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Interpretation of D.C. Resistivity, VLF, and Total Magnetic Field Intensity Measurements on Kilauea Iki Lava Lake 1979-1980

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Numerous electrical and magnetic measurements have been made on Kilauea Iki lava lake since it was formed during the 1959 eruption in Kilauea Iki (Richter and others, 1970). In 1961, vertical magnetic field intensities were measured over the lake surface (Decker, 1963) and in 1962, the electrical resistivity of the melt beneath the 13 m-thick crust was determined to be 2.1 ohm-m by induction loop-loop sounding (Frischknecht, 1967). In 1971, very low frequency (VLF) tilt-angle measurements, using as a source Navy radio station NLK (18.6 KHz), were made to delineate the edges of the conductive lens of melt (Jackson, D.B., Hawaiian Volcano Observatory, unpublished data). Tilt-angle surveys were repeated periodically between 1971 and 1976 (Zablocki, 1976; Anderson, L.A., and Zablocki, C.J., Hawaiian Volcano Observatory, unpublished data) and total magnetic field intensity surveys were made in 1973, 1974, and 1975 (Zablocki, 1976).

In 1975, a suite of electrical and magnetic measurements were made on Kilauea Iki in support of the Sandia Laboratories' program for extraction of energy from magmatic sources (Colp, 1979). These measurements included two Schlumberger D.C. soundings, a total-field magnetic intensity survey, VLF tilt-angle and induction resistivity measurements (Zablocki, 1976), loop-loop induction soundings (Smith and others, 1976), and electromagnetic Turam profiling (Flanigan and Zablocki, 1976).

This report summarizes preliminary interpretations of repeat measurements (made in 1979 and 1980) of the D.C. soundings, total field magnetic intensity measurements, and VLF tilt-angle and resistivity measurements made earlier.

1979-1980 Geophysical measurements and interpretations

All geophysical measurements made in 1979 and 1980 on Kilauea Iki lava lake are referenced to a system of surveying nails that were established by the Hawaiian Volcano Observatory staff in 1960 (fig. 1). An EW baseline runs across the center of the lake with 41 nails (numbered 0 to 40 from east to west) on 30.5 m (100 ft) centers. A NS baseline, also on 30.5 m (100 ft) centers, intersects the EW baseline at nail 17. All other nails are on a 61 m (200 ft) grid aligned with the two baselines.

Two D.C. soundings, first made in 1975 at nail 17 (oriented EW) and at nail 17N1 (oriented NS) and expanded to a maximum half-current electrode separation (AB/2) of 152 m (500 ft), were repeated in 1979 and 1980. Figure 2 shows these repeat sounding curves before removal of discontinuities (jumps) which are caused by the expansion of the potential electrodes over lateral inhomogeneities and table 1 lists the values the curves were plotted from. Discontinuities were removed from the sounding curves by shifting curve segments to align with the section having the largest potential-electrode separation. The repeat soundings in 1979 and 1980 are "noisy" especially for soundings expanded in the east-west direction (fig. 3). The noise probably results from near-surface, abrupt changes in resistivity. In comparing the sounding curve shapes from 1975 through 1980 (figs. 3 and 4), it is evident from the progressive shift to the right of the curve minima that the conductive hot-water zone between the lake surface and a postulated hot, dry zone overlying the melt (Zablocki, 1976; Smith and others, 1976) has become significantly thicker and perhaps more conductive with time. The thickening of the hot-water zone is to be expected since drilling results have shown that the depth to melt has increased from about 44 m in 1975 to about 52 m in 1979 (Colp, 1979). A continued increase in the thickness of the hot-water

Table 1. Observed dc sounding values for 1979 and 1980 in Kilauea Iki. Values for ab(AB/2 in ft.) and obs(apparent resistivity in ohm-m) are read as ordered pairs from the listing below.

```
EW expansion 5/11/79
      ab=     13.0,     16.0,     20.0,     25.0,     30.0,     30.0,
   40.0,     50.0,     65.0,     80.0,    100.0,    100.0,    130.0,    160.0,
  200.0,    250.0,    200.0,    250.0,    300.0,    300.0,    400.0,    500.0,
 obs = 18000.00,10800.00, 4830.00, 3270.00, 2740.00, 2250.00,
 1740.00, 1230.00,  780.00,  630.00,  660.00,  815.00,  450.00,  420.00,
  515.00,  620.00,  490.00,  580.00,  580.00,  580.00,  708.00,  875.00,

NS expansion 5/11/79
      ab=     10.0,     13.0,     16.0,     20.0,     25.0,     30.0,
   30.0,     40.0,     50.0,     65.0,     80.0,    100.0,    100.0,    130.0,
  160.0,    200.0,    200.0,    250.0,    300.0,    300.0,    400.0,    500.0,
 obs =  7400.00, 6500.00, 5180.00, 2150.00, 1760.00, 1370.00,
 1670.00,  880.00,  690.00,  540.00,  470.00,  410.00,  500.00,  460.00,
  505.00,  564.00,  610.00,  710.00,  810.00,  730.00,  890.00, 1050.00,

EW expansion 4/7/80
      ab=     10.0,     13.0,     16.0,     20.0,     25.0,     30.0,
   30.0,     40.0,     50.0,     65.0,     80.0,    100.0,    100.0,    130.0,
  160.0,    200.0,    250.0,    300.0,    300.0,    400.0,    500.0,
 obs =  4642.00, 5033.00, 5020.00, 3035.00, 1686.00, 1358.00,
 1742.00, 1089.00,  892.00,  522.00,  522.00,  499.00,  630.00,  534.00,
  459.00,  397.00,  400.00,  410.00,  420.00,  413.00,  492.00,

NS expansion 4/7/80
      ab=     10.0,     13.0,     16.0,     20.0,     25.0,     30.0,
   30.0,     40.0,     50.0,     65.0,     80.0,    100.0,    100.0,    130.0,
  160.0,    200.0,    250.0,    300.0,    300.0,    400.0,    500.0,
 obs =  7365.00, 7087.00, 4705.00, 2306.00, 1680.00, 1621.00,
 1545.00,  932.00,  761.00,  594.00,  515.00,  446.00,  479.00,  446.00,
  449.00,  439.00,  522.00,  551.00,  499.00,  591.00,  673.00,
```

zone is apparent when comparing the 1979 and 1980 results. The turndown (decrease in slope) on the terminal branches of the 1975 sounding curves is not seen on the 1979 and 1980 soundings. The turndown on the 1975 soundings was explained by Zablocki (1976) as the influence of the underlying conductive melt, however; the effect of the melt is suppressed on the 1979 and 1980 soundings although they were expanded to the same maximum current electrode separations as the 1975 soundings because of the increased thickness of the conductive, hot-water zone and the apparent increase to the depth of the melt since 1975.

Only the NS sounding curves obtained in 1979 and 1980 were chosen for modeling (figs. 5 and 6) because they are significantly smoother than the EW curves. There are differences in the EW and NS soundings for a given year that reflect lateral changes in resistivity, but the amount of smoothing that would be required on the EW curves to allow a layered interpretation is such that any interpretation for the EW data would be very speculative. In modeling the NS sounding curves, the same types of constraints were used as those used for the interpretation of the 1975 data (Zablocki, 1976). The model for the 1979 NS sounding (fig. 5) was calculated for a melt-dry rock interface at 53 m (1979 drill-hole data) with an 8 ohm-m resistivity value for the melt complex[1] (from 1980 Kilauea Iki loop-loop sounding; personal communication, Bruce Smith, U.S. Geol. Survey). As in 1975, an 11 m-thick hot, dry zone of high resistivity (~30,000 ohm-m) was assumed to exist between the melt complex and the overlying zone of hot-water saturated rocks. Using these constraints, a good fit can be made to the field data (fig. 5) provided that the resistivity

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[1] "Melt complex" is used rather than "melt" because this zone is probably not a simple pod, but instead, a complex of foundered crust, segregation seams, crystal mush, and melt.

of the hot-water zone is reduced from the 1975 value of about 600 ohm-m to about 300 ohm-m. Such a large resistivity change is difficult to reconcile because it requires a two-fold increase in fluid salinity, a significant addition of alteration products[1], or approximately a 40 percent increase in effective liquid-phase water content. Although these are possibilities, another explanation for the apparent large change would be a two-fold data error in resistivities for the 1975 data. Theoretically, one can halve all the layer resistivities (except the melt resistivity which is still held constant at 8 ohm-m) and thus halve the apparent resistivity values without changing the shape of the field curve except for shifting it downward by a factor of 2. In doing so, the goodness of theoretical curve fit to the shifted data will not change, the hot-water zone will have an interpreted resistivity of about 300 ohm-m, and the D.C. data sets for 1975, 1979, and 1980, will be internally consistent.

The 1980 NS D.C. sounding (fig. 6) was also interpreted with the same constraints as used with the 1979 sounding except for the hot-water-zone resistivity (layer 4 in fig. 6) which was held at 320 ohm-m to agree with the 1979 sounding and its thickness was allowed to vary. An acceptable match to the field data was obtained (fig. 6) with the depth to the top of the hot dry zone at 62 m and a depth to the top of the melt complex at 73 m (11 m assumed thickness for the hot dry zone). This interpretation would imply that the depth to melt has increased about 20 m between 1979-80. This seems to be excessive, requiring a cooling rate about 9 times greater for the 1979-80 period than for the 1975-79 period.

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[1] Inspection of core from 1975 and 1979 drill holes shows no apparent increase of alteration products with time (personal communication, Thomas Casadevall, Hawaiian Volcano Observatory).

There are other models that will thin the hot-water zone appreciably, and accordingly, decrease the depth to melt; however, they are not very satisfying solutions. For example, the hot-water zone may be split into 2 layers and a lower resistivity assigned to the deeper layer (the dashed model on fig. 6). Another alternative solution to effect a shallower depth to the melt would be to replace the 11 m hot-dry zone and the 8 ohm-m half-space with a resistive half-space of about 1300 ohm-m. This model will also give a match to the field data similar to the calculated curve shown in figure 6. Accordingly, the depth to the base of the hot-water zone can be made the same or slightly deeper than for the 1979 model (43 m). However, this interpretation implies that the melt complex no longer exists and is inconsistent with the results obtained from loop-loop induction soundings made in 1980 that indicate a strong conductive zone (melt complex) still exists in the lake.

It seems likely that depth to melt has increased between 1979 and 1980, and at a faster rate than in pre-1979.

VLF measurements

Figures 7 and 8 are percent tilt-angle contour maps of the lake surface for VLF stations NLK at Seattle, Washington and NPM at Lualualei, Hawaii, respectively. The edges of the conductor in the lava lake (melt complex) couples best with the radio station whose bearing is parallel to the conductor's edges. Accordingly, NLK best defines the NE and SW edges of the conductor (fig. 7) and NPM best defines the NW and SE edges of the conductor (fig. 8). The response for a 2-dimensional conductive slab in a high resistivity half-space (Zablocki, 1976, fig. 3) shows that the surface projection of the edge of a conductive slab is located between the steepest gradient and the tilt-angle maxima or minima (for a 2-dimensional slab, the tilt-angle response is antisymmetric having a tilt-angle maximum on one edge of the slab and a tilt-angle minimum on the opposite edge). Even though the lava lake conductor is a 3-dimensional body the tilt-angle map should be a good indicator of the approximate edges of the conductor. Estimated positions for the conductor edges on figures 7 through 10 are shown by the heavy solid-dashed lines. The VLF map for the 1971 survey (fig. 9) is contoured in degrees of tilt angle rather than percent tilt-angle [percent tilt angle = 100 X tan (tilt angle)] and therefore, the more shallow anomaly gradients are only a function of scaling. For example, the value of 25 degrees on the NW side of the lake in figure 9 would be 47 percent tilt-angle.

To steepen the anomaly gradients around the lake, the absolute values of tilt-angle responses for NLK and NPM surveys made in 1979 were added and contoured (fig. 10). This map appears to show the outline of the conductor better than either the NLK or NPM map along (heavy solid line). Included in figure 10 is the approximate location of the conductor edge from the 1971 NLK tilt-angle map in figure 9 (heavy dashed line). It appears that the edge of the conductor has migrated about 65 m toward the lake center between 1971 and 1979.

Induction resistivities were measured for the NS and ES baselines in 1979 and 1980 for both NLK and NPM (figs. 11, 12, and 13). As with previous measurements made in 1975 (Zablocki, 1976, fig. 4), the data are very noisy. These large variations possibly resulted from high, but variable, contact resistances at the E field electrodes, although the input impedance of the measuring instrument was $10^8\ \Omega$. As in the 1975 survey by Zablocki, salt-water saturated cloths were used under the electrodes and salt water was poured on the ground beneath the cloths.

The 1979 VLF resistivity profiles (figs. 11 and 12) for NLK and NPM are much the same and do not differ greatly from the 1975 survey (fig. 14). The noisy data make it difficult to pick the conductor boundaries on the EW line although it appears that the high resistivity zone east of nail 8 has migrated to the west between 1979 and 1980. The resistivity profile along the NS baseline also seems to be losing definition on the south side, possibly because the melt complex is cooling there more rapidly.

Total magnetic field intensity measurements

In 1979, total magnetic field intensity measurements made at a sensor height of 2.44 m were repeated for all nail stations on the lake surface. A contour map was prepared but is not presented here because it is essentially identical to a total magnetic field intensity map made in 1975 (Zablocki, 1976, fig. 10). However, figure 15 shows a comparison of the total magnetic field intensity along the NS baseline together with similar data obtained in 1973, 1974, and 1975 taken from Zablocki (1976, fig. 11).

A plot of calculated total field intensity measurements for assumed lava lake geometries in 1973 and 1979 and their differences (1973 minus 1979) versus differences of measured total field intensities for the same period is shown in figure 16 for line 17ns. To obtain a fit between the observed and calculated differences, it was necessary to subtract 120 gammas from the observed differences to remove the effect of the long-term secular variation. The average secular variation deduced from the shift of the observed data is -21 gammas a year (120 γ/5.6 yrs). Both models assume a paramagnetic slab (melt) 600x800 m embedded in a 7×10^{-3} cgs susceptibility half-space using the melt thicknesses and depths to tops as shown in figure 16. With secular variation removed it appears that most changes between the 1973 and the 1979 data along line 17ns can be explained by a progressive solidification of the melt lens.

Conclusions

Direct current soundings, first made in 1975 and then repeated in 1979 and 1980, can be interpreted with good fits between calculated and field curves using similar parameter constraints as used in the 1975 model. However, the interpreted depth to melt of 73 m in 1980, is 20 m deeper than the known depths determined from drilling in 1979 (52 m). If depth-to-melt is now truly at about 72 m, then solidification of the lava lake must be nearly complete. Seventy-two meters is 65% of the original lake depth of 111 m and if taken at face value, the cooling rate between 1979 and 1980 is 9 times the rate between 1975 and 1979. It is also noted that the D.C. soundings for 1979 and 1980 no longer require a conductive layer of melt for their interpretation, and without this constraint the interpreted thickness of the hot-water zone is quite open.

Repeats of VLF tilt-angle surveys since 1971 continue to delimit effectively the boundaries of the lava lake conductor. For the period 1971 to 1979, the conductor margin has migrated inward by approximately 65 m. VLF induction resistivity measurements suggest a westward movement of the conductor edge near nail 8 between 1979 and 1980 and greater cooling of the lake on the south side of the NS baseline than on the north side.

Comparison of total magnetic field intensities for 1979 on the NS baseline with previous surveys also indicates the effects of the cooling lava lake due to the diminishing size of the paramagnetic body (i.e., lavas above their Curie temperature).

References

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Smith, B.S., Zablocki, C.J., Frischknecht, F.C., and Flanigan, V.J., 1977, Summary of results from electromagnetic and galvanic soundings on Kilauea Iki lava lake: Open-File rept. 77-94, 13 p., 4 figs.

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Figures

13) VLF induction resistivity and phase at 18.6 KHz (NLK) along EW and NS baselines, 1980.

14) VLF induction resistivity and phase at 18.6 KHz (NLK) along EW and NS baselines, 1975 (from Zablocki, 1976).

15) Total magnetic field intensities along NS baseline for 1973, 1974, 1975, and 1979.

16) Residual total field intensities for models of melt distribution in 1973 and 1979 and their differences versus differences of measured total field on line 17ns for 1973 minus 1979. All observed differences are minus 120 gammas to remove the effect of long-term secular variation. Both calculated models assume a 600x800 m paramagnetic sheet embedded in a 7×10^{-3} cgs susceptibility half-space.

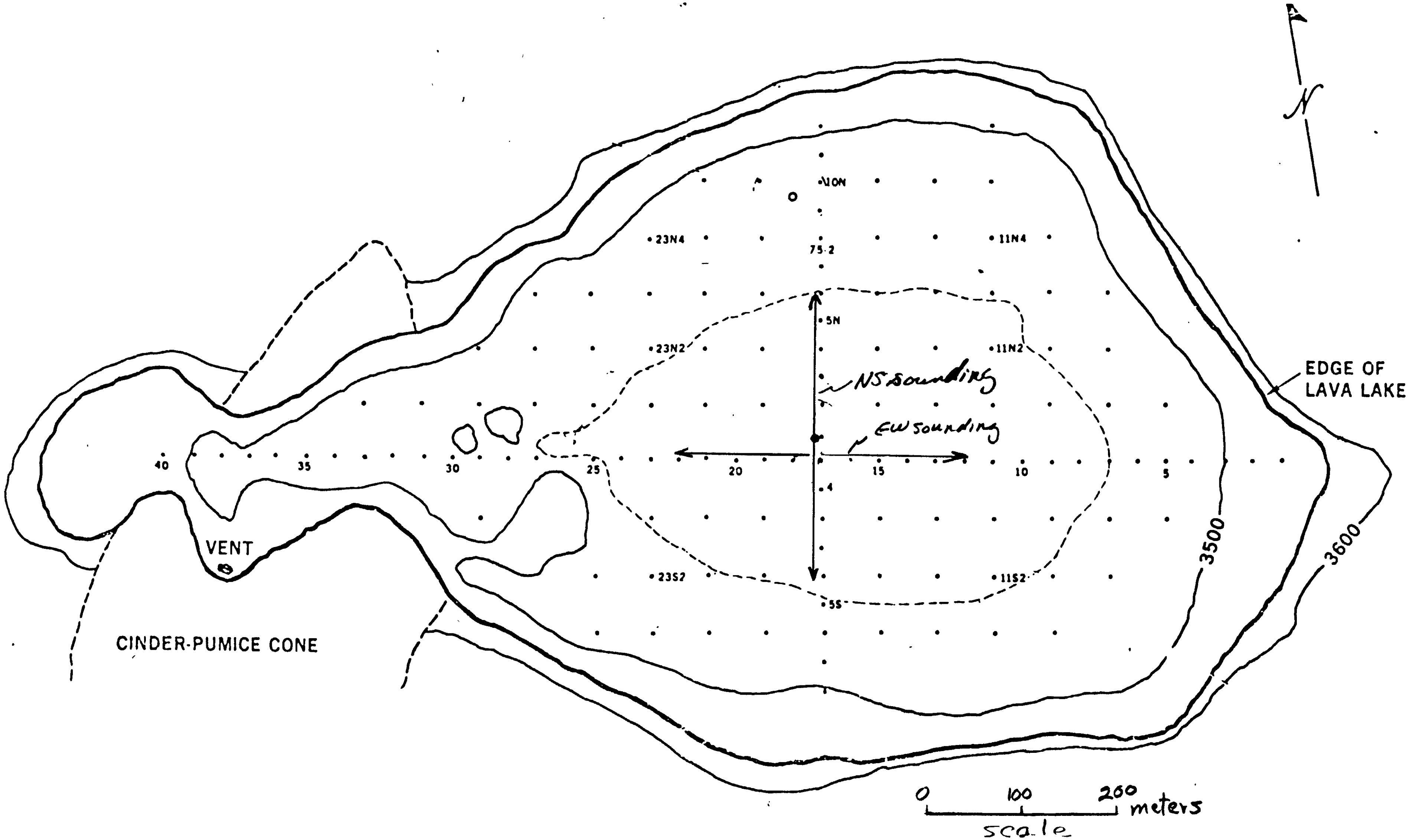
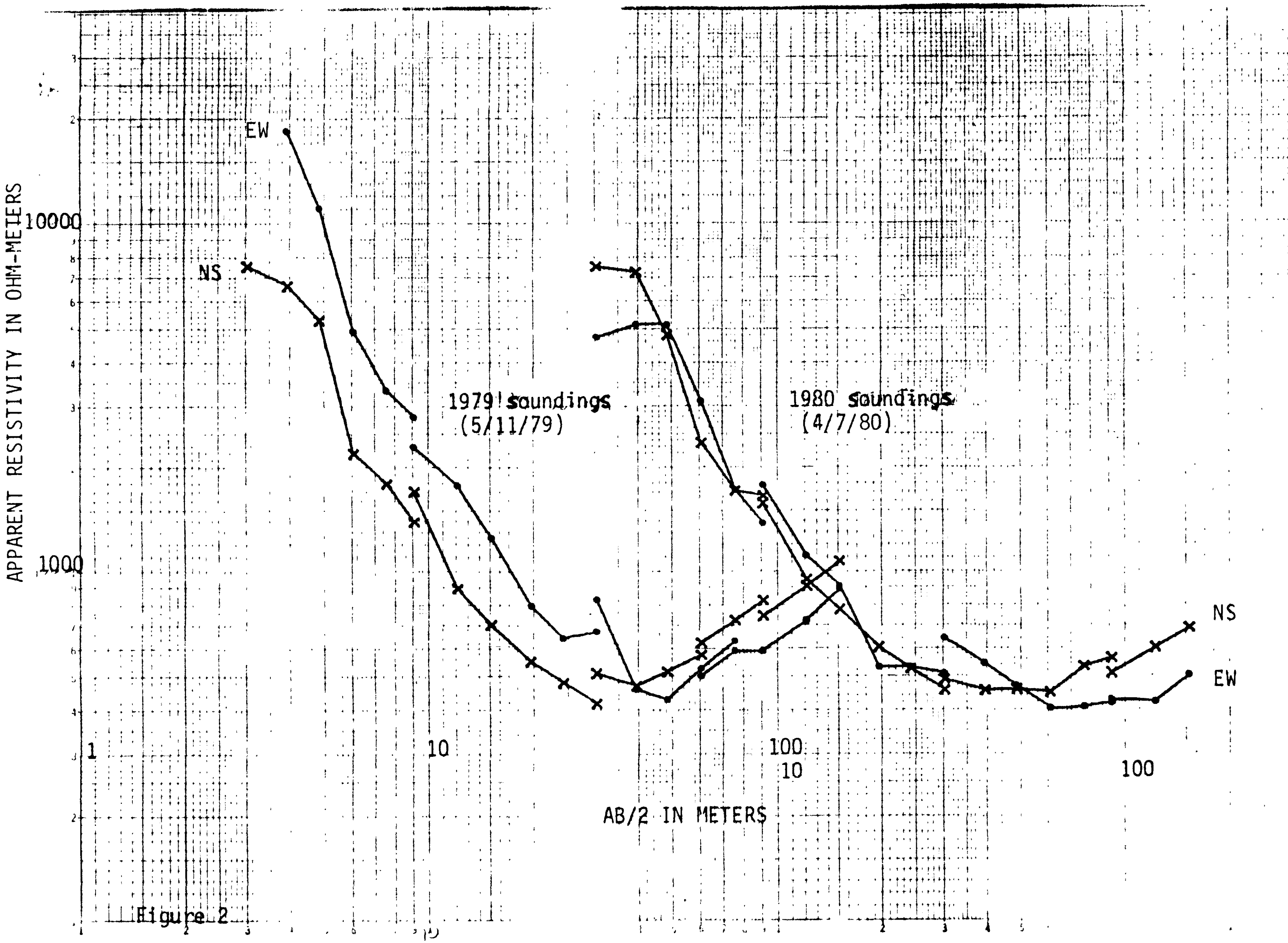
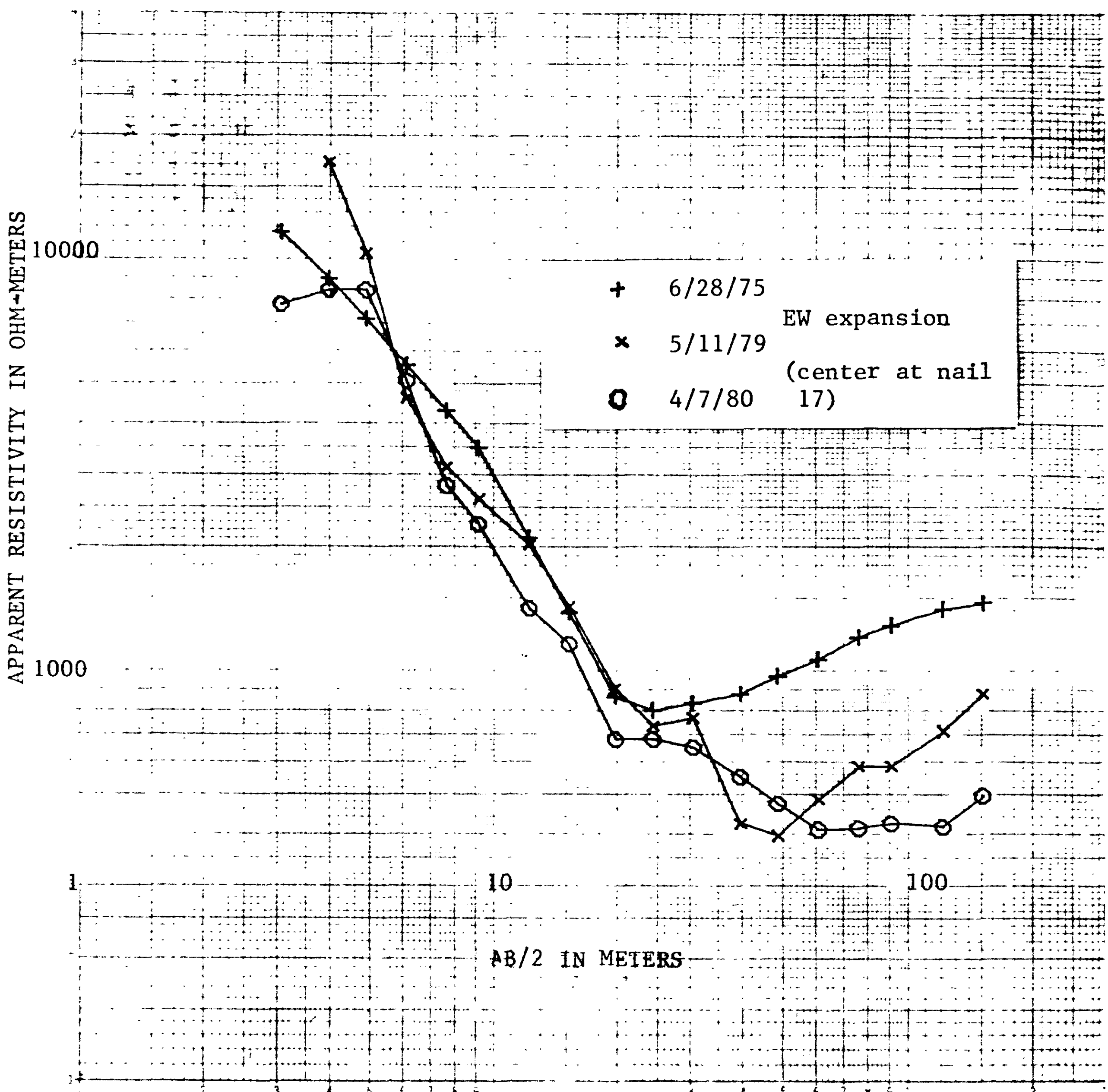

N
EDGE OF
LAVA LAKE
3600
3500
10N
75.2
23N4
11N4
5N
23N2
11N2
NS sounding
EW sounding
40
35
30
25
20
15
10
5
4
23S2
11S2
5S
VENT
CINDER-PUMICE CONE
0
100
200
meters
scale

Figure 1



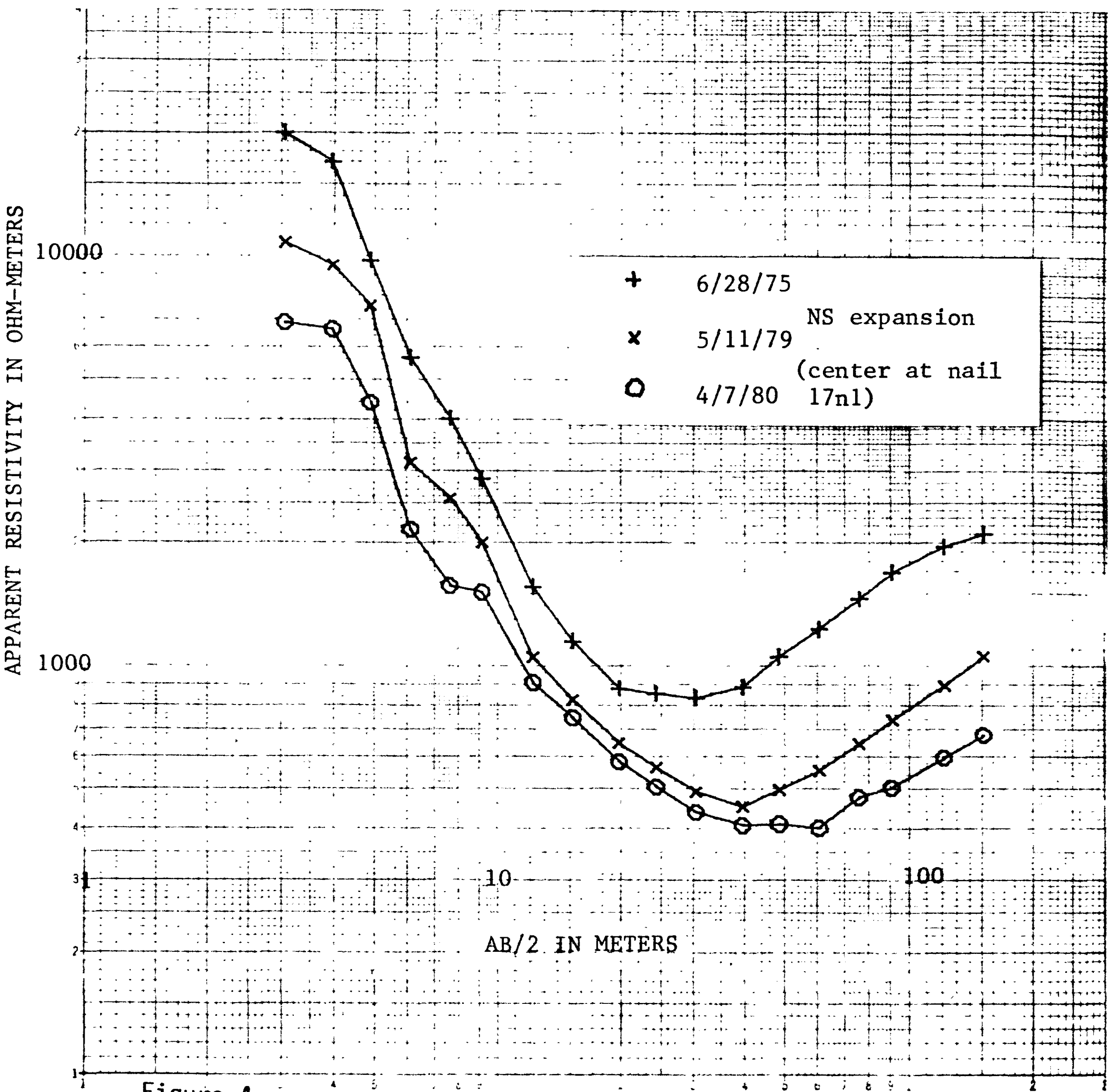
APPARENT RESISTIVITY IN OHM-METERS
10000
1000
AB/2 IN METERS
1
10
100
10
100
EW
NS
1979 soundings
(5/11/79)
1980 soundings
(4/7/80)
NS
EW

Figure 2



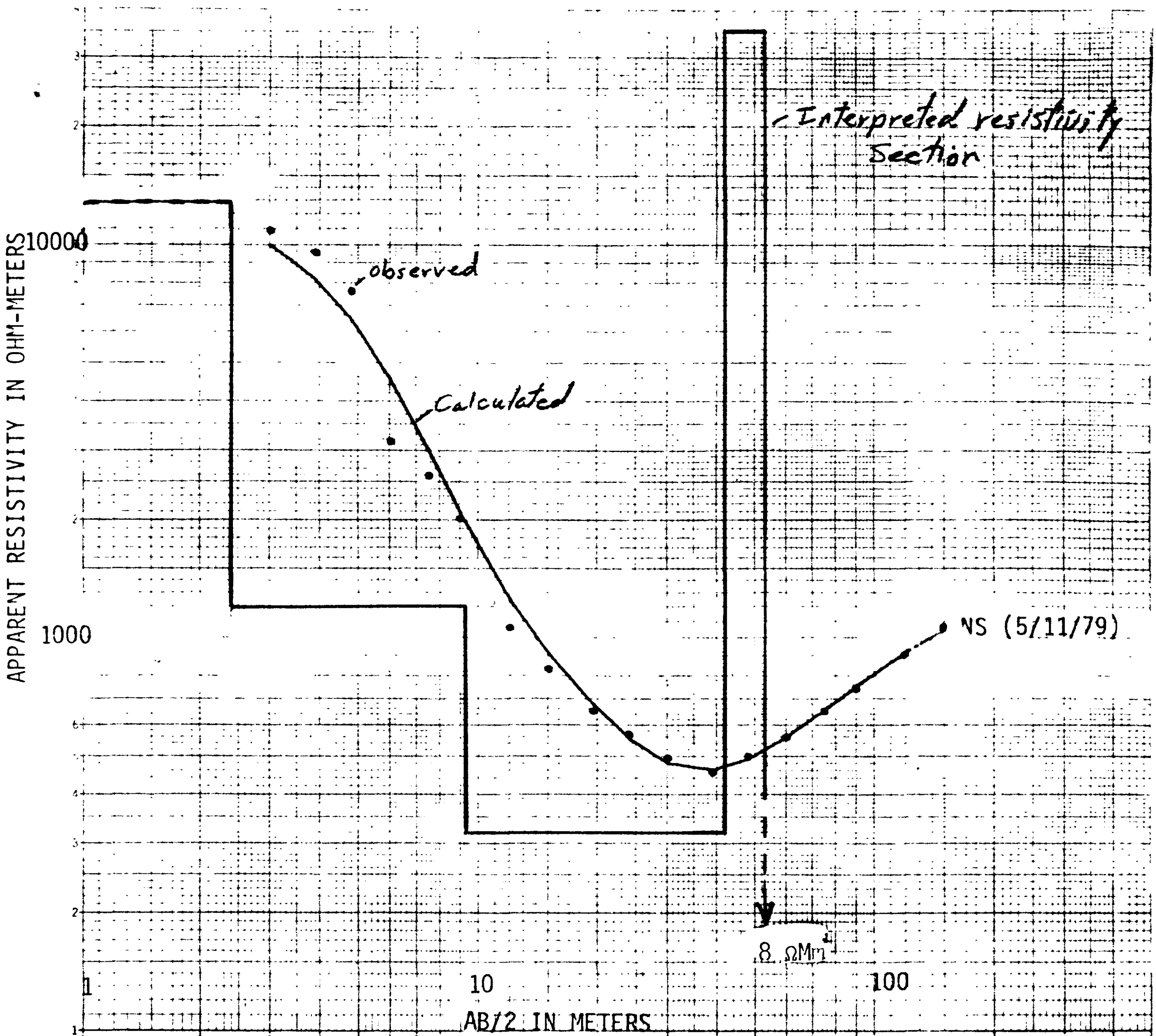
APPARENT RESISTIVITY IN OHM-METERS
10000
1000
1
10
100
AB/2 IN METERS
+ 6/28/75
× 5/11/79
O 4/7/80
EW expansion
(center at nail
17)

Figure 3



APPARENT RESISTIVITY IN OHM-METERS
10000
1000
10
100
AB/2 IN METERS
6/28/75
5/11/79
4/7/80
NS expansion
(center at nail
17nl)

Figure 4



Interpreted resistivity Section
observed
Calculated
APPARENT RESISTIVITY IN OHM-METERS
10000
1000
NS (5/11/79)
8 ΩMm
1
10
100
AB/2 IN METERS

Figure 5

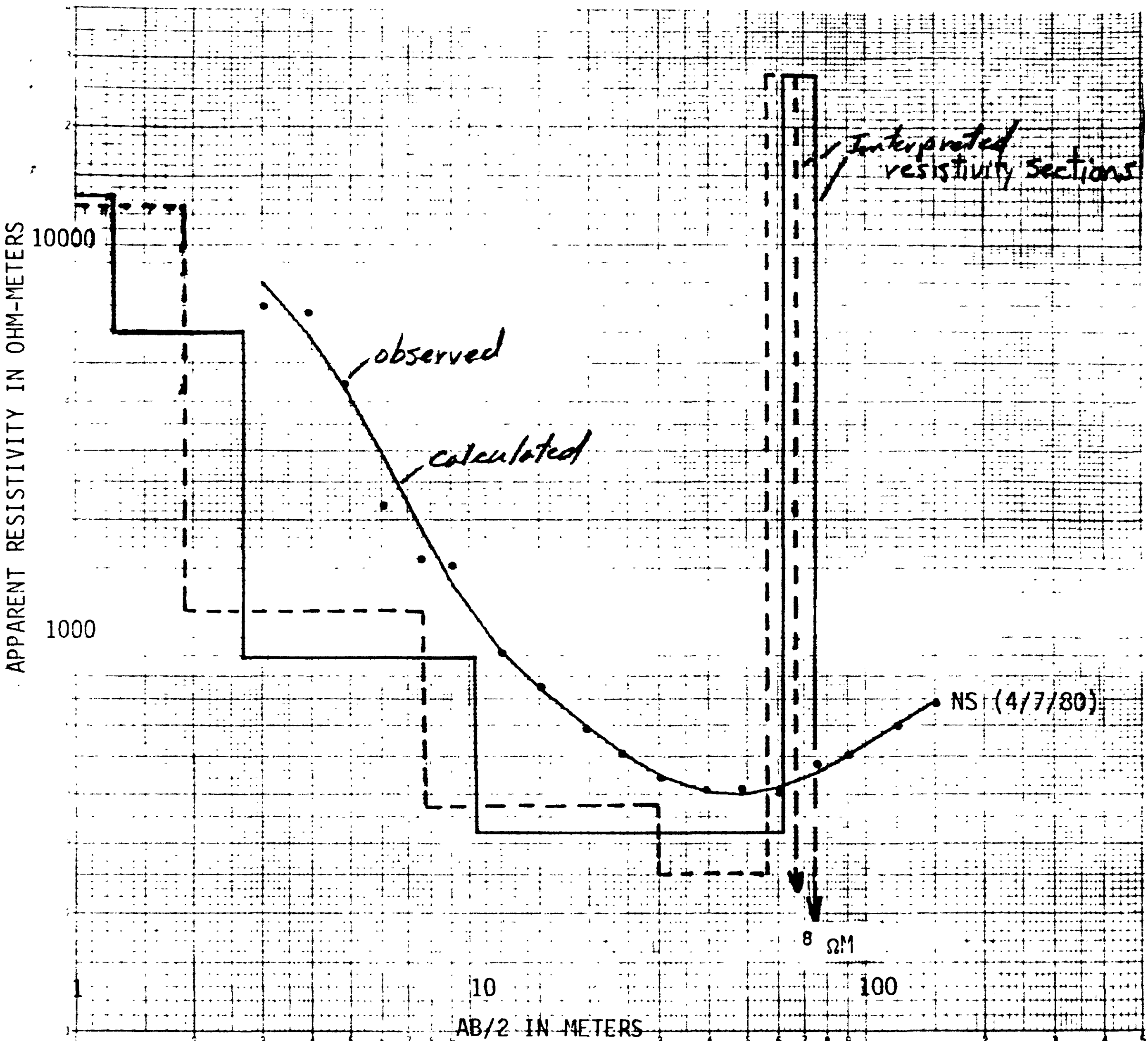

APPARENT RESISTIVITY IN OHM-METERS
10000
1000
observed
calculated
Interpreted resistivity sections
NS (4/7/80)
8 ΩM
1
10
100
AB/2 IN METERS

Figure 6

NLK 1979

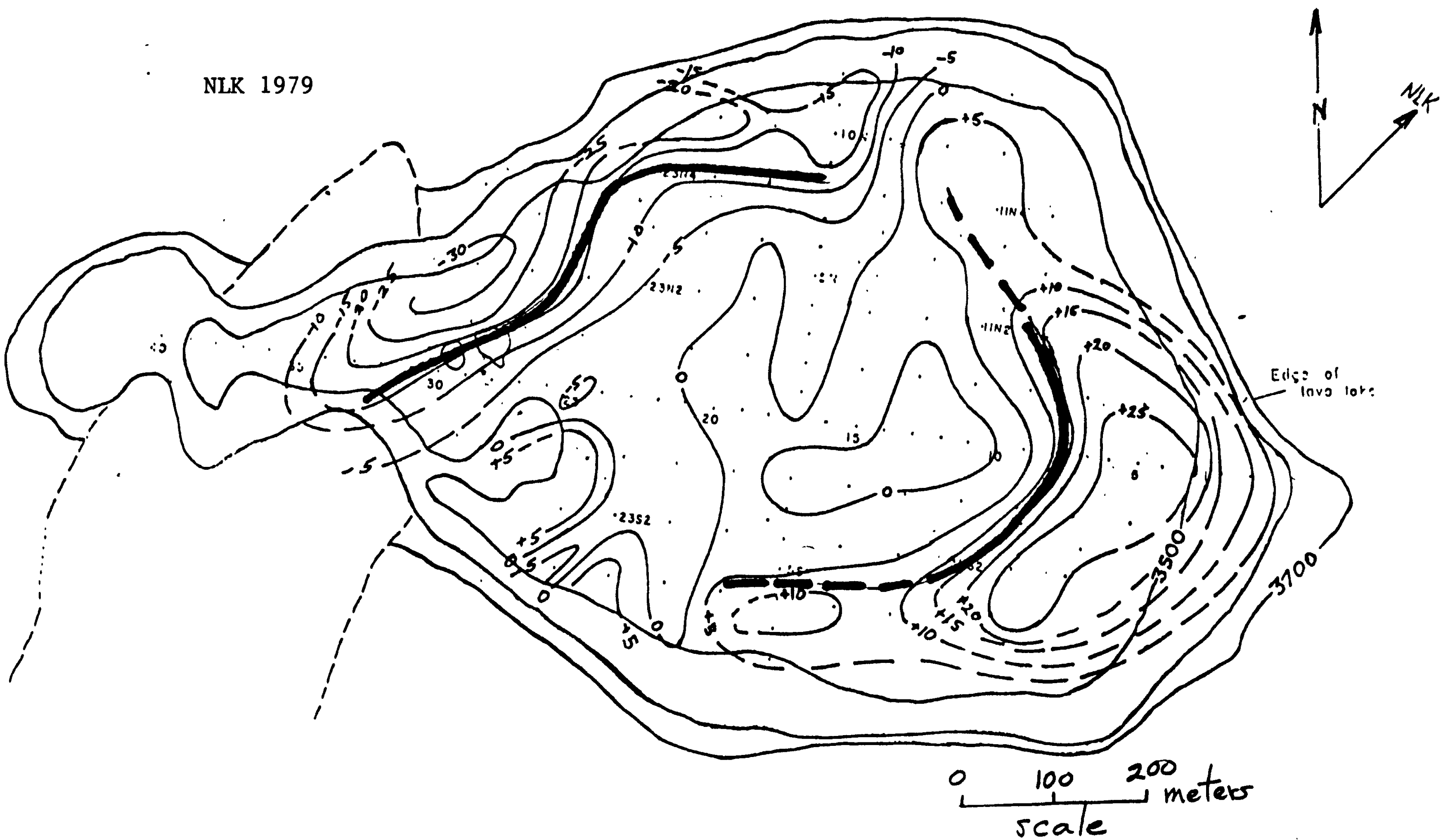


Figure 7

NPM 1979

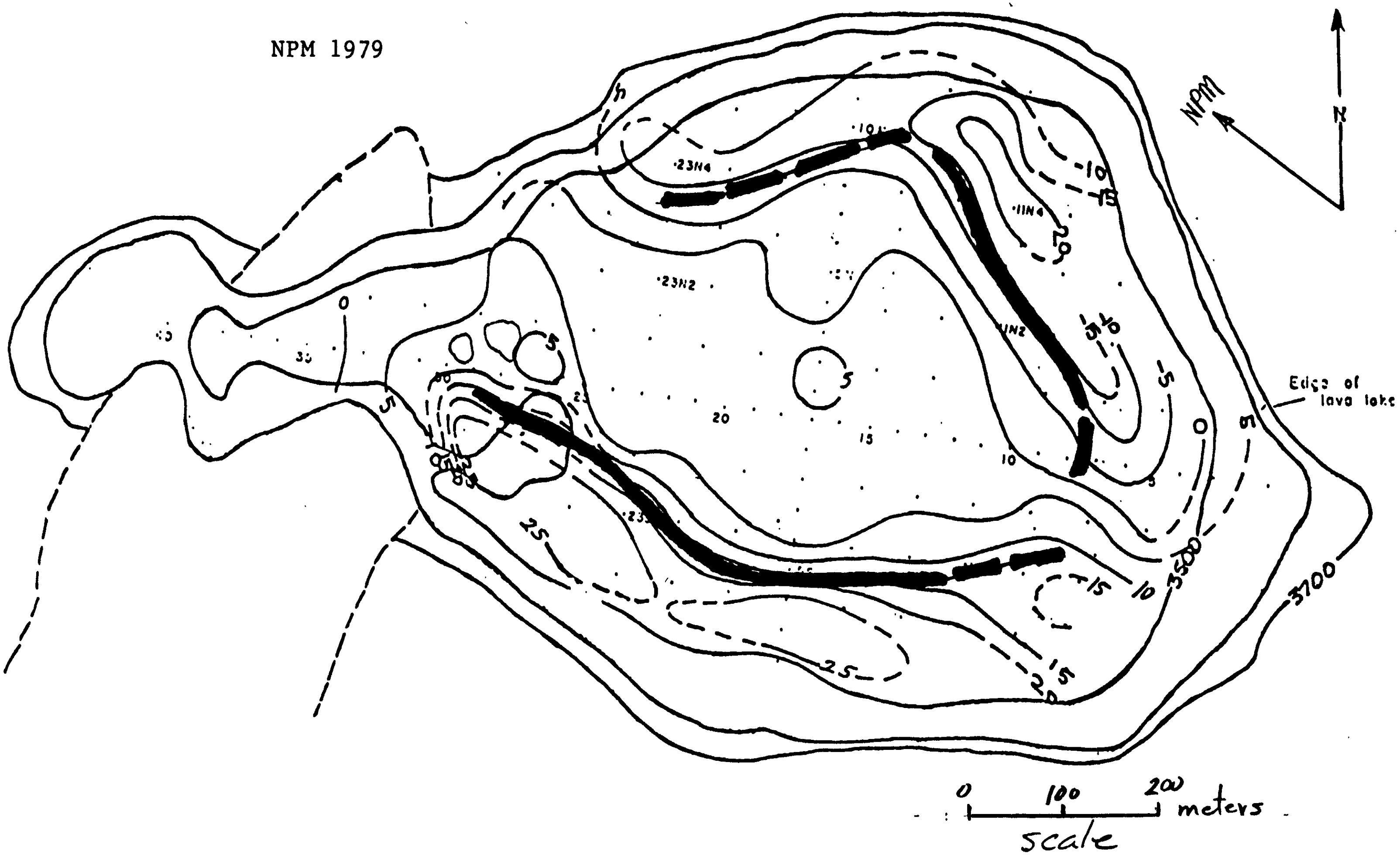
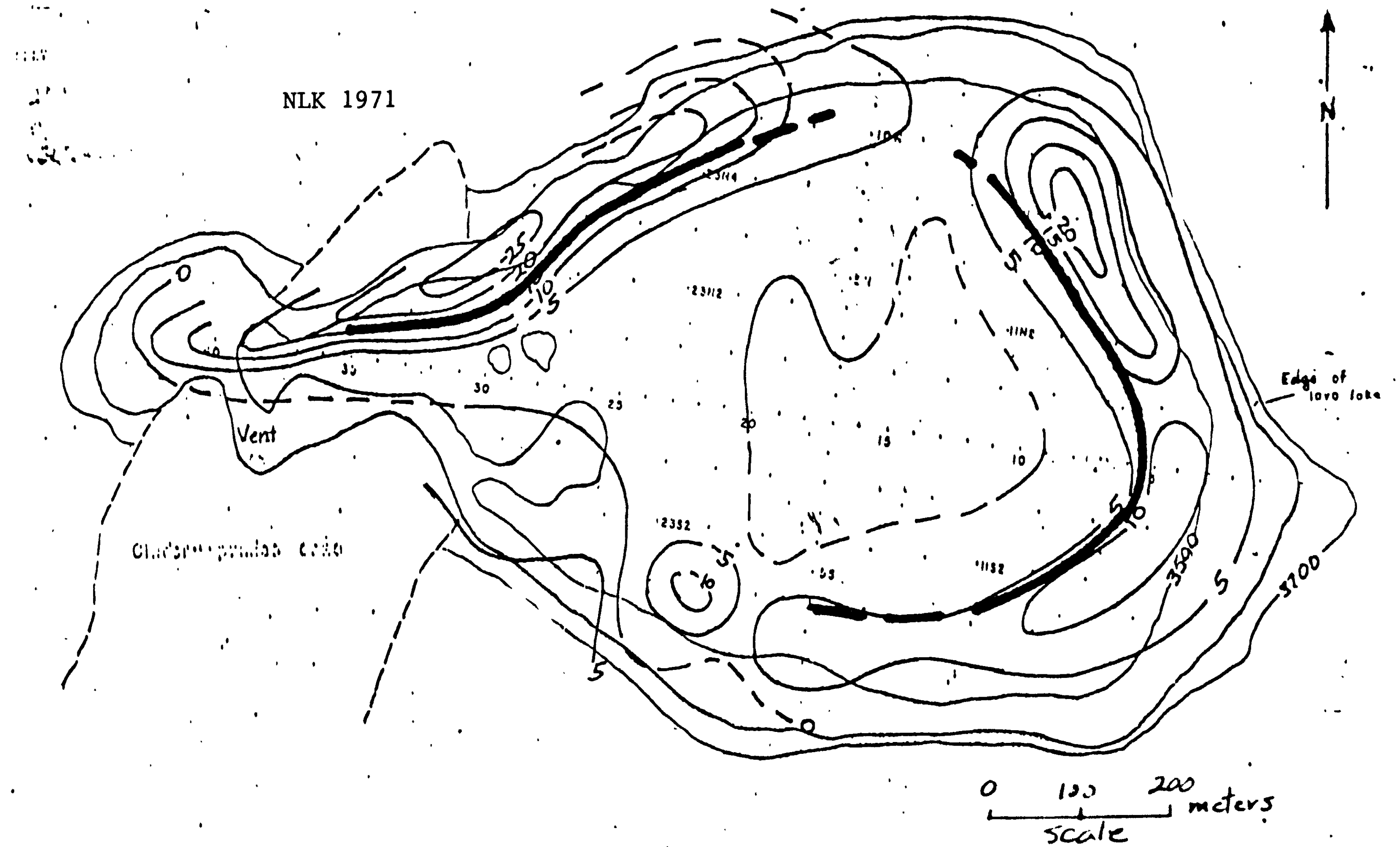


Figure 8



NLK 1971
N
Edge of lava lake
Vent
3500
3700
0 100 200 meters
scale

Figure 9

NLK-NPM 1979

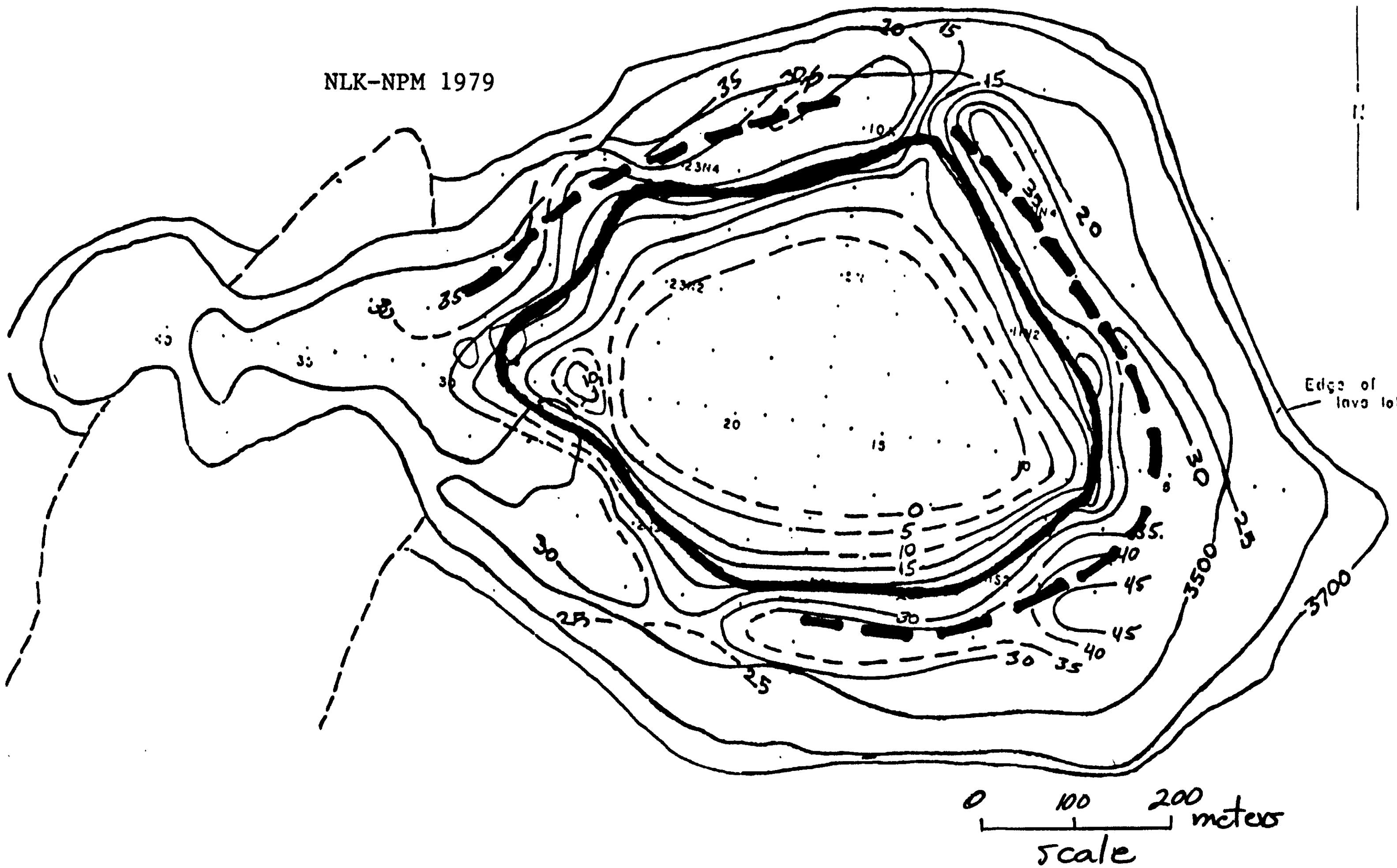


Figure 10

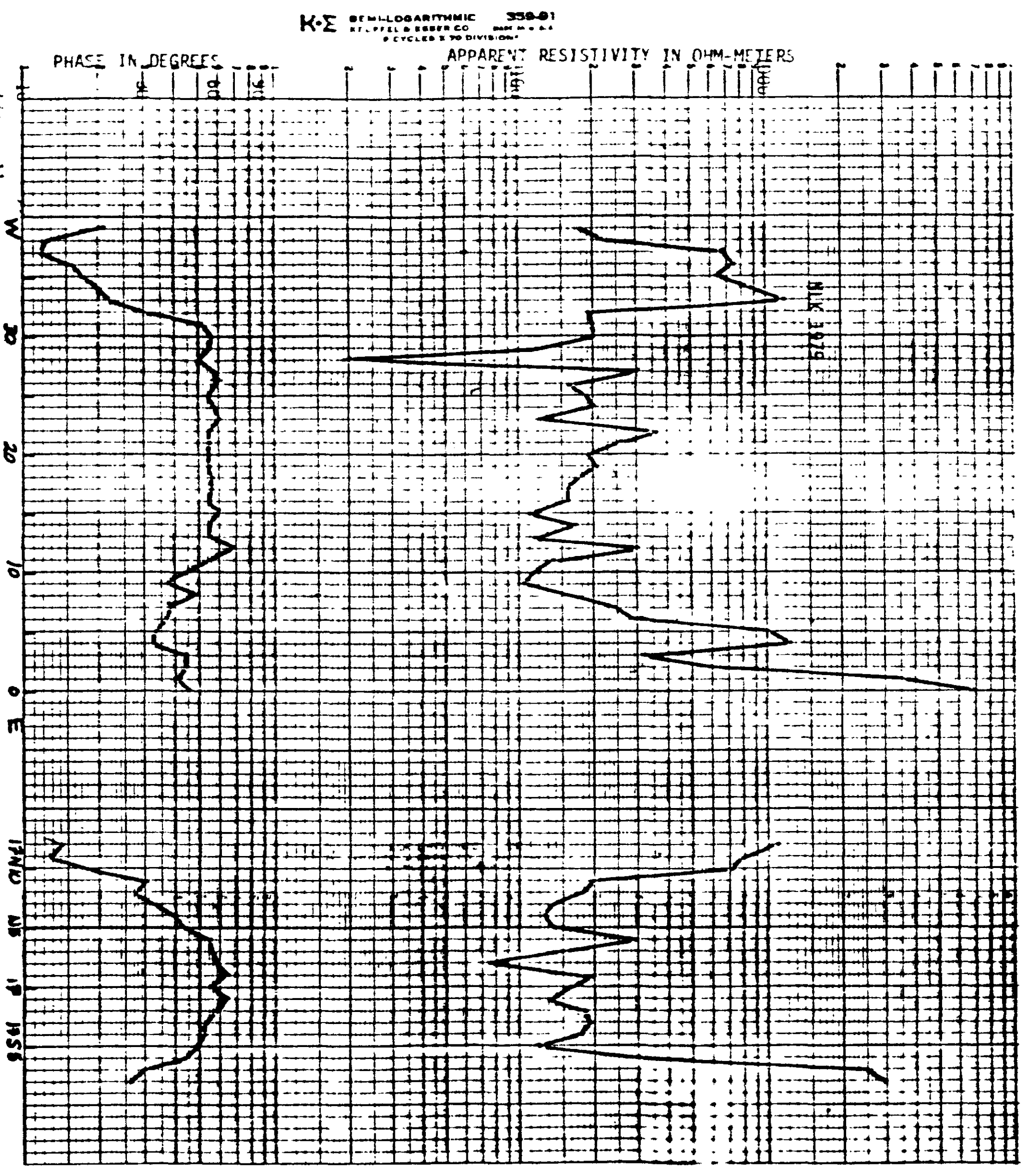

K·E SEMI-LOGARITHMIC 359-81
PHASE IN DEGREES
APPARENT RESISTIVITY IN OHM-METERS
W
30
20
10
0
E
NAIL
NLK 1979

figure 11


K+E SEMI-LOGARITHMIC 359-81
KEUFFEL & ESSER CO.
5 CYCLES X 70 DIVISIONS
PHASE IN DEGREES
APPARENT RESISTIVITY IN OHM-METERS
30
60
90
100
NPM 1979
30
20
10
0
NAIL
1958

Figure 12

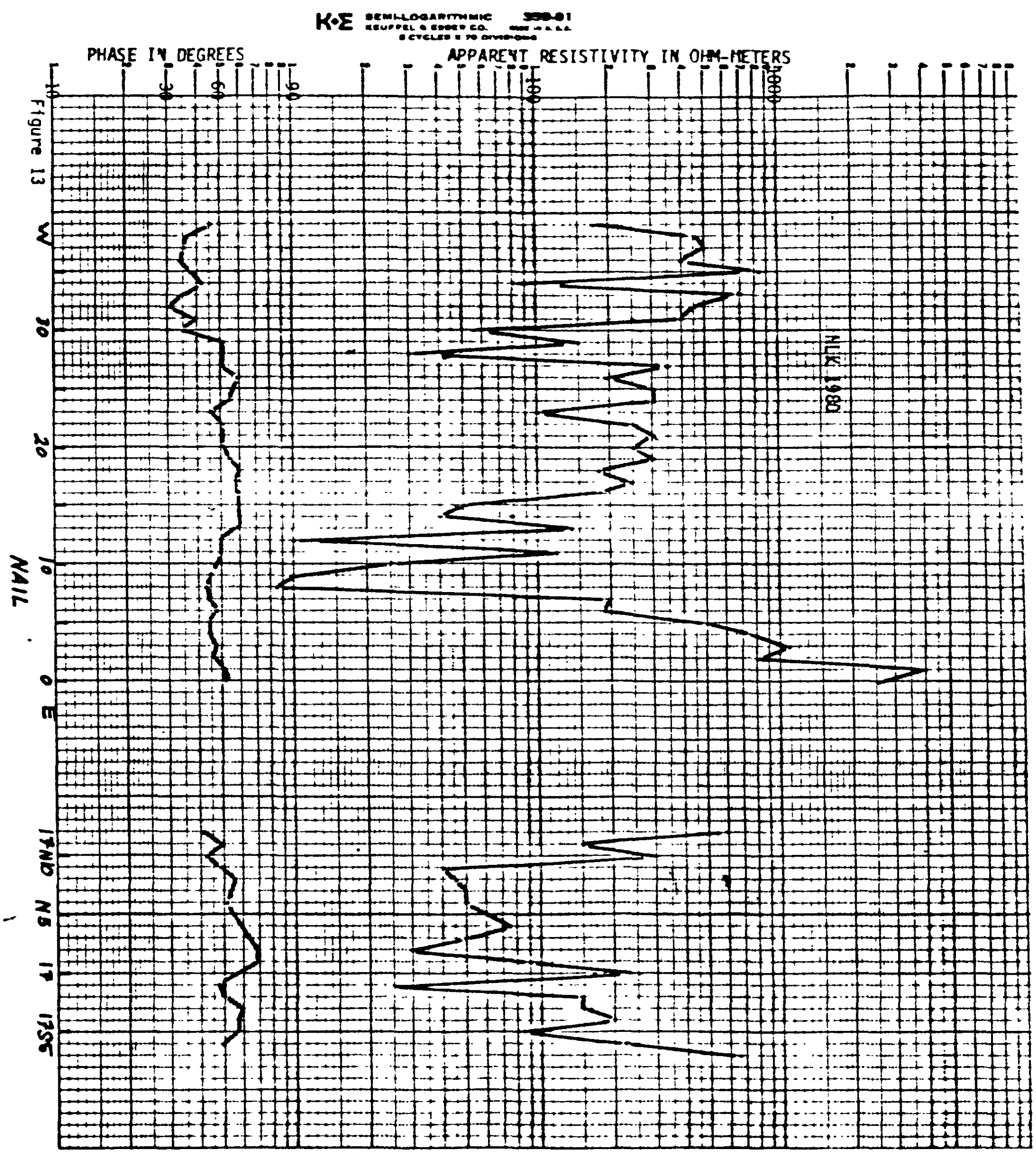
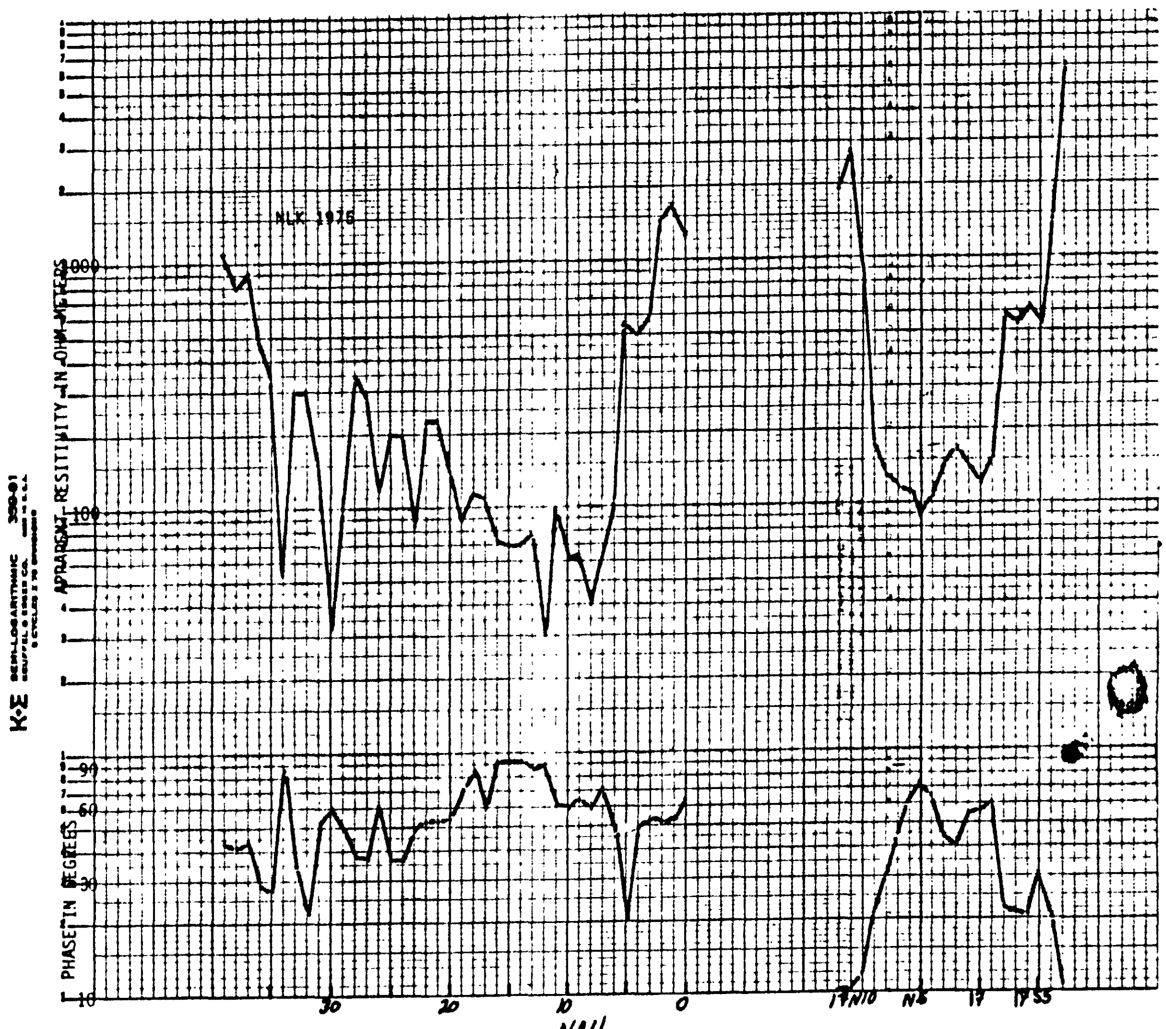
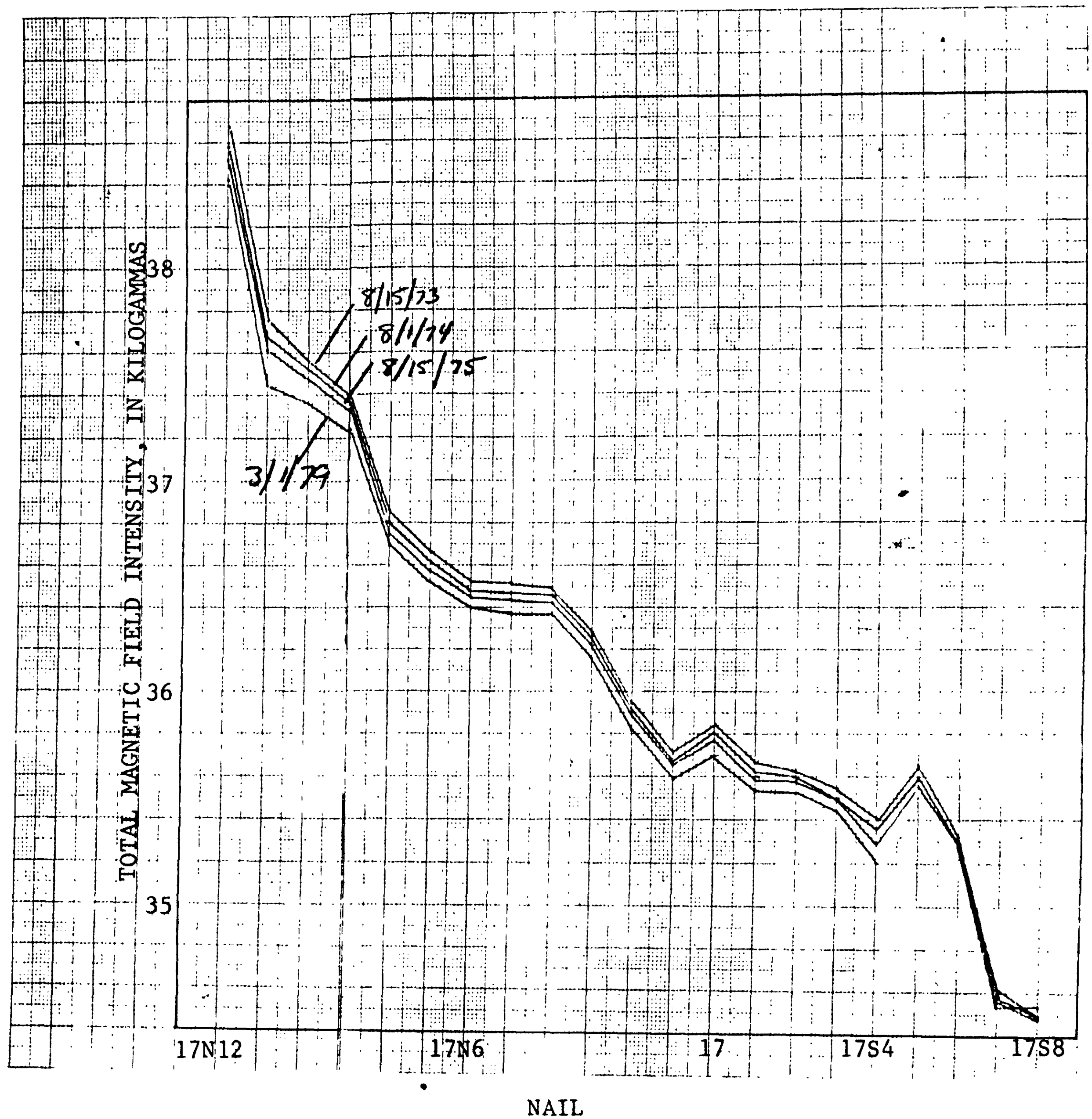

K·E SEMI-LOGARITHMIC 359-81
KEUFFEL & ESSER CO.
3 CYCLES X 70 DIVISIONS
PHASE IN DEGREES
APPARENT RESISTIVITY IN OHM-METERS
10
30
60
90
100
1000
W
30
20
10
0
E
NAIL
NLK 1980

Figure 13



K·E SEMI-LOGARITHMIC 359-81
NLK 1976
APPARENT RESITIVITY IN OHM METERS
PHASE IN DEGREES
1000
100
10
90
60
30
30
20
10
0
NAIL

Figure 14



TOTAL MAGNETIC FIELD INTENSITY, IN KILOGAMMAS
38
37
36
35
8/15/73
8/1/74
8/15/75
3/1/79
17N12
17N6
17
17S4
17S8
NAIL

Figure 15

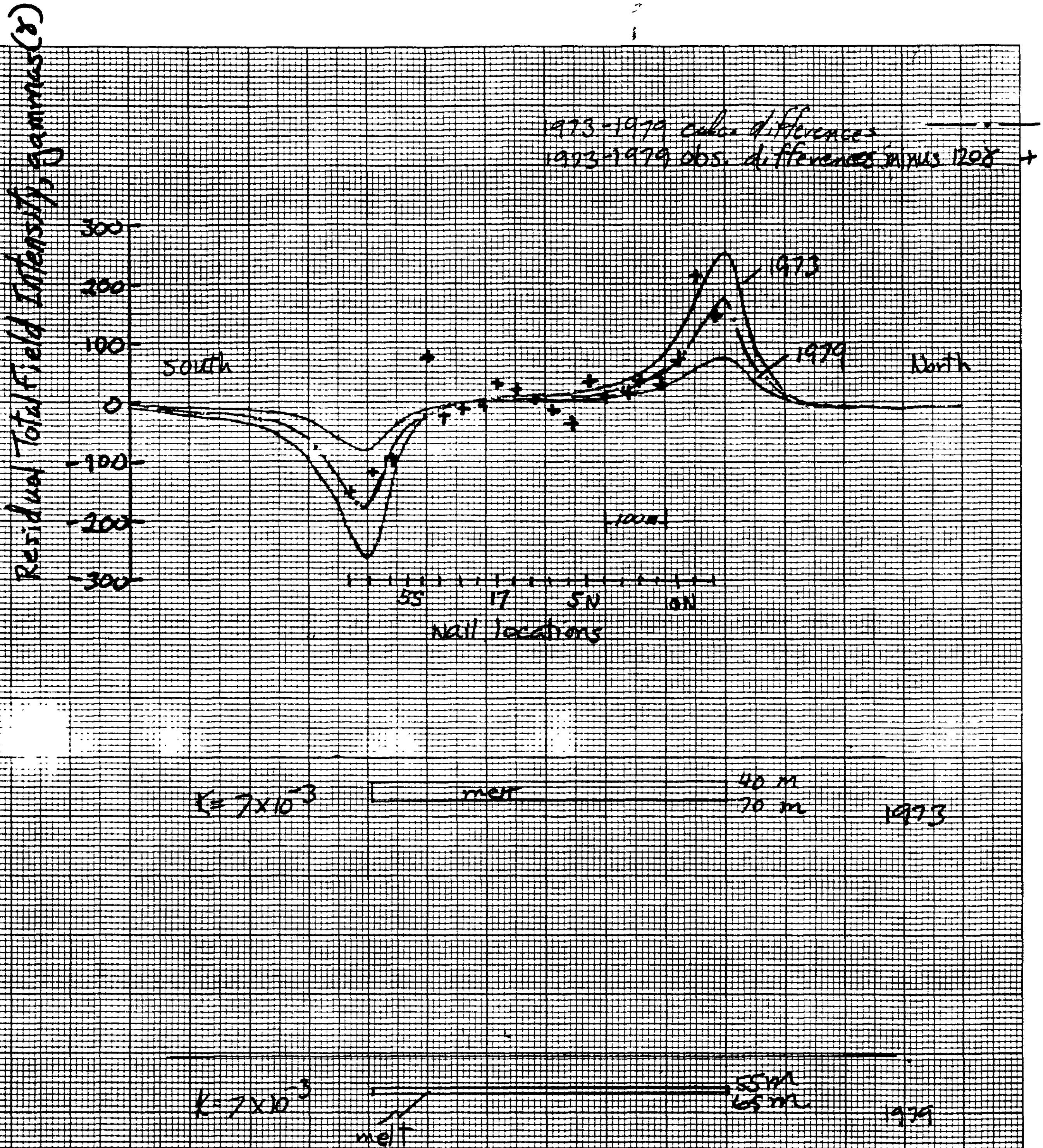

1973-1979 calc. differences
1973-1979 obs. differences minus 120γ
Residual Total Field Intensity, gammas (γ)
300
200
100
0
-100
-200
-300
South
North
1973
1979
100 m
55
17
5N
10N
Nail locations
k= 7x10^-3
melt
40 m
70 m
1973
k= 7x10^-3
55 m
65 m
melt
1979

Figure 16