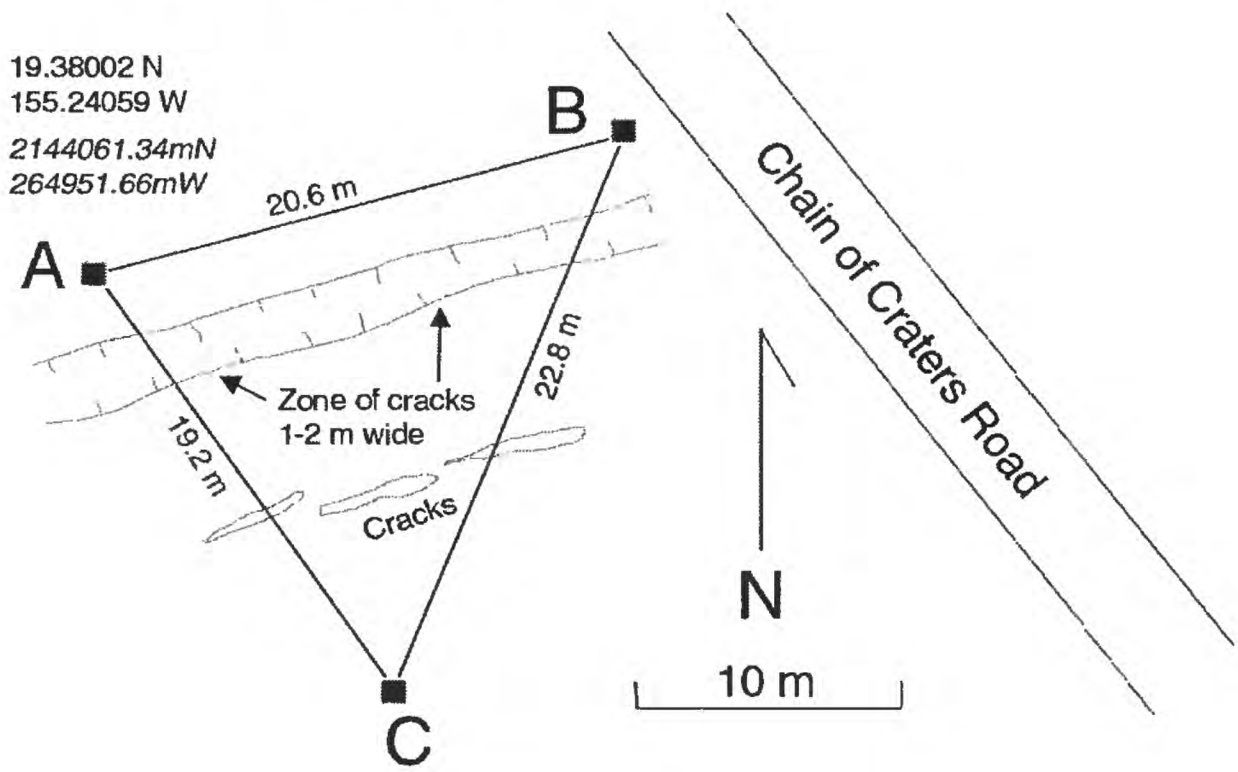


Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
1B to 1A	263	9.780	0.2295
1B to 1C	224	10.977	(-.7786)
1C to 1A	340	6.990	1.0081
1D to 1A	350	8.927	0.9406
1B to 1D	219	12.987	(-.7711)

Figure 11. Crack monitoring station 1.

Station 2

Spans a crack zone about 15 m SW of Chain of Craters Road; this fault zone passes just to the SE of Devil's Throat. All marks are 1966 vintage PK nails set into top of 1-inch square rebars cemented into rock. Area is open and nearly brush free.

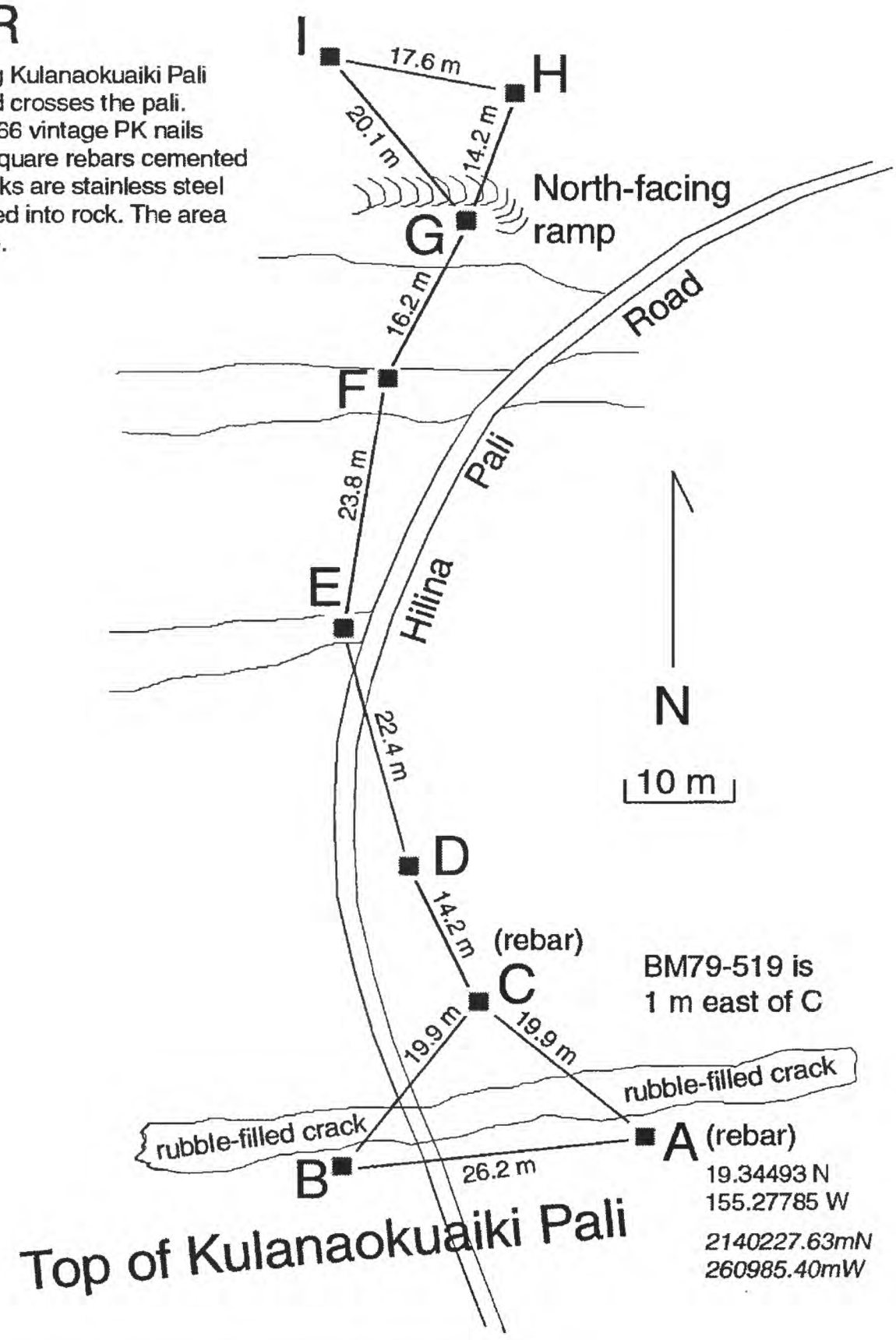


Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
2A to 2B	75	20.560	-0.5245
2A to 2C	145	19.155	-1.8467
2C to 2B	22	22.816	(1.3222)

Figure 12. Crack monitoring station 2.

Station 9R

Spans the north-facing Kulanaokuaiki Pali where Hilina Pali Road crosses the pali. Marks A and C are 1966 vintage PK nails set into top of 1-inch square rebars cemented into rock; all other marks are stainless steel carriage bolts cemented into rock. The area is open and brush free.

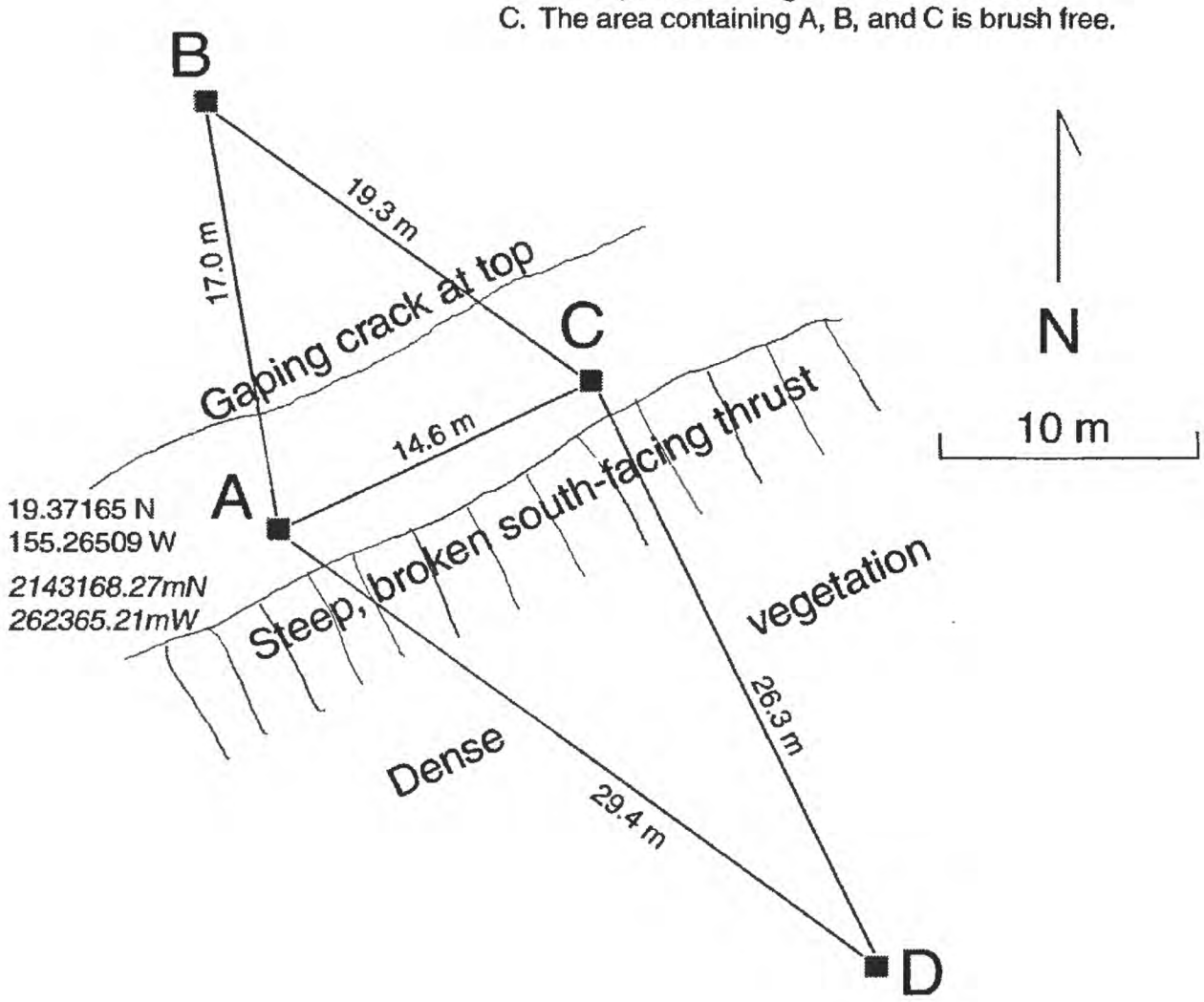


Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
C to B	218	19.910	2.7902
C to A	129	19.850	(4.1608)
B to A	80	26.192	1.3706
C to D	334	14.175	-1.5013
D to E	345	22.435	0.1685
E to F	9	23.802	-1.3834
F to G	28	16.170	-1.3332
G to H	24	14.174	-1.6394
G to I	321	20.141	(-2.6918)
H to I	281	17.565	-1.0524

Figure 13. Crack monitoring station 9R.

Station 10R

Spans steep south-facing pali that marks the northern boundary of the Koa'e fault system in this area. Located about 135 m SE of 3900RC of the Central level line. All marks are stainless steel carriage bolts cemented into rock. Lines A-D and C-D are brushy near D, and D is likely hidden in tall grass. Line C-D passes through tree branches near C. The area containing A, B, and C is brush free.

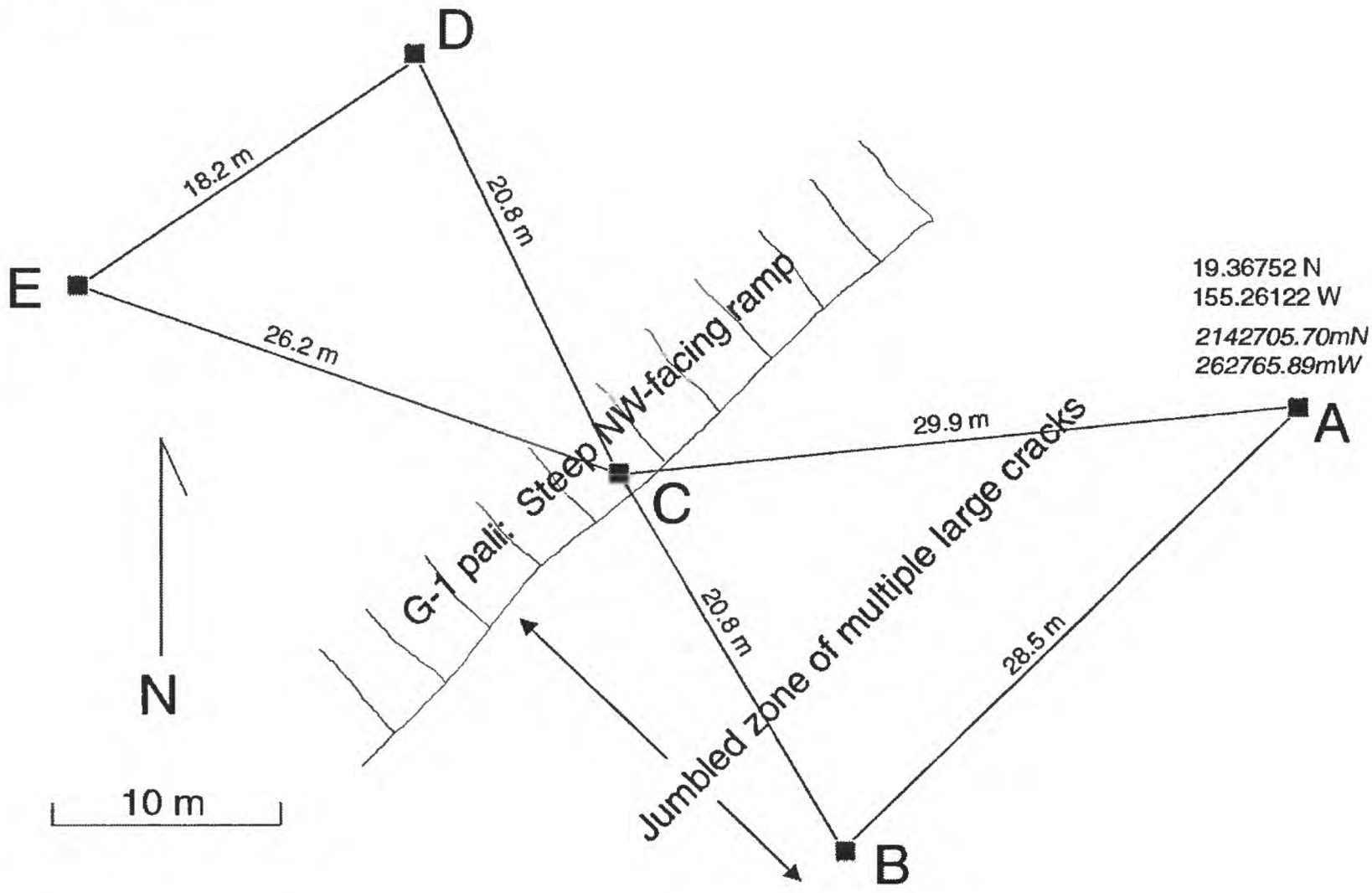


Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
A to D	127	29.355	-6.1977
D to C	339	26.296	(7.6321)
B to C	126	19.275	0.1273
C to A	245	14.629	-1.4344
B to A	170	16.988	(-1.3071)

Figure 14. Crack monitoring station 10R.

Station 11R

Spans north-facing ramp/pali marking the south side of the Doughnut graben; located about 60 m NE of EDM station G-1. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.

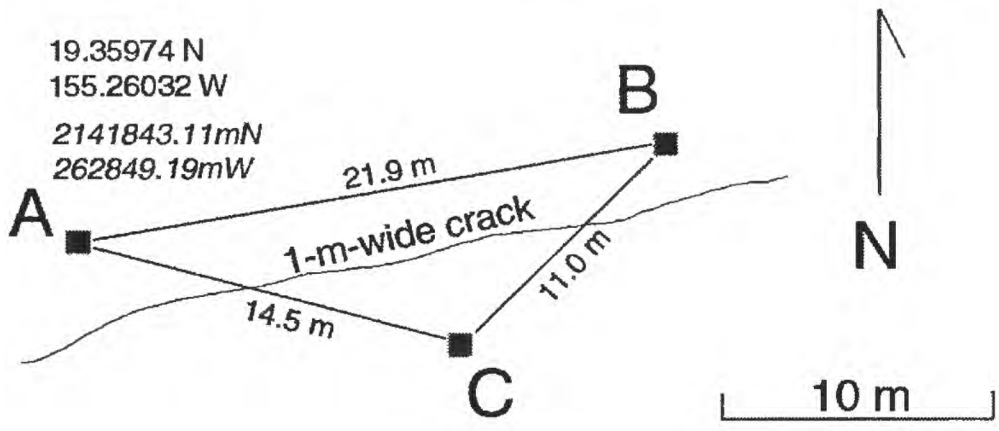


Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
A to B	225	28.459	-1.3451
A to C	264	29.900	(-.5714)
C to B	160	20.763	-0.7737
E to C	110	26.230	(4.9759)
D to C	155	20.938	4.0243
E to D	52	18.240	0.9516

Figure 15. Crack monitoring station 11R.

Station 12R

Spans gaping 1-m crack near middle of White Rabbit graben zone about 230 m E of 8400RC on the Central level line. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.

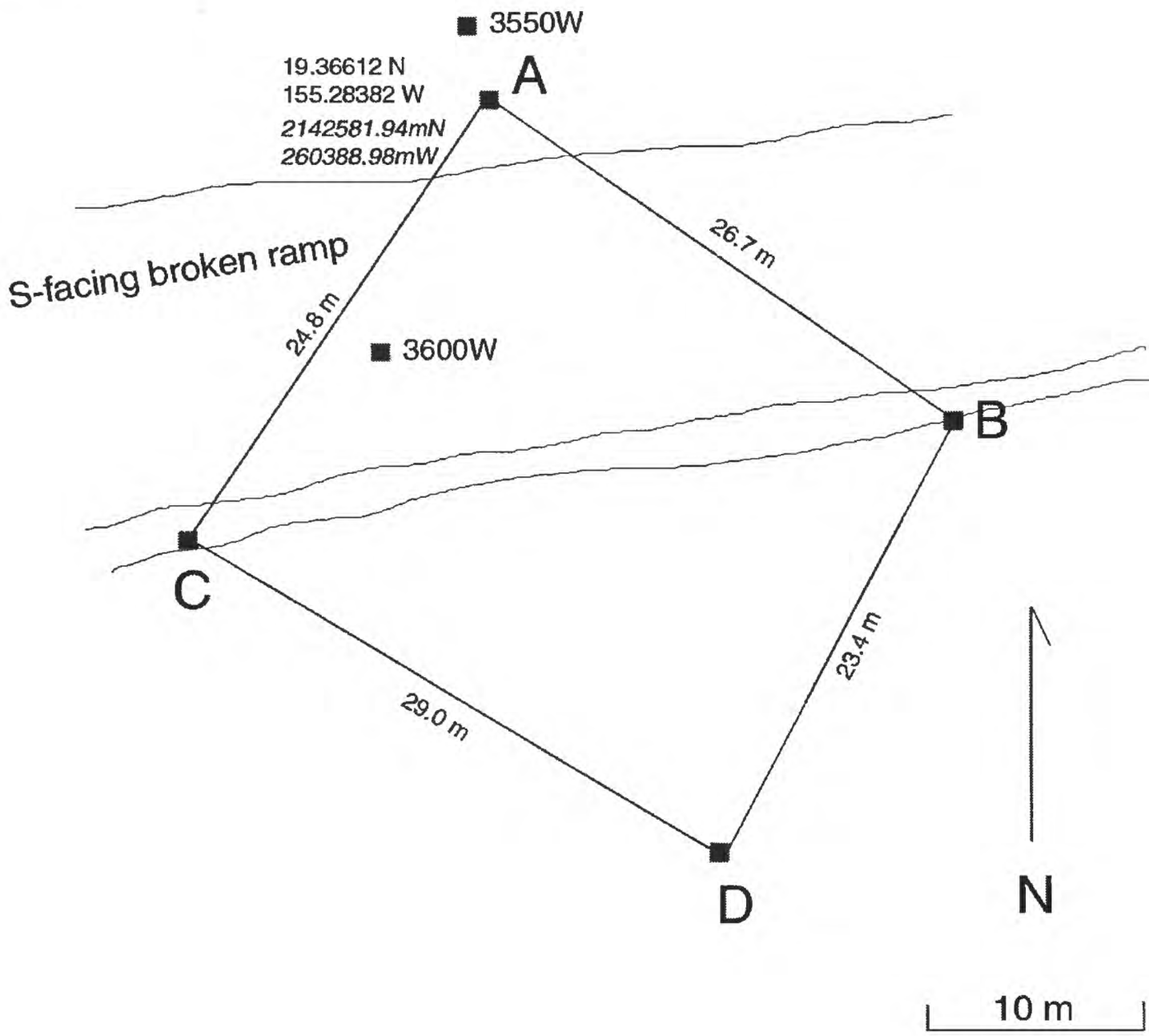


Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
A to B	80	21.898	-0.3730
A to C	105	14.549	(-.9549)
B to C	225	11.031	-0.5819

Figure 16. Crack monitoring station 12R.

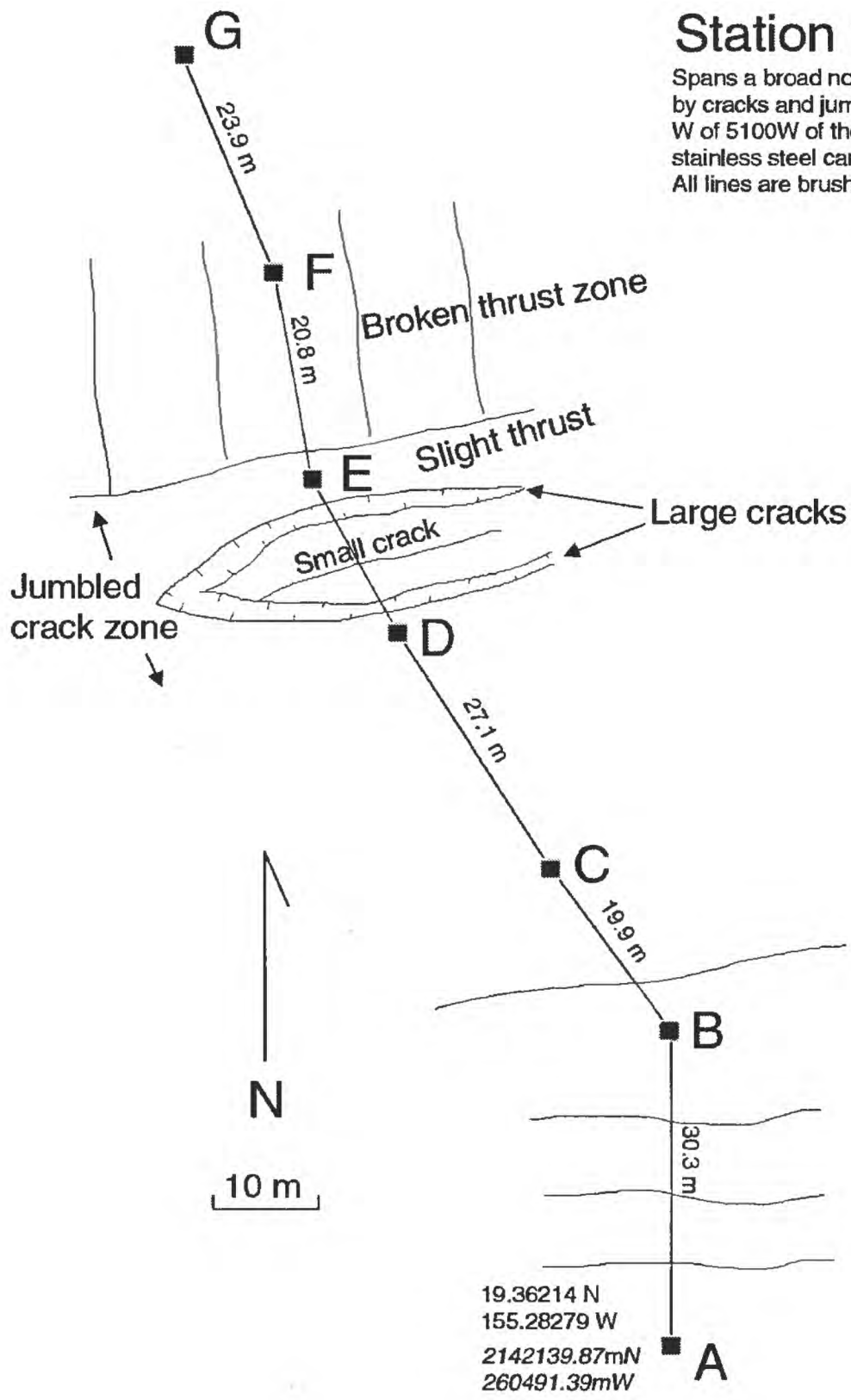
Station 14R

Spans broken south-facing ramp in northern part of the Koa'e fault zone; 3600W of the Western level line is located near middle of station. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.



Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
C to D	121	28.960	-1.4528
D to B	28	23.417	1.6706
B to A	305	26.675	2.6542
C to A	35	24.790	-5.7775

Figure 17. Crack monitoring station 14R.



Station 15R

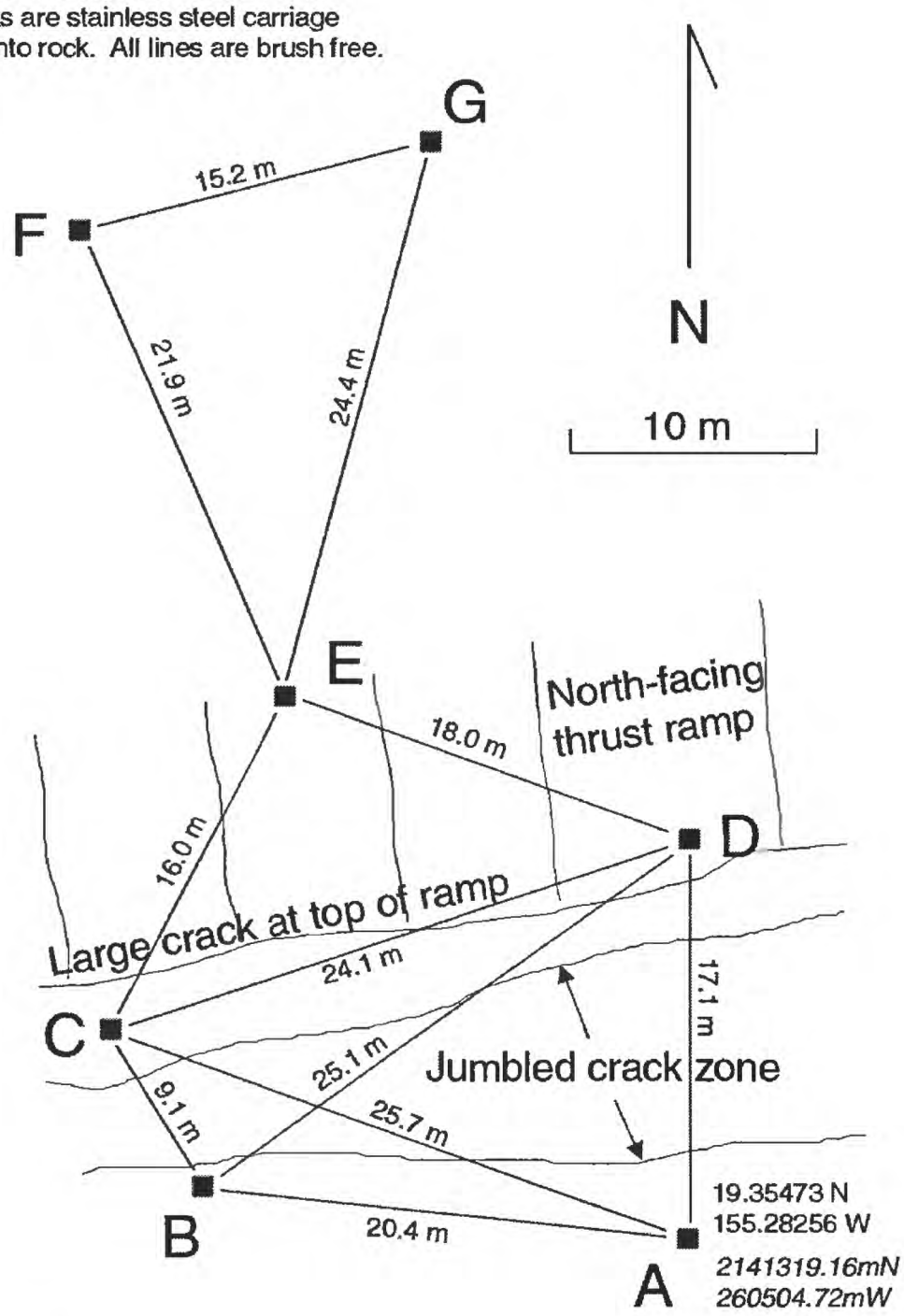
Spans a broad north-facing ramp, moderately broken by cracks and jumbled zones. A is located 25 m W of 5100W of the Western level line. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.

Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
F to G	338	23.930	-3.7348
E to F	350	20.765	-5.3617
D to E	332	17.492	-1.7541
C to D	328	27.137	-1.4686
B to C	324	19.915	-3.4210
A to B	0	30.264	-1.6839

Figure 18. Crack monitoring station 15R.

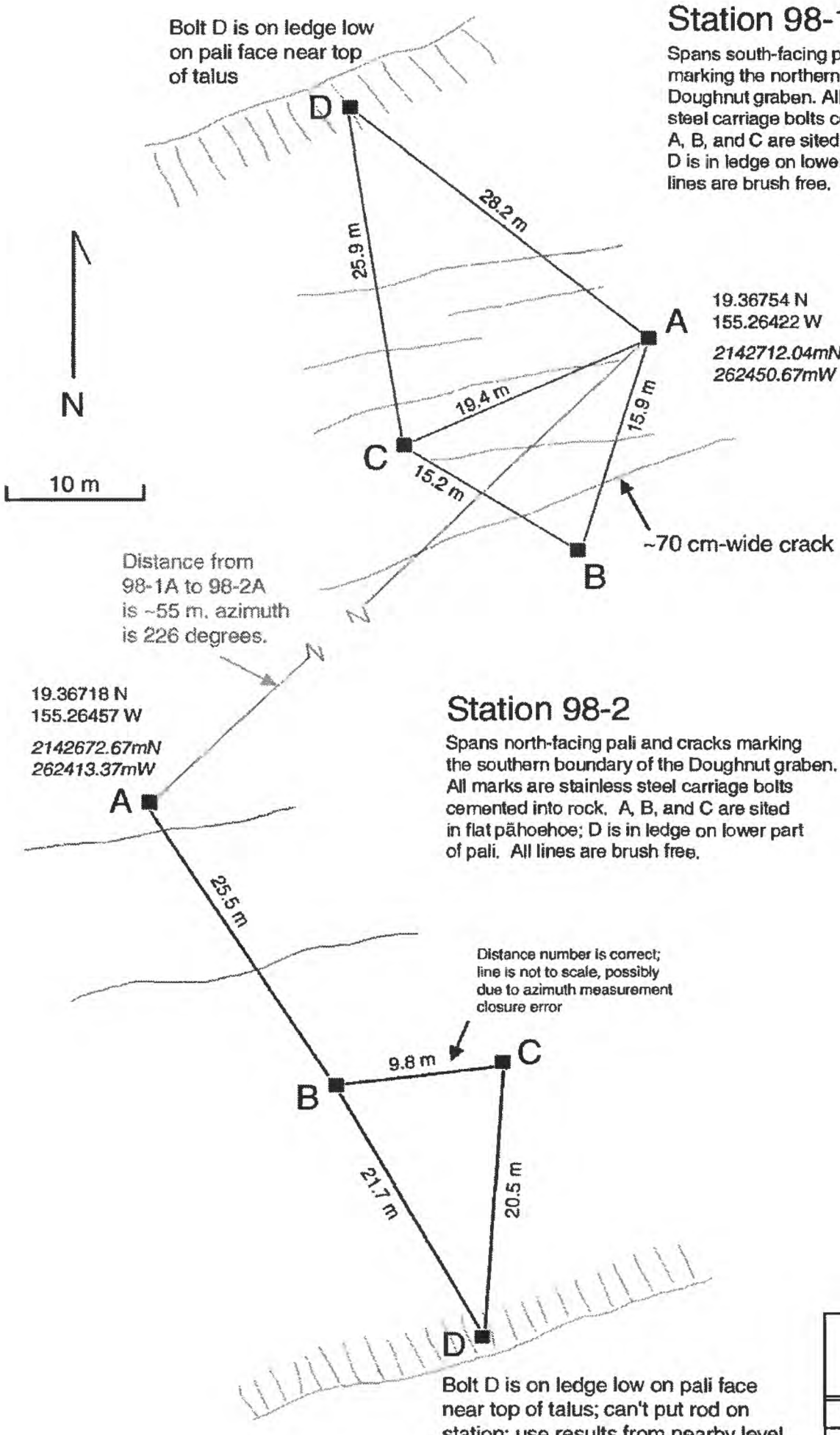
Station 16R

Spans north-facing Ohale pali about 240 m W of Western level line between 7500W and 7800W. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.



Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
G to F	256	15.200	-0.2218
G to E	195	24.358	3.6674
F to E	153	21.900	(3.8892)
D to E	290	18.024	-2.6433
C to E	27	15.980	(-3.5388)
C to D	75	24.079	(-.8955)
B to D	54	25.123	(-1.1247)
A to D	0	17.090	-0.9945
B to A	95	20.430	-0.1302
C to A	115	25.708	(0.099)
C to B	161	9.120	0.2292

Figure 19. Crack monitoring station 16R.



Station 98-1

Spans south-facing pali and cracks marking the northern boundary of the Doughnut graben. All marks are stainless steel carriage bolts cemented into rock. A, B, and C are sited in flat pāhoehoe; D is in ledge on lower part of pali. All lines are brush free.

Station 98-2

Spans north-facing pali and cracks marking the southern boundary of the Doughnut graben. All marks are stainless steel carriage bolts cemented into rock. A, B, and C are sited in flat pāhoehoe; D is in ledge on lower part of pali. All lines are brush free.

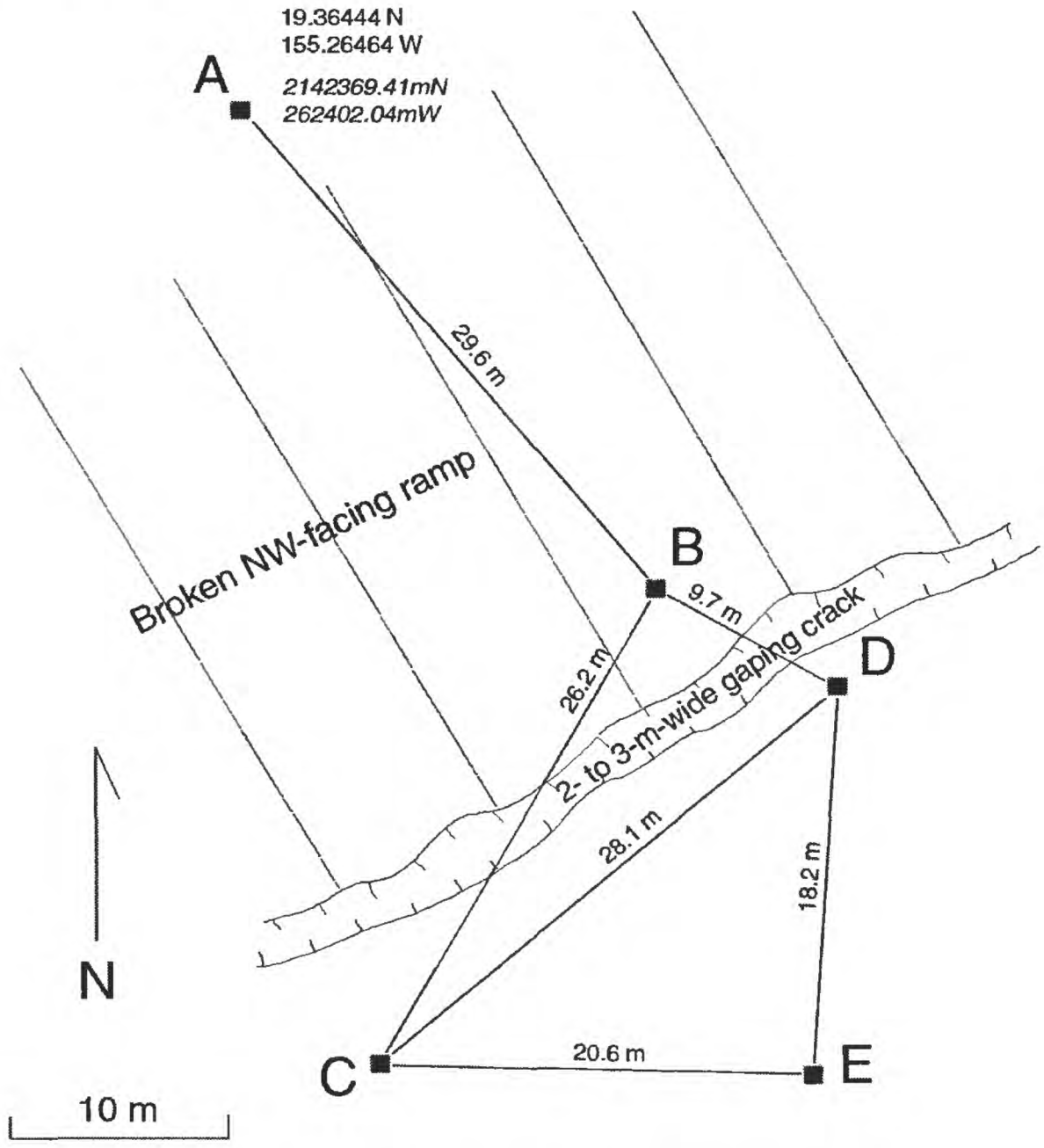
Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
1A to 1B	200	15.920	-0.5149
1C to 1B	120	15.233	(1.2432)
1C to 1A	69	19.410	1.7581
1D to 1A	133	28.162	(.3579)
1D to 1C	180	25.910	-1.4002
1C to 2A	no data	no data	-0.9937
2D to 2B	330	21.668	(-.4706)
2D to 2C	4	20.493	-0.2136*
2B to 2C	80	9.769	0.2570
2A to 2B	147	25.525	-0.3135

*2000 data obtained with tape measure held vertically on station; did not level this in 1998

Figure 20. Crack monitoring stations 98-1 and 98-2.

Station 98-3

Spans broad north-facing ramp and associated cracks. Located about 60 m SW from 6530C on the Central level line. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.

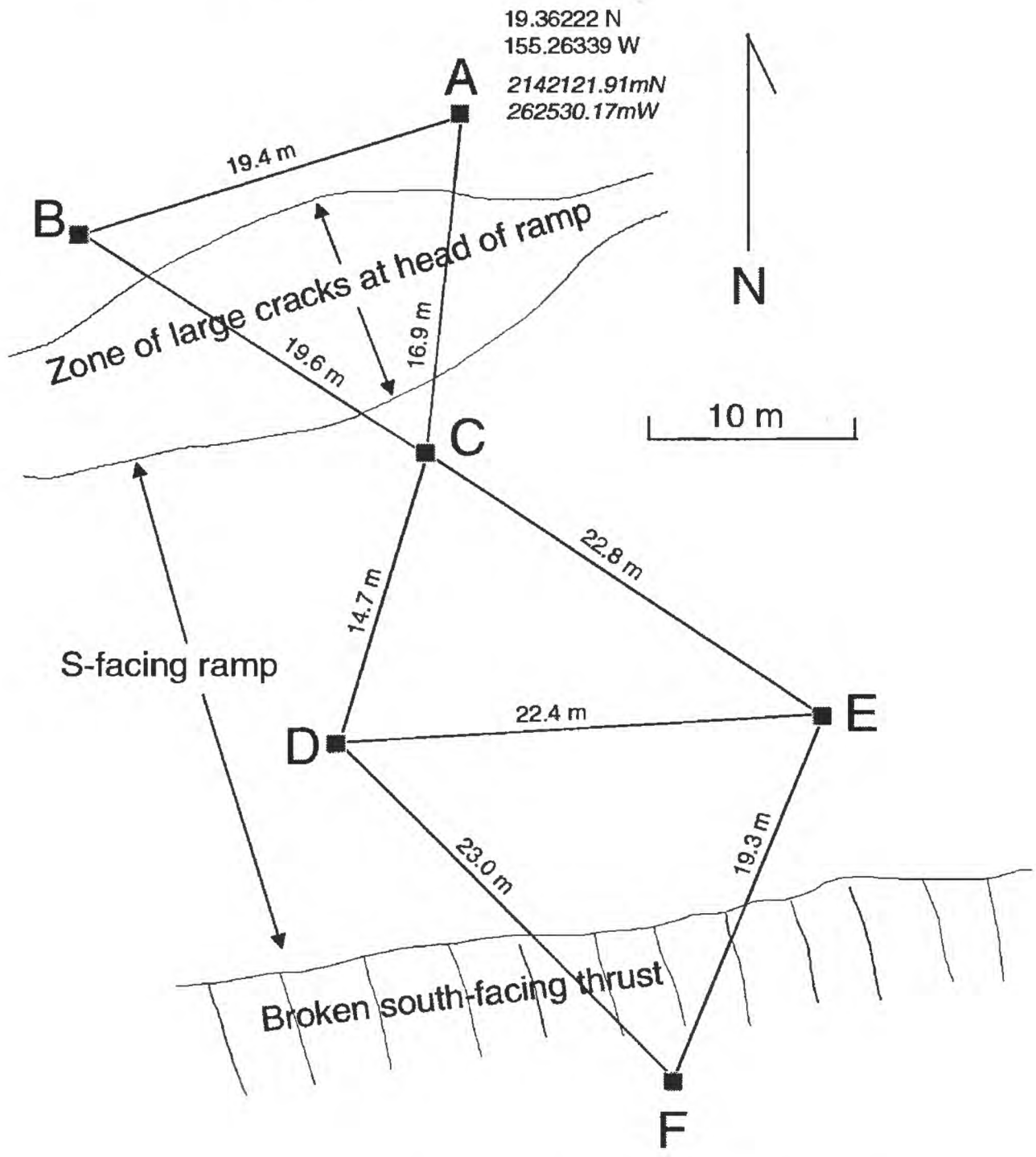


Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
E to C	270	20.554	(.1434)
D to E	184	18.171	-0.7036
D to C	230	28.140	-0.5602
D to B	114	9.695	(-.9959)
C to B	30	26.215	-0.4357
A to B	140	29.593	5.3617

Figure 21. Crack monitoring station 98-3.

Station 98-4

Spans low south-facing ramp and cracks marking the northern boundary of the White Rabbit graben. 7500RC of the Central level line lies about 13 m N of A. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.



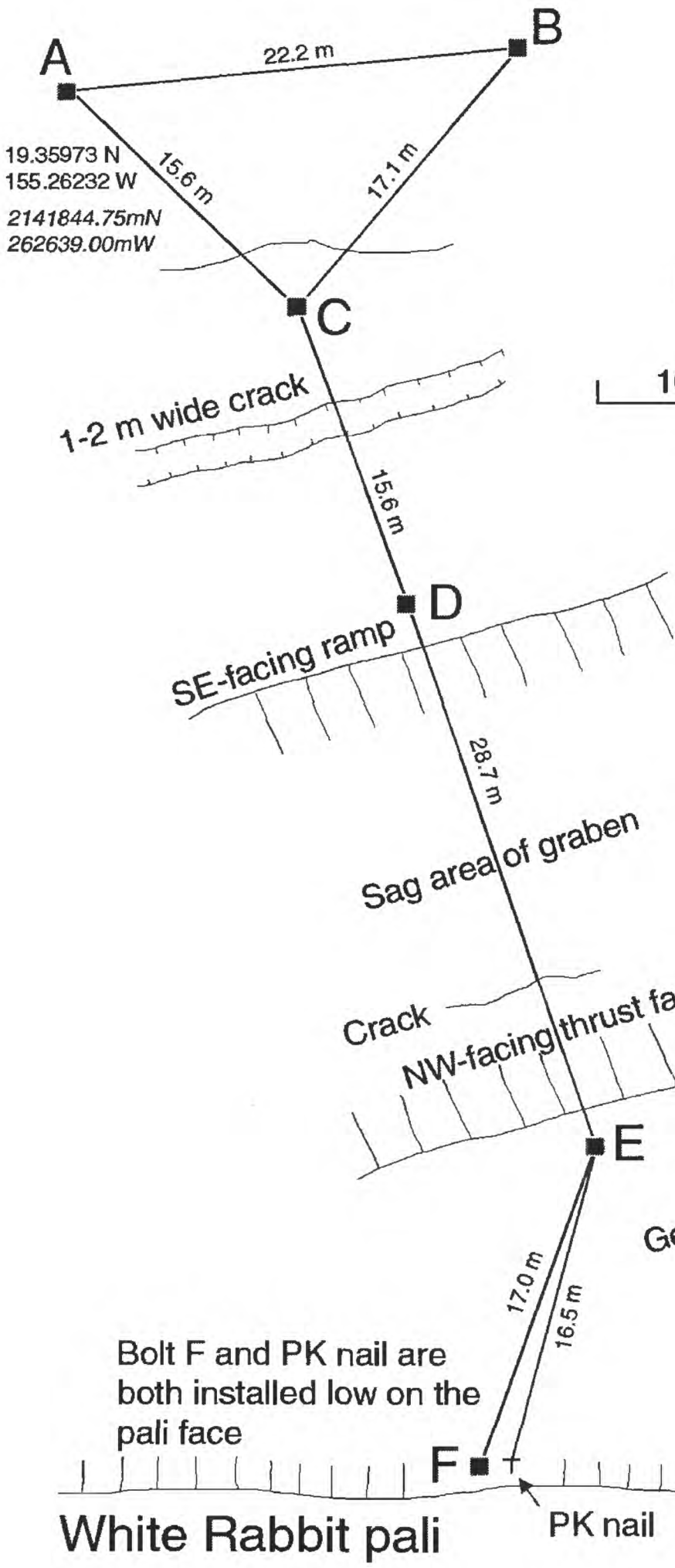
Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
F to E*	22	19.304	(3.6560)
F to D*	316	23.029	3.2617
E to D	265	22.390	-0.3943
E to C	304	22.810	1.8147
D to C*	10	14.678	(2.2090)
C to A	6	16.900	(1.4765)
C to B*	303	19.615	0.5181
A to B	252	19.360	-0.9584

*Tape skimmed surface

Figure 22. Crack monitoring station 98-4.

Station 98-5

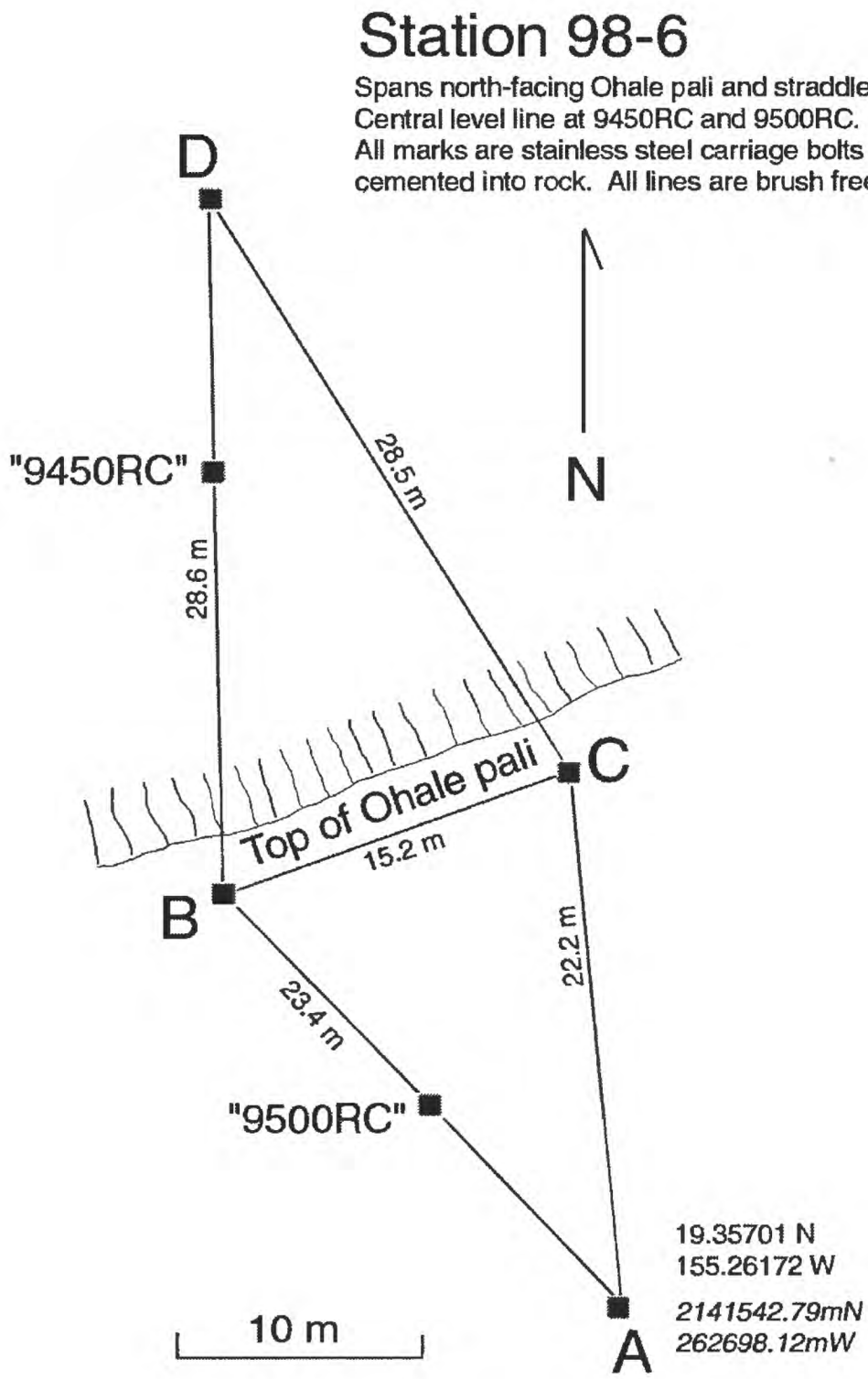
Extends northward from near-vertical pali marking the southern boundary of the White Rabbit graben. A is located about 54 m SE of 8400RC of the Central level line. A to E are stainless steel carriage bolts cemented into rock. F is a stainless steel carriage bolt cemented into narrow ledge on pali face. Because this bolt is subject to damage from falling rock, we hammered a PK nail into another small ledge just to the east, providing redundancy for this site. All lines are brush free.



Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
F to E	20	16.977	-1.7790
PK nail to E	--------	16.546	-1.5707
E to D	341	28.736	2.1179
D to C	340	15.639	1.5488
C to A	314	15.607	(2.0994)
B to C	220	17.073	-1.7813
B to A	265	22.192	0.3181

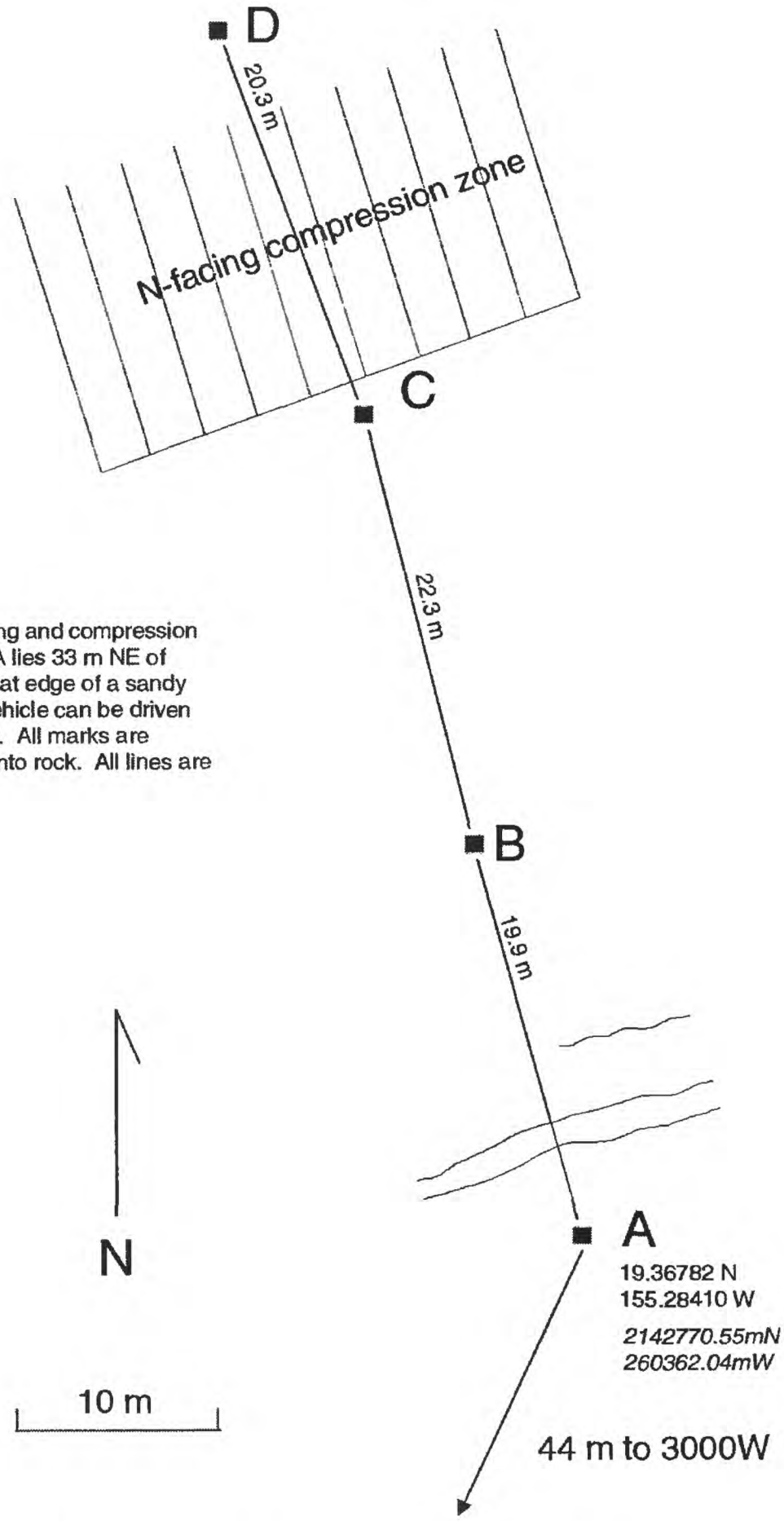
*Note: Foresights on bolt F and PK nail are on metal tape measure held vertically on both; irregularities on pali face prohibit use of leveling rod; error = +/- 5 mm

Figure 23. Crack monitoring station 98-5.



Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
A to B	317	23.394	0.5858
A to C	355	22.164	(1.9947)
B to C	68	15.151	1.4089
B to D	359	28.550	(-1.0269)
C to D	330	28.544	-2.4358

Figure 24. Crack monitoring station 98-6.



Station 98-7

Spans broad north-facing zone of cracking and compression at northern margin of Koa'e fault zone. A lies 33 m NE of 3000W on the Western level line. D lies at edge of a sandy drainage, down which a 4-wheel drive vehicle can be driven (from the NE) to within about 100 m of D. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.

Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
7D to 7C	159	20.345	3.5624
7C to 7B	166	22.310	1.7603
7B to 7A	165	19.195	-0.0736
7A to W3000R	205	~44	-1.6494

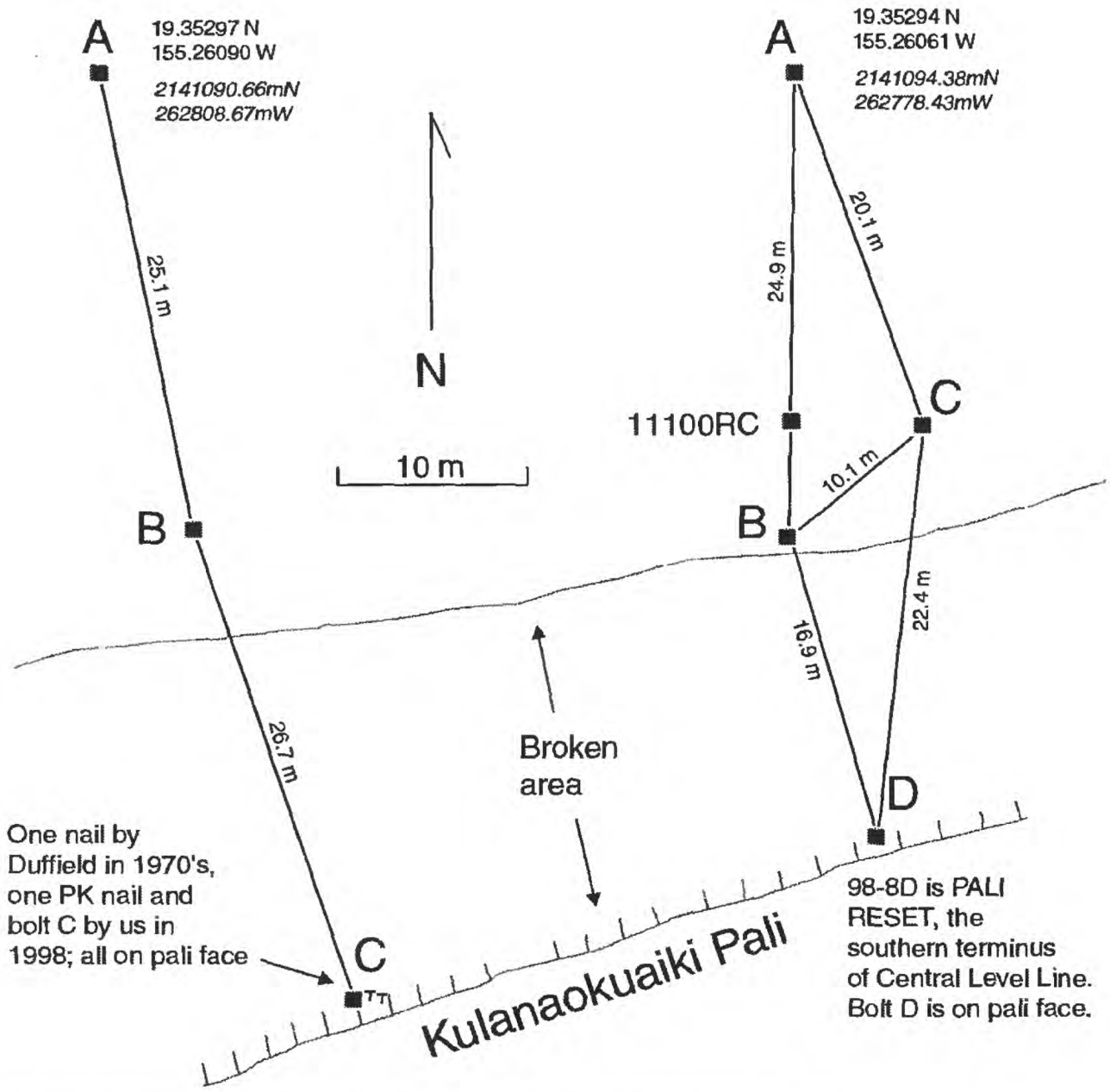
Figure 25. Crack monitoring station 98-7.

Station 98-9

Spans the Kulanaokuaiki Pali at a site about 30 m west of crack station 98-8. A and B are stainless steel carriage bolts cemented into rock; C is a similar bolt cemented into narrow ledge on pali face. We tape the distance from B to C and to two PK nails hammered into rock just to the east (for rsdundancy). Loose rubble and overhanging cliff pravent us from leveling from B to any of the three marks on the pali face. All lines are brush free.

Station 98-8

Spans the Kulanaokuaiki Pali at the south end of the Central level line. 11100RC on the Central level line lies a few meters N of B. All marks are stainless steel carriage bolts cemented into rock. D is cemented into ledge on pali face and is tagged "PALI RESET." All lines are brush free.



Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
98-8D* to 98-8B	344	16.901	1.0961
98-8B to 98-8A	1	24.920	1.2689
98-8B to 98-8C	54**	10.056**	1.3313
98-8D to 98-8C	9	22.441	(2.4274)
98-8C to 98-8A	340	20.138	(-0.0624)
98-8A to 98-9B	no data	no data	-1.8678
98-9C to 98-9B	342	26.716	***
98-9B to 98-9A	349	25.143	-0.1088
1998 PK nail to 98-9B	no data	27.150	no data
Duffield nail to 98-9B	no data	26.890	no data

*From high part of rim on bolt D

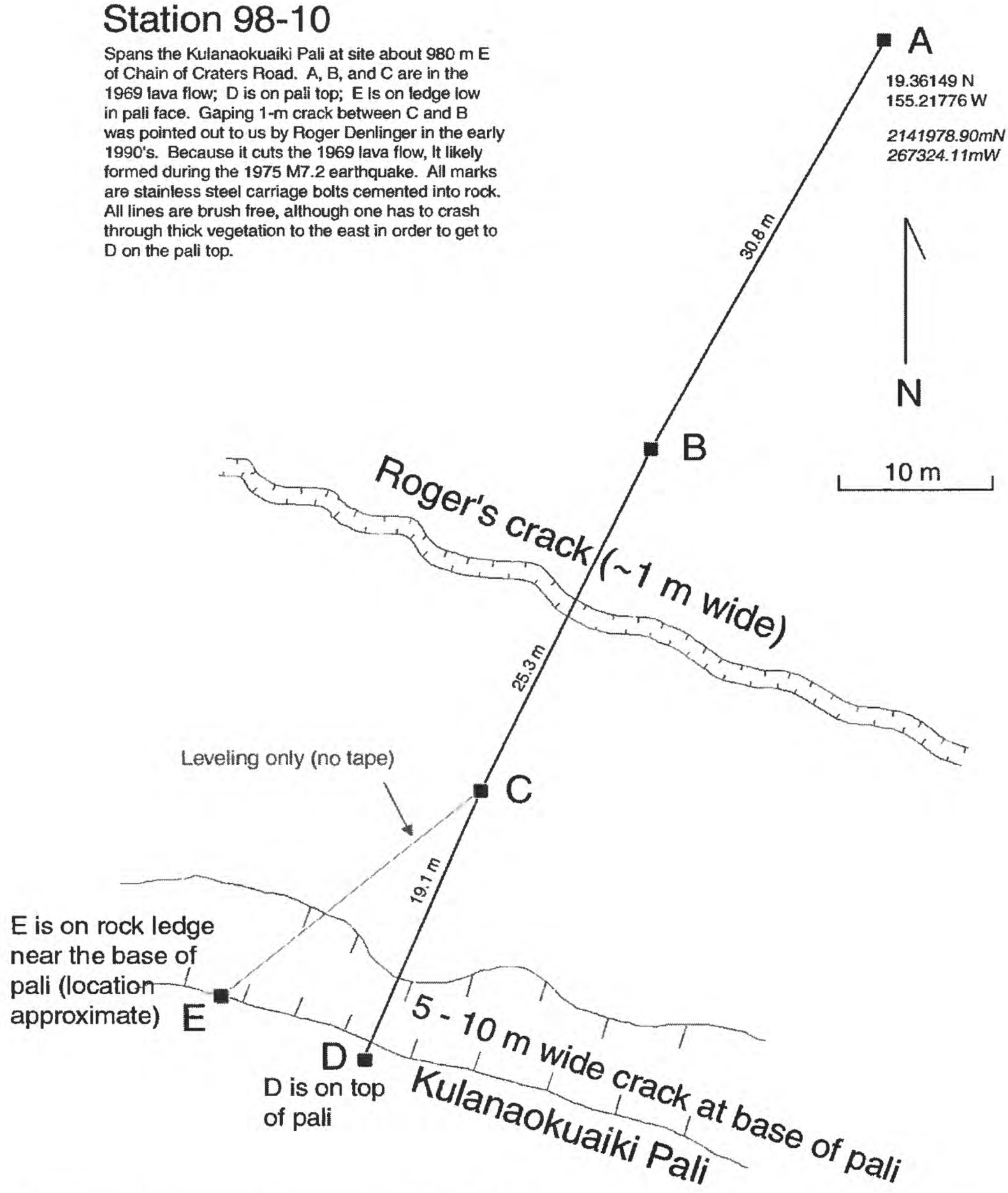
**Measured in 2000

***Can't level to 98-9C on pali face

Figure 26. Crack monitoring stations 98-8 and 98-9.

Station 98-10

Spans the Kulanaokuaiki Pali at site about 980 m E of Chain of Craters Road. A, B, and C are in the 1969 lava flow; D is on pali top; E is on ledge low in pali face. Gaping 1-m crack between C and B was pointed out to us by Roger Denlinger in the early 1990's. Because it cuts the 1969 lava flow, it likely formed during the 1975 M7.2 earthquake. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free, although one has to crash through thick vegetation to the east in order to get to D on the pali top.



Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
D to C	23	19.108	*
C to B	26	25.279	-1.3374
B to A	29	30.815	1.6208
C to E*	no data	no data	-1.4206

*Too difficult to level to D

Figure 27. Crack monitoring station 98-10.

Station 98-11

Spans Kulanaokuaiki Pali on W side of Chain of Craters Road. A is in outcrop several meters W of road; B and C are in ledges in road cut. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.

Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
C to B	338	8.059	0.4663
B to A*	2	83.630	0.1110

*Mark-to-mark slope distance measured by EDM

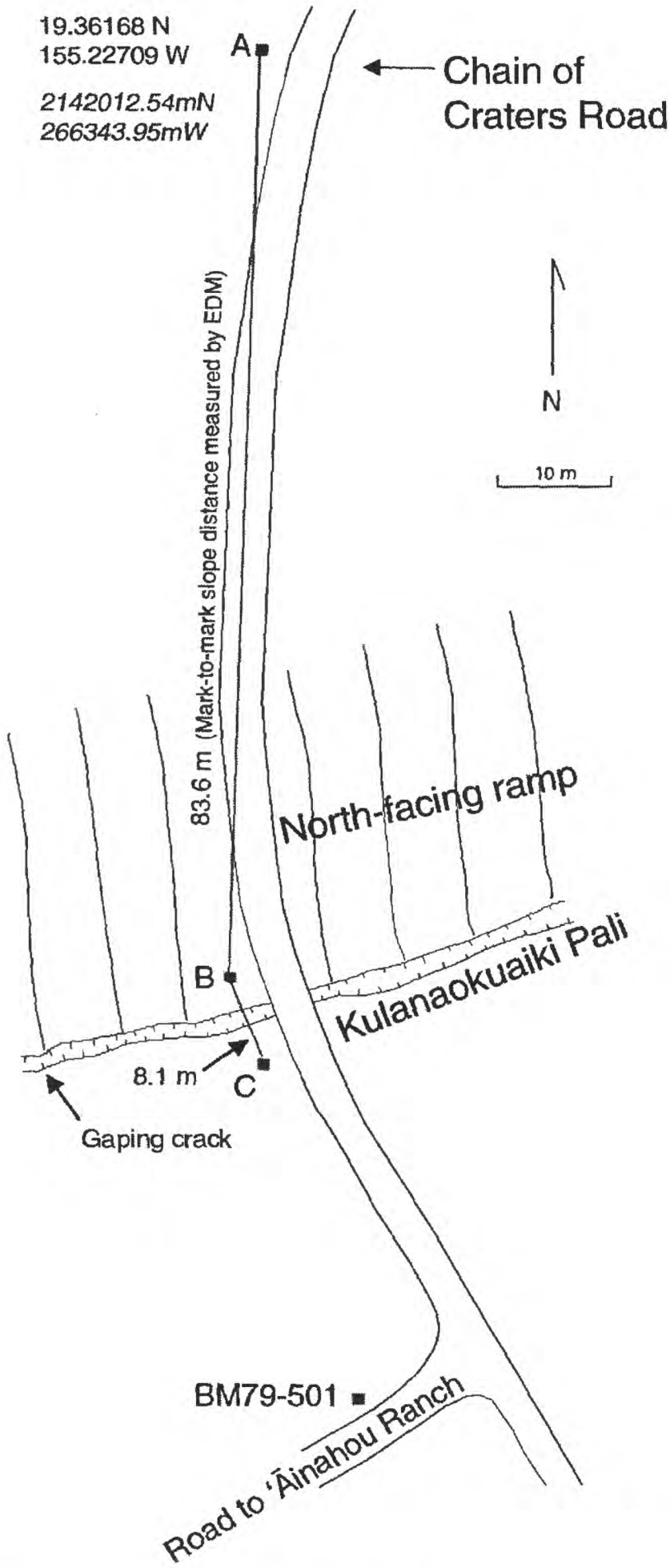
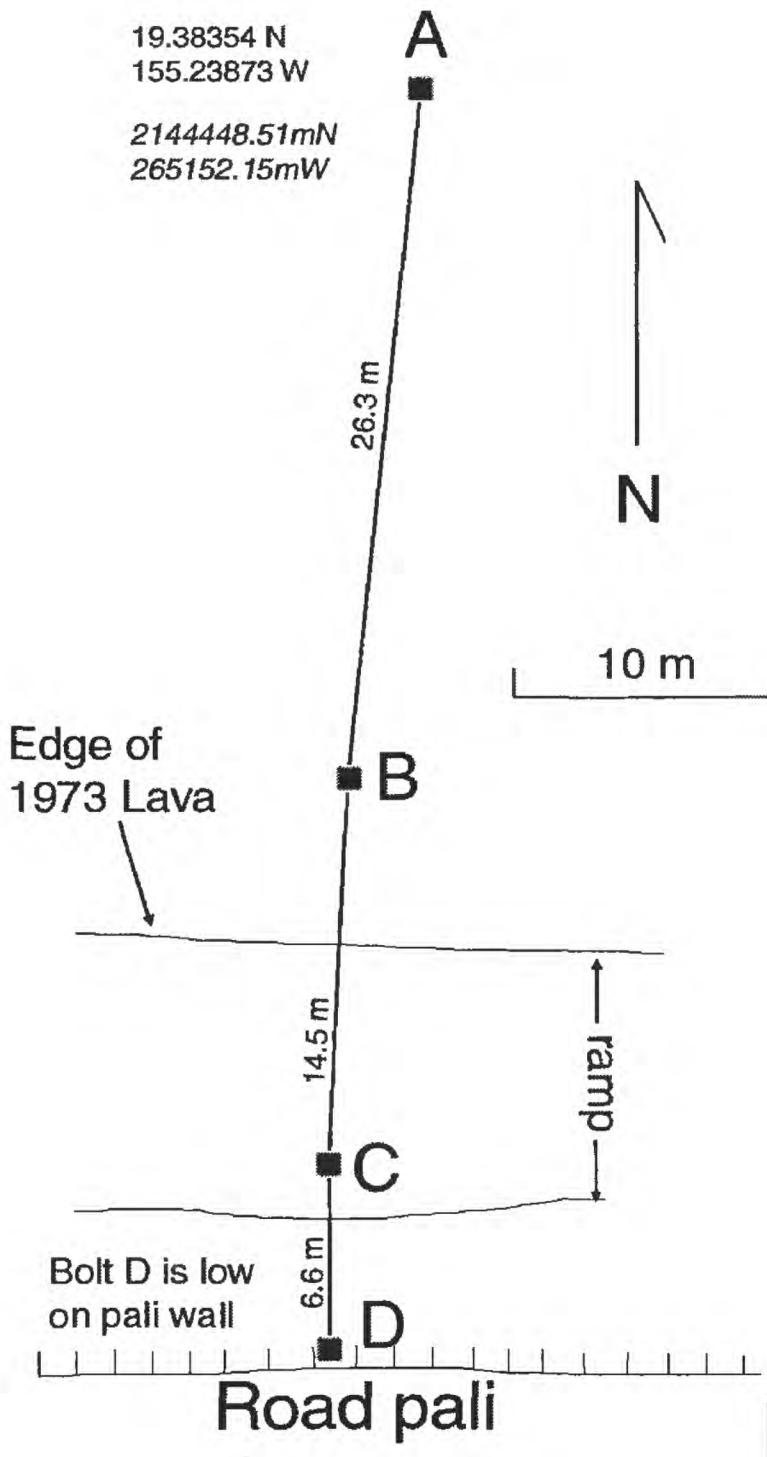


Figure 28. Crack monitoring station 98-11.

Station 98-12

Spans north-facing Road pali at point about 300 m SE of Hi'iaka Crater parking pullout on the Chain of Craters Road. A and B are set in 1973 lava; C is at top of ramp; D is in ledge low on pali face. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.

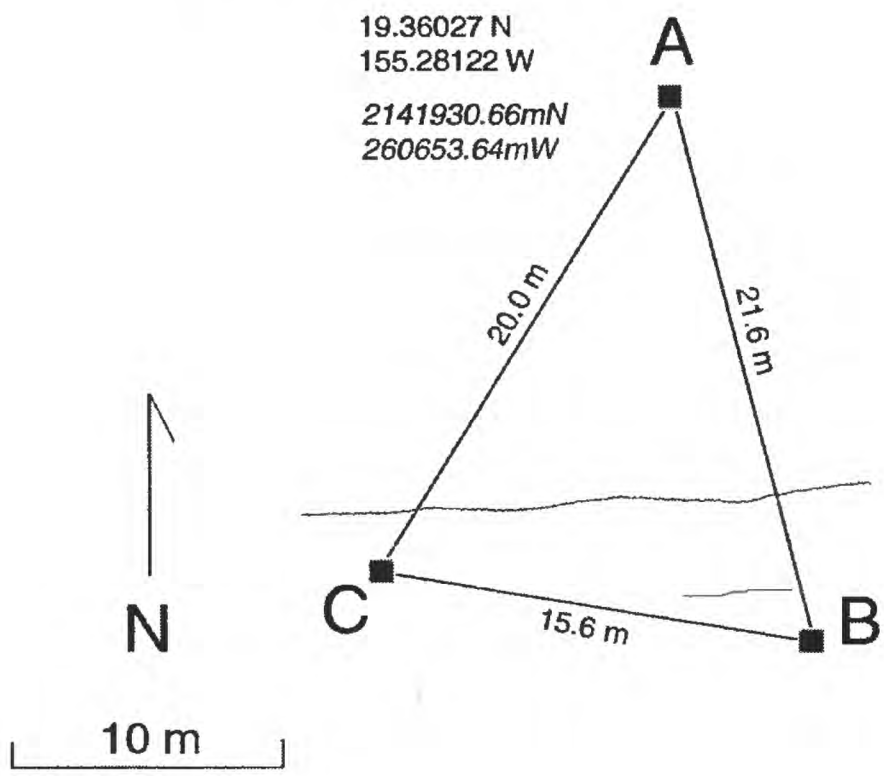


Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
C to D	180	6.574	no data
C to B	3	14.513	-3.6087
B to A	6	26.232	-0.1178
B to D	no data	no data	1.6931

Figure 29. Crack monitoring station 98-12.

Station 00-1

Spans fresh, gaping cracks that likely widened during the Koa'e intrusion event of May 1973. Located 85 m NE of 6000W on the Western level line. All marks are stainless steel carriage bolts cemented into rock. All lines are brush free.



Line	Azimuth (degrees)	Distance (m)	Height Difference (m)
A to C	211	19.975	0.5259
A to B	166	21.576	(-1.1492)
B to C	280	15.619	1.6751

All measurements made in August 2000

Figure 30. Crack monitoring station 00-1.

ACKNOWLEDGEMENTS

We thank Gene Iwatsubo and Arnold Okamura for their valuable reviews of this report.

REFERENCES CITED

Delaney, P.T., Denlinger, R.P., Lisowski, M., Miklius, A., Okubo, P.G., Okamura, A.T., and Sako, M.K., 1998, Volcanic spreading at Kīlauea, 1976–1996: Journal of Geophysical Research, v. 103, p. 18,003–18,023.

Denlinger, R.P, and Okubo, P., 1995, Structure of the mobile south flank of Kīlauea Volcano, Hawaii: Journal of Geophysical Research, v. 100, p. 24,499–25,507.

Dieterich, J.H., 1988, Growth and persistence of Hawaiian rift zones: Journal of Geophysical Research, v. 93, p. 4258–4270.

Duffield, W.A., 1975, Structure and origin of the Koa'e fault system, Kīlauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 856, 12 p.

Fiske, R.S., and Koyanagi, R.Y., 1968, The December 1965 eruption of Kīlauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 607, 21p.

Hanatani, R.Y., 1988, Permanent-glass EDM measurements on Kīlauea, Hawaii, from June 6, 1979 to September 23, 1987: U.S. Geological Survey Open-File Report 88–202, 97 p.

Owen, S., Segall, P., Lisowski, M., Miklius, A., Denlinger, R., and Sako, M., 2000, Rapid deformation of Kīlauea Volcano: Global positioning system measurements between 1990 and 1996: Journal of Geophysical Research, v. 105, p. 18,983–18,998.

Swanson, D.A., Duffield, W.A., and Fiske, R.S., 1976, Displacement of the south flank of Kīlauea Volcano: The result of forceful intrusion of magma into the rift zones: U.S. Geological Survey Professional Paper 963, 39 p.